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Feasibility of Recovering a One-Million-Pound Booster (Deceleration System)

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As space technology and applications mature, the concept of reuse of spacecraft and launch systems becomes more important, especially from the standpoint of efficient utilization of resources. This is currently exemplified by the Space Shuttle Orbiter and the two recoverable and reuseable Solid Rocket Boosters which are part of its launch system. As we move toward the year 2000 and the design of more advanced orbital and interplanetary spacecraft, the likelihood of requirements to recover larger and heavier vehicles is considerably increased. This study indicates that it is feasible to recover launch systems weighing as much as one million pounds at reasonable impact velocities using a hybrid parachute-retrorocket recovery system for weight penalties of about 5% of the total recovered weight.

Introduction

THE concept of reusing spacecraft and launch vehicles is currently exemplified by the Space Shuttle Orbiter and the two recoverable and reuseable Solid Rocket Boosters (SRBs) which are part of its launch system (Ref. 1). The Space Shuttle Orbiter has wing surfaces and, after deorbit at the proper location, uses the high-lift, high-drag entry concept to fly to a specific landing site (Ref. 2). The propellant tank, which is the largest part of the launch system, is jettisoned in space and is not recovered. The two SRBs, each weighing 166,000 lb after burn-out (Ref. 3), are individually recovered by parachute systems that weigh on the order of 7500 lb for each SRB including storage and support structure. This allows each SRB to be recovered for reuse for a weight penalty of about 4.5%.

Although the current space shuttle has not yet flown, studies have been performed to define a variety of larger space vehicles and launch systems for future applications (Ref. 4). The concept of recovery and full reuseability of space vehicles and launch systems is still of prime importance. In most instances winged launched systems recovered by horizontal landing are considered, but there are some applications where a parachute-type recovery would be more applicable. Therefore, it is appropriate to consider if it is feasible to recover boosters larger and heavier than the Space Shuttle SRBs for a similar recovery system weight penalty.

The SRBs are recovered over the ocean using conventional parachutes or ribbon canopy design constructed of nylon materials. The SRBs are relatively sturdy structures that can withstand water impact at the 85-ft/s final-descent velocity provided by the parachute system. Larger, less-sturdy boosters, such as more likely will be used on some future systems, would probably require much lower impact velocities. Weight estimates indicate that, for the lower impact velocities, that is, 60 ft/s or less, the hybrid parachute-retrorocket recovery systems may be more practical. The new Kevlar materials, which have a much higher strength-to-weight ratio than nylon materials, help make it feasible to recover a one-million-pound booster for a reasonable weight penalty.

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Feasibility Restraints

The feasibility of recovering a one-million-pound booster or any other vehicle heavier than the Space Shuttle SRB could be dependent on factors completely unrelated to the parachute aspects of the recovery, such as: Would retrieval from the ocean cause the required refurbishment to be so extensive as to be uneconomical? Or, would the impact area be so far away from the refurbishment facility so as to make retrieval impractical? An item more closely related to the recovery system would be a determination if the booster structure could withstand loads imparted to it by the recovery system. The capability of the booster to withstand water impact would determine the final impact velocity required.

A factor concerning the feasibility of recovering a large booster that is directly related to the recovery system selected would be the weight penalty associated with including a recovery system as part of the launch weight.

For the SRB recovery system, the parachute-portion weight is about 6444 lb for recovery of a booster having an empty weight of 166,000 lb. This is a recovery-system weight factor of about 4%. For this analysis we have arbitrarily considered that a recovery-system weight factor of 5% would represent a feasible system.

Booster Drag

A key element in the recovery of the Space Shuttle SRB is that it must reenter the atmosphere in a flat spin oriented essentially 90 deg to the flight path. In this way the SRB provides sufficient drag to reduce the flight dynamic pressure to a nominal value of 210 lb/ft^2 at an altitude of 15,000 ft (Mach = 0.5). An earlier evaluation (Ref. 5) indicated that a one-million-pound booster of the shape shown in Fig. 1 would provide sufficient drag, when oriented at 90 deg to the flight path, to reduce the flight dynamic pressure to 260 lb/ft^2 by the time it would have descended to altitudes where parachute deployments would be initiated. Therefore, for analysis of the SRB recovery system, the initial drogue-parachute deployment dynamic pressure was assumed to be 210 lb/ft^2, whereas for the heavier booster vehicles it was assumed to be 260 lb/ft^2.

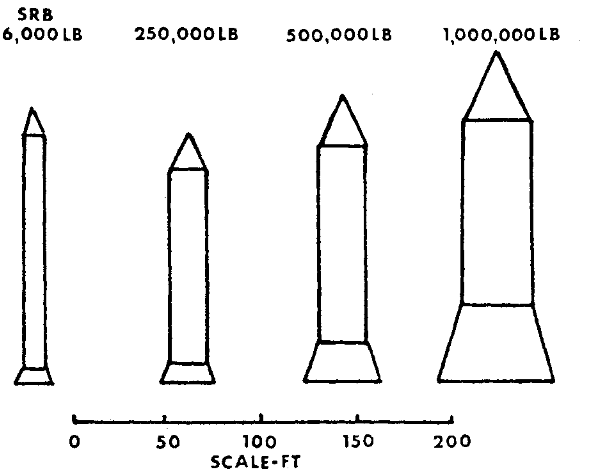

Fig. 1 Size and weights of boosters analyzed for recovery-system weights.

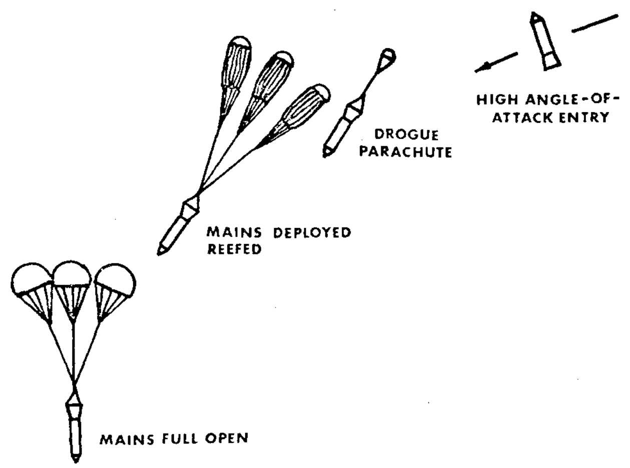

Fig. 2 All-parachute recovery system.

All-Parachute Recovery System

A schematic of an all-parachute recovery system is presented in Fig. 2. As mentioned previously, a high angle-of-attack entry was assumed in order for the booster to achieve subsonic velocities and dynamic pressure levels reasonable for parachute deployment. The all-parachute recovery system considered for analysis purposes is essentially identical to the SRB recovery system in that it uses a single drogue parachute and a cluster of three main parachutes for all applications. The single drogue parachute provides a substantial increment of deceleration before the main parachutes are deployed; but, its main purpose is to change the position or attitude of the booster from a horizontal flat-spin condition to a vertical position and therefore more suitable for the complex process of simultaneously deploying and inflating the three main parachutes in a clustered configuration.

The changes in dynamic pressure and altitude that would typically occur during the deployment process are shown in Fig. 3 for both the drogue and main parachutes. The drogue parachute would be deployed at an altitude of 30,000 ft, a velocity of 764 ft/s, and a dynamic pressure of 260 lb/ft^2. To reduce parachute opening forces, the drogue parachute has two stages of reefing in addition to the full-open stage. At about 9500-ft altitude, the drogue parachute would be released and used to deploy the main parachutes. During the interval of time the main parachutes are being deployed, the booster gains speed and the dynamic pressure level increases until the main parachutes develop sufficient drag area to slow the booster again. The main parachutes also have two stages of reefing and a full-open stage.

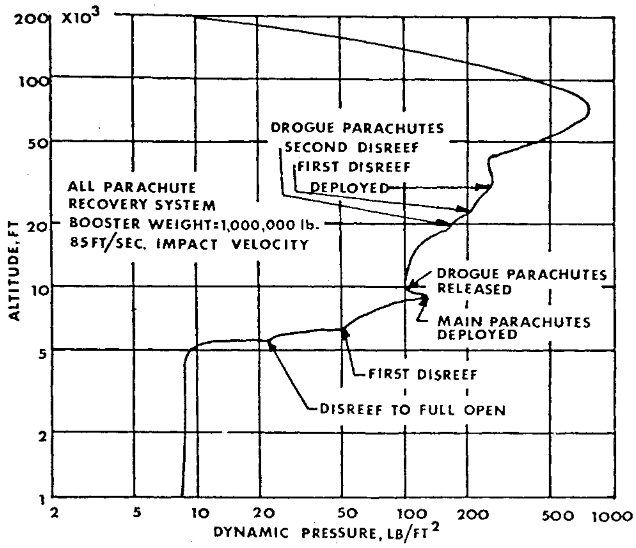

Fig. 3 Dynamic pressure changes with parachute deployment.

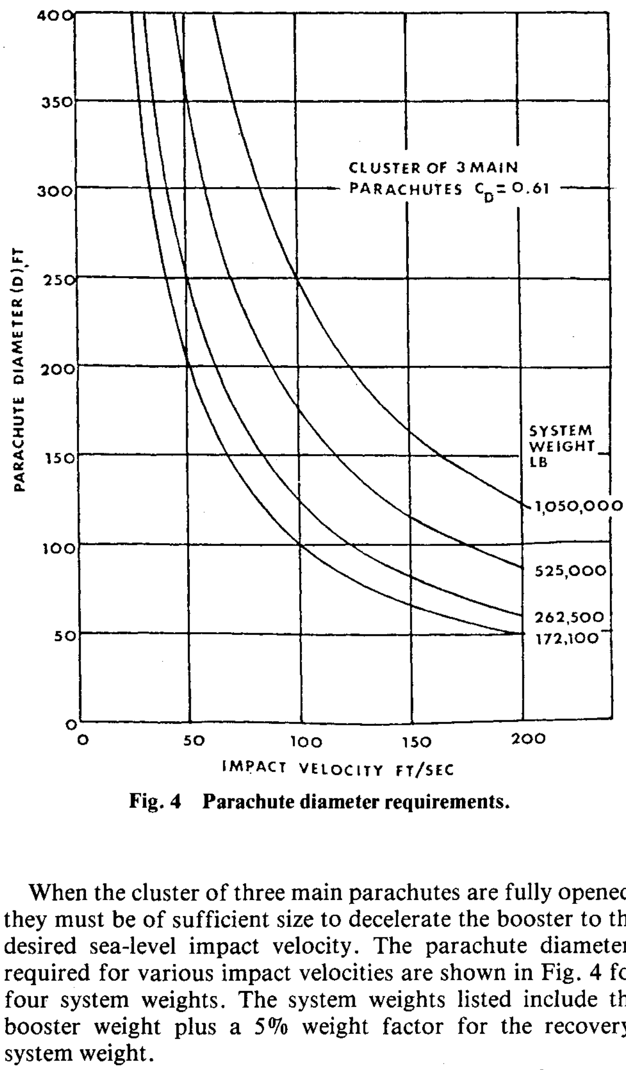

Fig. 4 Parachute diameter requirements.

When the cluster of three main parachutes are fully opened, they must be of sufficient size to decelerate the booster to the desired sea-level impact velocity. The parachute diameters required for various impact velocities are shown in Fig. 4 for four system weights. The system weights listed include the booster weight plus a 5% weight factor for the recovery-system weight.

The procedure followed in estimating weights of recovery systems for various impact velocities was to first estimate the weights of the Space Shuttle SRB recovery parachutes as they have been designed, tested, and fabricated for use. This was done to provide confidence that the parachute portion of the recovery-system weight estimates are realistic. Once the weight estimates for the SRB recovery parachutes were considered satisfactory, the input parameters to the weight equations were modified only as necessary to estimate the

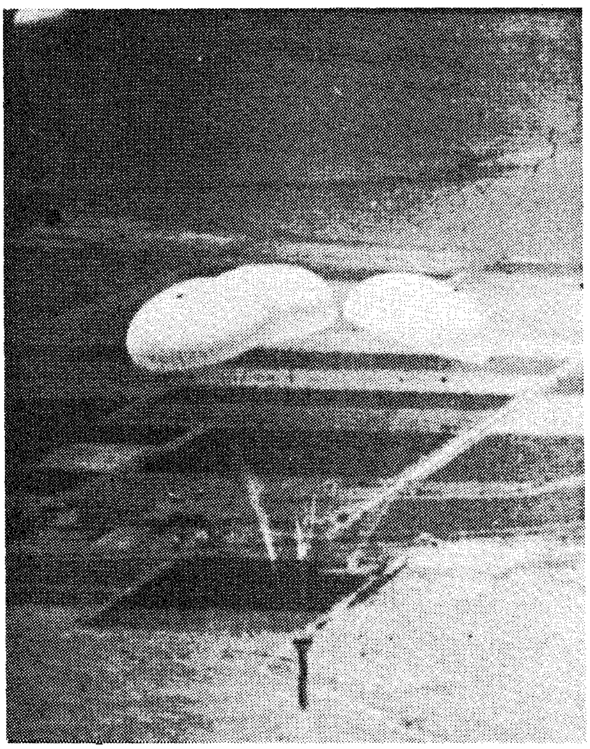

Fig. 5 All-parachute recovery system for the Space Shuttle Solid Rocket Booster.

recovery weights for larger and heavier booster vehicles. Booster vehicle weights of 250,000, 500,000, and 1,000,000 lb were used. The shapes of the different weight boosters are assumed to be as shown in Fig. 1.

SRB Recovery System Definition

The SRB recovery system is an all-parachute system which consists of an 11.5-ft diameter pilot parachute, a 54-ft diameter drogue parachute, and a cluster of three 115-ft diameter main parachutes. A photograph of both the drogue and main parachutes taken during testing is shown as Fig. 5.

All of the parachutes are constructed of nylon materials and all are of 20-deg conical ribbon design with 16% geometric porosity. The drogue parachute has a system of suspension lines and risers that are 105-ft long for a suspension-line length-to-diameter ratio (l_s/D) of 1.94. The l_s/D ratio of the main parachute was slightly less at a value of 1.7. The drag coefficient, C_D, for the drogue parachute is 0.65. The drag coefficient for the main parachutes are somewhat less at 0.61 due to a reduction in efficiency because of clustering.

The deployment conditions for the drogue parachute are a Mach number of 0.5 at an altitude of 15,000 ft (a dynamic pressure of 210 lb/ft^2). The deployment dynamic pressure for the main parachutes is a function of the equilibrium descent conditions on the drogue parachute with an allowance for an increase in velocity when the drogue parachute is released from the SRB and used to deploy the main parachutes. To reduce parachute opening forces, both the drogue and main parachutes are equipped with two stages of reefing. The impact velocity of the SRB on the three 115-ft diameter main parachutes is expected to be 85 ft/s.

Parachute Weight Equation

The equation used to determine the weights of the SRB parachutes, and all other parachute systems analyzed herein (refer to Refs. 6 and 7) is

$$\text{Parachute weight} = \text{weight of risers and suspension lines} + \text{canopy fabric} = b_q(C_DA)^{3/2} + cd_fq(C_DA) \qquad (1)$$

where q is the free-stream dynamic pressure; C_D is the drag coefficient (=0.65); A is the parachute reference area; d_f is the canopy weight per unit area per unit dynamic pressure (=0.00125 lb-M/ft^2); and, b and c are constants that depend on parachute design and performance but not on size. These are defined as

$$b = \frac{K_d}{\pi^{1/2}\cos\theta}\left(\frac{\bar{q}}{q}\right)\frac{\rho l_s}{D}\frac{1}{K_e(C_d)^{1/2}} \quad c = \frac{K_c}{C_d}(1-\lambda) \qquad (2)$$

where K_d is the parachute design factor (=3.33); θ is the suspension-line confluence angle (=11.3 deg); $\bar{q}/q$ is the parachute opening shock factor (=1.1); ρ is the ratio of suspension-line loop length to length of suspension line (=2.59); l_s is the length of suspension line (=1.70D); D is the diameter of the parachute; K_e is the strength-to-mass ratio of suspension lines (=175,000 ft for nylon and 385,000 ft for Kevlar); K_c is the construction efficiency factor (=1.25); C_d is the drag coefficient (=0.65); and, λ is the geometric porosity (=0.16).

The parachute weight is determined in two parts. The first part of Eq. (1) is for the weight of the risers and suspension lines considering that the lines (or their equivalent) are continuous over the top of the canopy. The second part of Eq. (1) is for the weight of the canopy fabric which, in this case, is ribbon material. The constants are defined in Eqs. (2).

Some adjustments to input parameters from those used in Ref. 5 were required to more properly represent those actually used in the design of the SRB parachutes. The values shown for input parameters for Eqs. (2) are those used in estimating the weights of main parachutes, both for the SRB recovery system and for heavier boosters. For the weight estimates of the drogue parachute an additional factor of 1.14 was included in the first part of the equation to account for the longer suspension lines used on the drogue parachute in SRB recovery.

Weight Estimate for SRB Recovery System

Using an initial drogue deployment dynamic pressure of 210 lb/ft^2 and a final impact velocity of 85 ft/s, Eq. (1) was used to estimate the weight of the SRB parachute recovery system. The weight of the SRB drogue parachute was estimated to be 1263 lb (actual weight is 1247 lb) and the main parachutes were estimated to weigh 1722 lb each (actual weight is 1714 lb). The total estimated weight of the drogue and main parachute portions of the SRB recovery system is 6427 lb which is only 17 lb less than the total weight of the actual parachutes. It was therefore considered that a valid set of input values had been selected for the parachute weight equations.

Weight Estimates for Heavier Boosters

Two changes were implemented in estimating recovery-system weights for the heavier boosters. The first change was in the initial deployment conditions. For the SRB, at a system weight of 172,000 lb, the initial deployment dynamic pressure is 210 lb/ft^2 at an altitude of 15,000 ft, whereas for the heavier booster (i.e., system weights of 252,500, 525,000, and 1,050,000 lb) the initial deployment dynamic pressure used for analysis purposes is 260 lb/ft^2 at an altitude of 30,000 ft as established in Ref. 5 for a 1,050,000-lb booster of the shape shown in Fig. 1. Note that the system weights listed above include the booster weight plus a 5% weight allowance for the recovery system.

The second change between the SRB and heavier booster recovery systems has to do with the shape of the boosters and the manner in which they are recovered. The SRB is a long, slender vehicle which is recovered with the parachutes attached to the nose-cone end of the vehicle and the tail-cone end impacts the water first. The recovery parachutes, both drogue and mains, were of sufficient size that they operated far enough aft of the SRB to avoid detrimental wake effects. The one-million-pound booster analyzed in Ref. 5 was considered to be typical of a pressure-fed booster and it was considered more appropriate to recover it with the nose-cone end impacting the water first. This is significant because the recovery parachutes are, therefore, attached to and operate in the wake of the rather large tail cone. To assure that the efficiency of the recovery parachutes would not be significantly degraded by the wake of the booster a requirement was implemented for the parachutes to be located at least 8-base diameters aft of the booster base. If this did not occur simply because of the size of the parachute with respect to the booster, then a riser of required length was inserted between the booster and the parachute(s) and its weight included in the estimate of recovery-system weight. The 8-base-diameter trailing distance requirement was imposed for all three of the heavier boosters shown in Fig. 1. To show the effects of these two changes, the weight of the SRB-type recovery system is presented in Fig. 6 as a function of impact velocity for three conditions: 1) an initial deployment dynamic pressure of 210 lb/ft^2 with no added trailing distance requirement, 2) an initial deployment dynamic pressure of 260 lb/ft^2 with no added trailing distance requirement, and 3) both an initial deployment dynamic pressure of 260 lb/ft^2 and a trailing distance requirement of 162 ft. At all impact velocities the increased deployment dynamic pressure results in a very small increase in recovery system weight (2% increase in recovery system weight for an impact velocity of 85 ft/s). The added trailing distance requirement results in a much larger increase in recovery-system weight (12% increase for an impact velocity of 85 ft/s).

Results from the weight analysis of an all-parachute recovery system for the heavier boosters is presented in Fig. 7

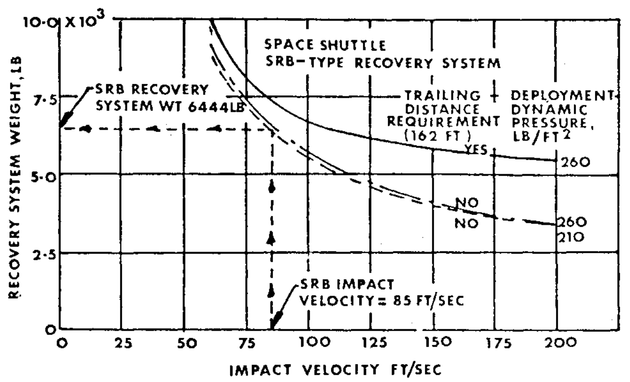

Fig. 6 Effects of deployment dynamic pressure and trailing distance changes on recovery-system weight for an SRB-type recovery system.

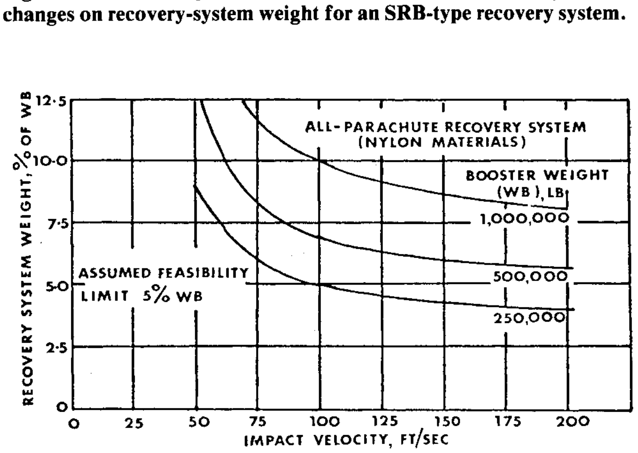

Fig. 7 Weight of all-parachute (nylon material) recovery systems for three booster weights.

for parachutes constructed of all-nylon materials (except for reefing-line cutters, suspension-line fittings, etc.). A significant result is that for 1,000,000- and 500,000-lb boosters the all-parachute recovery systems constructed of nylon materials weigh more than the 5% weight limit for all impact velocities considered. For the 250,000-lb booster a nylon all-parachute recovery system does not exceed the 5% weight limit for impact velocities of 100 ft/s or greater.

Significant savings in recovery-system weight can be achieved by using Kevlar materials instead of nylon. As indicated in Eq. (2), Kevlar has a much better strength-to-mass ratio than nylon. Kevlar also has much less elasticity than nylon and therefore the design and fabrication technology developed for nylon parachutes has not been directly applicable for parachutes constructed of Kevlar. Much progress has been made, however, in determining design and fabrication techniques for Kevlar parachutes (Refs. 8, 9, and 10). The analysis presented herein assumes that Kevlar parachutes can be constructed with no significant changes required in parachute design factors or in parachute construction efficiency factors. Estimated weights of Kevlar material all-parachute recovery systems are presented in Fig. 8. Using Kevlar materials reduced the recovery-system weights for the 500,000-lb booster to less than the 5% weight limit for impact velocities of 60 ft/s or greater. For the 1,000,000-lb booster the 5% recovery-system weight limits the reduction of impact velocity to 80 ft/s.

Parachute-Retrorocket (Hybrid) System

A schematic showing how a hybrid (parachute-retrorocket) system would function is shown in Fig. 9. Although a drogue parachute is not shown on Fig. 9, the analysis herein assumed

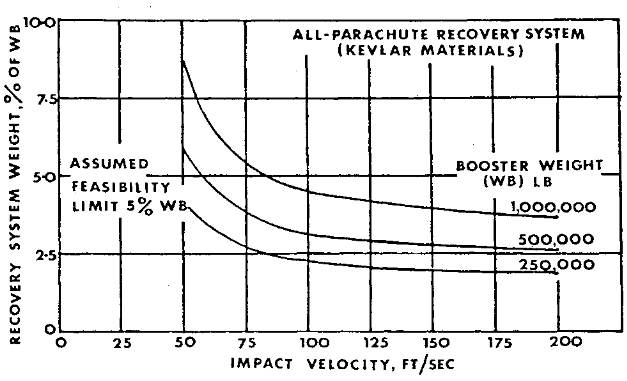

Fig. 8 Weight of all-parachute (Kevlar material) recovery systems for three booster weights.

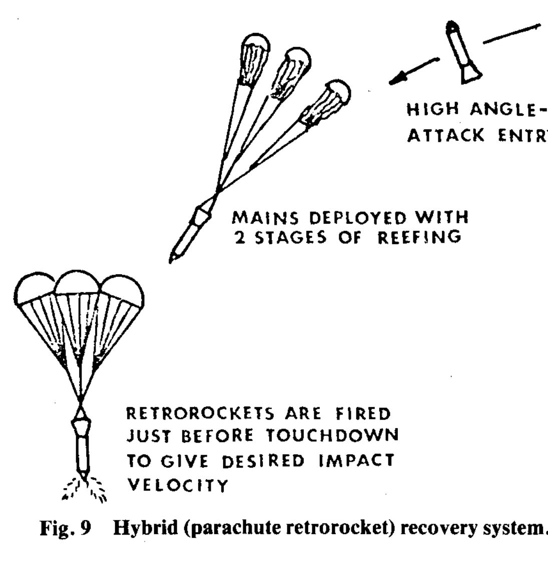

Fig. 9 Hybrid (parachute retrorocket) recovery system.

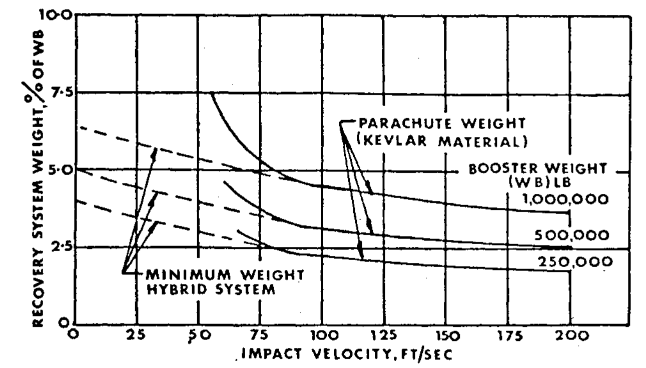

Fig. 10 Hybrid parachute-retrorocket system weights vs impact velocity for three heavy boosters.

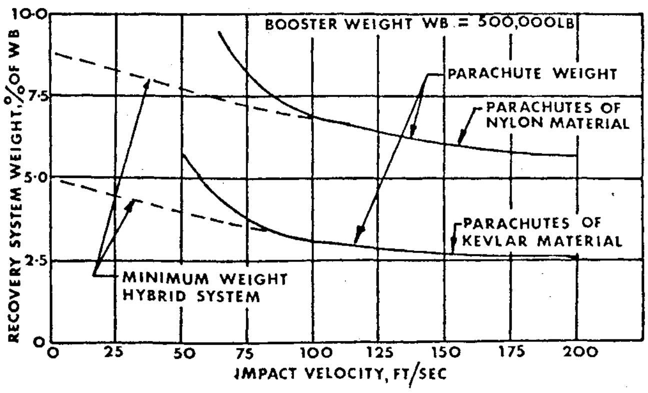

Fig. 11 Effect of Kevlar technology on hybrid recovery-system weight.

that a drogue parachute would be used. The hybrid system is essentially an all-parachute system with the addition of retrorockets located in the nose cone of the recovered booster. The booster would descend on the main parachutes until shortly before touchdown at which time the retrorockets would be fired to slow the booster to the desired impact velocity.

The retrorocket weight requirement for a hybrid system is defined as

$$W=\frac{tT}{(\mathrm{S.I.})(\mathrm{M.F.})} \tag{3}$$

where t is the thrust time in seconds; T is the thrust (lb $=3W$); S.I. is the propellant specific impulse ($=275$ s); and M.F. is the propellant mass fraction ($=0.92$). A value for t, the thrust time, can be obtained by integrating the equilibrium equation

$$W-T-D=\frac{W}{g}\frac{\mathrm{d}v}{\mathrm{d}t} \tag{4}$$

where D is parachute drag, to arrive at

$$t=\frac{1}{g}\int_{v_{\mathrm{ignition}}}^{v_{\mathrm{impact}}}\frac{\mathrm{d}v}{(T/W-1)+D/W} \tag{5}$$

As can be seen, the retrorocket weight is a function of the time and thrust requirements to provide the proper velocity decrement in addition to rocket propellant specific-impulse and mass-fraction characteristics. The values used in the evaluation for propellant specific impulse, propellant mass fraction, and the thrust-to-weight ratio are stated.

The reason for considering a hybrid system was to determine its potential for providing a recovery system capable of providing impact velocities down to or near zero for recovery system weights within the 5% feasibility limit. Results of including a retrorocket on recovery-system weights are shown in Fig. 10. Both the parachute weight curves and the minimum hybrid system weight curves are shown.

With a hybrid recovery system, the 250,000-lb booster could be recovered at a zero impact velocity with a recovery-system weight factor of only 4%. For the 500,000-lb booster and an impact velocity of zero, the recovery-system weight factor is right at the defined feasibility limit weight factor of 5%. For the 1,000,000-lb booster the 5% feasibility limit weight factor limits the minimum impact velocity to 70 ft/s.

An indication of how much weight is saved by using Kevlar material for the parachute portion of a hybrid recovery system is shown in Fig. 11 for a 500,000-lb booster. Recovery-system weight, in percent of booster weight, is presented as a function of impact velocity for both a nylon parachute system and a Kevlar parachute system. A major difference resulting from using Kevlar rather than nylon material is that the terminal velocity on the parachute portion of the recovery system is reduced from about 110 ft/s (for nylon parachutes) to about 85 ft/s (for Kevlar parachutes). Returning to Fig. 4 it can be seen that in order for a 500,000-lb booster to achieve a terminal descent velocity of 110 ft/s, parachutes of 159-ft diameter would be required. For a terminal descent velocity of 85 ft/s, the required parachute size is 206-ft diameter. For the hybrid recovery system on a 500,000-lb booster, the use of Kevlar material results in a recovery system weight reduction of about 19,000 lb for impact velocities between 0 and 75 ft/s.

Conclusions

1) The selected input parameters to the parachute weight equation result in an accurate estimation of the current Space Shuttle Solid Rocket Booster (SRB) parachute recovery system.

2) Use of an initial deployment dynamic pressure of 260 lb/ft^2 (rather than the 210 lb/ft^2 for SRB design) resulted in only a 2% increase in estimated parachute recovery-system weight for the SRB system at an impact velocity of 85 ft/s.

3) Use of a trailing distance requirement of 8-booster-base diameters results in a 12% increase in estimated parachute recovery-system weight for the SRB at an impact velocity of 85 ft/s.

4) A nylon material all-parachute recovery system exceeds the 5% feasibility limit on recovery-system weight for all impact velocities for the 500,000- and 1,000,000-lb boosters considered.

5) Use of Kevlar materials significantly reduces the all-parachute recovery-system weight, allowing recovery of the 250,000-lb booster at impact velocities as low as 50 ft/s without exceeding the 5% recovery-system weight feasibility limit. Similarly, for the 500,000- and 1,000,000-lb boosters, impact velocities as low as 60 and 80 ft/s can be achieved for the 5% weight limit.

6) Use of a hybrid (parachute-retrorocket) system allows recovery of the 250,000- and 500,000-lb boosters to zero impact velocity for less than the 5% recovery-system weight feasibility limit. For the 1,000,000-lb booster, the hybrid system allows recovery at impact velocities as low as 70 ft/s for the 5% recovery-system weight limit.

7) Use of Kevlar materials rather than nylon results in hybrid recovery-system weight savings of over 19,000 lb for the 500,000-lb booster for impact velocities of 0-75 ft/s.

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