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by

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SURVEY OF VELOCITY REQUIREMENTS AND REENTRY FLIGHT MECHANICS FOR MANNED MARS MISSIONS

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Summary

The manned Mars mission is discussed in terms of the propulsive velocity requirements of the mission; the Earth entry velocities associated with short mission trip times; and reentry vehicle lift-drag-ratio requirements for Earth atmospheric braking and landing.

A survey of the recent literature reveals that total propulsive velocities of about 64,000 fps are required for the so-called short (400-500 day) missions utilizing the orbital rendezvous concept in the most favorable launch period, 1970-72. The least favorable period of 1978-80 requires about 92,000 fps for the all-propulsive mission mode. Utilizing aerodynamic braking on Earth return reduces these values of propulsive velocity to 38,000 fps and 49,000 fps, respectively. A further reduction is obtained by the use of the atmospheric braking mode at both Earth and Mars. In this case, the propulsive velocity requirement is 26,000 fps and 34,000 fps, respectively.

The mission times associated with these velocity requirements vary slightly with the launch year. Minimum total propulsive velocity requirements for the short trips generally occur for mission times of 400 to 500 Earth days. Long trip times, of the order of 900 to 1,000 days, require minimum propulsive velocities of 20,000 to 40,000 fps, depending on the mission mode assumed. Earth entry velocities were found to vary from about 46,000 fps to 73,000 fps for the short trips. For the long trips, reentry velocities as low as 38,000 fps are attainable.

Since a survey of reentry vehicle system weights indicated that atmospheric braking is far superior to rocket braking, an analysis was conducted to investigate the flight mechanics and stagnation point heating associated with Earth entry at these high speeds. Corridor widths much smaller than those for the Apollo mission must be accepted if a pitch modulation capability is not available. Vehicles capable of the pitch modulation maneuver for peak g reduction are shown to require significantly lower L/D than vehicles capable of the roll-control maneuver only. This lower L/D results in a reduction in the convective and radiative stagnation point heating rates and loads encountered during reentry. Adequate longitudinal ranging capability appears to be available to both the modulated and unmodulated entry vehicles.

Introduction

At the present time we are in the early planning stage of manned flight to another planet, 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. It must be our purpose to define the most attractive mission profiles in accord with the national resources which may be available for such a mission.

Many preliminary studies have been initiated both within the NASA organization and by industry. As pointed out in these studies, 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 and optimization procedures developed to minimize the total propulsion energy requirements of the manned Mars mission.

This mission is primarily influenced by two factors: the eccentricity of the Martian orbit about the Sun and the angularity of the Mars orbital plane with respect to the plane of the ecliptic. Minimum energy missions obviously occur for transfer when Mars is near the nodal point and also near perihelion. Maximum energy missions occur for maximum transfer plane angle changes when Mars is near aphelion. Since the period of the Earth-Mars cycle is approximately 15 years, the energy requirements are cyclic in nature.

It is the purpose of this paper to present a survey of the energy requirements of the manned Mars mission and to analyze the reentry flight mechanics on return to the Earth's atmosphere. Mars arrival velocities are discussed but the flight mechanics associated with entry into the Martian atmosphere were not considered. Several 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 included in the present literature survey. These studies consider both chemical and nuclear propulsion systems for launches in the 1968 to 1984 period, which covers the entire Earth-Mars cycle. In this paper, the primary emphasis is placed on studies of the short trip mission initiated from a near Earth orbit.

In the study of Earth entry flight mechanics no particular vehicle was investigated. At this early stage it appears more reasonable to concentrate on defining the basic reentry vehicle characteristics, that is, the range of vehicle lift-drag ratio which will be required for a safe entry as well as the desired atmospheric maneuvers. A preliminary assessment of the heating problem is given in terms of the stagnation point heating loads.

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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 which 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 take place from 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 shown in Fig. 1. In this case the perihelion of the transfer ellipse occurs at the 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 450 Earth days. Therefore, total mission times of 900 to 1,000 Earth days are required for the minimum energy mission. This may not be desirable from life support system and reliability considerations as well as consideration of psychological factors affecting the crew. Thus the primary emphasis at the present time is being placed on the "short trip" mission shown in Fig. 2.

This reduction in total mission time to 400 to 500 days is accomplished by allowing one leg of the mission to pass inside of the Earth's orbit. Indeed, the space vehicle may pass within 1/2 a. u. or less of the Sun for some missions. In general, in order to optimize the energy requirements, the inbound leg of the mission is the short leg of the mission. This is due to the lower weights which must be accelerated to the higher velocities associated with trajectories passing inside the Earth's orbit.

Of course the penalties associated with the short trip are evidenced in increased propulsive energy requirements. This necessitates larger vehicles at Earth and gives rise to many novel mission concepts such as convoys of vehicles, supply vehicles preceding the manned vehicles, and hyperbolic rendezvous and crew transfer to a reentry 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 1970-71 and 1979-80 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. 3. The curves shown are for three types of missions initiated from a circular orbit about the Earth. These are: 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 reentry vehicle technology beyond Mercury or Gemini vehicles. Use of the second and third classes of missions requires significant advances in reentry vehicle technology beyond that of Apollo. As shown in Fig. 3, there are two distinct minimum energy points for each mission which are separated by a region of excessively high-energy requirements. The "long trip" minimum occurs at about an 850-day mission for a 40-day stay at Mars. True minimum energy requirements are obtained for a 450-day stay at Mars and a total mission time of about 950 days as indicated by the near Hohmann transfer points. The short trip minimum energy missions occur at trip times of about 400 to 500 days depending on the year and type of mission.

The use of atmospheric braking yields great savings in propulsion velocity requirements at the expense, however, of increased heat-shield weights. For instance, a decrease in propulsive velocity requirement from 63,000 fps to 36,500 fps is obtained by using atmospheric braking on Earth return for the 1970-71 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 1979-80 mission is shown to require much higher propulsive velocities than the 1970-71 mission since the distance and plane angle change is a maximum at that time. For the all-propulsive mission, this difference in velocity requirement is some 20,000 fps. The effect of launch year is greatly reduced however, if atmospheric braking is utilized on Earth return.

A significant penalty in propulsive velocity requirement is associated with going to shorter trip times from either of the minimum points. Therefore, early manned Mars missions will probably be restricted to total mission times of either 400 to 500 days or 900 to 1,000 days.

The results of Fig. 3 are presented for stay times at Mars of 40 days and 450 days only. 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.

Having considered the effects of mission or trip time on the propulsive velocity requirements, it is desirable to look more closely at the effects of launch year. The results of the literature survey[1-10] are presented in Fig. 4 for launch years from 1967 to 1986. Each symbol represents a specific mission which has been optimized to some extent. Note that the use of atmospheric braking at Earth and at Mars reduces the effects of launch year significantly as well as shifts the maxima and minima towards 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 95,000 fps for the worst. The use of atmospheric braking at Earth results in a variation in velocity requirement with launch year by about 11,000 fps. A further reduction in this variation to about 8,000 fps, is afforded by utilizing atmospheric braking at both Earth and Mars.

A significant point indicated by this figure is that if the Manned Mars Mission is funded and a launch date in the mid 1970's selected, the mission must be designed on the basis of the maximum requirements of the 1979-80 period to allow for any schedule slippage. If this is not done the mission might have to be canceled until 7 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.

Figs. 3 and 4 indicate a significant reduction in propulsion requirements if atmospheric braking is used on Earth return. This, of course, requires that the reentry vehicle be capable of entry into the Earth's atmosphere at hyperbolic velocities. As is to be expected, both mission time and launch period have a considerable effect on the Earth entry velocities. Fig. 5 presents the effect of trip time on the Earth and Mars entry velocities for the 1970-71 and 1979-80 missions as calculated by Knipp and Zola.[1] The results presented are for a 40-day stay at Mars and minimized total propulsive velocity requirements. Relatively low entry velocities are obtained for the long trips where atmospheric braking is used at both Earth and Mars. Thus, little or no increase in reentry vehicle technology beyond that for Apollo would be required for these missions. For the short trips, our prime area of interest, the Earth entry velocities vary from a minimum of 46,000 fps for the 1970-71 mission to a minimum of 63,000 fps for the 1979-80 mission assuming atmospheric braking at both Earth and Mars. If the propulsive braking mode is used at Mars, these entry velocities increase to 48,500 fps and 67,500 fps, respectively. This increase is due to the optimization process by which the minimum total propulsive velocity requirements are defined.

A comparison of Figs. 3 and 5 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 are only slightly increased, the Mars entry velocities may be increased considerably by this restriction. Mars entry velocities of 19,500 fps 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 to 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. This is primarily due to the formation of cyanogen in the hot gas cap. 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 with which we must be concerned is presented in Fig. 6 for the short trip class of mission. Minimum Earth entry velocities occur for the 1970-71 mission and maximum velocities occur for the 1978-79 launching. These mission studies indicate that entry velocities as high as 73,000 fps must be considered. The values for the long trip, or Hohmann trajectories (≈37,000 fps), are not shown. Based on this figure, an entry velocity range of 37,000 fps to 75,000 fps was chosen to be studied in the reentry flight mechanics section of this paper in order to include all reasonable manned Mars missions.

Vehicle Weight Requirements

No survey of the manned Mars mission could be considered complete without a consideration of the vehicle weight requirements for such a mission. Both chemical and nuclear propulsion systems have been considered in many mission studies. Electric propulsion has generally not been considered since it is believed to be only marginal for the early Mars mission.

Due to the many different ground rules set up by Mars mission investigators, no clear-cut band of data may be presented as to the vehicle weights required in Earth orbit to complete the manned Mars mission. A better definition of optimum crew size and crew life support requirements is needed, for instance. Weight of the Earth entry vehicle is of critical importance since a pound saved here is worth from 10 to 100 pounds on the orbital launch vehicle.

The mission studies surveyed indicate that chemical propulsion systems with several million pounds in Earth orbit are capable of only the most marginal Mars missions. Reasonable missions are available for nuclear systems with weights in orbit of about 1 to 1.5 million pounds. For comparable missions, the chemical system weights may be greater than the nuclear system weights by a factor of five or more.

Reentry Vehicle Weights

The reduction of total mission propulsion velocity requirements by the use of atmospheric braking, while advantageous, is obtained only at the expense of increased reentry vehicle thermal protection requirements. To realize any reduction in launch-vehicle weight the increased heat-shield weights must be somewhat less than the propulsion system weights which would otherwise be used. In Fig. 7 the ratio of the reentry vehicle weight for entry at escape speed to the reentry vehicle weight with the additional thermal protection required for entry at any higher speed is presented in terms of Earth entry velocity. Two types of braking were considered, aerodynamic and propulsive. The band of results for the vehicles utilizing aerodynamic braking were obtained from a survey of the literature.[2-11] The upper region of the band is composed of vehicles with L/D capabilities of about 1/2 to 1 and relatively pointed noses. The lower region is composed of low L/D bodies (0 to 1/2) with relatively blunted noses.

For the propulsive braking band, specific impulses of 300 to 900 seconds were considered. A specific impulse of 300 seconds represents a reasonable value of a storable chemical propellant and a specific impulse of 900 seconds represents a very good nuclear system capability.

Thus, the use of aerodynamic braking on Earth return is most advantageous throughout the velocity range considered. At 75,000 fps, the maximum entry velocity which might 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.

Since 1 pound saved on the reentry vehicle can be worth from 10 to 100 pounds on the orbital launch vehicle, a weight saving of the magnitude indicated by Fig. 7 is quite significant. Atmospheric braking on Earth return therefore appears to be a basic requirement of the manned Mars mission. However, it is obvious from the spread of the data that much further work is necessary in the area of reentry vehicle design.

Reentry Flight Mechanics

Reentry Maneuvers

It is the purpose of this section of the paper to define the reentry flight mechanics and stagnation point heat loads for entry into the atmosphere on Earth return from a manned Mars mission. The maneuvers considered here are shown in Fig. 8. For maximum ranges and maximum heating the vehicle is considered to fly a positive L/D trajectory from entry to pullout. At that point, 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 pullout.

Two basic reentry modes were considered: one requiring a vehicle capable of roll angle modulation only and the other requiring a vehicle capable of both roll angle modulation and pitch angle modulation. The pitch modulation technique is used only for peak g alleviation to achieve increased reentry corridor width capability as suggested by Becker.[12]

This technique, when initiated at high entry velocities, usually required a pullup to a higher altitude as shown by the lower sketch of Fig. 8. In this case the vehicle angle of attack is modulated towards that for zero lift until peak dynamic pressure is reached, the vehicle then is rolled 180° and the angle of attack increased to maintain the same constant g loading. Negative lift is thus obtained to hold the vehicle in the atmosphere and allow a constant altitude flight path to be flown from the second pullout.

In the present analysis, the Earth is assumed to be spherical and nonrotating and reentry is initiated at an altitude of 400,000 feet. 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 pullup utilizing its full negative L/D capability. The undershoot boundary is defined as that entry for which the maximum deceleration loads do not exceed 12g.

The results were obtained by machine calculation for the region from entry to pullout and by analytic methods from pullout to landing.

Limiting Entry Velocity

It is well known that an increase in reentry velocity results in a decreased reentry corridor for a specific vehicle. This is simply due to the fact that the vehicle must dip deeper into the atmosphere to prevent skipping although high deceleration loads are encountered at higher altitudes. For a given vehicle, the overshoot initial entry angle must increase for increased entry velocity and the undershoot initial entry angle must decrease as is indicated by the sketch in Fig. 9. Since the boundaries approach each other, the overshoot boundary deceleration loads must increase with increasing entry velocity. As shown by this figure, these deceleration loads may be significantly reduced by increasing the vehicle L/D capability. However, even a vehicle with infinite L/D capability would have a 7.5g maximum load at the overshoot boundary for entry at 75,000 fps, the maximum considered here for the manned Mars mission. Therefore, high g loads are a basic requirement for the atmospheric braking mission mode. The effects of prolonged weightlessness on the crew's tolerance to deceleration loadings must be defined and, if necessary, a centrifuge included in the mission module to maintain crew effectiveness in g tolerance. If the undershoot boundary is based on man's tolerance to high deceleration loadings, it becomes apparent that the overshoot boundary maximum deceleration loads may exceed the chosen limits. Thus, some entry velocity exists for which the overshoot and undershoot boundaries coincide. This is the point of zero corridor width and is defined as the limiting entry velocity.

The limiting entry velocities associated with various levels of deceleration loading are presented in Fig. 10 in terms of vehicle L/D capability. Ballistic vehicles are completely inadequate for entry at velocities much in excess of 40,000 fps. Even a vehicle with an L/D capability of 1/2 would exceed 12g for entry at speeds in excess of 69,500 fps. A vehicle designed on the basis of the 1979-80 mission would require an L/D capability of about 0.7 as the minimum possible value for a 12g undershoot boundary and zero corridor width. To achieve any significant corridor width, a much higher value of L/D would be required. Thus, vehicles capable of roll control only, which enter the atmosphere initially with positive lift, may require L/D capabilities far in excess of 0.7.

Corridor Width

On the basis of guidance and control considerations an Earth entry corridor width of about 10 miles is required on return from the manned Mars mission. It is of interest, however, to consider the general effect of entry mode and vehicle L/D on the corridor width capability of entry vehicles. As shown in Fig. 11 quite sophisticated vehicles may be required to achieve significant corridor widths based on a 12g undershoot boundary unless pitch modulation is used for peak g reduction. With pitch modulation capability a reentry vehicle with $L/D < 1$ is capable of achieving a 10-mile corridor on return from a Mars mission in the worst launch period. This, compared to the unmodulated case requiring $L/D > 3$, indicates that a pitch modulation capability is necessary unless corridor widths of the order of 5 miles or less may be accepted for the present boundary definitions.

Fig. 12 gives an indication of the L/D capability required for the manned Mars mission for several corridor widths. For missions in the low-energy period, 1970-71 ($V_E \approx 45,000$ fps), a 10-mile corridor is available to a low L/D vehicle without the use of pitch modulation. This requirement rapidly increases if increased corridor widths are desired.

For missions in the 1978-79 period ($V_E \approx 75,000$ fps) pitch modulation is required to achieve a 10-mile corridor. Note that the L/D requirement is not high, only about a value of 0.75. Also of interest is the 1984 mission. In this case the reentry velocity is about 55,000 fps requiring a vehicle L/D capability of 0.62, unmodulated, or 0.31, modulated. Sufficiently wide reentry corridors are thus available to vehicles with fairly low L/D capabilities for the low and middle energy Mars missions but pitch modulation capability is required if the mission is to occur near the high-energy period. It is realized of course, that some increase in velocity and L/D requirements is necessary to provide for a reasonable launch window.

Aerodynamic Heating

Since the aerodynamic heating is a major factor in reentry vehicle design, the relative heating has been analyzed for the two reentry modes which have been examined. For the purpose of this paper, it was not considered desirable to restrict the analysis to any particular reentry configuration or heat-shield material. Thus, all heating comparisons are based on the stagnation point heat rates and loads.

It is well known that the radiative heating rate diminishes more rapidly than the convective heating rate along any contour line moving away from the stagnation point. Therefore the apparent dominance of radiative heating obtained here would be lessened if the entire body were considered. It is felt however, that for a preliminary definition of the heating penalty associated with atmospheric braking on Earth return from a manned Mars mission, the stagnation point heating rates and heating loads should be sufficient. In the present analysis the effects of nonequilibrium radiation have been neglected. Seiff,[13] in his analysis of ballistic entry at high speeds, indicates that the nonequilibrium radiative heating is small in comparison to the equilibrium radiative heating.

Obviously, maximum stagnation point heating rates occur at the undershoot boundary. The maximum convective heating rates are presented in Fig. 13 for both the modulated and unmodulated entries. As shown, use of the pitch modulated entry mode results in large increases in the maximum convective heating rates for entry at the same velocity. This would seem to preclude use of the pitch modulated entry maneuver. However, the difference in L/D required by the two modes of operation, for the same corridor width, completely changes this conclusion. In fact, lower stagnation point convective heating rates are obtained for the pitch modulated entry vehicle than for the unmodulated entry vehicle with an equivalent corridor as may be seen from Figs. 12 and 13.

The maximum radiative heating rates are shown in Fig. 14 to increase much more rapidly with increasing entry velocity than do the convective rates. The use of pitch modulation may result in large increases in the maximum radiative heating rates, depending on the vehicle L/D capability. Comparing the radiative heating rates in terms of equivalent corridor widths for the two entry modes indicates that a reduction in maximum heating rate is obtained by use of vehicles with pitch modulation capability.

Perhaps more significant than a comparison of the heating rates is a comparison of the stagnation point total heat loads. The convective total heat loads are presented in Figs. 15 and 16 for entries at the overshoot and undershoot boundaries. Entry at the undershoot boundary utilizing pitch modulation results in lower convective heat loads than for the unmodulated maneuver. This is primarily due to the fact that the pitch modulated entries dive deeper into the atmosphere and pull out at significantly lower altitudes than do the unmodulated entries. The convective heating load obtained during a constant altitude flight is proportional to the inverse of the square root of the atmospheric density. Since most of the convective heating occurs during the constant altitude flight, minimum heat loads occur for those entries with the lowest pullout altitudes, the pitch modulated entry cases. Maximum convective heating loads are obtained for entry at the overshoot boundary where the vehicles maneuver at maximum altitudes and minimum atmospheric densities. Since the pitch modulated entries require less L/D and lower altitudes, lower maximum convective heating loads are obtained with this maneuver for vehicles with a reentry corridor width of 10 miles as shown in Fig. 17. The results of this figure demonstrate the effectiveness of vehicles with pitch modulation capability in stagnation point convective heat load reduction. In addition, increasing vehicle L/D capability is generally attained only at the expense of exposing larger surface areas to high heating rates and loads. Thus, all heating comparisons based on the stagnation point results should be conservative from the standpoint of demonstrating the effectiveness of the pitch modulation maneuver.

For a given value of L/D, the equilibrium radiative stagnation point heat loads presented in Figs. 18 and 19 indicate a somewhat different result than that obtained for convective heating loads. That is, maximum radiative heating occurs at the undershoot boundary rather than at the overshoot boundary. The use of pitch modulation results in large increases in the undershoot heat load, for a given entry velocity. Radiative heating is much more strongly dependent on the atmospheric density and entry velocity than is convective heating. Also, the radiative heating is directly proportional to the density for the constant altitude maneuver. Thus, entry at the undershoot boundary with its lower pullout altitudes results in greater radiative 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. 20. The ratio of the modulated heat loads to the unmodulated heat loads would be about the same as for the convective heating loads. In the radiative heating case, the stagnation point heating loads may not be as conservative as in the case of convective heating but should still be valid.

It has been demonstrated that vehicles capable of the pitch modulation technique are advantageous in terms of reduction of both convective and radiative stagnation point heating rates and heating loads. Also, this maneuver is required only 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 as a desirable feature for Earth entry vehicle systems although further study is necessary in the area of total body heat loads and thermal protection system requirements for this type of maneuver before any definite conclusions may be drawn.

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[14] indicate that vehicle shape optimization and ablation material development may be a more efficient method.

Optimum Nose Radius

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 $Q_c \propto \frac{1}{\sqrt{R_n}}$ 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. It is assumed that the reentry trajectory is independent of the nose radius of the reentry vehicle. The sum of the undershoot boundary radiative heating loads and the overshoot boundary convective heating loads was used to optimize the reentry vehicle nose radius for vehicles capable of a 10-mile reentry corridor. These optimum nose radii are presented in figure 21. This is in agreement with the work of Seiff[13] and also Bobbitt.[15] Radiative heating is shown to become the dominant heating mode at entry velocities in excess of about 50,000 fps. It is interesting to note that the optimum nose radius is only slightly different for vehicles with pitch modulation capability.

The total stagnation point heat loads associated with the optimum nose radii of Fig. 21 are presented in Fig. 22 for vehicles with a 10-mile entry corridor capability. The marked superiority of reentry 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.

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 reentry vehicle system. The efficiency of the vehicle insofar as range control is concerned is strongly dependent on the sophistication of the system. The ability of the reentry vehicle to fly difficult maneuvers involving exact control of the vehicle and perhaps both roll and pitch angle variation is important. The discussions thus far have been based on the requirement of safe entry only, regardless of landing site. It is desirable to have a reentry vehicle which is at least capable of zero range overlap. That is, the minimum range traversed on the overshoot trajectory is 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 effected.

The effects of entry velocity and vehicle L/D capability on the longitudinal range overlap are presented in Fig. 23 for the unmodulated and modulated entry techniques. The dashed lines indicate the range overlap capability of the minimum vehicle with a 10-mile reentry corridor capability. Range overlap increases with entry velocity and significant values are obtained for the unmodulated case. Note the unusual result for modulated entry of decreasing range overlap with increasing L/D capability. These results are for vehicles requiring all their L/D capability for use in peak g reduction. Since $L/D < 1$ is all that is required to achieve safe entry for this maneuver, the high L/D results may be neglected. Also, positive range overlap occurs only at the higher entry velocities and is quite small. However, for entry velocities in excess of 45,000 fps the pitch modulation entry maneuver is at least acceptable from the range standpoint. It should be pointed out, however, that additional range overlap capability may be expected by providing the pitch modulated entry vehicle with a slight excess of L/D.

Lateral range capabilities are not considered here since the lateral range capability of these vehicles would probably be greater than the longitudinal overlap capability.

Concluding Remarks

The mission studies surveyed in this paper have shown that the propulsive velocity requirements for the manned Mars mission are strongly dependent on mission time and launch year. The short trip missions, desirable from the standpoint of life-support system and reliability requirements, require about 400 to 500 days trip time. The Earth entry velocities associated with these missions vary from 45,000 fps to 75,000 fps depending on the launch period. A survey of reentry vehicle system weights indicated a significant weight saving by utilizing aerodynamic braking rather than propulsive braking at Earth.

For the range of Earth entry velocities considered, an analysis was performed to evaluate the minimum reentry vehicle L/D requirements. A reasonable reentry corridor width of 10 miles was chosen to define the minimum L/D requirement. It was shown that safe entry at velocities greater than about 68,000 fps was available only to vehicles with an L/D capability in excess of three for vehicles capable of roll control only. The use of the pitch modulation technique for peak g alleviation and reentry corridor width increase was shown to require a maximum vehicle L/D of 0.75 at an entry velocity of 75,000 fps. The pitch modulation maneuver resulted in lower heat loads than did the unmodulated maneuver for the minimum entry vehicle.

Only small range overlap was available to the minimum entry vehicle using pitch modulation. However, zero range overlap occurred at an entry velocity of 45,000 fps, indicating that the pitch modulation maneuver is acceptable for entry at velocities in excess of this value.

On the basis of this study it appears that the pitch modulation maneuver is a desirable maneuver for reentry at the velocities associated with Earth return from a short trip manned Mars mission. This maneuver requires further study, especially as to the total body heating since this study of stagnation point heating gives only a broad indication of the total heating picture.

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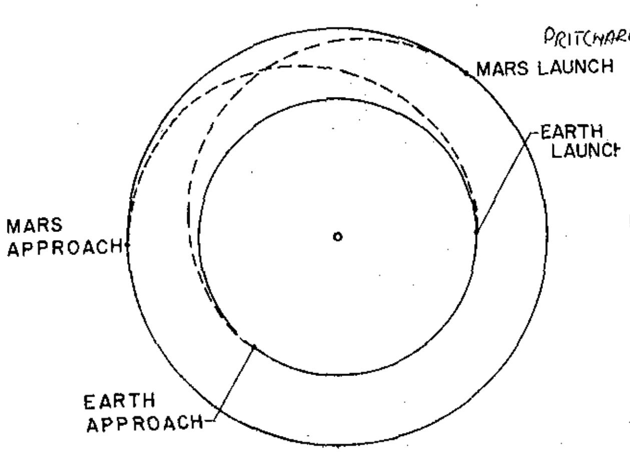

Figure 1.- Manned Mars mission (long trip, 900-1,000 days).

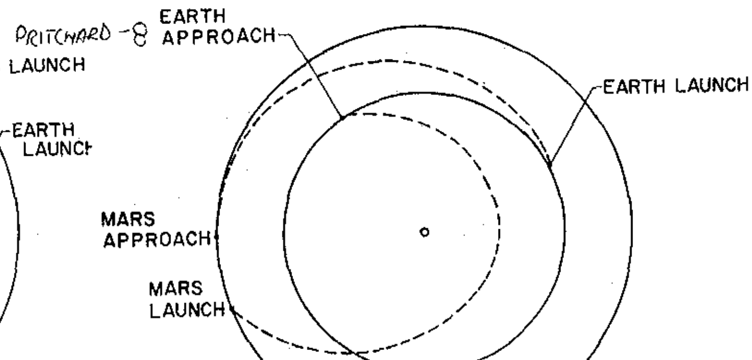

Figure 2.- Manned Mars mission (short trip, 400-500 days).

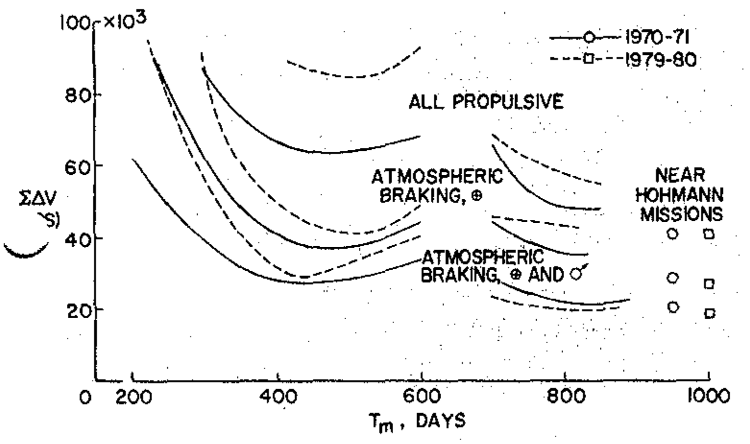

Figure 3.- Propulsive velocity requirements for the manned Mars mission with a 40-day wait time at Mars.

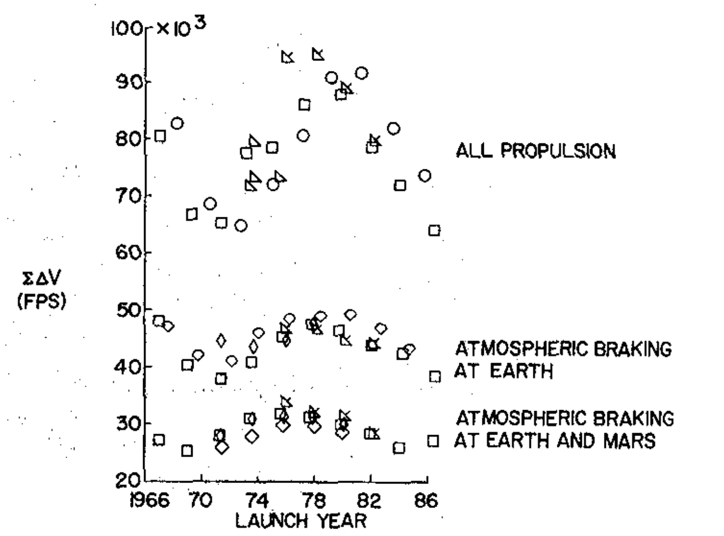

Figure 4.- Launch year effects on total propulsive velocity requirement for the short trip Mars mission.

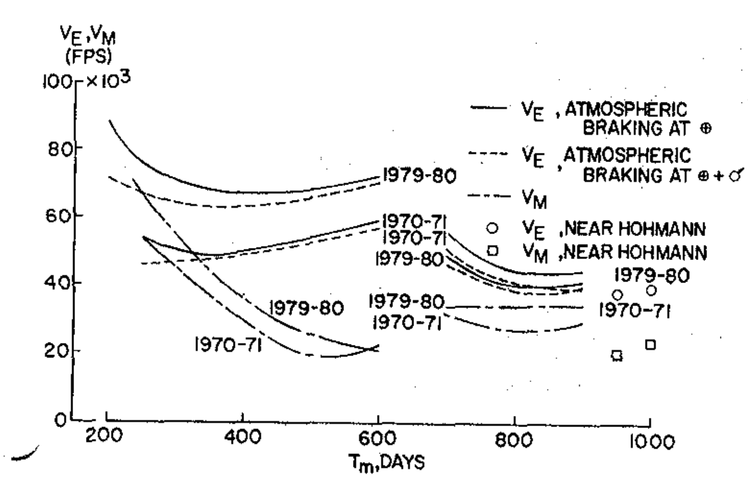

Figure 5.- Earth and Mars arrival velocities for round-trip missions with a 40-day wait time at Mars.

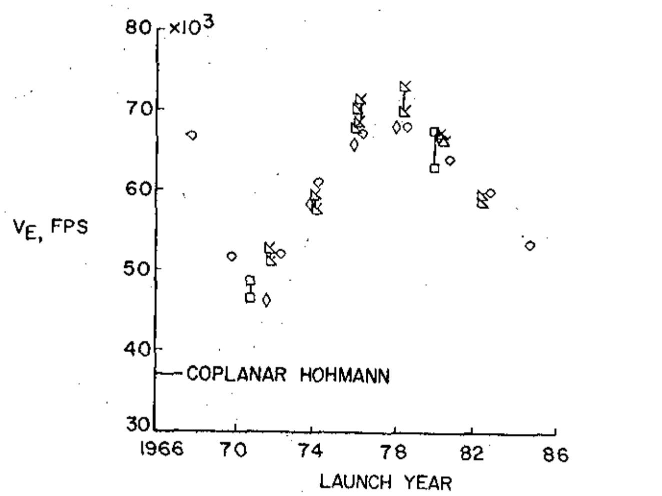

Figure 6.- Launch year effects on Earth entry velocity for the short trip Mars mission.

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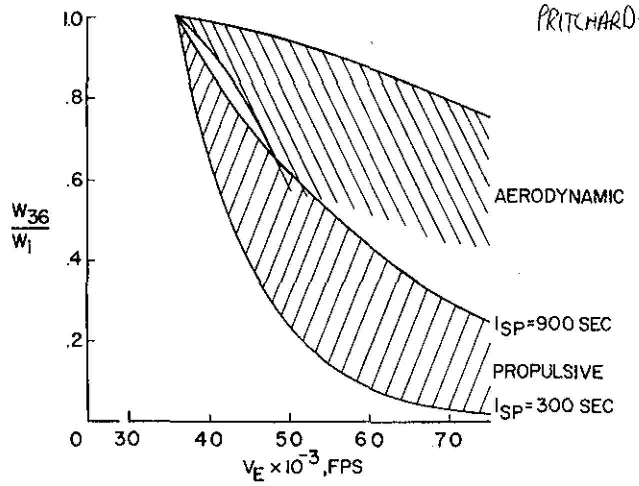

Figure 7.- Comparison of weight requirements for atmospheric and propulsive braking on Earth return.

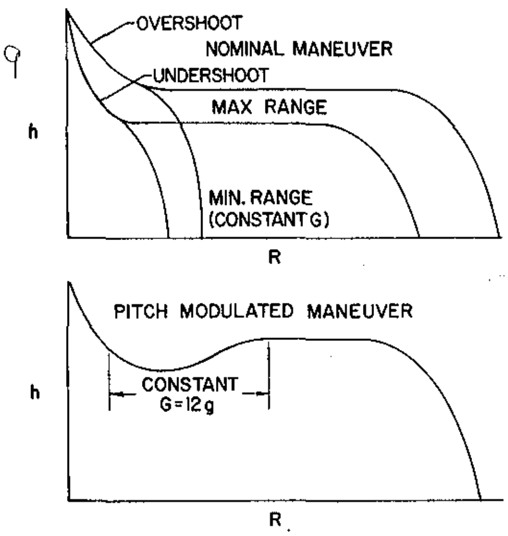

Figure 8.- Reentry flight maneuvers.

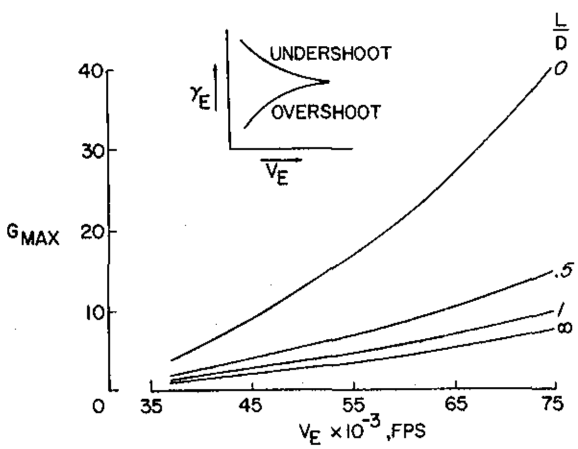

Figure 9.- Maximum deceleration load for overshoot entry.

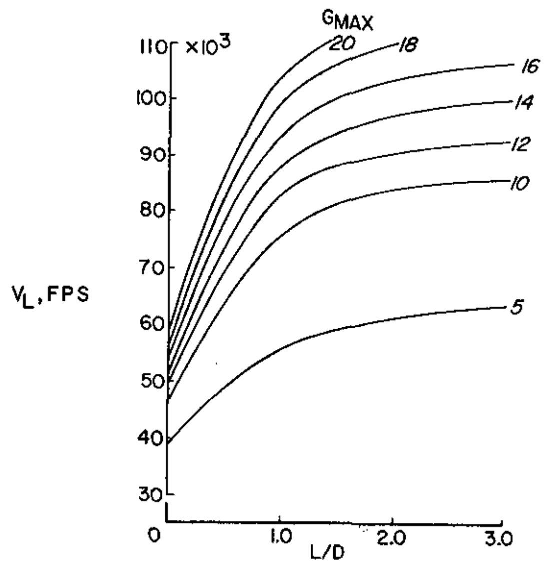

Figure 10.- Limiting entry velocity for roll-controlled vehicles.

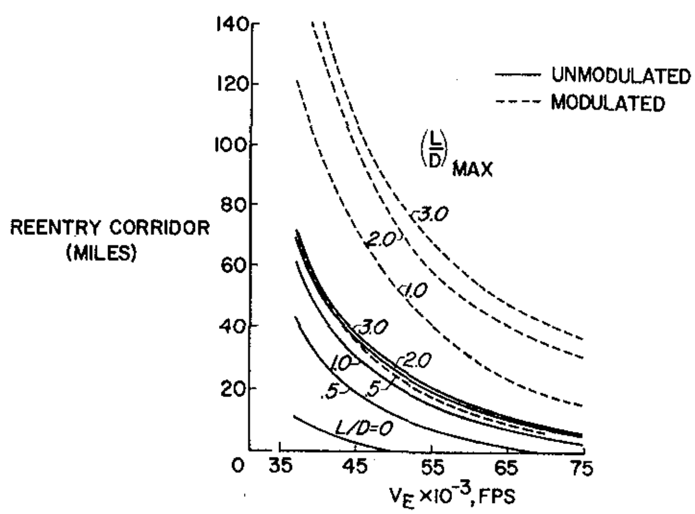

Figure 11.- Reentry corridor width.

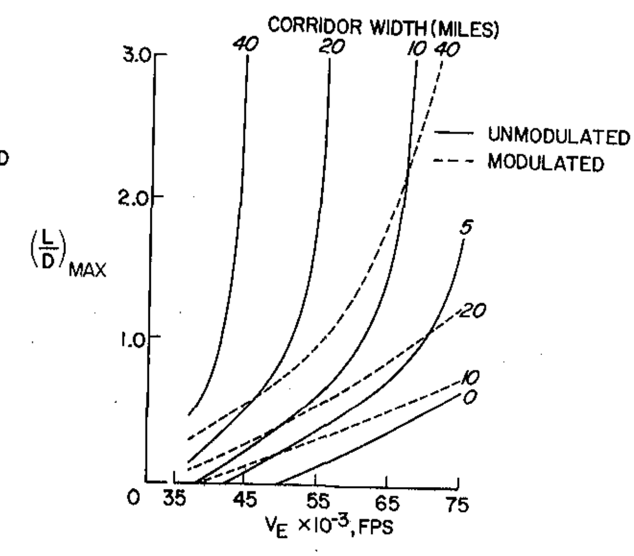

Figure 12.- Lift-drag-ratio requirements as affected by reentry corridor width.

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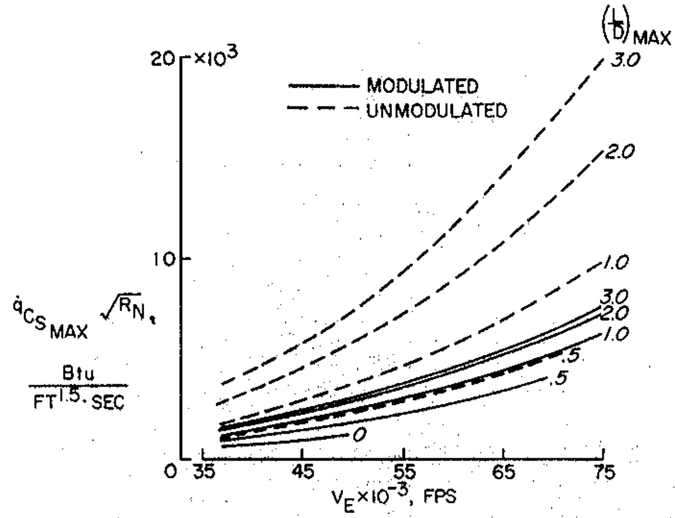

Figure 13.- Maximum stagnation point convective heating rate (undershoot entry).

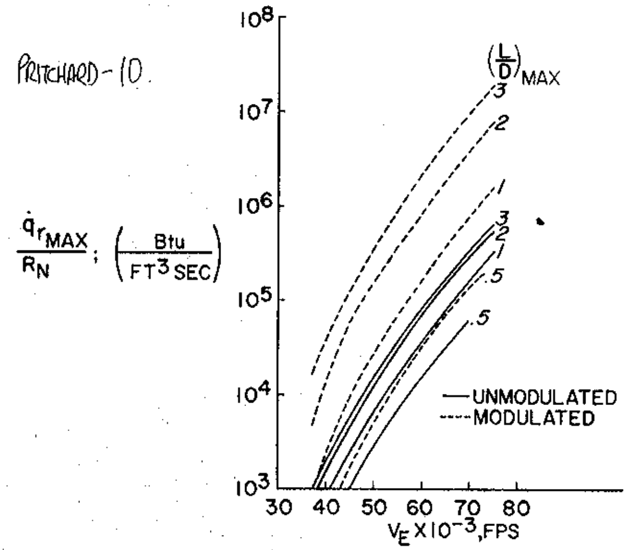

Figure 14.- Maximum stagnation point radiative heating rate (undershoot entry).

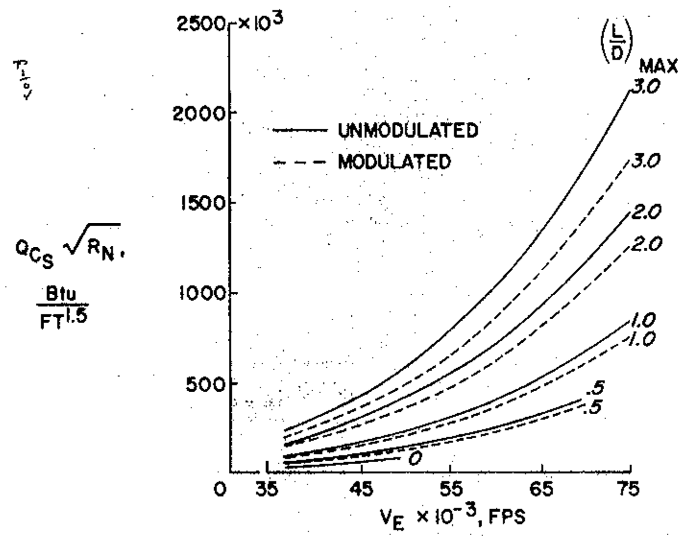

Figure 15.- Convective stagnation point heat load (undershoot entry).

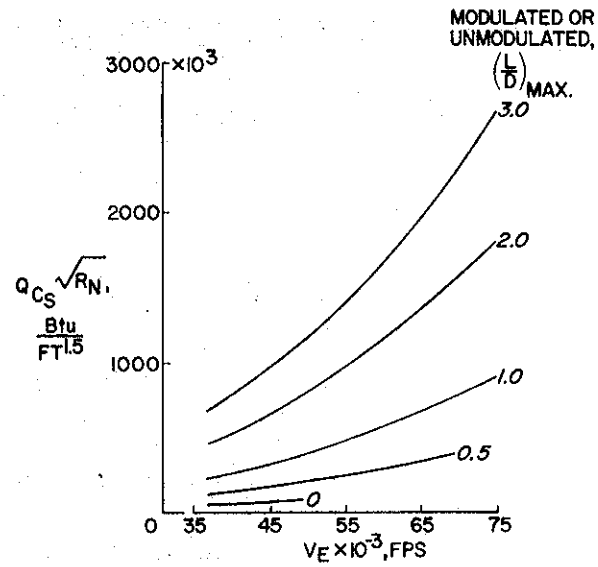

Figure 16.- Convective stagnation point heat load (overshoot entry).

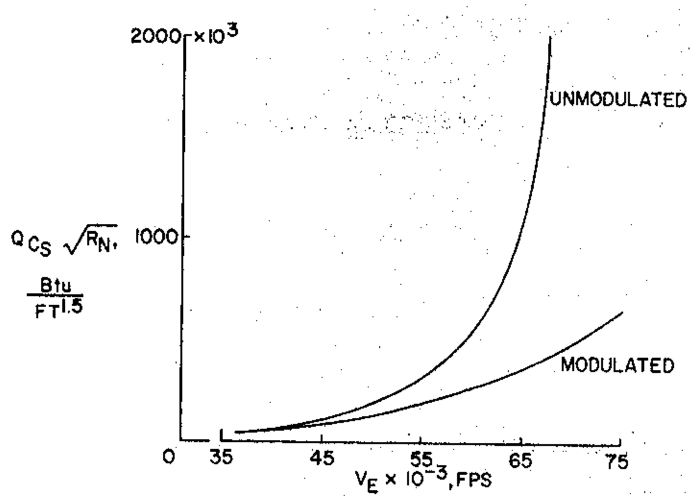

Figure 17.- Convective stagnation point heat load for vehicles with a reentry corridor width capability of 10 miles.

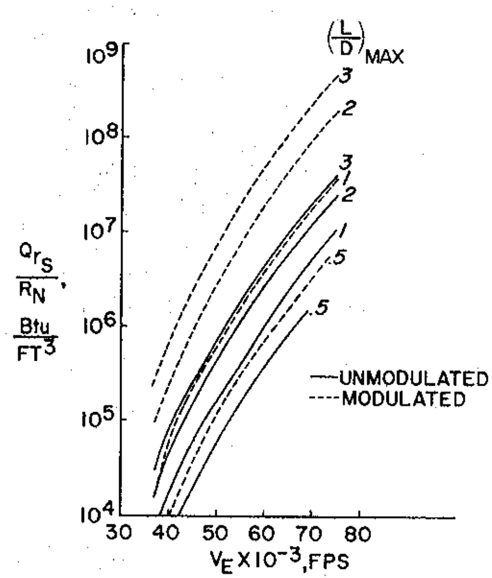

Figure 18.- Radiative stagnation point heat load (undershoot entry).

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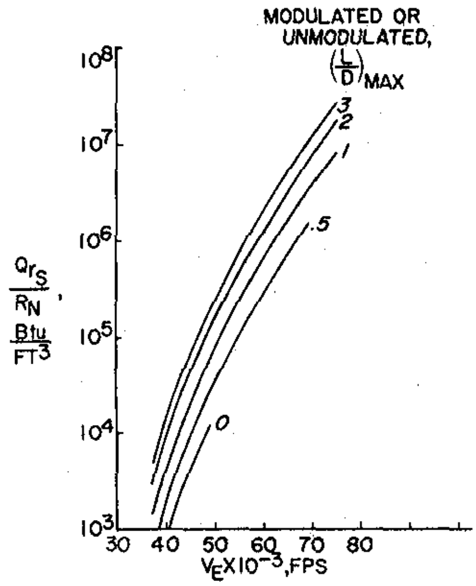

Figure 19.- Radiative stagnation point heat load (overshoot entry).

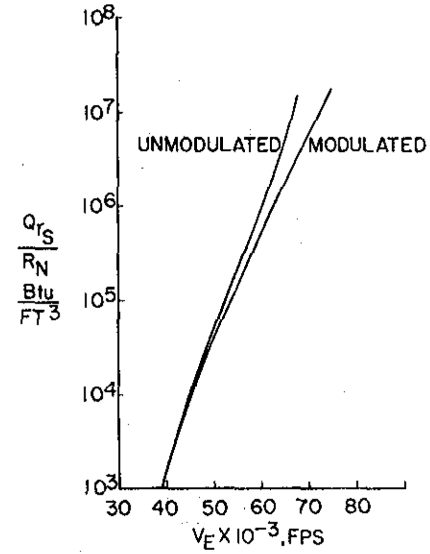

Figure 20.- Radiative stagnation point heat load for vehicles with a reentry corridor width capability of 10 miles.

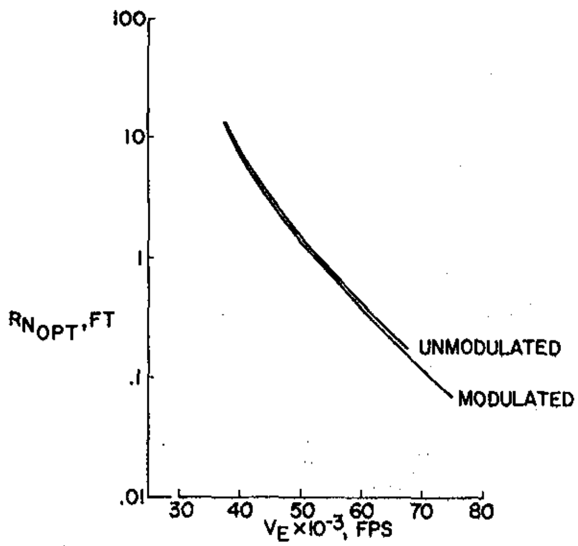

Figure 21.- Optimum vehicle nose radius based on stagnation point heat loads (10-mile corridor).

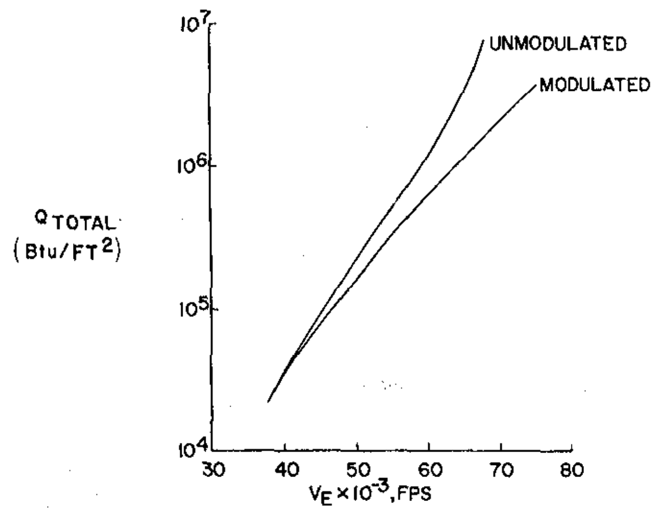

Figure 22.- Total stagnation point heat load for the optimum nose radius (10-mile corridor).

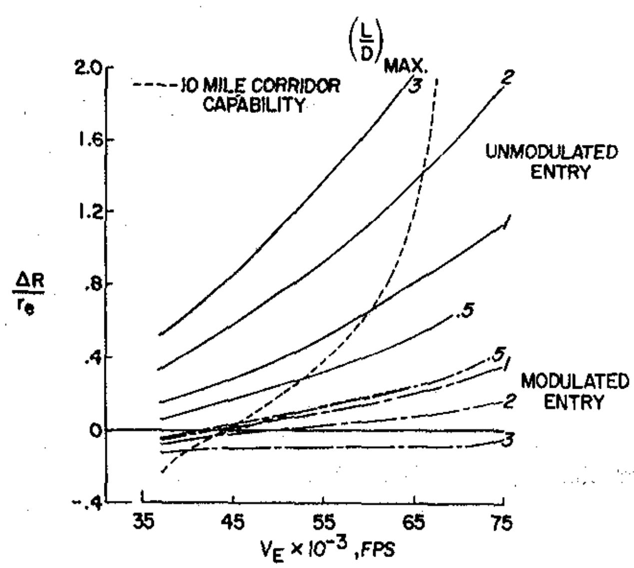

Figure 23.- Longitudinal range overlap.