Performance Optimization Technique for the 1975 Mars Viking Lander

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This paper presents a technique for optimizing the entry-to-touchdown performance of a planetary vehicle. Developed for the 1975 Mars Viking Lander, this technique is characterized by a graphical tradeoff approach including design parameter and atmosphere model variations. From entry (800,000 ft above the mean surface) to touchdown a lifting entry phase provides for deceleration to low supersonic speeds; the terminal phase includes a parachute and terminal propulsion system. Entry lift-to-drag ratio and the parachute diameter are principal design parameters used for performance optimization. Optimum performance is measured in terms of entry flight-path angle corridor, landing terrain elevation, and terminal phase system weight. Chief among the uncertainties with which the design must contend is the atmosphere. Lift is assumed to be generated passively using a lateral center of gravity offset, resulting in a trim angle of attack that produces lift. Entry phase analysis indicates that a hypersonic lift-to-drag ratio of 0.150 results in the maximum entry flight-path angle corridor. The terminal phase analysis indicates that the same L/D and a parachute diameter of 53 ft produce minimum terminal phase system weight (i.e., maximum useful landed weight) for a desired terrain elevation capability. Also indicated is that these values are optimum for a significantly heavier entry weight, as well as for the current Viking Lander.

Nomenclature

A = area
B = ballistic coefficient
C_D = drag coefficient
D = diameter
DR = downrange angle
F_D = opening shock force
h = altitude
i = orbit inclination
L/D = lift-to-drag ratio
M = Mach number
max $H_{\rho,s}$, max ρ_s, mean, min $H_{\rho,s}$, min ρ_s = Mars atmosphere model designations, see text
MSL = mean surface level
q = dynamic pressure
t = time
V = velocity
W = weight
$X_{c.g.}$ = longitudinal center of gravity location
α = angle of attack
Δ = incremental
γ = flight-path angle
$\sigma\gamma_E$ = 1σ uncertainty in γ_E

Subscripts

A/S = aeroshell
D = parachute deployment (mortar fire)
E = conditions at entry
F = final conditions on parachute at vernier ignition
P = parachute
T = terrain
T_Φ = terminal phase system

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Introduction

THE entry-to-touchdown portion of the 1975 Viking Mars mission is characterized by three phases: the entry phase, the aerodecelerator phase, and the terminal descent and landing phase. The entry phase of the mission is defined as extending from an entry altitude of 800,000 ft above mean surface to the altitude at which the parachute is deployed. The aerodecelerator phase begins with parachute deployment; the terminal descent and landing phase extends from terminal descent engine ignition to touchdown. The terminal phase, as used herein, includes the aerodecelerator as well as terminal descent and landing phases. Deceleration and Lander protection during the entry phase are provided by a high-drag aeroshell that incorporates an ablative heat shield; the Lander in the aeroshell is referred to as the entry vehicle. The terminal phase system includes the parachute system (parachute, mortar, etc.) and the terminal descent propulsion system. This discussion presents a technique for optimizing performance during the entry phase of the mission using a lifting entry approach and for optimizing performance and weight during the terminal phase.

Performance analysis and design of the 1975 Mars Viking Lander must accommodate a number of knowns and unknowns. The unknowns result from lack of precise knowledge of the Mars environment or of tolerances associated with performance characteristics. Known requirements and constraints generally result from preliminary design or from the state-of-the-art. The basic entry vehicle design has associated with it a given weight allocation and drag characteristics evolved from preliminary design. The drag area is usually constrained within some given range by the size of the launch vehicle payload shroud. Thus, for performance purposes, the basic entry vehicle may be described by its ballistic coefficient.

The entry trajectory performance is a function of the entry vehicle ballistic coefficient, conditions at entry (especially flight-path angle), and the atmosphere. Entry condition uncertainties result from orbit determination and deorbit maneuver inaccuracy. Atmospheric uncertainty is encompassed by five model atmospheres, as defined by the Mars Engineering Model.[1] In addition, since the elevation of the landing site will be uncertain (within some tolerance), the entry vehicle performance must also include a terrain height capability. Entry performance is constrained by design

Table 1 Performance requirements and constraints

Parameter	Value	Source
	Entry dispersions	
$\sigma\gamma_E$	0.20°–0.50°	Orbit determination,
V_E	15,050–15,175 fps	deorbit maneuver accuracy and targeting
	System baseline design and requirements	
W_E	1872 lb	Preliminary design, launch vehicle performance
$D_{A/S}$	11.5 ft	Shroud size
M_D	2.2	Parachute deployment confidence due to test results (state-of-art)
F_D	15,000 lb	Structural integrity, weight limitations
γ_F	−60°– −90°	Radar lockup probability
V_F	100 fps, min	Radar lockup, terminal propulsion design optimization
	Environmental unknowns	
Atmo	5 equally probable models, 4 mb–10 mb surface pressure	Mars Engineering Model[1]
h_T	10,000 ft above mean surface level	Mars Engineering Model[1] 3σ tolerance (± 3 km)

requirements, such as maximum dynamic pressure on the entry vehicle or dynamic pressure and Mach number at parachute deployment. There is also an optimum flight-path angle and accompanying velocity at terminal descent propulsion ignition; this affects the terminal phase system optimization. Performance capability is measured in terms of successful operation over as wide a range as possible of terrain elevation and entry trajectory conditions in the most adverse atmosphere model. The parameters (just previously discussed), with Viking values, where appropriate, are summarized in Table 1.

The Mars atmospheric models that are used in this analysis are: 1) minimum density scale height, min $H_{\rho,s}$; 2) minimum surface density, min ρ_s; 3) mean; 4) maximum surface density, max ρ_s; and 5) maximum density scale height, max $H_{\rho,s}$. Altitude-density profiles are shown in Fig. 1. As might be expected, different atmosphere models are critical to different parameters in the analysis. The critical atmosphere model will be indicated, where appropriate.

Analyses of Viking Lander performance have shown that lifting entry is a significant technique for enhancing entry performance.[2] The use of lift during the entry phase tends to desensitize the design parameters to the uncertainty in atmosphere, entry conditions, and terrain elevation. Lift may be generated passively using a center-of-gravity offset from the geometric longitudinal centerline for a symmetric entry body such as the Viking Lander. This produces a trim angle of attack, and thus, lift. The simplicity of this technique minimizes additional technical problems or increased cost, which might result from the incorporation of lift using an active system. With the incorporation of lift, design analysis questions that must be answered are: 1) How much lift must be employed for optimum performance using the criteria and constraints discussed above? 2) How is the entry corridor affected by lift? 3) What are the effects on other performance parameters? 4) What are the effects of trim angle of attack on dynamic stability characteristics?

After choosing a range of values for the L/D ratio and the entry flight-path angle corridor, the terminal phase system performance may be varied by selecting the parachute diameter and the terminal descent engine propellant load. Optimization of the terminal phase system is accomplished by determining the minimum weight that yields the desired performance (i.e., landing at a maximum design terrain elevation under critical entry conditions and atmosphere).

This paper discusses the relationship between the L/D for the maximum entry flight-path angle corridor and the optimum terminal phase payload and performance. Finally, the capability of the optimization technique to cope with design changes, such as weight increase, change in entry conditions, and changes or improvements in knowledge of uncertainties, is discussed.

Entry L/D Range and Entry Corridor

Entry phase performance is measured by the ability of the entry vehicle to deliver the Lander to the terminal phase initiation altitude at the most favorable conditions of relative velocity and flight-path angle in the critical atmosphere. Entry phase performance is a strong function of the flight-path angle corridor and atmosphere model. Entry-angle dispersions indicate that the entry corridor ($\Delta\gamma_E$) should be at least 3° wide. The min $H_{\rho,s}$ atmosphere is critical to corridor conditions and is the atmosphere used in the subsequent discussion. The minimum and maximum boundaries of the corridor must next be established. For this purpose four different types of lifting entry trajectories are defined. These are shown pictorially in Fig. 2, where the trajectories are identified as follows: 1) flight-path angle is always below the local horizontal; 2) flight-path angle reaches a limit value of zero (level flight); 3) flight-path angle becomes positive; and 4) circular orbital velocity is reached and skip-out would occur except fot atmospheric drag.

For Lander system evaluation purposes a lower γ_E limit based on the level flight boundary is established. This is

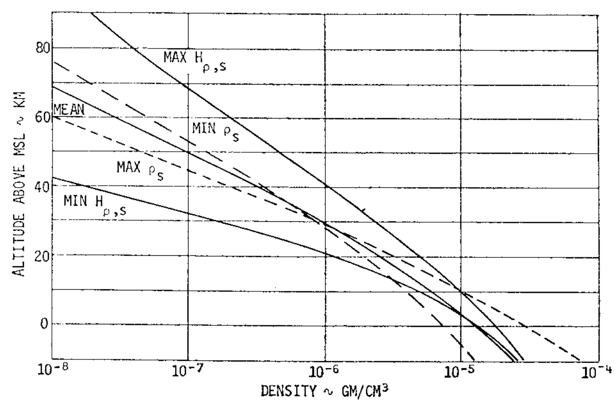

Fig. 1 Mars atmospheric density profiles.

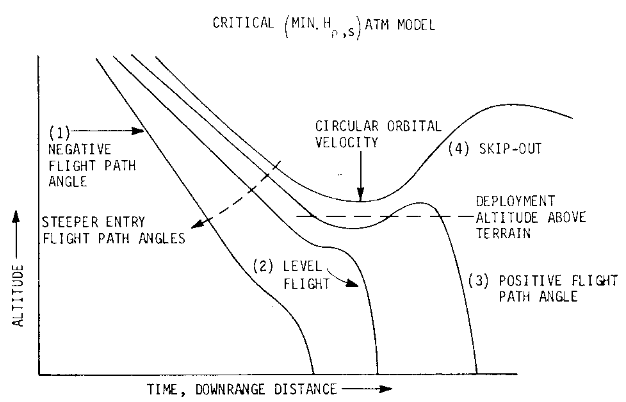

Fig. 2 Types of lifting entry trajectories.

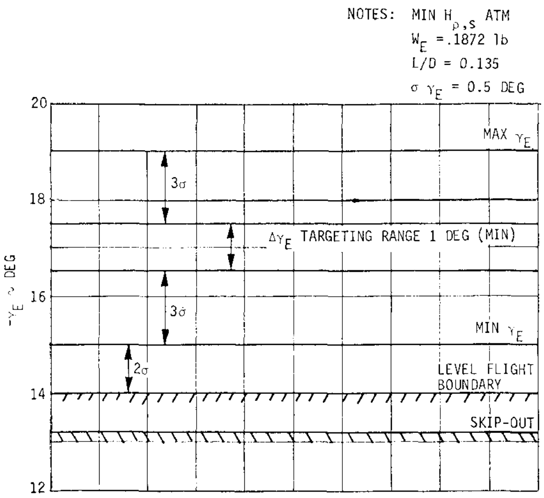

Fig. 3 Typical entry flight-path angle limits.

defined as the entry flight-path angle resulting in an entry trajectory described by 2). This boundary for the shallowest entry flight-path angle is chosen primarily to simplify the parachute deployment sequence. The simplest parachute deployment signal is a radar altimeter signal, as used on Viking. With such a system, deployment could occur at too high a Mach number on (3)- or (4)-type trajectories since deployment altitude could be encountered several times during entry. This possibility is illustrated on Fig. 2.

A typical entry flight-path corridor based on this level flight lower boundary assumption is shown on Fig. 3. A 2σ (1°) margin above the level flight boundary is somewhat arbitrarily defined using the maximum value of $\sigma\gamma_E$ expected. This definition establishes the minimum flight-path angle that may be encountered with a 3σ dispersion from the shallowest targeted angle ($-16.5°$ in this case). Allowance of a 1-° targeting range results in an upper 3σ corridor boundary of $-19°$. We thus fix a usable design corridor of $-15°$ to $-19°$ for the example illustrated. Performance of the Lander-to-Orbiter entry communications relay link, which is of extreme importance to the Viking mission, depends on the behavior of entry downrange angle and time. These are shown in Fig. 4. As skip-out (4-type trajectory) is approached, the downrange angle and time become excessive. Further, the sensitivity of time and downrange angle to entry angle dispersions increases rapidly as the skip-out boundary is approached; resultant landing footprints and time dispersions would be excessive.

The level flight boundary is a function of entry vehicle lift characteristics as well as of the entry flight-path angle—all illustrated in Fig. 5. The skip-out (4-type trajectory)

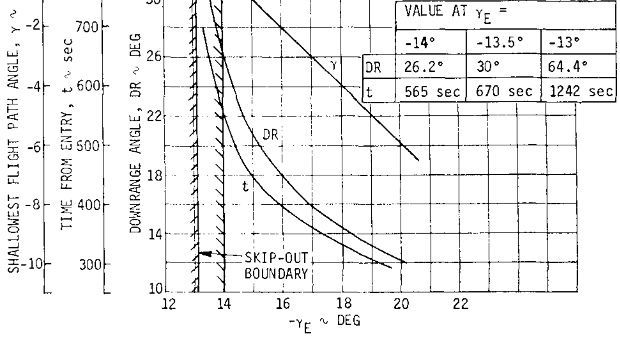

Fig. 4 Effect of shallow entry angle.

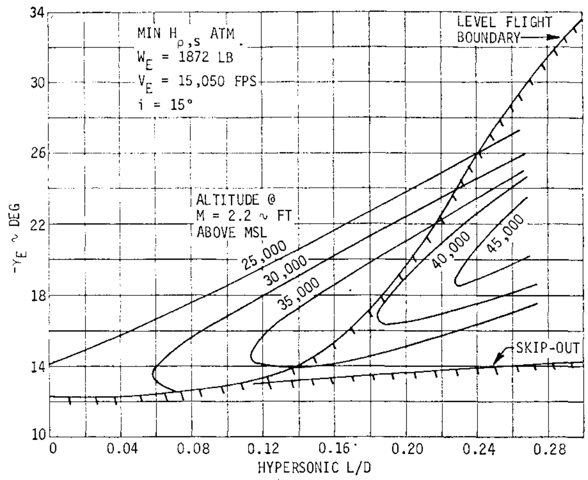

Fig. 5 Entry angle sensitivity to lift.

boundary is shown to be relatively insensitive to L/D. The altitude at which a Mach number of 2.2 occurs is also a function of lift and entry flight-path angle. Figure 5 illustrates that the γ_E margin between skip-out or level flight and Mach 2.2 altitudes decreases as the L/D ratio is reduced. The γ_E margin between the level flight boundary and a constant Mach 2.2 altitude increases with increasing L/D ratio until an optimum is reached. This effect may be seen in Fig. 5 and is plotted as $\Delta\gamma_E$ vs L/D on Fig. 6. The $\Delta\gamma_E$ was obtained from Fig. 5 from the difference between the level flight boundary and the Mach 2.2 altitude line or the difference between the two branches of the Mach 2.2 altitude line when both branches are above the level flight boundary. The $\Delta\gamma_E$ curves in Fig. 6 graphically indicate that 0.150 is the optimum (hypersonic) L/D ratio from the standpoint of maximum entry corridor. This L/D ratio is optimum for the current entry weight of 1872 lb and also for a weight of 2000 lb, a topic that will be discussed later.

The limit $\Delta\gamma_E$ line of 4°, shown on Fig. 6, represents a somewhat arbitrary minimum allowable total corridor width above the level flight boundary. The 4° corridor is made up of 3° tolerance ($\pm 1.5°$ 3σ) and 1° margin. The corridor discussed previously (Fig. 3) used an additional 1° of margin; thus, it represented a total corridor of 5° above the level flight boundary. However, only 4° ($-15°$ to $-19°$) is considered usable for mission and vehicle design purposes.

In the terminal phase optimization discussion that follows, total entry corridor values of 4.5° and 5.0° above the level flight boundary are chosen for investigation. In this selection

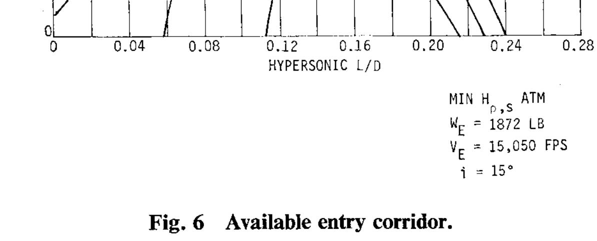

Fig. 6 Available entry corridor.

Table 2 Entry flight-path angle limits

L/D	$\gamma_E(°)$ for 4.5° total corridor min	$\gamma_E(°)$ for 4.5° total corridor max	Level flight γ_E (deg)	$\gamma_E(°)$ for 5.0° total corridor min	$\gamma_E(°)$ for 5.0° total corridor max
0.135	−14.5	−18.5	−14	−15	−19
0.150	−15.1	−19.1	−14.6	−15.6	−19.6
0.171	−16.7	−20.7	−16.2	−17.2	−21.2

it is important to consider other mission requirements or constraints, such as targeting, relay link communications, and design considerations. Use of the two total entry corridors, in combination with $\Delta\gamma_E$ and L/D values near the optimum in Fig. 6, results in certain entry flight-path angle limits, as shown in Table 2. The maximum value in Table 2 is always 4.5° or 5.0° above the level flight boundary. The minimum value is 4° shallower; this reflects the current position on targeting flexibility, i.e., the usable corridor is always 4.0° (1° for targeting ±1.5°, 3σ).

Terminal Phase Optimization Approach

The foregoing discussion has dealt with the optimization analysis through the entry phase of the mission. With a definition of the range of L/D ratio and entry angles with associated deployment altitudes, the analysis now proceeds with the terminal phase optimization. Design variables are the parachute diameter and the final parachute flight-path angle at terminal propulsion ignition. Performance parameters are landing terrain elevation capability and terminal phase system weight.

For the particular set of Viking design requirements and environmental uncertainties, the parachute performance is critical in the min ρ_s atmosphere and at the shallow entry angle limit. Under those conditions the maximum altitude increment is required by the parachute to reach a given flight-path angle (γ_F). Landing terrain height capability results from the deployment altitude, discussed in the preceding paragraph, less the terminal phase altitude increment. The parachute altitude increment is the difference between the deployment altitude and the altitude where the desired γ_F is reached. It is primarily a function of parachute diameter for a given parachute type. The terminal propulsion altitude increment depends on the initial velocity and, to a lesser extent, the flight path angle, γ_F. The initial conditions for terminal propulsion design include the effects of a maximum tailwind velocity of 213 fps. It is assumed that the vehicle has accumulated the total wind velocity added vectorially to the no-wind velocity. The terminal phase system weight includes total terminal descent propulsion system (function of initial conditions that depend on parachute diameter) plus the total parachute system (function of parachute diameter). The maximum thrust of the terminal propulsion system is 1800 lb. The subsystem weights are given for a typical set of conditions in Fig. 7.

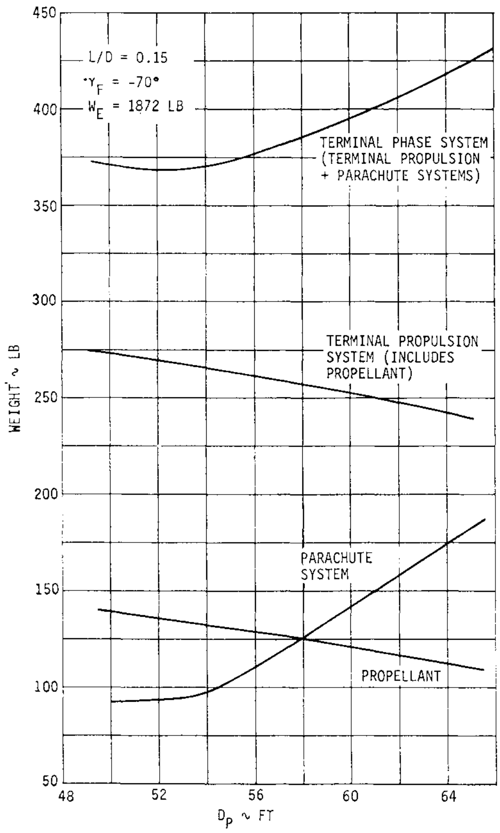

Fig. 7 Typical weights.

Terminal Phase Optimization

Combination of the data, presented immediately preceding this section, yields terminal phase system weight optimizations, as shown in Fig. 8. Terminal phase system weights are given for various parachute diameters, terrain heights, and flight-path angle, γ_F, at terminal propulsion ignition.

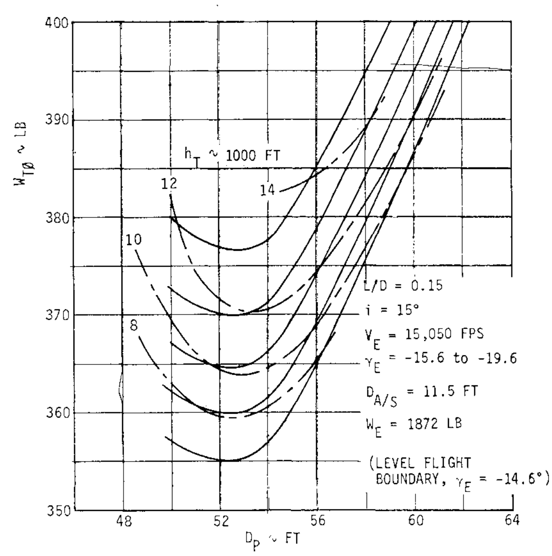

Fig. 8 Terminal phase system optimization.

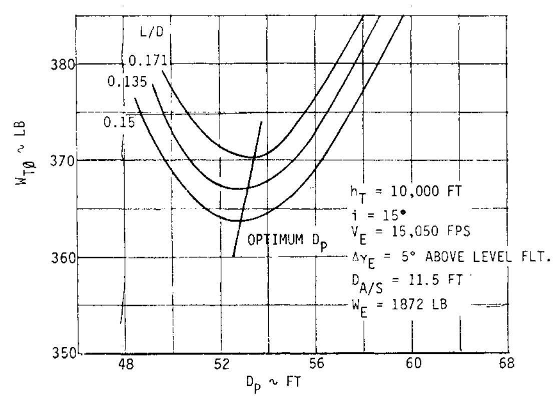

Fig. 9 Optimum parachute diameter for minimum terminal phase system weight.

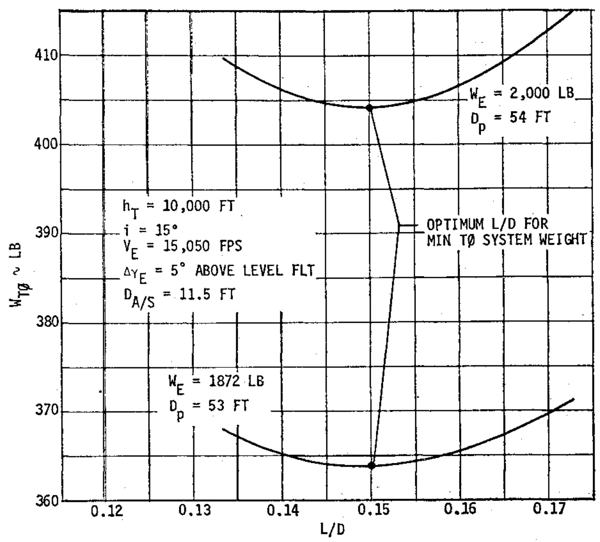

Fig. 10 Optimum L/D for minimum terminal phase system weight.

The terminal phase system weight may be optimized according to either of two criteria—terrain height or flight-path angle. It is evident from Fig. 8, for $h_T = 10{,}000$ ft, that a parachute diameter of 53 ft is optimum. Also evident is that a design for 10,000 ft is lighter in terms of terminal phase system weight than is a design for a greater h_T. Results are summarized in Fig. 9 for a terrain height of 10,000 ft for the L/D of 0.15 as shown in Fig. 8 and also for L/D of 0.135 and 0.171. A cross plot, shown in Fig. 10, indicates that a L/D ratio of 0.15 is optimum. The γ_F at ignition is $-71°$, taken from Fig. 8

To further verify the choice of an optimum L/D, the maximum terrain height capability for $D_P = 53$ ft is shown in Fig. 11. Unlike the previous optimization, the propellant weight is held constant. The optimum L/D is 0.15 for maximum terrain height capability for total entry corridors of 4.5° and 5°, respectively. Parachute deployment dynamic pressure for the previous optimizations is given in Fig. 12. The parachute opening shock is considered proportional to the dynamic pressure; the minimum q is at $L/D = 0.15$. The impact of the dynamic stability of the entry vehicle as it affects the selection of lift is illustrated in Fig. 13. Note that any significant trim angle of attack increases dynamic stability at all Mach numbers.

Design Flexibility

The optimization data, given in the previous paragraph, have dealt with the current Viking Lander weights. An important criterion in evaluating any analysis is the ability

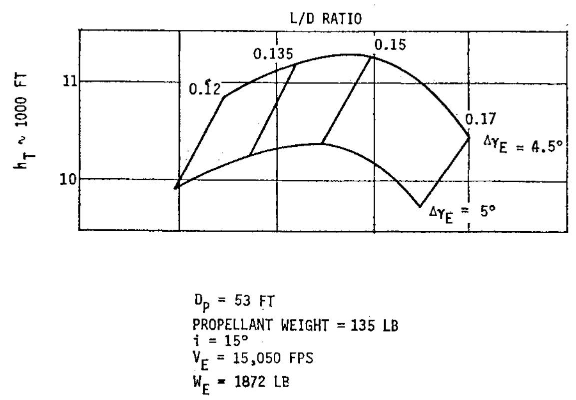

Fig. 11 Maximum terrain height capability.

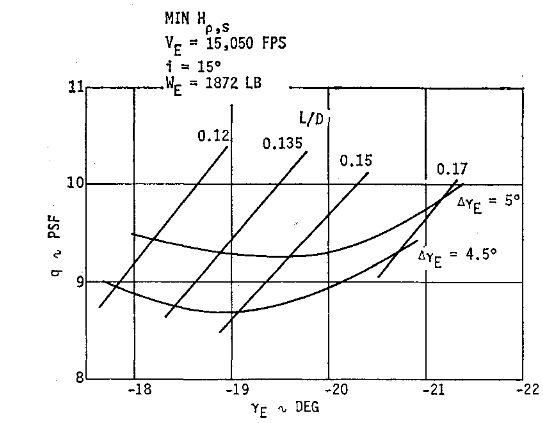

Fig. 12 Deployment dynamic pressure.

of the design choice to cope with system changes—in particular, weight increases.

In a manner similar to that just presented, the optimum L/D for $W_E = 2000$ lb is concluded to be 0.15. The level flight boundary is nearly insensitive to this weight increase. Data, given in Fig. 6, indicate that a L/D ratio of 0.15 results in the maximum $\Delta\gamma_E$ for a 2000-lb entry weight. Data similar to those given in Fig. 9 show that at $L/D = 0.15$, the optimum parachute diameter is 54 ft for $h_T = 10{,}000$ ft. The L/D ratio of 0.15 also results in the minimum terminal phase system weight, as shown in Fig. 10 and presented earlier. Figure 10 also indicates that a portion of the entry weight increase must go into the terminal phase propellant and tank weights to maintain the 10,000-ft terrain height capability. Deployment dynamic pressure and opening shock are also minimum at $L/D = 0.15$ for 2000 lb.

The 1975 Viking mission is designed to accommodate a combination of the most critical Martian model atmospheres. However, subsequent Viking missions will know the particular atmosphere in question. Other studies have shown that this will permit the present design to land nearly 200 lb more payload with only an increase in propellant and tankage for even the worst model atmosphere.

Summary and Conclusion

The preceding discussion has resulted in an optimum L/D ratio and parachute diameter on the basis of a number of constraints and requirements. On the basis of the 1975 Viking data presented, a L/D ratio of 0.150 is recommended. This value yields an optimum entry corridor plus optimum terminal phase system weight and performance. A para-

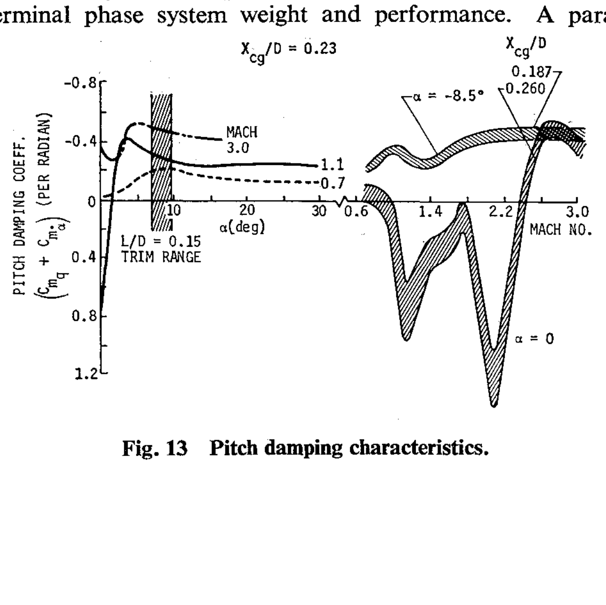

Fig. 13 Pitch damping characteristics.

chute diameter of 53 ft is optimum. These values are also near optimum for weight increases, as discussed. In addition, the following conclusions are reached. 1) Lifting entry and terminal phase system design performance may be optimized with respect to several performance parameters. 2) Criteria and results upon which optimization are based are usually compatible with little or no compromise in performance requirements. That is, the requirements of maximum entry corridor, maximum terrain height, and minimum terminal phase system weight are achieved within reasonable constraints and ground rules for the 1975 Mars lander. However, for a different set of constraints and ground rules, it might be possible that all requirements could not be mutually achieved. 3) Results of the optimization analysis depend on the constraints and requirements imposed by preliminary design results and other systems considerations.

References

[1] "Mars Engineering Model," M75-125-0, March 13, 1970; also April 22, 1970, NASA.

[2] Pritchard, E. B. and Harrison, E. F., "Lifting Entry ($L/D \leq 0.2$) for Unmanned Viking Class Mars Landers," TN D5828, June 1970, NASA.

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Preliminary Results of Manned Cargo Transfer Studies under Simulated Zero-*g* Conditions

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A parametric investigation to determine man's capability to perform intravehicular cargo transfer tasks in simulated zero-*g* has been conducted in Langley Research Center's water-immersion facility. Packages with masses up to 51 slugs, volumes up to 142 ft³, and moments of inertia about their center of mass of up to 285 slug-ft² were used. All tests were conducted using both one- and two-rail motion aids. All subjects were able to transfer satisfactorily all of the packages tested. Based on subject's comments, it was concluded that 1) the effects of package mass, size, and so forth, are minimal, therefore the maximum size package to be transferred will probably be determined by the restraints of the space vehicle, that is, tunnel size, hatch openings, and so forth, rather than man's capabilities; 2) even though the cargo could be handled using a one-rail motion aid, a two-rail motion aid is preferred, and 3) the use of a two-man team substantially reduces the task effort for large packages.

Nomenclature

I = moment of inertia, slug-ft²
M = mass of the package, slugs
V = volume, ft³
X,Y,Z = reference axis
$\Delta x, \Delta y, \Delta z$ = package dimensions

Subscript

c.m. = moment of inertia about center of mass

Introduction

THE transfer of large quantities of a wide range of cargo will be a requirement in future long-duration manned space missions. It is important to determine in the early planning stages of these missions the limits of astronaut participation in cargo transfer. Several preliminary studies have been conducted on various aspects of the problem using ground-based simulation. For example, one zero-*g* simulation study has indicated that man can control and transfer packages with masses up to a limit of 5 slugs.[1] In contrast, other studies[2,3] have indicated that man can handle packages up to approximately 10 slugs. Such studies have generally been limited in scope and the results obtained are difficult to correlate because of the differences in simulation and testing techniques used.

In an attempt to examine man's cargo transfer capabilities in a more comprehensive manner and to contribute information to the development of a set of guidelines, a series of studies has been conducted at the Langley Research Center. The over-all program is designed to investigate test subjects' ability to control and transfer cargo for both intravehicular (IVA) and extravehicular activities (EVA). The initial phase of the program discussed herein was a parametric study to determine the limits of IVA manual cargo transfer capability. The package parameters (mass, moment of inertia, etc.) were varied so that their criticality, with respect to the over-all transfer task, could be determined. Tests were carried out using the water-immersion technique for zero-*g* simulation. The results of this study should be useful in the determination of the IVA cargo transfer tasks which can be accomplished manually and those which require mechanical assistance.

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