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Effect of Parking Orbit Period on Aerocapture for Manned Mars Missions

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Aerocapture has previously been identified as a critical technology for manned Mars missions. A wide range of parking orbits is available into which an aerobraking vehicle could be captured, and earlier authors have advocated different target orbits for various reasons. The choice of the parking orbit impacts the amount of energy which must be dissipated during the atmospheric trajectory. The effect of this choice on the entry corridor width, the required vehicle L/D, and the aerothermal environment are explored in this paper.

Nomenclature

A = entry vehicle reference area, m^2
C_D = entry vehicle drag coefficient
D = drag, N
L = lift, N
m = mass, kg
m/C_DA = ballistic coefficient, kg/m^2
R_n = nose radius, m
V_e = velocity at atmospheric interface, km/s

Introduction

DURING the last 30 years, several investigators have shown that the use of aerobraking at Mars on a manned mission could result in substantial savings in the initial weight required in low Earth orbit (LEO).[1,2] For such a mission to be successful, the vehicle must dissipate enough energy in its initial pass through the atmosphere to be captured into a planetocentric orbit without overheating or subjecting the crew and structure to excessive deceleration. To accomplish this, the vehicle's atmospheric entry angle must fall within a fairly narrow range known as the entry corridor. If the angle is too small (less than the overshoot limit), the vehicle will fail to be captured and will continue in a heliocentric orbit; conversely, if the entry angle is too steep (greater than the undershoot limit), the vehicle will either hit the surface, overheat, or subject the crew and structure to excessive deceleration loads (Fig. 1). The location and width of the entry corridor depend on the vehicle's arrival velocity V_e and aerodynamic characteristics (ballistic coefficient m/C_DA and lift-to-drag ratio L/D).

Recent studies of aerocapture at Earth have shown the impact of the period of the selected target orbit (into which the vehicle captures) on corridor width and aerothermodynamics.[3] In addition, it has been recognized that capture to higher altitude, longer period orbits will decrease corridor width at Mars for certain missions.[4,5] Some authors have argued that these high-energy parking orbits are precisely the ones which should be used for Mars aerocapture since they minimize trans-Earth injection delta V.[6] However, more detailed studies have shown that the impact of parking orbit selection on the initial mass required in LEO depends on inclination and other parameters in addition to orbital energy and eccentricity.[7]

Since several parking orbits are currently being considered for manned Mars missions, it is necessary to understand the impact of this factor on the entry corridor width. This is particularly critical since corridor width is the major determinant of the required aerobrake L/D, and thereby the overall vehicle configuration. Although parking orbit selection has been examined extensively from an orbital mechanics point of view,[6,7] the only in-depth investigation of its impact on the atmospheric trajectory has been limited to the relatively low velocity, 6.7 km/s entry selected for the unmanned Mars Rover Sample Return Mission.[5] However, many proposed manned mission architectures differ markedly from this case with respect to the arrival conditions at Mars.[8,9] Launch date and the type of interplanetary trajectory which is flown significantly influence the atmospheric entry velocity. This paper will examine the effect of parking orbit choice over the entire range of probable entry velocities and ballistic coefficients.

Methods

For an aerocapture maneuver to be successful, it must dissipate the proper amount of energy without over stressing the vehicle or the crew. For this study, the trajectory was not allowed to exceed a peak deceleration of 5 g. This limit was based on Soviet experience with re-entry after prolonged spaceflight and is determined by the tolerance of a crew deconditioned by many months of micro-

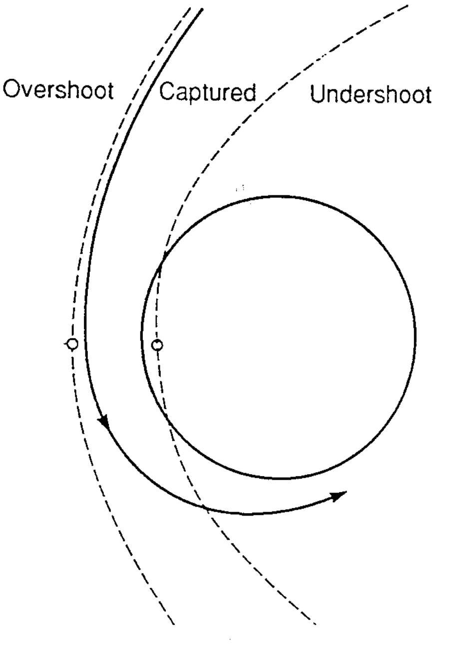

Fig. 1 Aerocapture.

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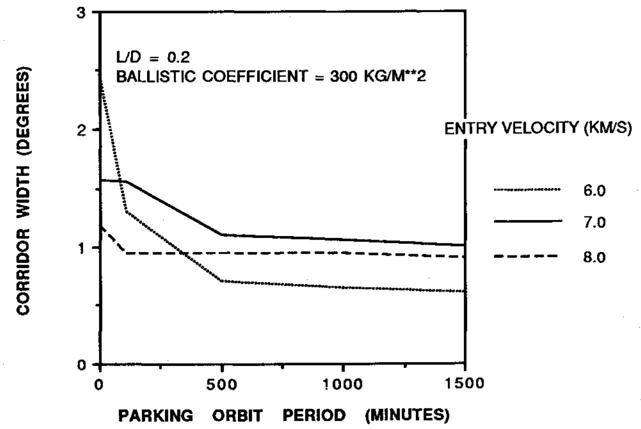

Fig. 2 Corridor width vs parking-orbit period.

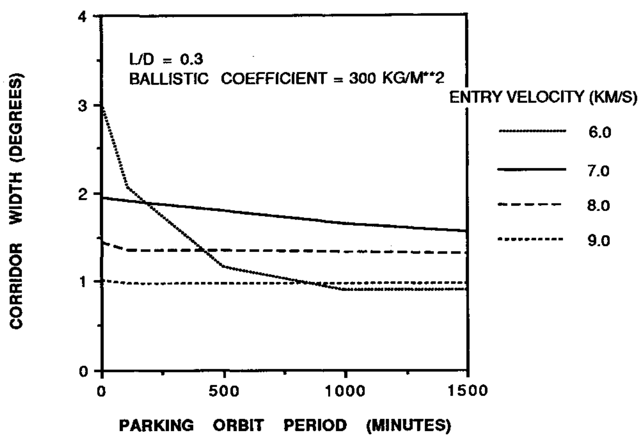

Fig. 3 Corridor width vs parking-orbit period.

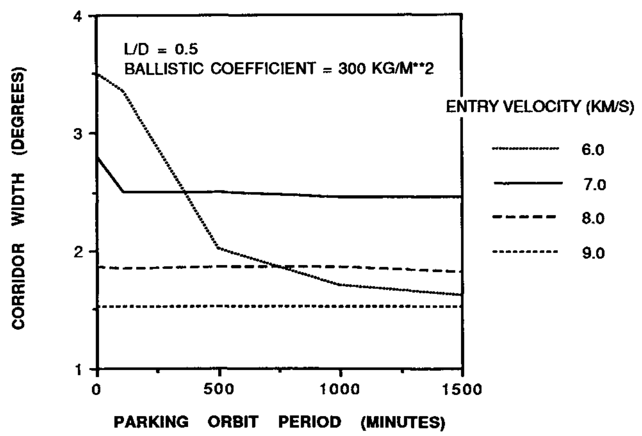

Fig. 4 Corridor width vs parking-orbit period.

gravity. Moreover, the vehicle was not allowed to pass below 30 km at any point in its trajectory (except in the case of direct entry to the surface); this indirectly limits heating and provides a margin of safety to avoid terrain collisions. No direct limit was placed on heating rate or heat load. It is necessary not to limit these factors since, as will be shown later, the heating environment for all cases examined was considerably less severe than that encountered by Apollo entry capsules upon return from the Moon.

In each simulation, the vehicle was captured into an orbit with a period of 110, 500, 1000, or 1500 mins or was allowed to enter directly and land on the planetary surface. The 110-min case is equivalent to a 500-km circular orbit, whereas the 1500-min period corresponds to the 1-sol orbit.

The trajectory simulations were carried out by numerically integrating the system of three first-order, ordinary differential equations which describes the motion of an unpowered vehicle in a nonrotating atmosphere.[10] Two algorithms were used, one of which found the overshoot boundary and one of which found the undershoot boundary. A variable bank-angle guidance scheme was employed to maximize the entry corridor width.[4]

The Martian atmospheric model was based on Viking lander data.[11] The density was fitted with a series of three exponential expressions. Entry was defined to occur at 125 km, and the atmosphere was assumed to be insensible at higher altitudes. This altitude has been used as the entry interface in previous guidance and

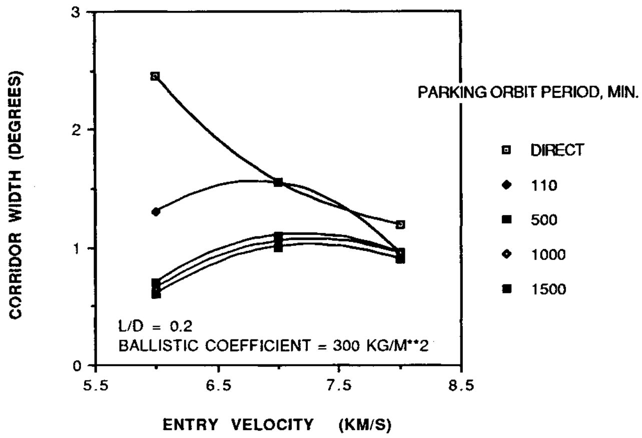

Fig. 5 Corridor width vs entry velocity.

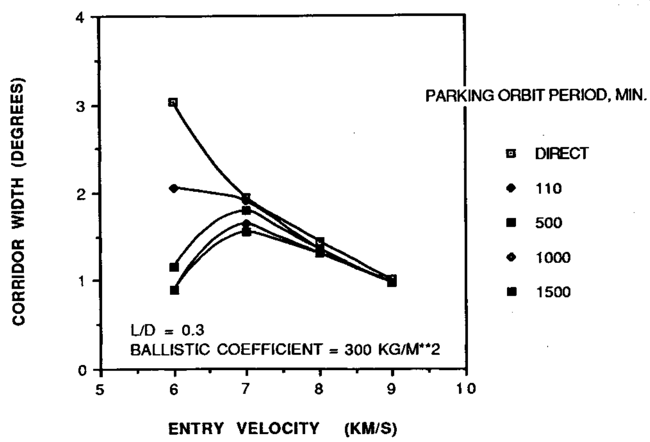

Fig. 6 Corridor width vs entry velocity.

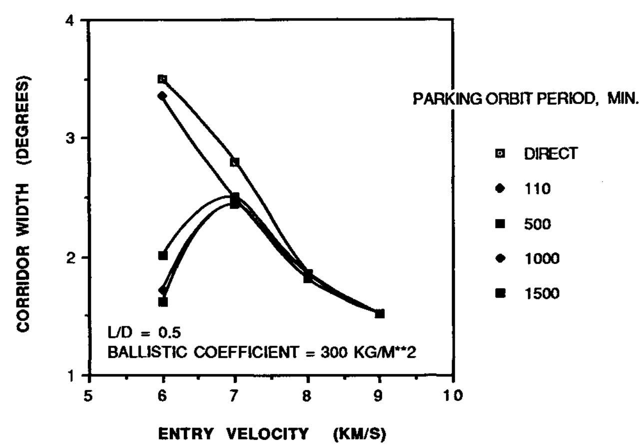

Fig. 7 Corridor width vs entry velocity for various parking orbits.

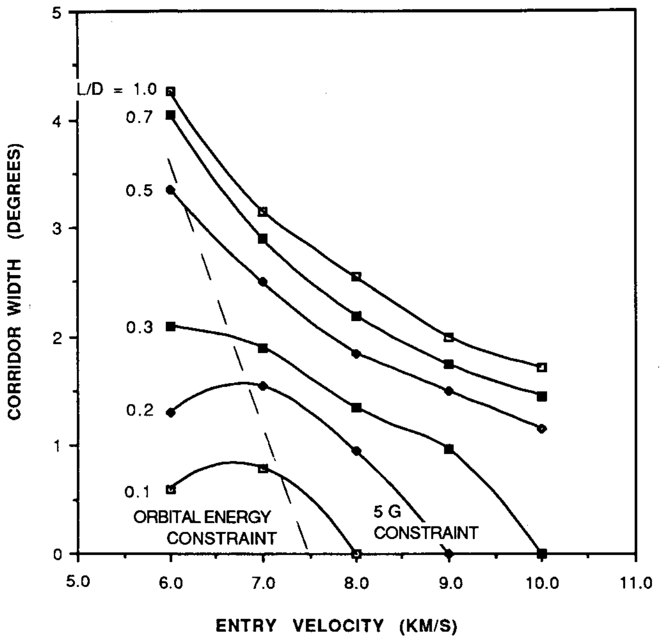

Fig. 8 Corridor width vs entry velocity for vehicles with various *L/D*s.

control studies.[12] The atmosphere was assumed to be nonrotating and was not varied with latitude, longitude, or season.

Stagnation-point heating rate and integrated heat load were calculated as described in Refs. 13 and 14. Both convective and equilibrium radiative processes were considered. As is discussed in Ref. 14, it should be realized that current techniques for calculating radiative heating yield uncertainties on the order of 20%. The wall was assumed to be fully catalytic and "cold" (nonablating and, therefore, not affecting heat transfer via alterations of the boundary layer). All calculations were made using a vehicle nose radius of 16 m and assuming that the inviscid shock layer was in thermochemical equilibrium.

The vehicles' peak *L/D*s were decreased at high altitude to account for increased laminar skin friction relative to wave drag in the high-altitude flight regime (see Ref. 4 for further details).

Results

Figures 2–4 show corridor width as a function of parking orbit period for aerobrakes with *L/D*s of 0.2, 0.3, and 0.5. As can be seen, the effect of parking orbit on corridor width is more pronounced for lower entry velocities. In these instances, the energy requirements of the target orbit constrain the undershoot boundary to shallower angles than would be allowed by the 5-*g* limit. When the vehicle has a higher entry velocity (and thus more initial kinetic energy), the deceleration limit determines the undershoot boundary. In addition, corridor widths of vehicles with low *L/D* are more strongly effected than those of vehicles with greater control authority. For example, the vehicle with an *L/D* of 0.2 shows considerable variation of corridor width with orbital period for an entry velocity of 7 km/s; this effect is almost eliminated when the *L/D* is increased to 0.5. The same data are presented from a different viewpoint in Figs. 5–7. Here corridor width is shown as a function of entry velocity.

Figure 8 shows corridor width as a function of entry velocity for vehicles with *L/D*s ranging from 0.1 to 1.0. Cases to the left of the dashed line have their undershoot boundary limited by the energy requirement of the target orbit (which for this figure is a 500-km circular orbit); for scenarios to the right of the dashed line, the undershoot boundary is constrained by the vehicle's peak deceleration. If it were not for the imposed deceleration limit, corridor width would increase steadily with entry velocity.[1] It is apparent that the entry corridors of vehicles with low *L/D*s are more subject to the impact of target orbit energy requirements than those of vehicles with high *L/D*. For example, for the vehicle with an *L/D* of 1.0, the undershoot boundary is constrained in every case shown by the deceleration limit. Conversely, the vehicle with an *L/D* of 0.1 has its undershoot boundary set by the orbital energy requirements for entries at both 6 and 7 km/s.

Table 1 Undershoot trajectory peak heating rate, W/cm^2

	Entry velocity, m/s			
Orbital period, min	6000	7000	8000	9000
Direct entry	19.0	73.1	182.7	246.0
110	17.4	72.7	173.9	244.6
500	14.4	66.5	173.9	244.6
1000	13.6	64.7	173.9	244.6
1500	13.1	64.1	173.9	244.5

Previous studies have suggested that a vehicle with an *L/D* of 0.3 should be adequate for aerocapture at Mars.[4] However, that work assumed capture to a low Mars orbit. Figure 6 shows that if a 1.0-deg corridor width requirement is assumed (as was done in Ref. 4) and the vehicle captures to a high orbit, an *L/D* of 0.3 is not quite adequate for an entry velocity of 6.0 km/s whereas it becomes sufficient as the vehicle's velocity increases. However, in the great majority of cases, the effect of the parking orbit selection is not great enough to decrease the corridor width below the 1.0-deg requirement previously stipulated for the guidance system. It is also notable that the use of a direct entry trajectory or capture to a low orbit could significantly widen the entry corridor for cases with low approach velocities (6–7 km/s), especially for low *L/D* vehicles.

Stagnation-point peak heating rates for undershoot trajectories are shown in Table 1 for a vehicle with an *L/D* of 0.3 and a ballistic coefficient of 300 kg/m^2. (Undershoot trajectories encounter the highest peak heating rates whereas overshoot trajectories experience the greatest integrated heat loads.) The peak rate varies significantly only for entry velocities of 6 and 7 km/s; for 6 km/s entries, a direct entry results in a peak rate 45% higher than would be experienced during capture to a 1500-min orbit. For a 9-km/s entry, this difference in peak rate is virtually eliminated. A similar trend can be seen in Table 2, which shows integrated heat loads for overshoot trajectories. For the lower velocity entries, heating is benign enough that it may be possible to use a radiatively cooled surface similar to the ceramic tiles of the Space Shuttle. Currently, such surfaces can tolerate up to about 50 W/cm^2. The heating rates presented in Table 1 would be decreased somewhat if a partially catalytic, radiatively cooled ceramic surface were assumed. Therefore, it would be useful to perform a more detailed analysis of the aerothermal environment in this flight regime to determine the requirements of the thermal protection system and the entry velocities for which a radiatively cooled surface may be feasible. In all cases, the peak rate and integrated heat load are well below the levels encountered during Apollo lunar return (500 W/cm^2 and 43 kJ/cm^2, respectively).

Conclusions

From the perspective of entry corridor width, aerocapture to low Mars orbit or direct entry is preferable to capture to a high orbit if the interplanetary vehicle has an approach velocity less than about 7 km/s. Such speeds are typical of the conjunction class transfers which some authors have advocated for manned Mars missions.[15] This implies that for missions of this type (with low atmospheric entry velocities), capture to low Mars orbit or direct entry may permit the use of less-sophisticated interplanetary navigation systems than would be needed if the vehicle were to be captured to a high orbit. However, it should be realized that direct entry may not be feasible because of the possibility of Martian dust storms.

Opposition class missions have frequently been advocated for early manned excursions to Mars. These typically have entry velocities in excess of 7 km/s. The results of this study indicate that, for such missions, the vehicle can be captured to the high, long-period orbits which are generally considered more desirable without incurring penalties in entry corridor width. An extension of the present study to include the effects of atmospheric density fluctuations would be useful.[16]

Acknowledgment

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