Final MARS AEROCAPTURE STUDIES FOR THE DESIGN REFERENCE MISSION

Report on a cooperative study done between the University of Tennessee, NASA Ames Research Center, and North Carolina State University under Cooperative Agreement NCC2-5198

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INTRODUCTION

The recent discovery of possible fossilized microbes in a Martian meteorite sample and the spectacular success of the Mars Pathfinder mission have substantially increased public interest and support for future robotic and manned exploration of Mars. NASA is currently refining a plan known as the Design Reference Mission (DRM) in which the first human landing would occur in 2014 after a series of cargo launches which would place surface systems and an Earth return vehicle at Mars two years prior to the crew's arrival.[1] At each subsequent launch opportunity (which occur approximately every twenty-six months), an additional Earth return vehicle, surface facility and crew would depart for Mars, with each crew employing the systems launched during the previous opportunity. The mission design calls for a long-duration surface stay, rapid crew transits, in-situ manufacture of the Mars ascent propellant, nuclear thermal propulsion for the trans-Mars injection burn, and the use of

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aerocapture for both the cargo and crew vehicles at Mars. Aerocapture is a technique in which a spacecraft on a hyperbolic trajectory is decelerated into a closed orbit about some target planet through the use of aerodynamic drag rather than propulsive methods. Numerous studies have previously shown that this approach may significantly benefit human Mars missions by allowing a substantial reduction in the initial mass in low Earth orbit (IMLEO).

A prominent criticism of many previous aerobrake designs has been the requirement for substantial on-orbit assembly.[2] This is undesirable and may subject the crew to increased risks if the assembly operations require human participation in the form of extravehicular activity. Therefore, to eliminate this problem, a triconic configuration has been selected which can be launched as a single piece and will serve in a dual-role as the launch shroud during Earth lift-off. Cargo and crew vehicles would use a common aeroshell design with a base diameter of 8.6 meters and a total length of 24 meters. The current paper presents an analysis of entry trajectory and heating studies for this triconic vehicle for fast-transit, crew flights.

RESULTS

While the entry velocity for the cargo flights is fairly well established at approximately 5.7 km/s (based on the use of minimum energy interplanetary transfers), Figure 1 shows the sensitivity of the crew vehicle's inertial atmospheric entry velocity (measured at 125 km) to transit time to Mars for the 2014 crew transfer. The upper curve is based on a mission profile optimized to minimize the trans-Mars injection (TMI) delta V, while the lower curve is for a mission optimized to minimize the atmospheric entry velocity at Mars. The middle curves are for fixed TMI dates of 1/19/14 and 1/30/14. The corresponding plots of TMI delta V as a function of transit time are shown in Figure 2.

An explicit ground rule of the design reference mission has been to limit crew interplanetary transfers to 180 days or less in order to minimize human radiation exposure.[1] Very rapid transits may be beneficial from a human factors point of view and can be accomplished for little in terms of TMI delta V (see the bottom curve in Figure 2); however, it is necessary to restrict the transit times to prevent excessive entry speeds at Mars and the severe radiative and convective heating which would result. Nevertheless, it is clear from Figures 1 and 2 that the DRM's 180 day guideline can be accomplished with Mars entry velocities of 8.4 km/s or less while minimizing the TMI delta V. Moreover, shorter transit times can be provided with the same Mars entry speed for a relatively small cost in TMI delta V (see the curves for fixed TMI dates in Figure 2). In general, as the atmospheric entry velocity increases, the mass of the aerobrake's ablative thermal protection system (TPS) must increase in order to accommodate the higher total heat load. This implies that the TPS mass reduction afforded by longer transit times and lower entry speeds must eventually be weighed against the increased mass of consumables and the potentially heavier radiation shielding necessitated by longer interplanetary transits.

The aerodynamic coefficients for the triconic aeroshell have been calculated using both Newtonian aerodynamics and computational fluid dynamics including real gas effects; the results are presented in Figure 3 as a function of angle of attack. The lift-to-drag ratio of this vehicle is substantially higher than for many aerobrakes previously considered for manned Mars arrival.[3-5] These aerodynamic characteristics influence the entry corridor width (the range of angles in which the vehicle must enter the atmosphere in order to execute a successful aerocapture), the aerodynamic heating rates, and the timing of the vehicle's intra-atmospheric roll control maneuvers.

Initial studies of aerocapture trajectories for the crew vehicle at inertial entry velocities from 7.2 to 8.8 km/s have been performed using the 3-D version of the Program to Optimize Simulated Trajectories (POST).[6] In this work, the vehicle has been assumed to have a total entry mass of 65 metric tons and to fly at a trim angle of attack of 47 degrees. Aerodynamic characteristics of the vehicle were assumed to be those shown in Figure 3 and were not varied with altitude or Mach number. Peak decelerations were limited to 5 G's or less to avoid overstressing the crew. The vehicle performed a due-east, posigrade, equitorial entry, and an oblate, rotating planetary model was used. The vehicle was adjusted into a 1 Sol orbit by means of one or two propulsive burns (Isp = 320 sec) once it exited the atmosphere. Since previous studies have shown the significance of atmospheric density variations,[7] the entries were considered both for nominal conditions using the COSPAR Northern Summer mean atmosphere and for high and low density variations (130% and 70% of nominal density respectively). The undershoot limits (the steepest angle at which the vehicle can enter and execute a successful aerocapture) were established using the high density atmospheric models, while the overshoot boundaries (the shallowest entry angle which can lead to a successful capture) were determined using the low density models. The control logic for the undershoot trajectory required the rate of change of the vehicle bank angle not to exceed 11 degrees/second.

Undershoot and overshoot limits are presented in Figure 4 as a function of entry speed. This figure shows the bounds for a COSPAR NS Mean Atmosphere and the bounds for the off-nominal atmospheres as described above (all angles are measured at 125 km). Characteristic trajectories are presented in Figure 5. It was found that "near-undershoot" trajectories were possible that required much smaller post-aeropass propellant usage than the full 5 G undershoot. In fact, such trajectories were found for which the propellant requirement was approximately 25 percent of that for the 5 G undershoot. These trajectories are referred to as "reduced propellant undershoots;" the corresponding entry angles are shown in Figure 4 as "Reduced prop under." For these trajectories, peak G loads encountered by the aerobrakes are reduced to approximately 3.9 G rather than the nominal limit of 5.0 G. However, the triconic aerobrake provides an ample entry corridor to allow for this limitation while still meeting the width requirement of one degree typically imposed in several previous studies.[3-5]

Accurate calculations of the aerodynamic heating rate and its distribution over the vehicle's surface are necessary in order to design the aerobrake's thermal protection system (TPS). Typically, heat shield thickness and mass is governed by the highest potential integrated heat load which a vehicle may experience. The overshoot and undershoot trajectories described above may be considered bounds on the aerodynamic environment which the vehicle may experience and are therefore quite useful in TPS design. Although the highest heating *rates* are experienced on undershoot trajectories, overshoot trajectories, because of their longer duration, produce the maximum integrated heating loads; therefore, they typically serve as the design cases. While detailed CFD studies based on these trajectories are required to thoroughly map TPS material distributions and thickness (work which is currently in progress), preliminary calculations of stagnation-point heating rates may be performed using the relatively simple analytical formulations of references 8 and 9. Representative heating pulses calculated using these methods for the trajectories shown in Figure 5 are presented in Figure 6. The effect of angle of attack (AOA) on overshoot bounds and stagnation-point heating are shown in Table I. (The values in Table I were generated using a spherical, rotating planetary model, rather than the oblate model used for Fig. 4.) As the angle of attack increases, the coefficient of drag goes up, causing the vehicle to decelerate more rapidly; as a result, the overshoot angle becomes shallower and the minimum altitude reached during the overshoot trajectory becomes higher. This results in a lower integrated *stagnation-point* heat load for higher angles of attack; however, it also causes a larger portion of the vehicle's surface to be at a high angle of incidence to the flow, thereby driving up the afterbody windward centerline heating distribution. Therefore, minimization of the TPS mass will require a proper selection of the vehicle's angle of attack to provide the most favorable *overall* heating distribution.

TABLE I

EFFECT OF ANGLE OF ATTACK, ENTRY SPEED = 7.6 KM/S

AOA, degrees	C_L	C_D	Overshoot angle degrees	Stag. pt max. heating rate, W/sq cm	Stag. point Heat load, J/sq cm	Min. altitude, km
15	0.45	0.5	-11.575	194	42185	25.77
20	0.68	0.67	-11.327	152	37179	29.66
25	0.82	0.82	-11.211	134	33107	31.68
30	1.03	1.1	-11.073	114	27627	33.87
35	1.2	1.38	-10.979	103	23872	35.31
40	1.31	1.72	-10.922	95	20362	36.44
47	1.35	2.14	-10.898	88	17136	37.05

CONCLUDING REMARKS

Preliminary studies of the aerobrake's roll control maneuvers - the intra-atmospheric banking sequence used to dissipate the necessary amount of energy during the atmospheric passage and to target the vehicle to the desired exit orbit - have shown that the high ballistic coefficient of the triconic has a significant impact on the maneuver timing. Previous studies of roll control sequences for lower ballistic coefficient entries have typically maintained full lift up for undershoot trajectories up to the point of the peak vehicle deceleration and then rolled the vehicle over to hold it down in the atmosphere so that the correct target orbit could be achieved; this approach allows the steepest possible undershoot bounds without violating the imposed G constraints. However, for the current vehicle, it appears that for undershoot trajectories, a rollover maneuver must be initiated much earlier in the atmospheric passage in order for the vehicle to have adequate control authority over its trajectory to avoid skipping out into a hyperbolic escape trajectory. This results in a shallower undershoot boundary than would be possible if full lift up could be maintained until later in the atmospheric trajectory. However, when bank angle modulation was initiated early in the undershoot trajectories, the triconic configuration was shown to have relatively wide aerocapture corridors. The maximum-width corridor (between the nominal atmosphere overshoot and 5 G undershoot bounds) ranged from 2.7 degrees at an entry velocity of 7.2 km/s to 1.5 degrees at 8.8 km/s. When off-nominal atmospheric densities were assumed (70 percent of nominal for overshoot and 130 percent of nominal for undershoot), the corridor was reduced to 2.3 degrees at 7.2 km/s and 1.3 degrees at 8.8 km/s. Furthermore, when the reduced propellant undetshoot trajectories were flown with nominal atmospheric density profiles, the corridor was still acceptable, ranging from 2.1 degrees at 7.2 km/s to 1.2 degrees at 8.8 km/s. Hence, this investigation shows that the high L/D (and the resulting high control authority) of the triconic configuration results in entry corridor widths which are more than adequate to accomodate anticipated errors in approach guidance and navigation and uncertainties in vehicle aerodynamics for a wide range of entry velocities, while requiring modest post-aeropass propellant expenditures. Future studies must investigate the impact of variations in the trim angle of attack on the integrated heat load distribution over the surface of the vehicle.

REFERENCES

1) Human Exploration of Mars: "The Reference Mission of the NASA Mars Exploration Study Team", NASA SP 6107, March 1997.

2) "America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative", May 1991.

3) Tauber, M.E., "Aerobrake Design Studies for Manned Mars Missions, Journal of Spacecraft and Rockets", Vol. 30, No. 6, 1993.

4) Lyne, J.E., "Physiologically Constrained Aerocapture for Manned Mars Missions", NASA TM 103954, Aug. 1992.

5) Braun, R.D. and Powell, R.W., "Aerodynamic Requirements of a Manned Mars Aerobraking Transfer Vehicle", AIAA Paper 90-2817, Aug. 1990.

6) Brauer, G.L., Cornick, D.E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)", NASA CR-2770, Feb. 1977.

7) Powell, R.W. and Braun, R.D., "A Six Degree-of-Freedom Guidance and Control Analysis of Mars Aerocapture", AIAA Paper 92-0736, Jan. 1992.

8) Tauber, M.E., Bowles, J.V., and Yang, L., "The Use of Atmospheric Braking During Mars Missions", AIAA Paper 89-1730, June 1989.

9) Tauber, M.E. and Sutton, K., "Stagnation Point Radiative Heating Relations for Earth and Mars Entries", Journal of Spacecraft and Rockets, Vol. 28, No. 1, 1991, pp. 40-42.

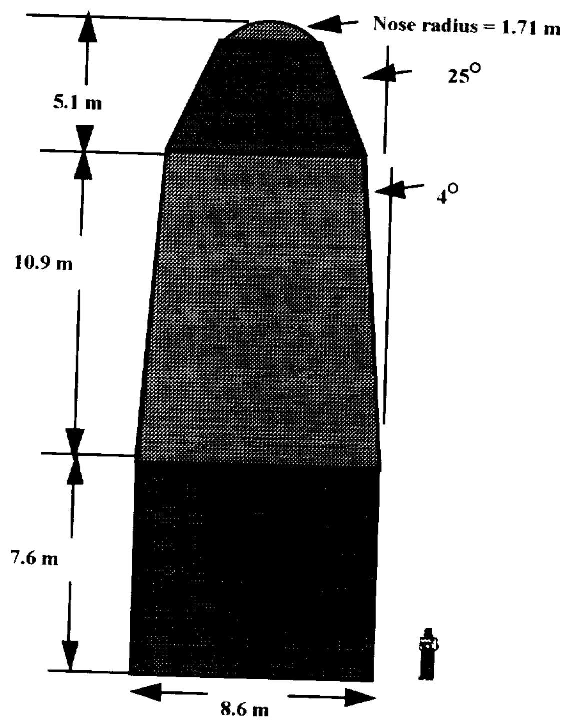


Figure1. Triconic Entry Vehicle

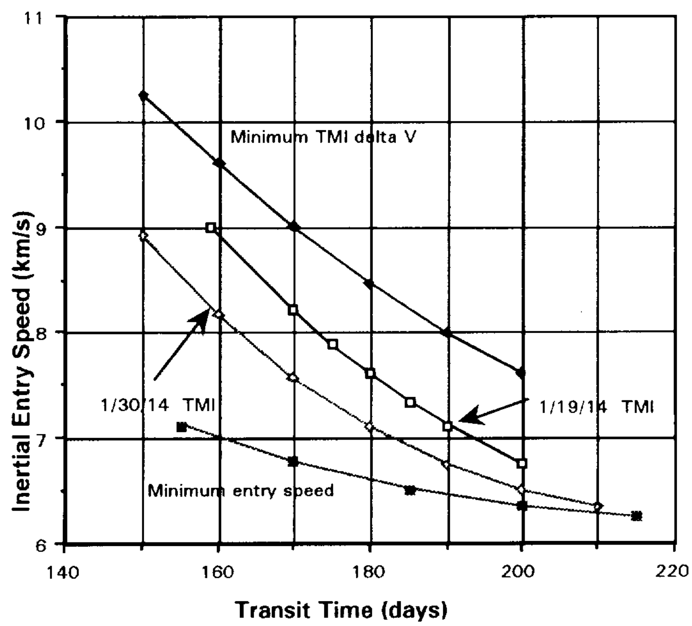


Figure 2. 2014 Mars Crew Entry Speed vs Transit Time

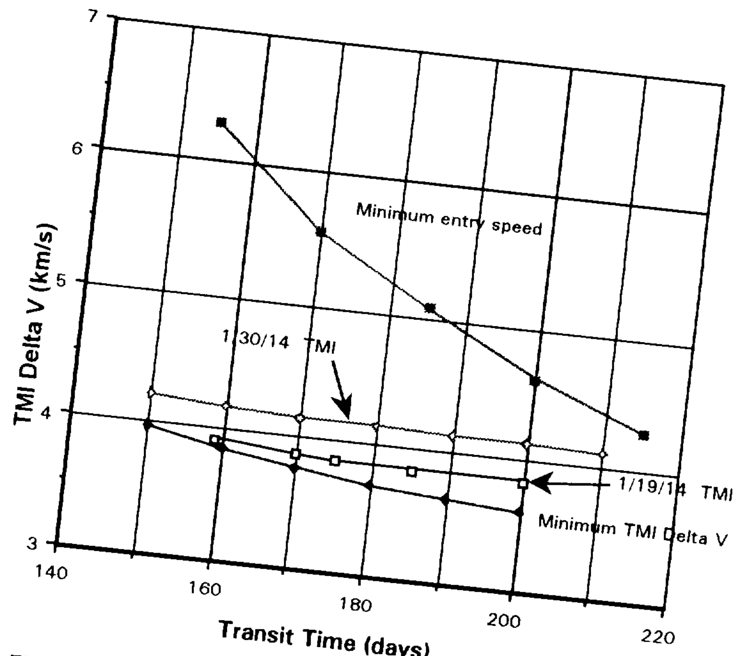
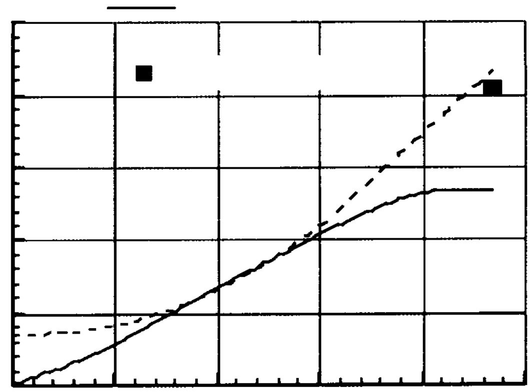


Figure 3. 2014 TMI Delta V vs Transit Time



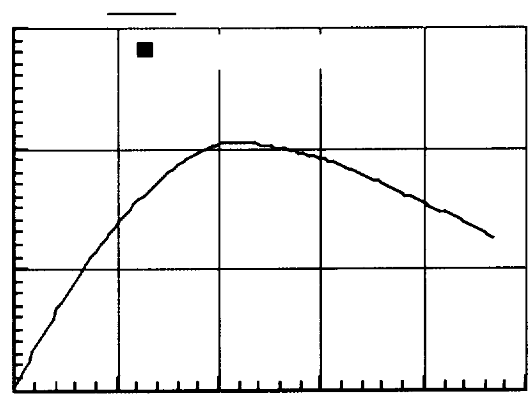


Figure 4. Triconic Aerodynamic Coefficients

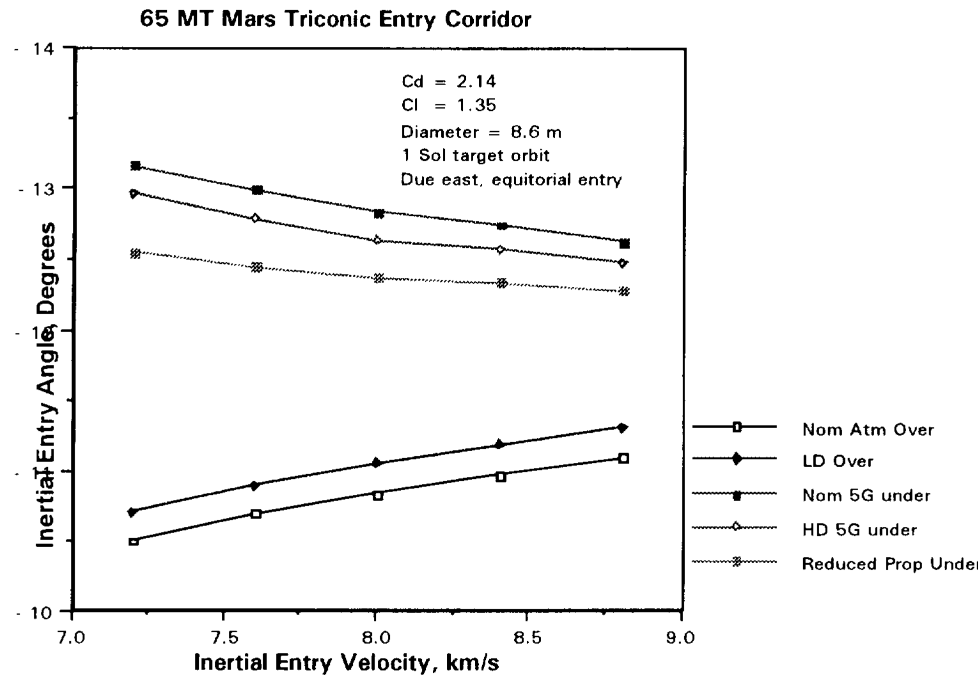


Figure 5. Overshoot and undershoot bounds for the DRM Mars triconic aerobrake. "Nom atm" indicates values for a nominal COSPAR Northern Summer Mean atmosphere. LD indicates a 70% density atmosphere, and HD indicates a 130% density atmosphere

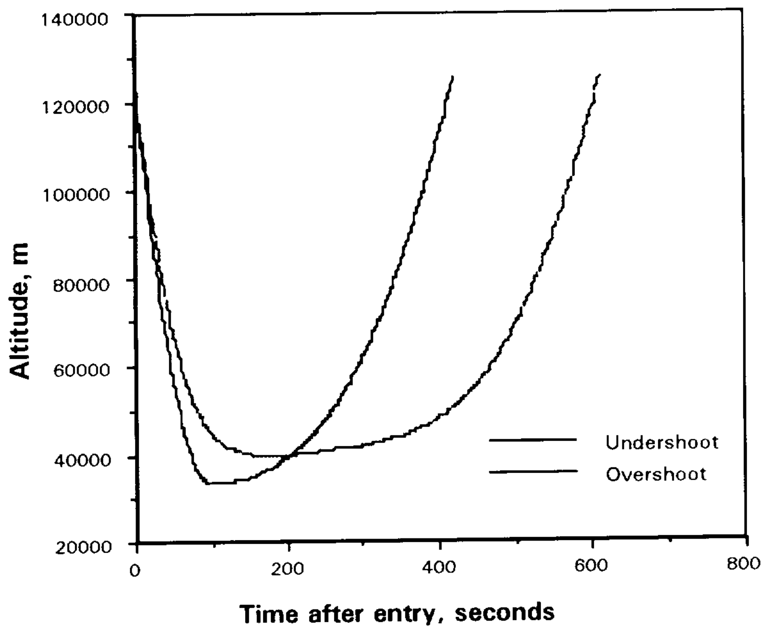


Figure 6. Mars Triconic Aerocapture Trajectories for 8.0 km/s Entry and Nominal Atmospheric Density

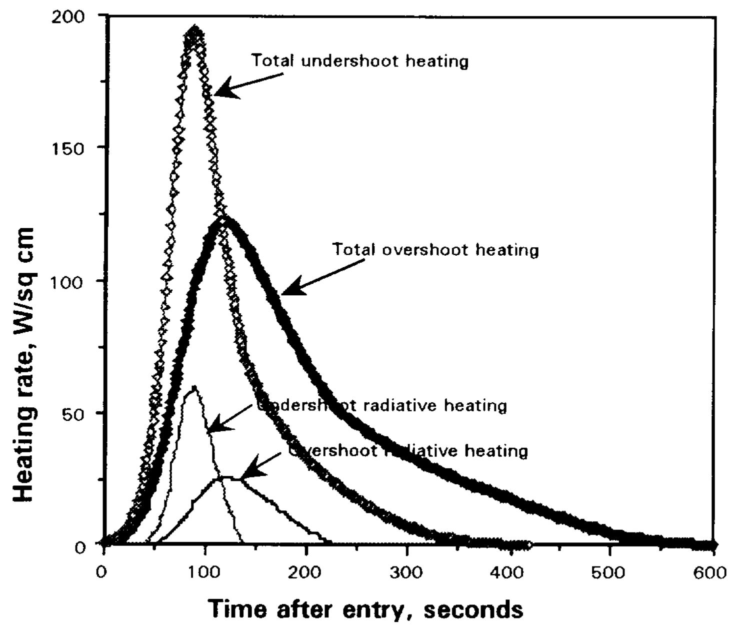


Figure 7. Stagnation-point heating rate for 8.0 km/s aerocapture trajectories of Mars triconic for COSPAR NS MEAN atmosphere