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Parametric Study of Modern Airship Productivity

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16. Abstract

~~This paper develops~~ a method~~ology~~ for estimating the specific productivity of both hybrid and fully-buoyant airships is developed ① and derives a weight estimating relationship for the empty weight of deltoid hybrids. Specific productivity is used as a figure of merit in a parametric study of fully-buoyant ellipsoidal and deltoid hybrid semi-buoyant vehicles. The sensitivity of results as a function of assumptions is also determined.

Various methods of estimating structural weight of deltoid hybrids are discussed and a ~~new~~ derived weight estimating relationship is presented.

No airship configurations were found to have superior specific productivity to transport airplanes.

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NOMENCLATURE

AR	aerodynamic aspect ratio
a	empty weight exponent
a/b	ratio of semimajor-to-semiminor axis of ellipse
C_D	drag coefficient
C_{D_F}	miscellaneous component drag coefficient
$C_{D_{HULL}}$	hull zero-lift drag coefficient
C_{D_i}	induced-drag coefficient
C_{D_o}	zero-lift drag coefficient
C_f	skin-friction coefficient
C_L	lift coefficient
C_{L_α}	lift curve slope
D	drag
DH	deltoid planform hybrid airship
E	nonpropulsive empty weight
EB	ellipsoidal fully-buoyant airship
EH	ellipsoidal hybrid airship
e	induced-drag efficiency factor
F	mission fuel weight
FE	fuel efficiency
f	fuel weight
H	propulsion system weight
HP	cruise horsepower required
HP_{RATE}	rated horsepower at sea level
h	altitude
IC	intercontinental mission

K	nonpropulsive empty weight coefficient
K_G	buoyant lift per unit displacement
K_H	propulsion system weight coefficient
K_T	throttle setting
K_1	nonpropulsive empty weight coefficient based on volume
K_2	nonpropulsive empty weight coefficient based on dynamic lift
L	dynamic lift
ℓ/d	fineness (length-to-diameter) ratio
P	payload weight
q	dynamic pressure
R	range
Re	Reynolds number
R'	range to neutral buoyancy
S	specific productivity
S_F	frontal area
S_P	planform area
SR	short range mission
S_R	reference area
T	temperature
TC	transcontinental mission
t	time into mission
t/c	thickness-to-chord ratio of deltoid airship
V	velocity
$\mathcal{V}$	volume
W	gross weight
W_{STRUC}	structural weight

α	angle of attack
β	buoyancy (buoyant-to-total lift) ratio
Δf	fuel remaining
η	propulsor efficiency
ρ	atmospheric density
ϕ	productivity

Subscripts:

DH	deltoid planform hybrid airship
EB	ellipsoidal fully-buoyant airship
EH	ellipsoidal hybrid airship
f	end of mission
o	beginning of mission

PARAMETRIC STUDY OF MODERN AIRSHIP PRODUCTIVITY

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SUMMARY

Past studies of airships of various types and configurations have used different approaches for estimating performance and different criteria for judging concept merit. These differences have caused significant differences in conclusions regarding the potential of these vehicles to compete with each other and with other vehicles such as transport airplanes.

This paper develops a methodology for estimating the specific productivity of both hybrid and fully-buoyant airships and derives a weight estimating relationship for the empty weight of deltoid hybrids. Specific productivity is used as a figure of merit in a parametric study of fully-buoyant ellipsoidal and deltoid hybrid semi-buoyant vehicles. The sensitivity of results as a function of assumptions is also determined.

Several past studies are reviewed and some are found to have overestimated the induced drag of deltoid hybrid airship types by a factor of 2. However, the present study shows that this difference does not alter relative productivity comparisons to any significant extent. A more important factor is weight. It is found that empty weight assumptions in the various analyses differ by factors of up to 3 and that this is the main source of the discrepancies in the conclusions of past studies.

Based on the methods developed in this paper, deltoid hybrids with aspect ratios of 1.74 and constructed similar to ellipsoidal buoyant airships have: (1) slightly higher values of specific productivity than the fully-buoyant types for short ranges, (2) about equal values for transcontinental ranges, and (3) lower values for intercontinental ranges. Very low aspect ratio (0.58) hybrids appear to be slightly superior to other hybrids and to the fully-buoyant types at all ranges. No airship configurations are found to have superior specific productivity to transport airplanes. However, if the more optimistic weight assumptions adopted in some past studies are used for both buoyant and hybrid airships, then specific productivity superior to airplanes is indicated for both.

INTRODUCTION

Recent reexamination of several studies of deltoid hybrid (DH) airships has revealed substantial differences in the methods used to estimate both induced drag and empty weight. These differences in methods have resulted in substantial differences in the values of induced drag and empty weight; in turn, those differences have led to discrepancies in study results. In particular, some studies have concluded that DH's have inferior productivity characteristics and operating economics when compared with classical, fully-buoyant, approximately ellipsoidal (EB) airships; other studies have concluded that DH's are greatly superior to EB's and in fact are competitive with existing and anticipated transport airplanes. It is shown in reference 1 that EB's are not economically competitive with transport airplanes for long-haul cargo transportation. Thus, it is important to examine the methodological differences of past analyses of DH airships.

In the present study, the methods and results of several studies of airship productivity and economics (refs. 2-7) are first critically reviewed, with particular attention to induced drag and empty weight. The differences in induced drag are largely resolved and a new equation for nonpropulsive empty weight of DH airships is developed.

A parametric study of deltoid and ellipsoidal airships is then undertaken. The study covers three transportation missions and uses specific productivity as the figure of merit. This figure of merit was used because it historically has been a good indicator of transport aircraft economic performance and because it has been used in many studies, thus facilitating comparison of results. Use of a more accurate and realistic figure of merit, such as direct operating cost, is beyond the scope of the present study.

Optimum operating conditions for both vehicle shapes are determined for various assumptions about vehicle technology, operating concept, and geometry. Comparison of cases with each other and with data for existing transport airplanes allows assessment of the relative performance potential of both EB and DH airships.

A recent study (ref. 8) has also analyzed the productivity of airships in transportation missions. Although the present study is a completely independent effort, the results are in general agreement with those of reference 8. The economic characteristics of modern airships in long-haul transportation are reviewed in reference 1 which also contains an extensive list of references of past airship economic studies.

The authors wish to thank Jennifer Himler for assistance in programming the equations and obtaining the numerical results.

ANALYTICAL METHODS

Induced Drag

Comparison of early studies of deltoid hybrid airships reveals that there were many different formulas used for estimating induced drag. These different formulas in some cases led to significant differences in the estimated value of induced drag and possibly influenced the selection of optimum vehicle shape and cruise conditions. Although the methods generally cannot be compared numerically (without specifying vehicle shape and operating conditions) they can be put into a common form for direct comparison under the restriction that angle of attack and aspect ratio are small.

In reference 2, the induced-drag coefficient was computed from

$$C_{D_i} = C_{L_\alpha}\alpha^2 + C_{D_i}\alpha^3 \tag{1}$$

In this equation, C_{L_α} and C_{D_i} are to be input from the best available data. For small aspect ratio,

$$C_{L_\alpha} \approx \frac{\pi AR}{2} \tag{2}$$

and for small values of angle of attack,

$$C_L \approx C_{L_\alpha}\alpha \tag{3}$$

$$C_{D_i} \approx C_{L_\alpha}\alpha^2 \tag{4}$$

Thus, for small α and AR equation (1) is approximately

$$C_{D_i} \approx \frac{2C_L{}^2}{\pi AR} \tag{5}$$

In reference 3, C_{D_i} was computed from

$$C_{D_i} = C_L \tan\alpha \tag{6}$$

which was taken from reference 9. For small AR and α, this is approximately

$$C_{D_i} \approx \frac{2C_L{}^2}{\pi AR} \tag{7}$$

The induced-drag formula used in reference 4 was

$$C_{D_i} = \left(\frac{\pi AR}{2} + \frac{2S_F}{S_P}\right)\left(\frac{4}{4 + AR}\right) K_1\alpha \sin\alpha \tag{8}$$

For small AR and α, slender configurations, and ideal leading-edge geometry, this is approximately

$$C_{D_i} \approx \frac{2C_L{}^2}{\pi AR} \tag{9}$$

The study of reference 5 adopted an induced-drag law of the form

$$C_{D_i} = KC_L{}^2 \tag{10}$$

where $K = 0.273$ for $AR = 1.2$. Putting this in the form of the induced-drag for a configuration with leading-edge suction gives

$$C_{D_i} = \frac{C_L{}^2}{0.97\ \pi AR} \tag{11}$$

Finally, in a more recent study than reference 4, Goodyear (ref. 6) used the equation

$$C_{D_i} = \frac{C_L{}^2}{0.9\ \pi AR} \tag{12}$$

These five induced-drag laws are shown in table 1. It is apparent that there will be significant differences in the induced drag they predict, the difference approaching a factor of 2 in some cases. It is, therefore, important to resolve these disagreements. The deltoid shape aerodynamically behaves as a slender (highly-swept, low-aspect-ratio) wing. Figure 1, taken from reference 10, shows data from large-scale wind-tunnel tests of a slender wing. At low values of α, the C_L vs C_D curve closely follows the relationship

$$C_{D_i} = \frac{C_L{}^2}{\pi AR} \tag{13}$$

indicating that a leading-edge suction force is developed. At some critical value of α (corresponding to about $C_L = 0.3$ in the figure), flow separation occurs and the C_L vs C_D curve follows

$$C_{D_i} = C_L \tan \alpha \tag{14}$$

except that it is shifted by a constant value.

At the cruise lift coefficients appropriate for deltoid airship designs (which range from 0.026 to 0.230 in the present study) it should be possible to achieve unseparated leading-edge flow. Therefore, the proper formula for induced drag is

$$C_{D_i} = \frac{C_L{}^2}{\pi ARe} \tag{15}$$

where e is the spanwise lift distribution efficiency factor. For an ideal lift distribution, e = 1.0; however, in practice e will have a value somewhat less than 1.0.

Although manned flight-test data (proprietary to Aereon Corporation) have been obtained for a deltoid hybrid configuration of AR 1.2 (ref. 7), the best source of available data on the aerodynamics of deltoid shapes is the testing done on lifting body reentry shapes in the late 1960's (refs. 11-13 and the unpublished data of K. W. Mort, Ames Research Center, NASA). Figure 2, taken from Mort, shows curves of C_D vs C_L for the full-scale M2 and X-24A vehicles tested in the Ames 40- by 80-Foot Wind Tunnel. These data show that the relationship (15) is valid at least up to $C_L = 0.5$. Curve-fitting with the trimmed data gives a value of e of about 0.87 for both vehicles. This case is also shown in table 1. Thus, it appears that some studies (refs. 2-4) overestimated the induced drag of deltoid airships by a significant amount. In the present study, an induced-drag law of the type of equation (15) is used with a value of $e = 0.9$, that is, equation (12). This is the same value as used in reference 6 and is intermediate between the value used in reference 5 and the value given by the unpublished data of Mort.

Since the ellipsoidal-shaped airship is also considered as a hybrid in the present study, an expression for induced drag for this shape is needed. Figure 3, derived from data in reference 14, shows that the relation (15) is generally valid; a curve fit gives $e = 0.87$. The test data in reference 15 tend to confirm this result. Note that this is in disagreement with reference 9, which states that the formula (14) is appropriate for the ellipsoidal shape. In the present analysis, the formula (15) is adopted with $e = 0.85$ for the ellipsoidal hybrid, that is,

$$C_{D_i} = \frac{{C_L}^2}{0.85\ \pi\ AR} \tag{16}$$

Empty Weight

There is even more disagreement in studies concerning the nonpropulsive empty weight fractions of deltoid hybrid airships than there is over their induced drag. The disagreement in empty weight is more significant than the one in induced drag both because the discrepancy is larger and because performance, as measured by specific productivity, is much more sensitive to changes in empty weight than to changes in induced drag. In the present paper, vehicle empty weight is taken to be the sum of the nonpropulsive empty weight E and the propulsion system weight H; E is the sum of the structural weight and the weight of the fixed equipment. Nonpropulsive empty weight estimating relationships (WER's) used in past studies of deltoid airships will now be reviewed.

The two "Feasibility Study of Modern Airships" contractors, Boeing and Goodyear, approached the task of estimating the structural weight of deltoid hybrids in two different ways. Boeing (ref. 2) derived empirical formulas for the principal structural elements based on regression analysis of past conventional, ellipsoidal airship designs. Therefore, those WER's can be expected to give good results for ellipsoidal shapes but are of doubtful value for deltoid shapes because the latter are outside the range of the data base on which the formulas were derived. For example, deltoid empty weight does not show dependence on key geometrical parameters with the Boeing formulas.

Goodyear (ref. 4), on the other hand, based their estimate of the structural weight of deltoid hybrids on simplified structural analysis. This gives weights derived on first principles and directly relates weight to vehicle geometry. However, the analysis included only first-order effects and therefore gives only first-order estimates. The methods have been recently improved in reference 6.

In reference 3, the nonpropulsive empty weight was taken to be

$$E = K_1 V + K_2 L_o \tag{17}$$

where L_o is the dynamic lift at the start of cruise, K_1 is derived from past airship designs updated for modern materials and construction, and K_2 is derived from current transport airplane designs. This WER has the advantage that for $V = 0$, transport airplane empty weight is accurately predicted and for $L_o = 0$ conventional airship weight is accurately predicted. However, there is no assurance that this formula accurately predicts the weight of hybrid designs ($V \neq 0$ and $L_o \neq 0$).

An even simpler approach has been used by Aereon (refs. 5, 7). In these references the WER

$$E = K W_o^{\,a} \tag{18}$$

is used. In this equation, K and a are derived from current transport airplane designs. Equation (18) is probably a valid "first cut" relation for narrow classes of vehicles with known properties limited to small shape variations. It is inadequate when applied to a totally new vehicle shape, such as the deltoid hybrid; in particular, it is insensitive to many important design parameters, including vehicle geometry and maximum speed capability.

Further, even if the basic approach was correct, the empty weight WER's used in references 5 and 7 may be in error in possibly two regards. First, they predict a trend of increasing structural efficiency with increasing size (i.e., $a < 1$ was used) and, consequently, the structural weight fractions of very large aircraft are predicted to be very low. This trend is contradictory to the "square-cube" growth law for large conventional aircraft, which implies decreasing structural efficiency with increasing size. The reverse trend in references 5 and 7 appears to arise from correlating small, relatively-old technology (and therefore relatively heavy) aircraft (which are heavier than predicted by the square-cube relation anyway because of their small size) with large, relatively-new technology (and therefore relatively light) aircraft. Second, references 5 and 7 seem to confuse structural weight with empty weight with the possible result that nonstructural weight items were left out of the nonpropulsive empty weight estimate (see also the discussion following eq. (37)).

The various empty weight methodologies are summarized in table 2. Typical weight fractions for deltoid airships as produced by the various WER's are shown in table 3. Boeing empty-weight fractions varied from 0.4 to 0.8 in their parametric study, depending on W_o, β_o, V_o. Goodyear structural-weight values ranged from 0.3 to 0.8, depending on W_o, β_o, V_o, AR, and thickness-to-chord ratio. For the study of reference 3, structural and empty-weight fractions of 0.38 and 0.43, respectively, were estimated using equation (17). For the relatively high aspect-ratio design (AR = 1.5) of references 5 and 7, inspection of the "Feasibility Study of Modern Airships" parametric data shows that the Boeing equations give an empty-weight fraction of about 0.5 and that the Goodyear equations give a structural-weight fraction of about 0.6. In reference 7, however, use of equation (18) gives an empty-weight fraction of 0.22 for this case. Thus, there is a disagreement in empty weight approaching a factor of 3. An attempt will now be made to resolve this discrepancy and to obtain a more rational nonpropulsive empty-weight estimating relationship for deltoid hybrid airships for conceptual design purposes. A rigorous structural analysis of the deltoid shape will be very difficult due both to its span being nearly equal to its length and to its noncircular sections.

Historically, the critical structural design condition for airships has been longitudinal bending. Although the deltoid is inherently a biaxially loaded structure, the ability to resist longitudinal bending still will be of key importance. As in any bending-loaded structure, vehicle geometry will have a strong effect on vehicle structural weight. When compared with the ellipsoidal shape, the deltoid shape has "flatter" (higher eccentricity) cross sections which lead to lower section moduli and higher structural weight per unit surface area to resist longitudinal bending. Further, the deltoid shape has more surface area for equivalent volume, which will also lead to higher weight. On the other hand, the deltoid shape is more compact and its relatively smaller overall dimensions would tend to lead to lower weight.

Structural weights of vehicles of noncircular cross sections are discussed in reference 16. Figure 4 (fig. 27 of ref. 16) shows the increase in weight of an elliptical section relative to a circular section for two different structural concepts as a function of the ratio of semimajor-to-semiminor axis (a/b) of the ellipse. The curves in figure 4 are for straight cylinders of equal length and equal enclosed cross-sectional area (and hence equal volume) loaded with pure longitudinal bending. It is assumed that the shells are buckling-critical and that they are optimally designed for simultaneous failure of all structural elements. The "frame-stabilized, integrally-stiffened shell" structural concept is representative of rigid airship construction. Figure 4 shows that for this concept the weight of an elliptical shell will be approximately (2/3 + a/3b) times that of an equivalent circular shell (the "exact" expression is given in eq. (B18) of ref. 16). This factor gives a first-order estimate of the structural weight increment of deltoids over ellipsoids. It accounts for both the greater weight-per-unit surface area and the greater surface area of the deltoid relative to the ellipsoidal shape for equal volumes assuming longitudinal bending loads are critical.

For pressurized shells, the noncircular shape has a further weight penalty compared with the circular one. As discussed in reference 16, even at very low pressures the noncircular sections are not able to resist pressure-induced bending of the main frames without prohibitive frame weights. Thus, transverse tension members will be needed. The weight of these members was not accounted for in the present study.

A parameter that must be factored into the structural weight is design speed, since the higher dynamic pressures associated with higher speeds will require higher weights. Boeing (ref. 2) used a logarithmic factor to account for this; adopting 80 knots as a baseline and taking design speed equal to cruise speed, the factor can be written as ($\ln V_o/\ln 80$).

Based on the above discussion, the following formula is adopted for the nonpropulsive empty weight of deltoid hybrid airships in the present study:

$$E_{DH} = \left(\frac{2}{3} + \frac{a}{3b}\right) \frac{\ln V_o}{\ln 80} \left(K_1 V\!\!\!\!- + K_2 L_o\right) \tag{19}$$

The historical value of K_1 for rigid airships is approximately 0.035 (refs. 2, 4, 8). Use of modern technology (e.g., aluminum alloys and structural design techniques used in current transport aircraft designs) would reduce this factor to about 0.025. Use of advanced materials, such as composites with high-strength filaments, would give a value of K_1 of about 0.020; that value for K_1 would not be appropriate for use in this study, however, because it is desired to compare results with existing technology transport airplanes. Such a comparison is only meaningful at the same technology level. In fact, the beneficial effects of advanced composites may be less for airships than for airplanes due to the relatively lightly loaded structure typical of airships. Values of K_1 and K_2 of 0.025 and 0.325, respectively, were adopted for the baseline case of the present study, reflecting current technology.

Although there are many arguable assumptions inherent in equation (19), it would seem to be a reasonable relationship for preliminary parametric studies because: (1) it is based (at least indirectly) on established structural analysis procedures; (2) it gives valid answers for the limiting cases of airplanes and conventional airships; and (3) it displays the most important parametric trends correctly (flatter sections and high speeds give higher structural weight). It is the only equation among those just discussed which meets all of these requirements. If anything, this equation may be conservative because it ignores many factors which are likely to lead to higher weight for deltoid shapes. For example: (1) minimum gage constraints will probably influence the weight of the relatively lightly-loaded deltoid structure to a greater extent than for the structure of conventional airplanes; (2) as just discussed the weight of structure required to resist pressure-induced bending stresses, neglected in the analysis, is higher for noncircular shapes than for circular ones; and (3) the analysis does not account for biaxial bending loads which are important for deltoids but relatively insignificant for slender structures such as high-aspect ratio wings, fuselages, and conventional airship hulls.

For the ellipsoidal hybrid, equation (19) reduces to

$$E_{EH} = \frac{\ln V_o}{\ln 80} \left(K_1 V\!\!\!\!- + K_2 L_o\right) \tag{20}$$

and for the fully-buoyant airship

$$E_{EB} = \frac{\ln V_o}{\ln 80} K_1 \forall \tag{21}$$

This latter relation shows good correlation with past airship designs.

Aerodynamics

Aerodynamic lift and drag of the hybrid airships are represented by

$$L = C_L q S_R \tag{22}$$

$$D = C_D q S_R \tag{23}$$

where q is the dynamic pressure and S_R is the vehicle planform area. Using equation (15), the drag coefficient is given by

$$C_D = C_{D_o} + \frac{C_L{}^2}{\pi ARe} \tag{24}$$

with $e = 0.9$. The zero-lift drag coefficient is computed as described in reference 3, and will be quickly reviewed here. After the Reynolds number Re has been computed, the skin-friction coefficient C_f is determined from (ref. 18)

$$C_f = \frac{0.03}{Re^{1/7}} \tag{25}$$

The hull drag coefficient is (ref. 18)

$$C_{D_{HULL}} = C_f\left[4\left(\frac{\ell}{d}\right)^{1/3} + 6\left(\frac{d}{\ell}\right)^{1.2} + 24\left(\frac{d}{\ell}\right)^{2.7}\right] \tag{26}$$

where (ℓ/d) is the fineness ratio. The zero-lift drag coefficient is then

$$C_{D_o} = \left(C_{D_{HULL}} + C_{D_F}\right)\frac{\forall^{2/3}}{S_R} \tag{27}$$

where C_{D_F} accounts for the fins and car and other miscellaneous components of drag and is taken as equal to 0.005 (refs. 17, 18). In the present study, L_o is determined by input (see eq. (31)). Since h and V_o are also specified, equation (22) may be solved for C_{L_o}; the initial drag is then computed from equations (23), (24), and (27). If ballast is collected to maintain constant weight, L, D, V, etc. will remain constant throughout the mission. If the angle of attack is of interest, it may be computed from the lift-curve slope relation.

It should be noted that there is a fair amount of uncertainty in the aerodynamic characteristics of deltoid hybrids, due to the fact that the only deltoids for which data have been collected [lifting body reentry vehicles (refs. 11-13 and the unpublished work of Mort) and the Aereon 26 (ref. 7)] are several times smaller than potential full-scale deltoid airships. The uncertainty in induced drag generally, and in the value of e specifically, has already been discussed. However, there is also some uncertainty in the values of C_{D_o} and lift-curve slope.

Weights and Productivity

The gross takeoff weight and initial buoyancy ratio are defined by

$$W_o = B + L_o \tag{28}$$

$$\beta_o = \frac{B}{W_o} \tag{29}$$

respectively, and both are fixed inputs. The buoyant lift and initial (i.e., at the beginning of cruise) dynamic lift are computed from

$$B = \beta_o W_o \tag{30}$$

$$L_o = (1 - \beta_o) W_o \tag{31}$$

The envelope volume is

$$\forall = \frac{\rho(o)}{\rho(h)} \frac{B}{K_G} \tag{32}$$

where K_G is conservatively taken as 0.06 to allow for unusable volume and to give a pressure height somewhat greater than design cruise altitude. (Use of pure helium and full inflation would give $K_G = 0.066$.) Determination of the volume allows vehicle dimensions to be computed. The gross weight at any time, if ballast is not collected, is the sum of four terms:

$$W = E + H + P + \Delta f \tag{33}$$

If ballast is collected on a pound-for-pound basis as fuel is consumed, the gross weight is constant and given by

$$W = E + H + P + F \tag{34}$$

In either case, at the takeoff condition

$$W_o = E + H + P + F \tag{35}$$

or, solving for the payload,

$$P = W_o - E - H - F \tag{36}$$

Computation of E has been discussed previously and F is determined for several different cases in appendix A.

The propulsion system weight estimating relationship (WER) is

$$H = K_H HP_{RATE} \tag{37}$$

where the rated installed horsepower is given by

$$HP_{RATE} = \frac{1}{K_T} \frac{\rho(o)}{\rho(h)} \sqrt{\frac{T(o)}{T(h)}}\, HP \tag{38}$$

where HP is given by equation (A4) in appendix A. In the present study, the values $K_H = 1.3$, $K_T = 0.6$, and $\eta = 0.82$ were used; these are typical values for existing aircraft propulsion systems. The weight H is meant to account for the total propulsion system weight, including engines, rotors-propellors, drive trains, transmissions, hull-thrust structure, controls, etc. The propulsion system WER used in reference 5 gives weights that are only 20% of those predicted by the method here, possibly because in that reference many propulsion system components either were included in the nonpropulsive empty weight or were not accounted for at all. The propulsion system WER used in reference 8 gives values which agree with the present study.

The productivity is defined as

$$\phi = VP \tag{39}$$

and the specific productivity as

$$S = \frac{\phi}{E + H} = \frac{VP}{E + H} \tag{40}$$

Productivity is the vehicle's rate of doing useful work and is directly proportional to the rate of generation of revenue for a transportation vehicle. Specific productivity normalizes productivity by dividing by empty weight. Assuming vehicle cost to be proportional to empty weight, S is then a measure of the vehicle's revenue generation capability per unit of investment cost. This neglects the fact that different components of vehicle structure have different unit costs. The fuel efficiency is defined by

$$FE = \frac{PR}{F} \tag{41}$$

In this study, specific productivity is adopted as the figure of merit (FOM). Use of this FOM emphasizes the importance of empty weight, perhaps somewhat too strongly. Use of S as the FOM as opposed to ϕ results in relatively lower optimum cruise velocities (ref. 8). More preferable FOM's than either ϕ or S are direct operating cost, total operating cost, and rate of return on investment; however, these all require economic and operational analyses and assumptions and are, therefore, beyond the scope of the present study.

For a given vehicle size, shape, and mission, S depends on the selected value of V_o for fully-buoyant airships and on V_o and β_o for hybrids. Although it is technically possible to find the values of V_o and β_o that maximize S by setting

$$\frac{\partial S(V_o,\beta_o)}{\partial V_o} = 0 \; ; \qquad \frac{\partial S(V_o,\beta_o)}{\partial \beta_o} = 0 \tag{42}$$

this approach is not adopted here. Rather, a parametric study is undertaken because (1) specification of an optimum vehicle implies a well-defined design (this would be misleading, since the present analysis is a highly simplified conceptual design study); (2) generation of parametric data provides more insight into the vehicle performance trends; and (3) the equations resulting from (41) would be extremely cumbersome.

It is also technically possible to optimize vehicle shape for a given mission. This was not even done parametrically in the present study because it is felt that a more detailed and better justified structural weight estimating procedure for the deltoid shape is needed to make detailed shape optimization meaningful. Instead, nominal shapes were adopted for the ellipsoid and deltoid vehicles and these shapes were held fixed throughout the major part of the study.

Parametric Study

In order to confine the number of cases to be computed in the parametric study to a manageable number, consideration was restricted to three missions. These missions are based on the missions used in reference 2. The mission parameters are given in table 4. As opposed to reference 2, in the present study (1) the pressure altitude was taken to be equal to the cruise altitude (although the low value of the buoyant lift per unit volume that was used could account for a higher pressure altitude than cruise altitude) and (2) the gross weight at the beginning of cruise was specified. The entire mission is flown at the design altitude. Although it would be somewhat better to compare vehicles on the basis of fixed payload weight rather than fixed gross takeoff weight, this would require iteration and was judged not to be worth the extra work.

The short-range (SR) mission represents an intercity, low-altitude service by a relatively small vehicle. The transcontinental (TC) mission represents a cross-country service by a moderate-size vehicle with enough altitude capability to cross U.S. mountain ranges. The intercontinental (IC) mission represents over-ocean flight of a large, low-flying vehicle.

Three vehicles are considered in the parametric study. The first two have the classical, approximately ellipsoidal airship shape with fineness ratios of 4. The first is in fact a classical fully-buoyant airship and is designated EB. The second is the same shape vehicle flown at angle of attack to develop dynamic lift, that is, a hybrid; this vehicle is designated as EH.

The third vehicle is a delta planform hybrid, designated DH. For the purpose of geometric computations, the deltoid shape described in references 3 and 16 was used. The level of the present analysis is such that small differences in vehicle shape would not effect any study results.

The deltoid hybrid with performance as computed with the equations developed in this report is denoted DHbase. For this case: (1) ballast is collected, so that F is computed from equation (A6) in appendix A; (2) E is computed from equation (19) with $K_1 = 0.025$ and $K_2 = 0.325$; (3) H is computed from equation (37) with $K_H = 1.3$; C_d is estimated from equation (15) with $e = 0.9$; and (4) the vehicle shape parameters are selected to give a shape that approximates the vehicle studied in references 5 and 7. The DHbase vehicle has $AR = 1.74$ and $a/b = 1.64$, giving a nonpropulsive empty weight 21% greater than that for an equivalent ellipsoidal airship.

To assess the effects of using other assumptions, five other DH cases will be considered. Three cases compare the effects of induced drag and empty weight assumptions: (1) induced drag, computed according to equation (15) but with $e = 0.5$ instead of $e = 0.9$, denoted DHe.5; (2) empty weight, computed according to equations (19) and (37) but with K_1, K_2, and K_H set to one-half their nominal values, denoted DHw/2, and (3) both of these changes, denoted DHe.5w/2. For purposes of comparison, the fully-buoyant ellipsoidal vehicle was also considered for the case of empty weight reduced by half, denoted EBw/2. Two additional cases were considered to assess the effects of ballast strategy and shape changes. The deltoid hybrid performance was computed for no ballast collection until neutral buoyancy (case (b) of appendix A), denoted DHbal. Finally, a case was run for a low aspect ratio ($AR = 0.58$ and $a/b = 1.0$) representing the shape used in references 6 and 19. All the vehicles used in the parametric study are listed in table 5.

RESULTS

Short-Range Mission

The variation of specific productivity S with cruise speed V, is shown in figure 5 for the fully-buoyant ellipsoidal vehicles, EB, for all three missions. Values of V somewhat higher than the speeds for maximum S were chosen for the baseline case (denoted by the circles) because high speed is desirable for many operational reasons, most notably because it minimizes the effects of headwinds and other adverse weather conditions. This philosophy was also adopted in reference 8. The speed selected for EBbase for the 300-n. mi. mission was 80 knots, which gives an S of about 78 knots; this value is plotted in figure 6. Selected characteristics of EBbase sized for the short-range mission are presented in table 6.

As compared with a transport airplane of similar size (the Boeing 737-200C), EBbase has about one-fourth the specific productivity but about 9 times the fuel efficiency (FE). Also shown in figure 6 and table 6 is the case of the fully-buoyant ellipsoidal airship with the empty weights halved, EBw/2. The best speed increases to about 100 knots and the nonpropulsive empty weight E has been nearly halved. The increase in speed causes the propulsion system weight H to remain about the same with respect to EBbase, since H is highly dependent on speed. The net effect is that S has gone up by about a factor of 5 while FE has stayed about the same. This illustrates the strong effect empty weight has on airship productivity performance.

As mentioned previously, the ellipsoidal shape was also considered as a hybrid, denoted EH. Figure 6 shows that the best performance is obtained at $\beta = 0.7$ and $V = 90$ and that the specific productivity of EH is slightly higher than that of EBbase.

The sensitivities of S to W_o, R, and h for EBbase are shown in figure 7. Increasing W_o and decreasing R and h leads to increased S, although the sensitivities are low. For example, a 20% change in either W_o, R, or h results in only about a 2% change in S.

Next, consider the deltoid hybrids for the short-range mission. Figure 8 shows the variation of S with β and V for these vehicles. It is clear that the optimum tends toward $\beta = 0$, that is, an airplane, but a lower bound of $\beta = 0.1$ was imposed for the purpose of comparison. Based on the data of figure 8, $\beta = 0.1$ and $V = 150$ were selected for DHbase. The variation of S with β is shown in figure 6 and selected data for DHbase is presented in table 6. As compared with EBbase, DHbase has an 87% higher best-cruise speed, 18% higher empty-weight fraction, 27% higher specific productivity, and 35% lower fuel efficiency. Note that the empty-weight fraction of DHbase is only slightly higher than that of the Boeing 737-200C. Note also that in the limiting case of $\beta = 0$, a nonbuoyant deltoid vehicle would have higher productivity than either EBbase or DHbase. The sensitivities to W_o, R, and h of DHbase (fig. 9) are similar to those of EBbase.

Figure 6 and table 6 compare DHbase with DH vehicles sized for different assumptions. Comparison of DHbase with DHe.5 shows that using the higher-induced drag has only a small effect on performance. Comparison of DHbase with DHw/2, however, shows once again the strong influence of empty weight; halving the empty weight estimating relationship gives a 3.5-fold increase in specific productivity when β and V are reoptimized. The productivity of DHw/2 is in fact slightly better than that of the Boeing 737-200C. The implication of the low empty-weight is that with this assumption the limiting case of a nonbuoyant deltoid aircraft is predicted to have better performance than that of a conventional wing-body airplane.

The effects of differences in shape and ballast strategy are also illustrated in figure 6 and table 6 for the deltoid hybrids. Collecting ballast vs not collecting ballast makes little difference for this short-range mission since the fuel consumed is very low.

The low-aspect-ratio shape has significantly better performance than the high-aspect-ratio shape. This low-aspect-ratio deltoid has a cylindrical forebody ($a/b = 1$) and is actually geometrically more similar to the ellipsoidal shape than to the high-aspect-ratio delta shape. It is essentially a classical airship with a "blended" instead of a "descrete" horizontal tail. The low-aspect-ratio delta seems to offer a good compromise between the good structural efficiency of the ellipsoid and the good aerodynamic efficiency of the high-aspect-ratio deltoid. As in conventional heavier-than-aircraft design, selection of the best aspect ratio involves a trade-off between aerodynamic efficiency (increasing with increasing AR) and structural efficiency (decreasing with increasing AR).

Transcontinental Mission

Based on figure 5, a cruise speed of 60 knots was selected for EBbase for the 2,000-n. mi., high-altitude mission. Figure 10 and table 6 compare the characteristics and performance of this vehicle with those of the other vehicles. For this mission, the fully-buoyant airship compares even less favorably with transport airplanes than it does for the short-range mission, having about one-sixth the specific productivity of the Lockheed L-1011-500. Even the EBw/2 case does not have performance competitive with airplanes. As before, EBw/2 has higher V, much lower E, about the same H, much higher S, and about the same FE as does EBbase. For the TC mission, EH has specific productivity inferior to EBbase and tends to optimize near $\beta = 1$, that is, at EBbase.

The primary reason for the relatively poor performance of the fully-buoyant airship in the TC mission is the high-altitude requirement, which requires a larger volume (and hence more empty weight and drag) for a given amount of buoyant lift. This is illustrated in figure 11, which shows that a 20% increase in h results in over a 20% decrease in S.

The baseline deltoid hybrid has maximum S near $\beta = 0.3$ and $V = 100$ (fig. 12), and the value of its maximum productivity is about the same as that of EBbase. Because of the poor performance of airships for this relatively high-altitude mission, the DH vehicle is now more sensitive to changes in assumption. Comparing DHe.5 with DHbase shows that the former optimizes at a lower V and higher β relative to the latter and that its specific productivity is 31% less. The performance is even more highly sensitive to empty weight than before and DHw/2 has in fact performance comparable to the Lockheed L-1011-500. As before, the trend of DHw/2 with β indicates that a deltoid nonbuoyant aircraft would have higher specific productivity than an equivalent-size conventional transport airplane, again making the low empty weight assumption highly questionable.

Changing to the lower-aspect-ratio shape gives an increase in the optimum value of β to 0.7 and an increase in S of 17%, indicating that it is desirable to trade-off some aerodynamic efficiency for increased structural efficiency. Figure 10 also shows that it is advantageous to not collect ballast (compare DHbal with DHbase) for the TC mission.

Figure 13 shows that the DHbase vehicle is very sensitive to both R and h, once again indicating the unsuitability of airships of any shape for "high" altitude missions.

Intercontinental Mission

From figure 5, a best speed of 60 knots was selected for EBbase for the 5,000-n. mi. intercontinental mission. The resulting specific productivity is about one-third that of a slightly smaller transport airplane, the Boeing 747-200C (fig. 14 or table 6), but the airship fuel efficiency is 9 times better. Halving the empty weight estimating relationship gives a vehicle with a greater specific productivity than the Boeing 747. The relatively good performance relative to airplanes for this long-haul mission reflects the well-known fact that airships, because of their low fuel consumption, compare more favorably with airplanes at longer ranges. Figure 14 shows that flying the ellipsoidal shape heavy decreases performance for this mission. The sensitivity data (fig. 15) indicate an increased sensitivity to range when compared with the shorter range missions.

The variation of S with β and V for DHbase is shown in figure 16. Because of their generally higher empty-weight fractions and poorer fuel efficiency, the DH vehicles are generally inferior to the EB vehicles for the IC mission. For example, DHbase ($\beta = 0.8$, V = 60) has a specific productivity 31% lower than EBbase. Since the deltoids tend to optimize at high-buoyancy ratios for long ranges, different assumptions on induced drag have little effect on performance for this mission, as evidenced by figure 14 and table 6. Once again, however, halving the empty weight has a strong effect, increasing the best speed from 60 to 80 knots and increasing the specific productivity by about 250%. Note that the empty-weight fraction used in a recent study (ref. 5) is even less than that of DHw/2.

Not collecting ballast increases the performance of the DH airship by a small amount. The greatest improvement (other than that due to the unrealistic empty weight assumption) accrues from changing to the low-aspect-ratio shape; DHa.58 has a specific productivity that is even slightly better than that of EBbase. The sensitivity of the performance of DHbase to mission parameters (fig. 17) is similar to the sensitivity of EBbase.

CONCLUDING REMARKS

The analyses and results of this report, particularly the data shown in figures 6, 10, and 14 and in table 6, indicate the following conclusions. It is cautioned that many of these conclusions are based on the use of specific productivity as a figure-of-merit and therefore may change if another figure-of-merit is used.

1. Several early studies (refs. 2-4) of deltoid hybrid (DH) airships used formulas for induced drag that overestimate the induced drag by a factor of nearly 2.

2. Other studies (refs. 5, 7) have used formulas for empty weight that give empty weight fractions of deltoid hybrid airships which are lower than those of existing aircraft by a factor of nearly 3.

3. Because large, high-aspect-ratio deltoid hybrid airships have never before been designed, built and flown, there is significant uncertainty regarding their aerodynamic coefficients and structural weights, particularly the latter.

4. Induced drag has a relatively small effect on specific productivity and the discrepancy in induced-drag methods caused a negligible effect in two of the three missions considered. For the transcontinental mission, the difference was significant; the higher induced-drag estimate resulted in an underestimation of specific productivity of about 30% and a shift to a higher optimum buoyancy ratio and a lower optimum speed.

5. Empty-weight fraction has a relatively large effect on specific productivity. Reducing the empty weight by half and reoptimizing the vehicles resulted in higher best speeds, about the same fuel efficiency, and large increases in specific productivity (between 200% and 500%, depending on vehicle shape and mission). The deltoids are more sensitive to empty weight than the ellipsoids.

6. In view of the great sensitivity of deltoid hybrid airship performance (as measured by specific productivity) to empty weight and the substantial uncertainty regarding structural weight of this concept, particularly at high aspect ratios, it is clear that if a reason were found for serious interest in the concept for application to transportation missions, the primary technical need would be a credible structural analysis.

7. The high-aspect-ratio (1.74) deltoid hybrid airship has specific productivity comparable to that of the fully-buoyant ellipsoidal airship, except at long ranges where the fully-buoyant ellipsoidal vehicle is significantly superior.

8. The low-aspect-ratio (0.58) deltoid hybrid airship has higher specific productivity than the fully-buoyant ellipsoidal vehicle, except at long ranges where they are comparable. The low-aspect-ratio delta hybrid, which has a cylindrical forebody, is actually conceptually closer to the ellipsoidal shape than to the high-aspect-ratio deltoid shape, being essentially a classical airship with a "blended" instead of a "descrete" horizontal tail.

9. For hybrid airships, it is better not to collect ballast (until neutral buoyancy is reached) than to collect ballast and maintain constant weight.

10. Among the vehicle concepts considered in this study, the best airship for all three missions, considered from a specific productivity standpoint, is the low-aspect-ratio, delta-planform, hybrid with no ballast collection. Such a vehicle seems to be an effective compromise between the good aerodynamic efficiency of the high-aspect-ratio deltoid and the good structural efficiency of the classical ellipsoidal airship. At longer ranges than those considered here, the classical airship would tend to be slightly superior; however, the differences in performance between airship concepts is not great and determination of the best vehicle concept for a given mission would likely be based on detailed considerations of economics, operational characteristics, and other factors.

11. For all airship concepts considered, performance is degraded as altitude is increased.

12. For equivalent empty weight fractions, airships cannot compete with existing transport airplanes on a specific productivity basis, regardless of vehicle concept, mission parameters, or induced-drag estimate. Values of airship specific productivity were approximately one-third, one-fifth, and one-third those of equivalent size airplanes for the short range, transcontinental, and intercontinental missions, respectively.

13. The cruise speeds for maximum specific productivity of airships are very low compared with those of jet transport airplanes. This is particularly true for fully-buoyant airships at intermediate to long ranges for which optimum cruise speeds of 60 knots are typical. These low speeds have many adverse effects on performance, economics, and operations. Consideration of prevailing winds, weather avoidance, and the passengers' or shippers' value of time (all neglected in the present study), would likely mandate cruise speeds of at least 100 knots; consideration of such factors would adversely affect the productivity performance of all airships. Thus, the results of the present study should be regarded as optimistic, particularly for the fully-buoyant airships.

14. If the empty weights, as computed by the methods of the present paper, are halved and the airship vehicles reoptimized, the resulting specific productivities are comparable to those of existing transport aircraft for all airship concepts considered. Thus, it is the low empty weight estimates of some past studies that have led to the optimism regarding the potential of airships for transportation missions.

15. The fuel efficiencies of fully-buoyant ellipsoidal airships range from 5 to 9 times better than those of transport airplanes, depending on mission parameters. The fuel efficiencies of deltoid hybrid airships are intermediate between those of fully-buoyant ellipsoidal airships and airplanes, ranging from 1.5 to 6 times better than those for airplanes. Because airship fuel efficiency is highly sensitive to cruise speed, fuel efficiencies will be greatly reduced if higher speeds are adopted for operational reasons (as described above). In any event, airships will use less fuel than airplanes and will, therefore, become increasingly more competitive as fuel prices increase.

Taken together, these conclusions suggest that airships, regardless of design concept, cannot compete with fixed-wing transport airplanes on established transportation routes. It may be that the unique characteristics of airships may make them competitive in certain exceptional situations, but such situations have not been clearly identified. If such situations were identified, it would still remain to be determined whether the market justifies development of a new vehicle concept.

If at some time in the future a legitimate need for a transportation airship can be identified, a detailed analysis would then be required to establish the best vehicle concept and design, and to verify the performance estimates. Necessary elements of that analysis are listed in appendix B; a key element would be a structural investigation of large deltoid shapes.

APPENDIX A

RANGE EQUATION

In this appendix, the relation between range and fuel consumed is derived for various assumptions regarding flight at cruise speed. The basic kinematic equation is

$$R = \int_{t_o}^{t_f} V\, dt \tag{A1}$$

which can be rewritten as

$$R = \int_{f_o}^{f_f} \frac{V}{\dot{f}}\, df \tag{A2}$$

For a turboshaft engine,

$$\dot{f} = -HP\ SFC \tag{A3}$$

where

$$HP = \frac{VD}{550\ \eta} \tag{A4}$$

Putting equations (A3) and (A4) into equation (A2) gives

$$R = -\frac{550\ \eta}{SFC} \int_{f_o}^{f_f} \frac{df}{D} \tag{A5}$$

To integrate equation (A5), assumptions concerning the mode of cruise flight must be made. For transport airplanes, it is customary to assume a "Breguet cruise" in which lift-to-drag ratio is held constant at its maximum value and speed is also held constant. Altitude is selected to maximize the "Breguet factor" and is steadily increased as fuel is burned off ("cruise-climb"). The Breguet cruise is not optimum in the sense of maximizing range for a given amount of fuel, but is very nearly so.

For airships, the situation is clouded by the fact that there are two kinds of lift and by the possibility of collecting ballast. Therefore, three cases will be considered:

1. Case (a): Ballast is collected at the same rate as fuel is burned off. Flight is at constant W, V, and h (and also therefore, at constant L and D). This is the case of the classical, fully-buoyant airship as well as the hybrid that flies at constant W.

2. Case (b): No ballast is collected; flight is at constant W/D and h.

3. Case (c): No ballast is collected; flight is at constant L/D and h.

Cases (b) and (c) are generalizations of the Breguet cruise condition suitable for hybrid airships; constant h is used instead of constant V because the optimum altitude for turboshaft-powered airships is as low as is operationally acceptable. Equation (A5) will now be integrated for these three cases.

Case (a)— Since $D = D_o$ is a constant, equation (A5) gives

$$R = -\frac{550\ \eta}{SFC\ D_o}\int_{f_o}^{f_f} df = \frac{550\ \eta\ F_a}{SFC\ D_o}$$

so that the desired relationship is

$$F_a = \frac{R\ SFC\ D_o}{550\ \eta} \tag{A6}$$

Case (b)— Since W/D is a constant and $df = dW$ for this case,

$$R = -\frac{550\ \eta}{SFC}\int_{W_o}^{W_f} \frac{W}{D}\frac{dW}{W} = -\frac{550\ \eta(W_o/D_o)}{SFC}\ \ln\frac{W_f}{W_o}$$

Solving for W_f,

$$W_f = W_o \exp[-R\ SFC/550\ \eta(W_o/D_o)]$$

so that the fuel weight is

$$F_b = W_o - W_f = W_o\{1 - \exp[-R\ SFC/550\ \eta(W_o/D_o)]\} \tag{A7}$$

Case (c)— For constant L/D,

$$R = -\frac{550\ \eta}{SFC}\int_{W_o}^{W_f} \frac{L}{D}\frac{dW}{L} = -\frac{550\ \eta(L_o/D_o)}{SFC}\int_{W_o}^{W_f}\frac{dW}{L - B}$$

The fuel weight is then

$$F_c = L_o\{1 - \exp[-R\ SFC/550\ \eta(L_o/D_o)]\} \tag{A8}$$

To aid in comparing these equations, we expand equations (A7) and (A8) in a Taylor's series:

$$F_b = \frac{R\ SFC\ D_o}{550\ \eta} - \frac{1}{2W_o}\left(\frac{2\ SFC\ D_o}{550\ \eta}\right)^2 + \frac{1}{6W_o{}^2}\left(\frac{R\ SFC\ D_o}{550\ \eta}\right)^3 + \ldots \tag{A9}$$

$$F_c = \frac{R\ SFC\ D_o}{550\ \eta} - \frac{1}{2L_o}\left(\frac{2\ SFC\ D_o}{550\ \eta}\right)^2 + \frac{1}{6L_o{}^2}\left(\frac{R\ SFC\ D_o}{550\ \eta}\right)^3 + \ldots \tag{A10}$$

Comparing (A6), (A9), and (A10) shows that: (1) for low values of $[(R)(SFC)(D)]$, $F_a \approx F_b \approx F_c$ and (2) for best fuel efficiency, it is best not to collect ballast since the second terms in the series expansions (A9) and (A10) are negative. At long ranges, where the relative advantages of not collecting ballast will be highest, vehicles tend to optimize at high initial values of β so that neutral buoyancy ($L = 0$) will be achieved prior to the end of cruise. When this occurs, the constant L/D solution requires that $D \to 0$ and hence also $V \to 0$, an obviously unacceptable situation. Therefore, case (c) is not considered further.

Since it is easy to show that further decreasing weight after neutral buoyancy is achieved is nonoptional, for case (b) it is assumed that ballast is collected to maintain neutral buoyancy if required. Let

$$R' = -\frac{550\ \eta(W_o/D_o)}{SFC} \ln \frac{B}{W_o} \tag{A11}$$

There are then two subcases.

Case (bI)— If $R' > R$, the fuel weight is

$$F_{bI} = W_o\left\{1 - \exp[-R\ SFC/550\ \eta(W_o/D_o)]\right\} \tag{A12}$$

Also for this case,

$$W_f = W_o - F_{bI},\ D_f = (D_o/W_o)W_f,\ L_f = W_f - B \tag{A13}$$

and the final velocity is obtained by solving the quartic equation

$$\frac{1}{2}\rho S_R C_{D_o} V_f{}^4 - D_f V_f{}^2 + \frac{2L_f{}^2}{\rho S_R \pi A e} = 0 \tag{A14}$$

Case (bII)— If $R' < R$, the fuel weight is

$$F_{bII} = W_o\{1 - \exp[-R'\ SFC/550\ \eta(W_o/D_o)]\} + \frac{(R - R')SFC\ D_o W_f}{550\ \eta\ W_o} \tag{A15}$$

and

$$W_f = B \ , \quad L_f = 0 \ , \quad D_f = \frac{D_o}{W_o} W_f \ , \quad V_f = \sqrt{\frac{2D_f}{\rho C_{D_o} S_R}} \tag{A16}$$

For the parametric analysis, case (a) was adopted as the nominal for the sake of simplicity for all vehicles and missions. This is justified because selected calculations show that the difference in vehicle performance between cases (a) and (b) is small.

APPENDIX B

POSSIBILITIES FOR FURTHER STUDY

The following is a list of items that would have to be pursued should serious interest develop in using LTA vehicles for conventional transportation missions.

1. A detailed structural analysis of the deltoid shape and development of improved structural weight estimating relationships for this shape. The structural analysis must include formulation of design criteria and comparison of different structural concepts.

2. Definition of realistic mission profiles (climb, descent, cruise, wind effects, weather avoidance, etc.) and calculation of performance based on such profiles rather than on idealized cruise flight.

3. A study of ballast collection methods and systems, including weight and cost estimates for such systems, and further study of ballast collection strategy.

4. A cost analysis that includes RDT and E costs, unit manufacturing cost, direct operating costs (DOC), indirect operating costs and calculation of the discounted rate of return on the original investment (ROI).

5. Economic and operational comparison of LTA vehicles with fixed-wing air transport and other potential competing modes of transportation.

6. Consideration of missions other than the three discussed in this report.

7. Optimization of vehicle shape (primarily fineness ratio of the ellipsoidal shape and sweep and forebody eccentricity of the deltoid shape) for specific missions. Consideration of other hybrid concepts.

8. Optimization to criteria other than specific productivity; for example, productivity, fuel consumption, DOC, ROI, or combinations of these.

The most important of these is item (1). Performance of the deltoid vehicle is highly dependent on empty-weight fraction and there is a great deal of published disagreement concerning the empty-weight fraction of deltoid airships. Unfortunately, large, lightly-loaded, deltoid-shaped vehicles have never been built nor have they been subjected to a rigorous structural analysis. Until such an analysis is undertaken, it makes little sense to pursue the other topics listed above.

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TABLE 1.- INDUCED-DRAG ESTIMATES OF DELTOID AIRSHIPS

Source	Induced-drag law	e
Ref. 3, based on ref. 9	$C_L \tan \alpha$	0.5[a]
Ref. 2	$C_{L_\alpha} \alpha^2 + C_{D_C} \alpha^3$	.5[a]
Ref. 4	$\left(\frac{\Pi\ AR}{2} + 2\frac{S_F}{S}\right)\left(\frac{4}{4 + AR}\right)K_1\alpha \sin \alpha$	~.5[a]
Ref. 6	$\frac{C_L^2}{\Pi\ AR\ e}$	.9
Ref. 5	$K\ C_L^2$	.97
Mort[b]	Lifting Body Test Data	0.87

[a]If linearized in α for small AR and put in form $C_L^2/(\Pi\ AR\ e)$.

[b]Unpublished data, K. W. Mort, Ames Research Center, NASA.

TABLE 2.- METHODS OF ESTIMATING STRUCTURAL WEIGHT OF DELTOID AIRSHIPS

Source	Structural weight methodology
Ref. 3	$K_1 \maltese + K_2 L_o$; K_1 from past airships updated for modern technology, K_2 from transport airplanes
Ref. 2	Regression analysis on past airships updated for modern technology
Refs. 4, 6	Simplified structural analysis
Refs. 5, 7	KW_o^a; K and a from correlation with transport airplanes

TABLE 3.- ESTIMATES OF STRUCTURAL WEIGHT OF DELTOID AIRSHIPS

Source	Range of parametric studies		Point design values	
	W_{struc}/W_o	$(E + H)/W_o$	W_{struc}/W_o	$(E + H)/W_o$
Ref. 3			$0.38^{a,b}$	0.43^{a}
Ref. 2		$0.4\text{-}0.8^{c}$		$\sim.5^{d}$
Ref. 4	$0.3\text{-}0.8^{e}$		$\sim.6^{d}$	
Ref. 6			$.37^{f}$	$.56^{f}$
Ref. 5			$.21^{d}$	$.22^{d}$

[a] W_o = 1,724,000 lb, β_o = 0.58, V_o = 100 knots.

[b] E/W_o

[c] Depending on W_o, β_o, and V_o.

[d] W_o = 866,000 lb, β_o = 0.55, V_o = 100 knots, AR = 1.5, t/c = 0.22.

[e] Depending on W_o, β_o, V_o, AR, and t/c.

[f] W_o = 223,000 lb, β_o = 0.64, V_o = 150 knots, AR = 0.58, t/c = 0.25.

TABLE 4.- MISSIONS

Mission	Symbol	Range (R), n. mi.	Altitude (h), ft	Gross takeoff weight (W_o), lb
Short range	SR	300	2,000	100,000
Transcontinental	TC	2,000	13,000	500,000
Intercontinental	IC	5,000	2,000	1,000,000

TABLE 5.- VEHICLES

Vehicle	Shape	Lift	e	E + H	AR	Ballast
EBbase	Ellipsoidal	Buoyant	---	Ecalc. + Hcalc.	---	Collected
EBw/2	Ellipsoidal	Buoyant	---	(Ecalc. + Hcalc.)/2	---	Collected
EH	Ellipsoidal	Hybrid	0.85	Ecalc. + Hcalc.	---	Collected
DHbase	Deltoid	Hybrid	.9	Ecalc. + Hcalc.	1.74	Collected
DHe.5	Deltoid	Hybrid	.5	Ecalc. + Hcalc.	1.74	Collected
DHw/2	Deltoid	Hybrid	.9	(Ecalc. + Hcalc.)/2	1.74	Collected
DHe.5w/2	Deltoid	Hybrid	.5	(Ecalc. + Hcalc.)/2	1.74	Collected
DHa.58	Deltoid	Hybrid	.9	Ecalc. + Hcalc.	.58	Collected
DHbal	Deltoid	Hybrid	.9	Ecalc. + Hcalc.	1.74	Not collected

TABLE 6.– VEHICLE CHARACTERISTICS

Mission	Vehicle	Cruise speed[a] V_o, knots	Buoyancy ratio[a] β_o	Nonpropulsive empty weight E, K lb	Propulsion weight H, K lb	Fuel weight F, K lb	Payload weight P, K lb	Empty weight fraction $(E+H)/W_o$, %	Forebody flatness a/b	Lift coefficient C_{L_o}	Drag coefficient C_{D_o}	Specific productivity S, knots	Fuel efficiency FE, n. mi.
SR	EBbase	80	1.0	44	5	3	48	49	1.0	0	0.0234[b]	78	4,600
	EBw/2	100	1.0	23	5	5	67	28	1.0	0	.0228[b]	242	4,300
	EH	90	.7	42	7	4	47	49	1.0	.053	.0123	86	3,500
	DHbase	150	.1	47	11	4	38	58	1.64	.137	.0093	99	3,000
	DHe.5	150	.1	47	14	5	35	61	1.64	.137	.0093	86	2,200
	DHw/2	170	.1	24	7	4	65	31	1.64	.107	.0091	353	4,500
	DHe.5w/2	190	.1	24	10	5	60	35	1.64	.086	.0090	328	3,300
	DHa.58	140	.2	39	14	5	42	53	1.0	.085	.0074	112	2,600
	DHbal	140[c]	.1	46	10	3	41	56	1.64	.158	.0093	101	3,700
	737-200C[d]	500	0	59[e]	—	12	35	55	—	—	—	298	900
TC	EBbase	60	1.0	290	8	30	172	60	1.0	0	0.0232[b]	34	11,400
	EBw/2	80	1.0	155	10	52	283	33	1.0	0	.0224[b]	138	11,000
	EH	70	.9	287	15	47	151	60	1.0	.047	.0120	35	6,400
	DHbase	100	.3	264	41	88	107	61	1.64	.221	.0089	35	2,400
	DHe.5	70	.7	313	18	54	115	66	1.64	.110	.0090	24	4,300
	DHw/2	190	.1	129	51	115	206	36	1.64	.164	.0086	217	3,600
	DHe.5w/2	160	.2	135	51	135	180	37	1.64	.129	.0086	155	2,700
	DHa.58	80	.7	266	23	61	150	58	1.0	.081	.0072	41	4,900
	DHbal	120[f]	.2	255	57	84	105	62	1.64	.230	.0089	40	2,500
	L1011-500[g]	525	0	241[e]	—	92	97	56	—	—	—	211	2,100
IC	EBbase	60	1.0	413	9	128	450	42	1.0	0	0.0222[b]	64	17,600
	EBw/2	70	1.0	214	7	171	608	22	1.0	0	.0218[b]	192	17,800
	EH	70	.95	423	15	178	384	44	1.0	.026	.0115	61	10,800
	DHbase	60	.8	474	11	156	358	48	1.64	.103	.0087	44	11,500
	DHe.5	60	.9	488	11	148	354	50	1.64	.047	.0086	43	12,000
	DHw/2	80	.7	247	11	241	501	26	1.64	.095	.0084	155	10,400
	DHe.5w/2	80	.8	254	12	247	488	27	1.64	.058	.0084	147	9,900
	DHa.58	60	.9	402	10	134	454	41	1.0	.046	.0070	66	16,900
	DHbal	70[h]	.7	479	17	174	330	50	1.64	.124	.0086	47	9,500
	747-200c[i]	500	.0	362[e]	—	328	130	44	—	—	—	180	2,000

[a]For airship maximum specific productivity as appropriate

[b]$S_R = \forall^{2/3}$ for these cases, otherwise $S_R = S_{Plan}$

[c]$V_f = 138$

[d]$W_o = 107{,}500$ lb

[e]Total empty weight

[f]$V_f = 133$

[g]$W_o = 430{,}000$ lb

[h]$V_f = 72$

[i]$W_o = 820{,}000$ lb

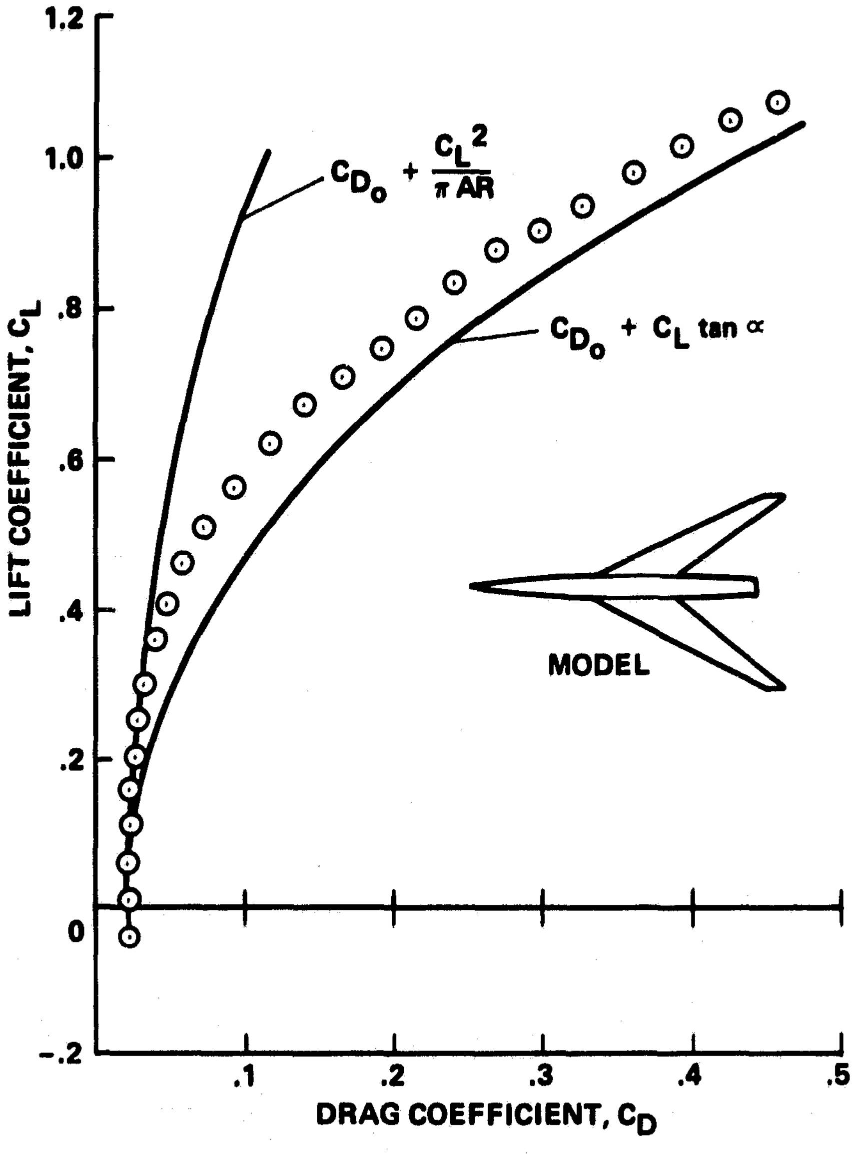

Figure 1.- Force coefficients on highly-swept, low-aspect-ratio models at low speed (source: ref. 10).

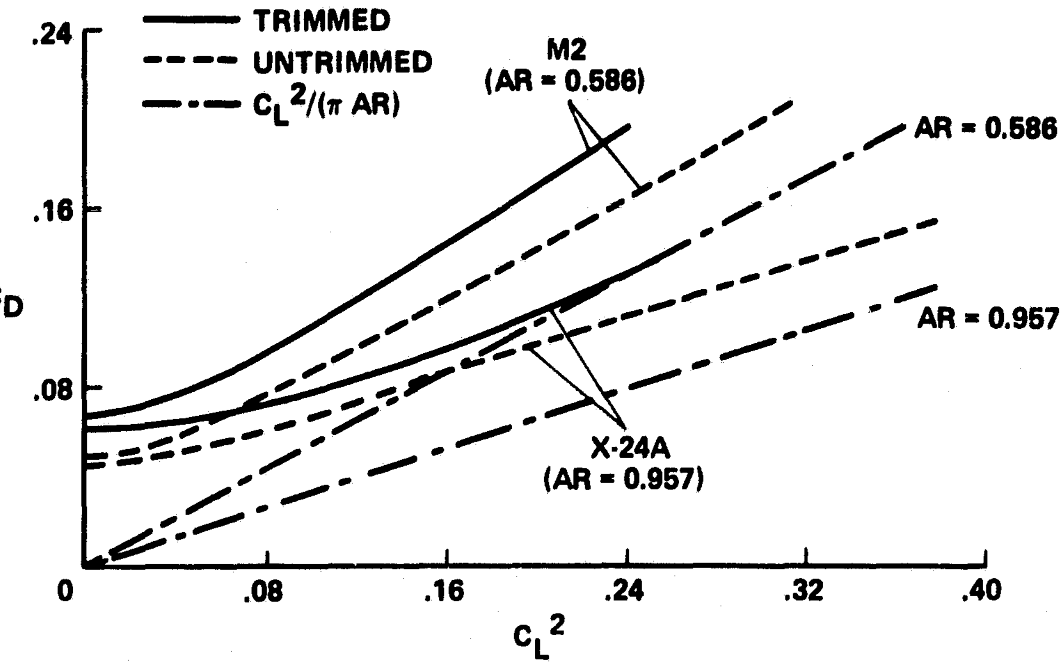

Figure 2.- Lifting-body aerodynamic characteristics as taken from wind-tunnel tests of flight vehicles (source: unpublished data from K. W. Mort, Ames Research Center, NASA).

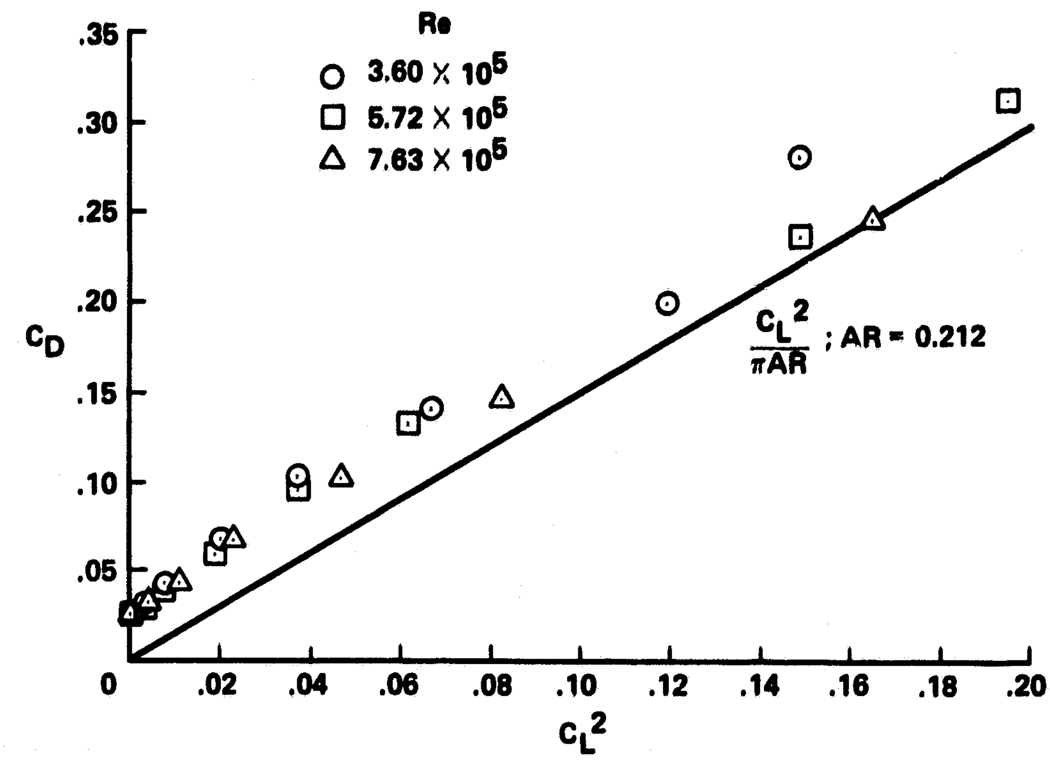

Figure 3.- Ellipsoid aerodynamic characteristics, fineness ratio = 6 (source: ref. 14).

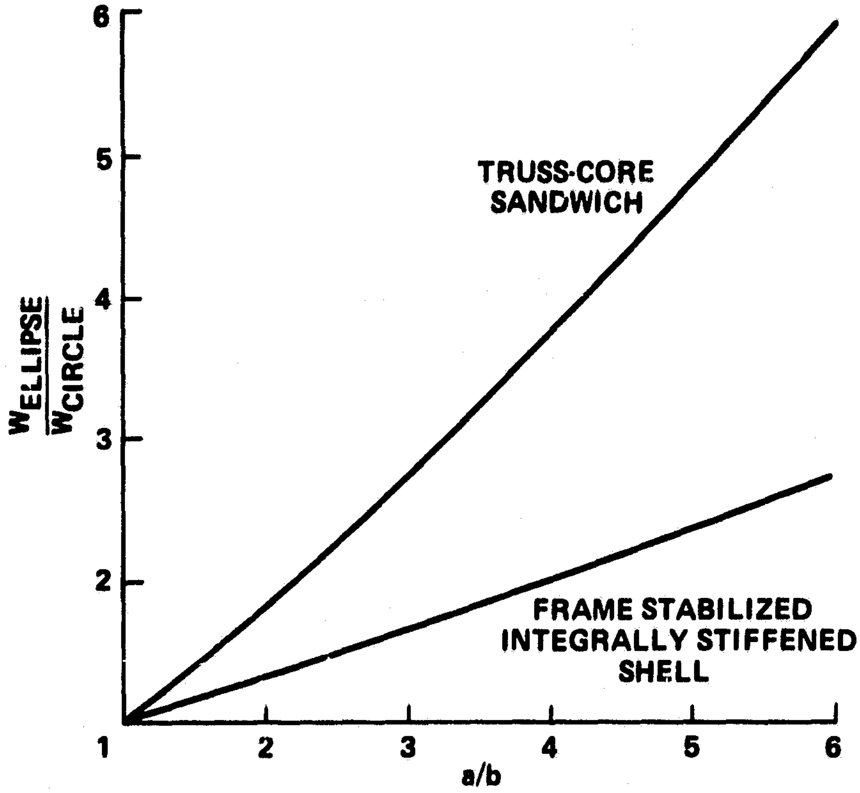

Figure 4.- Comparison of weights of unpressurized elliptic and circular shells (source: ref. 16).

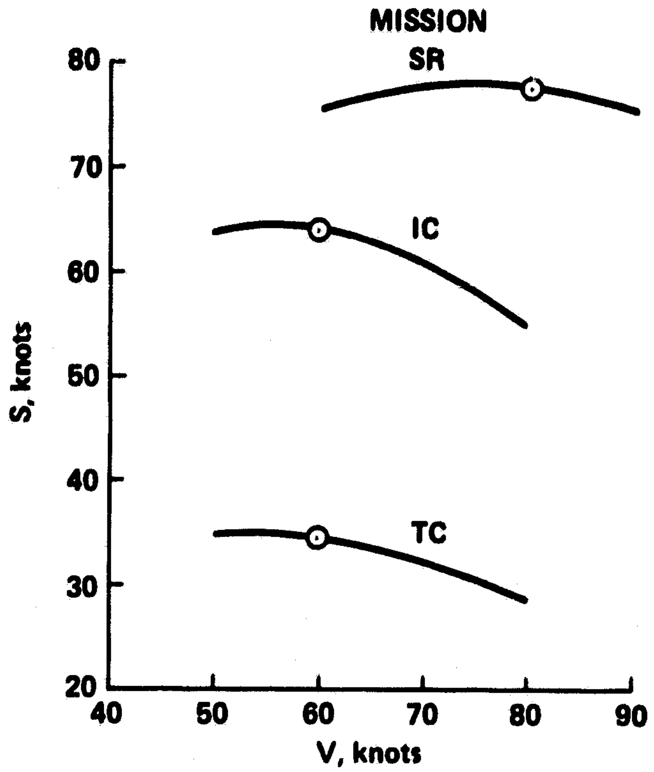

Figure 5.- Parametric data for EBbase airships.

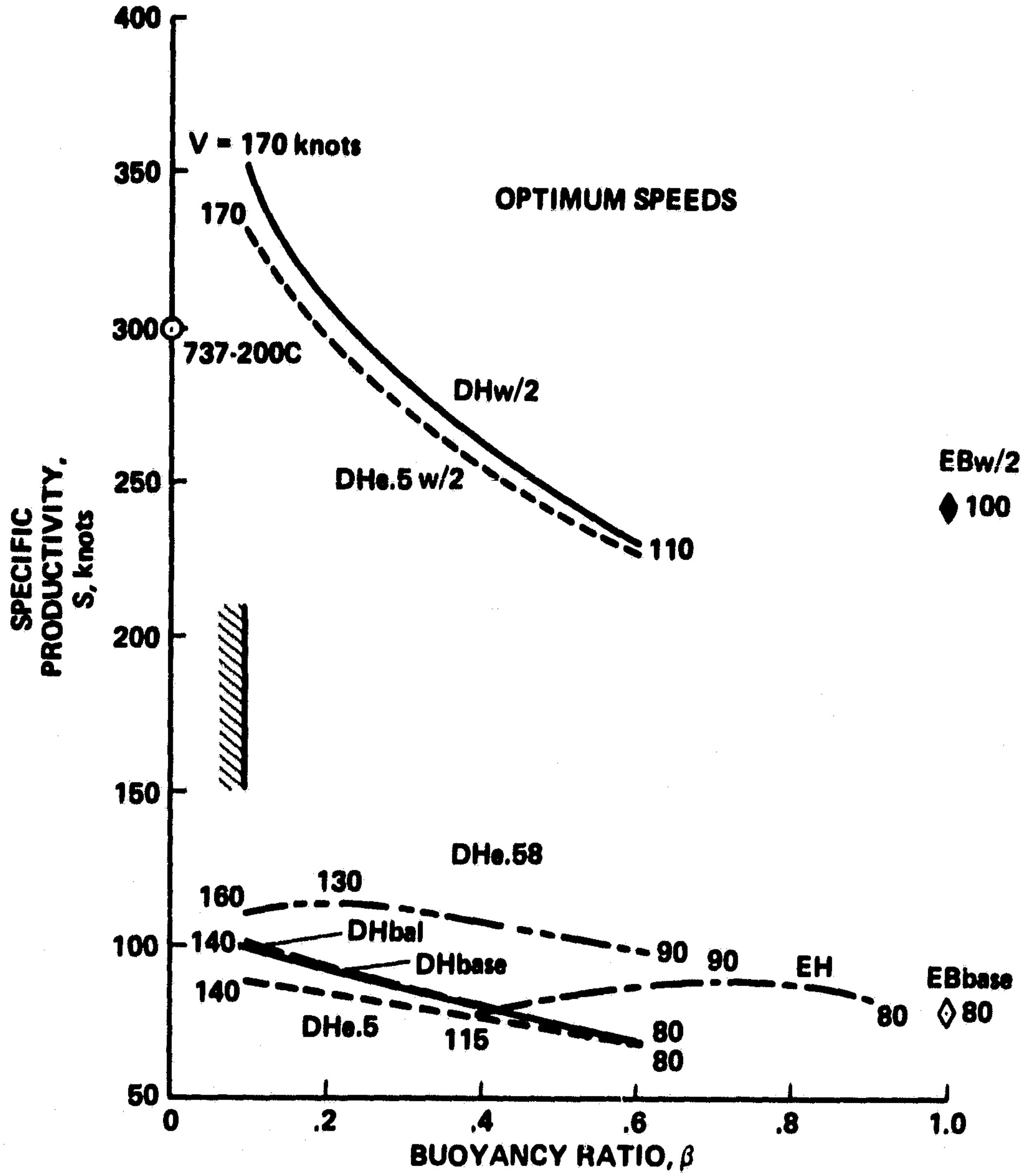

Figure 6.- Airship specific productivity short-range mission.

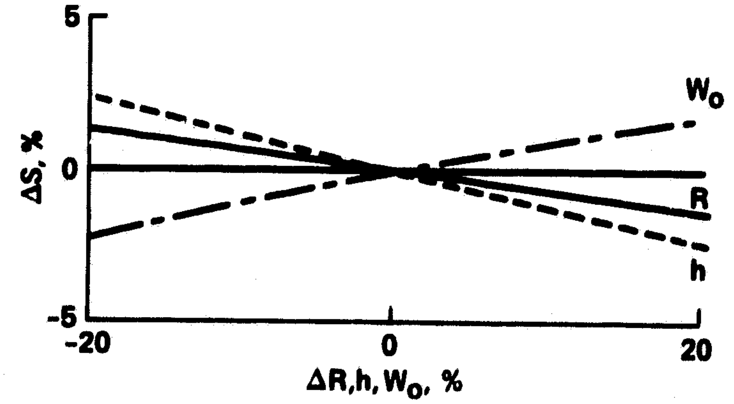

Figure 7.- Sensitivity data for EBbase for short-range mission.

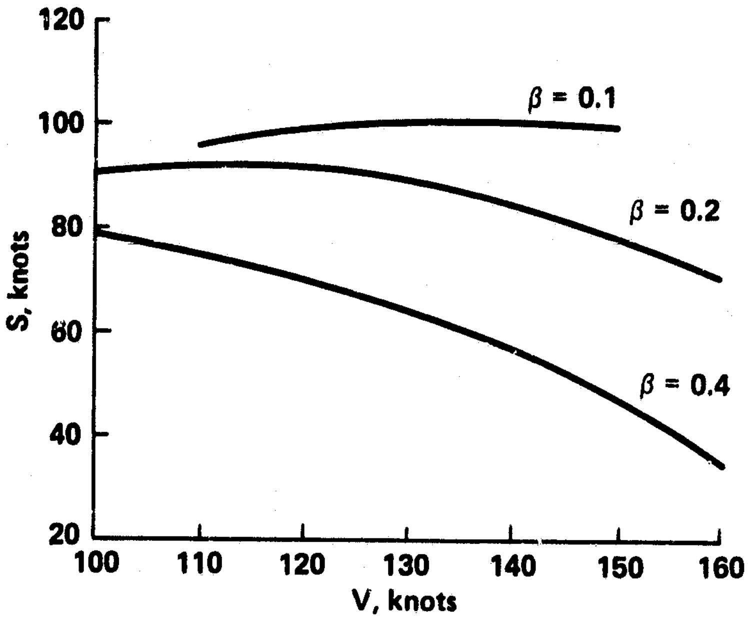

Figure 8.- Parametric data for DHbase for short-range mission.

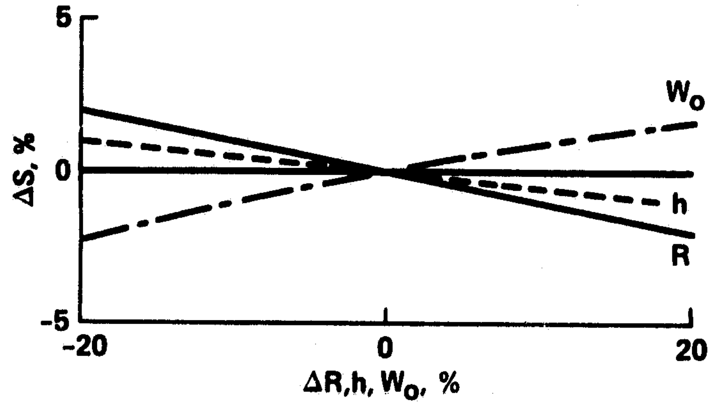

Figure 9.- Sensitivity data for DHbase for short-range mission.

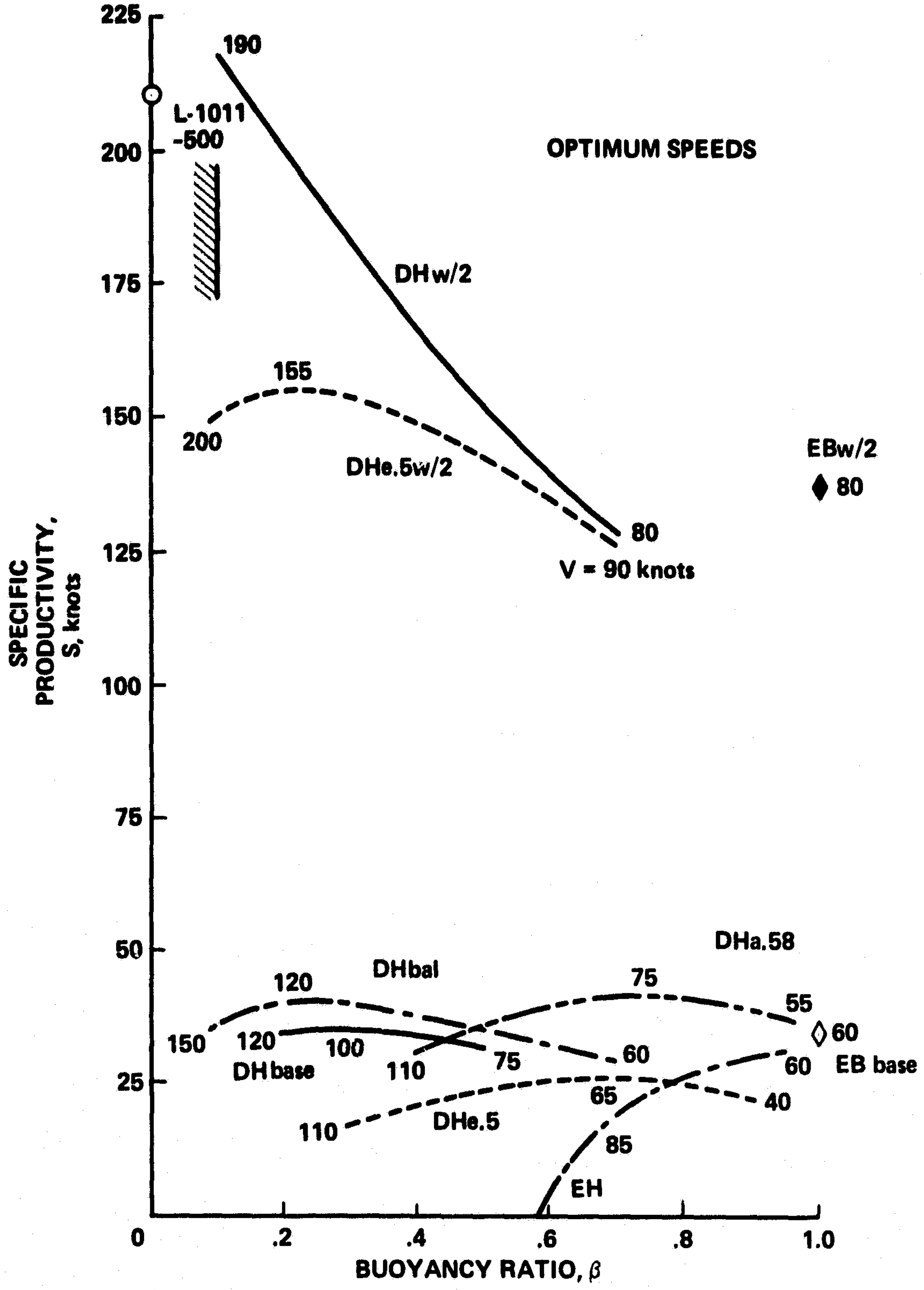

Figure 10.- Airship specific productivity, transcontinental mission.

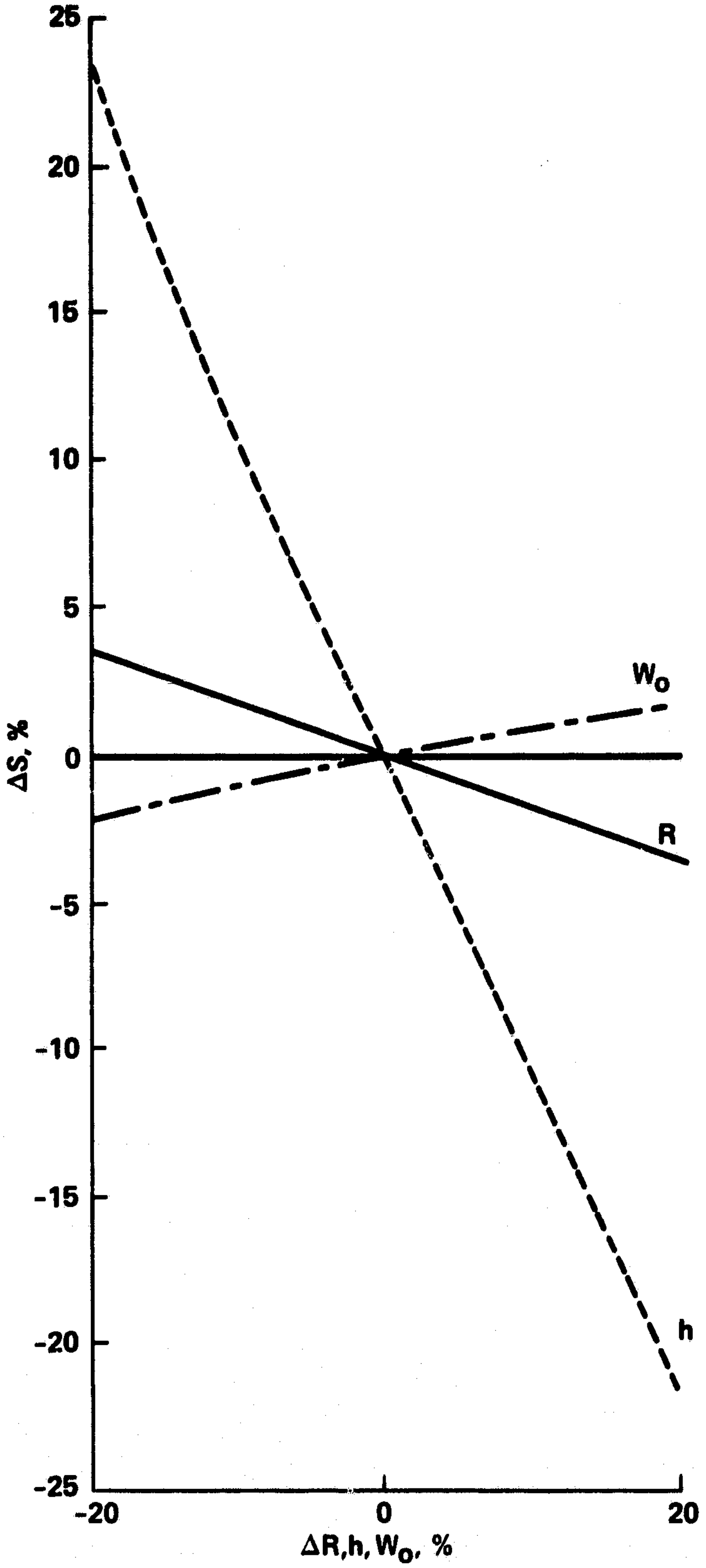

Figure 11.- Sensitivity data for EBbase for transcontinental mission.

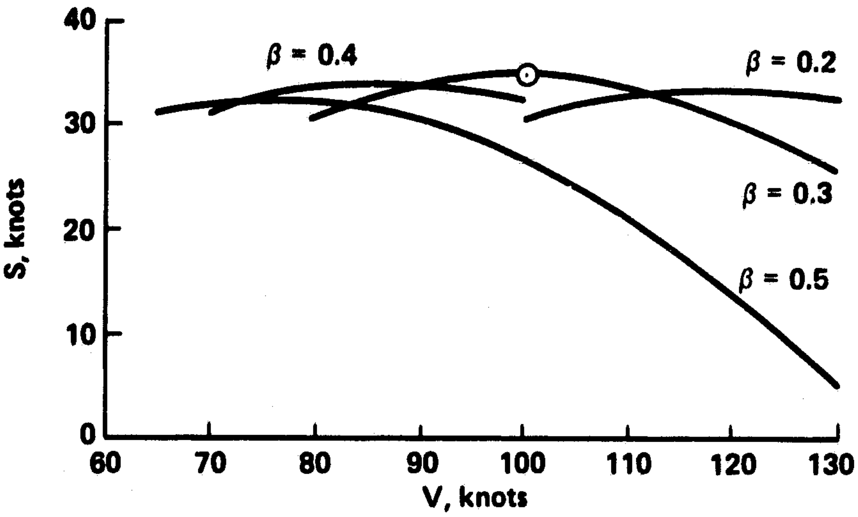

Figure 12.- Parametric data for DHbase for transcontintal mission.

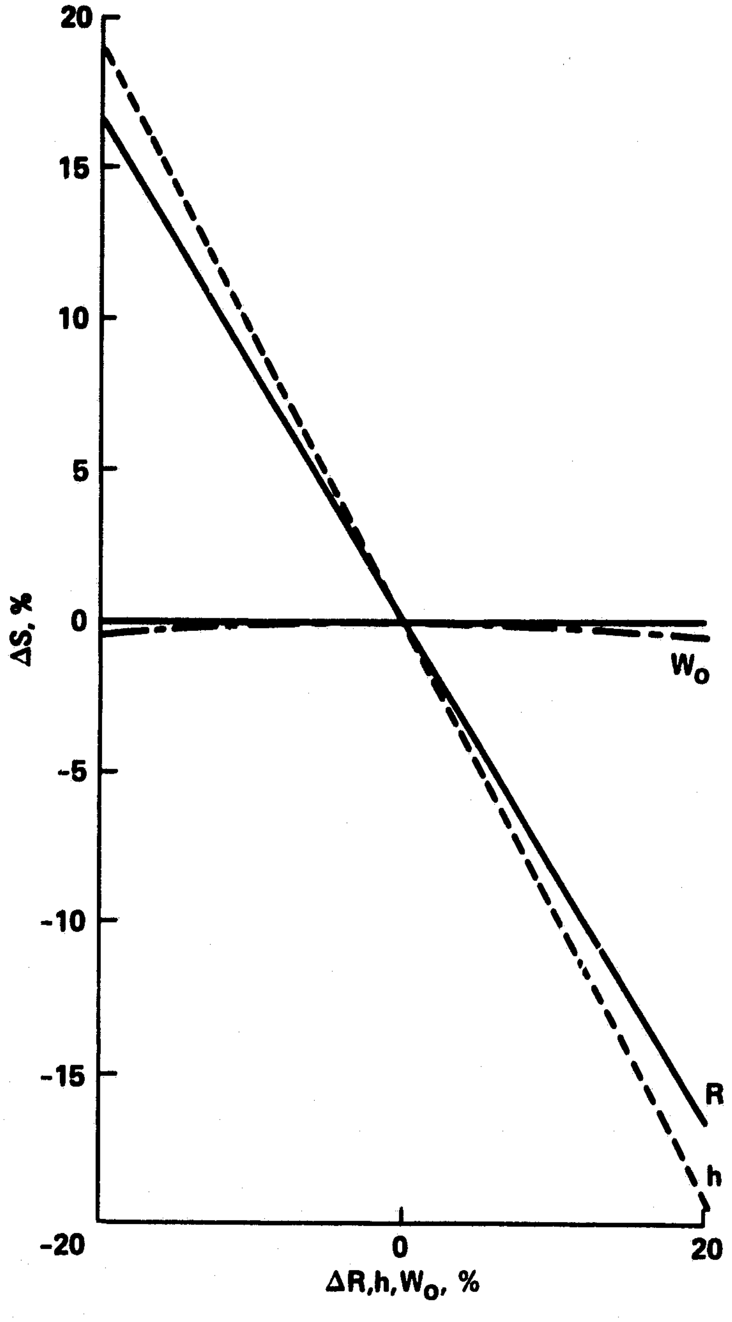

Figure 13.- Sensitivity data for DHbase for transcontinental mission.

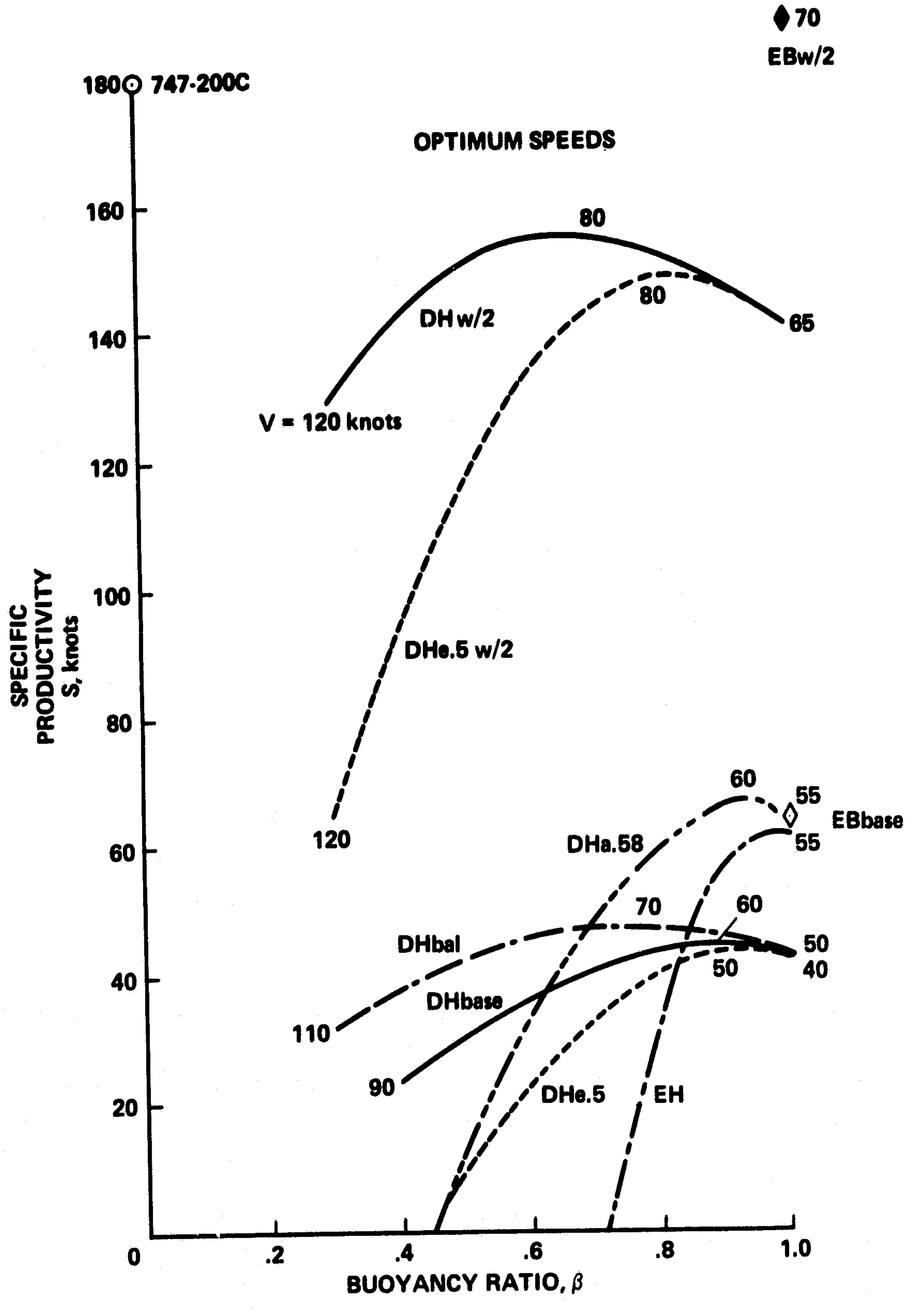

Figure 14.- Airship specific productivity, intercontinental mission.

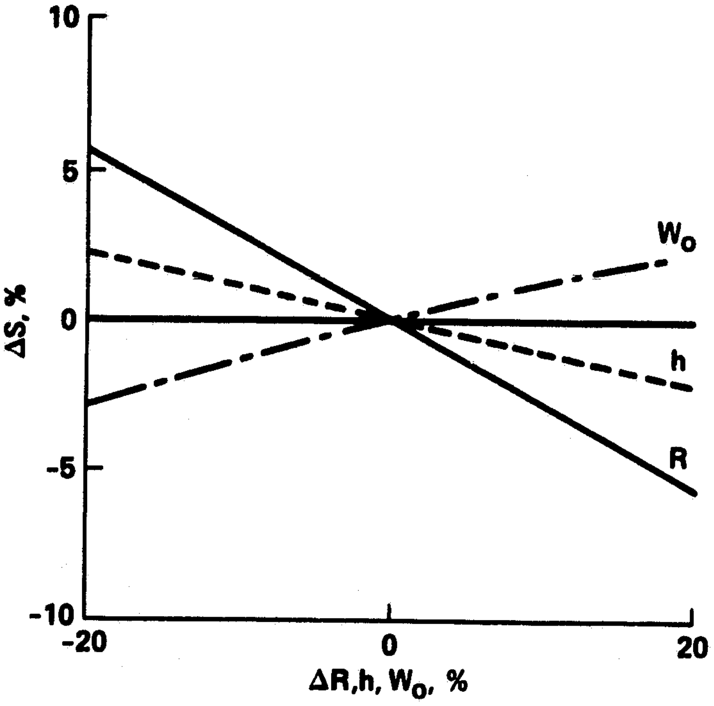

Figure 15.- Sensitivity data for EBbase for intercontinental mission.

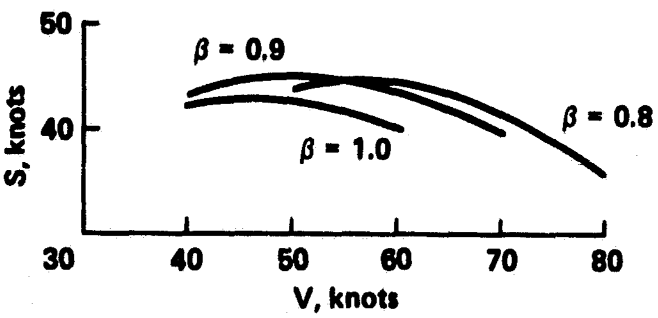

Figure 16.- Parametric data for DHbase for intercontinental mission.

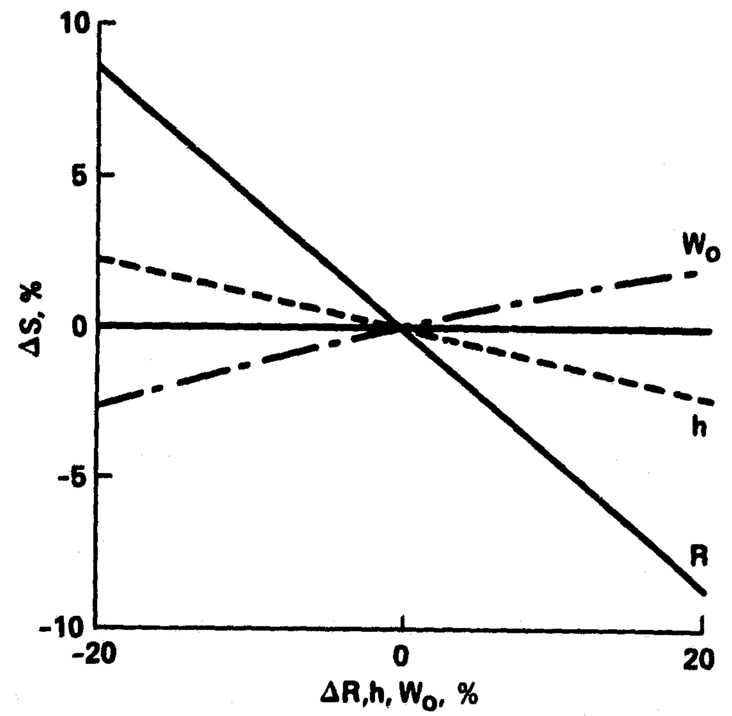

Figure 17.- Sensitivity data for DHbase for intercontinental mission.

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16. Abstract

This paper develops a methodology for estimating the specific productivity of both hybrid and fully-buoyant airships and derives a weight estimating relationship for the empty weight of deltoid hybrids. Specific productivity is used as a figure of merit in a parametric study of fully-buoyant ellipsoidal and deltoid hybrid semi-buoyant vehicles. The sensitivity of results as a function of assumptions is also determined.

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