

ADEPT, A Mechanically Deployable Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions

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ABSTRACT

There is growing interest for utilizing Small Satellites beyond low Earth orbit. A number of secondary CubeSat payload missions are planned at Mars, cis-Lunar Space, near Earth objects, and moons of the Gas Giants. Use of smaller systems may enable utilization of otherwise unused capacity of larger “host” missions. Development of re-entry systems that leverage and accommodate Small Satellite technology will substantially expand the range of mission applications by offering the capability for high speed entry or aerocapture at destinations with atmospheres. Deployable entry vehicles (DEVs) offer benefits over traditional rigid aeroshells including volume, mass and payload form factor. The Adaptive Deployable Entry and Placement Technology (ADEPT) offers such a delivery capability for Small Sat or CubeSat orbiter(s), in-situ elements, or landers. The ADEPT system can package with off the shelf CubeSat deployment systems (1U-16U) to offer a delivery capability for a single CubeSat or constellations. Furthermore, ADEPT can deliver the same science payload to a destination with a stowed diameter a factor of 3-4 times smaller than an equivalent rigid aeroshell, alleviating volumetric constraints on the secondary payload accommodation or primary carrier spacecraft bus. This paper will describe ADEPT's current development status and define various interplanetary mission concepts in order to provide guidelines for potential Small Satellite payload developers and mission implementers.

INTRODUCTION

CubeSats are rapidly gaining traction as cost-effective secondary payloads to enhance the primary mission or as stand-alone interplanetary missions.¹ The Mars InSight lander recently launched with two 6U CubeSat free-flyers (MarCO) that will serve as real-time telemetry relays to Earth during the critical entry, descent and landing (EDL) phase.² MarCO will be the first time that CubeSats have been utilized in deep space. The upcoming Orion Exploration Mission-1 (EM-1) will launch with thirteen CubeSats as secondary payloads that deploy from the upper stage after Orion has separated on its journey to cis-Lunar space.³ Each CubeSat will perform their own experiments to further their science and technology objectives. Together, these CubeSat demonstrations beyond LEO will establish the

viability of operating CubeSat class missions in deep space. NASA is expected to continue investing in SmallSat and CubeSat missions beyond LEO through the Stand Alone Missions of Opportunity Notice (SALMON) calls that seek to utilize excess launch capacity on cis-Lunar and interplanetary missions. It is anticipated that even more demanding SmallSat missions will be conceived that incorporate an entry segment into the overall mission operations.

A number of investigators have proposed CubeSat design concepts that directly integrate a deployable entry system or de-orbit device within the CubeSat form factor.^{4,7} These concepts have primarily assessed the integration of a deployable decelerator within the popular 3U or 6U CubeSat, which leaves little volume/mass for a science payload. While this approach takes advantage of existing CubeSat deployment

systems, the volume and mass constraints limit the entry performance, especially for high speed entries that require high temperature capable flexible materials to protect the payload during entry. An alternative approach would be to integrate a deployable entry system around the standard CubeSat or CubeSat deployer form factors as shown in Figure 1.

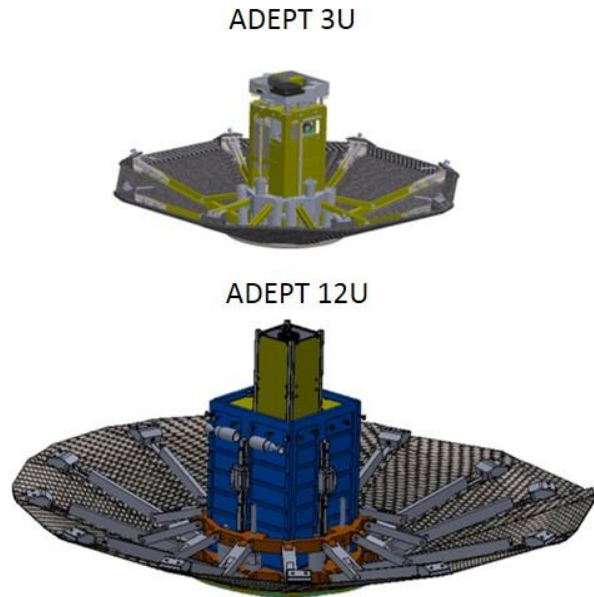


Figure 1- ADEPT CubeSat design concepts. The 3U design uses a spring based deployment system and the 12U dispenser design employs electrically actuated deployment.

The top panel in figure 1 shows the ADEPT 3U configuration. The centerbody is comprised of the standard 3U CubeSat form factor with ADEPT integrated around it. The bottom panel in figure 1 shows the ADEPT 12U dispenser concept that could deploy four 3U, two 6U or one 12U CubeSat after direct entry or aerocapture. One of the key objectives for the ADEPT development is to broaden CubeSat and SmallSat mission applications by developing a highly capable entry system to enable in-situ probes, landers, orbiters and orbiting constellations.

TECHNOLOGY DESCRIPTION

ADEPT

ADEPT is a low ballistic coefficient planetary entry system that employs an umbrella-like deployable structure. The ADEPT “skin” is a 3-D woven carbon fabric that serves as a thermal protection system (TPS) and as a structural surface that transfers aerodynamic deceleration forces to the underlying ribs.⁸ The ADEPT structural skeleton is made up of four primary structural elements: main body, nose cap, ribs, and struts. These

components are shown in Figure 2. The main body consists of lower and upper rings that are separated by a truss structure. The main body lower ring is a box section that supports the lower ends of the rib support struts and serves as the attachment interface to a spacecraft or secondary payload adapter. The main body upper ring (supported by the main body struts) acts as the attach/latch location for the nose cap ring. In alternate embodiments, the main body structure (and/or deployment mechanism) can be incorporated as part of the payload interface, such as a 12 U CubeSat deployer.

The nose cap acts as the leading edge of the entry vehicle and is constructed much like a conventional rigid aeroshell. Its shape is a sphere-cone that provides the transition to the faceted pyramid shape of the deployed carbon fabric. The nose cap is typically covered with an ablative TPS. The perimeter of the nose cap is reinforced by a ring frame that also supports the upper ends of the ribs.

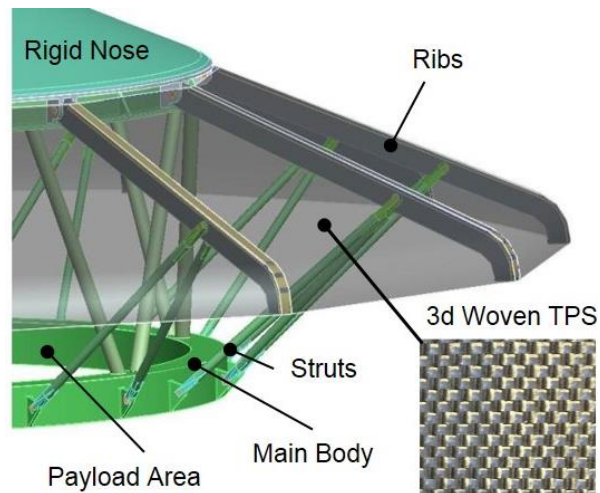


Figure 2- A general description of ADEPT components.

The ribs provide the framework that supports the tensioned carbon fabric. The ribs are hinged at their attachment to the nose cap, and are supported via struts at a point along their span that minimizes overall bending. The struts that support the ribs are installed in pairs to carry the aerodynamic loads transmitted from the carbon fabric and ribs back to the main body lower ring. The pairing of struts also provides lateral stability, torsional stability, and improved folding of the ADEPT structure.

The aerodynamic surface is formed by tensioning 3D-woven carbon fabric over the ribs of the structural skeleton. High-purity intermediate modulus carbon fiber yarn is used to create a membrane that serves as the structural surface and the thermal barrier. The high

temperature capability of the carbon cloth allows it to operate at high temperatures seen during entry (~2000° C). Several of the top layers of the carbon fabric are allowed to oxidize and recede away during the entry heat pulse, but the construction of the 3D woven fabric allows the deployable aeroshell to maintain its structural integrity.

Aerothermal Testing

Arc jet testing has been performed at the component and sub-system levels to assess various 3D-woven designs, seams, and system-level design features to develop predictive analytical tools and show performance with representative mission relevant heat rates and loads.⁹⁻¹¹ One such test methodology that is especially applicable

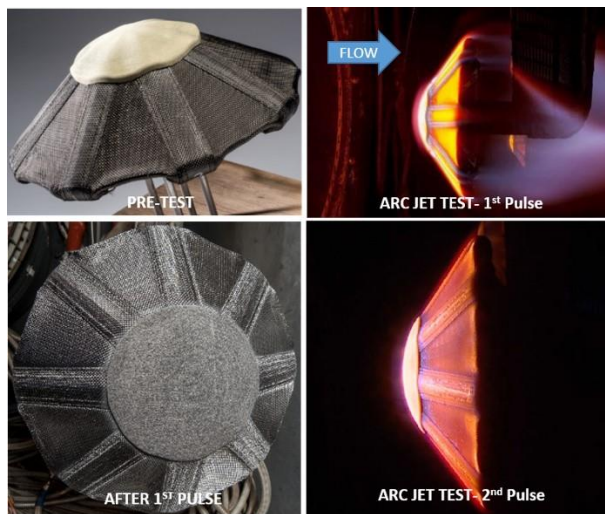


Figure 3- System level aerothermal ground testing of the ADEPT 3d woven carbon fabric and rigid nose ablative TPS.

to the entry environments relevant for SmallSat entries is a variation of the SPRITE (Small Probe Re-Entry Investigation for TPS Engineering) test approach¹² using the NASA Ames arc jet facilities. The SPRITE test methodology has many advantages including the capability to qualify flight-scale or scaled entry vehicle designs for the re-entry portion of flight without the need for a dedicated re-entry flight test. This approach, modified for the ADEPT project is termed SPRITE-C (C=cloth), and reduces the need for extensive coupon and component level tests, which can dramatically increase development costs. Results from the SPRITE-C tests help define areas of focused component-level testing in order to mature material response and thermal response design codes.

Figure 3 shows results from the SPRITE-C test series, which was used to characterize key components, features, and interfaces in the ADEPT aeroshell. The

SPRITE-C configuration is an open-back blunt body that blends from a typical spherical section at the nose to an 8-sided pyramid (55 degree rib angle), as shown in the pre-test photo panel of Figure 3. The blunter cone angle of the flight designs cannot be matched in this test without significantly compromising test article diameter because of shock impingement constraints from the flow diffuser of the arc jet facility. However, facility settings were implemented that allowed for testing at or above the aeroheating environments predicted in flight for the nose TPS, joints (over the ribs), and acreage carbon fabric material. The high test condition was a stagnation point heat flux of ~120 W/cm², while the low test condition was conducted at 60 W/cm². A number of key component features were explored in this test configuration including: rigid nose to carbon fabric transition, fabric joint to rib interface, and trailing edge close-out. The results of the SPRITE-C pathfinder test established the feasibility and thermostructural performance limits for the test article design that encompass the expected environments relevant for Mars entries. The facility employed can also bound Venus and Earth entry environments.

Two key robustness demonstrations were explored during the SPRITE-C arc jet testing. The first was the capability of the carbon fabric to withstand two separate heat pulses representative of aerocapture followed by entry. The pre and post-test photos in Figure 3 show the test article that was subjected to the dual heat pulse operational environments. Temperatures on the surface of the carbon fabric reached 1500 °C and 1300 °C for the aerocapture and entry heating exposures, respectively. In the second robustness demonstration, we subjected a sample of the carbon fabric to simulated impact damage (~ 6 mm hole punched through the fabric) to assess fabric response while under combined tension and aerothermal loading. The fabric maintained its integrity and did not unravel or fail. Together the aerothermal tests have demonstrated that the 3D woven carbon fabric is able to withstand the harsh environments encountered during high speed entry in order to protect the payload.

Aeroloads Testing

Another technical challenge area is to assess the shape change that aerodynamic loading imparts on the flexible carbon fabric. This is critical because the aerothermal heating and aerodynamic forces imparted on the vehicle can be sensitive to the degree of static deflection imparted in the fabric gores by the entry flow field. A sub-sonic wind tunnel test was conducted to generate deflected shape data as a function of key design parameters for ADEPT missions: aerodynamic load, angle of attack, and the amount of pre-tension put in the fabric prior to atmospheric entry. These data are being

used to improve structural modeling tools used in the design of ADEPT for multiple mission architectures.

Prior to this test there was concern that the carbon fabric free edge could experience dynamic fluid structure interactions (“buzz” or flutter) and cause a catastrophic structural failure. High-speed video was used in this test to capture any potential high-frequency gore movement. No flutter/buzz of the fabric was observed for any test condition and should also not occur at hypersonic speeds due to the natural frequency of the trailing edge being far lower than the flow shedding frequency.

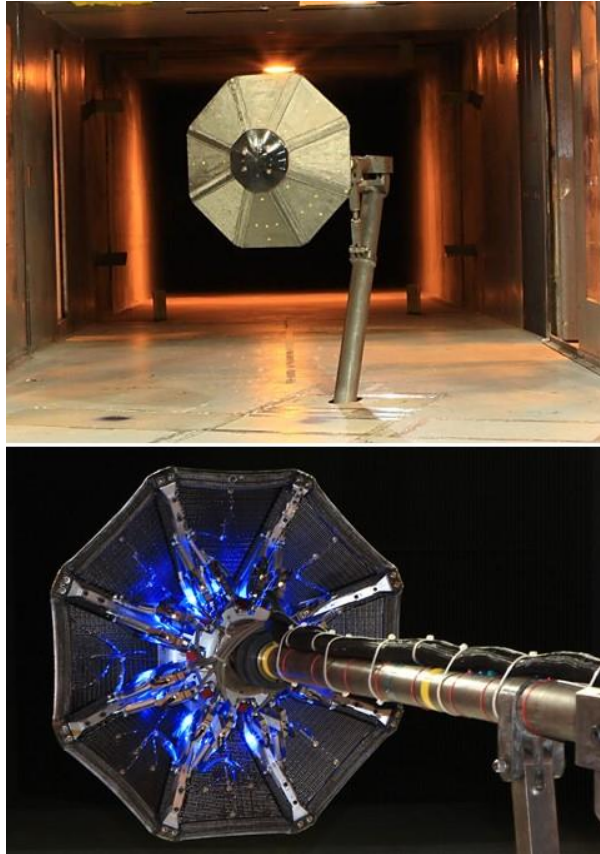


Figure 4- Aeroloads testing of the ADEPT 3U configuration to determine deflected shape under various experimental conditions.

Figure 4 shows two views of the ADEPT test article installed in the tunnel. The test article is comprised of eight ribs that are deployed like an umbrella to create tension in the carbon fabric. The geometry is an octagonal pyramid with rib-tip to rib-tip length of 0.70 m, a 70° half-angle forebody cone angle, a nose-to-base radius ratio of 0.7 and mid-gore-to-mid-gore length of 0.66 m. The nose cap geometry (3D-printed) is a sphere cap blended to an octagonal pyramid at the interface with the fabric gores. Some of the instrumentation can be seen on the rear view. Pressure tubes are visible at each of the

gores. The blue lights are from light-emitting diodes (LED) located on the amplifiers of each strut load cell. The front view in Figure 4 shows the nose cap, pressure taps, and test article support hardware. The geometry of the design replicates the 3U configuration shown in Figure 1. Detailed test results can be found in reference 13.

Sub-Orbital Flight Test

The initial system-level development of the ADEPT 3U architecture (also referred to as nano-ADEPT) will culminate in the launch of a 0.7 meter deployed diameter ADEPT sounding rocket flight experiment named, SR-1. Launch is planned for September 2018. The test will utilize the NASA Flight Opportunities Program sounding rocket platform provided by UP Aerospace to launch SR-1 to an apogee over 100 km and achieve re-entry conditions with a peak velocity near Mach 3. The SR-1 flight experiment will demonstrate most of the primary end-to-end mission stages including: launch in a stowed configuration, separation and deployment in exo-atmospheric conditions, and passive ballistic re-entry of a 70-degree half-angle faceted cone geometry. ADEPT SR-1 will determine supersonic through transonic aerodynamic stability of the unique ADEPT blunt body shape with an open back entry vehicle configuration. On-board instrumentation will measure position, velocity and body rates, as well as record HD video during descent back to Earth. Further details of the sounding rocket flight experiment can be found in reference 14.

MISSION CONCEPTS

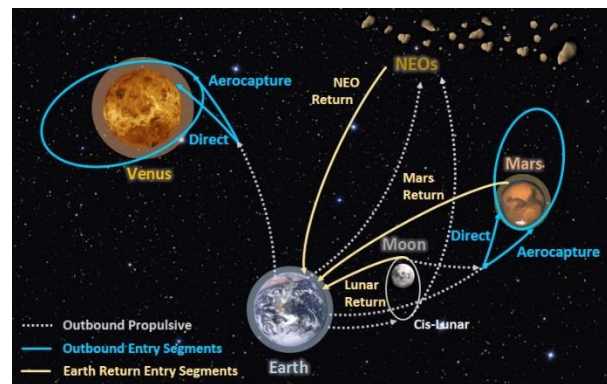


Figure 5- Inner Solar System transportation overview highlighting Venus, Mars (blue) and Earth (yellow) entry segments.

ADEPT can be utilized for a number of mission concepts. Figure 5 highlights some of the inner solar system mission concepts that include an atmospheric entry segment. At Venus and Mars, ADEPT could be utilized for delivering in situ probes (landers and/or

aerial platforms) or delivering orbiters via aerocapture. There are a number of Earth return possibilities from Near Earth Objects (NEOs), Mars and cis-Lunar space (Venus return not shown). Below, a few examples will be highlighted to illustrate the type of missions being considered.

Entry Environments

| ADEPT Design Parameters | | |
|-------------------------|--|-------------------------|
| Half Cone Angle | 70° | 70° |
| Diameter | 1.5 m | 1.5 m |
| Entry Mass | 150 kg | 75 kg |
| Ballistic Coeff | ~50 kg/m ² | ~25 kg/m ² |
| Mars Direct | V _{inertial} =6 km/s; EFPA=-15° | |
| Peak Heating | 58 W/cm ² | 44 kJ/cm ² |
| Total Heat Load | 1.9 kJ/cm ² | 1.3 kJ/cm ² |
| Peak Dynamic Pressure | 7.1 kPa | 3.85 kPa |
| Venus Direct | V _{inertial} =11 km/s; EFPA=-8° | |
| Peak Heating | 235 W/cm ² | 179 kJ/cm ² |
| Total Heat Load | 10.2 kJ/cm ² | 6.9 kJ/cm ² |
| Peak Dynamic Pressure | 8.9 kPa | 5.3 kPa |
| Earth Return | V _{inertial} =11 km/s; EFPA=-8° | |
| Peak Heating | 190 W/cm ² | 152 kJ/cm ² |
| Total Heat Load | 18.3 kJ/cm ² | 11.3 kJ/cm ² |
| Peak Dynamic Pressure | 2.9 kPa | 2.2 kPa |

Table 1- Entry environment summary for three representative mission classes. Peak heating, total heat load and peak dynamic pressure are highlighted for two bounding ballistic coefficients for the 70 deg half cone angle forebody shape. Nose radius was 0.5 m.

It is important to consider the entry environments encountered for the various mission concepts. This helps define the sizing of the ablative nose TPS, the number of layers required in the flexible 3D woven carbon fabric, and the design of the underlying structural elements. Table 1 shows representative entry environments for the three primary entry mission classes described in figure 5. The entry velocity and flight path angle chosen for each mission are representative of “typical” entry conditions at those destinations. There can be quite a bit of variation in these parameters depending on the creativity of a given mission design. Peak heat rate, total heat load and peak dynamic pressure are shown for two different

ballistic coefficients. In these trajectory cases, the nose radius was assumed to be 0.5 m. It is necessary to present these environments in terms of ballistic coefficient because there is insufficient knowledge of what the non-payload mass might be until we have completed a design cycle. The selected ballistic coefficients are an attempt to bound the entry mass based on our experience with the technology. Environments are calculated using TRAJ assuming a sphere-cone aerodynamic model for the drag coefficient (CD) calculation.¹⁵ TRAJ calculates the stagnation point environments and can be used as a first approximation when performing mission concept sizing analysis.

Mission Concepts at Venus

Venus entry is particularly challenging as compared to Earth or Mars, primarily due to differences in the atmospheric profile. Past missions and proposed mission concepts have primarily utilized high ballistic coefficient rigid aeroshell technology based upon the Pioneer Venus heritage design. The PV missions flew steep entry trajectories in order to minimize the heatshield material mass (carbon phenolic) and provide more mass for the science payload. Venus mission designers are now considering low ballistic coefficient aeroshells, including deployable entry vehicles that obviate the need to enter at high entry flight path angles.

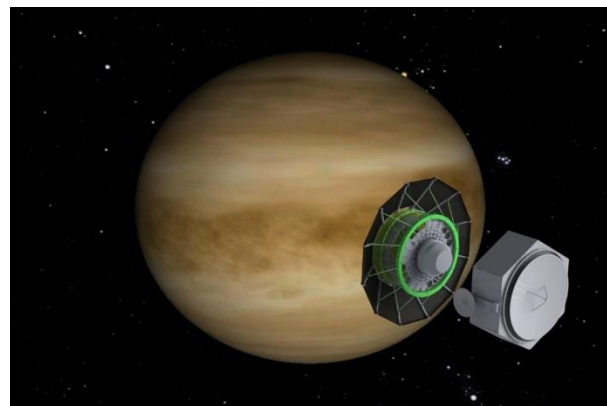


Figure 6- Artist rendering of the ADEPT-VITaL mission concept on approach to Venus.

A number of Venus mission concepts have been considered that employ ADEPT. A mission feasibility study was conducted in 2013 highlighting the benefits of using a 6 m class ADEPT for the Venus In-Situ Explorer (VISE) mission.¹⁶ In the study, ADEPT was used to deliver the Venus Intrepid Tessera Lander to its parachute deploy point. The goal of the study was to understand how a deployable entry system could provide operational benefits over the heritage rigid aeroshell approach. The study concluded that the use of ADEPT did not adversely impact other mission elements and did

not alter the science payload or mission operations approach. In addition, it was found that ADEPT could fly at shallower entry flight path angles, which reduced the peak deceleration loads. Figure 6 shows the ADEPT-VITaL mission concept separating from the cruise stage on approach to Venus. While this mission does not fall within the scope of SmallSat class, it illustrates the type of operational characteristics to consider for SmallSat class missions to Venus.

More recently, SmallSat class secondary payload missions have been considered that take advantage of Venus “fly-by” opportunities hosted as part of New Frontiers or Discovery class missions. The Venus Exploration Analysis Group (VEXAG) study teams have been considering how such hosted ‘small missions’ could be formulated under a \$200 M cost cap.¹⁷ The study charter includes evaluating mission architectures, technology and science that could be pursued if launched in the early-to-mid 2020s. As part of these efforts, ADEPT is being considered for use to deliver an atmospheric probe, aerial platform or lander via attachment to a secondary payload interface, such as the ESPA ring.¹⁸ The standard ESPA ring has six secondary payload attachment flanges that accommodate up to 180 kg payload within a 60 cm x 71 cm x 90 cm dynamic payload volume. A few secondary payload concepts are shown attached to the standard ESPA ring in figure 7. The maximum diameter rigid aeroshell that could be accommodated on the standard ESPA ring is ~0.6 m. In contrast, ADEPT based designs could stow within this volume and deploy to diameters up to 1.7 m, a factor of 10 increase in the drag area obtainable with this operational approach.

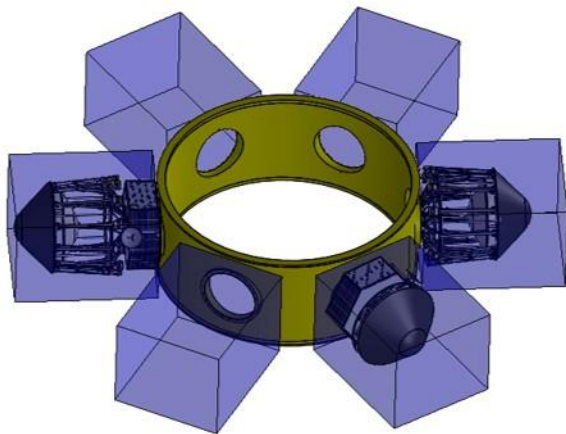


Figure 7- ADEPT is able to efficiently stow within the ESPA envelope. This helps maximize delivered payload volume.

Another mission concept being considered is to utilize ADEPT as a detachable aft skirt, whereby ADEPT would replace a rigid based drag skirt to capture a

science payload into orbit around Venus.¹⁹ The operations concept is shown in figure 8. In preparation for aerocapture, ADEPT would deploy and then separate from the spacecraft bus. The bus would perform a divert maneuver while the aerocapture element would enter the atmosphere in its low ballistic coefficient configuration. After the required amount of energy is removed to achieve the desired orbit, the aft skirt is jettisoned to the high ballistic coefficient configuration with much lower drag, and exits the atmosphere.

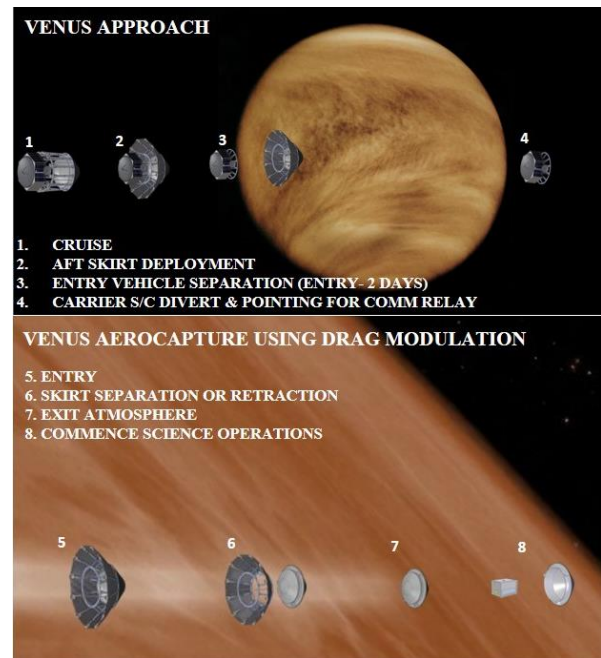


Figure 8- Operational concept for the ADEPT drag modulation mission concept.

Mission Concepts at Mars

There has been a few attempts to deliver secondary payloads to Mars. Deep Space 2 was a mission that attempted to deliver two small impactor probes as part of the Mars Polar Lander mission utilizing rigid aeroshell technology.²⁰ Although not successful, Deep Space 2 demonstrated the concept of a low-cost ride along mission to Mars that was deployed from the primary spacecraft prior to atmospheric entry. Another ride-along small probe mission, BEAGLE 2 was deployed from the Mars Express orbiter as a lander to perform exobiology and geochemistry research.²¹ The BEAGLE 2 lander had a failure after reaching the Martian surface and was unable to perform its mission.

Building on these mission architectures, we have studied the applicability of the ADEPT technology to similar ride along missions as shown in figure 9. We envision missions similar to the network of SmallSat landers

described in figure 9 to deliver scientific instruments and support Human Mars exploration.

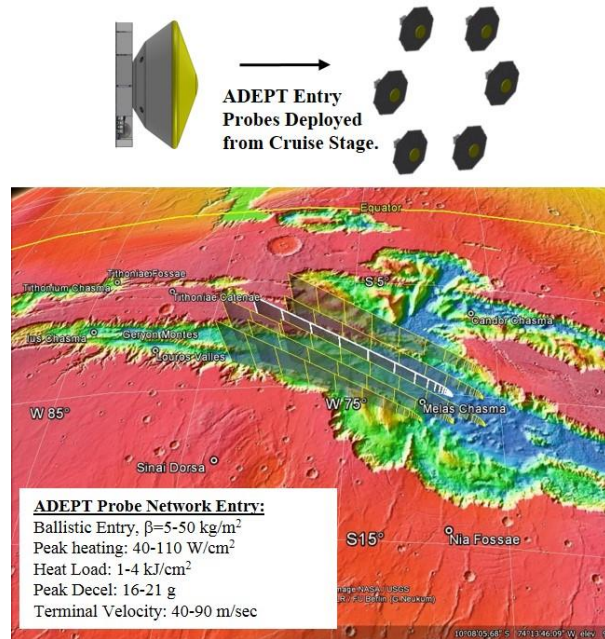


Figure 9- A network of SmallSat class probes deployed from the cruise stage of a Mars lander mission.

Earth Return Missions

Sample return missions such as Stardust, Genesis and Hayabusa have reignited interest in returning extraterrestrial material or conducting research in the harsh conditions of Space and delivering the samples for in-depth analysis in well-equipped Earth based laboratories. ADEPT is applicable for Earth return missions and ongoing studies are considering various mission concepts to return lunar samples or samples of biological interest that have been exposed to the radiation and microgravity environment experienced in deep space. In addition, efforts are underway to develop a guided version of the ADEPT vehicle to enable precision targeting²² and to lessen the entry loads (aerodynamic and aeroheating) encountered with Earth return, where the entry velocities could be in excess of 11 km/s.

SUMMARY

Deployable entry vehicles offer a new approach for mission designers to consider for SmallSat class missions that incorporate an atmospheric entry segment. This overview provided a description of ADEPT, its current development status, and described some of the destinations where the ADEPT system could be utilized for SmallSat and CubeSat class payloads. The upcoming

ADEPT sub-orbital flight test describes the applicability of the ADEPT design to 3U CubeSat class payloads that can be extended to larger CubeSat form factors and deployer systems. It is our hope that the SmallSat community will propose mission concepts that incorporate ADEPT to design a much broader set of missions than have been considered until now.

Acknowledgments

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