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AIAA Paper No. 73-889

A NEW APPROACH TO PERFORMANCE OPTIMIZATION OF THE 1975 MARS VIKING LANDER

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AIAA PAPER 73-889

AIAA Guidance and Control Conference

KEY BISCAYNE, FLORIDA / AUGUST 20-22, 1973

A NEW APPROACH TO PERFORMANCE OPTIMIZATION OF THE 1975 MARS VIKING LANDER†

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Abstract

The design of the 1975 Viking lander is based, in part, upon performance optimization analyses and a requirement to maximize operational flexibility. The analysis technique is characterized by a graphical tradeoff approach found to be the most effective for evaluating lifting-entry trajectory performance. The analysis eliminates the constraint of a level flight trajectory and allows the lander to reach positive flight-path angles before parachute deployment. Updated Mars environmental knowledge and recent test results and design decisions are analysis factors. The entry-phase analysis indicates that a hypersonic lift-to-drag ratio of 0.18 and an entry flight-path-angle corridor of -15° to -19° satisfies the requirements of optimum performance (maximum payload and sufficient terrain height capability). In addition, the optimization incorporates a high degree of operational flexibility and is relatively insensitive to additional design changes such as increased lander weight.

Symbols and Nomenclature

h	Altitude
L/D	Hypersonic Lift-to-Drag Ratio
MSL	Mean Surface Level
M	Mach Number
q	Dynamic Pressure
t	Time
W	Weight
Δ	Incremental
γ	Flight-Path Angle (measured positive up from the horizontal)
$\sigma_{\gamma E}$	1σ Uncertainty in γ_E

Subscripts

A/S	Aeroshell
D	Parachute Deployment (mortar fire)
E	Entry (800,000 ft. above MSL)
R	Relative to Rotating Atmosphere
LE	Landed Equipment
F	Final Conditions on Parachute

I. Introduction

The 1975 Viking mission involves the sending of two spacecraft to Mars, each consisting of an orbiter and a soft-landing vehicle. The spacecraft will be launched by two Titan III/Centaur vehicles within a 30-day period. This paper presents the method used to optimize lander performance during that portion of the mission from entry into the Martian atmosphere until landing. This part of the mission is characterized by three phases: the entry phase, and aerodecelerator phase, and the terminal descent and landing phase.

The entry phase of the mission extends from an entry altitude of 800,000 ft above mean-surface-level (MSL) to the altitude at which the parachute is deployed. During this phase, deceleration and lander thermal protection are provided by a high-drag aeroshell that incorporates an ablative heat shield. While in this configuration the lander is referred to as the entry vehicle. The aerodecelerator phase begins with parachute deployment; the terminal descent and landing phase extends from terminal-descent-engine ignition (and parachute jettison) to touchdown. Because of their critical interaction in the trajectory design and optimization process, these latter two phases are combined herein and will be referred to as the terminal phase, which extends from parachute deployment to touchdown.

Entry phase performance is constrained by such design requirements as maximum dynamic pressure on the entry vehicle or dynamic pressure and Mach number at parachute deployment. These design constraints must accommodate a broad spectrum of uncertainties that result from imprecise knowledge of performance characteristics or from lack of knowledge of the Mars environment. Uncertainties in performance characteristics include those related to entry vehicle aerodynamics and entry conditions. Dispersions in entry conditions (particularly flight path angle) result from inaccurate orbit determination and from de-orbit maneuver dispersions. The primary environmental uncertainties are elevation of the landing site and the Mars atmosphere. Elevation uncertainty is handled by designing the lander trajectory so it can safely land at some elevation above the mean surface level (MSL), whereas atmospheric uncertainty is encompassed by a range of model atmospheres.

†The work described in this paper was performed under NASA Contract NAS1-9000. The Viking Project is managed by NASA's Viking Project Office Langley Research Center (VPO-LRC), Hampton, Virginia.

The present optimization technique was developed using atmosphere models defined in the Mars Engineering Model;[2] these are referred to as the M75-125-2 atmosphere models. As our study neared completion, new, less severe atmospheres were introduced for design purposes; these were incorporated as the final step in the trajectory design process and are referred to as the revised atmosphere models. Density profiles for the atmospheres most critical for entry to touchdown performance are shown in Figure 1.

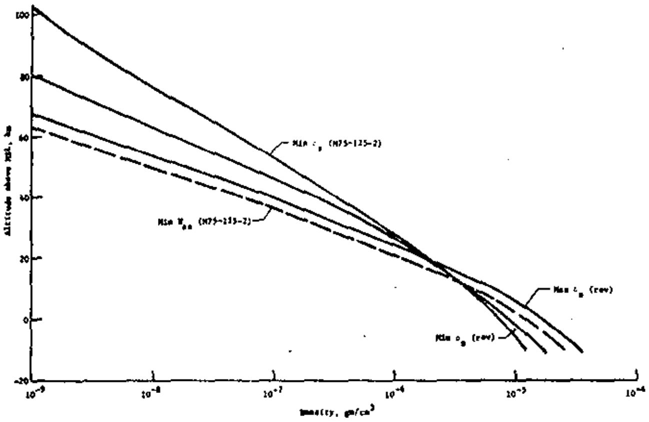

Figure 1. Critical Atmospheres for Optimization

It is pointed out that the performance design criteria based on the Mars environment and Viking hardware testing results are undergoing continual evaluation and update. Therefore, the values shown herein may not represent the final Viking performance design values. However, they illustrate the optimization technique described in this paper and represent the Viking values extant at the time this paper was prepared.

II. Entry Phase Optimization

Analyses of Viking lander performance[1][3] have shown that lifting entry is a significant technique for enhancing entry performance; that is, increasing payload capability or reducing parachute deployment conditions. For such symmetrical entry vehicles as Viking, lift may be generated passively using a center-of-gravity offset from the geometric longitudinal centerline, thereby, producing a trim angle-of-attack. Simplicity of this passive technique precludes additional technical problems of increased cost that might result from incorporating lift by using an active lift control system.

Entry-phase performance is a strong function of the flight-path corridor and atmosphere model. The types of entry trajectories that can be obtained by varying the flight-path angle or L/D are shown in Figure 2 and identified below.

- Type 1 - Flight-path angle is always below the local horizontal.
- Type 2 - Flight-path angle reaches a limit value of zero (level flight).
- Type 3 - Flight-path angle becomes positive (pullup).
- Type 4 - Circular orbital velocity is reached and skipout would occur except for atmospheric drag.

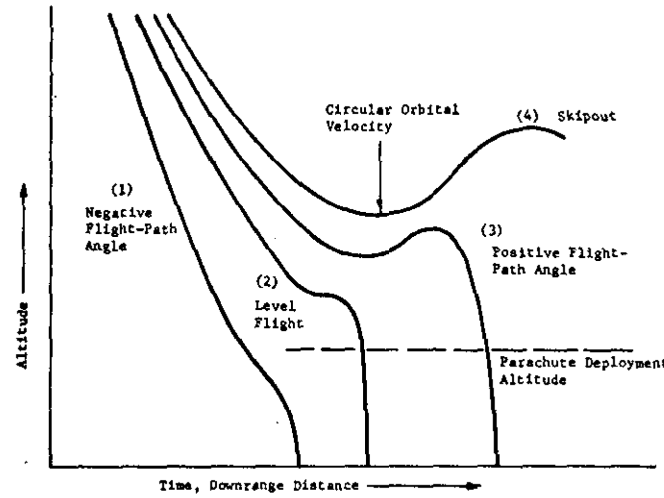

Figure 2. Type of Lifting Entry Trajectories for a Critical Atmosphere Model

Entry-phase performance is also measured by (1) the ability of the entry vehicle to deliver the lander to the programmed terminal-phase initiation altitude at the most favorable conditions of relative velocity and flight-path angle and (2) the ability to maintain adequate Viking lander to Viking orbiter relay communication while the vehicle is in the vicinity of level flight.

Trajectories (Type 3) that exceed level flight had previously been ruled out because of communication and parachute deployment considerations. The altitude gained during the pullup maneuver is a function of flight-path angle at entry and the lift-to-drag ratio, as illustrated in Figure 3.

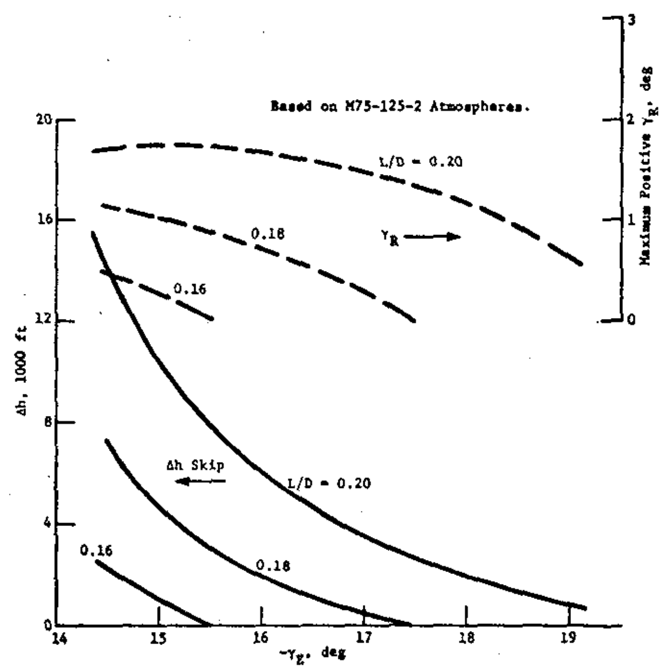

Figure 3. Δh Skip and Maximum Positive Flight-Path Angle during Lifting Entry

The maximum positive relative flight-path angle attained during pullup is also shown. The maximum value of +1.75 deg does not result in significant degradation of the lander-to-orbiter relay communication performance during entry. The minimum altitude during pullup ranges from 55,000 to 95,000 ft above the surface. If suitable parachute deployment conditions can be guaranteed at altitudes below this range of values, Type 3 trajectories may be considered for this optimization analysis. Due to the better energy dissipation characteristics of the pullup trajectory, the altitude at which suitable parachute deployment conditions are reached will be higher for a Type 3 trajectory than for Type 1 of 2. The aerodecelerator and terminal-phase performance will therefore be improved, as is shown.

In general, as the deployment altitude increases, the terminal engine propellant required decreases, the payload increases, and the terrain height at which a safe landing may be made increases. The interaction of L/D and entry flight-path angle is shown in Figure 4 for representative values of entry and deployment Mach numbers. The altitude for a deployment Mach number of 2.2 is shown.

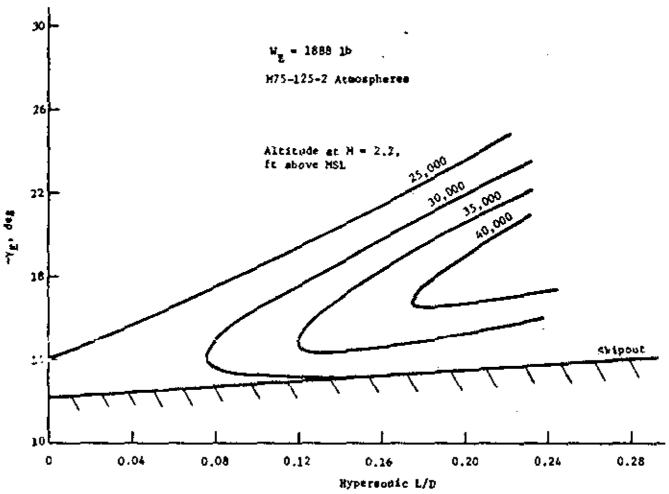

Figure 4. Entry Angle Sensitivity to Lift

The above data are cross-plotted in Figure 5 to show how the combinations of L/D and corridors to be investigated are determined. Increasing L/D increases the deployment altitude. However, higher L/D require higher γ_E. This leads to higher structural loads and eventually to lower payloads. The optimization of the entry system is therefore essentially a choice of the proper combinations of lift-to-drag ratio and entry flight-path angle corridor such that entry vehicle structural limits will not be exceeded and that will allow the parachute to be deployed at the highest possible altitude consistent with design deployment conditions. Two sets of corridors are chosen (each 4° wide); one set is -15 deg to -19 deg for all L/D; the other, to be called the optimum corridor, is centered about the peak of the deployment altitude curve. The optimum corridor for L/D = 0.23 is shown in Figure 5. The other corridor (-15 to -19 deg) was determined in previous optimization analyses.(1) The design deployment altitude must be the lowest altitude throughout the corridor because the corridor bounds the γ_E uncertainty. The entry-angle corridors and deployment altitudes for the L/D investigated are shown in Table I.

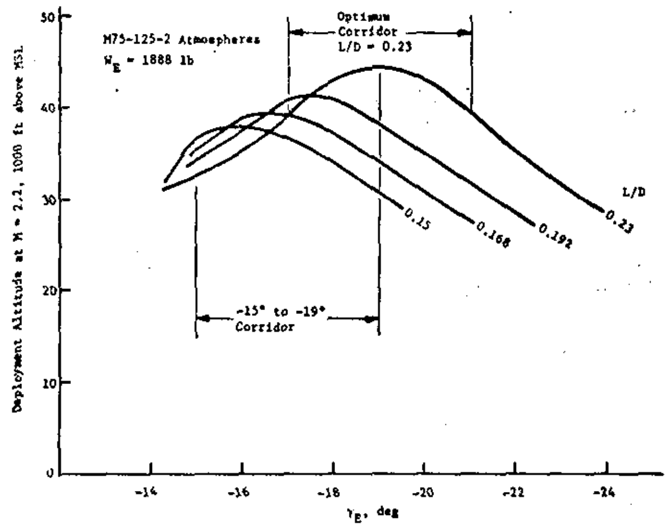

Figure 5. Entry Corridor Selection

Table I Entry Flight-Path-Angle Corridor, Min $H_{\rho,s}$ Atmosphere (M75-125-2)

-15° to -19° Corridor		
L/D	γE (deg)	Deployment Altitude, ft above MSL
0.15	-15 to -19	31,000
0.168	-15 to -19	34,200
0.192	-15 to -19	34,000
0.23	-15 to -19	32,500

Optimum Corridor		
L/D	γE (deg)	Deployment Altitude, ft above MSL
0.15	-14.4 to -18.4	32,700
0.168	-14.7 to -18.7	34,200
0.192	-15.6 to -19.6	36,500
0.23	-17.0 to -21.0	39,000

We anticipate that the corridors shown will blanket the range of entry weights and other design parameters needed to determine the optimum performance. All corridors are at least 1 deg above the skipout boundary.

The portions of a typical entry flight-path corridor are shown in Figure 6. The lower limit of the corridor is set at least 1 deg above the skipout value of -13.5 deg. The corridor illustrated in the figure is 1.5 deg above skipout. The 1 deg value is chosen as $2\sigma\ \gamma_E$ based on worst-case analysis of orbit determination and deorbit execution errors. 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. As skipout 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 skipout boundary is approached; the resultant landing footprints and time dispersions

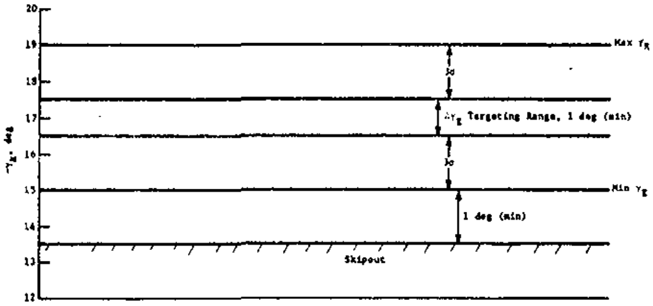

Figure 6. Typical Entry Flight Path Angle Limits

would be excessive. For these reasons it is desirable to keep the lower end of the entry corridor at least 1 deg above skipout. A 1-deg γ_E range is allocated for targeting flexibility. This is necessary to compensate for dispersion in the orbit position at deorbit or to allow landing site adjustments in order to avoid major terrain hazards. A 3σ $\dot{\gamma}_E$ increment on each side of the targeted range results in the 4-deg entry corridor illustrated. Thus, a 4-deg corridor is used for lander design and performance optimization analyses.

Figure 7 shows the parachute deployment altitude, with a constant Mach number, as a function of entry angle for a range of entry weights to be investigated. The range of entry weights expected varies from 1888 to 2200 lb. However, the entry angle at which the peak deployment altitude occurs is not sensitive to entry weight, as shown in this figure.

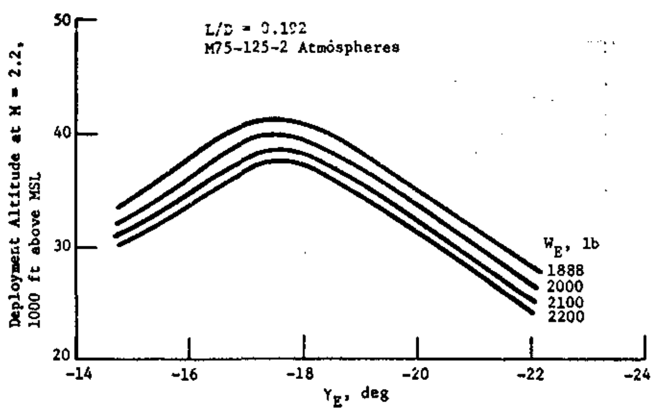

Figure 7. Entry Weight Sensitivity

III. Terminal Phase Optimization

The application of the optimization technique to the terminal phase system is best understood by first directing attention to Viking lander characteristics. The terminal-phase system design is based on previous optimization studies.[1] The disc-gap-band parachute is 53 ft in diameter and is designed for a maximum deployment Mach number of 2.2. The three terminal descent engines has a maximum thrust of 600 lb each and a throttling ratio of 6 to 1. The terminal propulsion system follows a gravity turn trajectory; the engines slow the lander to 8 fps at landing. Still to be chosen are the altitudes at which the parachute is deployed and the engines are ignited. The terminal engine propellant weight may also be varied; the design tank capacity is 197 lb. The proper choice of all these factors leads to the maximum payload that can be landed at the desired terrain elevation.

An indicator of payload is landed equipment weight, W_{LE}. This is the landed weight minus the terminal propulsion inerts. The basic weight equation used is:

$$W_{LE} = W_L - W_{PROPELLANT\ INERTS}. \tag{1}$$

Substituting for total landed weight, W_L,

$$W_{LE} = W_E - W_{AEROSHELL} - W_{PROPELLANT} - W_{PARACHUTE} - W_{PROPELLANT\ INERTS}. \tag{2}$$

The propulsion system weight varies with the propellant weight as shown in Figure 8. The aeroshell weight varies with the loads created by entry maximum dynamic pressure. The maximum dynamic pressure is, in turn, a function of L/D and γ_E (see Fig. 9). As L/D and γ_E increase, the aeroshell weight increases and the payload decreases for a given entry weight. An example of how propellant weight is determined is shown in Figure 10 for $W_E = 2200$ lb and the optimum corridor described earlier. The parachute is deployed at an altitude above MSL corresponding to $M_D = 2.2$ in the most critical atmosphere.

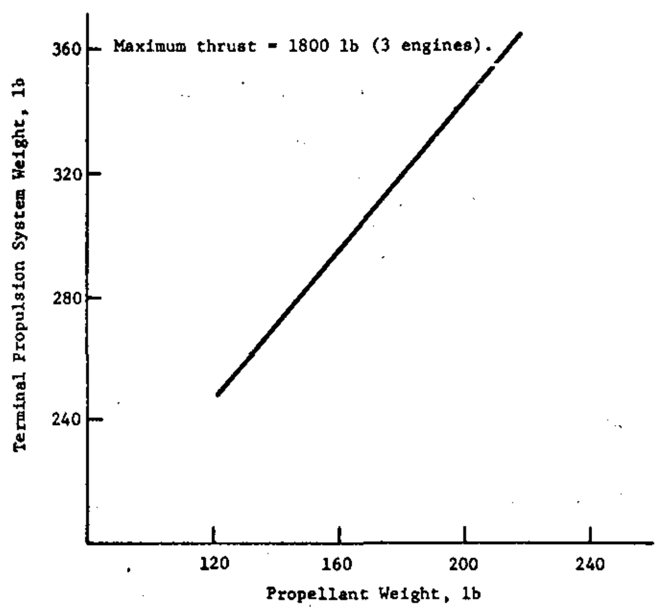

Figure 8. Terminal Propulsion System Weight, Including Propellant

A constant L/D curve represents ignition of the engines at various points on the parachute trajectory. At each point the initial ignition conditions vary: the altitude above MSL, the flight-path angle, and the velocity (which includes a 213 ft/sec tailwind). The lower the terrain height at which a landing is made, the less the propellant required. This is because the atmospheric density is greater; as a result, the lander is on the parachute longer and the ignition velocity is then lower.

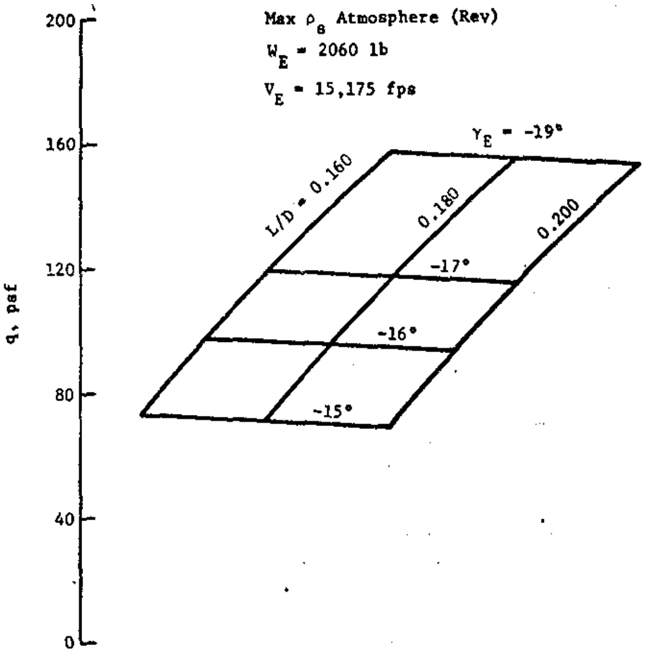

Figure 9. Maximum Entry Dynamic Pressure

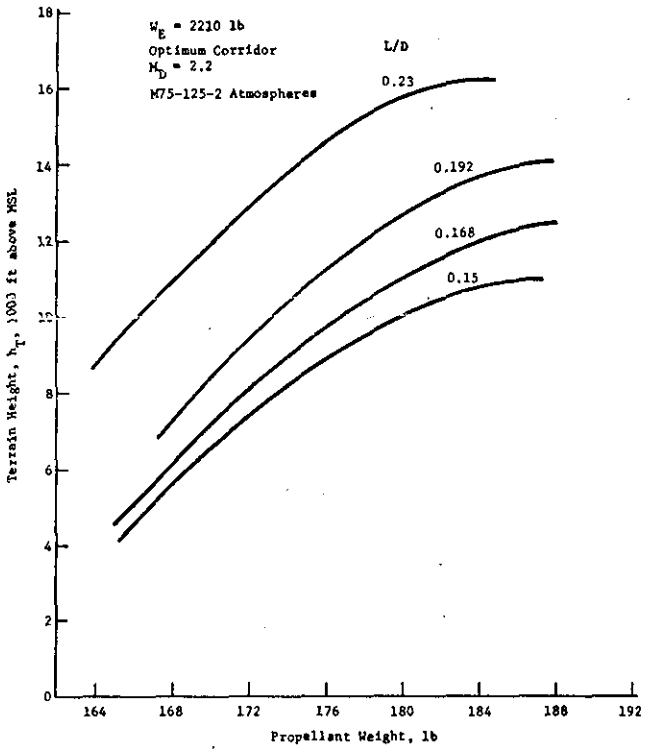

Figure 10. Terrain Height Capability vs Propellant Weight

Solving the weight equation for W_{LE} using data as shown in Figure 10 results in the relationship between W_{LE} and terrain-height capability shown in Figure 11. It can be seen that crossovers exist between the L/D that give the maximum W_{LE}, depending on the terrain height capability. The maximum required terrain height at landing is 10,000 ft above MSL for Viking. A cross-plot of data similar to those in Figure 11 (for all entry weights, L/D and corridors) is shown in Figure 12 for a terrain-height capability of 10,000 ft. Data are shown for the two entry corridors discussed earlier, the optimum corridor and the fixed -15 to -19 deg corridor. For the -15 to -19 deg corridor, the W_{LE} is almost constant for L/D greater than 0.18. For the optimum corridor, W_{LE} decreases with increasing L/D because of the steeper γ_E and heavier aeroshell weights required. At about L/D = 0.17, both corridors yield equal W_{LE} for all entry weights. For greater L/D, the -15 to -19 deg corridor yields a higher W_{LE}.

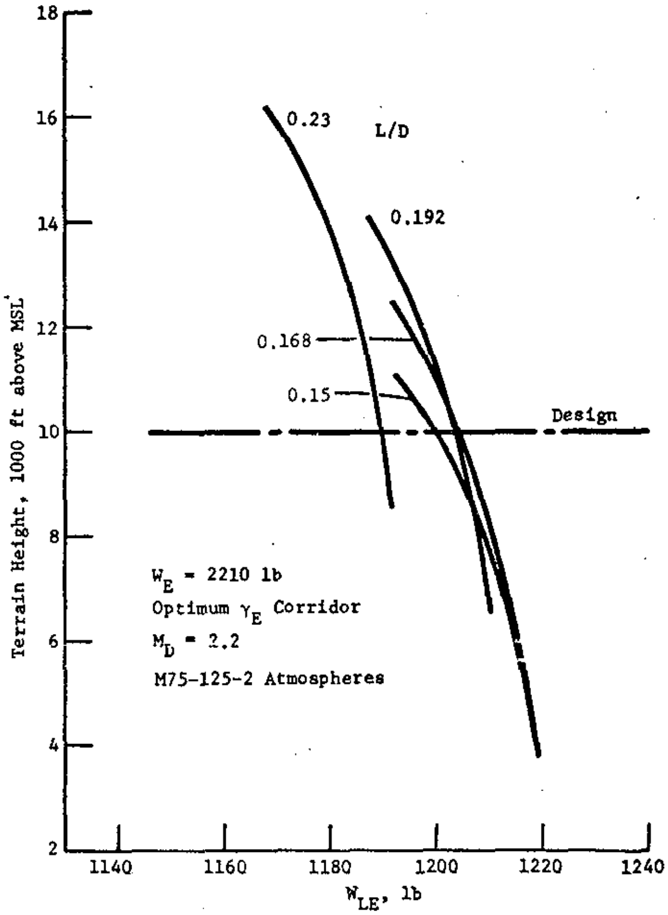

Figure 11. Terrain-Height Capability vs Landed Equipment Weight

At this point, a basic decision must be made. As indicated earlier, performance may be optimized in terms of maximum terrain height capability or maximum useful landed weight. Use of the optimum corridor will maximize terrain height and for higher terrain heights, higher L/Ds are indicated (see Fig. 5). However, as noted above, the higher L/Ds require steeper γ_E and higher entry dynamic pressures; the resulting heavier aeroshell weights cause a decrease in W_{LE}. If a required terrain height can be defined, the L/D for a fixed entry corridor or the optimum corridor can be chosen to maximum W_{LE}.

For Viking, two factors lead to the choice of L/D based on the fixed -15 to -19 deg corridor. These are the definition of a terrain height requirement of 10,000 ft and the advanced state of hardware design

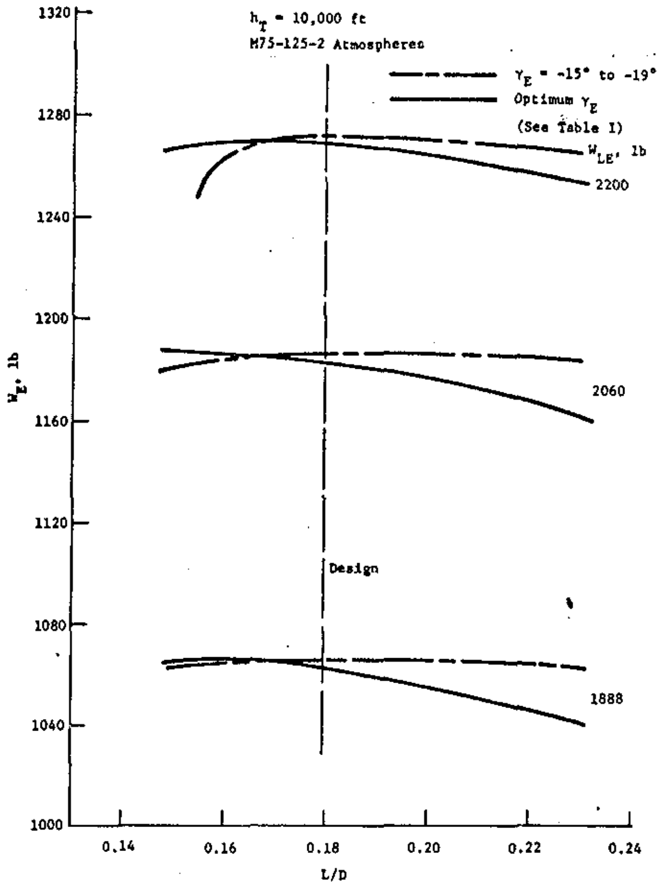

Figure 12. Landed Equipment Weight

indicating a fixed maximum γ_E of -19 deg based on previous studies. An L/D of 0.18 is chosen as the optimum for the -15 to -19 deg corridor. Although at W_E = 2060 lb the optimum corridor at L/D = 0.15 (which is no steeper than -19 deg) has a higher W_{LE}, the choice of L/D = 0.18 at γ_E = -15 to -19 deg allows for growth to W_E = 2200 lb. This choice also takes into account the tolerance of ±0.02 on L/D. For the higher entry weights, a value of L/D = 0.16 is about the minimum desirable. It is important to understand the differences between these results and previous studies.(1) Eliminating the level flight constraint during entry allows the choice of the 0.18 optimum L/D. In previous work, the L/D was limited to about 0.15, maximum.

IV. Design Flexibility

The optimization selection should have the ability to cope with design changes. The choice of L/D = 0.18 is optimum for γ_E = -15 to -19 deg for entry weights up to 2200 lb. The present entry weight is 2060 lb. If the terrain-height capability must be incresed above 10,000 ft due to a landing site change, an L/D of 0.18 is near optimum as shown in Figure 11. Of course, the propellant load must be increased for higher terrain heights, as shown in Figure 10.

Full-scale parachute qualification tests dictated that the parachute deployment dynamic pressure should not exceed 8.62 psf. This corresponds to the Mach number/weight combinations shown in Figure 13. An L/D of 0.20 is used for design because the tolerance on L/D is ±0.02. For the present entry weight of 2060 lb, the maximum Mach number is 1.9. The sensitivity of propellant weight to deployment Mach number and terrain-height capability is shown in Figure 14. In the region of interest, the performance is relatively insensitive to deployment Mach number. For the design terrain height of 10,000 ft, the cost of decreasing the deployment Mach number from 2.2 to 1.9 is less than 2 lb of propellant.

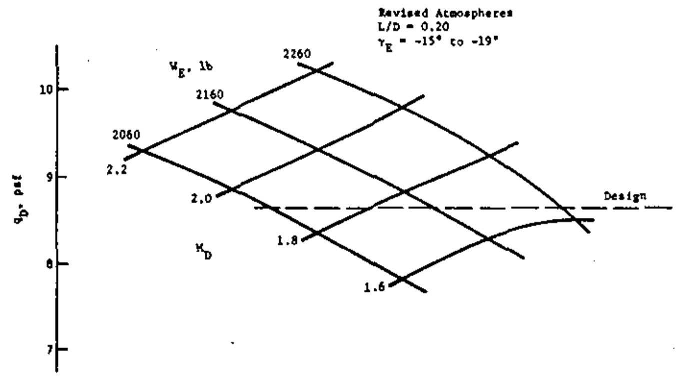

Figure 13. Parachute Deployment Dynamic Pressure

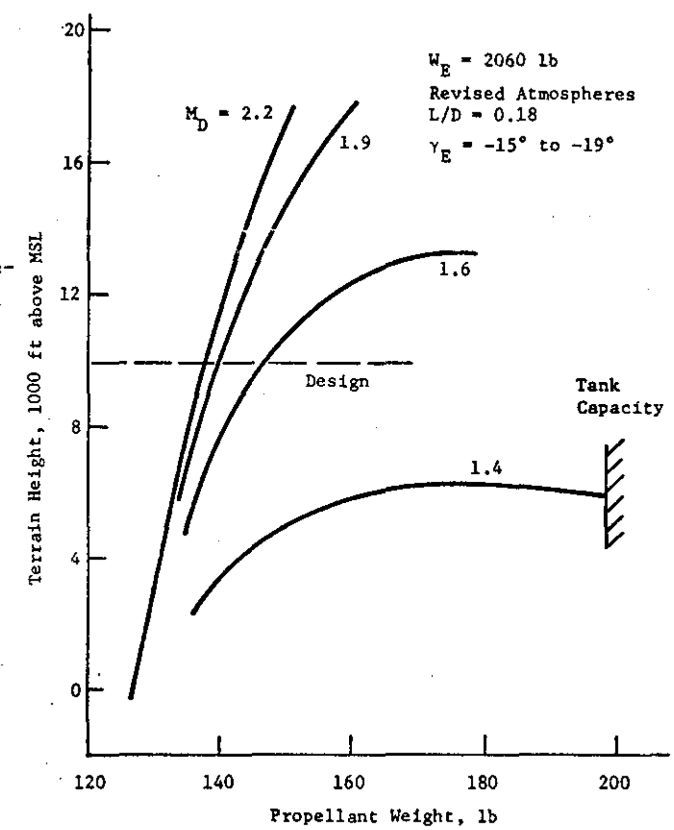

Figure 14. Performance Sensitivity to Mach Number

The flexibility of the design is illustrated in Figure 15. Should the entry weight be increased above 2060 lb, there is sufficient tank capacity for entry weights to about 2200 lb for a terrain height of 10,000 ft. If higher landing sites are chosen, the terrain height may be increased to 21,400 ft for W_E = 2060 ft. It should be noted that deployment Mach numbers are used that are consistent with the maximum dynamic pressure of 8.62 psf shown earlier in Figure 13.

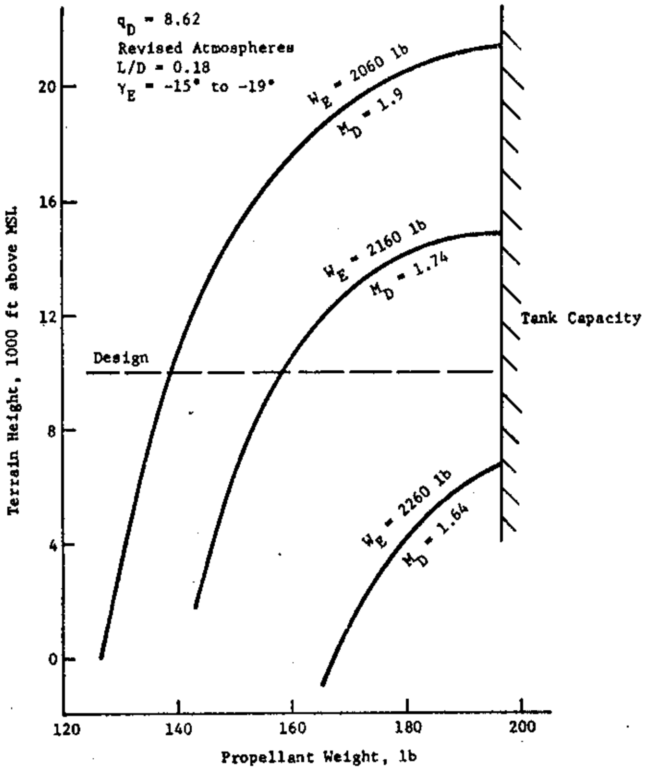

Figure 15. Design Flexibility of Present Configuration

There is also some design flexibility that may be used during the mission. If winds, atmosphere, etc, are more severe than expected, the trajectory may be changed for the second lander by a lander update through the communication link prior to separation. The deployment altitude, the terminal-descent-engine-ignition altitude, and the trajectory contour on the descent engines all may be changed. A landing site lower than 10,000 ft could also be chosen. The propellant saved (see Fig. 14) could be used to overcome the effects of higher winds or a more severe atmosphere.

References

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Acknowledgement

The cooperation of the NASA Viking Project Office at the Langley Research Center in the review of this paper is gratefully acknowledged. Particular appreciation is expressed to J. W. Youngblood for his many suggestions and recommendations.

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Paper 73-889, A New Approach to Performance Optimization of the 1975 Mars Viking Lander, H. N. Zeiner, C. E. French and D. A. Howard.

On Figure 12 the title on the vertical scale should read W_{LE} and the symbol on the curves should read W_E.