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ABSTRACT

The subsonic aircraft mode of a Space Shuttle booster establishes design requirements on airbreathing engine size and flyback fuel allotment. Trade study results show the influence of wing geometry variations on the flyback systems weight (wing, jet engine and flyback fuel weight) of a canard Space Shuttle booster. The influence of such wing geometry parameters as aspect ratio and wing area is discussed.

Wing weight trends with wing geometry, obtained from conventional cargo, bomber and fighter airplane weight histories, are correlated with predicted values for Space Shuttle wings where structural span, load factor, and other design parameters are taken into account.

For other than cruise performance reasons, a lower limit of wing area is defined; the influence of other phases of the booster mission profile, including launch, entry, and landing is presented. Aspect ratio, however, is influenced primarily by cruise performance and cost considerations. The influence of ground rules, such as choice of flyback fuel, headwind profile, and required range is discussed.

INTRODUCTION

The booster wing geometry trade studies have been directed toward determining the wing aspect ratio that results in minimum system weight. A parameter referred to as flyback systems weight (FSW), the sum of wing airbreathing engine and flyback fuel weights, is used to relate the influence of wing geometry on the booster flyback leg of the overall Space Shuttle mission.

However, other portions of the booster mission profile must be considered in studying wing geometry. Secondary considerations, which influence wing size, include the hypersonic entry stability and trim and landing performance characteristics of the booster.

Any changes resulting from cruise optimization must be carried through the entire mission; hence, system weights can spiral. Total mission performance sensitivities reflect changes to system weight due to changes in structural weight, flyback fuel and launch drag.

The trade study used a family of aft wing, forward canard booster configurations with aspect ratio varying between 2 and 8.

Two candidate Space Shuttle airbreathing engines were studied with bypass ratios of 0.7 and 1.8. Two different flyback fuels — kerosene (JP-4) and hydrogen (H_2) — were considered. Cruise performance was determined at optimum altitude or 10,000 ft., whichever was greater. Current Space Shuttle ground rules of operation against the NASA/Kennedy Spaceflight Center 95% headwind profile were used.

For the flyback analysis trade study, the main fuselage was held at a constant size and the structure and systems were assigned a constant weight of 400,000 lb. The entry weight of all configurations was, then, the sum of 400,000 lb. and the FSW. The FSW (flyback system weight) is defined as:

$$FSW = W_W + W_{ENG} + W_{F_R}$$

where

W_W = wing structure + TPS

W_{ENG} = engine weight + installation

W_{F_R} = fuel weight + 10% tank and line weight + reserves

Figure 1 presents wing weights of a number of existing aircraft plotted versus a term ($WnbS/t_R$), which seems to represent more the bending moment of the wing,

where

W = vehicle weight
n = design load factor
b = wing span
S = wing area
t_R = wing thickness at root

All data falls within a reasonable band around a straight line on the log-log plot.

The resulting wing weights are presented in Figure 2 as a function of the aspect ratio with the exposed wing area as parameter. For the wing weight calculation some parameters were held constant:

1. The entry weight of the booster was assumed to be W_E = 650,000 lb. and invariant with aspect ratio or wing size.
2. The ultimate load factor was assumed to be n = 4.75.
3. The spar height was held constant at h_s = 3.7 ft. The thickness ratios of the wings of S_W = 3,000 and 4,000 sq. ft. for instance, changed therefore from approximately τ = 6% at an aspect ratio of A = 2 to approximately τ = 12% at an aspect ratio of A = 8.

The family of boosters subjected to the trade study had one fuselage of 220 ft. length of constant shape and a constant canard surface of S_c = 800 sq. ft. The canard was mid-fuselage mounted and located at the intertank region; it is all-movable and can therefore be unloaded during hypersonic entry. The different wings, all provided with a constant leading edge sweep of $\Lambda_{LE} = 40^o$ and a constant taper ratio of λ = 0.4 varied in aspect ratio from A = 2 to A = 8 and in exposed wing area from S_W = 1,000 sq. ft. to S_W = 6,000 sq. ft. The aerodynamic characteristics of the family of boosters are presented in Figure 3, in terms of lift to drag ratio and corresponding lift coefficient. The maximum lift to drag ratios of two configurations are compared with wind tunnel test data obtained in the General Dynamics Low Speed Wind Tunnel. We notice that the magnitude of $(L/D)_{max}$ is reasonably well reproduced. The Space Shuttle booster, however, flies generally at lower lift coefficients and therefore faster (M $\sim$ 0.6) to obtain maximum range or at fixed range R = 400 n.mi. to obtain minimum FSW.

BOOSTER FLYBACK MISSION INFLUENCES ON SYSTEM WEIGHT

The flyback systems weight of a Space Shuttle booster with a fixed exposed wing area and flyback range is presented in Figure 4. The flyback systems weight decreases with increasing aspect ratio until a minimum is reached. At this point, increasing wing weight influences the decreasing fuel plus propulsion weight and reverses the trend of the FSW. With decreasing range, however, the minimum should occur at smaller aspect ratios since the fuel weight is proportionately less and the wing weight more dominating. From the plot we obtain aspect ratios ranging from A $\leq$ 3 for a range of R = 100 n.mi. to A $\sim$ 5 for a range of R = 500 n.mi. The influence of the bypass ratio of the jet engine on the optimum aspect ratio is small. However, the trend that higher bypass ratio engines yield smaller FSW reverses between R = 200 n.mi. and R = 100 n.mi. In this region, the smaller thrust to weight ratio of the higher bypass ratio engines plays the significant role in reversing the trend.

The FSW changes drastically when liquid hydrogen (H_2) is used as jet engine fuel instead of kerosene (JP-4), as shown in Figure 5. For a range of R = 400 n.mi. and an exposed wing area of S_W = 4,000 sq. ft. a weight difference of approximately ΔW = 120,000 lb. can be saved. We also notice that the minimum FSW for JP-4 occurs at approximately $\Delta A \sim 2$ units higher than the minimum FSW for hydrogen (H_2). If we consider only JP-4 as flyback fuel we notice that the stability margin has an influence on FSW. Increasing the stability margin from $\Delta h = 2\%\ L_B$ to $\Delta h = 5\%\ L_B$ results in an FSW increase of ΔW = 15,000 lb. On the other hand an increase in jet engine bypass ratio from BPR = 0.7 to BPR = 1.8 results in a FSW decrease of ΔW = 13,000 lb.

The flyback systems weight for a range of R = 400 n.mi. is presented in Figure 6 as a function of the exposed wing area S_W with the aspect ratio A as parameter. The optimum exposed wing area where FSW has a minimum from the flyback performance point of view decreases with increasing aspect ratio. In the neighborhood of A = 5 and S_W = 3,300 sq. ft. an absolute minimum in FSW is reached, FSW = 287,000 lb. For higher aspect ratios and smaller exposed wing areas the FSW is increasing rapidly. The entry weight obtained by adding the FSW to a partial dry weight of ΔW = 400,000 lb. is W_E = 687,000 lb. Superimposed on the plot are lines of constant numbers of jet engines which have an approximate sea level static thrust of T_{SLS} = 18,000 lb. In order to fly the Space Shuttle booster at an altitude of 10,000 ft. approximately N_E = 14 jet engines of the BPR = 0.7 type are necessary.

EFFECT OF ENTRY AND LANDING ON FLYBACK SYSTEMS WEIGHT

The previous paragraphs have discussed the influences of wing geometry on systems weight when only the cruise segment of the Space Shuttle booster mission is studied. For maximum cruise efficiency, a wing area/aspect ratio combination can be selected. A lower limit of wing area is determined by other phases of the mission profile, primarily entry and landing. The influences of these considerations on the flyback systems analysis will be discussed in the following paragraphs.

The family of boosters for the trade study has the wing located to provide a subsonic stability margin of 2% of fuselage length. As indicated by the stability diagram (normal force versus pitching moment coefficient) shown in Figure 7, the resulting hypersonic stability and trim characteristics of each aspect ratio family vary with wing area. Typically, as area increases, the vehicle trims to progressively lower angles of attack, with the elevons neutral and the canard surfaces unloaded (aligned with the freestream). Static stability is generally not of concern; the angle of attack for neutral stability ($dC_m/dC_n = 0$) is considerably lower than that for trim. The trim angle of attack for each family, as a function of exposed wing area, is also presented in Figure 7. Current Space Shuttle design studies indicate that a trim angle of attack of 60^o is a good compromise from heating and entry loading considerations. For the trade study, this criterion was adopted as a possible constraint to wing area.

The landing weights of the family of boosters, as determined from entry weight minus cruise fuel weight, are shown in Figure 8. Typically, landing weight increases with aspect ratio, at constant area, due to the increase in wing structure weight. The A = 2 family has a different trend, influenced primarily by the number of engines required. Landing performance of the family was estimated assuming the use of the elevons deflected down 10° as simple landing flaps. Stall characteristics are reflected; the higher aspect ratios are restricted to lower landing angles. However, the higher aspect ratios still have better landing performance, as indicated by lower landing speeds at the same area. Operational considerations (gear, brake, and tire design, field lengths) indicate a landing speed of 180 knots as being maximum. To preserve a margin of safety for operations at higher landing weights and lower density (hot day, altitude) a design landing speed of 165 knots was selected for the trade study.

The constraints on wing area imposed by entry trim and landing performance are superimposed on the plot of FSW versus aspect ratio and wing area for R_{CR} = 400 n. mi., as presented in Figure 9. In general, these constraints prohibit attainment of the area for minimum FSW. For aspect ratios of 5 and 6, the hypersonic trim requirement establishes minimum area. For the lower aspect ratios, the minimum wing area is established by the landing speed requirement.

The variation of entry weight (FSW + 400,000 lb.) with aspect ratio is presented in Figure 10, corresponding to the wing area sized by landing or entry considerations. Minimum entry weight occurs at A = 4. The maximum difference in entry weight over the range from A = 2 and A = 6 is seen to be 24,000 lb. The corresponding variation in landing weight is also presented. It is indicated that minimum landing weight occurs at a lower aspect ratio, near A = 3. Typical Cost Estimating Relationships (CER) used in Space Shuttle studies relate RDT&E costs to dry weight; in this case, booster landing weight. Minimum cost would appear to coincide with that for minimum landing weight. The direct cost of JP-4 is insignificant. However, the JP-4 must be carried over the entire Space Shuttle mission profile. Differences in JP-4 weight spiral total system weights, including structures.

TOTAL MISSION PERFORMANCE INFLUENCES ON FLYBACK SYSTEMS WEIGHT

The flyback analysis previously presented was based on a constant fuselage structure and systems weight (400,000 lb.). With payload fixed, the differences in the factors that contribute to FSW between configurations in the trade study should be influenced by total mission performance. These effects can be estimated by the introduction of total mission sensitivities. Representative sensitivities relating changes in booster entry and landing weights due to changes in structural weight, flyback propellant weight and drag velocity losses during ascent to staging are presented in Table I. These are based on holding payload constant.

The influence of wing geometry to total mission performance of the booster includes the contribution of wing to the launch drag and, hence, drag velocity losses through staging. Presented in Figure 11 are predicted values of the wing drag contribution over the significant ascent Mach number range, for aspect ratios of 2, 4, and 6. For the wings sized previously, the booster wing comprises from approximately 15% to 23% of the total configuration peak drag. The lower aspect ratio wings offer a potential advantage in reducing launch drag, since the greater chord lengths may permit stowage of the airbreathing engines within the wing. The higher aspect ratios require external podding: the increase in drag due to an underwing nacelle is seen to greatly increase the launch drag contribution.

The effect of aspect ratio upon entry and landing weight, based on flyback analysis and with adjustment by total mission performance sensitivities, is presented in Figure 12. The sensitivities were applied by normalizing to the performance of the system with A = 2.7. It is indicated that the differences of the original analysis are accentuated by the influence of total performance spiralling. Minimum entry weight is at A = 3.9 and landing weight is minimum at A = 3.5. If an external airbreathing engine nacelle is included in the launch drag, both entry and landing weights are increased, as shown. A discontinuity is expected when the aspect ratio wing which permits internal engine stowage is reached. As previously discussed, booster RDT&E costs estimates follow dry weight. This would indicate minimum cost at A = 3.5. Additional cost considerations include differences in structural complexity of wings and number of engines.

CONCLUSIONS

The results of the booster wing geometry trade study have established the following trends:

1. For the current design mission ($R_{CR} \approx$ 400 n. mi., JP-4) minimum FSW occurs at an aspect ratio of 4.
2. System RDT&E cost follows dry weight; minimum landing weight occurs at an aspect ratio of 3.5.
3. Reduction of cruise range lowers aspect ratio for minimum FSW.
4. Use of H_2 fuel lowers aspect ratio for minimum FSW.

The trends above indicate the influence of basic groundrules for Space Shuttle. Selection of wing planform on the basis of current groundrules would indicate an aspect ratio of 3.5-4. However, potential changes to groundrules to gain performance or mission flexibility, such as downrange landing or conversion to H_2 flyback fuel, may be anticipated. These considerations would bias selection towards a lower aspect ratio.

A significant design feature of the lower aspect ratio wings is internal stowage of the airbreathing engines. With this approach incorporated, the aspect ratio 2.5 configuration has 14,000 lb more FSW and the same landing weight as the optimum aspect ratio configuration with an external engine installation.

ILLUSTRATIONS

Figure 1. Aircraft Wing Weight Data Correlation
Figure 2. Space Shuttle Booster Wing Weight Trends
Figure 3. Space Shuttle Booster Cruise Aerodynamics
Figure 4. Effect of Cruise Range on FSW
Figure 5. Effect of Cruise Fuel on FSW
Figure 6. Effect of Wing Area on FSW
Figure 7. Hypersonic Trim Considerations
Figure 8. Landing Performance
Figure 9. Effect of Entry and Landing on FSW
Figure 10. Wing Geometry from Flyback Analysis
Figure 11. Wing Contribution to Launch Drag
Figure 12. Total Mission Performance Results

Table I. Total Mission Performance Sensitivities

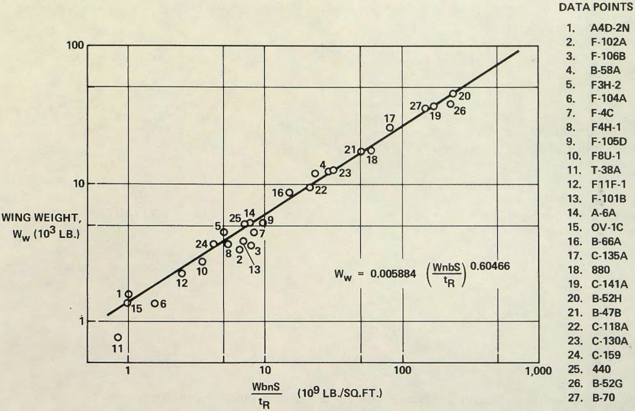
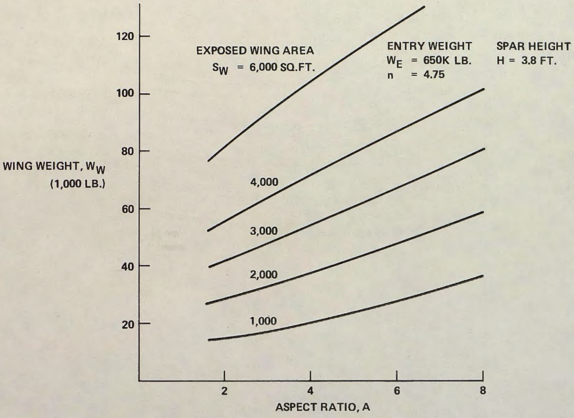


Figure 1 Aircraft Wing Weight Data Correlation



igure 2 Space Shuttle Booster Wing Weight Trends

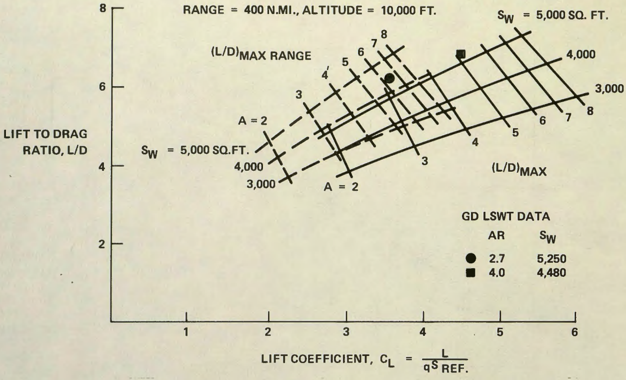


Figure 3 Space Shuttle Booster Cruise Aerodynamics

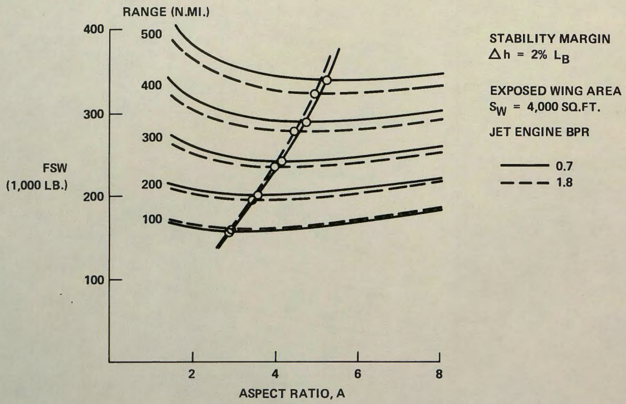


Figure 4 Effect of Cruise Range on FSW

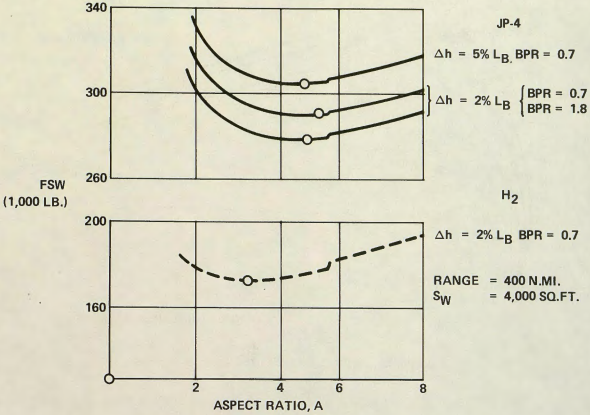


Figure 5 Effect of Cruise Fuel on FSW

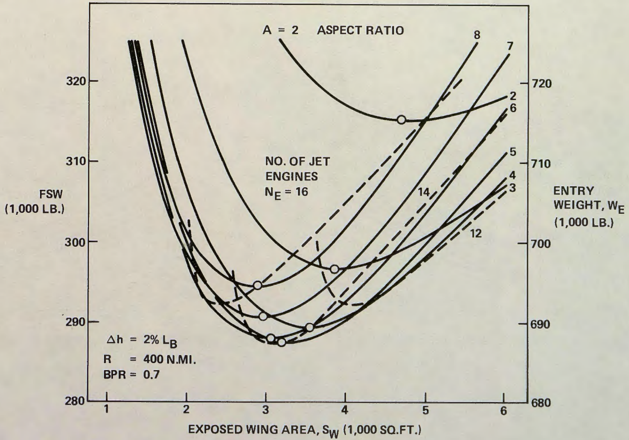


Figure 6 Effect ow Wing Area on FSW

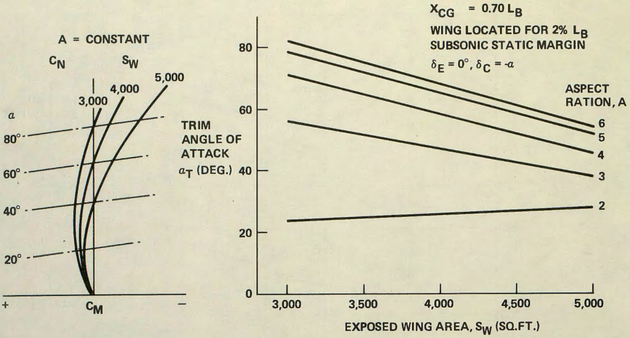


Figure 7 Hypersonic Trim Considerations

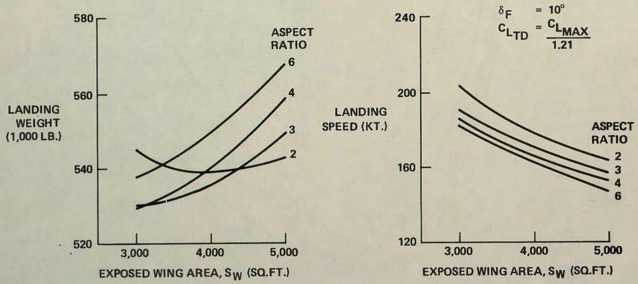


Figure 8 Landing Performance

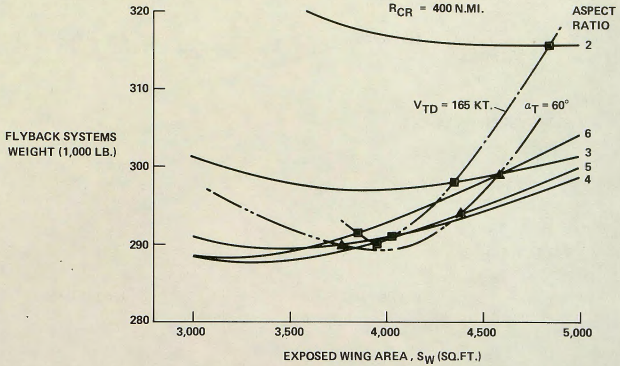


Figure 9 Effect of Entry and Landing on FSW

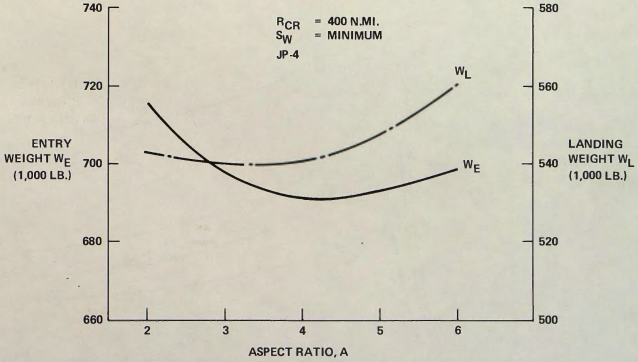


Figure 10 Wing Geometry from Flyback Analysis

STRUCTURAL WEIGHT

$$\frac{\partial W_E}{\partial W_{STRUCT}} = 2.2 \text{ LB./LB.} \qquad \frac{\partial W_L}{\partial W_{STRUCT}} = 2.0 \text{ LB./LB.}$$

FLYBACK PROPELLANT

$$\frac{\partial W_E}{\partial W_{JP\text{-}4}} = 1.8 \text{ LB./LB.} \qquad \frac{\partial W_L}{\partial W_{JP\text{-}4}} = 0.6 \text{ LB./LB.}$$

LAUNCH DRAG

$$\frac{\partial W_E}{\partial \Delta V_{DRAG}} = 160 \text{ LB./FPS} \qquad \frac{\partial W_L}{\partial \Delta V_{DRAG}} = 120 \text{ LB./FPS}$$

Table I Total Mission Performance Sensitivities

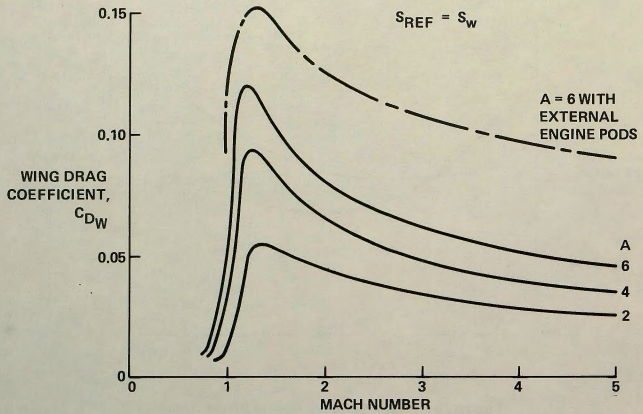


Figure 11 Wing Contribution to Launch Drag

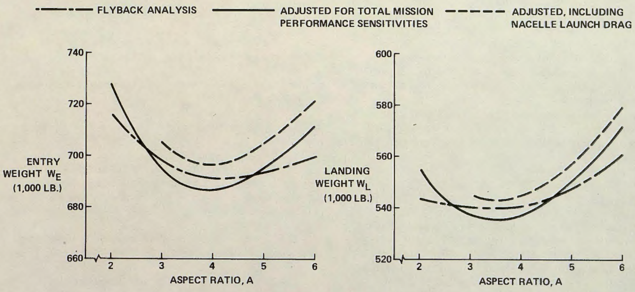


Figure 12 Total Mission Performance Results