Entry, Descent, and Landing Technology Concept Trade Study for Increasing Payload Mass to the Surface of Mars

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ABSTRACT

A trade study was conducted that compared various entry, descent, and landing technologies and concepts for placing an 1,800 kg payload on the surface of Mars. The purpose of this trade study was to provide data, and make recommendations, that could be used in making decisions regarding which new technologies and concepts should be pursued. Five concepts were investigated, each using a different combination of new technologies: 1) a *Baseline* concept using the least new technologies, 2) *Aerocapture and Entry from Orbit*, 3) *Inflatable Aeroshell*, 4) *Mid L/D Aeroshell-A* (high ballistic coefficient), and 5) *Mid L/D Aeroshell-B* (low ballistic coefficient). All concepts were optimized to minimize entry mass subject to a common set of key requirements. These key requirements were: A) landing a payload mass of 1,800 kg, B) landing at an altitude 2.5 km above the MOLA areoid, C) landing with a descent rate of 2.5 m/s, and D) using a single launch vehicle available within the NASA Expendable Launch Vehicle Contract without resorting to in-space assembly. Additional constraints were implemented, some common to all concepts and others specific to the new technologies used. Among the findings of this study are the following observations. Concepts using blunt-body aeroshells (1, 2, and 3 above) had entry masses between 4,028 kg and 4,123 kg. Concepts using mid *L/D* aeroshells (4 and 5 above) were significantly heavier with entry masses of 5,292 kg (concept 4) and 4,812 kg (concept 5). This increased weight was mainly due to the aeroshell. Based on a comparison of the concepts it was recommended that: 1) re-qualified and/or improved TPS materials be developed, 2) large subsonic parachutes be qualified. Aerocapture was identified as a promising concept, but system issues beyond the scope of this study need to be investigated. Inflatable aeroshells were identified as a promising new technology, but they require additional technology maturation work. For the class of missions investigated in this trade study, mid *L/D* aeroshells were not competitive on an entry mass basis as compared to blunt-body aeroshells.

SYMBOLS AND ACRONYMS

C3	hyperbolic excess velocity squared
g	Earth acceleration of gravity (9.81 m/s^2)
h	altitude above the surface (AGL) at the landing site
L/D	lift-to-drag ratio
M	Mach number
q	dynamic pressure
V_v	vertical descent velocity

AGL	Above Ground Level
DGB	Disk-Gap-Band (parachute type)
EDL	Entry, Descent, and Landing
MOLA	Mars Orbiter Laser Altimeter
NASA	National Aeronautics and Space Administration
POST II	Program to Optimize Simulated Trajectories version II
RCS	Reaction Control System
TPS	Thermal Protection System
TRL	Technology Readiness Level

INTRODUCTION

Recent NASA studies indicate that the entry, descent, and landing (EDL) technologies currently available (e.g., Viking-type blunt-body aeroshells, disk-gap-band (DGB) parachutes) will not be adequate to support future missions to Mars with payloads[1] significantly greater than 900 kg. Larger, more challenging missions will need new technologies and EDL system concepts. The present trade study compares various new technologies and system concepts suitable for future robotic missions to Mars. Five concepts were investigated, each using a different combination of new technologies. The concepts, and the new technologies required to make them feasible, are shown in table 1. All five concepts were optimized to minimize the entry mass at Mars while meeting the same set of key requirements. This paper describes these concepts, discusses the optimized designs, compares their relative merits, and makes recommendations regarding which new technologies and concepts should be pursued.

KEY REQUIREMENTS AND ASSUMPTIONS

All concepts were optimized for minimum entry mass while meeting the following four key requirements:

- *Payload mass of 1,800 kg.* This payload mass is high enough to support Mars sample return missions.

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[1] In this paper, payload is defined as the scientifically useful portion of the landed mass. Thus the payload includes, for example, the scientific instruments, power, mobility, and communications systems but excludes items such as terminal descent propulsion systems, airbags, and landing platforms.

- *Landing altitude 2.5 km above the MOLA (Mars Orbiter Laser Altimeter) areoid* [1]. This landing altitude requirement sets a challenging minimum performance threshold for the EDL system since higher landing altitudes, with their corresponding lower atmospheric densities, reduce the time and altitude available to successfully complete the EDL sequence.

- *Descent rate at touchdown of 2.5 m/s.* This requirement was selected to be consistent with that specified for the Viking landers [2].

- *Utilize a single launch vehicle available within the NASA Expendable Launch Vehicle Contract without resorting to in-space assembly.* Limiting the selection of launch vehicles in this way is an acknowledgement that a new launch vehicle will probably not be developed in the near future for a robotic mission to Mars. The launch vehicle requirement imposes the most important constraints on the concepts: a rigid aeroshell diameter no greater than 4.572 m.

Several assumptions were made that either implemented the key requirements or completed the definition of the optimization problem. Among these assumptions were the landing site (0.33° N, 46.19° E), which implemented the landing altitude requirement, using a prograde direct entry, and selecting launch/landing dates and times that helped in specifying the atmospheric profile, inertial entry velocity, and C3 required.[2]

OPTIMIZATION METHODOLOGY

The design of the five concepts was posed as an optimization problem to minimize entry mass subject to a series of constraints. All calculations were performed with POST II - Program to Optimize Simulated Trajectories version II [3]. Parametric mass models for all components and expendables were embedded into the optimization. All "best estimate" mass models were multiplied by a factor of 1.3 to generate the allocation mass values used in the optimization calculations. Numerous constraints were implemented. Some of these constraints, such as the descent rate at touchdown, were enforced in the optimization for all concepts. Additional concept-specific constraints were also applied. For example, in concepts using supersonic DGB parachutes, the parachute's nominal diameter was constrained to be less than or equal to 19.7 m, a limit based on available flight test experience. Each concept had its own set of design variables, including quantities such as those that governed the entry guidance, parachute size, and terminal descent fuel consumption. Various databases and models were required to perform the optimizations. Among these were aerodynamic databases for the aeroshells and parachutes, and the Mars-Gram 2001 [4] model of the martian atmosphere. In defining constraints, databases, and models, a "cautiously aggressive" approach was used – although the limits of the specific technologies were approached, these limits were not exceeded. All optimizations were conducted on nominal trajectories; no dispersed Monte Carlo analyses were conducted. To avoid unrealistic results, some parameters were constrained to include a margin for uncertainty. For example, although 30 to 40 seconds was considered to be sufficient to complete all tasks required by the EDL sequence from subsonic parachute deployment to the start of the terminal propulsive descent, this time was constrained in the optimization to be greater than or equal to 72 seconds. This time constraint provided margin to account for uncertainties and dispersions in such things as the parachute drag coefficient and atmospheric density.

CONCEPTS INVESTIGATED

Five concepts were investigated, each using a different combination of new technologies. The *Baseline* concept is similar to those currently in use by Mars missions, thus minimizing the use of new technologies. The other four concepts: *Aerocapture and Entry from Orbit*, *Inflatable Aeroshell*, *Mid L/D Aeroshell-A*, and *Mid L/D Aeroshell-B*, use at least one new technology. These four concepts are named after the entry technology used. Because of the descent rate requirement, all five concepts use the same terminal descent strategy: a subsonic parachute followed by liquid-fueled rockets for the terminal descent stage. Impact attenuation systems such as airbags were not considered.

Baseline

The *Baseline* concept consists of a 4.572 m diameter Viking-type aeroshell,[3] a supersonic DGB parachute, a subsonic ringsail parachute, and liquid-fueled rocket engines for the terminal descent stage. Figure 1 shows the concept of operation. Entry is lifting and guided. The supersonic parachute decelerates the entry vehicle from supersonic to subsonic speed, and serves as a pilot parachute for the subsonic parachute. After the heatshield is released during the subsonic parachute stage, the lander separates and completes the descent with the propulsive terminal descent stage. Table 2 lists several key parameters for this concept. Of most interest is the peak stagnation heat rate at 70 W/cm^2 near the nose of the heatshield. Because of the size of the aeroshell, it is likely that the boundary layer will transition downstream of the stagnation point. The peak heat rate somewhere downstream of the stagnation point on the heatshield is expected to be two to three times the stagnation value, that is 140 to 210 W/cm^2. NASA has used SLA-561V as the thermal protection system (TPS) for its previous missions to Mars. Although SLA-561V has been tested at heat rates up to 237 W/cm^2 [6], it has not been qualified for flight at such high heat rates. Thus, to make this concept viable, either SLA-561V must be re-qualified at heat rates between 140 and 210 W/cm^2, or a new TPS material must be qualified. A subsonic parachute[4] is another new technology that would also be required by this concept, as shown in table 1. Table 3 shows the allocated

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[2] C3 is the hyperbolic excess velocity squared; it is a measure of the energy required for the chosen interplanetary trajectory.

[3] A Viking-type aeroshell consists of a 70° sphere-cone forebody and a biconical aftbody.

[4] A subsonic parachute is included as a new technology in this study because the concepts investigated here require canopies with large nominal diameters (43.1 to 57.2 m) or equivalently, a cluster of smaller canopies. For comparison, the largest parachute yet flown on Mars was 16.15 m in a single canopy configuration by the Viking mission [2].

mass breakdown for this concept. With a launch mass of 4,708 kg, this concept could be launched with either a Delta IV 4050H-19 or an Atlas V 551. The entry mass is 4,099 kg. A key measure of the EDL efficiency is the entry mass to payload mass ratio. For the *Baseline* concept this ratio is 2.28.

Aerocapture and Entry from Orbit

To reduce the challenges imposed on the TPS by the peak heat rate on the *Baseline* concept, a related concept involving aerocapture and entry from a subsequent orbit was investigated. This concept uses a 4.572 m diameter Viking-type aeroshell with two heatshields, a supersonic DGB parachute, a subsonic ringsail parachute, and liquid-fueled rocket engines for the terminal descent stage. Figures 2A and 2B show the concept of operation. In an initial aerocapture pass, the entry vehicle is captured into a 3-hour orbit. After aerocapture the first heatshield is released. Doing so eliminates issues related to re-using the heatshield TPS and heat transfer from the heatshield to the spacecraft. Once apoapsis is reached during the first orbit, a propulsive maneuver raises the periapsis. At this point the entry vehicle is in a stable orbit from which entry, descent, and landing can proceed as in the *Baseline* concept. In both the aerocapture and final entry passes the entries are lifting and guided. Table 2 lists several key parameters for this concept. The aerocapture and entry peak stagnation heat rate entries are, respectively, 38 and 33 W/cm^2 – approximately half the 70 W/cm^2 value of the *Baseline* concept. Thus, the *Aerocapture and Entry from Orbit* concept achieves one of its desired goals – to reduce the peak heat rate to a level within the qualified capabilities of the SLA-561V TPS material. An additional benefit of this concept, as compared to the others considered here, is the lower peak entry acceleration (5.2 g). Thus, this concept may be useful for payloads that require lower peak entry acceleration. Because of the energy lost during the aerocapture pass, the entry pass is initiated at a lower velocity. One of the consequences of this lower entry velocity is that the supersonic parachute must be deployed at nominal Mach number of 2.75 (3.0 maximum) to satisfy timeline constraints on descent. This implies development of a new supersonic parachute – something that has not been done since Viking. Thus, a Mach 3 parachute is listed in table 1 as a required new technology. This concept also requires a subsonic parachute – another new technology. In addition to the new technologies, this concept adds system design and operational complexity to its development since it has to function as an entry vehicle during the aerocapture pass, as an orbiter, and as an entry vehicle again during the final entry pass. Table 3 shows the allocated mass breakdown for this concept. With a launch mass of 5,077 kg, this concept could be launched with a Delta IV 4050H-19. The entry mass for this concept is 4,428 kg for the aerocapture pass and 4,123 kg for the final entry pass. This concept has an entry mass to payload mass ratio (i.e., EDL efficiency) of 2.29.

Inflatable Aeroshell

Many of the EDL challenges with the concepts in the present study arise from the launch vehicle fairing maximum diameter constraint, which limits rigid aeroshells to 4.572 m in diameter. To circumvent this constraint, the *Inflatable Aeroshell* concept was studied. This concept consists of a 14.4 m diameter, sphere-cone inflatable aeroshell with a rigid spherical nose cone (i.e., heatshield) of 4.572 m in diameter, a supersonic drogue parachute, a subsonic ringsail parachute, and liquid-fueled rocket engines for the terminal descent stage. Figure 3 shows the concept of operation. Before entry, the aeroshell is inflated by a set of gas generators. Entry is lifting and guided. At a Mach number of approximately 1.75 a drogue parachute is deployed to assist in stabilizing the inflatable aeroshell from the low supersonic through transonic speed range. Once the Mach number drops below one, the inflatable aeroshell, backshell, and drogue parachute are released and the subsonic parachute is deployed. Shortly thereafter the heatshield is released. At this point the terminal descent and landing proceeds as in the *Baseline* concept. Table 2 lists several key parameters for this concept. An important difference in the optimization for the *Inflatable Aeroshell* concept, as compared to the other concepts, is that the peak stagnation heat rate is used as a constraint. This is done to protect the textile materials in the inflatable portion of the aeroshell from excessive heat rates. The value selected for the peak stagnation heat rate, 10 W/cm^2, is an estimate based on our current understanding of inflatable aeroshells. Changing the value of the peak stagnation heat rate has a significant effect on the inflatable aeroshell diameter and the entry mass as shown in table 4. Because the appropriate value for the allowable peak stagnation heat rate is uncertain, our results for the *Inflatable Aeroshell* concept should be considered preliminary – improved understanding of these systems will yield more accurate results.[5] It is also worth noting that this concept subjects the payload to large sustained accelerations with a peak up to 11.8 g during entry. Thus, as proposed here, this concept may not be suitable for payloads that require low entry accelerations. In addition to the inflatable aeroshell, a subsonic parachute is another new technology required by this concept as shown in table 1. The mass breakdown for this concept is shown in table 3. With a launch mass of 4,627 kg, this concept could be launched with either a Delta IV 4050H-19 or an Atlas V 551. The entry mass is 4,028 kg. This concept has an EDL efficiency of 2.24.

Table 4. Sensitivity of the inflatable aeroshell diameter and entry mass to the peak stagnation heat rate

Peak Entry Stagnation Heat Rate	Inflatable Aeroshell Diameter	Entry Mass	Entry Mass / Payload Mass
10 W/cm^2	14.4 m	4,028 kg	2.24
15 W/cm^2	9.6 m	3,867 kg	2.15
20 W/cm^2	9.0 m	3,857 kg	2.14

Mid *L/D* Aeroshell-A

The *Baseline*, *Aerocapture and Entry from Orbit*, and *Inflatable Aeroshell* concepts utilize blunt-body aeroshells with low lift-to-drag ratios (*L/D*). An alternate option is to use an aeroshell that provides higher *L/D* values. The *Mid L/D Aeroshell-A* concept[6] consists of an ellipsled aeroshell,[7]

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[5] NASA has ongoing programs to increase the technology readiness level of inflatable aeroshells [7].

[6] Mid values of *L/D* for aeroshells are considered to be in the range from 0.3 to 0.9.

an inflatable supersonic decelerator, a subsonic ringsail parachute, and liquid-fueled rocket engines for the terminal descent stage. Figure 4 shows the concept of operation. Entry is lifting and guided. An inflatable supersonic decelerator is deployed at a nominal Mach number of 3.25 and shortly thereafter the ellipsled aeroshell is released. Once the lander decelerates to subsonic speeds, the inflatable supersonic decelerator is release and a subsonic parachute deployed. Terminal descent and landing then continue as in the *Baseline* concept. Table 2 lists several key parameters for this concept. The mass density of the entry vehicle for this concept, its entry mass divided by the ellipsled aeroshell volume, is as high as was deemed feasible. Because of this, the ellipsled aeroshell in this concept is smaller in diameter (3.0 m) than the available launch vehicle fairing (4.572 m). Thus this is the only concept studied for which the launch vehicle fairing diameter is not an active constraint. The peak stagnation heat rate is 63 W/cm². Increases in the peak heat rate beyond this value downstream of the stagnation line are possible if boundary layer transition occurs. Thus, as was the case for the *Baseline* concept, this concept requires either re-qualification of the currently used TPS material, SLA-561V, or development and qualification of a new TPS material. Because of the high entry vehicle mass density, the supersonic to subsonic deceleration stage needs to start at a nominal Mach number of 3.25 to meet the timeline constraint. Parachute performance (e.g., drag coefficient, inflated stability) degrades rapidly at high Mach numbers in low-density atmospheres. Thus, an inflatable supersonic decelerator was used in this concept instead of a supersonic parachute. The specific inflatable supersonic decelerator used in this concept is the hypercone [8] - an inflated torus attached to the entry vehicle through a textile cone. As shown in table 1, this concept will require the development of four new technologies: TPS, a mid *L/D* aeroshell, an inflatable supersonic decelerator, and a subsonic parachute. The mass breakdown for this concept is shown in table 3. With a launch mass of 6,043 kg, this concept could be launched with a Delta IV 4050H-19. The entry mass for this concept is 5,292 kg. The EDL efficiency is 2.94.

Mid *L/D* Aeroshell-B

Whereas in the *Mid L/D Aeroshell-A* concept the ellipsled aeroshell volume (and diameter) was kept to the minimum required to accommodate the payload, in the *Mid L/D Aeroshell-B* concept the ellipsled aeroshell diameter was chosen to be as large as possible while satisfying the launch vehicle fairing constraint. Using two different aeroshell diameters for the *-A* and *-B* concepts allowed for a more complete investigation of the design tradeoffs associated with mid *L/D* aeroshells. The *Mid L/D Aeroshell-B* concept consists of an ellipsled aeroshell, a supersonic DGB parachute, a subsonic ringsail parachute, and liquid-fueled rocket engines for the terminal descent stage. Figure 5 shows the concept of operation. Entry is lifting and guided. Note, that the top portion of the ellipsled

aeroshell is open in this concept.[8] A thermal cover over the payload is sufficient to protect it from hot recirculating gases during the entry heat pulse. This thermal cover is released once the entry heat pulse is over (i.e., below Mach 3). A supersonic parachute is deployed at a nominal Mach number of 2.25, and the ellipsled aeroshell is released shortly afterwards. Once the Mach number has been reduced to 0.9 (nominal), the supersonic parachute is released and used as a pilot parachute to deploy the subsonic parachute. Terminal descent and landing then continue as in the *Baseline* concept. Table 2 lists several key parameters for this concept. The ellipsled aeroshell diameter used in this concept is as large as could be accommodated by the launch vehicle fairing – 4.572 m. Using a larger diameter aeroshell allows the *Mid L/D Aeroshell-B* concept to use a supersonic parachute instead of the inflatable supersonic decelerator required by the *Mid L/D Aeroshell-A* concept. The peak stagnation heat rate is 35 W/cm². Thus, re-qualification or development of a new TPS material is probably not required. As shown in table 1, this concept will require the development of two new technologies: a mid *L/D* aeroshell, and a subsonic parachute. The mass breakdown for this concept is shown in table 3. With a launch mass of 5,721 kg, this concept could be launched with a Delta IV 4050H-19. The entry mass is 4,812 kg. The EDL efficiency is 2.67.

COMPARISON OF CONCEPTS

The primary figure of merit used in this study is the entry mass or equivalently, since the payload mass is fixed at 1,800 kg, the entry mass to payload mass ratio (see table 3). Concepts that use blunt-body aeroshells, that is the *Baseline*, *Aerocapture and Entry from Orbit*, and *Inflatable Aeroshell*, have values of the entry mass in the narrow range from 4,028 kg to 4,123 kg (entry mass to payload mass ratios from 2.24 to 2.29).[9] Given the approximate nature of the mass models used in this study, the differences in entry masses for these blunt-body aeroshell concepts are within the uncertainty bounds of the analysis. Concepts using the mid *L/D* (ellipsled) aeroshells have significantly larger entry masses of 5,292 kg (*-A*) and 4,812 kg (*-B*) (entry mass to payload mass ratios of 2.94 and 2.67, respectively) as shown in table 3. This is due to the higher mass of the mid *L/D* aeroshells as compared to the blunt-body aeroshells. Thus the blunt-body aeroshell concepts have a definite advantage in entry mass. This mass difference carries over to launch, where the blunt-body aeroshell concepts have launch mass values from 4,627 kg to 5,077 kg, whereas the values for the mid *L/D* aeroshell concepts are 6,043 kg (*-A*) and 5,721 kg (*-B*). Lighter concepts have more launch mass margin (when using the Delta IV 4050H-19 launch vehicle), which can be used to support increased launch mass or widening of the launch window.

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[7] An ellipsled aeroshell is bullet shaped. It is a body of revolution consisting of a cylindrical aft body with half an ellipse of revolution for a forebody. It operates at high angles of attack (approximately 45 to 55 degrees).

[8] In the *Mid L/D Aeroshell-A* concept the top portion of the aeroshell is closed to maintain symmetry when the attached inflatable supersonic decelerator is deployed.

[9] In this discussion the entry mass value being used for the *Aerocapture and Entry from Orbit* concept is that for the final entry pass. Also note the previous remarks made regarding the sensitivity of the *Inflatable Aeroshell* concept entry mass to the peak stagnation heat rate constraint.

Another important discriminant among concepts is how much new technology development is required. Of the six new technologies listed in table 1, the TPS and subsonic parachute are probably the easiest and least expensive technologies to develop and qualify. Developing and qualifying a Mach 3 parachute [9] or a mid L/D aeroshell can be accomplished, but it will be expensive. Inflatable aeroshells, especially those with the large diameters considered in this study, and inflatable supersonic decelerators are still at a low technology readiness level (TRL). Their development must be considered to be high-risk and expensive. Given these observations, the *Baseline* concept could probably be developed and qualified for the least cost. The *Aerocapture and Entry from Orbit* concept requires development of the Mach 3 and subsonic parachutes – both can be accomplished although the Mach 3 parachute development and qualification could be expensive. In addition, issues mentioned earlier with regards to operating the *Aerocapture and Entry from Orbit* concept both as an orbiter and entry vehicle will need to be investigated further. The *Inflatable Aeroshell* concept requires two new technologies, the inflatable aeroshell itself and the subsonic parachute. Although this concept is competitive in terms of entry mass, and its ability to circumvent the launch vehicle fairing constraint is useful, the low TRL (and corresponding risk and cost) of the inflatable aeroshell is of concern. Of all concepts, the *Mid L/D Aeroshell-A* requires the largest number of new technologies: TPS, mid L/D aeroshell, inflatable supersonic decelerator, and subsonic parachute. Given the cost and risk associated with developing and qualifying all of these new technologies, in addition to the previously stated issues regarding entry and launch mass, the *Mid L/D Aeroshell-A* concept is not a compelling choice for missions in the 1,800 kg payload mass category. Finally, the *Mid L/D Aeroshell-B* concept requires development and qualification of a mid L/D aeroshell, and a subsonic parachute. Although the subsonic parachute can be developed with a relatively modest funding, the cost of developing and qualifying the mid L/D aeroshell will be significant. The mid L/D aeroshell development and qualification costs, together with relatively large entry and launch mass, make the *Mid L/D Aeroshell-B* concept an unattractive choice for missions in the 1,800 kg payload mass range.

One final consideration in comparing the various concepts is their growth capability; that is, the extent to which could each of these concepts could accommodate payloads greater than 1,800 kg while still meeting other constraints such as launch vehicle fairing diameter and launch mass. Since no numerical analyses were conducted to address this question, the remarks made here are necessarily qualitative. The rigid blunt-body aeroshell concepts (i.e., *Baseline* and *Aerocapture and Entry from Orbit*) are growth limited by aeroshell diameter and volume. As entry mass grows without a corresponding increase in aeroshell diameter, peak heat rates and heat loads become higher, further stressing the TPS material and increasing the mass of the heatshield. Furthermore, increasing entry mass will also force reshaping of the Viking-type aeroshell to obtain additional volume. This can only be achieved by stretching the aftbody. However, there are limits on the extent to which this can be done with Viking-type aeroshells while staying within the bounds of the heritage qualification argument. These limits are associated with aftbody heating and center of gravity location. A large deviation from the Viking-type aeroshell shape would destroy the heritage argument for qualification, and the aeroshell would have to be considered new technology. Thus, TPS and aeroshell volume considerations will limit the growth capability of the *Baseline* and *Aerocapture and Entry from Orbit* concepts. The *Inflatable Aeroshell* concept is not tightly constrained by the launch vehicle fairing diameter. Furthermore, it has significant launch vehicle mass margin when using the Delta IV 4050H-19. Thus, the *Inflatable Aeroshell* concept may offer a path to larger payload mass missions within the constraints used in this study. However, the low TRL of inflatable aeroshells, including the uncertainty of how large a system can be designed and qualified, must temper this positive outlook. Growth in entry mass capability for the *Mid L/D Aeroshell-A* concept will be principally limited by the TPS material and the inflatable supersonic decelerator technology. Increasing the entry mass will further stress the TPS and require deployment of the inflatable supersonic decelerator at higher Mach numbers. Increasing the ellipsled aeroshell size will help in ameliorating these concerns. The *Mid L/D Aeroshell-A* and *-B* concepts growth capability will also be limited by the launch mass capability of the Delta IV 4050H-19 (7,200 kg launch mass for the required C3).

CONCLUSIONS

This study's main purpose is to provide guidance regarding which new technologies and system concepts should be pursued to support large missions to Mars, in particular those with payload mass of 1,800 kg. The results of this study support the following conclusions and recommendations:

1) Development and qualification of TPS materials with higher peak heat rate capabilities will benefit most concepts.

2) In all concepts the optimization found it advantageous to use a large subsonic parachute instead of increasing the fuel of the terminal descent stage. Development and qualification such a parachute, which can grow in drag area either through increasing its diameter or clustering, is recommended. The cost of developing such a parachute should be relatively modest.

3) Inflatable aeroshells are a promising technology with growth potential. However, their current TRL is low. Funding should be allocated to increase their TRL. Re-evaluation of the benefits of inflatable aeroshells in a study similar to this one should be conducted once improved understanding and models of their performance are available.

4) Aerocapture is a promising approach that greatly lowers the peak heat rate and thus reduces the performance requirements imposed on the TPS. In addition, aerocapture also reduces the peak entry acceleration as compared to the other concepts investigated here. However, system studies must resolve overall architecture issues involving operation of an entry vehicle as an orbiter after it has performed the aerobraking pass (e.g., communications, heat rejection).

5) Mid L/D aeroshells are not competitive compared with blunt-body aeroshells for missions with 1,800 kg payloads within the constraints used in this study.

CLOSING REMARKS

This study was conducted under a specific set of assumptions. Modifying these assumptions will produce different numerical results. For example, changes in the mass models, the scaling factor from "best estimate" to "allocated" mass estimates, and assumptions regarding the martian atmosphere dust load will impact the results. However, the trends illuminated by this study, in particular which technologies and concepts should be pursued for future missions, are relatively insensitive to such changes in assumptions. Thus, this study serves its stated purpose – to provide guidance for selecting new technologies and concepts for development.

ACKNOWLEDGEMENTS

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Table 1. New technology requirements for the various concepts

	Baseline	Aerocapture and Entry from Orbit	Inflatable Aeroshell	Mid L/D Aeroshell-A	Mid L/D Aeroshell-B
Re-Qualified or Improved Thermal Protection System	Required			Required	
Mid L/D Aeroshell				Required	Required
Inflatable Aeroshell			Required		
Inflatable Supersonic Decelerator				Required	
Mach 3 Parachute		Required			
Subsonic Parachute[A]	Required	Required	Required	Required	Required

A) A subsonic parachute is included as a new technology because the concepts investigated here require canopies with large nominal diameters (43.1 to 57.2 m) or equivalently, a cluster of smaller canopies. For comparison, the largest parachute yet flown on Mars was 16.15 m in a single canopy configuration by the Viking mission [2].

Table 2. Key parameters for the various concepts. Blank cells are not applicable to the specific concept.

	Baseline	Aerocapture and Entry from Orbit	Inflatable Aeroshell	Mid L/D Aeroshell-A	Mid L/D Aeroshell-B
Aeroshell Diameter (m)	4.572	4.572			
Heatshield Nose Radius (m)^A	1.112	1.112	6.684		
Inflatable Aeroshell Diameter (m)			14.4		
Ellipsled Aeroshell Nose Radius (m)^A				1.95	2.97
Ellipsled Aeroshell Diameter (m)				3.0	4.572
Ellipsled Aeroshell Total Length (m)				6.0	7.708
Inflatable Supersonic Decelerator Diameter (m)				14.6	
Supersonic Parachute Nominal Diameter (m)	18.9	19.6	B		19.4
Subsonic Parachute Nominal Diameter (m)	43.1	46.8	53.7	57.2	50.1
Aerocapture Flight Path Angle (°)		-10.4			
Entry Flight Path Angle (°)	-14.5	-12.5	-13.5	-13.0	-12.5
Aerocapture Peak Stagnation Heat Rate (W/cm^2)^C		38			
Entry Peak Stagnation Heat Rate (W/cm^2)^C	70	33	10	63	35
Aerocapture Total Heat Load (J/cm^2)^D		5,861			
Entry Total Heat Load (J/cm^2)^D	3,188	2,156	387	4,050	2,172
Aerocapture Peak Acceleration (g)		1.6			
Entry Peak Acceleration (g)	9.6	5.2	11.8	6.3	6.6
Peak Supersonic Parachute Acceleration (g)	4.3	4.2	B		3.9
Peak Subsonic Parachute Acceleration (g)	4.8	4.7	4.0	10.7	8.2
Suitable Launch Vehicles	E, F	E	E, F	E	E

A) This is the radius used in the heat rate calculations. **B)** The supersonic parachute is only used as a stabilizing drogue in the *Inflatable Aeroshell* concept. It was not sized beyond allocating a value for its mass. **C)** Peak stagnation heat rates were calculated using the Sutton/Graves convective heating equation [5]. **D)** Heat loads were calculated by integrating the peak stagnation heat rates with respect to time. **E)** Delta IV 4050H-19. **F)** Atlas V 551.

Table 3. Optimized mass allocation for the various concepts. All mass values shown in kilograms. Concept mass breakdown shown by font type and indentation. Blank cells are not applicable to the specific concept.

	Baseline	Aerocapture and Entry from Orbit	Inflatable Aeroshell	Mid L/D Aeroshell-A	Mid L/D Aeroshell-B
Launch Mass	**4,708**	**5,077**	**4,627**	**6,043**	**5,721**
Ellipsled Aeroshell Launch Cover^A					214
Cruise Stage (wet)	609	649	599	751	695
Aerocapture Mass		4,428			
Heatshield (aerocapture)		*305*			
Entry Mass	4,099	4,123	4,028	5,292	4,812
Orbital Maneuvering Fuel^B		*100*			
RCS Fuel^C	*26*	*57*	*26*	*43*	*53*
Ellipsled Aeroshell				*1,673*	*1,393*
Thermal Cover^D					*79*
Backshell	*397*	*429*	*389*		
Inflatable Aeroshell^E			*270*		
Heatshield (entry)	*427*	*252*	*75*		
Inflatable Supersonic Decelerator^F				*279*	
Supersonic Parachute^G	*54*	*56*	*8*		*55*
Subsonic Parachute	*200*	*236*	*311*	*352*	*273*
Terminal Descent Stage (wet)	*1,195*	*1,193*	*1,149*	*1,145*	*1,159*
Payload	*1,800*	*1,800*	*1,800*	*1,800*	*1,800*
Landed Mass^H	2,995	2,993	2,949	2,945	2,959
Entry Mass / Payload Mass (aerocapture)		2.46			
Entry Mass / Payload Mass (entry)	2.28	2.29	2.24	2.94	2.67

A) The ellipsled aeroshell launch cover is released shortly after launch. **B)** Although 100 kg of fuel are allocated for orbital maneuvering between the aerocapture pass and the entry pass, it is assumed in the analysis that none is used – thus it is part of the entry mass during the entry pass. **C)** Although mass is allocated for the guided entry RCS, it is assumed in the analysis that none is used. **D)** The thermal cover protects the payload during entry of the *Mid L/D Aeroshell-B* concept. **E)** The inflatable aeroshell mass includes both the textile components and the gas generator. **F)** The inflatable supersonic decelerator mass includes both the textile components and the gas generator. **G)** The supersonic parachute mass includes the mortar. **H)** Landed Mass = Terminal Descent Stage (wet) mass + Payload mass.
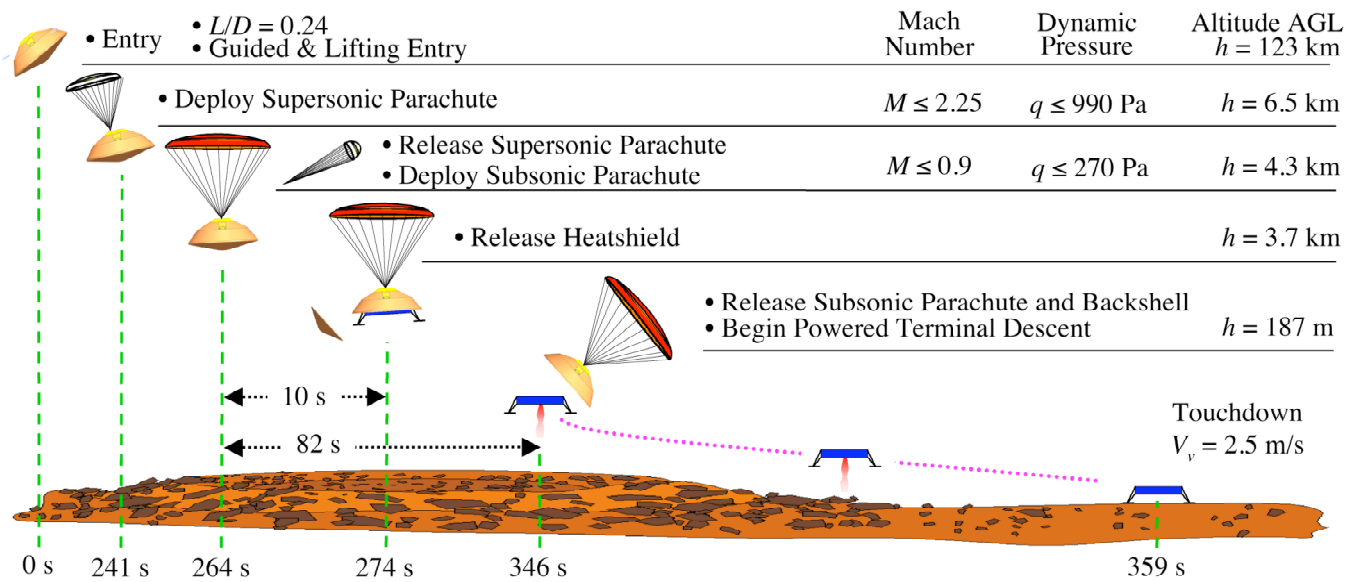
• Entry • L/D = 0.24 • Guided & Lifting Entry	Mach Number	Dynamic Pressure	Altitude AGL h = 123 km
• Deploy Supersonic Parachute	$M \leq 2.25$	$q \leq 990$ Pa	h = 6.5 km
• Release Supersonic Parachute • Deploy Subsonic Parachute	$M \leq 0.9$	$q \leq 270$ Pa	h = 4.3 km
• Release Heatshield			h = 3.7 km
• Release Subsonic Parachute and Backshell • Begin Powered Terminal Descent			h = 187 m
Touchdown V_v = 2.5 m/s			

10 s   82 s

0 s   241 s   264 s   274 s   346 s   359 s

Figure 1. Concept of Operations - *Baseline*

4. Parking Orbit

3. Raise Periapsis

5. Entry From Orbit

2. Release First Heatshield

1. Aerocapture Pass

Figure 2A. Concept of Operation – *Aerocapture and Entry from Orbit*

• Entry • L/D = 0.24 • Guided & Lifting Entry	Mach Number	Dynamic Pressure	Altitude AGL h = 123 km
• Deploy Supersonic Parachute	$M \leq 2.75$	$q \leq 1,440$ Pa	h = 9.2 km
• Release Supersonic Parachute • Deploy Subsonic Parachute	$M \leq 0.9$	$q \leq 270$ Pa	h = 6.3 km
• Release Heatshield			h = 5.7 km
• Release Subsonic Parachute and Backshell • Begin Powered Terminal Descent			h = 174 m
Touchdown V_v = 2.5 m/s			

10 s   123 s

0 s   278 s   309 s   319 s   432 s   445 s
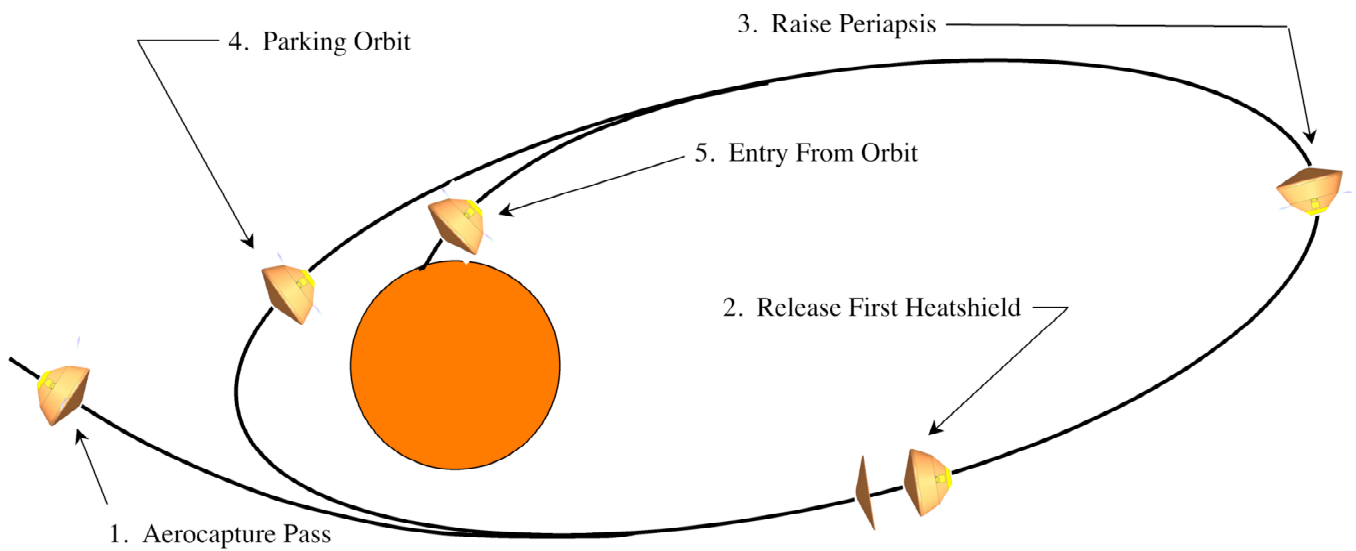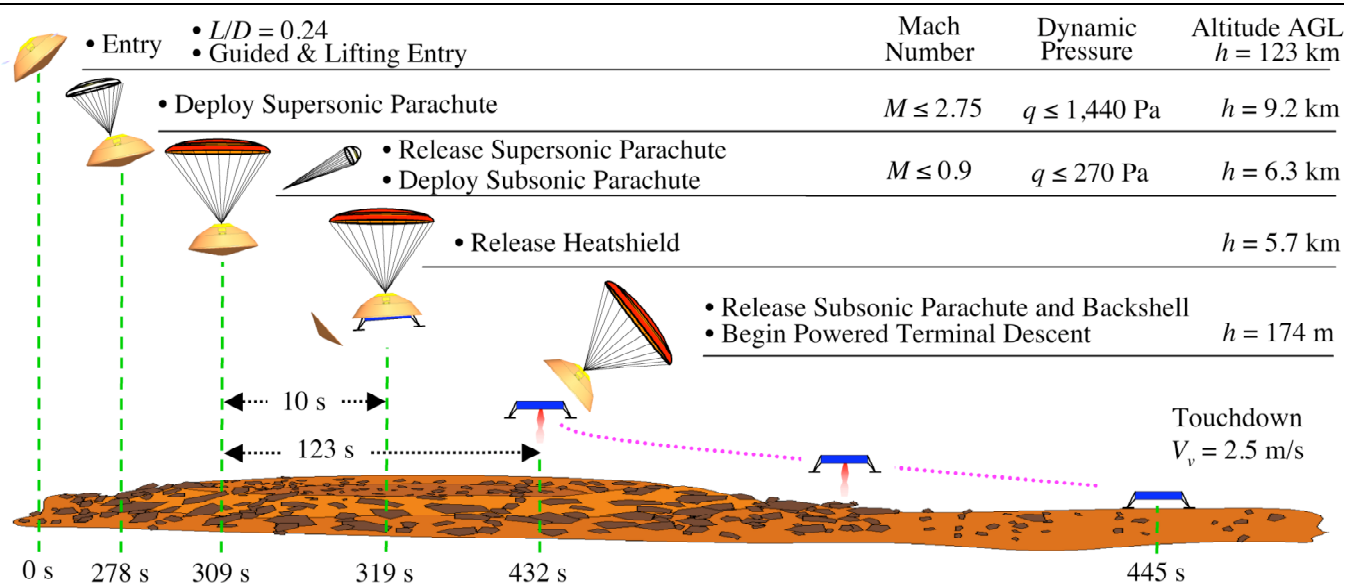
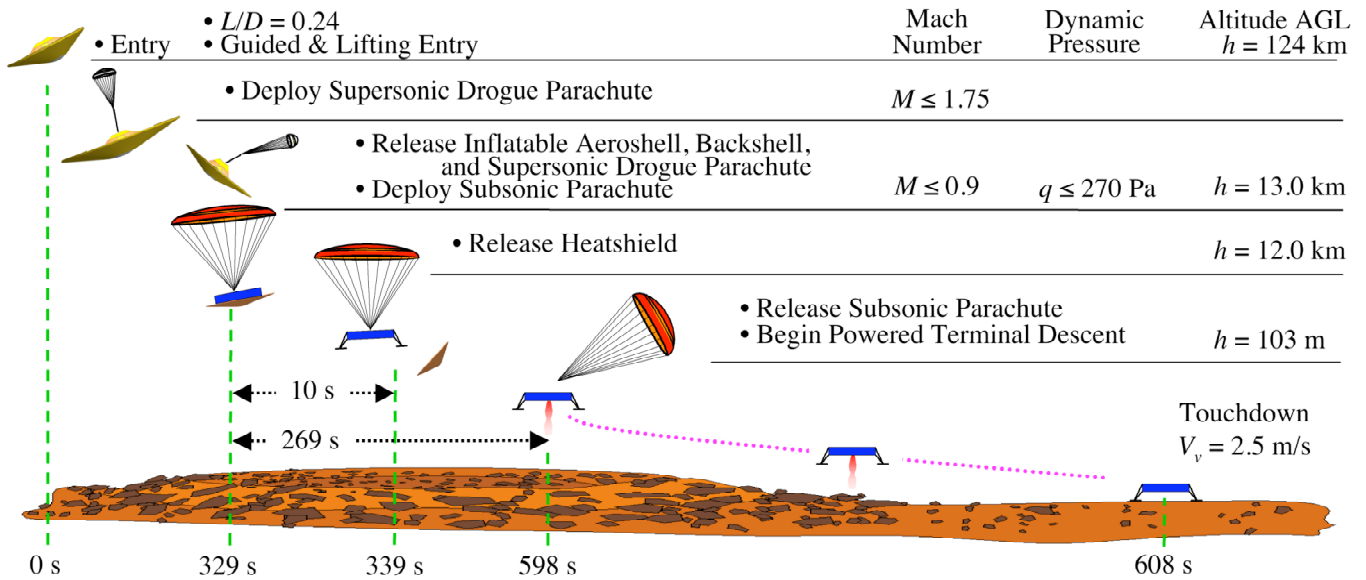Figure 2B. Concept of Operation – *Aerocapture and Entry from Orbit*

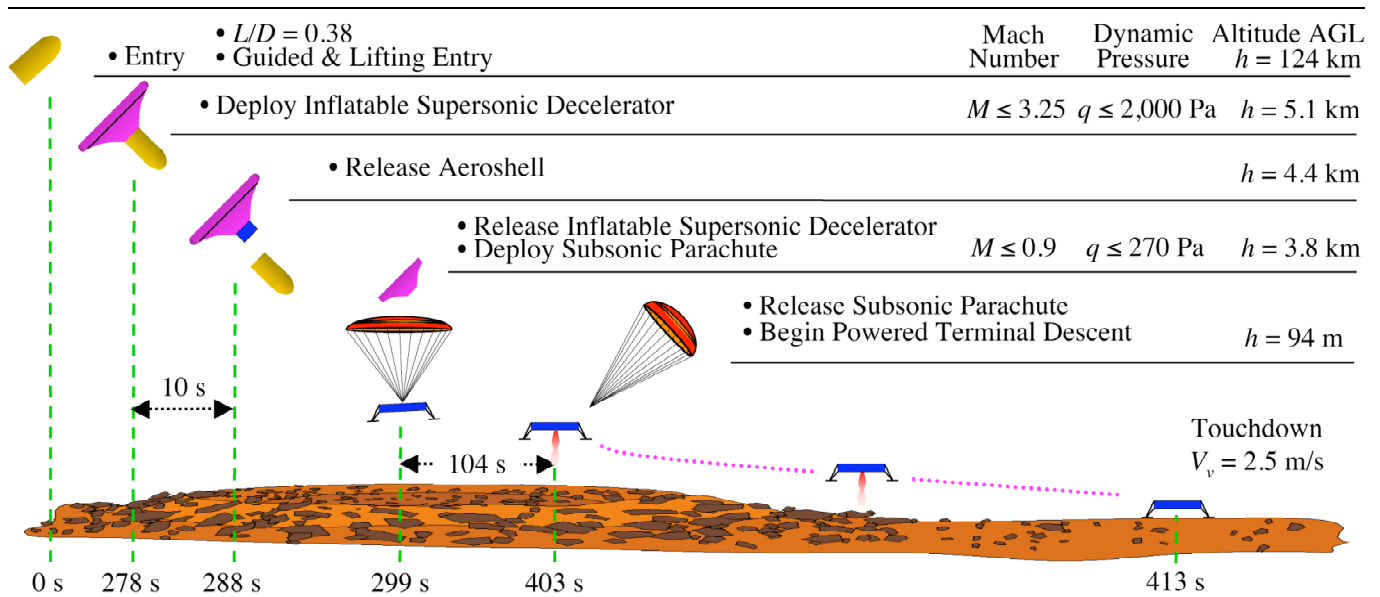Figure 3. Concept of Operation – *Inflatable Aeroshell*
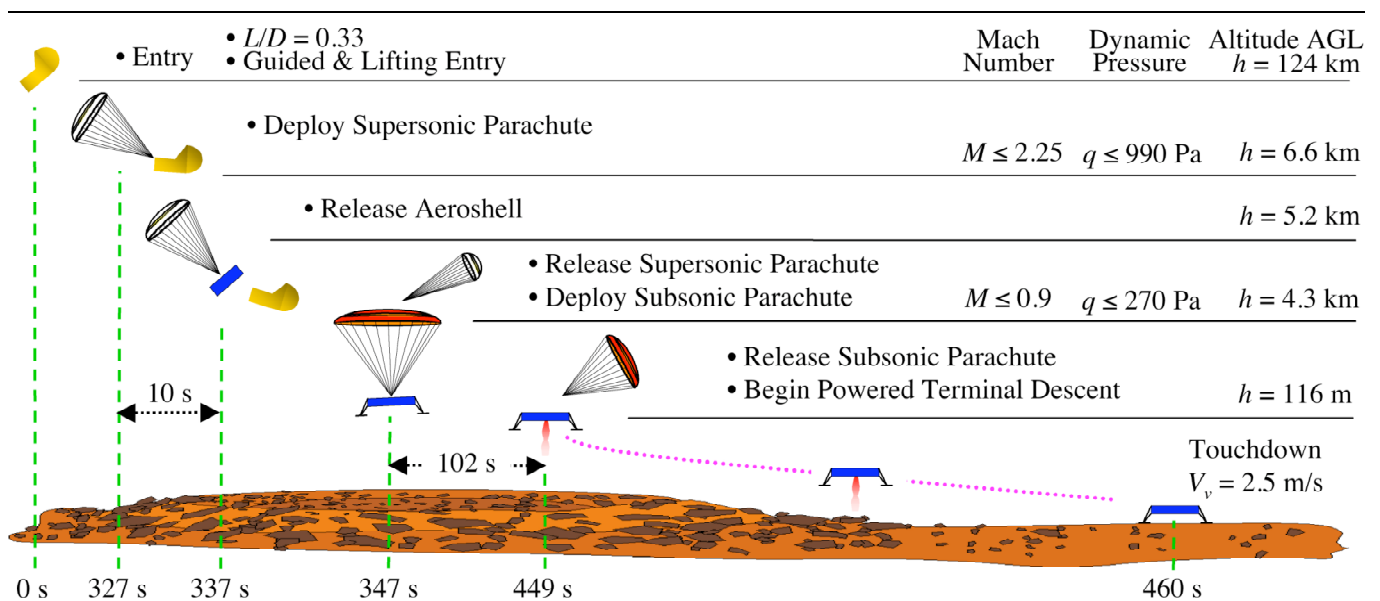

Figure 4. Concept of Operation – *Mid L/D Entry Aeroshell-A*

Figure 5. Concept of Operation – *Mid L/D Entry Aeroshell-B*