Velocity Requirements and Re-Entry Flight Mechanics for Manned Mars Missions

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A survey of manned Mars mission studies was conducted. For missions initiated from Earth orbit, these studies have shown that, without aerodynamic braking, the total propulsive velocity requirements are 64,000 to 95,000 fps for the "short" trip (400 to 500 days). The use of aerodynamic braking at Mars or on Earth return results in a significant reduction in total propulsive velocity requirements, as well as a reduction in the effects of launch year on these requirements. Earth entry velocities vary from 46,000 to 73,000 fps and Mars entry velocities from 19,000 to 36,000 fps for the Mars short trip, depending on the launch period. Following this survey, an analysis of the Earth entry phase of the mission was conducted to evaluate the minimum re-entry vehicle L/D requirements based on a re-entry corridor width of 10 miles. Vehicles capable of pitch angle modulation for peak g reduction were found to require significantly lower L/D capability and lower total stagnation-point heat loads than those with roll-control capability only. Earth entry vehicles capable of the pitch-modulation maneuver therefore merit further study, especially in the area of total body heating and thermal-protection requirements.

Introduction

At the present time we are in the early planning stage of manned flight to the planet Mars. The Mars landing mission is the easiest of all planetary landing missions and perhaps the most important, since Mars is more similar in nature to the Earth than any of the other planets of this solar system. The major technical problems to be resolved include such diverse areas as communications, long-term life support in space, guidance and navigation, meteoroid protection, solar radiation protection, propulsion, and high-speed entry into planetary atmospheres. The most sensitive parameters affecting the basic mission have been defined by many preliminary studies, and optimization procedures have been developed to minimize the total propulsion energy requirements of the manned Mars mission.

This paper presents a survey of the energy requirements of the manned Mars mission and analyzes the re-entry flight mechanics on return to the Earth's atmosphere. Chemical and nuclear propulsion systems are considered for launches in the 1968 to 1984 period, which covers the entire Earth-Mars cycle. The primary emphasis is placed on studies of the short-trip mission initiated from a near-Earth orbit. Mars arrival velocities are discussed, but the flight mechanics associated with entry into the Martian atmosphere are not considered. (Current studies of this problem for a variety of assumed Martian atmospheres are in progress elsewhere.) The results of the Early Manned Interplanetary Mission studies, the Manned Mars Landing and Return Mission studies, and the Manned Planetary Mission Technology Conference, as well as those of other mission studies[1-10] were considered.

Mars Mission Characteristics

Mission Profile

The manned Mars mission may be accomplished by any of several modes of operation. The concept predominantly considered in the studies that were surveyed is the Mars orbital rendezvous mode. This mode of operation is the only one considered in this paper and consists of, at most, four dominant impulsive periods: launch from a near-Earth orbit, deceleration into a Mars circular parking orbit, launch from the Mars orbit, and deceleration into a near-Earth circular parking orbit. Any Mars landing mission is assumed to be initiated from the Mars orbit and thus does not affect the velocity requirements of the main orbital vehicle.

True minimum energy missions involve the so-called Hohmann transfer ellipse (long trip) shown in Fig. 1. In this case the perihelion of the transfer ellipse occurs at Earth and the aphelion at Mars. Thus, heliocentric angles of 180° must be traversed on both the outbound and inbound legs of the mission. In order for the two planets to be in the correct position for initiation of the return trajectory, the space vehicle must remain in the vicinity of Mars for about 450 days, so that total mission times approach 1000 days. This may not be desirable from life-support system and reliability considerations, as well as consideration of psychological factors affecting the crew. In addition, the true Hohmann profile is only feasible at nodal-synodic intervals at which the spacecraft intercepts the target planet at the ascending or descending node of its orbit. Increased energy is required at other synodic intervals. For these reasons, the primary emphasis at the present time is being placed on the short-trip mission shown in Fig. 1.

This reduction in total mission time to 400 to 500 days is accomplished by allowing one leg of the mission to pass inside of Earth's orbit. Indeed, the space vehicle may pass within ½ a.u. or less of the sun for some missions. In general, the inbound (return) leg is the high-energy leg of the mission,

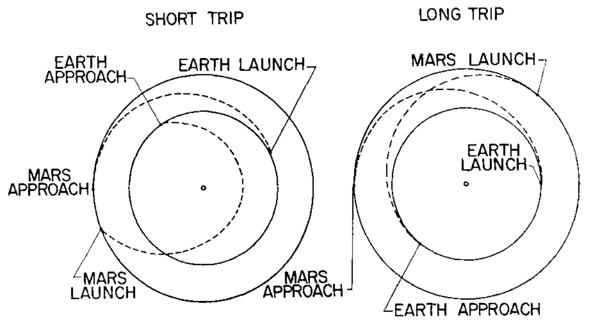

Fig. 1 Manned Mars mission profiles.

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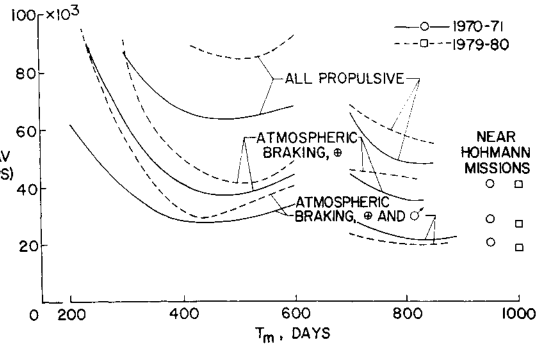

Fig. 2 Propulsive velocity requirements for the manned Mars mission with a 40-day stay time at Mars.

because of the lower weights, which must be accelerated to the higher velocities associated with trajectories passing inside the Earth's orbit. The increased propulsive energy requirements associated with this short trip have led to many novel mission concepts, such as convoys of vehicles, supply vehicles preceding the manned vehicles, and hyperbolic rendezvous and crew transfer to a re-entry vehicle on Earth return.

Velocity Requirements

It is necessary to define the propulsive velocity increments required to carry out the mission in order to determine the effects of launch year and trip time on the mission-energy requirements. Knipp and Zola[1] investigated the 1970–1971 and 1979–1980 missions, corresponding to the best and worst years for a Mars mission in that cycle. The total propulsive velocity increments for their optimized missions are shown in Fig. 2. The curves shown are for three types of missions initiated from a circular orbit about the Earth: all-propulsive missions, Earth-atmospheric-braking missions, and Earth- and Mars-atmospheric-braking missions. The first class of mission uses propulsive braking at Earth and Mars and therefore requires no advance in re-entry vehicle technology beyond Mercury or Gemini vehicles. Use of the second and third classes of missions may require significant advances in re-entry technology beyond that of Apollo. As shown in Fig. 2, two minimum energy points for each mission are separated by a region of excessively high-energy requirements. The long-trip minimum occurs at about an 850-day mission, and the short-trip minimums fall between 400 and 500 days, depending on the year and type of mission. Except for the 450-day stay time of the "near Hohmann" points, the results are presented for a stay time of 40 days. The effect of the stay time at Mars differs for the short and long trips. For short trips, the propulsive velocity requirement generally increases with increasing stay time. For long trips, a 300- to 450-day stay time results in minimum velocity requirements.

The use of atmospheric braking yields great savings in propulsion velocity requirements (at the expense of increased heat-shield weights). For instance, a decrease in propulsive velocity requirement from 63,000 to 36,500 fps is obtained by using atmospheric braking on Earth return for the 1970–1971 mission. Since the space vehicle would enter the Martian atmosphere at relatively low velocities, a smaller additional saving (about 10,000 fps) is available by using atmospheric braking at Mars as well as at Earth.

The 1979–1980 short-trip mission is shown to require much higher propulsive velocities than the 1970–1971 mission, for the all-propulsion mode, since Mars is near aphelion on arrival of the spacecraft in the 1979–1980 period. The effect of launch year is greatly reduced, however, if atmospheric braking is utilized. A more general indication of the effect of launch date on the propulsive velocity requirements for the short-trip, minimum-energy type of mission, as obtained from the literature survey, is presented in Fig. 3. Each symbol represents a specific mission, which has been optimized to some extent, and each symbol type represents a particular study. (The data spread is due to the variation in ground rules: trip time, stay time at Mars, etc.) The use of atmospheric braking at Earth and at Mars reduces the effects of launch year significantly and shifts the maxima and minima toward the earlier launch years. For the all-propulsive mode, the velocity requirement varies from about 64,000 fps for the best launch year to about 90,000 fps for the worst year. The use of atmospheric braking at Earth reduces the range to 40,000 to 50,000 fps, and atmospheric braking at both Earth and Mars brings it down to 25,000 to 32,000 fps.

A significant point indicated by this figure is that if the manned Mars mission is undertaken and a launch date in the mid-1970's selected, the mission must be designed on the basis of the maximum requirements of the 1979–1980 period to allow for any schedule slippage. If this is not done, the mission might have to be canceled until seven years later. However, if the early or mid-1980's were chosen as the launch period, the mission could be based on the velocity requirements for that particular launch period. For several years thereafter the mission could be carried out with a lower propulsive velocity requirement. Therefore, it may be desirable to set our sights on a 1984 mission rather than a 1976 mission.

The significant reductions in $\Sigma\Delta V$ due to atmospheric braking require that the entry vehicle be capable of entry into planetary atmospheres at hyperbolic velocities. Both mission time and launch period have a considerable effect on these entry velocities. Figure 4 presents the effect of trip time on Earth and Mars arrival velocities for the 1970–1971 and 1979–1980 missions with a 40-day stay at Mars and mini-

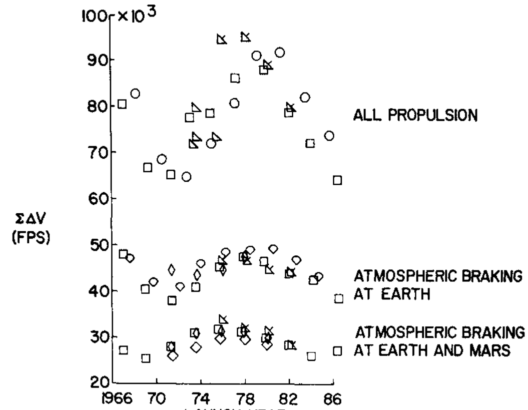

Fig. 3 Launch-year effects on total propulsive velocity requirement for the short-trip Mars mission.

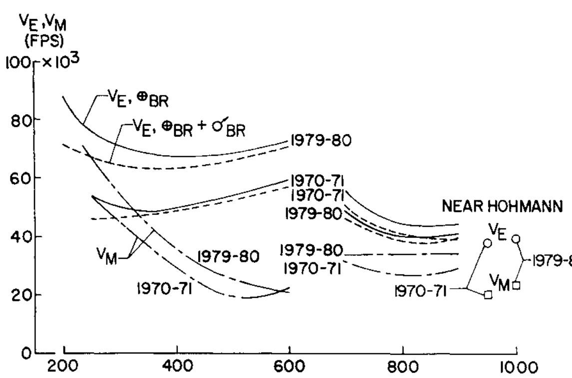

Fig. 4 Earth and Mars arrival velocities for the manned Mars mission with a 40-day stay time at Mars.

mized total propulsive velocity requirements.[1] For the long trips with atmospheric braking at both Earth and Mars, little or no increase in re-entry vehicle technology beyond that for Apollo would be required. For the short trips, our prime area of interest, the Earth entry velocities vary from about 46,000 fps for the 1970–1971 mission to about 70,000 fps for the 1979–1980 mission. The slight variation in arrival velocity with the mission mode is caused by optimization of the mission profile on the basis of minimum total propulsive velocity.

A comparison of Figs. 2 and 4 demonstrates that the mission times associated with minimum propulsive velocity requirements do not coincide with either minimum Earth or Mars entry velocities. Since minimum propulsive velocity is an optimal mission objective, the short-trip mission time must be between 400 and 500 days. Although the Earth entry velocities vary only slightly with mission time in the 400- to 500-day interval, for the same launch period, the Mars entry velocities exhibit a strong variation with trip time in this region of the curve. Mars-entry velocities of 19,500 to 36,000 fps must therefore be considered if atmospheric braking at Mars is to be a mission requirement. These velocities do not appear to be overly severe when compared with the Earth-entry situation. However, as pointed out by many investigators, the presence of a large percentage of carbon dioxide in the Martian atmosphere results in high-radiative heating at moderate entry velocities. Before any specific entry vehicle concept for entry into the Mars atmosphere is possible, a much more exact definition of the properties of the Martian atmosphere will be required.

A more definitive idea of the maximum Earth entry velocities for the short trip is given by Fig. 5. As in Fig. 3, each symbol and symbol type represents a specific mission and mission study, respectively. These studies indicate that entry velocities as high as 73,000 fps must be considered. Based on this figure, an entry-velocity range of 37,000 to 75,000 fps was chosen for study in the re-entry flight mechanics section of this paper.

Re-Entry Vehicle Weights

To realize any reduction in launch-vehicle weight due to atmospheric braking, the increased heat-shield weights must be somewhat less than the propulsion system weights that would otherwise be used. Figure 6 presents a comparison of the weight of Earth atmospheric entry vehicles using aerodynamic braking with those using propulsive braking. These results, based on a survey of the literature,[2–11] are presented as the ratio of the vehicle weight (W_i) required for a given Earth approach velocity to the weight required for entry at 36,000 fps (W_{36}), the Apollo entry condition. The lower region of the aerodynamic braking data represents relatively sophisticated vehicles with significant lifting capability and relatively pointed noses. The upper region represents relatively simple, blunt-nosed, low L/D vehicles. The solid boundaries represent approximate fairings of maximum and minimum vehicle weights, as obtained from the literature. Values of specific impulse of 300 to 900 sec were arbitrarily chosen to define the range of propulsion braking systems.

Aerodynamic braking on Earth return is shown to be far superior to propulsive braking throughout the velocity range of interest. At 75,000 fps, the maximum entry velocity to be expected, the most efficient propulsive vehicle must weigh at least three times as much as the most efficient aerodynamic vehicle. This, of course, assumes that the aerodynamic and propulsive vehicles have equivalent weights for entry at escape speed; no consideration was given to any differences in subsystems weights for the two vehicle types, since the dominating weight components are either structure and heat shield for atmospheric braking or structure and propellant for propulsion braking. Since 1 lb saved on the re-entry vehicle can be worth from 10 to 100 lb on the orbital launch vehicle, a weight saving of the magnitude indicated by Fig. 6 is quite significant.

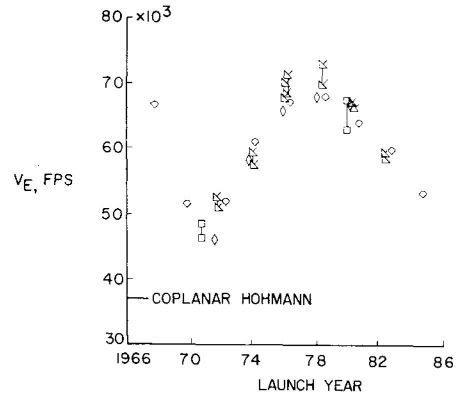

Fig. 5 Launch-year effects on Earth entry velocity for the short-trip Mars mission.

Re-Entry Flight Mechanics

Re-Entry Maneuvers

The purpose of this section is to define the re-entry flight mechanics and stagnation-point heat loads upon return from a manned Mars mission and (at least in a preliminary way) the minimum entry vehicle L/D requirements based on minimum corridor widths dictated by guidance and control considerations. Values of L/D from zero to three are considered for a constant W/SC_L of 150 psf.

Two basic re-entry modes are considered: one requiring a vehicle capable of roll-angle modulation only, and the other requiring a vehicle capable of both roll- and pitch-angle modulation. (These are the same as the mode U and mode M discussed by Love.[13]) The pitch-modulation technique is used only for peak-g alleviation to achieve increased re-entry corridor width capability, as suggested by Becker[12] and, as utilized here, requires vehicles capable of operation on a Newtonian type of drag polar. The Earth is assumed to be spherical and nonrotating, and re-entry is initiated at an altitude of 400,000 ft. (Analyses are the same as those employed by Love[11, 13] and Pritchard.[11]) The overshoot boundary is defined as that entry at positive L/D for which the vehicle can just maintain a constant-altitude flight path at the bottom of the pull-up utilizing its full negative L/D capability. The undershoot boundary is defined as that entry for which a maximum deceleration load of $12g$ is encountered during entry.

For maximum ranges and maximum heating, the vehicle is considered to fly a positive L/D trajectory from entry to pull-

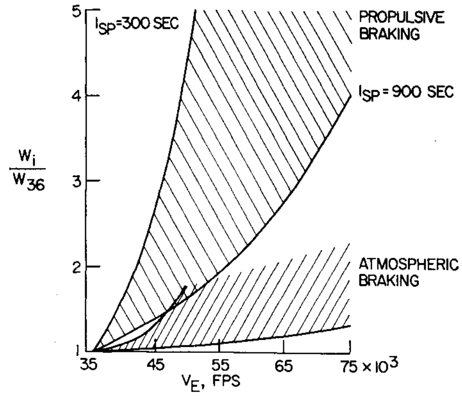

Fig. 6 Comparison of weight requirements for atmospheric and propulsive braking on Earth return from the manned Mars mission.

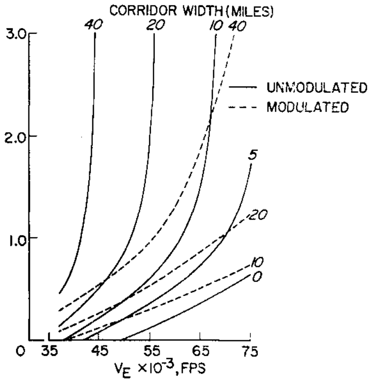

Fig. 7 Earth entry corridor width capabilities.

out. This portion of the trajectory requires constant L/D for the roll-control mode and either constant or variable L/D for the pitch-modulated mode depending on the location of the vehicle in the re-entry corridor. After pull-out, the same maneuver is assumed for either mode. Negative lift is applied by the roll-control mode to maintain constant altitude until sufficient lift can no longer be generated to maintain that altitude. An equilibrium glide is then flown to impact. The minimum range maneuver is a constant-g, roll-controlled maneuver initiated at the maximum-g point just prior to pull-out.

Corridor Width

The general effect of entry mode and vehicle L/D on the corridor width capability is treated in Fig. 7, wherein "unmodulated" denotes the roll-controlled entry mode and "modulated" denotes the entry mode utilizing pitch modulation for peak-g reduction during the initial pull-up and roll modulation thereafter. For the unmodulated-mode and corridor widths of current interest (about 10 miles or greater), increasing L/D beyond a value of about 1 provides only small gains in entry velocity for large increases in L/D which could be obtained only at the expense of increased vehicle weight and sophistication. In contrast, the pitch-modulated vehicle can employ higher L/D to significant advantage by allowing high entry velocity with large entry corridors. However, it is doubtful that there will be need to capitalize on this point, since with pitch-modulation capability an entry vehicle with L/D of about 0.8 is capable of achieving corridor widths of at least 10 miles on return from a Mars mission in the worst launch period. The unmodulated vehicle cannot cover the entire energy spectrum unless corridor widths of less than 5 miles may be accepted. Note, however, that significant corridor width capability is available to the unmodulated mode with only a moderate L/D requirement for missions in the low and middle energy periods. For either mode it is realized, of course, that some excess velocity and L/D may be desirable for a reasonable launch window.

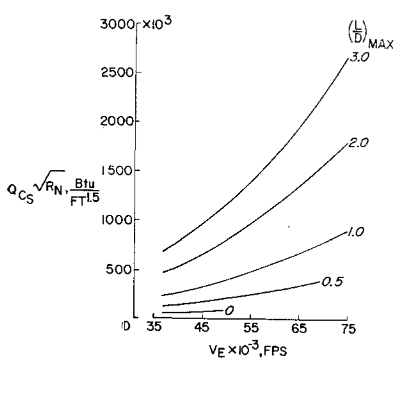

Fig. 8 Overshoot convective stagnation - point heat load.

Aerodynamic Heating

Since the aerodynamic heating is a major factor in re-entry vehicle design, the relative heating has been analyzed for the two re-entry modes that have been examined. For the purpose of this paper, all heating comparisons are based on the stagnation-point heating. Since the radiative heating rate diminishes more rapidly than the convective heating rate along any contour line moving away from the stagnation point, the apparent dominance of radiative heating obtained here would be lessened if the entire body were considered. However, for a preliminary definition of the heating penalty associated with atmospheric braking on Earth return from a manned Mars mission, the stagnation-point heating should be sufficient. Seiff,[14] in his analysis of ballistic entry at high speeds, indicates that the nonequilibrium radiative heating is small in comparison to the equilibrium radiative heating. Therefore, the effects of nonequilibrium radiation have been neglected in the present analysis.

Love[13] demonstrated the general effect of L/D, entry velocity, and entry mode on both the convective and radiative heating rates. He also indicated that maximum convective heat loads are generally obtained for entry at the overshoot boundary and maximum radiative heat loads are obtained for entry at the undershoot boundary. Maximum stagnation-point convective heating loads are obtained at the overshoot boundary, where the vehicles maneuver at maximum altitudes and minimum atmospheric densities (Fig. 8). Note that, for a given L/D and entry velocity, the two entry modes would have the same design heat load. This is to be expected, because the vehicle's pitch modulation capability is not required for entry at the overshoot boundary. However, if we compare the entry modes on the basis of the same corridor width capability of 10 miles, much lower convective heat loads are obtained for the pitch-modulated maneuver, because this maneuver requires less L/D to achieve the corridor requirement (Fig. 9).

The equilibrium radiative stagnation-point heat loads presented in Fig. 10 demonstrate that the use of pitch modulation results in large increases in the undershoot heat load for a given entry velocity and L/D. This is a somewhat different result than that obtained for convective heating where a reduction in undershoot boundary heat load is achieved by use of the pitch-modulation maneuver for the same conditions. Radiative heating is much more strongly dependent on the atmospheric density and entry velocity than is convective heating; it is directly proportional to the density for the constant altitude maneuver. Thus, entry at the undershoot boundary with its lower pull-out altitudes results in greater heating loads.

A comparison of the unmodulated and modulated entry vehicles on the basis of equal corridor widths of 10 miles in terms of maximum undershoot radiative heating is indicated in Fig. 11. The ratio of the modulated heat loads to the unmodulated heat loads would be about the same as for the

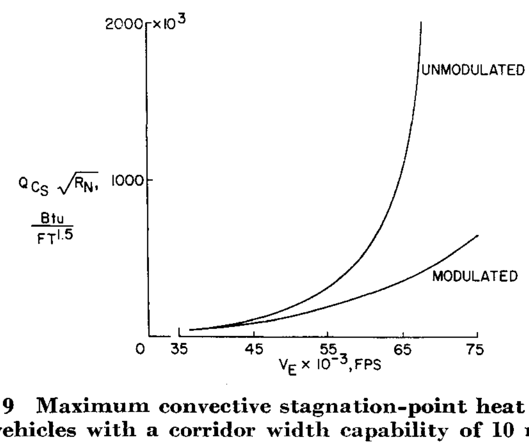

Fig. 9 Maximum convective stagnation-point heat loads for vehicles with a corridor width capability of 10 miles.

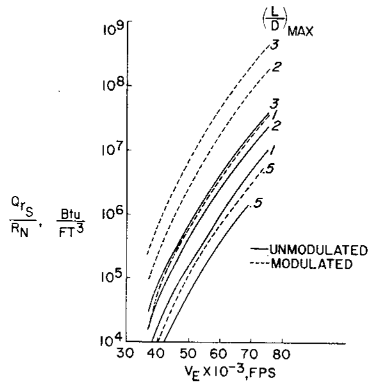

Fig. 10 Undershoot stagnation - point heat load.

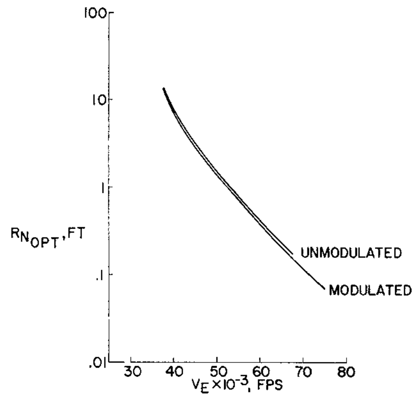

Fig. 12 Optimum vehicle nose radius for a corridor width capability of 10 miles.

convective heating loads. In the radiative-heating case, the stagnation-point heating loads may not be so conservative as in the case of convective heating but should still be valid.

It is a simple matter to define an optimum vehicle nose radius based on stagnation-point heating loads, since the convective total heat load is related to the vehicle nose radius by the proportionality $Q_c \propto R_N^{-1/2}$ and the radiative heat load by $Q_r \propto R_N$. The optimum nose radius is then the nose radius for which minimum total heat loads are obtained on a given re-entry trajectory. The optimum nose radii are presented in Fig. 12 for the minimum entry vehicle, the vehicle with a 10-mile re-entry corridor capability. This is in agreement with the work of Seiff[14] and Bobbitt.[15] Radiative heating is shown to become the dominant heating mode at entry velocities in excess of about 50,000 fps. It is noteworthy that $R_{N_{opt}}$ is only slightly affected by the entry mode.

The total stagnation-point heat loads associated with the optimum nose radii of Fig. 12 are presented in Fig. 13 for vehicles with a 10-mile entry corridor capability. The marked superiority of re-entry vehicles capable of the pitch-modulation technique over vehicles capable of only roll-angle modulation is obvious from this figure. At 68,000 fps, the highest velocity for which the unmodulated vehicle is capable of providing a 10-mile corridor, the modulated vehicle heat load is only one-fifth that of the unmodulated vehicle. However, we should keep in mind that vehicles with different values of L/D are involved in such comparisons. For the same L/D, the unmodulated vehicle has the lower heat load, and this vehicle can provide acceptable corridor widths at lower velocities.

It should be pointed out at this point that, in the low and middle energy period ($V_E < 55{,}000$ fps), the L/D requirement is low for either entry mode. Moreover, since low L/D values are involved, the assumption of constant W/SC_L may introduce some questions in the heat-load comparisons that remain to be assessed. At any rate, the roll-control mode becomes more efficient at low L/D where use can be made of the Apollo type of vehicle shape and may be more desirable than the pitch-modulated mode for the low and middle energy missions.

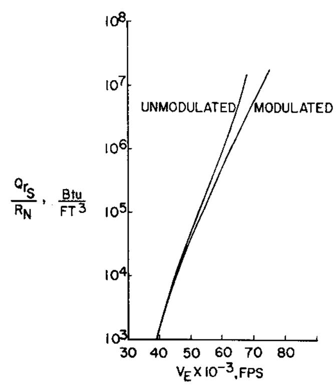

Fig. 11 Maximum radiative stagnation-point heat loads for vehicles with a corridor width capability of 10 miles.

It should be emphasized, however, that the pitch-modulation maneuver is required only for entry in the region of the undershoot boundary and would not necessarily be required for the nominal or midcorridor entry condition. Thus, it seems reasonable to consider this maneuver capability as a desirable feature for the Earth-entry vehicle system required for atmospheric braking on Earth return from the manned Mars mission at high velocity.

Finally, it appears that means of reducing the high heating rates and loads occurring at hyperbolic entry velocities need to be studied. Combined aerodynamic and propulsive braking may offer some advantages, although Yoshikawa and Wick[16] indicate that vehicle-shape optimization and ablation material development may be a more efficient method.

Range Capability

The ranging capabilities of both the modulated and unmodulated vehicles have been evaluated, since control of the landing point is a desirable characteristic for any re-entry-vehicle system. It is desirable to have a re-entry vehicle that is capable of at least zero-range overlap. That is, the minimum range traversed on the overshoot trajectory should be equal to the maximum range traversed on the undershoot trajectory. Then, if the vehicle approaches the atmosphere in the correct plane and at the correct time, a landing at the desired point may be achieved.

The effects of entry velocity and vehicle L/D capability on the ratio of the longitudinal range overlap to Earth radius are presented in Fig. 14 for the unmodulated and modulated-entry techniques. The dashed lines indicate the range overlap capability of the minimum vehicles with a 10-mile re-entry corridor capability. Use of the roll control, or unmodulated, entry mode results in large-range overlap at the higher entry velocities. As expected, the unmodulated vehicle with the required 10-mile corridor demonstrates ade-

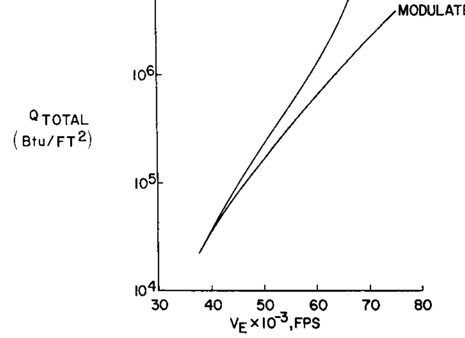

Fig. 13 Total stagnation-point heat load for vehicles with optimum nose radii and a corridor width capability of 10 miles.

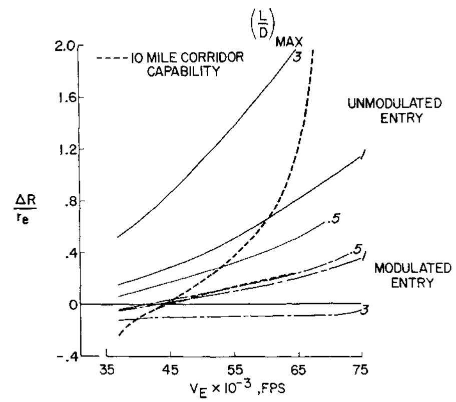

Fig. 14 Longitudinal range overlap.

quate ranging capability. Use of the pitch-modulated entry mode yields the unusual result of decreasing range overlap capability with increasing L/D capability, because all the vehicle L/D is required for peak-g alleviation for entry at the undershoot boundary. Note, however, that positive-range overlap is available for this entry mode with the 10-mile corridor requirement. Thus, for entry velocities in excess of about 45,000 fps, the pitch-modulation entry maneuver is at least acceptable from the range standpoint. It should also be pointed out that additional range overlap capability may be expected by providing the pitch-modulated entry vehicle with a slight excess of L/D.

Concluding Remarks

The mission studies surveyed in this paper have shown that atmospheric braking on Earth return from a manned Mars mission is highly desirable. The Earth-entry velocities associated with the attractive short-trip Mars missions may be as high as three times satellite velocity for missions occurring in a high-energy period when Mars is near aphelion.

The roll-control maneuver, for which valuable flight experience will be obtained from the Apollo program, is capable of achieving adequate re-entry corridor widths for Mars missions in the low and middle energy periods with only a moderate L/D requirement. However, a more sophisticated maneuver, such as the pitch-modulated maneuver discussed here, will probably be required to achieve adequate corridor widths for entry at the higher velocities. Also, on the basis of equivalent corridor widths, and therefore different values of L/D, lower stagnation-point heat loads are indicated for the pitch-modulated maneuver. This maneuver requires further study, especially as to the total body heating, since the study of stagnation-point heating conducted here gives only a broad indication of the total heating picture.

References

[1] Knipp, G., Jr. and Zola, C. L., "Three-dimensional trajectory analysis for round-trip missions to Mars," NASA TN D-1316 (October 1962).

[2] Gillespie, R. W., Ragsac, R. V., and Ross, S., "Prospects for early manned interplanetary flight," IAS Paper 1234 (January 1963).

[3] Ehricke, K. A., "Mission analysis of fast manned flights to Venus and Mars," *Advances in the Astronautical Sciences, Vol. 13. Proceedings of the Ninth Annual American Astronautical Society Meeting* (Western Periodicals Co., North Hollywood, Calif., 1964), pp. 470–546.

[4] Ehricke, K. A., "A study of interplanetary missions to Mercury through Saturn with emphasis on manned missions to Venus and Mars 1973/82 involving capture," AIAA Conference on Engineering Problems of Manned Interplanetary Exploration, Palo Alto, Calif. (October 1963).

[5] Dixon, F. P., "The empire dual planet fly-by mission," *AIAA Conference on Engineering Problems of Manned Interplanetary Exploration* (American Institute of Aeronautic and Astronautics, New York, 1963), pp. 3-18.

[6] Widmer, T. F., "Application of nuclear rocket propulsion to manned Mars spacecraft," *AIAA Conference on Engineering Problems of Manned Interplanetary Exploration* (American Institute of Aeronautic and Astronautics, New York, 1963), pp. 85–101.

[7] Martin, B. P., "Manned interplanetary missions based on current programs," AIAA Conference on Engineering Problems of Manned Interplanetary Exploration, Palo Alto, Calif. (October 1963).

[8] Neumann, T. W., "An analysis of a manned Mars landing mission," AIAA Conference on Engineering Problems of Manned Interplanetary Exploration, Palo Alto, Calif. (October 1963).

[9] Martin, B. P., "Manned flight to Mars and Venus in the 70's" *AIAA Second Manned Space Flight Meeting* (American Institute of Aeronautic and Astronautics, New York, 1963), pp. 236–253.

[10] Himmel, S. C., Dugan, J. F., Jr., Luidens, R. W., and Weber, R. J., "A study of manned nuclear-rocket missions to Mars," Aerospace Eng. **20**, 18, 19, and 51–58 (July 1961).

[11] Love, E. S. and Pritchard, E. B., "A look at manned entry at circular to hyperbolic velocities," *AIAA Second Manned Space Flight Meeting* (American Institute of Aeronautic and Astronautics, New York, 1963), pp. 167–180.

[12] Becker, J. V., "Entry vehicles," Astronaut. Aerospace Eng. **1**, 70–74 (November 1963).

[13] Love, E. S., "Factors influencing configuration and performance of multipurpose manned entry vehicles," J. Spacecraft Rockets **1**, 3–13 (January-February 1964).

[14] Seiff, A., "Atmosphere entry problems of manned interplanetary Flight," *AIAA Conference on Engineering Problems of Manned Interplanetary Exploration* (American Institute of Aeronautic and Astronautics, New York, 1963), pp. 19–33.

[15] Bobbitt, P. J., "Effect of shape on total radiative and convective heat inputs at hyperbolic enetry speeds," *Advances in the Astronautical Sciences, Vol. 13. Proceedings of the Ninth Annual American Astronautical Society Meeting* (Western Periodicals Co., North Hollywood, Calif., 1964), pp. 290–319.

[16] Yoshikawa, K., and Wick, B. H., "Aerodynamic and rocket braking of vehicles entering the Earth's atmosphere at very high speeds" NASA TND-2239 (April 1964).