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Physiological Constraints on Deceleration During the Aerocapture of Manned Vehicles

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The technique of atmospheric braking for manned interplanetary missions is described and the deceleration limits that must be imposed on the maneuver because of the physiological deconditioning of the crew are explored. Application of an appropriate deceleration constraint is important since it significantly impacts mission architecture and aerobrake design. Approximate re-entry deceleration pulses following long-duration Soviet flights are presented and compared with aerobraking deceleration profiles at Earth and Mars. For sprint class missions, Soviet data strongly support the use of a 5-*G* constraint but emphasize the need for an adequate in-flight exercise program to maintain deceleration tolerance. For long-duration missions (2.5–3 yr), a 5-*G* limit can be applied to the aerocapture at Mars, but further research is needed to determine an appropriate limit for the Earth return case.

Nomenclature

A = vehicle reference area, m^2
C_D = entry vehicle drag coefficient
C_L = entry vehicle lift coefficient
D = drag, N
G = gravitational acceleration at the Earth's surface
L = lift, N
m = mass, kg
α = angle of attack, deg

Introduction

MANNED voyages to Mars have been extensively studied over the last 30 years.[1–3] It is widely recognized that one of the most significant factors in determining the cost of such a mission is the initial weight that must be launched into low-earth orbit (LEO). To reduce this weight, numerous investigators have examined the use of atmospheric drag rather than propulsion to decelerate the spacecraft upon its arrival at Mars and Earth. This technique, known as aerobraking, has been found to decrease the initial weight required in LEO by 20–60% (Ref. 4). However, unlike propulsive deceleration, aerobraking inherently requires the spacecraft to decelerate over a brief period, typically lasting a few minutes; to protect the crew and avoid overloading the structure, the G load experienced during the aerocapture must be limited. This is particularly important because of the physiologically deconditioned state of the crew brought about by many months of weightlessness.

In discussing G limitations, one must consider the various directions of acceleration with respect to the human body since tolerance in the $+G_x$ direction is significantly higher than in other directions (see Fig. 1). In this paper all decelerations are assumed to be along the x axis. This is a reasonable assumption since spacecraft that employ roll control do not produce a change in the *orientation* of the deceleration vector with respect to the vehicle during the trajectory. This is true because the aerodynamic coefficients C_L and C_D do not change with bank angle, although the direction of the lift force does change. (The orientation of the force vector with respect to the vehicle does change if pitch control is used since C_L and C_D are not constant; however, pitch control is generally considered impractical for vehicles that are subjected to extreme heating since it requires either flaps to change the trim angle of attack or the expenditure of large quantities of propellant to vary the trim angle from its natural value.) Thus, proper orientation of the seats in the vehicle can result in deceleration forces along the desired body axis.

To successfully perform an aerobraking maneuver, the spacecraft must enter the atmosphere at a flight-path angle that falls within a fairly narrow range known as the entry corridor. If the entry is too shallow, the vehicle will fail to dissipate enough energy and will exit the atmosphere at too high a velocity and continue in a heliocentric orbit; conversely, if the entry angle is too steep, the vehicle will either hit the planet's surface or violate the deceleration limit (Fig. 2). The width of the entry corridor is determined by the vehicle's arrival velocity and aerodynamic characteristics (namely, the ballistic coefficient m/C_DA and lift-to-drag ratio L/D) in conjunction with the specified deceleration limit. The entry corridor must be wide enough to allow for inaccuracies in the interplanetary navigation system as well as uncertainties about the state of the planetary atmosphere at the precise time of entry. For a given arrival velocity, a more stringent deceleration limit will require greater control authority (a higher lift-to-drag ratio) to provide the needed entry corridor width. Thus, the level specified for the deceleration limit influences the aerobrake design (and thereby L/D) and the range of allowable atmospheric entry velocities. This point is illustrated in Fig. 3, which shows the required aerobrake

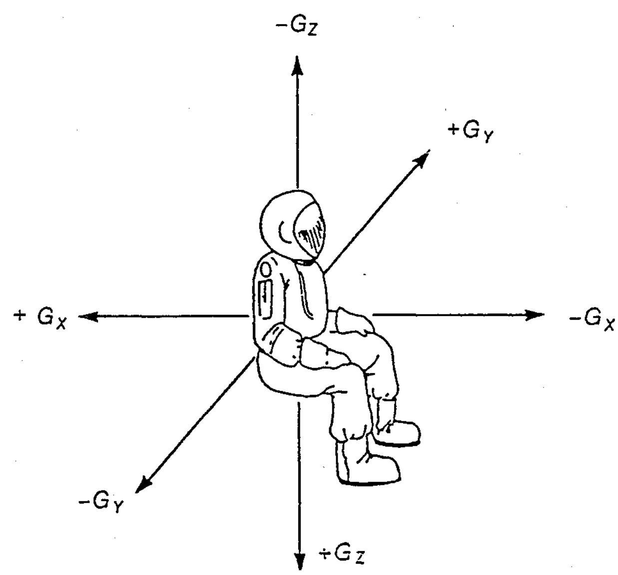

Fig. 1 ***G*-load nomenclature.**

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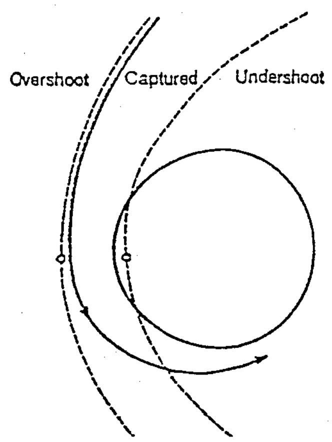

Fig. 2 Entry corridor.

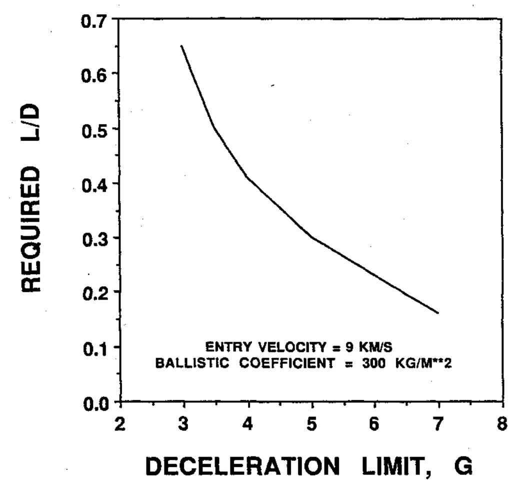

Fig. 3 Required Mars aerobrake L/D vs deceleration limit.

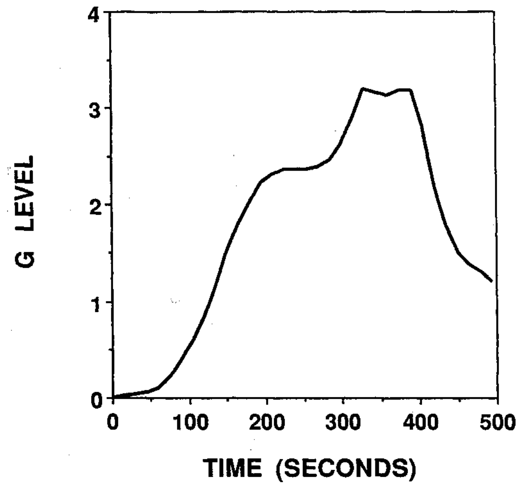

Fig. 4 Apollo capsule Earth orbital return profile (Ref. 11).

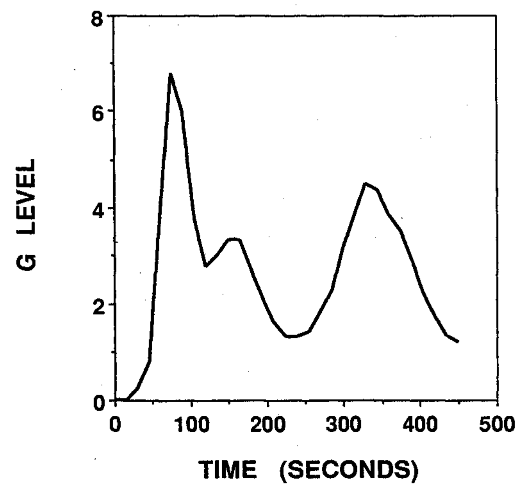

Fig. 5 Apollo capsule lunar return re-entry profile (Ref. 11).

L/D as a function of the deceleration limit for aerocapture at Mars assuming a 1-deg corridor width requirement. The required corridor width will depend on the accuracy of the interplanetary navigation system and the degree of knowledge of the Martian atmosphere. Although uncertainties about future technology make it difficult to predict the required corridor width precisely, several authors have adopted a 1-deg limit.[4,5] This has largely been based on analysis that was done for the Mars Rover Sample Return mission and assumes the use of optical sitings of the Martian moons to improve the interplanetary navigational accuracy.[6,7] The 1-deg corridor width is designed to allow for interplanetary navigational errors in addition to unexpected atmospheric density perturbations. A guidance algorithm using a predictor-corrector scheme that successfully handles such atmospheric perturbations has recently been described.[8] Nevertheless, whatever the required corridor width eventually proves to be, the general trend illustrated in Fig. 3 will remain applicable. This figure was developed for a fairly high velocity, 9 km/s atmospheric entry. The required lift-to-drag ratios range from 0.65 to 0.17 and decrease as the imposed deceleration limit increases. Lift-to-drag ratios in this range are definitely achievable by hypersonic entry vehicles. However, to appreciate the significance of this figure, one must realize that vehicle packaging and weight distribution become more difficult as L/D increases.[2,9] Moreover, the ballistic coefficient and thereby the peak heating rate tend to increase with L/D.[3] Thus, the selected deceleration limit has a very important impact on mission design and practicality. In recent studies, various authors have considered deceleration constraints ranging from 4 to 10 G (Refs. 4–11). Since this limit is critical to mission design, it is necessary to specify its appropriate value more precisely.

Relevant Spaceflight Experience

To date, American experience with extended-duration spaceflight has been limited to the Skylab flights of 28, 59, and 84 days. In each case, lifting re-entry was accomplished in an Apollo-type capsule and resulted in a deceleration pulse similar to that shown in Fig. 4 (Ref. 12). (For comparison, a typical Apollo lunar return G profile is shown in Fig. 5.) Although the Skylab re-entries were somewhat more benign than those typically expected for aerocapture maneuvers, Soviet cosmonauts have experienced re-entries with peak decelerations between five and six G after 8 months in orbit (Refs. 13 and 14). Those entries occurred at the end of the Soyuz T-10B and Soyuz TM-6 missions. During these extended flights, the cosmonauts exercised strenuously approximately 2 h a day to maintain their physical conditioning.[15] Figure 6 shows a calculated approximation of the deceleration profile during the entry of these Soyuz capsules. The figure also shows the maximum and minimum calculated deceleration pulses for aerocapture at Mars (corresponding to the undershoot and overshoot cases, respectively; see Fig. 2) for a high-velocity, 9 km/s atmospheric entry. Figure 7 shows the Soyuz deceleration with the corresponding Earth aerocapture pulses for a 14-km/s entry (for more details see Refs. 16 and 17). The approach velocities chosen for this comparison are near the maximum values that are being considered; as a result, these aerocapture deceleration pulses are more severe than they would be for the majority of probable mission scenarios. Nevertheless, both the peak G loads and the durations of the G pulses are more benign for the aerocapture maneuvers than for the Soyuz re-entry. For example, the time of exposure to 3 G or more is

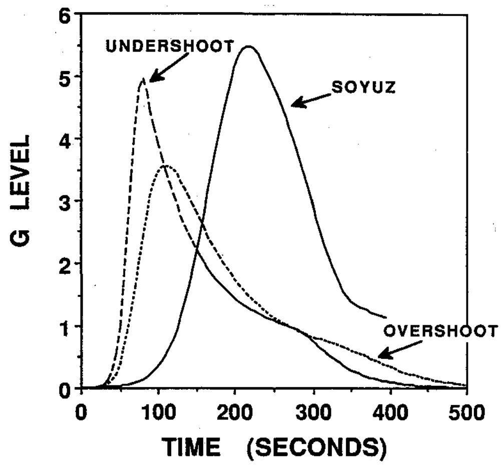

Fig. 6 Mars aerocapture compared with Soyuz re-entry.

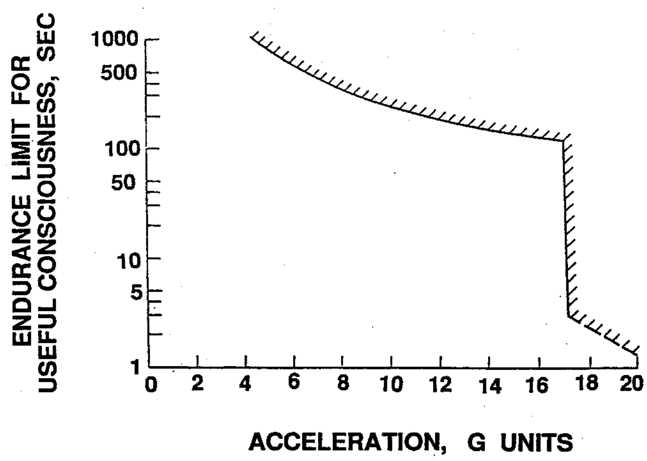

Fig. 8 Human endurance limits for G_x acceleration (Ref. 18).

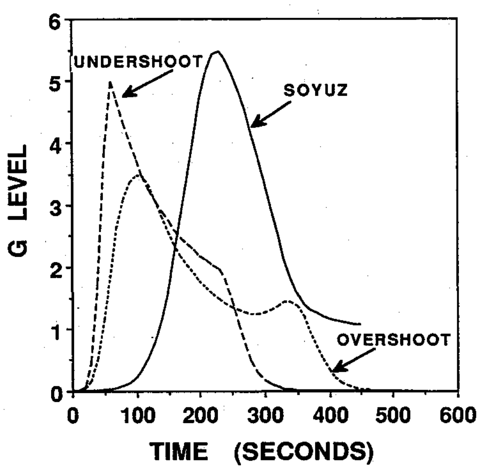

Fig. 7 Earth aerocapture compared with Soyuz re-entry.

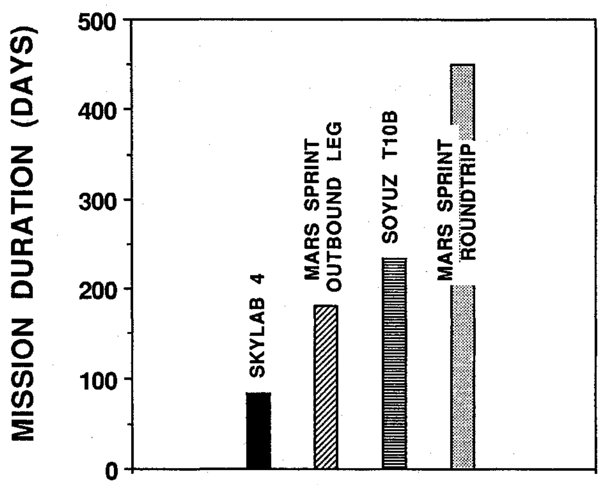

Fig. 9 Mission durations.

approximately 130 s for the Soyuz trajectory but only 55–85 s for the aerocaptures. The peak G load that can be tolerated is, of course, inversely related to the duration of exposure[18,19]; this trend is illustrated in Fig. 8 (Ref. 20). This figure was developed using data for healthy men wearing G suits and thus is not directly applicable to astronauts who have been deconditioned by prolonged exposure to weightlessness.

For peak G loads that can normally be tolerated without loss of consciousness or visual degradation, extremely rapid G onset rates (several G per second) decrease tolerance since the cardiovascular system does not have adequate time to initiate the appropriate pressor reflexes. However, for all aerocapture trajectories, G onset rates are modest (less than 0.5 G per second) and provide sufficient time for baroreceptor mediated responses to the increased inertial field.

From the foregoing, it is apparent that aerobraking maneuvers can be accomplished without deceleration pulses more severe than those encountered previously upon return from extended spaceflights. Of course, it could be argued that the duration of a manned Mars voyage will be greater than the 8-month missions discussed earlier and thereby will lead to a lower deceleration tolerance. Figure 9 illustrates the durations of the Soviet and American missions described earlier and compares these with a sprint mission to Mars. (A sprint mission is probably the most appropriate strategy for an initial excursion.[3,4,21] It allows a surface stay of 30–60 days and provides an opportunity to validate the performance of the interplanetary transfer apparatus before committing a crew to a voyage of several years.) There is strong evidence that the longer duration would *not* lead to further degradation in deceleration tolerance if adequate countermeasures are employed. Various studies have shown that the cardiovascular system (which has the most relevance for deceleration tolerance) adapts to zero gravity in 1–3 months.[22,23] Thus, one can reasonably infer that deceleration tolerance would not degrade further after this period. This is supported by Soviet ground-based and flight studies from the last 20 years. Kotovskaya et al.[24,25] found that G_x (chest-to-back) tolerance deteriorated over the first 15–30 days of bed rest but stabilized after that with no further significant degradation after 60 days. (Bed rest is frequently used by life scientists to simulate the physiological changes induced by zero gravity.) Reference 23 summarizes the Soviet experience with re-entry deceleration tolerance after flights of 8–326 days. It is noted that if the cosmonauts adhered to a strict exercise regime and wore anti-G suits during the re-entry, deceleration tolerance did not further deteriorate after the first month in space. It is critical to realize the importance of the exercise program in maintaining this tolerance; Kotovskaya et al.[23] compared the cardiopulmonary responses to re-entry of three groups: 1) cosmonauts on short-duration missions (less than 2 weeks), 2) cosmonauts on 2–8 month missions who employed inadequate exercise programs or did not wear anti-G suits upon re-entry, and 3) cosmonauts on long-duration missions (2–11 months) who adhered to adequate exercise regimes and wore anti-G suits upon re-entry. The use of appropriate countermeasures essentially stopped the degradation of G tolerance after 1 month, whereas failure to employ these methods resulted in continued deterioration. (Similarly, American studies have shown postflight exercise tolerance to be dependent on the in-flight exercise program rather than mission duration.[22]) Moreover, in comparing Mars missions to the long-duration Soviet flights, it should be remembered that the Mars crew would have the benefit of exposure to 3/8 G for approximately 1 month (for a sprint mission) about halfway through their voyage. This should provide some opportunity for reversing the physiological deconditioning processes.

Conclusions

Although American spaceflight experience has not subjected astronauts to periods of weightlessness comparable to those expected for Mars voyages, Soviet flight durations have approached the length of Mars sprint missions. Moreover, Soyuz re-entries have subjected their crews to peak decelerations of 5–6 *G* following 8 months in orbit. Physiological data suggest that if adequate countermeasures are employed, deceleration tolerance should not deteriorate further after 1–3 months in zero gravity. Therefore, at least for sprint class missions, it is reasonable to use the Soviet experience to set a 5-*G* maximum for deceleration during aerobraking maneuvers. For very long duration missions (2.5–3 yr) a 5-*G* constraint may be applied to the Mars arrival, but further research is needed to determine an appropriate limit for the Earth-return aerocapture. Recent analyses have shown that aerobrakes with low-to-moderate *L/D* can provide adequate entry corridors both at Mars and Earth while constrained not to exceed 5-*G* peak loads.

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