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PRELIMINARY ANALYSIS OF THE SPAN-DISTRIBUTED-LOAD CONCEPT FOR CARGO AIRCRAFT DESIGN

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16. Abstract

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PRELIMINARY ANALYSIS OF THE SPAN-DISTRIBUTED-LOAD CONCEPT

FOR CARGO AIRCRAFT DESIGN

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SUMMARY

A simplified computer analysis of the span-distributed-load airplane (in which pay-load is placed within the wing structure) has shown that the span-distributed-load concept has high potential for application to future air cargo transport design. Significant in-creases in payload fraction over current wide-bodied freighters are shown for gross weights in excess of 0.5 Gg (1 000 000 lb). A cruise-matching calculation shows that the trend toward higher aspect ratio improves overall efficiency; that is, less thrust and fuel are required. The optimal aspect ratio probably is not determined by structural limita-tions. Terminal-area constraints and increasing design-payload density, however, tend to limit aspect ratio.

INTRODUCTION

The greatest opportunity for air transport growth and application of advanced con-cepts of design may be in the air cargo field, where projections of current trends (refs. 1 and 2) indicate an eightfold increase in worldwide commercial air freight demand toward the turn of the century. That analysis excludes trade with mainland China and Russia; if the political climate permits free trade with these major blocs, such estimates may be far too conservative (ref. 3). Analysts of current air cargo market trends have observed that historically a product value of around $1.00 per pound appears to establish a "thresh-old" for "air-eligible" commodities. Other factors must also be considered. However, if that product value could be lowered by 30 percent, then an increased penetration of the total market could move a whole new array of products across the air-eligible threshold: washers, refrigerators, automobiles, air conditioners, stoves, etc. (ref. 4).

A lower and more attractive product value for air transport depends on the reduc-tion of freight rates by a decrease in the direct operating costs connected with the air-planes and by an increase in aircraft productivity. All current jet freighters compromise the efficiency of the air cargo operation because their design is based on passenger trans-port criteria. A new application of the distributed-load concept to air cargo transport design could have a major impact in improved payload fractions and productivity and in

significant reductions of operating costs. The essential feature of this concept is a wing section thick enough for the placement of the cargo (and perhaps the fuel). Thus, the design would be driven toward a reduction or elimination of the fuselage and empennage. The reduced structural weight fraction reflects this benefit. Reference 5 provides a historical review of the distributed-load concept, a market projection and analysis, and a more detailed discussion of the concept and its application to several configuration geometries. Reductions in direct operating costs exceeding 50 percent are projected for the distributed-load cargo aircraft in comparison with current wide-body freighters (ref. 5).

This report presents the results of a preliminary parametric study of an unswept distributed-load configuration in order to evaluate the sensitivity of payload and empty-weight fractions to geometric and mission variables. A cruise-matching exercise was conducted to provide a further basis for selection of meaningful design criteria. A parametric analysis was conducted to determine the empty weight of the design by assigning power-law variations to the various components making up the empty weight.

SYMBOLS

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

A	aspect ratio
A_{opt}	optimal aspect ratio for minimum W_G
a	speed of sound, m/s (ft/s)
b	wing span, m (ft)
$C_{D,o}$	profile drag coefficient
C_L	lift coefficient
c	wing chord, m (ft)
e	wing efficiency factor
h	altitude, km (ft)
K_1, K_2, K_3, K_4	(see fig. 1)

K_5, K_6 constants appearing in sizing formulation (defined in text)

k_1, k_2, k_3, k_4 power-law values for determination of operating empty weight W_O

L/D lift-to-drag ratio

M Mach number

q dynamic pressure, kPa   (lb/ft^2)

R range, km   (n. mi.)

S wing area, m^2 (ft^2)

SFC   specific fuel consumption, kg/N-hr   (lbm/lbf-hr)

T thrust, N   (lb)

t wing thickness, m   (ft)

V_P payload volume, m^3 (ft^3)

W_F fuel weight, Gg   (lb)

W_G gross weight, $W_F + W_O + W_P$, Gg   (lb)

W_G/S wing loading, kPa   (lb/ft^2)

W_O operating empty weight, Gg   (lb)

W_P payload weight, Gg   (lb)

W_U useful load, $W_F + W_P$, Gg   (lb)

ρ_F fuel density, kg/m^3 (lb/ft^3)

ρ_P payload density, kg/m^3 (lb/ft^3)

ρ_U useful load density, kg/m^3 (lb/ft^3)

Subscripts:

CR   cruise

P   payload

TO   take-off

U   useful load

ANALYSIS AND DISCUSSION

The unswept distributed-load configuration is modeled by assuming a contoured airfoil section housing a rectangular cargo bay. (See fig. 1.) A more realistic cargo bay structure would probably employ a contoured cross section, especially if the bay were to require pressurization. This study focuses on the relative values of the results rather than attempting to establish unquestionable validity for the absolute values.

The analysis of the appendix shows that the wing loading of the distributed-load design is proportional to the useful load density multiplied by the wing thickness:

$$\frac{W_G}{S} \propto \rho_U t$$

A reasonable value for minimum cargo bay height is 3 m (9.8 ft). The appendix example then shows that for a payload density typical of the contemporary commercial freight market, wing loading is around 3.3 kPa (less than 70 lb/ft^2). Current transport aircraft generally exhibit wing loadings exceeding 4.8 kPa (100 lb/ft^2). The span-distributed-load airplane must therefore be of considerable size or must carry a dense useful load in order to reach a wing loading approaching modern transports. A sufficiently high wing loading is required to minimize structural gust load requirements and to provide a matched-cruise condition (discussed subsequently). By defining configuration geometry in such a way as to fulfill a specified volume requirement within a wing of least surface area, wing loading can be increased toward an optimal value, and skin friction can be minimized. The nondimensional volume parameter $\left(V_P\right)^{2/3}\!\!\Big/S$, shown in figure 2, represents a "volume efficiency." This figure indicates that this efficiency is improved as aspect ratio is lowered or as thickness ratio is increased. The dashed lines on the figure indicate that an equivalent increase in the volume efficiency can be obtained by decreasing aspect ratio from 6 to 4 or by raising thickness ratio from 0.19 to 0.23.

A sizing program was written for a desk-sized computer. The operating empty weight was assumed to grow as a function of power-law variations of aspect ratio, wing

area, payload and fuel weights, and thickness ratio:

$$W_O = K_5 \cdot (A)^{k_1} \cdot (S)^{k_2} \cdot \left(W_P + W_F\right)^{k_3} \cdot (t/c)^{k_4}$$

Fuel weight is determined from the Breguet range equation, assuming that a fuel weight increment of $0.07\ W_G$ is required to cover fuel requirements for other than cruise operation (reserves, take-off and landing, etc.). Thus,

$$W_F = 1.07 W_G \left(1 - e^{-R/B}\right)$$

Also,

$$B \equiv \text{Breguet range factor} = \frac{Ma(L/D)}{SFC}$$

Let

$$\frac{L}{D} = \left(\frac{\pi e A}{4 C_{D,o}}\right)^{1/2}$$

where $e = 0.85$ and $C_{D,o} = 0.00583\left[1 + 2(t/c) + 60(t/c)^4\right]$. (The thickness-ratio effect on $C_{D,o}$ was obtained from ref. 6.)

For a current high bypass ratio turbofan engine operating around $M = 0.7$ and $h = 10.7$ km (35 000 ft),

$$SFC = 0.064\ \frac{kg}{N\text{-}hr}\ \left(0.63\ \frac{lbm}{lbf\text{-}hr}\right)$$

Now

$$W_G = W_O + W_F + W_P$$

and

$$\frac{W_G}{S} = K_4^{2/3} W_G \left[\frac{(t/c)^2}{A V_P^2}\right]^{1/3}$$

where

$$K_4 = \frac{t}{t_P} \cdot \frac{c}{c_P} \cdot \frac{b}{b_P}$$

The values of the constants K_4, K_5, k_1, k_2, k_3, and k_4 were determined from guidelines of empirical data, from an assumption of the structural composition of the wing, and from a study of the results of several unpublished analyses of the unswept span-distributed-load airplane. Values of the power law k_1 for the effect of aspect ratio on wing structural weight vary widely in the literature for conventional fuselage-loaded transport aircraft. The references shown in figure 3 represent the extremes of the results obtained in cases when the weight is normalized at $A = 6$. Because the increased aerodynamic loading experienced by increased aspect ratio can be offset by additional pay-load, the impact on distributed-load airplanes is assumed to be small. A value of $k_1 = 0.2$ was assigned to represent a slight structural weight increase which accounts for the effect of aspect ratio on landing loads.

The value of the power law on useful load k_3 was determined from an analysis of unpublished industry data on a preliminary distributed-load design. Several power-law fits to the available data are shown in figure 4. From this figure, a value of $k_3 = 0.35$ was selected. The values of k_2 and k_4 were set at 0.7 and -0.2, respectively, based on sources such as references 7 and 8.

It should be noted that this analysis covers a range of aspect ratio up to 14 and of gross weights up to 1.1 Gg (2 500 000 lb). The higher values of these parameters are beyond the range of available empirical data and may not properly account for flutter or ground-air-ground cycles. The results of this study simply show the nature of variation in the key design parameters as mission and geometric variables are changed; therefore, the importance of the absolute values must be considered in the proper context. The inputs to this program are t/c, A, W_P, R, S, and M. The outputs which are used in figures 5 to 11 are W_O/W_G, W_F/W_G, W_P/W_G, W_G, V_P, and W_G/S. All the analyses were conducted at $M = 0.7$. The results of this study show a variation in pay-load density to encompass a variety of design payloads and missions. The density of general air freight is assumed to range from about 130 to 300 kg/m^3 (8 to 18 lb/ft^3); liquid natural gas (LNG) has a density of about 400 kg/m^3 (25 lb/ft^3) and crude oil and JP-4 fuel a density of about 800 kg/m^3 (50 lb/ft^3).

Increasing gross weight has a beneficial impact on W_O/W_G and W_P/W_G, as seen in figures 5 and 6. The magnitude of the benefit is, of course, dependent on the manner in which the gross weight is increased. For example, the reduction in the empty-weight

fraction is relatively large when the gross-weight increase occurs because of an increase in payload weight and density (fig. 5) or an increase in thickness ratio (fig. 6(b)). In contrast, the reduction in empty-weight fraction is relatively small when the gross weight increases because of a wing area change with payload density held constant (fig. 6(a)). The shaded region on the lower portion of figure 5 bounds the range of payload density representative of general air freight. Data shown for the Boeing 747F dedicated (designed specifically for cargo) freighter indicate a potentially favorable application of the span-distributed load even for gross weights as low as 0.36 Gg (800 000 lb). The most favorable aspect-ratio benefit on payload fraction occurs at the highest gross weight. As aspect ratio increases, the aerodynamic efficiency increases to reduce the fuel required; balancing this favorable trend is the increase in structural weight W_O with increasing aspect ratio. The trade-off of these variables to produce the lowest gross-weight design results in the analysis shown in figure 7. The aspect ratio for minimum W_G (defined as A_{opt}) is found to increase with increasing payload weight and to increase with decreasing wing area. The payload volume shrinks with increasing aspect ratio when the wing area and thickness ratio are held constant. (Recall fig. 2.) Thus, as design-payload density increases, the optimal aspect ratio for minimum gross weight also increases.

Fuel consumption is strongly influenced by aspect ratio, with the most severe degradation in fuel efficiency occurring at the lowest aspect ratios and the highest payload weights (fig. 8). The results in figures 5, 7, and 8 show that, as payload weight (and payload density) increases, the trend toward a higher optimal aspect ratio reflects the increased importance of aerodynamic efficiency and reduced fuel consumption penalties in structural weight. No advances in engine technology have been assumed in this analysis.

In order to select a meaningful combination of mission and configuration variables, the sensitivity of payload density must be considered. Plots such as those in figure 9 are useful for determining values needed to describe the design characteristics. This process is necessarily an iterative one; for example, a cruise-matching analysis (discussed later) dictates the wing loading value required to enter the charts in figure 9. Minimum and maximum boundaries for payload density are somewhat arbitrarily selected to define a region of admissible values of the parameters. Four plots indicate the effect of changing range and wing area on the range of admissible values. The filled symbol represents aspect ratio 4 and $W_P = 0.27$ Gg (600 000 lb) and is located on all the plots to show the migration of the carpet plot with range and wing area variation. This figure shows that a reduction in aspect ratio reduces the design-payload density. The figure also indicates that the problem of achieving a high enough wing loading (discussed earlier) could be alleviated by keeping the aspect ratio low and the payload weight high; a long-range mission requirement also drives the design toward a higher wing loading. Thus, the selection of aspect ratio must strike a balance between the wing loading requirement and the payload and fuel efficiency associated with the higher values of this parameter.

Wing area is obviously a key design parameter and is the independent variable in figures 10 and 11. The effect of payload weight and aspect ratio is shown independently in figures 10(a) and 10(b). Results such as those in figure 8 for fuel required illustrate the benefit of higher aspect-ratio configurations. Figure 10 reveals that in order to maintain a selected value of payload density as aspect ratio (or payload weight) is increased, the wing area and hence vehicle size must be increased. For aspect ratio = 6 and payload weight = 0.36 Gg (800 000 lb), figure 11 shows the impact of wing area on payload density, wing loading, payload and empty-weight fractions, and gross weight. The dashed line shows the design selection for a payload density of 160 kg/m^3 (10 lb/ft^3).

A simple matching relationship was derived to determine desired wing loading and lift coefficient. A second-degree polynomial fit was made to prescribe the dynamic pressure variation with altitude:

$$\frac{q}{M^2} = a_1 + a_2 \cdot h^2 + a_3 \cdot h^3$$

where a_1, a_2, and a_3 are constants. Lift coefficient is determined from

$$C_L = \frac{W_G/S}{\left(q/M^2\right)M^2}$$

and cruise thrust-to-weight ratio is defined as

$$\text{Cruise} \frac{T}{W} = \frac{q}{W_G/S}\left[C_{D,o} + \frac{C_L^2}{\pi A e}\right]$$

Characteristics of a high bypass ratio turbofan engine were used to determine lapse ratio and to convert cruise thrust to take-off conditions.

Figures 12 and 13 are matching charts for a given payload of 0.36 Gg (800 000 lb), a payload density of 160 kg/m^3 (10 lb/ft^3), and a range of 4630 km (2500 n. mi.). All data are converted to take-off thrust-to-weight values. Boundaries on the chart are established by the second segment climb criterion (engine-out condition), an approach speed limit, and a 3-km (10 000-ft) take-off field length. Two values of take-off lift coefficient are shown: 1.5 and 2.0. The lower value is about the maximum lift obtainable with a simple mechanic flap system; $C_{L,TO} = 2.0$ could be obtained by augmenting the lift by blowing the control surfaces. It is apparent from figures 12 and 13 that for the mission variables selected, augmented lift is required to minimize T_{TO}/W_G and to provide for reasonable values of aspect ratio and cruise C_L.

Three design points are shown in figures 12 and 13; detailed analyses of these data are shown in table I to determine the best design selection. Contours of constant W_G are shown in figure 12. Of the three design points selected, the orientation of the constant W_G contours suggests that the highest wing loading (at about 4.5 kPa (94 lb/ft^2)) minimizes gross weight. Opposing this favorable trend in reduced W_G is the benefit in reduced T_{TO}/W_G obtained by moving to lower wing loading parallel to the take-off field-length boundary. The minimum matched-cruise wing loading is determined by the maximum allowable aspect ratio. (See fig. 13.) Detailed data given in table I show the option of lower T_{TO}/W_G to be more favorable than minimum W_G. The higher aspect ratio associated with the lowest wing-loading design point minimizes the fuel required for the mission; this design point further requires the least thrust, i.e., the smallest engines. An aspect-ratio-12 aircraft may be impractical, however, because of the potential terminal parking and maneuvering problems associated with the large span and because of the higher design-payload density associated with the high aspect ratio. Values of cruise C_L average about 0.46 for the three design points. This relatively low lift coefficient may be desired to maintain an attached boundary layer with high thickness-ratio airfoils and to provide a cruise match at the moderate wing loading which is characteristic of the distributed-load design. More detailed studies are necessary to evaluate the relative importance of conflicting design requirements.

CONCLUSIONS

The parametric analysis and cruise-matching exercise are preliminary in scope and require several assumptions for growth of structural weight with changes in geometry of the span-distributed-load design. However, the trends of these results do suggest some salient characteristics of a design of this type:

1. Increased gross weight provides a benefit in reduced empty-weight fraction and improved payload fraction. The magnitude of the benefit is highest when design-payload density is allowed to vary; however, the gains are relatively small when the gross weight is changed by variation in aspect ratio and wing area. A minimum gross weight of around 0.5 Gg (1 000 000 lb) is required to show an advantage over current wide-body freighters.

2. The matching exercise shows that a higher aspect ratio provides a more efficient configuration; that is, less thrust and fuel are required. However, the large span associated with the high aspect ratio may be incompatible with current or future runway facilities and, by reducing volumetric efficiency, the high aspect ratio may lead to a compromised efficiency in arrangement of cargo container bays. Further, the increased aspect ratio may force the design-payload density beyond the desired value for compatibility with

future market requirements. Thus, the maximum aspect ratio probably is not determined by structural limitations.

3. Gross weight is relatively insensitive to aspect ratio because the improvement in aerodynamic efficiency is offset by the increase in structural weight.

4. Fuel consumption improves rapidly with increased aspect ratio, with the greatest benefit found for the highest design payload.

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APPENDIX

APPROXIMATE AIRCRAFT SIZING FROM WING LOADING

Equations to determine approximate sizing are:

$$W_U = W_P + W_F = \rho_U \left(b_U c_U t_U \right)$$

$$S = bc$$

$$\frac{W_G}{S} = \frac{W_G}{W_U} \cdot \frac{W_U}{bc} = \frac{W_G}{W_U} \cdot \frac{b_U c_U t_U}{bct} \cdot \frac{W_U}{b_U c_U t_U} \cdot t$$

or

$$\frac{W_G}{S} = \frac{K_6}{1 - \dfrac{W_O}{W_G}} \cdot \rho_U \cdot t$$

where

$$\rho_U = \frac{W_F / W_G + W_P / W_G}{\dfrac{W_F / W_G}{\rho_F} + \dfrac{W_P / W_G}{\rho_P}}$$

and

$$K_6 = \frac{b_U c_U t_U}{bct}$$

Now, if $W_O / W_G = 0.30$ and $K_6 = 0.36$, then

$$\boxed{\frac{W_G}{S} = 0.52 \rho_U t}$$

For example, from figure 5, with $W_O / W_G = 0.30$ and $A = 7$,

$$\frac{W_P}{W_G} = 0.48$$

so

$$\frac{W_F}{W_G} = 1 - \left(\frac{W_P}{W_G} + \frac{W_O}{W_G}\right) \approx 0.22$$

Now set

$$\rho_P = 160 \text{ kg/m}^3 \ (10 \text{ lb/ft}^3)$$

$$\rho_F = 780 \text{ kg/m}^3 \ (49 \text{ lb/ft}^3)$$

giving

$$\rho_U = 213 \text{ kg/m}^3 \ (13.3 \text{ lb/ft}^3)$$

About 3-m (9.8 ft) clearance is required for 2.4- by 2.4-m (8- by 8-ft) containers; thus,

$$\frac{W_G}{S} = 0.52\rho_U t = 3.3 \text{ kPa} \ (69 \text{ lb/ft}^2)$$

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TABLE I.- DETERMINATION OF BEST DESIGN FOR FIXED PAYLOAD

$t/c = 0.19;$ $M = 0.7;$ $\rho_P = 160$ kg/m^3 (10 lb/ft^3);

$R = 4630$ km (2500 n. mi.);

$\boxed{}$ = Optimum value

A	7	9	12
h, km (10^3 ft)	9.1 (30)	9.7 (32)	10.4 (34)
W_G, Gg (10^6 lb)	$\boxed{0.693 \ (1.53)}$	0.704 (1.55)	0.720 (1.59)
T_{TO}/W_G, N/kg (lbf/lbm) . . .	1.77 (0.180)	1.65 (0.168)	1.53 (0.156)
T_{TO}, MN (10^6 lb)	1.22 (0.275)	1.16 (0.260)	$\boxed{1.10 \ (0.248)}$
C_L	0.451	0.463	0.473
L/D	23.3	26.6	30.5
W_G/S, kPa (lb/ft^2)	4.50 (94.0)	4.20 (87.7)	3.90 (81.5)
W_P/W_G	0.523	0.516	0.504
W_P, Gg (10^6 lb)	0.362 (0.8)	0.362 (0.8)	0.362 (0.8)
W_F/W_G	0.218	0.201	0.185
W_F, Gg (10^6 lb)	0.151 (0.333)	0.142 (0.313)	$\boxed{0.133 \ (0.294)}$
W_O/W_G	0.259	0.283	0.311
W_O, Gg (10^6 lb)	$\boxed{0.179 \ (0.395)}$	0.200 (0.439)	0.224 (0.495)

$$t_P = K_1 t$$

$$c_P = K_2 c$$

$$b_P = K_3 b$$

$$K_4 = K_1 \cdot K_2 \cdot K_3$$

Planform area .... $S = bc$

Aspect ratio .... $b^2/S = b/c$

Thickness ratio.... t/c

Payload volume .... $V_P = t_P c_P b_P$

$$= K_4 tcb$$

Cargo hold

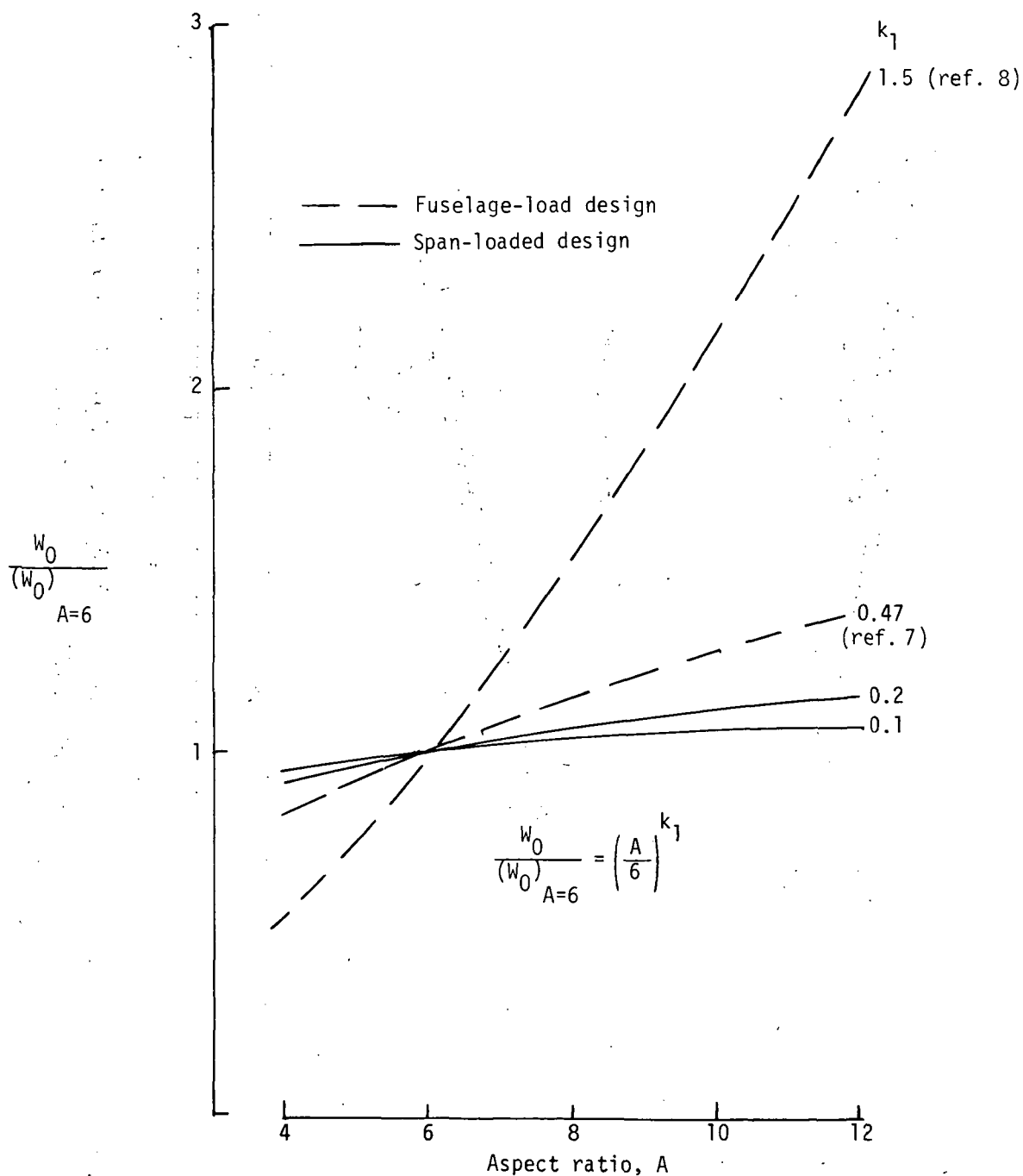Figure 1.- Sketch of span-distributed-load wing section.

15
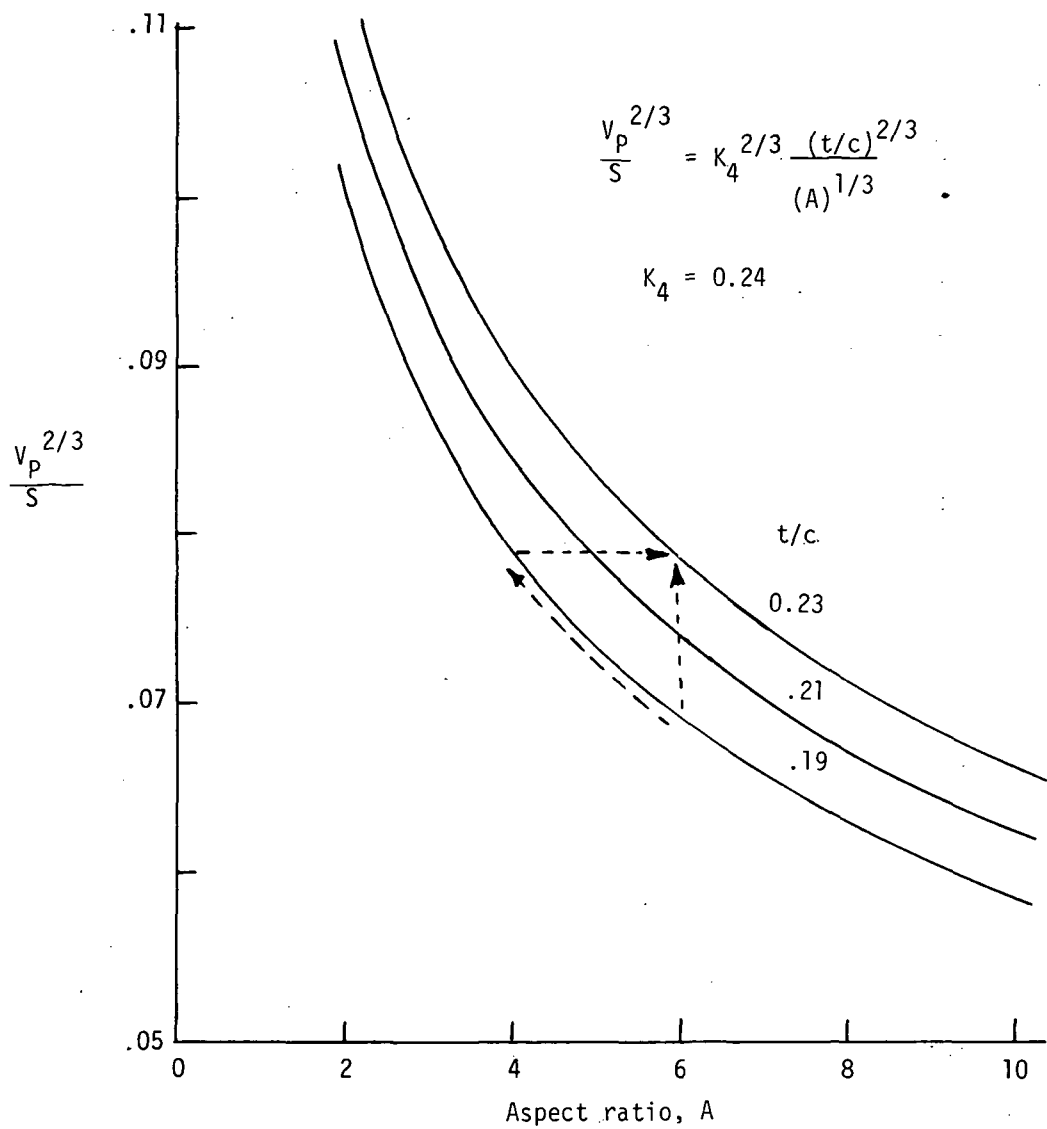
Figure 2.- Volumetric efficiency.

Figure 3.- Determination of constant k_1.
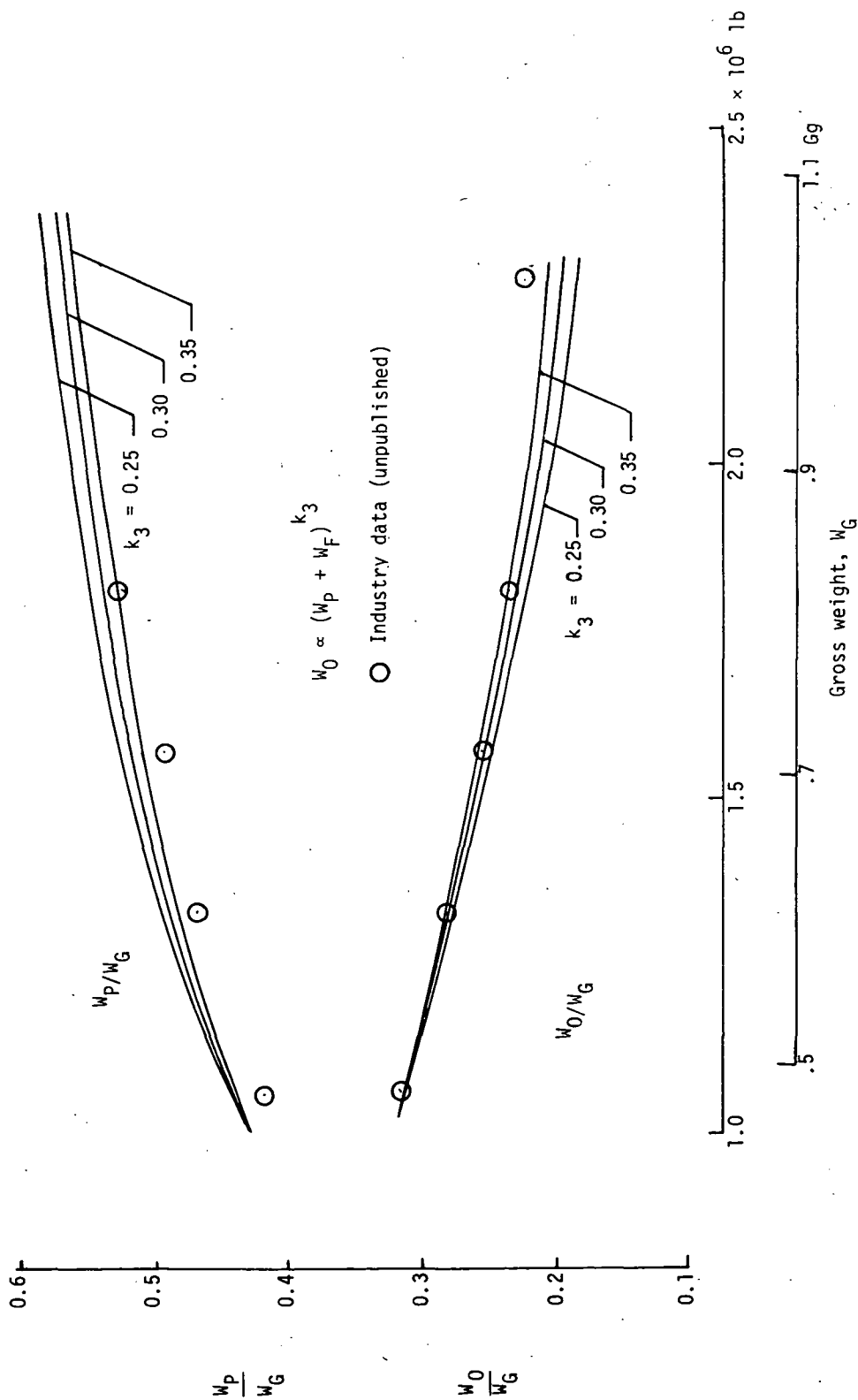
Figure 4.- Determination of constant k_3; $M = 0.75$; $t/c = 0.215$; $S = 1710 \text{ m}^2$ ($18\ 435 \text{ ft}^2$); $R = 4630 \text{ km}$ (2500 n. mi.); $A = 4.88$.
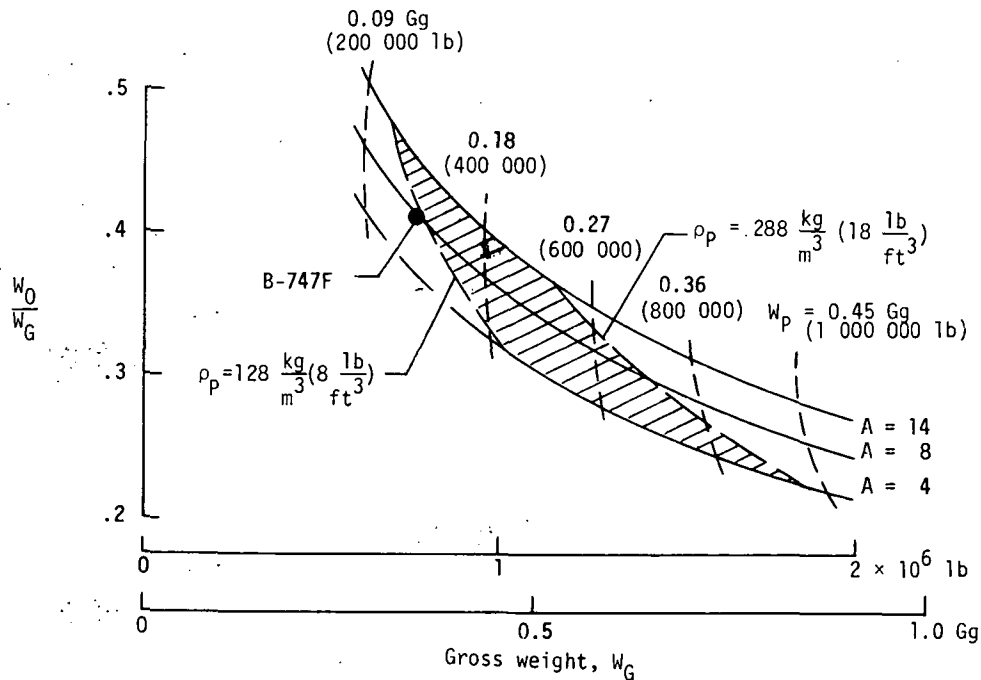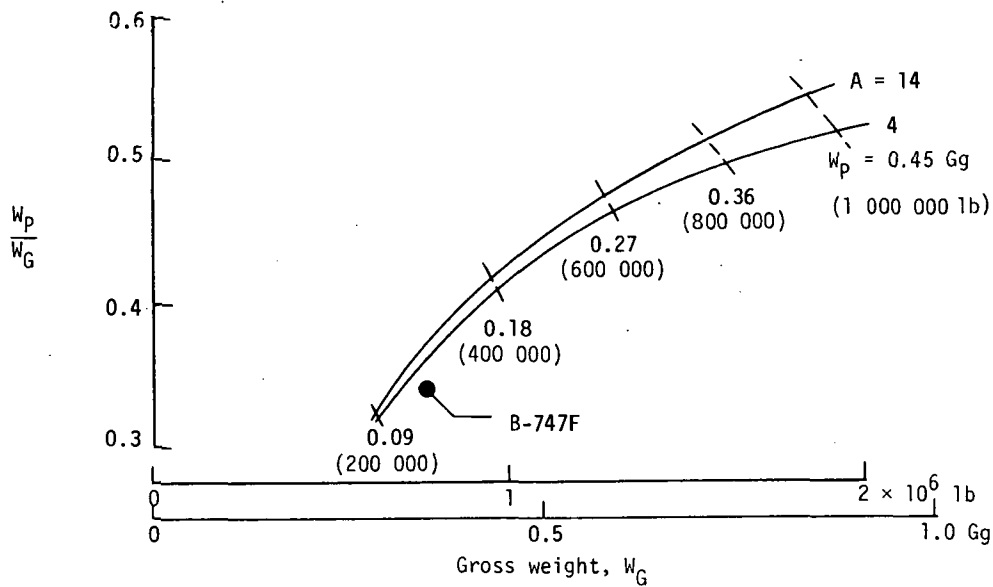
Figure 5.- Effect of geometry and gross weight on payload and empty-weight
   fractions with constant $t/c = 0.19$ and $S = 1670$ m^2 (18 000 ft^2);
   $M = 0.7$; $R = 4630$ km (2500 n. mi.); $t/c = 0.19$.

.5

.4

$\dfrac{W_O}{W_G}$

.3

.2

A = 14

A = 8

A = 4

S = 930 m^2
(10 000 ft^2)

1670
(18 000)

2410
(26 000)

0   1   2 × 10^6 lb

0   0.5   1.0 Gg

Gross weight, W_G

(a)   t/c = 0.19.

.5

.4

$\dfrac{W_O}{W_G}$

.3

.2

	t/c
O	0.13
□	.16
◇	.19
△	.22
◿	.25

A

Filled symbol,   14
Half-filled symbol 8
Open symbol   4

0   1   2 × 10^6 lb

0   0.5   1.0 Gg
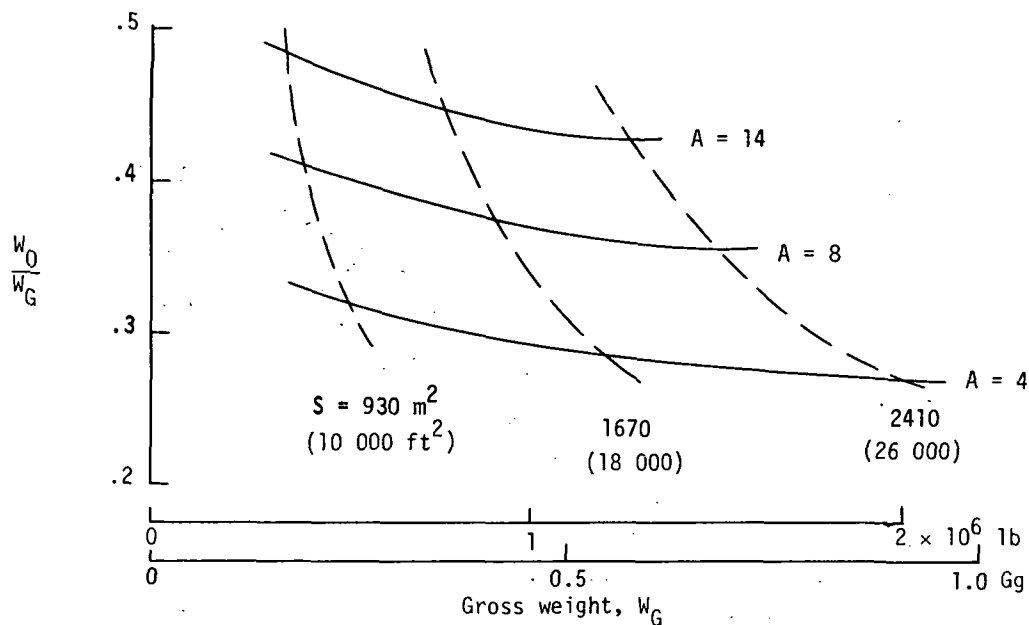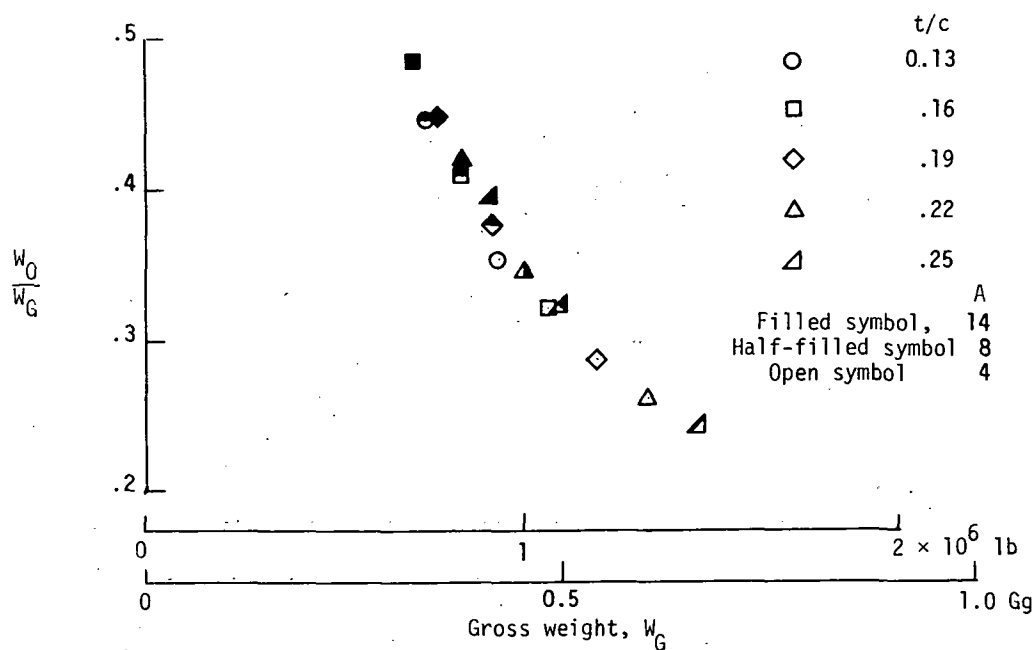
Gross weight, W_G

(b)   S = 1670 m^2 (18 000 ft^2).

Figure 6.- Effect of geometry and gross weight on empty-weight fraction with
constant ρ_P = 160 kg/m^3 (10 lb/ft^3);   M = 0.7;   R = 4630 km (2500 n. mi.).

Figure 7.- Effect of aspect ratio on gross weight at given wing area.
M = 0.7; t/c = 0.19; R = 4630 km (2500 n. mi.).
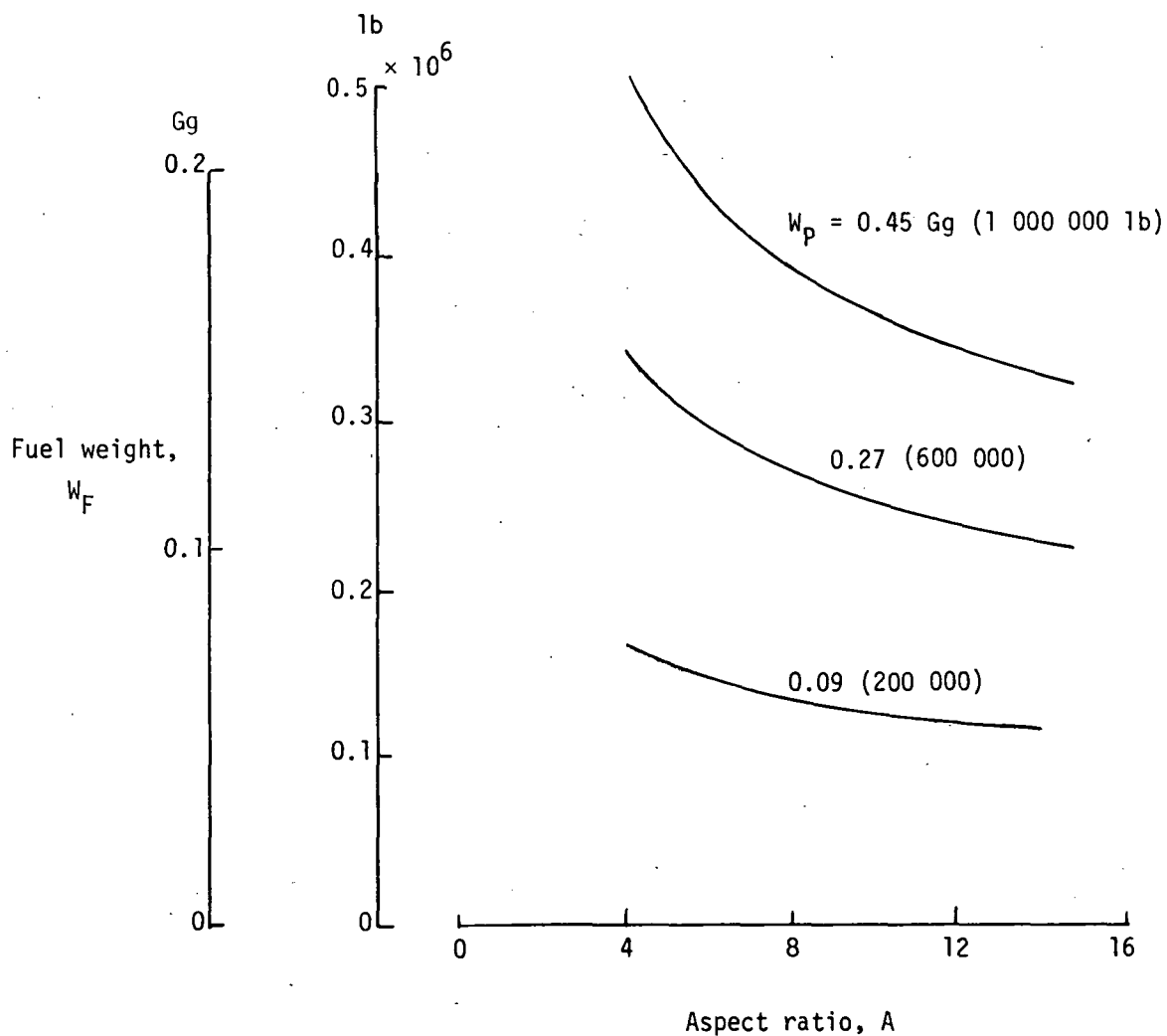
Figure 8.- Effect of aspect ratio on fuel weight;   M = 0.7;   t/c = 0.19;
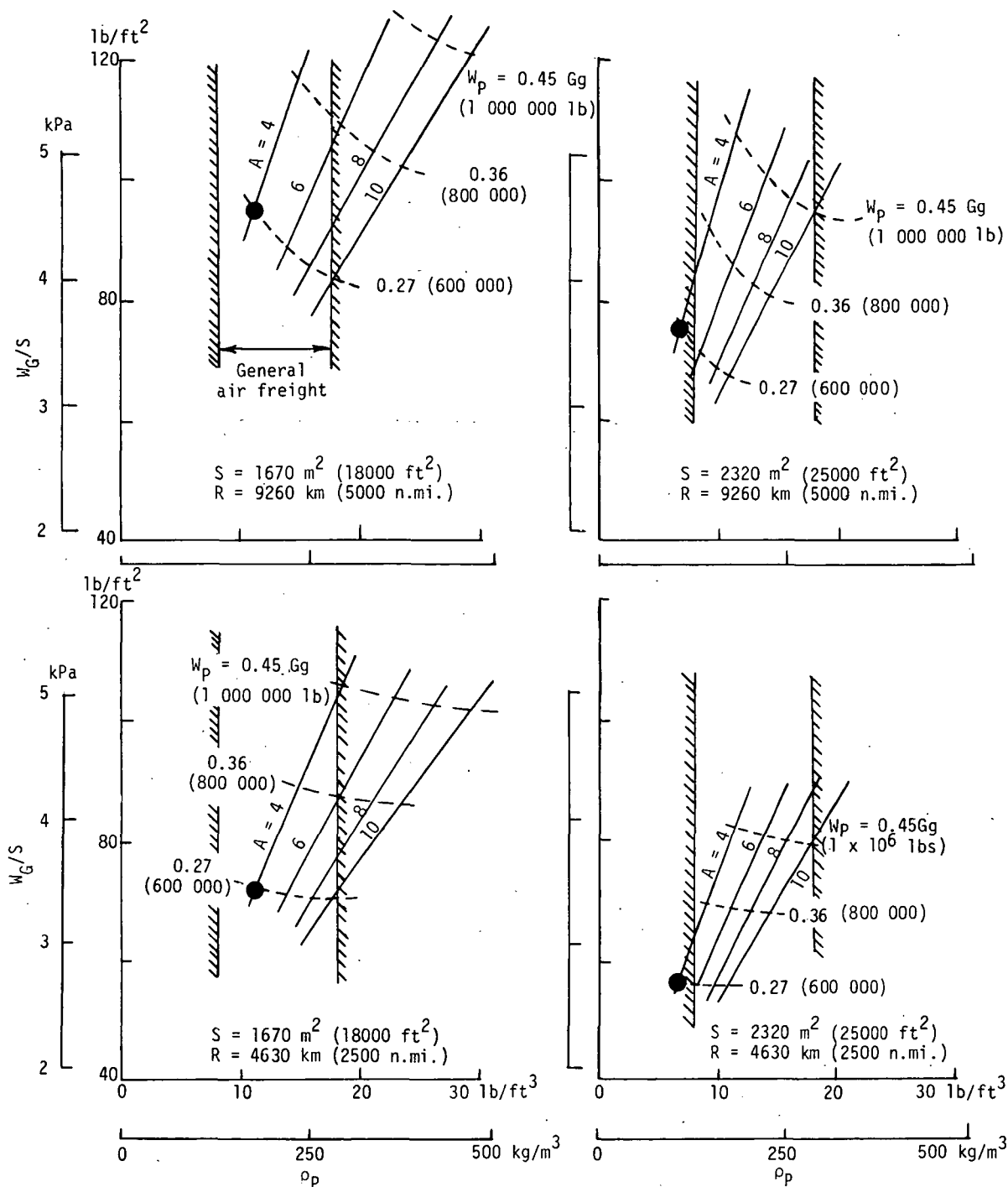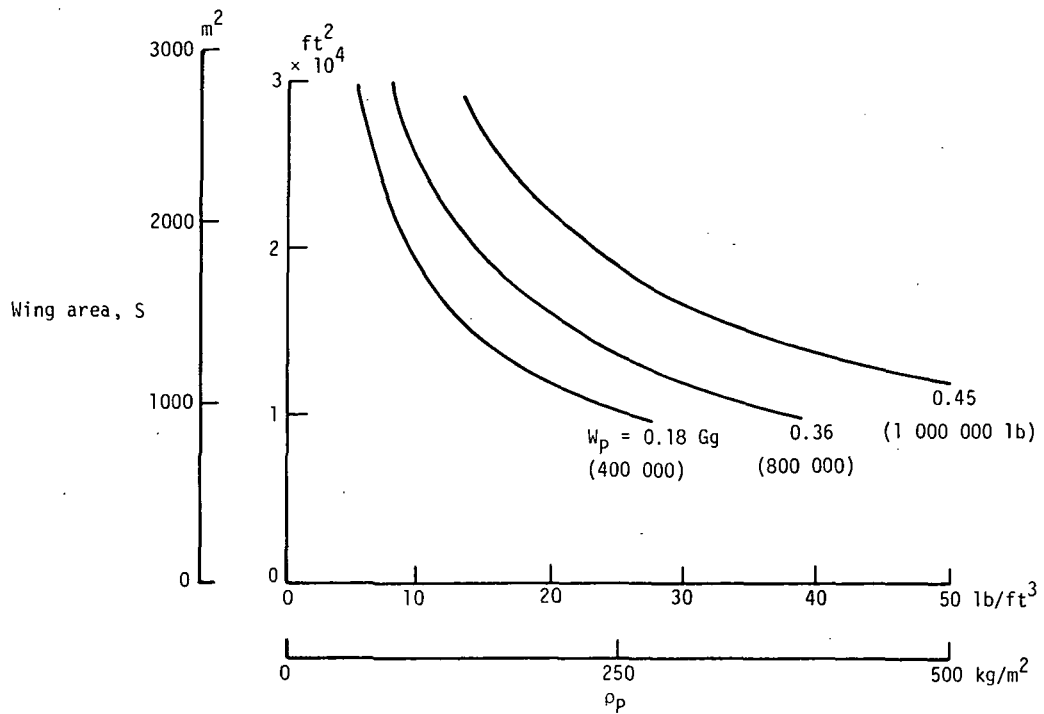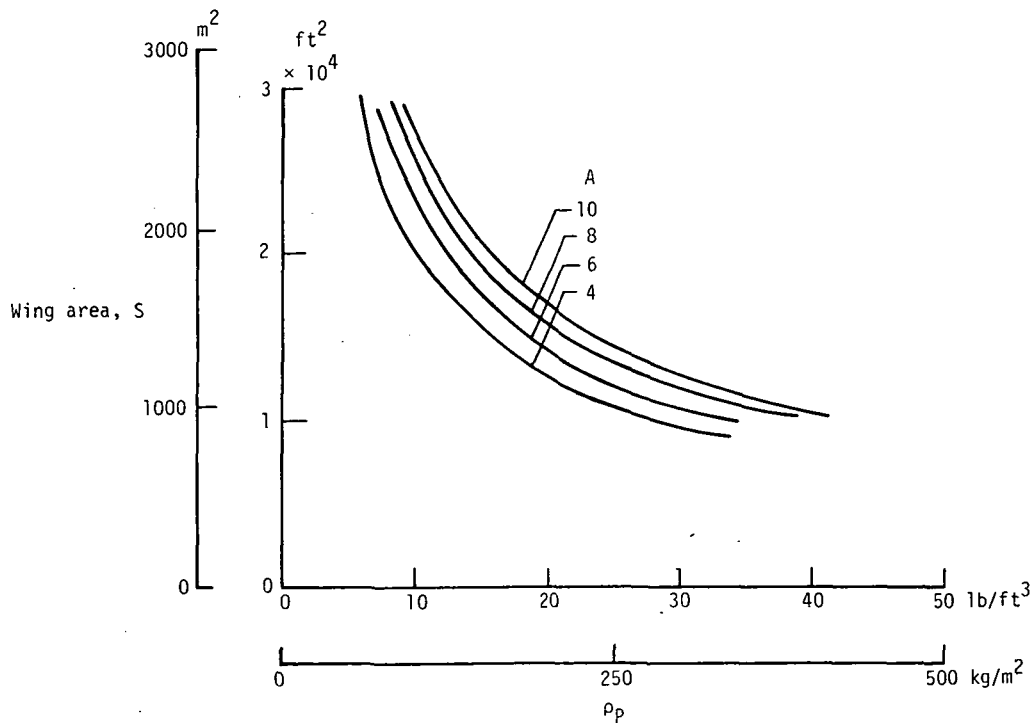S = 1670 m^2 (18 000 ft^2);   R = 4630 km (2500 n. mi.).

Figure 9.- Design selection charts; M = 0.7; t/c = 0.19.

(a)   A = 8.

(b) W_P = 0.27 Gg (600 000 lb).

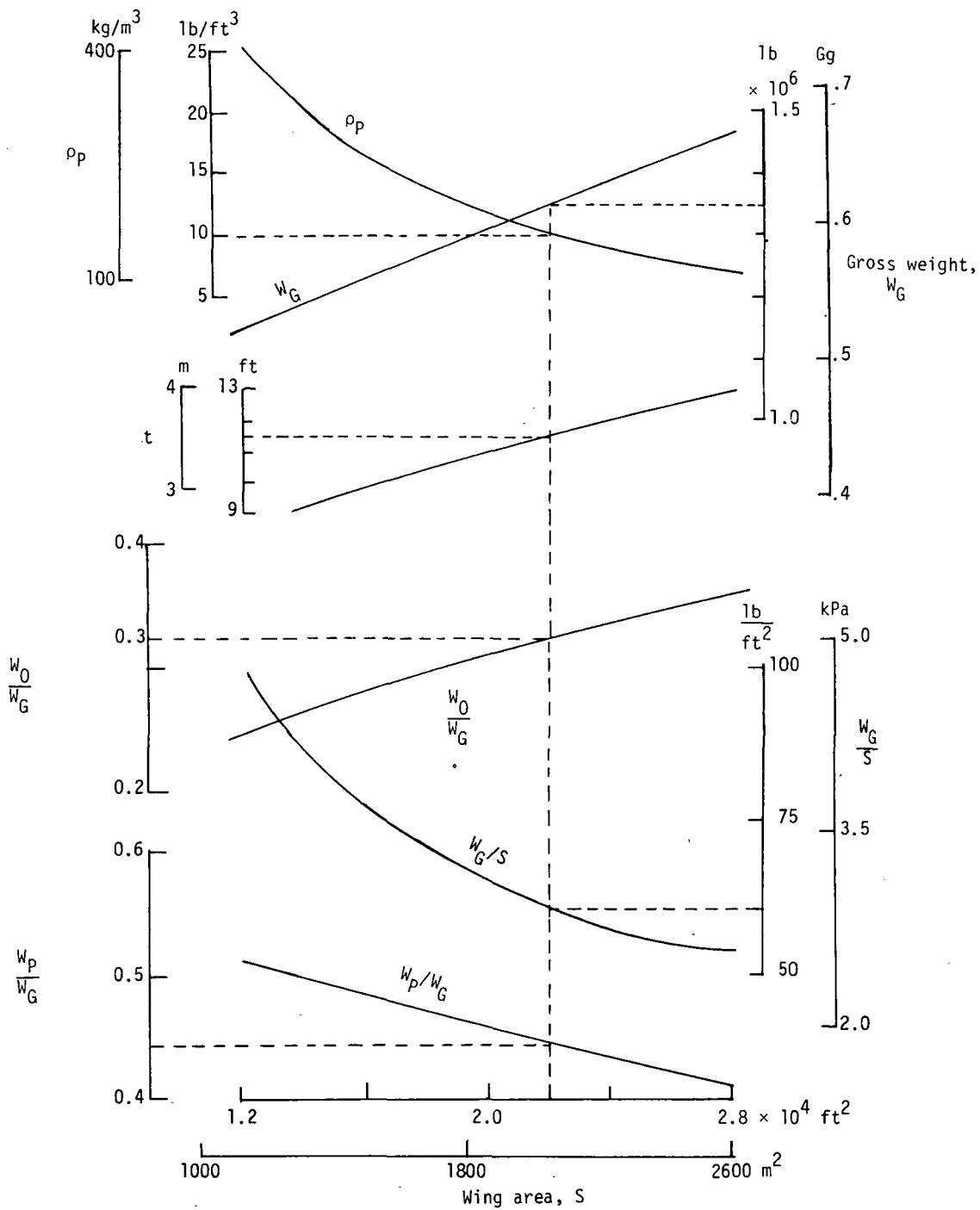Figure 10.- Wing area variation;   M = 0.7;   t/c = 0.19;   R = 4630 (2500 n. mi.).

Figure 11.- Sizing chart.   M = 0.7;   t/c = 0.19;   R = 4630 km (2500 n. mi.);
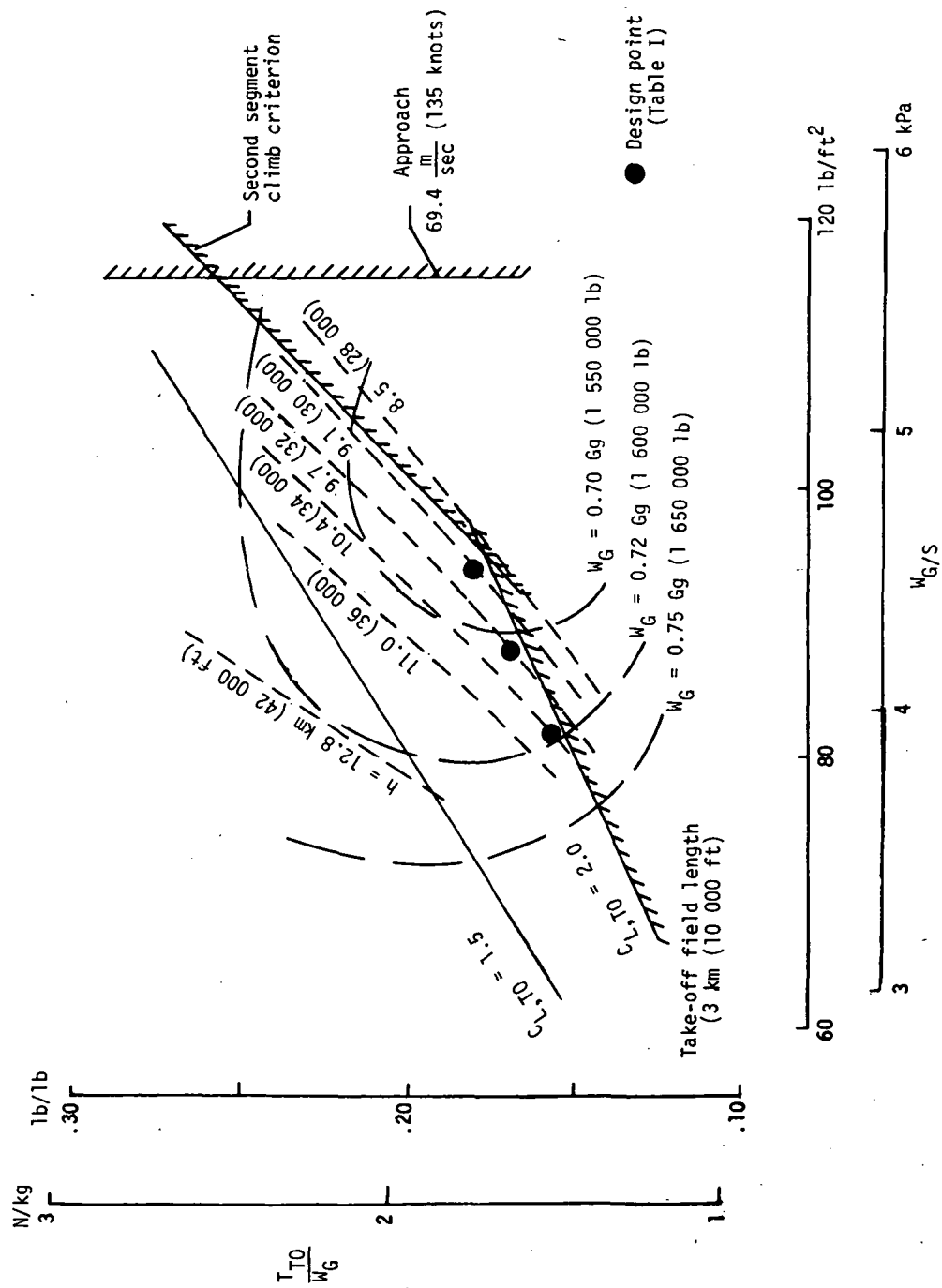W_P = 0.36 Gg (800 000 lb);   A = 6.

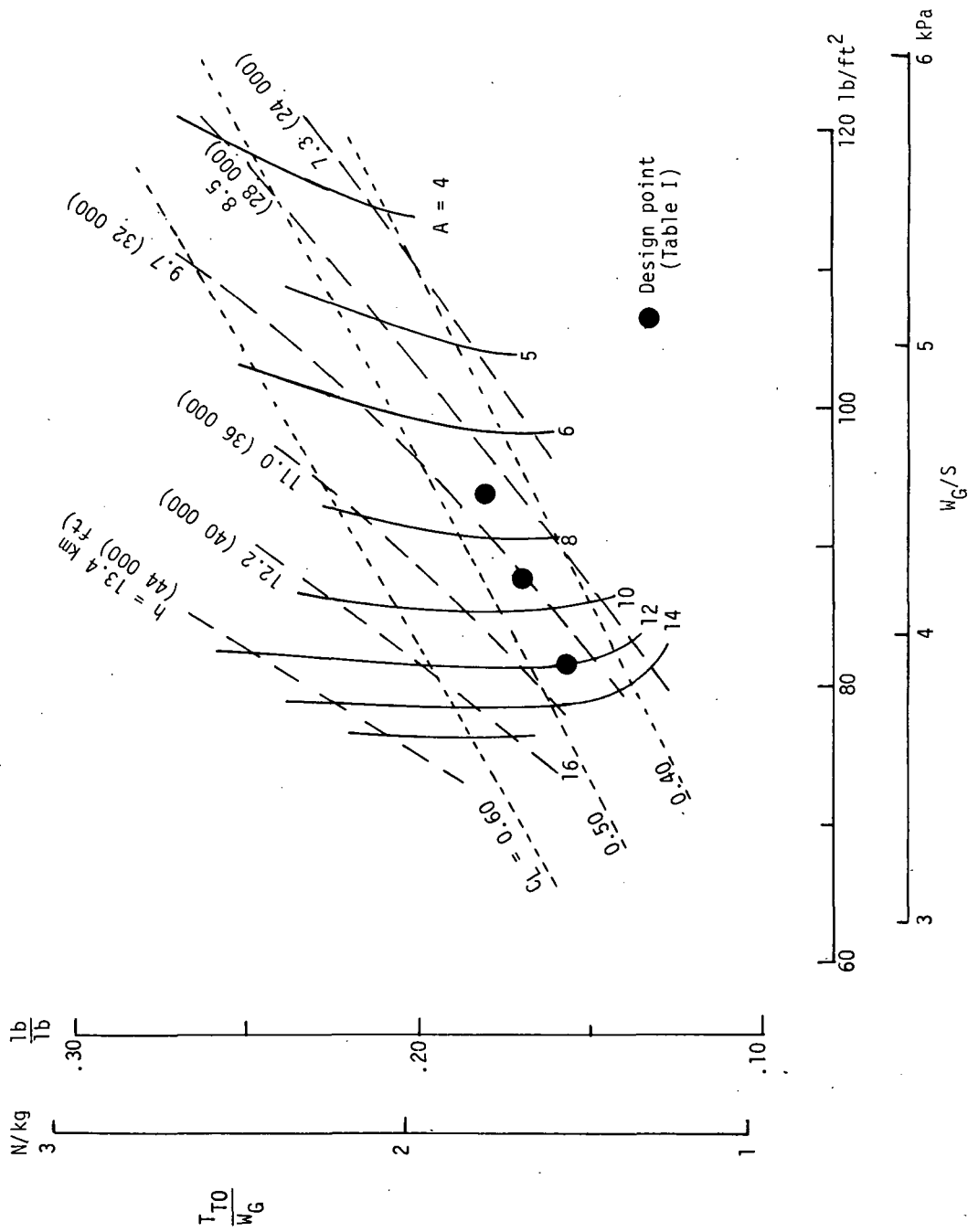Figure 12.- Cruise-matching boundaries. $W_P = 0.36$ Gg (800 000 lb); $\rho_P = 160$ kg/m^3 (10 lb/ft^3).

Figure 13.- Cruise matching to determine C_L and A. $W_P = 0.36$ Gg (800 000 lb); $\rho_P = 160$ kg/m^3 (10 lb/ft^3).

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