Aerodynamic Requirements of a Manned Mars Aerobraking Transfer Vehicle

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In this investigation, entry corridor analyses are performed to identify the aerodynamic requirements of a manned Mars aerobraking transfer vehicle. The major emphasis is on identifying the required aerobrake hypersonic lift-to-drag ratio (L/D) to insure a successful aerocapture. Aerobraking entry requirements are also imposed on a set of interplanetary mission opportunities to demonstrate their effect on mission flexibility. The entry corridor analyses are performed with the use of an adaptive atmospheric guidance algorithm that utilizes bank-angle modulation to relieve the high deceleration loads characteristic of interplanetary aerocapture and maximize the width of the flyable entry corridor. Based on the requirements of a 1-deg corridor width, deceleration into a parking orbit with an apoapsis altitude of 33,640 km, and a 5-g deceleration limit, this analysis has shown that a manned Mars aerobrake characterized by an L/D of at least 1.5 is required for entry velocities as high as 10.0 km/s. If Mars entry is limited to velocities below 8.5 km/s, a minimum L/D of 0.5 is required; over a very limited entry velocity range, an aerobrake with L/D of 0.3 is feasible. Limiting the Mars entry velocity to values below 8.5 km/s is shown to induce a minor restriction on mission flexibility while alleviating aerothermodynamic and vehicle packaging concerns; hence, Mars entry velocities in the range of 6.0–8.5 km/s are suggested, and a manned Mars aerobrake characterized by an L/D between 0.3 and 0.5 is recommended.

Nomenclature

e	= Mars parking orbit eccentricity
h_p	= Mars parking orbit periapsis altitude, km
L/D	= lift-to-drag ratio
V_{atm}	= inertial velocity at the atmospheric entry interface, km/s
α	= angle of attack, deg
γ_{atm}	= inertial flight-path angle at the atmospheric entry interface, deg
$\Delta\gamma$	= flyable corridor width, deg
atm	= atmospheric entry interface, 3000-km altitude

Introduction

Background and Objective

WITH renewed interest in manned lunar and planetary exploration, NASA is presently analyzing the aspects of an initial manned mission to Mars in the 2015–2020 time frame. For the early stages of manned exploration, a chemical propulsion system is generally considered to be the leading transportation candidate, and mission feasibility hinges upon minimizing the initial vehicle mass in low Earth orbit (LEO). Because a majority of the initial vehicle mass is propellant, an effective means of decreasing the LEO mass requirements is to reduce the vehicle's propellant needs. One means of accomplishing this is by employing aerobraking to decelerate the spacecraft upon Mars arrival and Earth return. In comparison with an all-propulsive, chemically propelled mission, aerobraking upon Mars arrival and Earth return yields an initial LEO mass savings of 20–60%.[1]

Aerobraking is defined as the deceleration resulting from the effects of atmospheric drag upon a vehicle. For an interplanetary mission in which aerobraking is included in the flight plan, an entry corridor analysis is required to insure that precisely enough energy is lost such that the vehicle transitions from its hyperbolic entry path to the desired parking orbit about the target planet. Hence, in an aerobraking scenario, aerodynamic issues must be considered in the interplanetary vehicle design.

In this investigation, entry corridor analyses are performed to identify the aerodynamic requirements of a manned Mars aerobraking transfer vehicle. The major emphasis is on identifying the amount of lift-induced control (hence, hypersonic L/D) the vehicle must be able to exert during its atmospheric flight to insure a successful aerocapture. Because a vehicle's aerodynamic requirements dictate its shape, the entry analyses are used to identify a general class of aerobrake configuration that is applicable to a manned Mars transportation system. In this study, the entry corridor analyses are performed with the use of an adaptive atmospheric guidance algorithm that utilizes bank-angle modulation. In this manner, the high deceleration levels characteristic of interplanetary aerocapture are diminished, and the width of the flyable entry corridor is maximized. Finally, the aerobraking entry requirements are imposed on a set of interplanetary mission opportunities to demonstrate their effect on mission flexibility.

Entry Corridor Definition and Requirements

Interplanetary transfer analyses have shown that a wide range of aerobraking mission possibilities exists with Mars entry velocities in the range of 6–10 km/s.[2] For a particular entry velocity, a lifting vehicle may follow one of numerous potential atmospheric trajectories while still achieving the desired atmospheric exit conditions; the difference in each of these transfers is the orientation of the vehicle's lift vector. If too steep an atmospheric pass is flown, the vehicle dissipates more energy than required for the parking orbit. On the other hand, by flying too shallow through the atmosphere, the vehicle will exit with more energy than the parking orbit requires. These two bounding conditions lead to the definition of an aerodynamic entry corridor as the set of all lift-modulated trajectories that yield the proper orbital conditions upon atmospheric exit. This corrido- is depicted in terms of altitude and velocity in Fig. 1. Note that, in this analysis, atmospheric exit into an orbit with an apoapsis altitude of 33,640 km was

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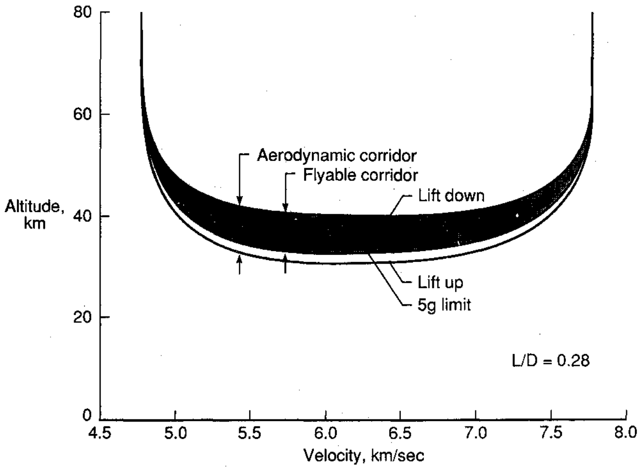

Fig. 1 Physical description of an entry corridor.

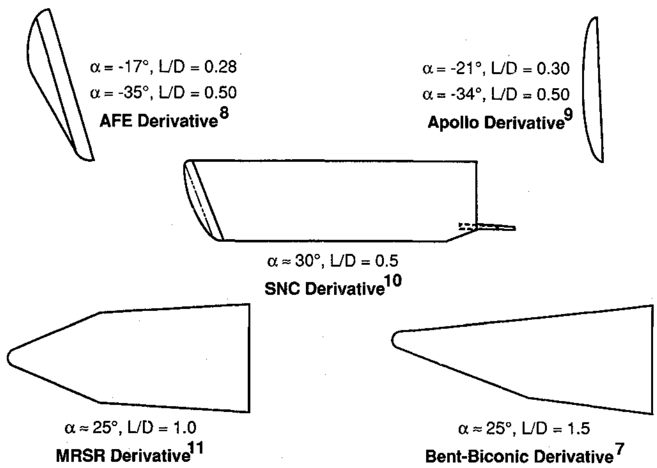

Fig. 2 Preliminary aerobrake vehicle concepts and *L/D* values.

required. At apoapsis, the parking orbit periapsis is propulsively raised out of the atmosphere to 500-km altitude such that a parking orbit with a period of one Martian day or 24.6 h (1 Sol) is achieved.

The aerodynamic corridor's upper bound, which is achieved by flying the vehicle in a lift-down attitude, is the shallowest trajectory that the vehicle is able to fly while still achieving the proper energy decrement. In this manner, the vehicle stays in the atmosphere as long as possible, decelerating at nearly constant altitude. Hence, the required energy loss, deceleration, and heat transfer are spread out over time. The lower corridor bound, which is attained by flying the vehicle in a lift-up attitude, is the steepest trajectory that still obtains the proper atmospheric exit conditions. By following this atmospheric flight path, the vehicle passes in and out of the atmosphere in the shortest amount of time. Because this trajectory must lose the same amount of energy as the lift-down transfer but in a shorter period of time, it is characterized by a higher maximum deceleration and heat rate.

Because of the large energy loss requirements associated with interplanetary transfer, the encountered deceleration and heat rate can be quite large. Therefore, in this investigation, a deceleration limit of 49.0 m/s^2 (5 times the acceleration of gravity at Earth, or 5 *g*) was imposed as an additional constraint for physiological reasons. At high entry velocities, this deceleration limit yields a smaller flyable corridor that is bound by the lift-down transfer and the 5-*g* limiting transfer (Fig. 1). In this analysis, an aerothermodynamic restriction was not included; however, this would also limit the flyable corridor.

In an aerobraking analysis, one figure of merit is corridor width. This parameter is a measure of the amount of aerodynamically induced control the vehicle may exert over its atmospheric flight path. Corridor width may be specified in a number of ways including 1) the range in inertial flight-path angle at the atmospheric entry interface, 2) the range in vacuum periapsis at the atmospheric interface, or 3) the range in actual periapsis altitude. In this analysis, corridor width is specified by the range in inertial flight-path angle at the atmospheric entry interface (300-km altitude). To insure mission success, the width of the flyable entry corridor must be large enough to compensate for the uncertainties associated with the flight. In the case of manned Mars aerocapture, these mission uncertainties include initial state errors due to limitations of the interplanetary navigation system, as well as potential deviations in the atmospheric flight resulting from Mars atmospheric uncertainties, mispredicted aerodynamics, and midcourse correction errors. In this analysis, these mission uncertainties are assumed to impose a ±0.5-deg corridor width requirement. This assumption dictates a flyable corridor width requirement of 1.0 deg to insure a successful aerobraking maneuver.

As discussed in Ref. 1, this 1.0-deg flyable corridor width requirement is utilized to account for limitations in the interplanetary navigation system as well as atmospheric and aerodynamic mispredictions. Approximately 0.5 deg of this 1.0-deg requirement is included to account for interplanetary navigation errors; whereas, the remaining 0.5 deg accounts for aerodynamic and atmospheric misprediction errors. The navigation estimate is based on the use of an onboard navigation system that utilizes optical sighting of the Martian moon Deimos until just prior to entry.[3] However, in a recent study, Konopliv and Wood[4] demonstrate that the interplanetary navigation error may be reduced even further with the use of optical sightings of a Mars orbiter. Additionally, as our knowledge of the Martian atmosphere increases through the evaluation of data obtained in unmanned precursor missions [e.g., the Mars Rover Sample Return (MRSR) mission], this corridor width requirement may decrease further. Hence, the 1-deg corridor width requirement used in this analysis may prove to be a conservative estimate depending on the Mars infrastructure at the time of the mission. If this estimate is indeed conservative, then the *L/D* requirements put forth in this document are too high and lower *L/D* aerobrake configurations would be feasible. A more detailed discussion pertaining to Mars aerobrake *L/D* requirements for a range of flyable corridor widths is presented in Ref. 5.

Preliminary Vehicle Concepts

In many recent studies that include high-energy aerobraking at Earth and Mars, low *L/D* configurations similar to the Apollo or Aeroassist Flight Experiment (AFE) shape have been analyzed.[6] However, as demonstrated in Ref. 1, at moderate angles of attack, this type of configurtion is not generally able to yield the required 1.0-deg corridor width at Mars. One way to alleviate this problem is to increase the vehicle *L/D*. Unfortunately, higher *L/D* vehicles are generally more difficult to package and are generally characterized by a higher ballistic coefficient.[7] As discussed in Ref. 6, minimizing the ballistic coefficient (hence, minimizing *L/D*) is desirable from an aerothermodynamic standpoint. Therefore, in this investigation, the approach is to identify the minimum required *L/D* configuration that adheres to the 1.0-deg corridor width requirement.

The optimal aerobrake shape depends on numerous synergistic issues including aerodynamic performance, aerothermodynamics, vehicle packaging, deceleration loading, and the required energy decrement. A few candidate shapes include 1) an AFE derivative,[8] 2) an Apollo derivative,[9] 3) a slant-nosed cylinder concept,[10] 4) a derivative of the MRSR shape,[11] and

5) a bent-biconic shape.[7] Each of these configurations is illustrated in Fig. 2 along with the achievable hypersonic L/D at specified angles of attack. Note that the hypersonic L/D varies from 0.28 to 1.5. Although other studies[12] have suggested Mars aerobraking concepts that achieve significantly higher L/D values (on the order of 2.0–3.0), the approach in this analysis is to identify minimum L/D candidate concepts for Mars aerocapture.

Computational Methods

The Mars entry corridor analysis was performed with the three-degree-of-freedom version of the Program to Optimize Simulated Trajectories (POST).[13] Within POST, the equations of motion are numerically integrated, and the targeting and optimization procedure uses numerically obtained partial derivatives. A predictor-corrector atmospheric guidance algorithm was utilized in this analysis by including a three-degree-of-freedom simulation as an inner loop to the main simulation.[14] Conceptually, this alogrithm determines the path required to direct the vehicle from its current position to the proper exit condition in the presence of off-nominal events. The algorithm is called by an outer-loop guidance routine at specified intervals throughout the atmospheric passage. With use of this guidance algorithm, the flyable entry corridor is expanded by predicting and reducing deceleration levels greater than 5 g through bank-angle modulation. Although several additional techniques exist to guide an atmospheric trajectory, including angle-of-attack modulation and synergistic thrusting, bank-angle modulation was the only control simulated in this analysis.

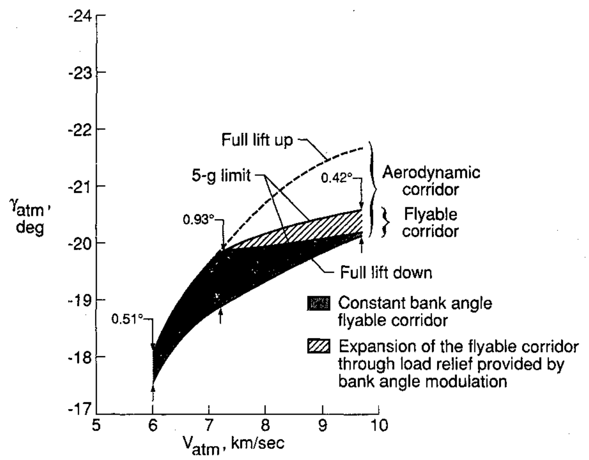

Fig. 3 Mars entry corridor results for an aerobrake L/D of 0.28 based on atmospheric exit into a 1 Sol parking orbit (numbers in the field indicate $\Delta\gamma$, deg).

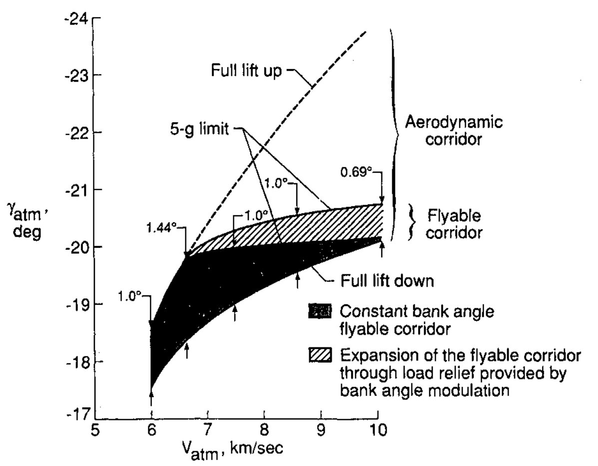

Fig. 4 Mars entry corridor results for an aerobrake L/D of 0.5 based on atmospheric exit into a 1 Sol parking orbit (numbers in the field indicate $\Delta\gamma$, deg).

Results and Discussion

Entry Corridor Results for Lift-to-Drag Ratio of 0.28

The aerodynamic and flyable entry corridors for an aerobraking vehicle with a trimmed hypersonic L/D ratio of 0.28 are presented in terms of flight-path angle at the atmospheric interface in Fig. 3. This L/D is equivalent to that predicted for the AFE and was originally simulated in Ref. 1 without bank-angle modulation. An L/D of 0.28 was re-evaluated in this investigation because of the inclusion of the atmospheric guidance algorithm within the simulation. Because lift varies with the square of velocity, the vehicle's potential control authority is increased substantially at higher entry speeds. Hence, the aerodynamic corridor width continuously increases with entry velocity. Because higher entry speeds yield increased deceleration loads, the width of the flyable corridor increases with entry velocity until achieving its maximum value when the lift-up boundary reaches the imposed 5-g deceleration limit. This occurs at approximately 7.4 km/s for this low-L/D concept where a maximum corridor width of 0.93 deg is achieved. As the entry velocity increases beyond this point, the flyable corridor width diminishes rapidly because of the restrictive effects of the 5-g limit.

The flyable corridor width shown in Fig. 3 is a function of several parameters. At the entry velocity range in which corridor width is increasing (entry velocities below 7.4 km/s in Fig. 3), the corridor width is completely a function of vehicle L/D and the required energy decrement (which, for a particular parking orbit, is equivalent to entry velocity). Hence, the feasibility of the aerobraking mission hinges on the vehicle's aerodynamic performance characteristics and the mission profile (launch and arrival dates as well as trip time). Once the 5-g limit is reached, the corridor width is dependent on vehicle L/D, the required energy decrement or entry velocity, and also the robustness of the vehicle's onboard atmospheric guidance algorithm. That is, in the entry velocity range in which the corridor width is decreasing because of the 5-g deceleration limit (entry velocities above 7.4 km/s in Fig. 3), bank-angle modulation can provide load relief while expanding the flyable corridor.[14] This is shown by the cross-hatched region of Fig. 3, which depicts the region of the flyable entry corridor that has been expanded through bank-angle modulation.

Note that because this simulation pertains to a low-L/D configuration that can only exert a slight amount of lift-induced control over its atmospheric flight path, inclusion of the atmospheric guidance algorithm has a relatively minor effect on corridor width. Additionally, the flyable corridor width never reaches the 1.0 deg required for successful aerocapture. Hence, a configuration with L/D of 0.28 is not feasible for a manned Mars aerobraking mission if a 1.0-deg corridor width is required.

Entry Corridor Results for Lift-to-Drag Ratio of 0.50

One means of increasing both the aerodynamic and flyable corridors is by utilizing a higher L/D configuration. Figure 4 shows the aerodynamic and flyable entry corridors that an aerobraking configuration with L/D of 0.5 can achieve. For an L/D of 0.5, the flyable entry corridor is significantly wider than it was for an L/D of 0.28. (Compare Figs. 3 and 4.) For this configuration, a maximum corridor width of 1.6 deg is obtained at an entry velocity of 6.8 km/s.

Note that in the region of the flyable corridor in which the 5-g limit is applicable (entry velocities above 6.8 km/s), by having a greater degree of lift-induced control than the L/D of 0.28 configuration, the guidance algorithm is able to significantly expand the flyable corridor width. As an example of the way in which bank-angle modulation can reduce the deceleration loading, a flight history in terms of bank angle, altitude, and deceleration is presented in Figs. 5–7. The aerocapture

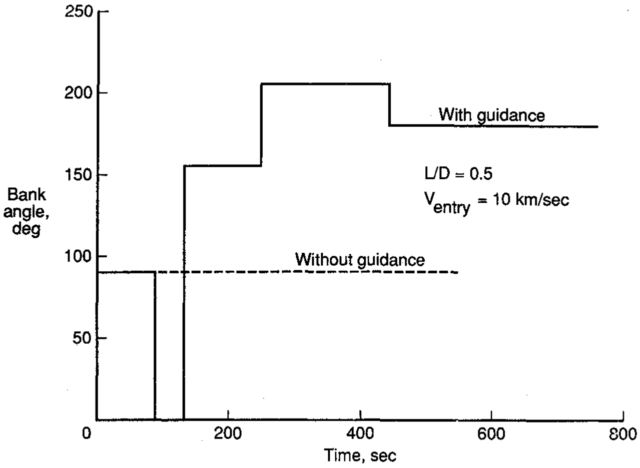

Fig. 5 Mars aerobraking with load-relief, bank angle profile.

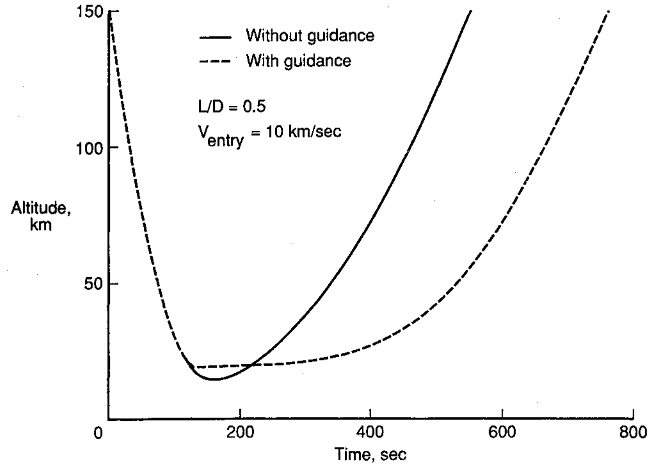

Fig. 7 Mars aerobraking with load-relief, altitude profile.

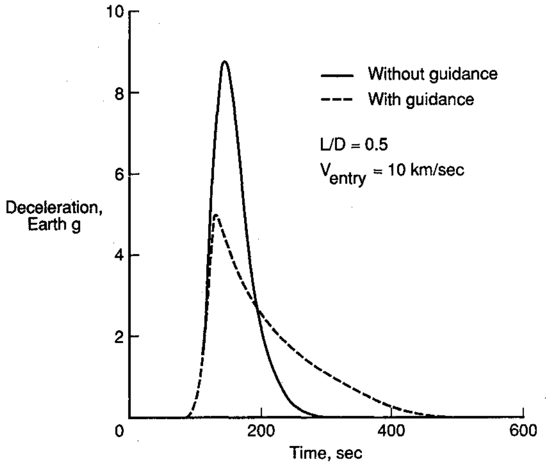

Fig. 6 Mars aerobraking with load-relief, deceleration profile.

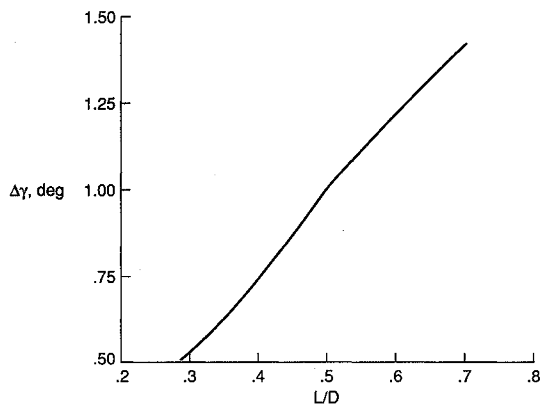

Fig. 8 Flyable corridor width at a Mars entry velocity of 10.0 km/s (5-g deceleration limit and atmospheric exit into a 1 Sol parking orbit).

trajectories shown are for a 10.0-km/s Mars entry in which the guidance algorithm was either on or off. These figures show that, by unrolling the vehicle's lift vector until a maximum 5-g deceleration is reached and then rolling the vehicle toward a lift-down orientation, the proper energy decrement is achieved. Note that a single roll reversal was also performed to eliminate cross range. As shown in Fig. 6, by utilizing bank-angle modulation, the deceleration is reduced in magnitude, but spread out over a longer time interval (from 100 to 500 s). Figure 7 shows that this deceleration is accomplished higher in the atmosphere, at near-constant altitude.

Based on the 1.0-deg corridor width requirement, Fig. 4 shows that, for an L/D of 0.5 configuration, the aerocapture maneuver is only feasible for entry velocities in the range of 6.0–7.3 km/s without the use of bank-angle modulation. However, with inclusion of an atmospheric guidance algorithm, this entry velocity range is increased to 6.0–8.5 km/s.

Flyable Corridor Width at Selected Entry Velocities

Figure 8 shows the flyable corridor width as a function of L/D for a Mars entry velocity of 6.0 km/s. Because 6.0 km/s is approximately the minimum entry velocity associated with manned Mars missions, this value was chosen to evaluate the minimum amount of aerodynamic control required for an aerobraking configuration to be feasible over a range of entry conditions. That is, an aerobraking configuration that can yield a wide enough flyable corridor at 6.0 km/s will only result in a wider corridor at higher entry velocities until the 5-g limit is approached. Hence, the configuration that yields a 1-deg corridor width at 6.0 km/s is the minimum required L/D capable of spanning the entry velocity range in which the entire aerodynamic corridor is flyable.

Based on the 1.0-deg corridor width requirement, this figure shows that an L/D of 0.5 is required to successfully aerocapture in this velocity range. If an L/D configuration lower than 0.5 is selected, a portion of this entry velocity range becomes unflyable; this unflyable region is at the low end of the entry velocity spectrum where the vehicle can not exert enough lift-induced control to perform a successful aerocapture. On the other hand, if a vehicle with an L/D above 0.5 is chosen, the vehicle would be overdesigned from a performance standpoint in the entry velocity region in which the entire aerodynamic corridor is flyable. Figure 8 also shows the effects on L/D if the 1-deg corridor width requirement were reduced. For example, if, through the use of advanced technology, this requirement was on the order of 0.5 deg, an L/D of 0.3 would be required in this entry velocity range.

As discussed previously, in the entry velocity range in which corridor width is increasing with entry velocity (entry velocities below 7.4 km/s in Fig. 3 and below 6.8 km/s in Fig. 4), the flyable corridor width is completely a function of vehicle L/D and the required energy decrement. In this entry velocity range where the deceleration limit is not a major concern, the flyable corridor width may be increased by requiring a larger energy decrement (atmospheric exit into a more circular parking orbit). The effect of parking orbit selection on flyable corridor width is shown for an aerobrake L/D of 0.5 in Fig. 9. Note that the solid line in this figure depicts the result of Fig. 8 that an L/D of 0.5 is required to generate a 1.0-deg flyable corridor width for a 1 Sol, Mars parking orbit. However, as shown in Fig. 9, by requiring a larger energy decrement during the aerobraking maneuver (i.e., by exiting into a more circular parking orbit), a larger flyable corridor width results. This additional corridor width allows the use of a lower L/D aerobrake configuration. Hence, the results presented in this investigation are dependant on the parking orbit chosen (in this case, a 1 Sol orbit). Additionally, for low entry velocities, deceleration into a more circular Mars parking orbit will significantly decrease the required aerobrake L/D.

Although a vehicle with an L/D of at least 0.5 is required over the lower end of the entry velocity region, Fig. 4 shows that even with the use of bank-angle modulation, this configuration can only satisfy the 1-deg corridor width requirement for entry velocities below 8.5 km/s. Because manned Mars missions may be characterized with entry velocities as high as 10.0 km/s, identifying the configuration that yields enough flyable corridor width at 10 km/s is warranted.

Figure 10 shows the flyable corridor width for a 10-km/s entry as a function of vehicle L/D. Note that at this entry velocity a much higher L/D vehicle must be designed to obtain the required performance. To achieve a 1-deg corridor width at 10 km/s, this figure shows that an L/D of 1.5 is required. Although a configuration with L/D of 1.5 could conceivably enter at any Mars entry velocity between 6 and 10 km/s and thus be free of mission-related constraints (i.e., trip time and launch/arrival geometry), the vehicle would be overdesigned at the moderate and low entry velocities. Additionally, because such a configuration would have to rely on a payload-encapsulating aeroshell as opposed to an open-wake aerobrake, the packaging and center-of-gravity difficulties inherent to such a configuration could significantly complicate the vehicle design process.

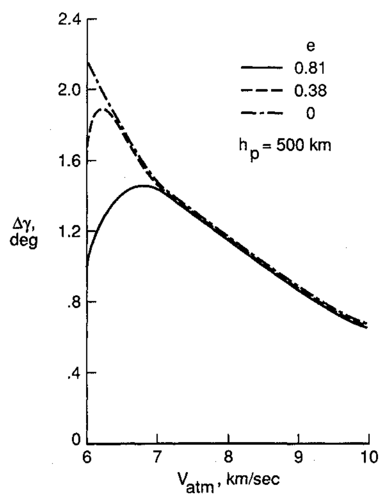

Fig. 9 Effect of parking orbit selection on the flyable corridor width (5-*g* deceleration limit).

Although configurations that are feasible over a range of entry velocities have been discussed, a nominal Mars entry velocity must be selected in the mission design process. This nominal Mars entry velocity will be a function of several interplanetary mission requirements, which include trip time and Earth departure and Mars arrival date selection. However, if the mission includes an aerocapture maneuver, a logical choice for the Mars entry velocity would be the entry velocity that results in the maximum flyable corridor width. As shown in Figs. 3 and 4, the maximum flyable corridor width occurs at the entry velocity where the full lift-up transfer encounters the deceleration limit (the 5-*g* restriction).

Figure 11 shows that the entry velocity that results in the maximum flyable corridor width is completely a function of vehicle L/D. This figure shows the maximum flyable corridor width as well as the Mars entry velocity at which this condition occurs. Note that, as the L/D is increased, the maximum flyable corridor width increases in magnitude, but occurs at lower entry velocities. This figure shows that a vehicle with an L/D as low as 0.3 may perform a successful aerocapture based on the 1-deg corridor width requirement. However, for the L/D of 0.3 configuration to be feasible, the Mars entry velocity must be between 7.2 and 7.3 km/s. Although this entry velocity requirement may limit the Earth departure window and number of mission opportunities, use of an aerobrake configuration characterized by an L/D of 0.3 would significantly ease the vehicle packaging and assembly process. Figure 11 also shows that aerobraking vehicles characterized by an L/D less than 0.3 are not feasible for a manned Mars mission based on the 1-deg corridor width requirement.

The tradeoff between aerobrake L/D (aerodynamic performance and vehicle packaging) and entry velocity (mission opportunity and flexibility) is summarized in Fig. 12, which presents the minimum required Mars aerobrake L/D as a function of entry velocity. Note that this figure is based on the assumptions of a 1-deg corridor width requirement, 5-*g* deceleration limit, and a 1 Sol Mars parking orbit. In this figure, typical aerobrake configurations are shown over the entry velocity regions in which they generate the minimum required L/D. As shown in Fig. 12, an aerobrake L/D of 0.5 is required for the lowest entry velocity of 6 km/s. As the entry velocity is increased, the vehicle is able to exert a greater degree of lift-induced control; hence, the required aerobrake L/D decreases. A minimum L/D of 0.3 is required for an entry velocity of 7.2–7.3 km/s. For an entry velocity above 7.3 km/s, an increased Mars aerobrake L/D is required to com-

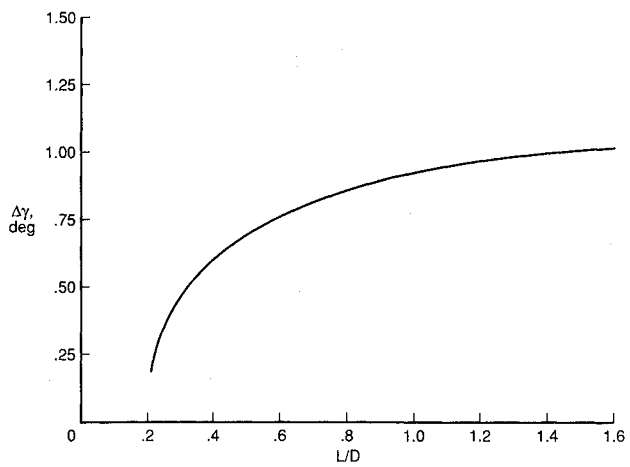

Fig. 10 Flyable corridor width and entry velocity of 10.0 km/s (5-*g* deceleration limit and atmospheric exit into a 1 Sol parking orbit).

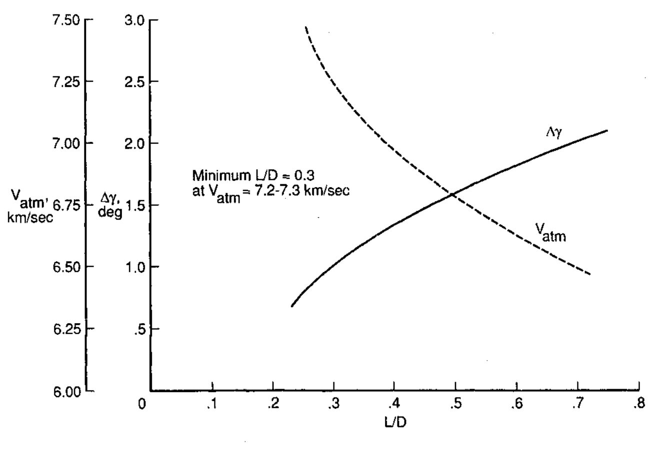

Fig. 11 Flyable corridor width and entry velocity at maximum flyable corridor width conditions (5-*g* deceleration limit and atmospheric exit into a 1 Sol parking orbit).

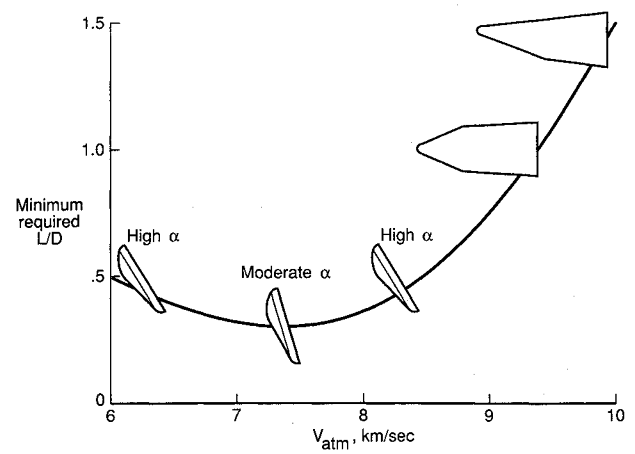

Fig. 12 Minimum required aerobrake L/D for Mars aerocapture (1-deg flyable corridor width, 5-g deceleration limit and atmospheric exit into a 1 Sol parking orbit).

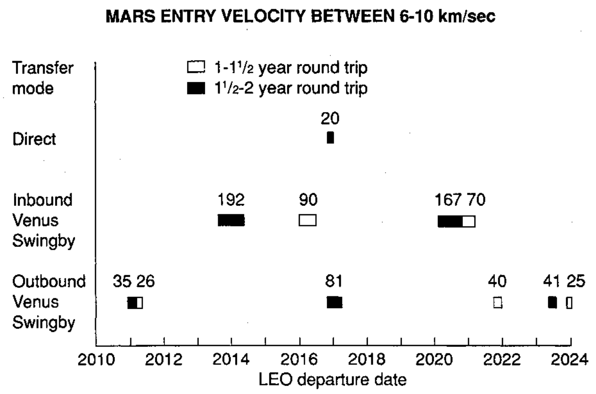

Fig. 13 Potential interplanetary mission opportunities for an aerobraking transfer vehicle with L/D of 1.5 based on a 1-deg flyable corridor width, 5-g deceleration limit and atmospheric exit into a 1 Sol parking orbit (numbers in the field indicate length of the departure opportunity, days).

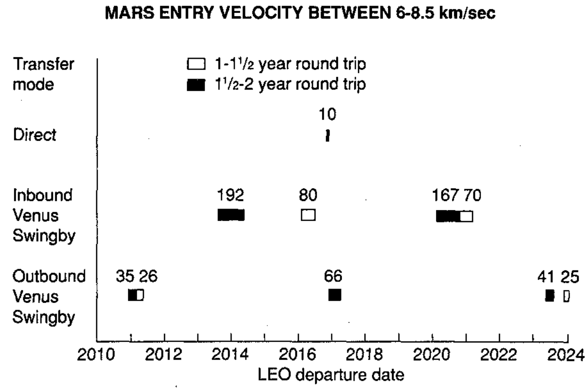

Fig. 14 Potential interplanetary mission opportunities for an aerobraking transfer vehicle with L/D of 0.5 based on a 1-deg flyable corridor width, 5-g deceleration limit and atmospheric exit into a 1 Sol parking orbit (numbers in the field indicate length of the departure opportunity, days).

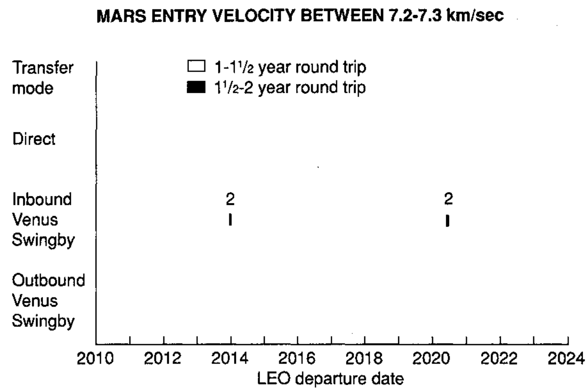

Fig. 15 Potential interplanetary mission opportunities for an aerobraking transfer vehicle with L/D of 0.3 based on a 1-deg flyable corridor width, 5-g deceleration limit and atmospheric exit into a 1 Sol parking orbit (numbers in the field indicate length of the departure opportunity, days).

pensate for the 5-g deceleration limit. The shallowness of the curve presented in Fig. 12 suggests that, for a minor increase in aerobrake L/D over 0.3, which is the absolute minimum required, a large entry velocity domain may be considered feasible. Hence, by slightly increasing the vehicle L/D, a major increase in mission flexibility results. For example, although an aerobrake L/D of 0.3 requires a Mars entry velocity in the range of 7.2–7.3 km/s, slightly increasing this L/D to 0.4 significantly expands the range of allowable entry velocities (entry velocities in the range of 6.4–8.1 km/s without substantially impacting vehicle packaging concerns.

Mission Opportunities

In Ref. 2, 11 manned Mars mission opportunities in the time frame 2010–2025 were identified that met a potential set of constraints for an initial manned exploration strategy. These constraints pertained to trip time, initial LEO mass, Earth reentry velocity, and launch period. However, in this reference, no limit was placed on the Mars entry velocity; instead, it was shown to vary unconstrained from 6.0 to 10.0 km/s. These mission opportunities for which minimum initial LEO mass was the primary concern are reproduced in Fig. 13. Based on the flyable corridor results identified through this investigation, an unconstrained Mars entry velocity requires a Mars aerobrake with a minimum L/D of 1.5. Hence, Fig. 13 shows the potential mission opportunities for an aerobrake configuration with an L/D of at least 1.5. Note that because these interplanetary mission opportunities were selected without Mars aerobraking requirements as an input, the Mars aerobrake configuration is required to yield substantial aerodynamic performance (L/D of 1.5).

By restricting the allowable entry velocity range to 6.0–8.5 km/s, few launch opportunities are lost. As shown in Fig. 14, 10 of the original 11 mission opportunities remain over the 15-year Earth departure period for a Mars aerobrake configuration with an L/D of 0.5. A comparison of Figs. 13 and 14 shows that only one mission opportunity is lost while only three other opportunities are slightly diminished. By restricting the Mars entry velocity to <8.5 km/s, the aerobrake design and vehicle integration process (in particular, the packaging and assembly tasks) benefits significantly without much loss in mission flexibility in comparison to an L/D of 1.5 configuration. Additionally, by limiting Mars entry to velocities below 8.5 km/s, the aerothermodynamic environment is less severe. Hence, through use of an aerobrake with an L/D of 0.5, a compromise is achieved between the conflicting requirements of interplanetary and atmospheric transfer. However, the packaging restrictions imposed by an aerobrake L/D of 0.5 may still be significant, and an L/D <0.5 may be required.

By restricting the Mars entry velocity range to 7.2–7.3 km/s, the L/D of 0.3 configuration is feasible based on the 1-deg corridor width requirement. However, this severely limits the number of mission opportunities. As shown in Fig. 15, only two significantly constrained mission opportunities remain. Thus, by tailoring the mission selection process exclusively to the design of the aerobrake (minimum aerobrake L/D), mission flexibility is significantly sacrificed.

The restricted number of mission opportunities shown in Fig. 15 could be enhanced through inclusion of a Mars entry velocity constraint in the interplanetary trajectory selection process. Note that the potential interplanetary mission opportunities (shown in Fig. 13) were initially determined in Ref. 2 where minimum initial LEO mass was the primary constraint. Although additional interplanetary transfers exist that adhere to the Mars entry velocity requirements identified in this analysis, these transfers do not represent the minimum initial LEO mass interplanetary flight path for a particular Earth departure date/trip time combination. Hence, the mission opportunities shown in Figs. 14 and 15 represent a subset of a larger number of opportunities in which the proper range of Mars entry velocity could be achieved. These additional interplanetary transfers, which are not identified in either Figs. 14 or 15, require either a larger initial LEO mass or a more complex propulsive burn sequence. By constraining the interplanetary trajectory design process to include a Mars entry velocity constraint in addition to an initial LEO mass requirement, additional trajectory opportunities could be identified to complement those shown in Figs. 14 and 15 and increase mission flexibility.[15] This is an example of the coupled interplanetary/atmospheric design requirements that must be accounted for in a manned Mars aerobraking vehicle design.

Conclusions

In a manned Mars aerobraking mission, the interplanetary and atmospheric trajectories are inherently coupled. This relationship must be accounted for in the mission and vehicle design processes for an aerobraking transfer. If the emphasis is placed solely on interplanetary transfer, an overdesigned aerobrake results. On the other hand, if the design emphasis is purely vehicle oriented, mission flexibility is sacrificed. Mars aerobrake L/D requirements are dependent on several factors including the 1) interplanetary navigation system, 2) knowledge of the mean atmospheric properties and expected variations on flight day, 3) magnitude of the deceleration limit, 4) Mars parking orbit selection, and 5) entry velocity.

Based on the requirements of a 1-deg corridor width, deceleration into a parking orbit with an apoapsis altitude of 33,640 km and a 5-g deceleration limit.

1) A minimum aerobrake L/D of 1.5 is required for a manned Mars vehicle to successfully aerocapture at entry velocities from 6.0 to 10.0 km/s. Because this aerobrake L/D is feasible over the entire range of entry velocities considered, the configuration is not limited by departure/arrival geometry or trip time. However, selection of an L/D of 1.5 induces numerous vehicle design considerations including significant packaging and aerothermodynamic constraints.

2) A minimum L/D of 0.5 is required for a manned Mars vehicle to successfully aerocapture at entry velocities between 6.0 and 8.5 km/s. By limiting the Mars entry velocity to values below 8.5 km/s and selecting an aerobrake L/D of 0.5, a compromise is reached between the conflicting interplanetary and atmospheric trajectory requirements. In this manner, a minor restriction on mission flexibility is induced while alleviating aerothermodynamic and vehicle packaging concerns. However, an L/D of 0.5 configuration may still prove difficult to package.

3) A minimum L/D of 0.3 is required for a manned Mars vehicle to successfully aerocapture. For an L/D of 0.3, the aerocapture must be initiated at an entry velocity between 7.2 and 7.3 km/s. A configuration with $L/D < 0.3$ does not result in enough lift-induced control to be considered feasible. Although an L/D of 0.3 imposes significant constraints on the number of potential mission opportunities, the limitations identified in this investigation may be alleviated by including a Mars entry velocity constraint in the interplanetary trajectory selection or the use of synergistic propulsion. A Mars aerobrake L/D configuration of 0.3 is optimal from a vehicle packaging and assembly standpoint.

In summary, through this investigation, a manned Mars aerobrake characterized by an L/D between 0.3 and 0.5 has been identified as being optimal. Further refinement in the aerobrake L/D depends on a more detailed analysis of the tradeoff between the number of interplanetary mission opportunities and aerobrake packaging constraints as well as better definition of the required flyable corridor width.

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