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Evaluation of Entry and Terminal Deceleration Systems for Unmanned Martian Landers

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Early unmanned Mars lander vehicles will be severely payload limited due to the low entry vehicle ballistic coefficient, and small launch vehicle (Titan III class) requirements. Since the deceleration systems comprise a major portion of the vehicle weight, a comprehensive study has been performed to minimize the decelerator weights in order to provide a maximum payload capability. Various terminal descent systems were considered with primary emphasis on the parachute-propulsion soft lander, and the parachute-impact attenuator rough lander for out-of-orbit and direct entry with ballistic and lifting entry vehicles. An important phase of the study was the comparison of recent contractural specific design results with the present parametric analysis. The results indicate that the soft lander deceleration systems are lighter than those of the rough lander when conditions of minimum surface density, maximum winds, and surface irregularities are considered. For less severe environmental conditions, the deceleration system weights are competitive.

Nomenclature

a_i = impact deceleration, Earth g's
A = reference area, ft^2
C_D = drag coefficient
h = altitude, ft
L/D = lift-drag ratio
M = Mach number
m = entry mass, slug
m/C_DA = ballistic coefficient, slug/ft^2
$T/W_{♂}$ = thrust-weight (Mars) ratio
V_e = entry velocity, fps
W = weight, lb
W_{ds} = total deceleration system weight, lb
W_e = entry weight, lb
γ_e = entry angle, deg

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Introduction

EFFORTS to minimize the cost of landing an instrumented payload on the surface of Mars require the consideration of launch vehicles in the Titan III-C class, which imposes severe weight restrictions on the design of the lander vehicle. Furthermore, the tenuous nature of the Martian atmosphere provides a limited aerodynamic retardation capability requiring a large fraction of the vehicle weight for deceleration systems. Particular entry and terminal deceleration systems for Mars missions using the Saturn V launch vehicle have been studied.[1,2] The purpose of the present study is to minimize and compare weights of several candidate deceleration systems so that maximum payload capability can be determined for the Titan III-C class launch vehicle. Primary emphasis was placed on the soft lander that employs a parachute prior to propulsive terminal descent and the rough lander which utilizes a parachute plus an impact attenuator. For these systems, both direct and out-of-orbit ballistic entries were examined as well as direct lifting entry. Other factors considered were entry corridor limitations, atmospheric structure, and surface irregularities. A comparison of the present

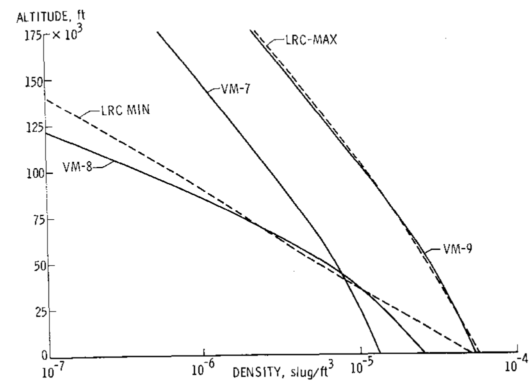

Fig. 1 Mars model atmosphere.

analysis with recent contractual results[3–6] was also an important phase of the study.

Mars Environment

A Mars entry vehicle must be capable of performing in a wide range of model atmospheres since the atmosphere of the planet is not yet well defined. The model atmospheres considered in this analysis are shown in Fig. 1; the most critical atmosphere was used in defining each aspect of the mission. For deceleration purposes, the atmosphere having the minimum density is most critical. Consequently, the VM-8 atmosphere was used to define the entry vehicle ballistic coefficient requirements for parachute deployment at a specific Mach number and altitude. The VM-7 atmosphere in combination with winds varying up to 220 fps were used to define the parachute size and the terminal deceleration system requirements. Some results were also obtained using the new model atmospheres, developed at the Langley Research Center (LRC), which are based on recently obtained high-resolution spectra data. As can be seen there is little difference between the LRC minimum and the VM-8 atmospheres above approximately 40,000 ft. The higher surface density of the LRC minimum atmosphere, if adopted as a standard, will provide more atmospheric deceleration capability near the surface which will relax the terminal deceleration system requirements. It might be noted that little difference exists between the LRC maximum and the VM-9 atmospheres. These high-density models must be considered in determining the low-thrust requirement for soft landers.

Since the surface of Mars may have high elevations and surface roughness, terrain altitudes up to 6000 ft above the mean surface and 5-in.-diam rocks were used as constraints in the landing analysis.

Terminal Descent Profiles

The terminal descent initiation conditions and constraints have an important bearing on entry vehicle as well as terminal system requirements. An illustration of the terminal mission modes considered in this study are presented in Fig. 2. When the entry vehicle, either ballistic or lifting, reaches a Mach number of 2, a drogue parachute is deployed and decelerates the vehicle to a dynamic pressure of 5 psf at which time the main parachute is deployed and the aeroshell is jettisoned. The deployment Mach number of 2 represents current parachute technology on the basis of the Planetary Entry Parachute Program (PEPP) flight tests,[7] and the low dynamic pressure of 5 psf was selected for deployment of the main parachute in order to reduce the opening loads, and hence decrease the weight of the parachute system.

For the rough lander mode, the drogue parachute is assumed deployed at an altitude of 15,000 ft, and the main parachute is deployed at an altitude of 12,000 ft in order to obtain maximum deceleration from the parachute and to allow for landing on elevations up to 6000 ft high. The rough lander stays attached to the main parachute to impact or possibly a few feet above impact.

For the soft lander the drogue parachute is assumed to be deployed at an altitude of 20,000 ft, followed by the main parachute deployment at an altitude of 17,000 ft, in order to allow for propulsion system initiation and parachute jettison at a height up to 5000 ft above the local terrain. Another candidate soft lander mode, the all-propulsion, was given a cursory examination. It was assumed that this system would be initiated at 15,000 ft.

Allowable m/C_DA, Entry Weights, and Diameters

The two entry vehicle parameters that determine the vehicle capability to decelerate aerodynamically are L/D and m/C_DA. Before an entry vehicle may be designed, it is necessary to define the L/D and m/C_DA requirements from entry trajectory analyses. It is desirable to have a vehicle with a reasonably large value of m/C_DA, since large m/C_DA's allow relatively small vehicle diameters, and hence lower structure and heat shield weights for a given entry weight. It is desirable to keep the entry vehicle diameter below the basic launch vehicle diameter to avoid the additional cost and weight of "hammerheading" the launch vehicle shroud.

The entry mode, entry vehicle L/D, and entry angle are important in maximizing the allowable m/C_DA as illustrated in Fig. 3. These results are based on a parachute deployment condition of $M = 2$ at an altitude of 15,000 ft for a rough lander and 20,000 ft for a soft lander in the most critical model atmosphere, VM-8. Also, some points are shown for the new LRC minimum model atmosphere, and are in close agreement with the VM-8 results.

For ballistic out-of-orbit entry, small corridors ($-15°$ to $-17°$) can be obtained, resulting in an allowable m/C_DA of about 0.38 slug/ft² for a soft lander and 0.46 slug/ft² for a rough lander. For direct ballistic entry, however, guidance uncertainties may require consideration of large entry corridors ($-17°$ to $-30°$ or ± 300 km) resulting in a low value of m/C_DA of around 0.2 slug/ft². Recent estimates of guidance

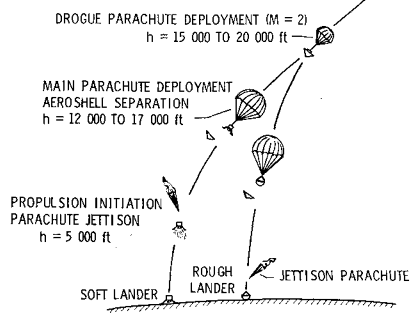

Fig. 2 Terminal descent modes.

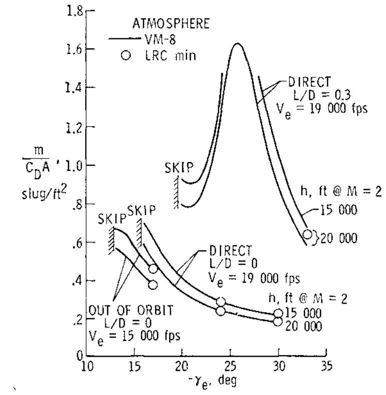

Fig. 3 Effect of entry mode on ballistic coefficient.

accuracies indicate the undershoot boundary may be decreased from $-30°$ to $-24°$, thus providing an increase in m/C_DA to about 0.27 slug/ft^2.

For direct entries where allowable ballistic m/C_DA's are relatively small, aerodynamic lift can be used to provide a substantial increase in m/C_DA.[8,9] As shown in Fig. 3, if a lifting vehicle (constant L/D of 0.3) is used, an m/C_DA of approximately 0.6 can be obtained for the largest entry corridor width considered.

For illustration purposes, the allowable m/C_DA values for the soft lander in Fig. 3 are resolved into required aeroshell diameters in Fig. 4 for the moderate weight range of entry vehicles. As a reference point, a 9-ft diam and 1500-lb entry weight are representative of the capability of the Titan III-C class launch vehicle. For this class of launch vehicle, diameters in excess of 9 ft require a hammerhead shroud for the launch phase of the mission. For the out-of-orbit case, a weight of 1200 lb is available for the ballistic entry capsule without hammerheading. Only a 570 to 780 lb ballistic capsule can be used for direct entry without hammerheading; however, this can be increased to 1480 lb if a lifting capsule with $L/D = 0.3$ is considered. Although packaging restrictions may not allow the use of the entire weight capability of the lifting vehicle, substantial gains are available. Thus, the lifting entry mode was included in the present deceleration systems weight analysis.

Method of Weight Analysis

An evaluation of several subsystems was required in order to determine the weight of a complete deceleration system necessary for the rough and soft lander vehicle. The subsystems analysis required certain assumptions and restrictions that are included in the brief description of each system that follows.

The rough lander deceleration system consisted of aeroshell, parachute, and attenuator subsystems. The aeroshell shape was a 120° blunted cone, and the variation of aeroshell weight as a function of entry weight, m/C_DA, and deceleration load were determined using the method of Ref. 10. As mentioned previously, the parachute subsystem is composed of a drogue parachute and main parachute. This type of parachute subsystem was chosen for this analysis in preference to a single mortar-deployed parachute because of an apparent weight savings obtained with the two chute subsystem. The parachute weights were based on PEPP flight data[7] and on extrapolation of the parachute design data given in Ref. 11. The attenuator subsystem consisted of a protective balsa wood layer surrounding a spherical payload with an assumed packaging density of 80 lb/ft^3. The attenuator weight varies only 5% for packaging densities ranging from 60 to 90 lb/ft^3; therefore, 80 lb/ft^3 was selected as a compromise between packaging limitations and maximum payload capability. As shown in the sketch of Fig. 5, two shapes were assumed for the balsa

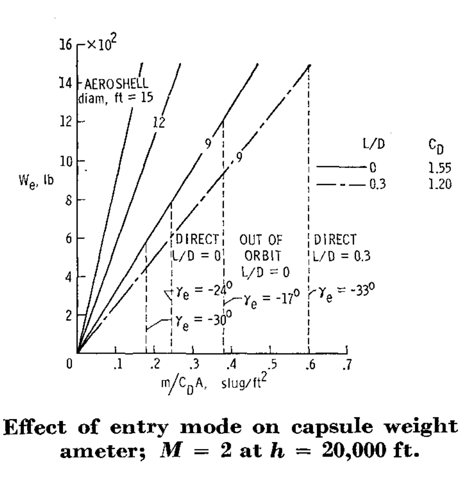

Fig. 4 Effect of entry mode on capsule weight and diameter; $M = 2$ at $h = 20,000$ ft.

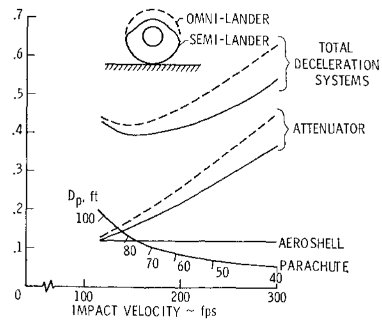

Fig. 5 Minimizing rough lander deceleration systems weight; W_e = 1200 lb, V_e = 15,000 fps, $\gamma_e = -17°$, L/D = 0, atmosphere VM-7 and Vm-8, no winds, $a_i < 2000$ g_e.

wood attenuator, the omni-lander and semi-lander. These shapes were selected as being representative of their respective classes, and do not represent optimized designs. The omni-lander is designed to protect the payload regardless of the orientation upon impact. The semi-lander assumes the parachute is jettisoned at impact; therefore, protection is required for the initial impact only on the bottom half of the payload with some protection provided on the upper half for secondary impacts. For both the omni-lander and semi-lander, the balsa wood grain was assumed to be aligned along radical lines emanating from the center of the payload. The balsa wood density was assumed to be 8 lb/ft,^{3} which accounts for the weight of bonding material, and a thin fiberglass cover. The balsa wood attenuator weights for impact velocities of 100 to 300 fps, and impact loads ranging up to 2000 Earth g's were determined by the method of Ref. 12. It has been demonstrated in the Capsule System Advanced Development (CSAD) program[13] that scientific instrumentation representative of that required for a Mars lander mission can be designed to withstand impact loads up to 2500 Earth g's.

The deceleration subsystems can be combined in a manner to provide a minimum total system weight which varies with entry weight and entry conditions. An example of the method used to determine the minimum rough lander deceleration system weights is shown in Fig. 5 for one set of entry conditions. Although the aeroshell weight is constant for this case, the opposing variation of parachute weights and attenuator weights as a function of impact velocity provide a minimum total-deceleration-system weight at a particular impact velocity. Since the deceleration system weights are smallest for the semi-lander, this configuration was used for the rough lander throughout the remainder of the study.

The soft lander deceleration system considered here employs aeroshell, parachute, propulsion, landing radar, and landing legs subsystems. The aeroshell and parachute subsystems are similar to those discussed for the rough lander. The propulsion system is a mono-propellant, liquid rocket having a three engine configuration with an assumed specific impulse of 225 sec, and a throttling ratio capability ranging up to 7. After initiation of the propulsion system at an altitude of 5000 ft or less, it was assumed that a Mars thrust-to-weight ratio of 0.8 was used until the vehicle reached velocity-altitude conditions matching a gravity-turn guidance law. At this point the maximum thrust-to-weight ratio would be employed to follow a gravity-turn maneuver (i.e., thrust applied opposite to the relative velocity vector) to the surface. The fuel requirements for the system were calculated with the trajectory computer program given in Ref. 14. The weight of the engines and landing radar and legs were obtained from unpublished manufacturer's data.

The soft lander deceleration system weights can be minimized for given entry conditions as shown in Fig. 6. In this analysis, there is one constraint on the parachute subsystem that has to be accounted for. It is necessary to determine the minimum parachute diameter required to separate the aeroshell from the lander and to assure that the aeroshell

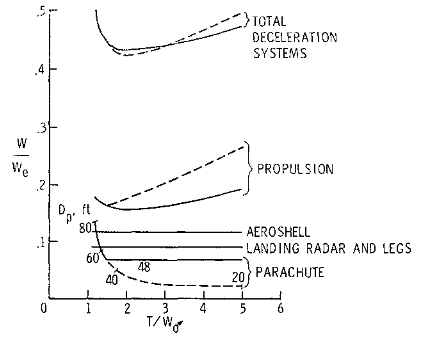

Fig. 6 Minimizing soft lander deceleration systems weight; W_e = 1200 lb, V_e = 15,000 fps, γ_e = −17°, L/D = 0, atmosphere VM-7 and VM-8, no winds.

reaches the ground prior to initiation of the landing radar and propulsion subsystem to prevent possible radar interference. This limitation increases the parachute weights, but lowers the propulsion system weights which results in little change in the total decelerator systems weight. In addition, the point at which the minimum deceleration system weight occurs provides the optimum maximum thrust-to-weight ratio from a deceleration system weight standpoint. In this analysis a maximum thrust-to-weight ratio of approximately 2.5 appeared to be near optimum for all entry conditions considered.

The minimization method described in this section was applied to determine the minimum total-deceleration-system weights presented throughout this study.

Environmental Effects

The effects of atmospheric structure, wind velocity, and surface roughness on deceleration systems weight are shown in Fig. 7 for the rough lander and soft lander configurations. The example chosen to illustrate the environmental effects on deceleration system weights corresponds to the out-of-orbit entry for an entry weight of 1200 lb. As indicated in Fig. 7, the soft lander offers the advantage of small variation in deceleration system weight with changes in atmospheric structure and wind velocity. This is due to the fuel consumption characteristic provided by the gravity-turn guidance law for the terminal propulsion system.

The rough lander, however, exhibits a strong dependence on the entry and surface environment. For the best environmental conditions such as no winds, LRC minimum atmosphere and smooth surface conditions, the rough deceleration system weight is approximately 85% of that of the soft lander. When the worst environmental conditions are imposed such as the VM-7 and VM-8 atmosphere models, 220 fps winds and surface irregularities corresponding to a 5-in.-diam rock, the rough lander deceleration system weight increases up to 160% of the soft lander deceleration system weight. Therefore, a more definitive comparison of the deceleration

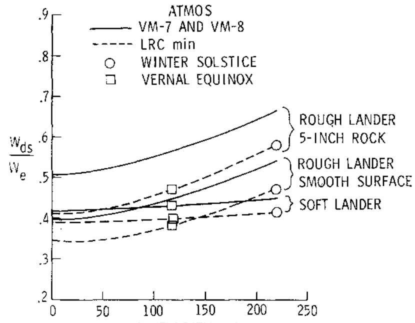

Fig. 7 Environmental effects on deceleration systems weight; W_e = 1200 lb, V_e = 15,000 fps, γ_e = −17°, L/D = 0.

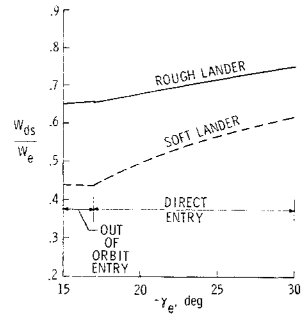

Fig. 8 Effect of entry angle on deceleration systems weight; W_e = 1200 lb, L/D = 0, atmosphere VM-7 and VM-8, 220 fps winds, 5-in. rocks.

system weights for the rough and soft landers is dependent on the reduction of Martian environmental uncertainties.

Entry Angle Effects

The entry angle range or entry corridor as dictated by guidance accuracies also has an effect on the weight of entry deceleration systems as illustrated in Fig. 8. For both rough and soft landers, there is negligible change in deceleration system weight over the flight-path angle range corresponding to an out-of-orbit entry. However, for the direct entry mode, an increase in γ_e, or corridor depth, results in increasing aeroshell weights and thus deceleration system weights. For example, in Fig. 8, if the undershoot γ_e is improved from −30° to −24° (which corresponds to recent estimates of guidance accuracies), the rough and soft lander deceleration system weights are decreased by approximately 5 and 8%, respectively. These deceleration system weights are still considerably higher than required for the out-of-orbit entry mode.

Entry Weight Effects

Figures 9 and 10 present the ratio of deceleration system weight to entry weight as a function of entry weight for the most severe environment conditions (i.e., VM-7 and VM-8 atmospheres, 220 fps winds, and surface irregularities corresponding to rocks five inches in diameter). In Fig. 9 the out-of-orbit entry mode is considered for both rough and soft landers. Included with the parachute-propulsion soft lander system is the all-propulsion terminal descent mode, taken here to be a Surveyor-type engine system. As can be seen, the parachute-propulsion soft lander is more efficient from a deceleration system weight standpoint than the all-propulsion mode, and is considerably more efficient than the parachute-impact attenuator rough lander. In all cases, the percentage of entry weight required for the deceleration system increases slightly as the entry weight decreases.

Also shown in Fig. 9 are the results of the recent contractural point-design studies[3–6] for rough and parachute-propulsion soft landers. In general, the contractural results are in reasonably good agreement with the present analysis. As would be expected, some small discrepancies exist between the results due to minor differences in ground rules and configurations. The omni-directional rough lander[3] is inherently less efficient than the semi-lander and the more sophisticated

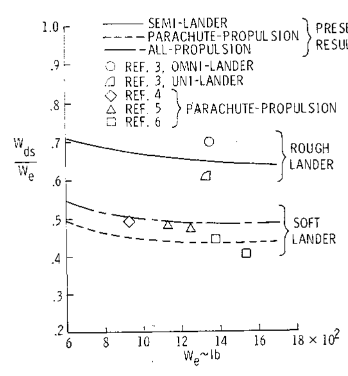

Fig. 9 Effect of entry weight on deceleration systems weight for out-of-orbit entry; L/D = 0, atmosphere VM-7 and VM-8, 220 fps winds, 5-in. rocks.

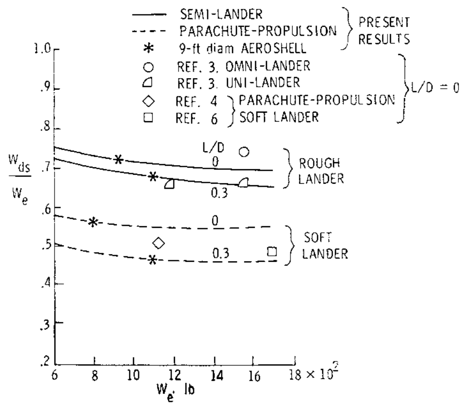

Fig. 10 Effect of entry weight on deceleration systems weight for direct entry; atmosphere VM-7 and VM-8, 220 fps winds, 5-in. rocks.

uni-lander design[3] provides the lowest deceleration system weight. The soft lander results of Refs. 4 and 5 are slightly higher than those of Ref. 6 and the present analysis, due to small differences in aeroshell and parachute subsystem weights.

In Fig. 10, the results are presented for direct ballistic and lifting entry for the rough and soft landers. As in the out-of-orbit case, the results indicate the soft lander deceleration system is lighter than that of the hard lander over the entry weight range considered. In comparing lifting entry with ballistic entry, the $L/D = 0.3$ entry vehicle provides a decrease in deceleration system weight over the entry weight range considered even though the allowable m/C_DA is restricted due to vehicle packaging limitations. In addition, higher entry weights are available with the lifting vehicle as opposed to the ballistic vehicle for an aeroshell diameter of 9 ft, above which hammerheading of the launch vehicle shroud is required.

Contractor point design results are also presented for the rough and soft lander configurations for the direct entry mode, which generally agree with the parametric results. The differences in the weight of the various rough lander configurations are for the same reasons as given in the out-of-orbit case. One reason the soft lander system weights of Refs. 4 and 6 are slightly lower than the present results is due to their use of lower parachute deployment altitudes. As a result, the aeroshell diameter, and hence the aeroshell weight, is less than for the present analysis.

Concluding Remarks

This study has shown that the total weight of the deceleration systems required to land a scientific payload on Mars can be minimized by a proper combination of deceleration subsystems. Of the deceleration modes examined, the parachute-propulsion soft lander is lighter than the parachute-impact attenuator rough lander when the minimum density atmosphere, maximum winds, and surface irregularities are considered. For less severe environmental conditions, the deceleration system weights for the soft and rough lander are competitive. The direct entry mode requires heavier deceleration systems than the out-of-orbit mode; however, reduction in these system weights can be realized by using a lifting vehicle. Specific design data from recent contractural studies support the parametric results presented in the present analysis.

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