Mars Sample Return Using Commercial Capabilities: Propulsive Entry, Descent, and Landing

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Abstract—**This paper describes a critical portion of the work that has been done at NASA, Ames Research Center regarding the use of the commercially developed Dragon capsule as a delivery vehicle for the elements of a high priority Mars Sample Return mission. The objective of the investigation was to determine entry and landed mass capabilities that cover anticipated mission conditions. The "Red Dragon" Mars configuration uses supersonic retro-propulsion, with no required parachute system, to perform Entry, Descent, and Landing (EDL) maneuvers. The propulsive system proposed for use is the same system that will perform an abort, if necessary, for a human rated version of the Dragon capsule. Standard trajectory analysis tools are applied to publically available information about Dragon and other legacy capsule forms in order to perform the investigation. Trajectory simulation parameters include entry velocity, flight path angle, lift to drag Ratio (L/D), landing site elevation, atmosphere density, and total entry mass. In addition, engineering assumptions for the performance of the propulsion system are stated. Mass estimates for major elements of the overall proposed architecture are coupled to this EDL analysis to close the overall architecture. Three, Type 1 synodic launch opportunities, beginning with the 2022 opportunity, define the arrival conditions. Results are given for a system reflecting a nominal baseline set of the analysis parameters as well as sensitivities to those parameters. The EDL performance envelope includes landing altitudes between 0 and -4 km referenced to the Mars Orbiter Laser Altimeter datum as well as minimum and maximum atmosphere density. Total entry masses between 7 and 10 mt are considered with architecture closure occurring between 9.0 and 10 mt. Propellant mass fractions for each major phase of the EDL - Entry, Terminal Descent, and Hazard Avoidance - have been derived. A useful payload mass of 2.0 mt is provided and includes mass and growth allowance for a Mars Ascent Vehicle (MAV), Earth Return Vehicle (ERV), and mission unique equipment. The useful payload supports an architecture that receives a sample from another surface asset and sends it directly back to Earth for recovery in a high Earth orbit. The work shows that emerging commercial capabilities as well as previously studied EDL methodologies can be used to efficiently support an important planetary science objective. The work has applications for human exploration missions that will also use propulsive EDL techniques.**

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1. INTRODUCTION

Mars Sample Return (MSR) has been identified as the highest priority planetary science mission for the next decade by the most recent version of the Decadal Survey of Planetary Science [1]. MSR has been the subject of several studies within the last three decades [2 – 6]. Proposed missions resulting from those studies have been large, complex, and by extension, costly.

This paper provides a description of a Propulsive Entry Descent and Landing technique. The technique is applied to support a broader study of a new MSR architecture. This new architecture leverages the use of emerging commercial capabilities in order to reduce the complexity and cost of previous approaches.

The objective of the study was to determine whether emerging commercial capabilities can be integrated into to such a mission. The premise of the study is that commercial capabilities can be more efficient than previously described systems, and by using fewer systems and fewer or less extensive launches, overall mission cost can be reduced.

Mars Sample Return (MSR) is practically the most complex robotic mission that can be envisioned for Mars [2 – 6], as it requires Entry Descent and Landing (EDL) in the Martian atmosphere, surface mobility with dexterous manipulators, the unavoidable need for a rocket powered Mars Ascent Vehicle (MAV) capable of launching an acquired sample into space from the Martian surface, transportation of the sample back to the vicinity of Earth, and some form of EDL of the sample at Earth in a manner that reduces the risk of planetary back-contamination to an acceptable level. The current Decadal Survey architecture includes Mars Orbit Rendezvous (MOR) to transfer the sample from the MAV onto an Earth Return Vehicle (ERV). Both NASA and the aerospace industry have understood for some time that the duration and complexity of MSR (and thus its cost and cost risk) could be reduced by a large factor if an Earth-direct architecture that entirely bypasses MOR were adopted [7].

An Earth-direct architecture requires the ability to throw to and land on Mars, integrated payloads that are heavier than those that can be accommodated with Viking-heritage EDL technology. For example, the study on which the cited IAF presentation was based found that the landed mass of a 3-stage MAV-ERV stack using a conventional spacecraft construction philosophy would be about 4,500 kg.

For the last two years, NASA-Ames Research Center (ARC) has been conducting an internal study to determine whether a spacecraft with the general properties of a (suitably modified) SpaceX Dragon capsule—dubbed a "Red Dragon"--could serve as the basis for an Earth-direct MSR architecture of the type suggested in the 2002 IAC paper. This paper presents general results and findings of the portion of that study that deals with the EDL problem. In a forthcoming companion paper [8], we estimate that a "2 ½ stage" MAV-ERV spacecraft system employing storable bi-propellant and constructed in a Small Spacecraft development culture, together with associated robotic sample handling systems can be constructed within a mass budget of 2000 kg. This paper examines the feasibility of a Red Dragon capsule, based on emerging commercial capability, to land 2000 kg of useful payload on Mars.

2. The Red Dragon Capsule

SpaceX designed the MK1 Dragon capsule primarily to transport cargo to and from LEO (specifically the ISS). The successful conduct of 2 cargo resupply flights to date of the MK1 Dragon has validated the aerodynamic design (e.g., hypersonic L/D) and aerothermodynamic design (i.e., the performance of the thermal protection system, or TPS, during the re-entry phase). The MK1 Dragon was designed with the intent to upgrade it through suitable modifications to transport crew to and from LEO—resulting in a MK2 version of Dragon. Among the modifications planned are the installation of storable, liquid bi-propellant ("Super Draco") thrusters to perform the launch abort escape maneuver and deployable legs to allow a soft landing on land (as opposed to a water landing for the MK1). SpaceX is currently working under a Space Act Agreement with NASA to develop and test these MK2 Dragon modifications, and is making satisfactory progress.

When the Dragon product line was conceived, SpaceX reportedly made a strategic decision to include design features that would allow (or at least not preclude) future development of a version of the Dragon capsule capable of landing on Mars. In 2010, ARC recognized that the MK2 Dragon design would potentially have or perhaps actually, has the capability of accomplishing Mars landings. Accordingly, ARC began an internal study to examine the basic feasibility of the concept, the modifications (if any) that would be necessary, and the estimated performance envelope of such a "Red Dragon". Because many of the design features of Dragon are considered proprietary by SpaceX, ARC undertook to construct its own conceptual design model of a putative Red Dragon capsule using only Dragon performance parameters which were either already in the public domain, or which could be estimated by ARC from open sources. Thus, results presented in this paper rest on a hypothetical Red Dragon design created by ARC, and should not be construed as representing the position of SpaceX. Nevertheless, we feel the performance capabilities discussed in this paper are conservative and represent a realistic picture of a hypothetical Red Dragon Mars lander.

3. Mars Entry, Descent, and Landing

The entire EDL sequence consists of 3 distinct phases. First, the probe enters the Martian atmosphere with an excess velocity determined entirely by celestial mechanics and the size of the Solar System; for this reason, the entry velocity is sometimes referred to as a cosmic velocity. During the entry phase, the probe decelerates entirely by transferring its kinetic energy into the Martian atmosphere by collision of its Outer Mold Line (OML) with air molecules. If the probe enters under conditions that do not either result in immediate collision with the surface or skipping out of the atmosphere, it will eventually end up asymptotically approaching the vertical terminal velocity it would have attained if it had been dropped into the top of the atmosphere with no excess velocity. At a suitable location along the altitude/terminal velocity curve, the probe has finished the entry phase and can begin the descent phase.

The second, or descent phase begins at a suitable combination of altitude and terminal velocity that is within the capability of the deceleration system to handle. To date, all NASA Mars probes have had ballistic coefficients high enough that the terminal velocity would never go below a Mach number =1 prior to hitting the ground. Thus, the descent phase is required to start from supersonic speeds and decelerate through the transonic range, down to subsonic speeds. All NASA soft landed Mars probes to date have used supersonically deployed parachute technology, developed as the result of large investments under the Viking program, to accomplish this phase of the EDL sequence. This parachute technology requires a deployment velocity of less than ≈ M 2 and an altitude above ground level of between ≈ 9 to 12 km before entering the terminal landing phase.

The third or landing phase begins at a suitable altitude and terminal velocity of the descent system that is within the ΔV/altitude capability of the landing system. The landing system delivers the probe into contact with the ground within pre-selected vertical and horizontal velocity constraints. For legged, propulsive soft lander probes, the vertical and horizontal velocity components are generally lower at touchdown than for airbag lander probes and the horizontal velocity component is generally lower than the vertical velocity component, because legged landers are sensitive to tip-over moments at the instant of touchdown. The Viking soft landers, for example were designed to a requirement of ≤ 2.4 m/s vertical touchdown velocity and ≤ 1 m/s horizontal velocity. By comparison, the MER-A airbag lander was designed to a requirement of ≤ 8 m/s vertical touchdown velocity and ≤ 11.5 m/s horizontal velocity.

The single most common feasibility issue that is raised by reviews of the Red Dragon entry concept is the hypersonic entry phase of the EDL problem. Red Dragon is a capsule that is designed to enter into the atmosphere of Earth, which is approximately 100 times thicker than Mars' atmosphere. In order to perform the MSR mission, the Mars entry mass is high, approaching 10 mt. The ability to successfully decelerate and land such a Red Dragon capsule using only Mars' thin atmosphere, is not obvious until analytical techniques are applied.

This issue was addressed computationally in detail by Braun and Manning [9] and later by ARC and the Jet Propulsion Laboratory (JPL) [10, 11]. The latter two works were presented at the Concepts and Approaches for Mars Exploration conference in June, 2012. A fundamental result discussed in these works is that a capsule with β ≥ 400 kg/m2 would not be able to execute a purely ballistic EDL (as did, e.g., Mars Pathfinder) because of Mars' thin atmosphere. However, a modest amount of aerodynamic lift during the hypersonic phase is adequate to perform a successful, lifting EDL, with margin. The reason for this may be thought of as follows: a probe executing a purely ballistic entry is constrained to exchange momentum with the atmosphere only in the direction of the probe velocity; it therefore must shed all its excess cosmic velocity in an atmospheric column ≈ 500 km in length or collide with the planet's surface. By contrast, a probe with a component of aerodynamic lift has an easier task; it must only nullify the vertical component of its entry velocity before colliding with the planet's surface. At typical entry angles (≈ - 15 deg.) the vertical component amounts to approximately 25% of the total.

The simplest strategy is to give the probe a constant angle-of-attack (α) from the atmospheric interface (≈ 125 km altitude) through the entire hypersonic deceleration phase. As the probe encounters atmospheric density that is increasing exponentially with depth into the atmosphere the magnitude of upward lift is also increasing exponentially with distance along the track. Eventually, the probe "bounces" off of a density altitude barrier as shown in Figure 1. At this inflection point in the trajectory the probe velocity is slightly greater than the orbital velocity of ≈ 4.1 km/s for that altitude producing an excess of centrifugal force over gravitational attraction. This condition causes the

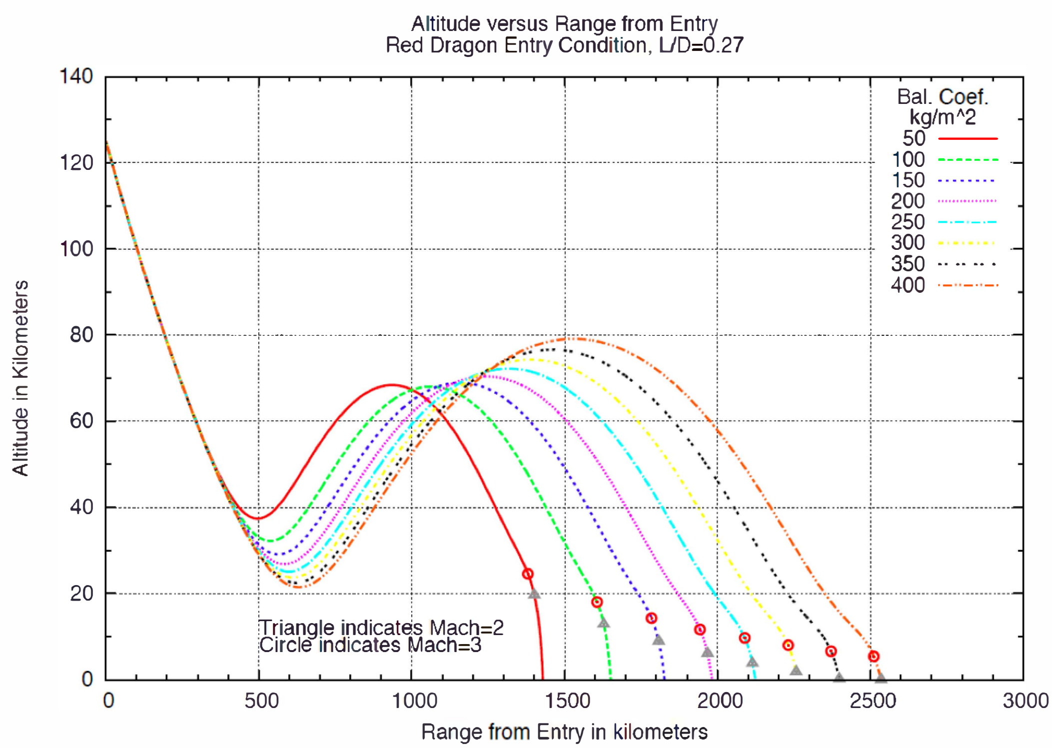

Figure 1. Range vs Altitude for High-β Mars Entry With Aerodynamic Lift

probe altitude to increase or "loft" for a period of time during which it continues to lose kinetic energy via atmospheric drag. Within ≈ 10 sec of substantially horizontal flight at high atmospheric density, the probe has dissipated sufficient kinetic energy that it is incapable of leaving Mars' gravitational field, and it ultimately must approach a terminal velocity condition. Flying along this arc, the capsule transects an atmospheric column that is thousands of km in extent instead of the hundreds of km that would be encountered with a purely ballistic entry. It is this greatly extended trajectory at low altitudes where atmospheric density is relatively high that is responsible for effectively decelerating the high-β capsule. Figure 1 shows a family of trajectories for a range of β values, of probes executing this of lift-up strategy with constant entry conditions (v = 6 km/s, γ = -13 deg., L/D = 0.27). The trajectories were computed with the ARC in-house computer program, TRAJ, which is used as a preliminary design and analysis tool for most NASA missions requiring atmospheric entry. Figure 1 shows that probes with higher β lose kinetic energy slower than probes with lower β. Probes with higher β also arrive at the inflection point later. Finally, probes with higher β pull-up at lower altitudes but with greater excess velocity (and therefore greater excess centrifugal force) than probes with lower β. This leads to the counterintuitive result that heavier probes loft to higher altitudes than lighter probes, prior to terminal descent.

As mentioned above, all NASA Mars probe missions to date (except for the ill-fated DS-2 probes) have been required to achieve a deployment Mach number, M ≤ 2.0 at an altitude of ≈ 10 km above ground level. One consequence of increasing the entry mass of a probe (and therefore its β) is that the altitude at which M ≤ 2.0 is achieved becomes monotonically lower. This pattern holds for either purely ballistic or for lifting entries at Mars. From Figure 1, it can be seen that a β of ≈ 250 results in reaching M = 2.0 at an altitude that is marginally acceptable for parachute deployment and descent to a landing at the lowest terrain elevations on Mars. This represents a hard limit for the β at which Viking heritage parachutes could be considered for supersonic deceleration. We estimate that payload-carrying Red Dragon capsules would be loaded to achieve a β in the range of ≈ 450 to 650. Moreover, the total mass of a Red Dragon capsule would require a parachute diameter that exceeds the size range to which a Viking heritage supersonic parachute design can be extended, even if the Mach number criterion could be met. For these reasons, the Red Dragon capsule cannot use parachute decelerators for the supersonic deceleration portion of EDL and instead is committed to use supersonic retro propulsion (SRP). Because rocket powered thrusters will be used for SRP, it would be advantageous to use the same thruster system for the final soft touchdown. Thus, one propulsive system will be used for both the Descent and the Landing phase of Red Dragon.

Given this choice, it is desirable to minimize the total energy of the capsule that must be removed propulsively during the supersonic deceleration and final landing, as that will minimize the propellant mass fraction required in the capsule. The total energy budget that must be removed propulsively contains a component due to the terminal velocity at the moment propulsive deceleration begins, a component due to gravity losses, and a component due to the final hazard avoidance and soft landing ΔV requirement. Of these three factors, the soft landing ΔV requirement is relatively small and fixed. However, the terminal velocity and gravity losses can be minimized relative to the trajectories depicted in Figure 1 by utilizing a more sophisticated bank-angle control strategy. In this strategy, the capsule enters the atmosphere with a lift-downward angle of attack. This causes the capsule to proceed to greater depth into the atmosphere, more quickly. Immediately prior to the inflection point in the trajectory, the capsule banks 180 deg. around the velocity vector to achieve a lift-up configuration. Figure 2, generated with the POST trajectory computer program, shows the effect of this strategy, graphically. This change in sign of the lift vector greatly suppresses the loft in the trajectory and creates a nearly constant altitude flight path. The result is a significant decrease in both the altitude and the vertical velocity component at the time propulsive deceleration begins, which acts to minimize the propellant mass fraction used for terminal descent. This entry strategy requires active flying of the capsule with reference to the density altitude of the atmosphere, as compared to the passive deceleration of the capsule depicted in Figure 1.

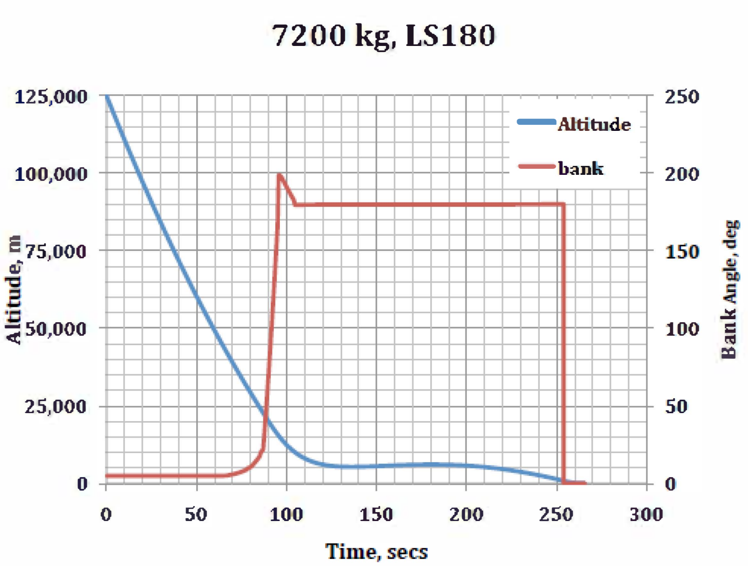

Figure 2. Baseline Trajectory

4. Performance Sensitivities

In the intervening time since the June, 2012 publications [9, 10], ARC has continued to explore the Red Dragon EDL problem, in

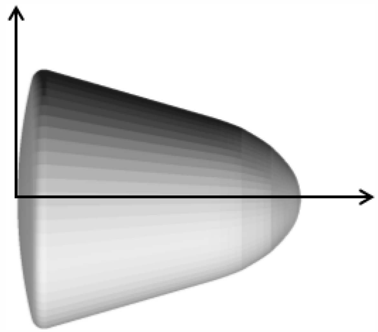

Figure 3. Ames Research Center Geometry Model for Red Dragon CFD and Engineering Analysis

order to estimate the amount of useful payload mass that could be landed over a range of arrival conditions. In this study, we have used the POST program to compute a large number of entry cases for the ARC Red Dragon configuration, varying parameters such as entry mass, entry angle, hypersonic L/D, landing site elevation, and atmospheric density at season of arrival. We assume the use of bank angle modulation (as depicted in Figure 2.) in all results.

Baseline Approach

Our study approach was to utilize a baseline EDL case and then perturb the parameters around the baseline and compare the resulting change in performance. A crucial part of estimating the performance of a putative Red Dragon capsule is knowledge of its hypersonic Drag Coefficient (CD) and its L/D. We independently estimated its hypersonic aerodynamic properties by creating an ARC geometry and mass properties model (Figure 3) and subjecting it to CFD and mass properties analyses using the CART3D and CBAERO computer codes. The results of these analyses are shown in Figure 4.

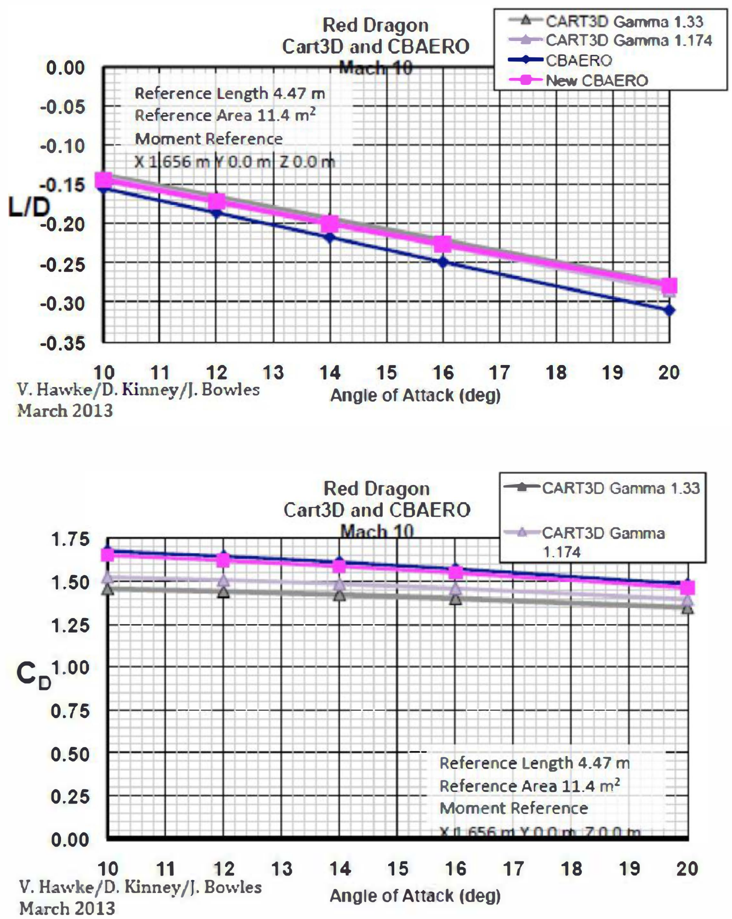

Figure 4. Aerodynamic Coefficients versus Angle of Attack, L/D (above) and C_D (below)

Our baseline trajectory enters a 7,200 kg mass into Mars' atmosphere in the low atmosphere density season (Ls = 180°) with inertial entry velocity = 6000 m/s, inertial flight path angle = -14o, entry altitude = 125 km, and L/D = 0.2.

Figure 5 shows the variation in Mars' atmospheric density as a function of altitude depending on the season of arrival for 0o latitude, 0o longitude, as computed by Mars GRAM 2010. As can be seen, the total atmospheric column density when Mars is at heliocentric longitude Ls =270° is approximately 25% greater than when it is at Ls = 180°. Intuitively, one would expect that an atmosphere with lower total mass will cause a given amount of aerodynamic deceleration to occur at a lower altitude than an atmosphere with greater mass and, indeed, this is found to be the case. For a constant entry mass, arriving at Mars at the season of minimum atmospheric mass will either reduce the amount of probe mass that can be landed to a given terrain elevation or lower the terrain elevation at which a given probe mass can be delivered, or a combination of both. By choosing the atmosphere model at Ls = 180° as the baseline, we are implicitly comparing other EDL conditions to the worst case.

In order to calculate performance all the way from the entry interface to the Martian surface, it was necessary to include parametric modeling of the Super Draco propulsion system. We model the propulsion system as consisting of 4 pairs of thrusters arranged symmetrically around the circumference of the capsule above the beltline, canted outward at a 20° angle. The total thrust level is 427,000 N, divided equally between the 8 engines. The assumed Isp is 265.3 sec.

We model the propulsive phase of the descent and landing as an optimal (bang-bang) propulsive burn that begins at 900 m above the target landing elevation (0 km, baseline) and decelerates the capsule from its velocity at that point (typically ≈ Mach 2.5) down to 3 m/s vertical and zero horizontal velocity 100 m above the targeted landing point.

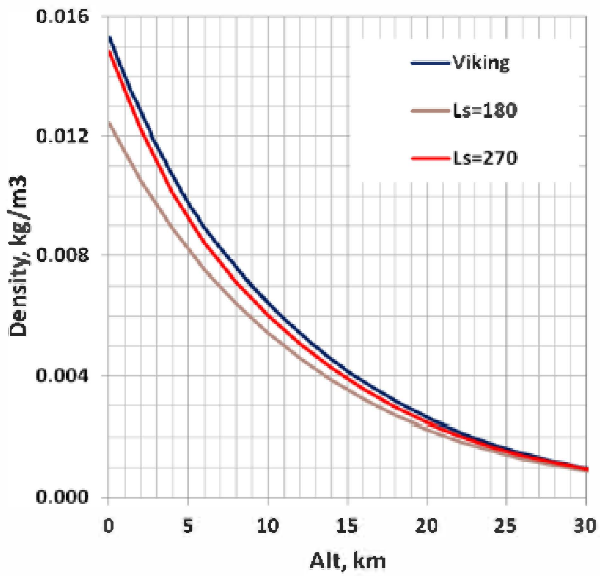

Figure 5. Mars GRAM 2010 at Latitude = 0^o, Longitude = 0^o

This is the SRP burn. The terminal landing phase is modeled as a constant rate descent at 3 m/s including a 100 m lateral divert maneuver, to accommodate terminal hazard avoidance.

Entry Flight Path Angle

We examined the effect of entry flight path angle errors on the EDL performance. First we considered the effect of entry flight path angle variation on the velocity remaining at the time SRP begins (the Staging Mach No.). We varied the entry flight path angle between – 13 and -15 degrees, from the baseline case and found negligible effect from this source (≈ 1%; Figure 6).

component that varies directly with the staging Mach number. Because the staging Mach number is only a fraction of the total ΔV budget, we would expect the variation in landed mass as a function of variation in entry flight path angle to be smaller than 1% and, indeed, we find that it is (≈ 0.4%). In recent NASA Mars missions it is common to arrive at Mars with an actual EFPA error of ≤ 0.25 degrees. Hence, these results gives confidence that adopting a nominal entry flight path angle of -14 degrees will result in a robust EDL solution.

Figure 7 shows the results of variation in entry flight path angle when propagated through the propulsive phase of EDL. It should be recalled that the propulsive ΔV budget contains a relatively invariant component due to gravity terms and terminal divert and descent budget, and a

Lift-To-Drag Ratio (L/D

As previously discussed, achieving a substantial L/D during the hypersonic phase of entry is critically important for the successful EDL of high-β probes. Fixed geometry capsules such as Red Dragon achieve lift via a static offset between the center of mass (CM) and the center of lift (CL) of the capsule. The resulting offset between the CL and the CM forces the capsule fore body into a fixed α relative to the free stream velocity. Over a broad range, the magnitude of the lift vector increases linearly with α. However, increasing α also can also result in an increase in localized aerothermodynamic heating on the fore body (and sometimes the aft body). Also, maintaining a large α requires either large static ballast or the dynamic expenditure of attitude control propellant. Either approach imposes parasitic mass on the capsule. Thus, for multiple reasons it is desirable limit α to the minimum necessary to accomplish the mission. In analogy with the EFPA study, we first examined the effect of variation in a on the staging Mach number. The results are shown in Figure 8. As expected, there is a substantial and significant effect from this source.

Figure 9 shows the results of the variation in a when propagated through the propulsive landing transfer function. The relation between L/D and landed mass is clearly non-linear, with a knee in the curve at L/D = 0.2 (corresponding to a ≈ 13 deg.) Blunt body entry vehicles similar to Red Dragon (such as the Apollo capsules) have been tested at a ≤ 24 degrees. Hence, selecting a = 12 degrees and L/D = 0.2 represents a conservative position, with performance margin held in reserve.

Season of Arrival

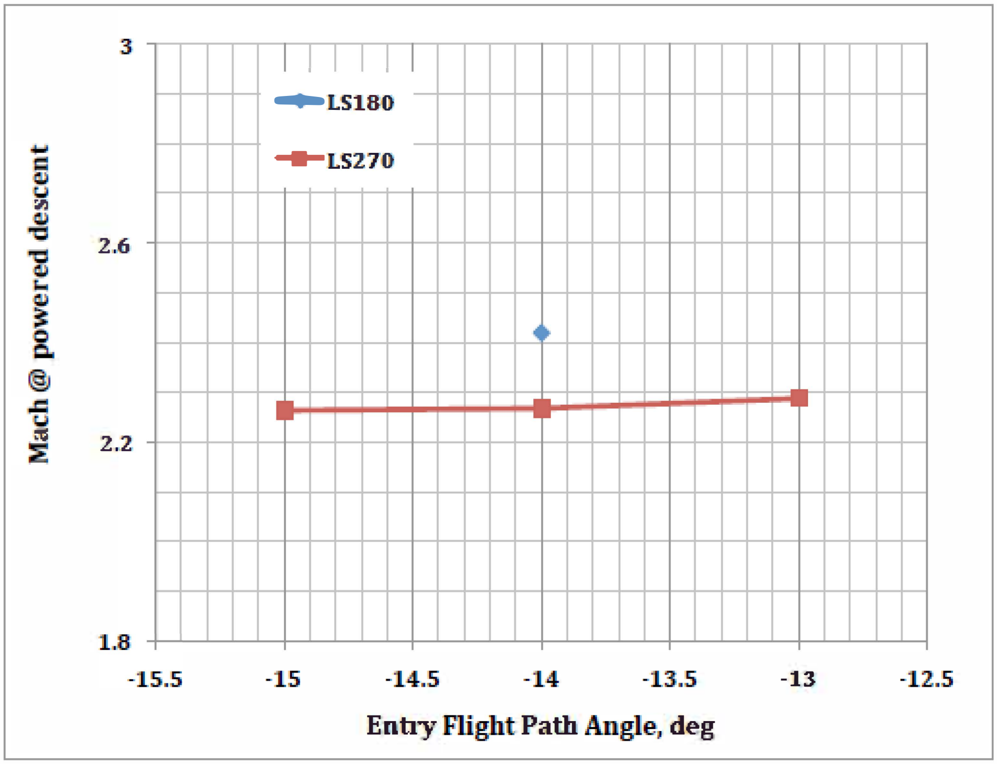

Figure 6. Staging Mach Number vs Entry Flight Path Angle

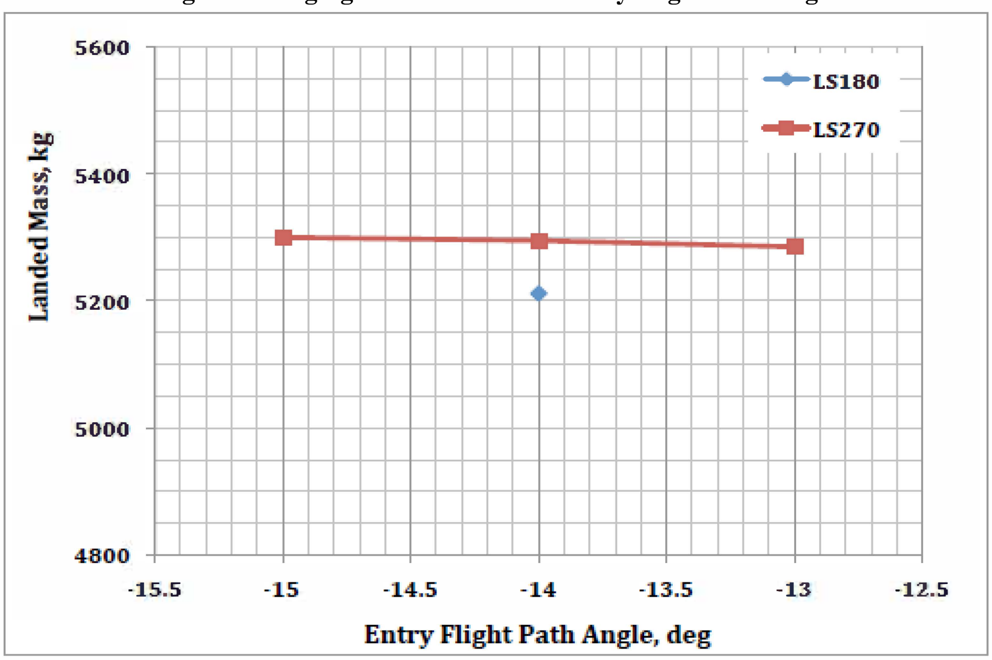

Figure 7. Landed Mass vs Entry Flight Path Angle

All the EDL performance parameters considered up to this point can be selected either directly or indirectly by the mission engineer. These parameters include entry velocity, v, EFPA, L/D, and β (or, alternatively, total mass, M). We will now turn our attention to the column density profile of Mars' atmosphere through which the capsule must fly on its way to the landing site. This parameter is determined by Mars, itself. For a given landing site elevation, the column density is determined by Mars' season at the time of arrival. For a given season of arrival, the column density is determined by Mars' terrain elevation at the desired longitude and latitude. For a fixed entry mass, a probe flying to a landing site through an atmospheric column with fewer air molecules in it has to perform a larger fraction of the deceleration work propulsively rather than aerodynamically. This will result in a probe with a higher propellant mass fraction that is expended during landing and therefore, a lower landed mass (and lower useful payload mass). This relationship is shown graphically in Figure 10. The landed mass varies essentially linearly with landing site elevation over the range of elevations considered, for both times of arrival. The curves effectively define the trade between payload and landing site elevation. A probe with the baseline entry mass considered (7200 kg) could land approximately 100 kg extra payload to a given landing site if it arrived at Ls = 270° instead of Ls =180°. Alternatively, such a probe could land with the same payload at a landing site 1.6 km higher if it arrived at Ls = 270° instead of Ls =180°.

Maximum Landed Mass

Finally, we consider how far the parametric Red Dragon model may be extrapolated. Performance of the Falcon Heavy has been derived by Tito, et al [12] and is shown in Figure 11, which shows the estimated capability of the SpaceX Falcon Heavy to launch payloads to deep space trajectories (e.g., C3 > 0).

In our MSR study, we considered Type-1 Earth-Mars launch opportunities in 2022, 2024, and 2026. The maximum C3 for that set of opportunities is 13.2 km2/s, associated with the September, 2022 launch window. The estimated throw capacity of a Falcon Heavy for that opportunity is about 13,500 kg. Within that launch mass budget, allowance must be made for the Red Dragon capsule, the "trunk" attached to it containing power, comm., and thermal control utilities, and reserve. Allowing approximately 1000 kg for the mass of the trunk and a 20% contingency reserve, we estimate the practical upper limit for the entry mass of a Red Dragon is 10,000 kg. Figure 12 shows the computed landing performance of a Red Dragon capsule in the mass range, 6,750 to 10,000 kg.

As expected, the relationship between entry mass and landed mass is essentially linear over the range considered. However, it should be noted that the propellant mass fraction is not constant over the interval. At the lower end of the mass range, the propellant mass fraction is ≈ 0.27 and at the upper end it is ≈ 0.31. This reflects the fact that, for a fixed OML, the heavier probe will have a higher β, which requires the propulsion system to handle a larger fraction of the total deceleration. The estimated (ARC estimate) empty mass of the Red Dragon capsule is 4620 kg, while the calculated landed mass of a Red Dragon entering the Martian atmosphere at 10,000 kg is 6850 kg. The difference between the two figures (2230 kg) represents the total that is available for useful payload (MAV, ERV, sample acquisition arm, etc.). The current mass required (including reserve) for the MSR payload is ≈ 2080 kg. The payload that can be accommodated in Red Dragon corresponds to an entry mass of ≈ 9,700 kg. and will allow the MSR mission to be accomplished. [8]

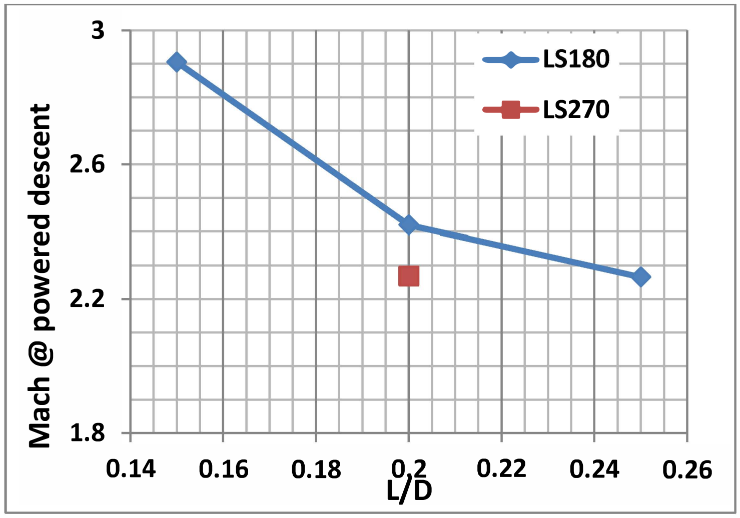

Figure 8. Staging Mach Number vs. L/D

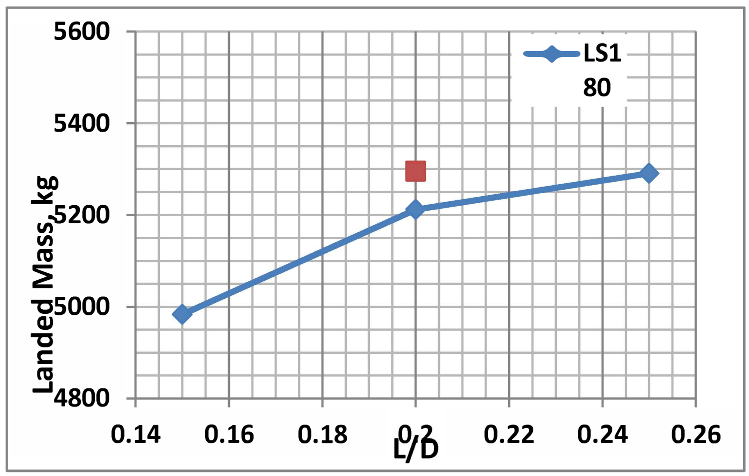

Figure 9. Landed Mass vs. L/D

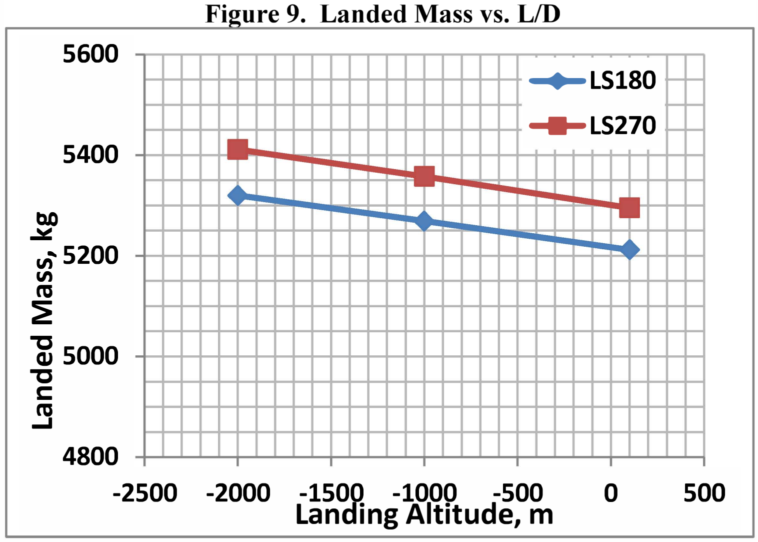

Figure 10. Landed Mass vs. Landing Site Elevation

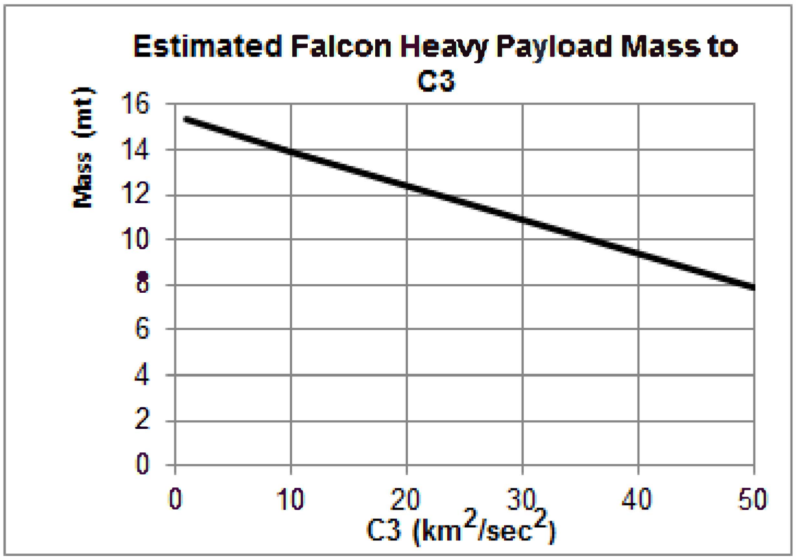

Figure 11. Derived Falcon Heavy Launch Performance [12]

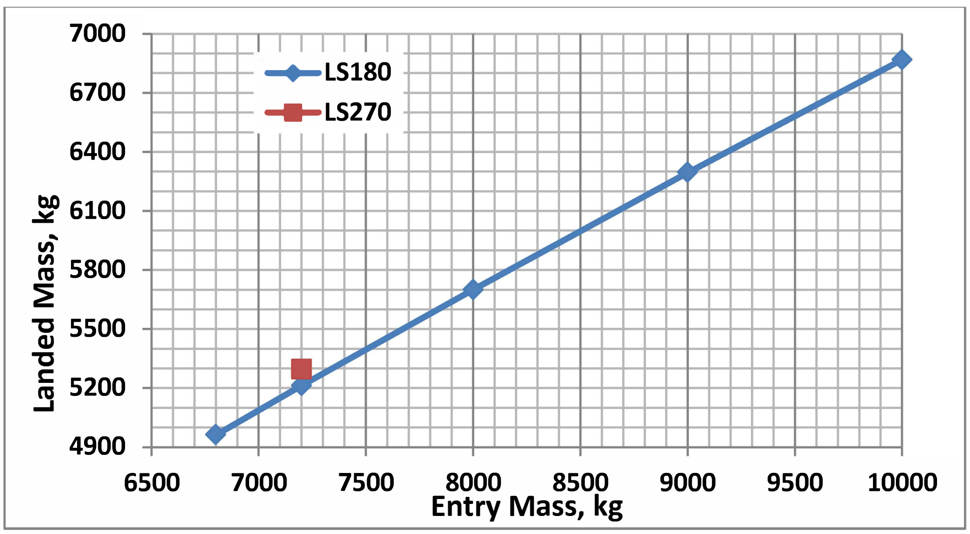

Figure 12. Landed Mass vs. Entry Mass

5. SUMMARY AND CONCLUSION

EDL capabilities of a putative Red Dragon capsule have been investigated using publicly available data and Ames Research Center engineering judgment. Among the 5 EDL parameters considered (atmosphere, L/D, landing elevation, entry mass, and entry flight path angle), entry mass is the most important contributor to landed mass. A 1.2% increase in entry mass results in 1% gain in landed mass. In contrast, L/D requires 32% increase for 1% gain in landed mass. Entry flight path angle has negligible effect on the landed mass. Landing elevation has a modest influence on the landed mass. For every 1 km reduction in landing elevation, landed mass increases by ~60 kg. The effect of the atmosphere is also modest. Landed mass gains about 100 kg when the EDL occurs during the high atmospheric density season compared to low atmospheric density season. The relationship between landed mass and entry mass is linear over a wide range of entry mass. An entry mass of ≈ 10,000 kg appears to be both deliverable by the Falcon Heavy launcher and able to successfully enter, descend, and land using the aerodynamics intrinsic to the Dragon OML and the propulsive capabilities of the Super Draco engines.

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Disclaimer

The work described in this paper was performed internally by NASA's Ames Research Center using information in the public domain and without the assistance of any commercial organization. There is no endorsement of any particular commercial organization by NASA. There is also no endorsement of this work by any particular commercial organization.

BIOGRAPHIES & CONTRIBUTIONS

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