Venus In Situ Explorer Mission Design using a Mechanically Deployed Aerodynamic Decelerator

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***Abstract*—The Venus *In Situ* Explorer (VISE) Mission addresses the highest priority science questions within the Venus community outlined in the National Research Council's Decadal Survey. The heritage Venus atmospheric entry system architecture, a 45º sphere-cone rigid aeroshell with a carbon phenolic thermal protection system, may no longer be the preferred entry system architecture compared to other viable alternatives being explored at NASA. A mechanically-deployed aerodynamic decelerator, known as the Adaptive Deployable Entry and Placement Technology (ADEPT), is an entry system alternative that can provide key operational benefits and risk reduction compared to a rigid aeroshell. This paper describes a mission feasibility study performed with the objectives of identifying potential adverse interactions with other mission elements and establishing requirements on decelerator performance. Feasibility is assessed through a launch-to-landing mission design study where the Venus Intrepid Tessera Lander (VITaL), a VISE science payload designed to inform the Decadal Survey results, is repackaged from a rigid aeroshell into the ADEPT decelerator. It is shown that ADEPT reduces the deceleration load on VITaL by an order of magnitude relative to a rigid aeroshell. The more benign entry environment opens up the VISE mission design environment for increased science return, reduced risk, and reduced cost. The ADEPT-VITAL mission concept of operations is presented and details of the entry vehicle structures and mechanisms are given. Finally, entry aerothermal analysis is presented that defines the operational requirements for a revolutionary structural-TPS material employed by ADEPT: three-dimensionally woven carbon cloth. Ongoing work to mitigate key risks identified in this feasibility study is presented.**

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1. INTRODUCTION

The most recent National Research Council (NRC) Planetary Decadal Survey report "Visions and Voyages" [1] identifies critical science questions for Venus as part of the Venus In Situ Explorer (VISE) New Frontiers class mission. VISE addresses the highest priority science objectives within the Venus community, including understanding the chemistry and mineralogy of the Venus crust, history of the Venus atmosphere and the role of water, and understanding the key drivers of the atmospheric dynamics and climate. Understanding the evolution of the Venus surface and atmosphere, through measurements of deep atmospheric gas compositions and surface mineralogy, requires an *in situ* measurement platform that can survive entry into the dense Venus atmosphere. As part of the Decadal Survey, a rugged lander concept called the Venus Intrepid Tessera Lander (VITaL) was examined [2]. VITaL meets the New Frontiers VISE science objectives, but is specifically targeted to the tessera terrain.

In 1978, Pioneer Venus (PV) became the first and only U.S. mission to survive the harsh Venus entry environment. This mission employed rigid aeroshell technology and a thermal protection system (TPS) comprised of fully dense carbon phenolic (CP). CP is the only material with flight heritage in the high heat flux and high pressure environment associated with Venus entry. The primary disadvantage of CP is its high density and high thermal conductivity. With these characteristics, mass efficiency considerations necessitate that the entry trajectory be designed to increase the heat pulse's severity but shorten the duration. The only way to achieve the desired effect for a ballistic (non-lifting) trajectory is to enter the atmosphere at a steep flight path angle. Such trajectory design has the severe disadvantage of deceleration loading in excess of 200 g. Furthermore, heritage CP is in extremely short supply, and the current industry manufacturing capability of CP is atrophying.

A recent study [3] shows that much shallower entry flight path angles become feasible with low ballistic coefficient—the entry vehicle's mass divided by its drag area. All previous planetary atmosphere entry missions have relied on rigid aeroshells with sizes and shapes constrained by the payload fairing of the launch vehicle. This fundamental limitation of rigid aeroshells can be overcome through in-space deployment of a high-temperature capable

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deceleration system. A mechanically deployed aerodynamic decelerator known as the Adaptive Deployable Entry and Placement Technology (ADEPT) is one such technology. In-space deployment of ADEPT decouples the geometry of the entry system from the geometry of the launch shroud and permits local optimization for each mission phase.

This paper assesses the feasibility, risks, benefits, and limitations of the ADEPT concept for the VISE mission through a launch-to-landing design study of repackaging the VITaL lander into the ADEPT structure. A relay spacecraft designed to mate with ADEPT and a candidate interplanetary trajectory provide key operational requirements. Details of the ADEPT structural design, aerothermal design, system mass benefits, and reduced deceleration loads are presented. Special emphasis is given to the key enabler for ADEPT: flexible multi-layer woven carbon cloth. Recent testing has shown this material is capable of transferring aerodynamic loads to the support structure while simultaneously operating at very high temperatures due to aeroheating.

2. Baseline Mission Concept

The baseline mission concept is intended to support the science objectives and associated instruments onboard the VITaL lander. A lander with a mass of about 1050 kg will carry the instruments in a pressurized vessel, with a thermal management system that can support 3 hours of operation, including 1 hour of descent after separation from the atmospheric entry system and two hours of surface operations. The lander will limit the deceleration loads on the instruments at surface impact, and will provide a stable platform on slopes up to 60º. The target landing location to fulfill science objectives is 3.7º East longitude and 25.4º South latitude with a Sun elevation at landing of 59º.

The ADEPT decelerator achieves the desired low ballistic coefficient through a 6 m deployed diameter and a 70º forebody cone angle. With an entry mass of 1620 kg, it will carry the payload from entry interface conditions of 10.8 km/s and flight path angle of -8.25º to subsonic parachute deployment at an altitude above 75 km. The baseline design relies on the parachute to extract the lander from the ADEPT decelerator. VITaL is cut from the parachute once ADEPT has separated a safe distance from the parachute and the probability of re-contact with VITaL is negligible. More detail on the ADEPT separation system concept and supporting analysis can be found in Reference [4].

Throughout the interplanetary coast phase, which lasts 16 months, the entry vehicle is attached to a 3-axis stabilized carrier spacecraft that provides power and communication for the lander, and releases the entry vehicle in the appropriate orientation for Venus entry. The ADEPT structure is folded throughout the interplanetary phase, with a diameter of 3 m, which is sufficient to enclose the lander. The carrier spacecraft is approximately 800 kg.

It is assumed that an Atlas V 551 will be used for launch. For a nominal launch date on May 29, 2023, this launch vehicle can carry 5360 kg to the required launch energy (C3) of 7.0 km^2/s^2. This mass capability provides a healthy margin for the proposed mission. The spacecraft and lander also package comfortably within the fairing. The ADEPT-VITaL master equipment list (MEL) is provided in Appendix A.

Critical events in the mission sequence, with nominal dates, are called out in Figure 2.

3. Cruise Operations

The three-axis stabilized carrier spacecraft shown attached to ADEPT-VITaL in Figure 1 performs four functions: Delivers the stowed ADEPT-VITaL probe on an interplanetary trajectory to Venus; deploys the ADEPT structure; releases the probe on an appropriately pointing trajectory to enter the Venus atmosphere, and acts as a communication relay between VITaL and the Earth. Because of the flyby trajectory, the required fuel mass is relatively small, thermal and power tasks are manageable, and electronics and communication systems are straightforward. The drivers for the carrier spacecraft design include spinning up the probe to 5 RPM prior to release and having a robust structure to support the probe. Requirements for the remaining sub-systems, which include star trackers, a reaction wheel assembly (RWA), a Ka-band downlink system and an S-band uplink, are modest. After launch, ADEPT remains stowed to allow the medium gain antenna (MGA) to view the Earth during all critical maneuvers.

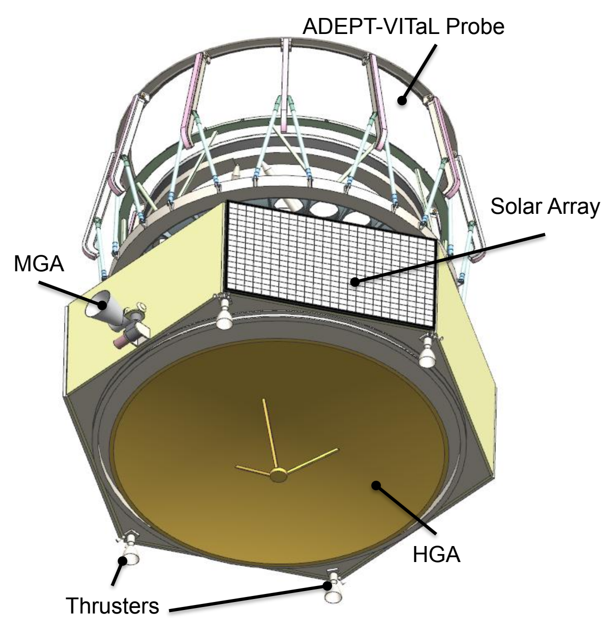


Figure 1. Cruise stage spacecraft with ADEPT and VITaL.

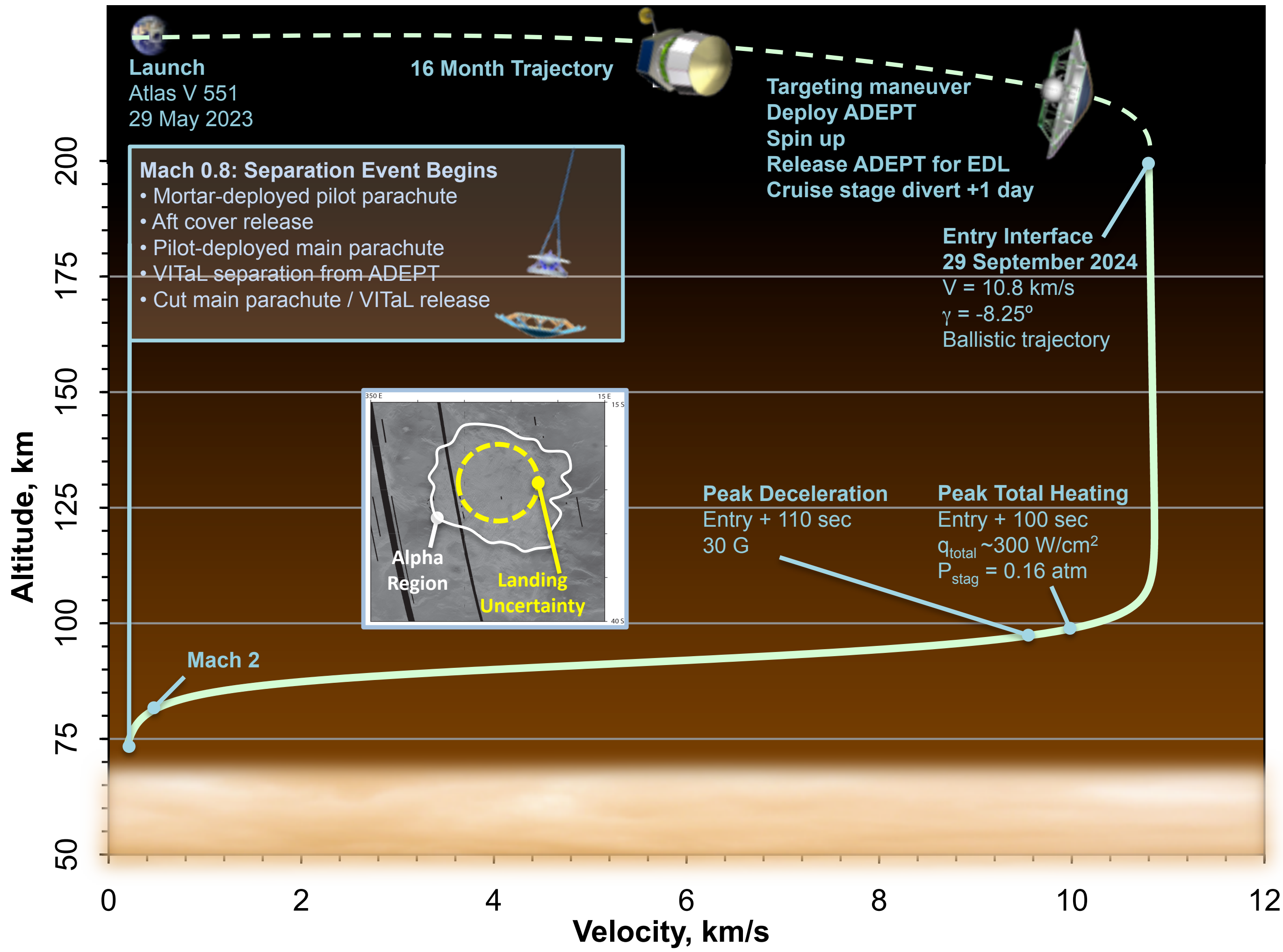


Figure 2. ADEPT-VITaL Concept of Operations.

In order to avoid blocking communication with Earth during cruise to Venus, ADEPT remains in a stowed configuration until approximately three days prior to arrival at Venus. At this time, the spacecraft is on a trajectory for direct entry into the Venus atmosphere with a surface landing target within the Alpha Regio landing site. Prior to spin-up and release, ADEPT is deployed using the carrier spacecraft power. The spacecraft is then spun to 5 RPM to stabilize the ADEPT-VITaL probe for release. One day after probe release, the spacecraft performs a divert maneuver that maximizes communication with VITaL throughout the descent and landed portion of the mission. The probe is in a low power mode during the three-day coast after separation from the carrier spacecraft. Daily brief telemetry transmissions to the carrier spacecraft are performed to enable the carrier spacecraft to verify pointing to the probe. The communications system turns on one hour before predicted atmospheric entry to ensure adequate time to adjust carrier pointing, if necessary. The probe transmits continuously for the next 4 hours. Figure 3 shows the spacecraft position at and after ADEPT-VITaL passes the Venus atmospheric entry interface (EI).

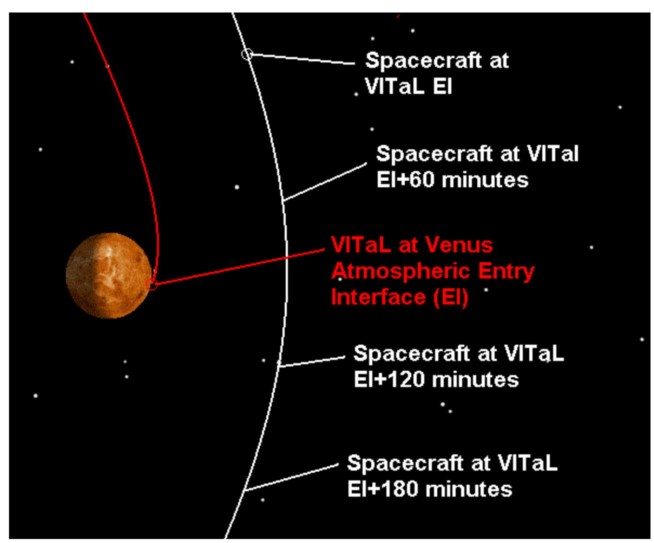


Figure 3. Spacecraft position at and after ADEPT-VITaL passes entry interface.

4. VENUS INTREPID TESSERA LANDER

VITaL is designed to safely transport the instrument suite to a tessera region on the Venus surface. An image of the lander is shown in Figure 4. The design of the lander is driven by the two most challenging requirements: the high temperature on the surface of Venus, and the operational stability of the system after landing on an unknown terrain. Due to the uncertainty about terrain conditions at the landing site, proposed designs were selected to provide a high level of assurance of success even if the terrain is extremely uneven. The worst-case scenario was assumed for this design, resulting in a requirement for stability on slopes up to 60º.

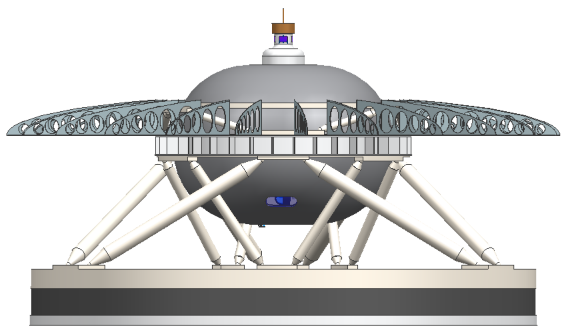


Figure 4. The Venus Intrepid Tessera Lander (VITaL).

ADEPT provides considerable mechanical load relief in the design of VITaL versus the traditional fixed aeroshell by lowering the peak deceleration loads by an order of magnitude. Table 1 shows how the masses of the instruments and lander subsystems are expected to decrease for the lower load case. The complexity of handling loads with ADEPT allowed savings in the instrument and structural areas. Masses were scaled in accordance with their sensitivity to launch loads. The mass reduction factor varied between 25% and 10%. The power system, and communication system are not expected to have much savings. The smaller instruments such as the atmospheric package, the magnetometer, descent camera, and LIBS/Raman Context camera have only 10% mass savings, as they are low mass items with minimum mass devoted to structure. The harness and thermal system each had 15% reduction in mass, where all other components were expected to benefit 25%.

Instead of realizing the benefit of reduced deceleration during entry as a reduction in entry mass, an alternate approach might augment instrument capability for the same total mass. The mass of the LIBS/Raman system could be increased, or it could be replaced with a heritage X-Ray Fluorescence/X-Ray Diffraction (XRF/XRD) system similar to Mars Science Laboratory (MSL) using a Honeybee robotics drill system. By reducing the fraction of the entry system that is not payload, ADEPT opens up the option space for adding mission capability or reducing component masses. ADEPT as an entry system revolutionizes what can be done in a Venus lander by providing opportunities in the following areas:

- Reduced cost of VITaL lander system
- Reduced launch system mass
- Increased launch mass available for the payload suite (Trade Raman/LIBS with XRF/XRD with Sample ingestion system)
- Increased thermal mass of system to increase time on the surface
- Increased overall instrumentation providing more context and or more in-situ sample locations
- Added mass to landing ring and landing system to enable landing on steeper slopes
- Reduced complexity and risk of the lander components

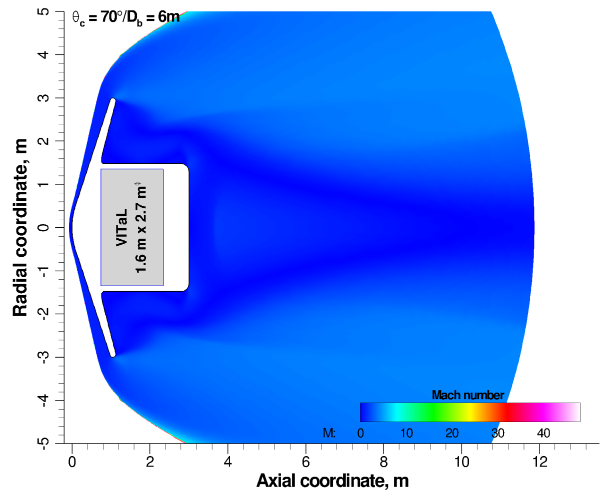
Table 1. VITaL mass savings from ADEPT entry environment

Item	Baseline VITaL CBE [kg]	Assumed mass savings from lower g-load [%]	ADEPT-enabled VITaL CBE [kg]
VITaL	**1061**	**--**	**813.5**
Lander Science Payload	**48**	**--**	**36.9**
Mass Spec	11	25%	8.3
TLS	5	25%	3.4
Atmospheric Package	2	25%	1.5
Magnetometer	1	10%	0.9
Descent Camera	2	10%	1.6
LIBS / Raman Context Camera	2	10%	1.8
LIBS / Raman	13	25%	9.8
Panoramic Camera	3	25%	2.3
Science Payload Accommodation	10	25%	7.5
Lander Subsystems	**1012**	**--**	**777**
Structure/Mech.	283	25%	212
Landing System	603	25%	452
Thermal	77	15%	66
Power	12	No change	12
Harness	10	No change	10
Avionics	8	15%	6.8
Mech. Control Electronics	10	15%	8.5
RF Comm	9	No change	9

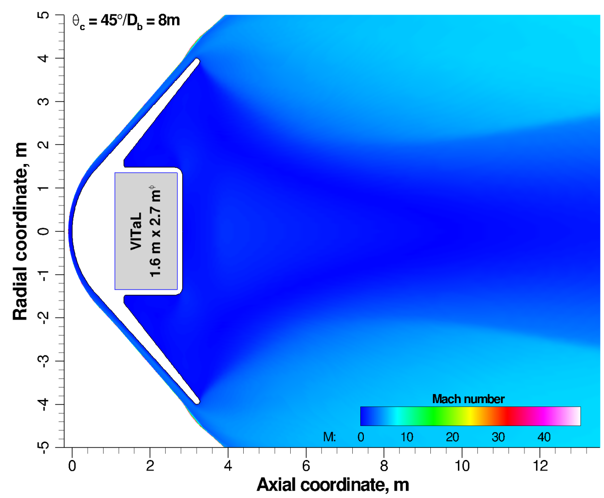
5. ENTRY CONFIGURATION

The feasible trajectory design space and sensitivity studies for low ballistic coefficient entry vehicles with shallow entry flight path angles at Venus has been established in earlier work [3]. The desired low g-load entry trajectory can be achieved by a continuum of entry vehicle forebody geometries: for a given entry mass, the same hypersonic ballistic coefficient is achieved with a 70º cone angle / 6 m diameter vehicle as a 45º cone angle / 8 m diameter vehicle. The flow simulation shown in Figure 5 illustrates the geometric difference between these two configurations and gives physical insight into how both configurations achieve the same drag force: the former with more bluntness, the latter with more area. The ADEPT-VITaL baseline entry configuration is a 70º cone angle / 6 m diameter / 12-rib faceted pyramid, and was established through a comprehensive trade study considering mass efficiency, static and dynamic stability at relevant speeds, convective and radiative aerothermodynamic heating, and candidate material survivability. There are no known issues that would clearly compromise the feasibility of the baseline 70º / 6 m diameter configuration, and the disadvantages of the baseline can likely be mitigated through design.

It is worth noting here that the VITaL-configured ADEPT entry vehicle is designed with the intent to minimize lander redesign impacts. The baseline ADEPT-VITaL configuration is shown in Figure 6 contrasted with the Decadal Survey's 45º rigid aeroshell with CP TPS configuration. Note that the nose cone is sized to be 3 m in diameter such that the VITaL landing ring can be secured directly to a structural nose ring when ADEPT is configured for reentry. This configuration helps to protect the landing ring from heat radiated off the back of the carbon cloth. Additionally, given that the landing ring constitutes the majority of VITaL's mass, this configuration ensures that the entry vehicle's center of gravity is placed as close to the nose as possible, maximizing static and dynamic stability. Also note that an aft-cover has been added around the VITaL pressure vessel. This component has the dual purpose of protecting the pressure vessel from base heating and storing the main parachute bag. The parachute is deployed subsonically with a side-mounted pilot parachute and its sole purpose is to aid separation of VITaL from ADEPT.

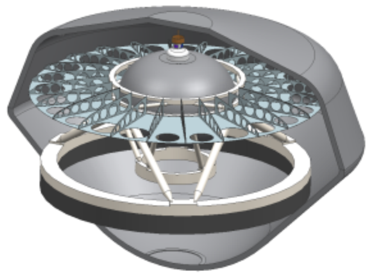


(a) Baseline (70°/6m)

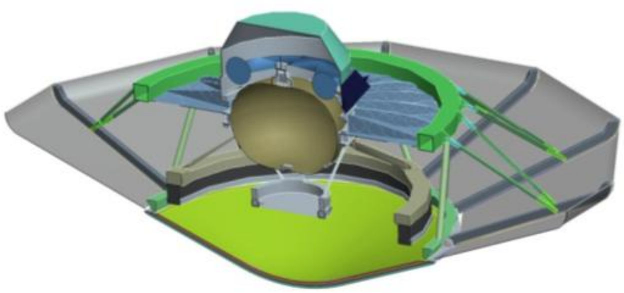


(b) Alternate (45°/8m)

Figure 5. Pitch plane contours of Mach number for ADEPT decelerators idealized as sphere-cone geometries. The VITaL lander is treated as a cylinder of 2.7 m diameter and 1.6 m height (shaded) region. Results are shown for the peak total heating point along a candidate flight trajectory with the following freestream conditions: Velocity = 10.6 km·s^{-1}, Density = 8.54 x 10^{-5} kg·m^{-3}, Temperature = 175 K, Mach number = 49, Dynamic pressure = 4.78 kPa, Unit Reynolds number = 1.0 x 10^{5} m^{-1}.



(a) VITaL mission baseline (Decadal Survey)



(b) ADEPT-VITaL

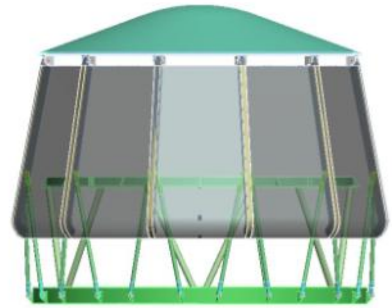
Figure 6. VITaL shown packaged in (a) a 3.5 m diameter / 45º sphere cone (Decadal Survey study) and (b) re-packaged in the 6 m / 70º diameter ADEPT-VITaL configuration.

6. ADEPT-VITaL Structures and Mechanisms

Structures

ADEPT achieves its low ballistic coefficient with a mechanically-deployable semi-rigid aeroshell. The ADEPT structure consists of a ribbed framework covered by a tensioned fabric skin, which shares many traits with an ordinary umbrella. This design allows a large and high-drag aeroshell to be packaged within available launch vehicle fairings, while still providing a stable and predictable aeroshell structure for reacting the aerodynamic loads experienced during Venus atmospheric entry. Figure 7 shows the ADEPT structure in the stowed and deployed configurations.

The ADEPT structural skeleton is made up of four primary subsystems: main body, nose cap, ribs, struts. These subsystems are shown in Figure 8. The main body consists of titanium lower and upper rings that are separated by a truss system of titanium struts. The main body lower ring is a box section that provides the attachment to the spacecraft cruise stage and supports the lower ends of the rib support struts. The main body upper ring (supported by the main body struts) provides the support interface to the VITaL landing ring and also acts as the attach/latch location for the nose cap ring.



(a) Stowed (launch and cruise)

(b) Deployed (entry and separation)

Figure 7. ADEPT structure in the (a) stowed and (b) deployed configurations.

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 rib and carbon cloth portion of the aeroshell. The nose cap uses Graphite/BMI over a titanium honeycomb core sandwich construction and is protected from the entry aerothermal environment using a lightweight ablative TPS such as Phenolic Impregnated Carbon Ablator (PICA). A titanium ring frame that also supports the upper ends of the ribs reinforces the perimeter of the nose cap.

Figure 8. ADEPT skeleton primary subsystems: main body, nose cap, ribs, and struts.

The ribs provide the framework that supports the tensioned carbon cloth. The ribs are hinged at their attachment to the nose cap, and are supported via pairs of struts at a point along their span that minimizes overall bending. Their construction is an advanced carbon carbon (ACC) box section, a material that can perform under the predicted aerothermal and thermostructural environment without the need of an insulation layer between the carbon cloth and the rib.

Struts that support the ribs are installed in pairs to carry the aerodynamic loads transmitted from the carbon cloth 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 rib support struts are currently specified as titanium tubes with titanium end fittings.

The aerodynamic surface is formed by tensioning 3D-woven carbon cloth 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 the high temperatures seen during entry (~1600° C) without the need for additional TPS materials. Several of the top layers of the carbon cloth are allowed to oxidize and recede away during the entry heat pulse, but the construction of the 3D woven cloth allows the aeroshell to maintain its structural integrity. The ADEPT carbon cloth surface is shown in the deployed position in Figure 9.

A substantial part of the current technology development effort is comprised of arc jet testing the carbon cloth in an arc jet under simultaneous structural and aerothermal loading that is relevant for the ADEPT-VITaL mission. Details of this testing as well as a description of the material can be found in Arnold [5], and nominal entry environments are compared with demonstrated test conditions later in this paper.

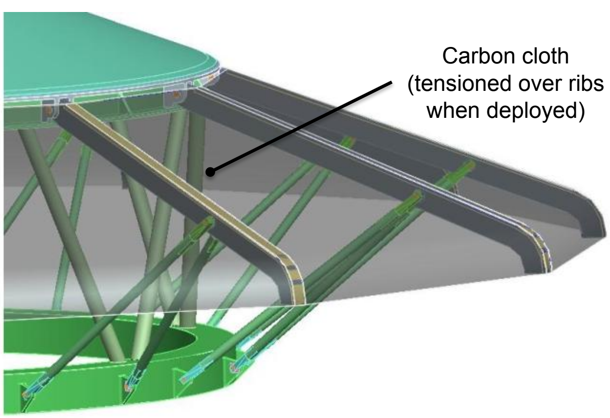


Figure 9. Carbon cloth tensioned over ADEPT ribs when deployed.

The ADEPT aeroshell skeleton was first sized for entry loads using MSC NASTRAN. This was followed by a more detailed non-linear analysis in LS-DYNA that included modeling of the carbon cloth to determine the stresses and deflections in the combined aeroshell structure. Rib and strut hinge pins and end fittings were also sized based on the loads extracted from the finite element model. All sizing information was used for the mass estimates provided in the MEL (Appendix A). Launch environments have also been considered, and preliminary analyses of the ADEPT aeroshell have been performed to evaluate structural performance during launch. A set of finite element models representing variations in the stowed (launch) configuration of ADEPT was used to analyze the aeroshell skeleton for modal frequencies and quasi-static launch loads. Results indicate that concepts with direct rib retention between each rib and the main body will be able to withstand the launch environments.

Mechanisms

Three mechanisms are required for deployment, in addition to the carrier spacecraft separation systems required by a conventional entry system. The three ADEPT deployment mechanisms are:

1) Stowed release

2) Primary deployment

3) End of travel latch

ADEPT is shown mid-deployment in Figure 10.

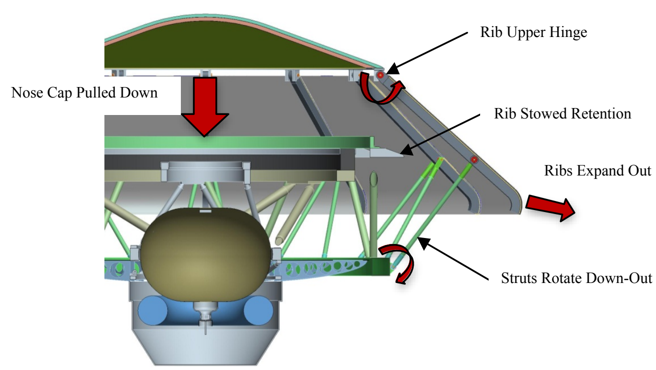


Figure 10. ADEPT shown mid-deployment.

The ADEPT structural skeleton is constrained at the ribs during launch to prevent excessive motion in response to the vibroacoustic environment. The stowed release mechanism removes the constraints on the ribs allowing the structure to begin deployment. The baseline concept for the stowed release mechanism employs a cable-activated pin-puller at each rib restraint as shown in Figure 11. Other options for stowed release are also feasible.

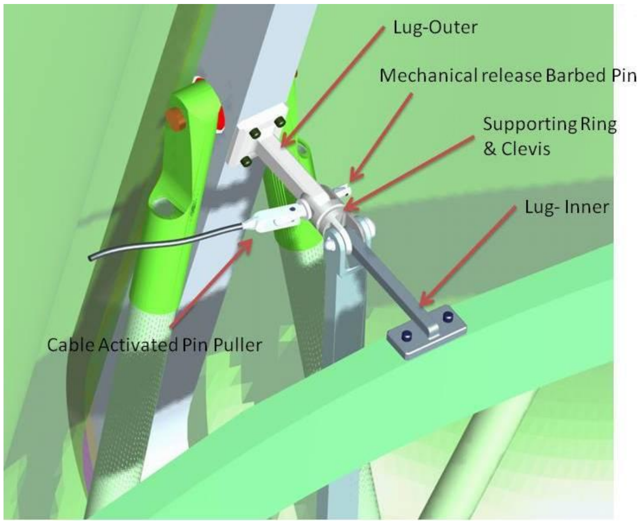


Figure 11. ADEPT stowed release mechanism.

The baseline concept for the primary deployment of the ADEPT aeroshell is a motor-driven winch and cable system. A cable is attached to the aft side of the nose cap and the motor-driven winch retracts the nose cap from its extended (stowed) position toward the main body upper ring. As the nose cap is pulled aft, the ribs and struts are forced to fold outward thereby deploying the aeroshell structure and the carbon cloth aero-surface with it. The motor/winch/cable system is sized to pull the ADEPT aeroshell into tension under loading that is equal to the loads expected during entry. In order to limit power demand, the deployment actuator uses significant gear reduction along with a small motor. Full deployment is expected to take approximately 10 minutes, although deployment duration can be increased in order to make use of lower power systems.

An end-of-travel latch system is used to retain the ADEPT structure in the deployed position once primary actuation is complete. This is intended to prevent excessive loading or possible back-driving of the actuation system during entry. The end-of-travel latch system consists of ball & pawl latches installed at the nose ring to main body upper ring interface. Once the deployment actuator pulls these two rings into contact with each other, the balls engage the pawl latches, locking the aeroshell into the deployed position. Sensors will be used to indicate that full deployment has been achieved.

The remaining mechanisms in the ADEPT-VITaL configuration are essentially the same as those employed by VITaL with a rigid aeroshell. These include: spacecraft separation from the launch vehicle, entry vehicle separation from the cruise stage, aft cover separation and parachute deployment, and ADEPT separation from VITaL. Key interfaces are shown in Figure 12. Separation from the carrier spacecraft is performed with electronics in the carrier spacecraft and aft cover separation, parachute deployment and ADEPT separation from VITaL are performed by electronics in VITaL.

The detailed master equipment list (MEL) for the ADEPT-VITaL vehicle is provided in Appendix A. There is a mass savings with ADEPT compared to a rigid aeroshell: ADEPT has a nominal mass of 807 kg compared to the baseline VITaL aeroshell at 1050 kg [2]. One caveat to this result is that the margins policy used to derived the 1050 kg baseline VITaL aeroshell mass is not clear in Reference [2]. If a more conservative margins policy was used to compute the aeroshell carbon phenolic thickness than the ADEPT structural mass, for example, than the mass benefit seen in Appendix A could be artificially high. These sizing results show that the ADEPT aeroshell mass is predictably lower, but certainly in family with a traditional rigid aeroshell.

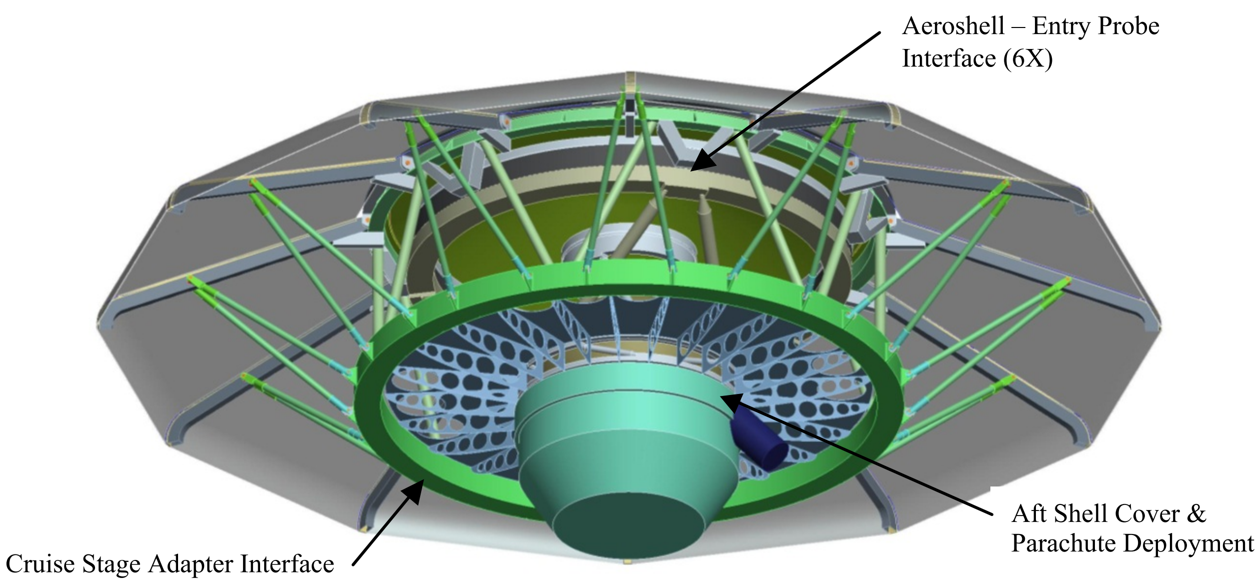


Figure 12. Aft-view of ADEPT-VITaL vehicle.

7. Entry Aerothermal Analysis and Design Challenges

ADEPT is designed to operate under simultaneous structural and aerothermal load by way of two state-of-the-art materials: 3D woven carbon cloth [5] and ACC. The unique entry architecture presents some challenges that are not common in entry vehicle design. This section presents aerothermal analysis used to show the robustness of the ADEPT-VITaL design for these key challenges: deflected surface heating, local wrinkling, and carbon cloth permeability. Finally, a summary of the entry environment is given in the context of demonstrated woven carbon cloth material performance.

Distributed aerothermal environments over the entire ADEPT decelerator surface have been computed using version 4.02.2 of a NASA Ames in-house Data-Parallel Line Relaxation Methods code (DPLR). DPLR solves the partial differential equations governing the three-dimensional flow of a reacting gas mixture in thermochemical nonequilibrium using a finite-volume method. For the case of atmospheric entries into Venus, a 16-species gas model has been used. The required freestream conditions are taken from the results of three degree of freedom (3DOF) trajectory simulations. The decelerator surface is assumed a hundred percent efficient in allowing recombination of atoms (from shock-heated dissociation of the freestream) and reradiates incident heat flux with an emissivity of 0.85.

Deflected surface heating

We first consider the possibility of cloth sag (or creasing) due to lack of pre-tension. We consider the smooth case and two additional cases of 5 and 10 cm maximum deflection at the mid point between the sphere-cone tangency point and cone-shoulder tangency point. Figure 13 shows ADEPT configurations idealized as a smooth sphere-cone, a ribbed blunted pyramid, and a blunted pyramid with deflected facets. For this particular analysis, the decelerator diameter is 8 m (not 6 m of the baseline), but we are most interested in the relative increase/decrease in environments compared to the baseline (undeflected facets) so the size is not critical as long as all variants are the same scale. Figure 14 shows surface distributions of pressure, hot-wall heat flux, and shear stress for the undeflected and deflected facets (5 cm and 10 cm). Results are shown for the peak heating point along a candidate flight trajectory.

There is clearly an impact of deflections. The flow dives into the troughs created by the deflections and renders ribs as attachment lines. Therefore, both rib heating and shear increase with deflection. The pressure too is impacted because of the recompression upon the flow moving out of the concave surface. Although there is some reduction in environment close to the sphere-cone junction because of the concavity of the surface to the oncoming flow, the recompression of the flow as it exits out of the troughs created by the deflections causes significant increases above the undeflected values for all three quantities – pressure, shear, and heat flux. However, it is anticipated that the right amount of pre-tension in the carbon fabric will keep deflections small enough that they are not an issue during the heating part of entry.

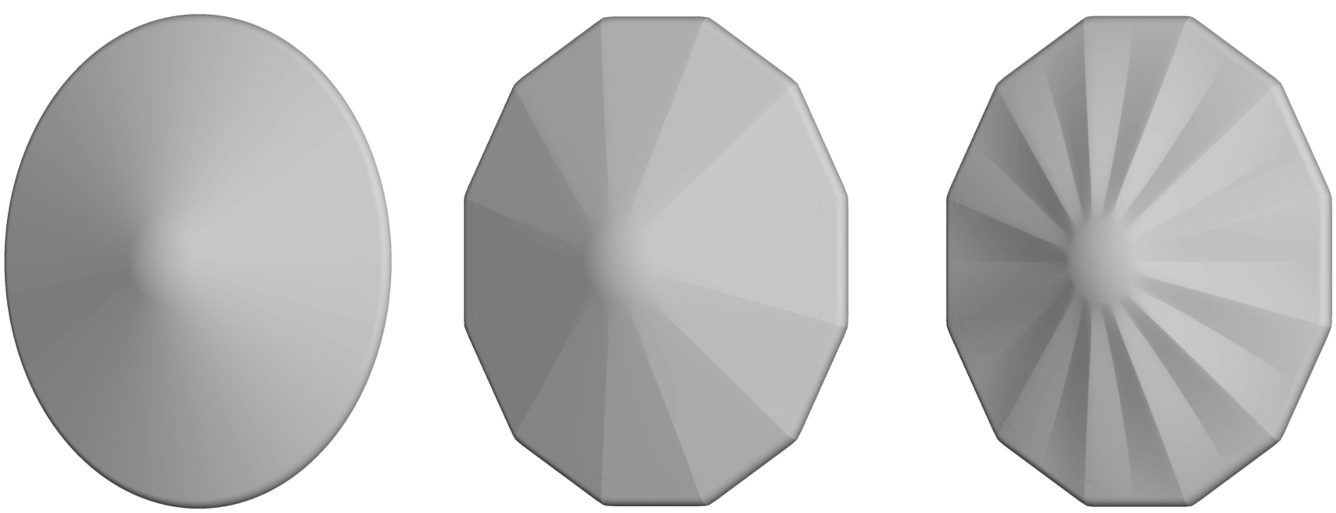
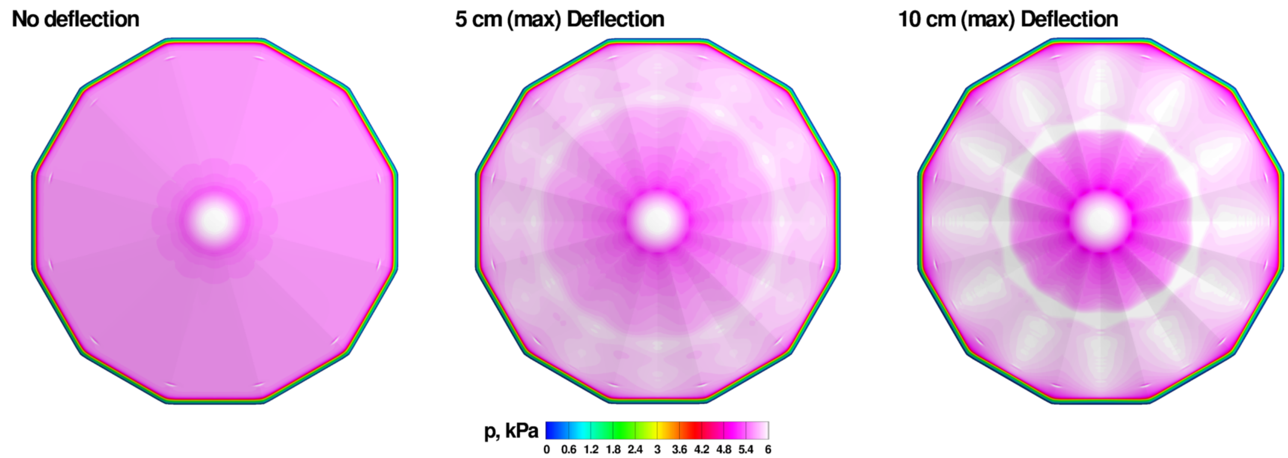
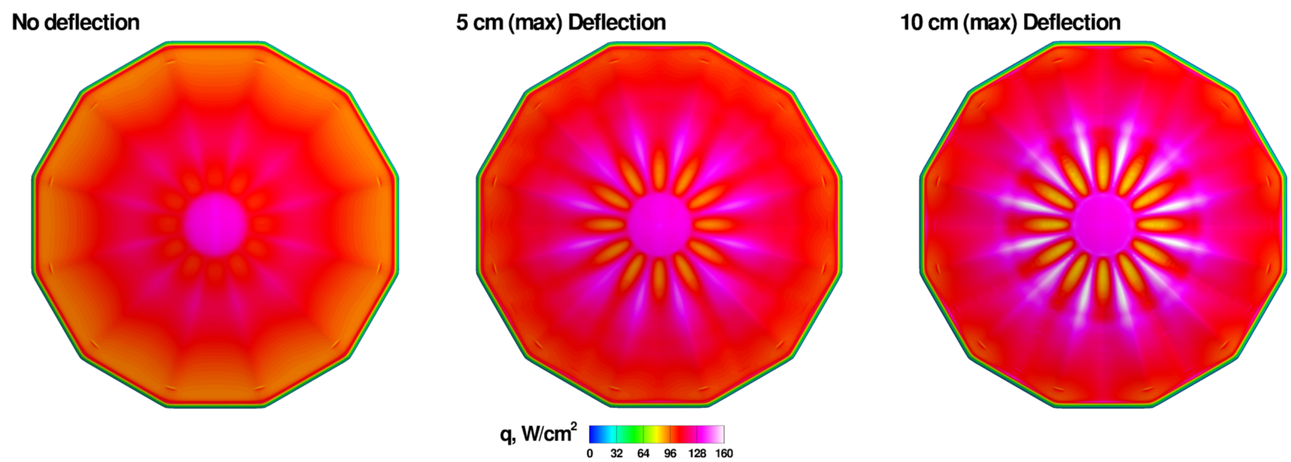


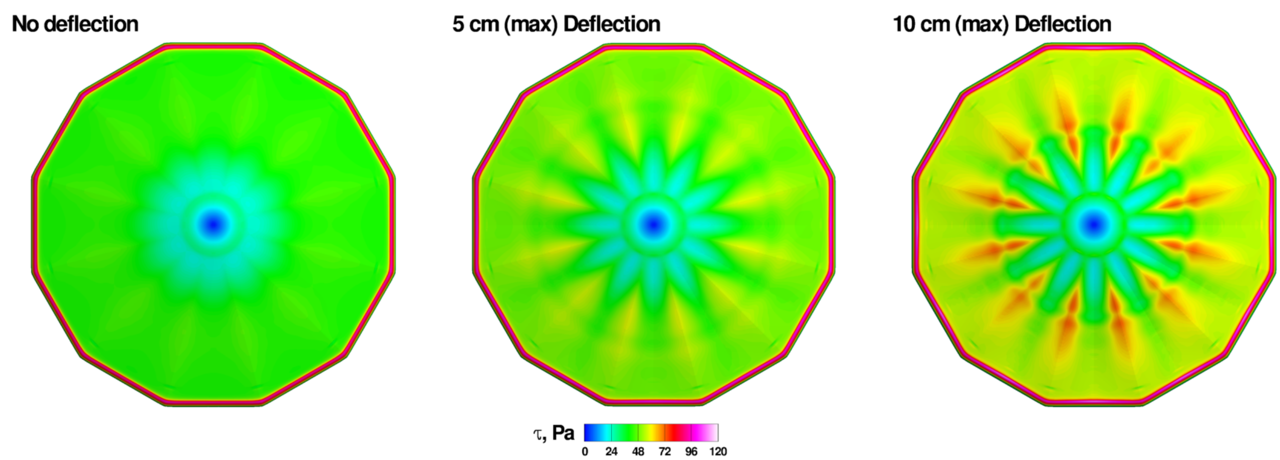
Figure 13. ADEPT configurations idealized as a smooth sphere-cone (left), a ribbed blunted pyramid (center), and a blunted pyramid with deflected facets (right). Although the deflected facets appear creased, there is compound curvature in the surface.



(a) Pressure



(b) Hot-wall heat flux



(c) Shear stress

Figure 14. Surface distributions of: (a) pressure, (b) hot-wall heat flux, and (c) shear stress for undeflected and deflected facets of a 12-rib, 70° blunted pyramid of 8 m diameter. Results are shown for the peak heating point along a candidate flight trajectory.

Local wrinkling

A second issue is that of local wrinkling in fabric (as opposed to large deflections under pressure loads). Such wrinkling is likely to occur at the foot of the carbon cloth panels, i.e., closer to sphere-cone junction area. Figure 15 shows smooth and “wrinkled” geometries that have been analyzed with CFD simulation tools. Note: the analysis presented here is for the ADEPT-VITaL baseline design, which is a 12-rib, 70° blunted pyramid of 6 m base diameter.

The maximum depth (at the mid point between two ribs) of a wrinkle is 1.2 cm, which is very small compared to the distance between two ribs. Furthermore, the wrinkles are aligned with the flow rather than perpendicular to it. Although this likely represents a worst-case scenario, it may be possible that wrinkles perpendicular to the flow direction act as trips and aid in early transition of the wall-bounded shear layer in flight.

Surface distributions of pressure, hot-wall heat flux, and shear stress for the smooth and wrinkled geometries are shown in Figure 16. These results are from computations at the peak total heating point along a candidate flight trajectory. Clearly wrinkling leads to local “hot spots” in the carbon fabric, with somewhat of an extended footprint downstream. Additionally rib heating and rib shear experience increases as well. However, the heating and shear increases are not beyond the expected capability of the carbon cloth.

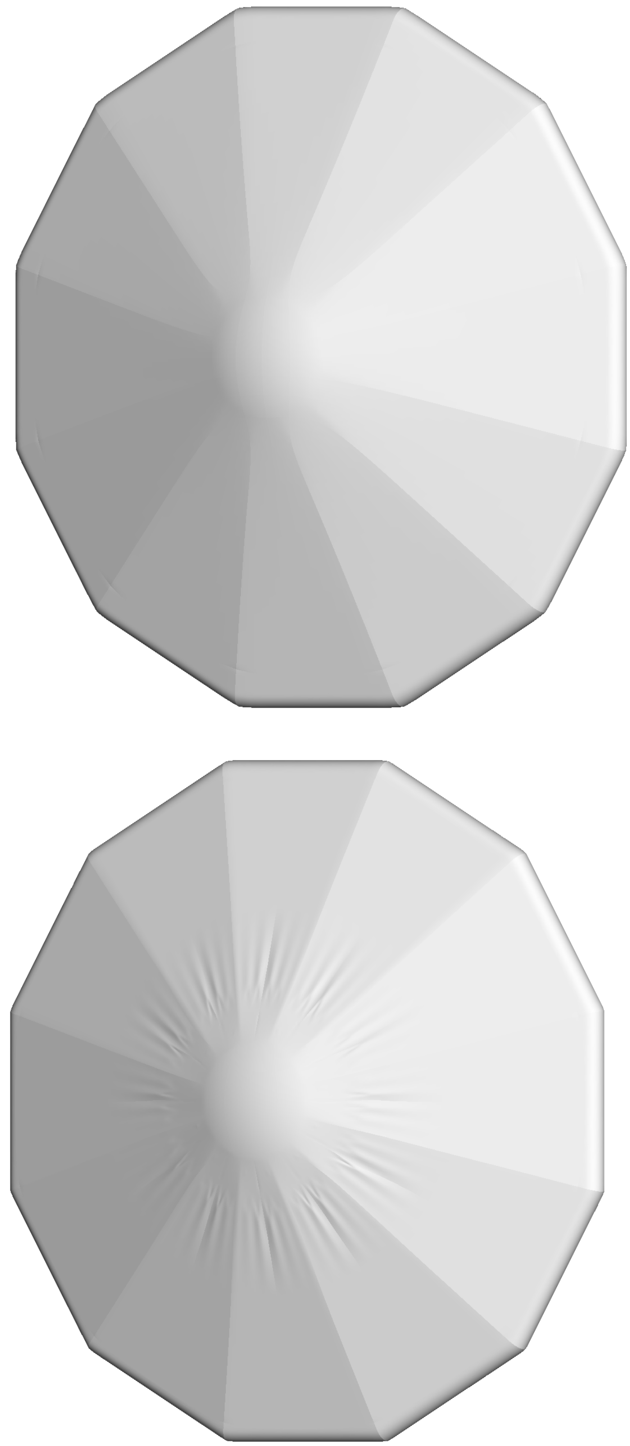
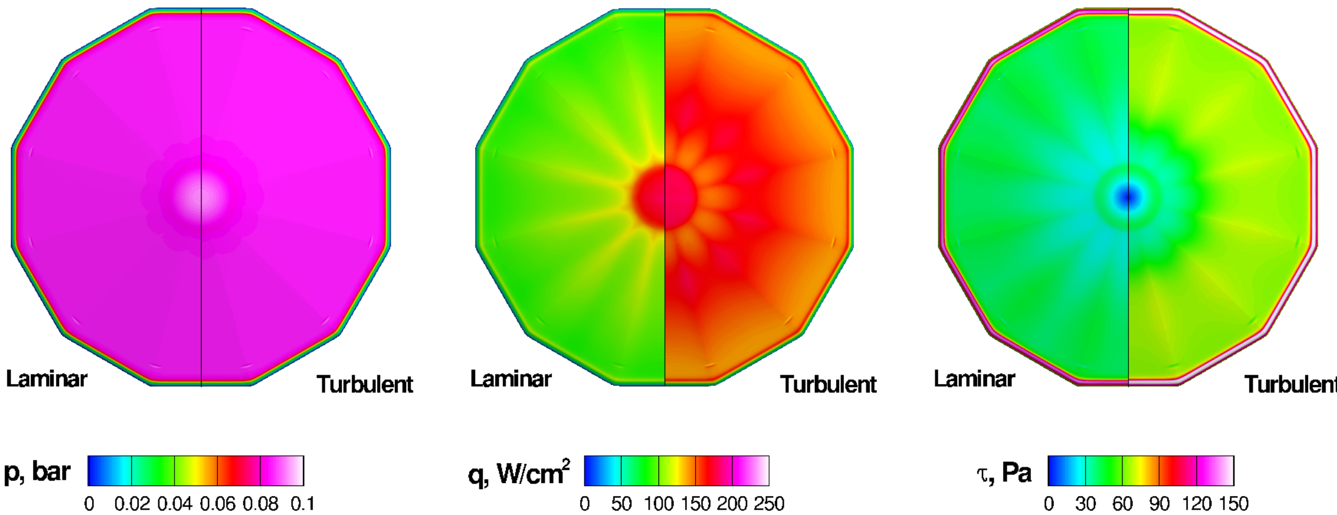
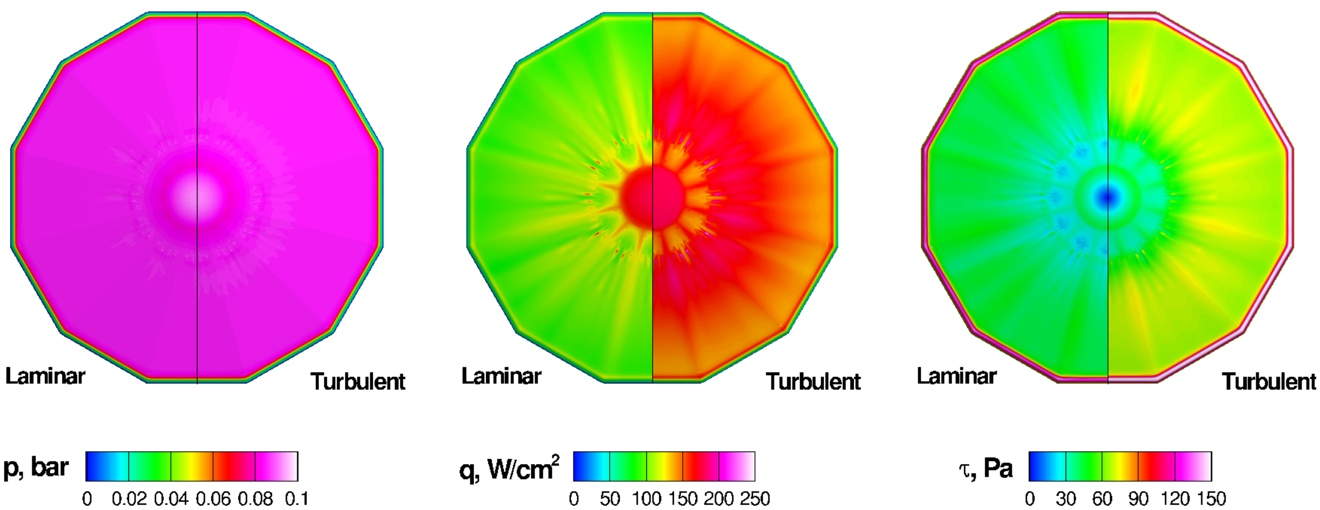


Figure 15. Smooth (left) and “wrinkled” (right) fabric geometries. Wrinkles are aligned with the flow (worst case scenario), and the maximum depth occurs at the mid-point between two ribs. Wrinkling is blended out from around the mid-point on the ribs out to facet-shoulder interface.



(a) Smooth geometry environment



(b) Wrinkled geometry environment

Figure 16. Surface distributions of pressure, heat flux, and shear stress for: (a) the 70°/6m smooth baseline and (b) the 70°/6m "wrinkled" configuration, and laminar/turbulent flow at the peak total heating point along a candidate flight trajectory.

Permeability

Yet another issue is that of permeability of carbon fabric and the sensitivity of predicted environments to permeability. Since few measurements of carbon cloth permeability have been made and have been constrained to room temperature only, limited computations have been performed with permeable material. Assuming that the permeability values (with good bit of scatter across different weaves) could be converted to an equivalent suction velocity, computations were performed for a small concept model to be tested in an arc-jet. Results are shown in Figure 17 for cold- and hot-wall cases for a 14-in diameter 55° sphere-cone model in an arc-heated stream. Key points from the figure are that as permeability increases, so does the heat flux, and the rate of increase with permeability depends on whether the wall is hot or cold. For a cold wall, suction draws the high-temperature boundary layer edge closer to the wall, whereas for a hot wall case, even if the boundary layer edge is drawn closer, the enthalpy potential (between edge and wall) does not change as much. These computations indicate that permeability will make only a small difference in the hot-wall case, but this conclusion remains to be demonstrated via an arc-jet experiment.

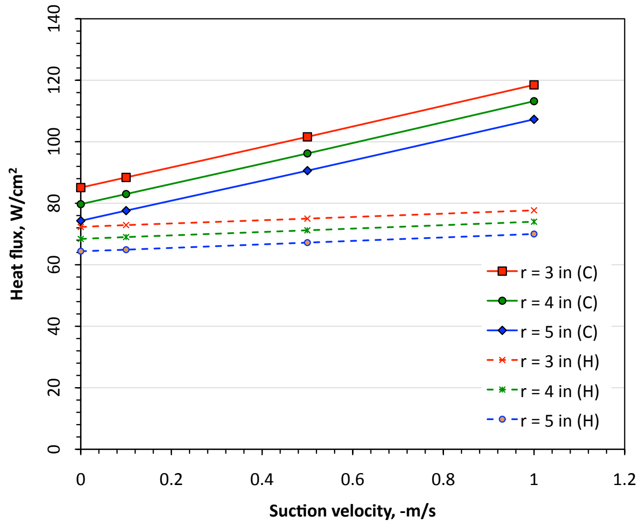
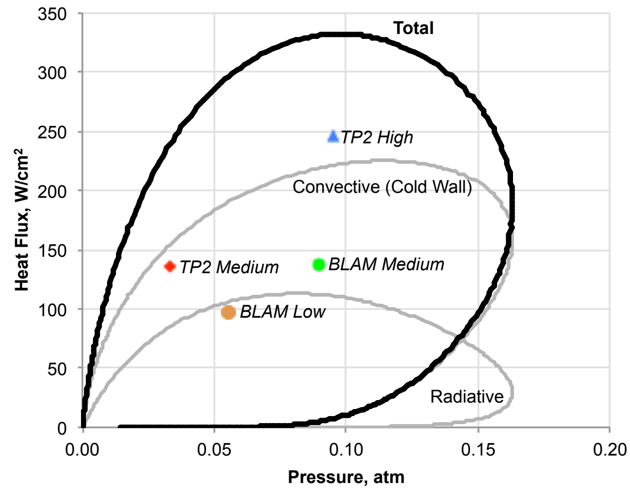


Figure 17. Variation of heat flux at 3 locations on the flank of a 55° sphere-cone in an arc-heated stream. Results are shown for both cold- and hot-walls with 4 values for suction velocity (representing 4 levels of permeability of carbon cloth).

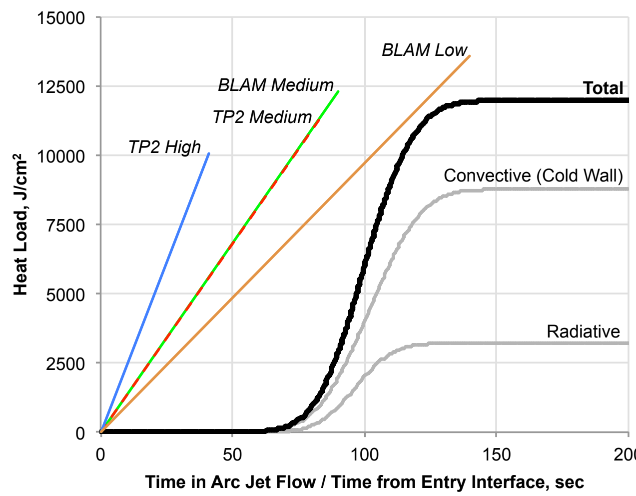
Woven Carbon Cloth Demonstrated Performance

Predicted entry environments must be bounded by material capabilities in order to achieve design closure. Arc jet testing has been performed on the woven carbon cloth under simultaneous structural and aerothermal load at relevant environments for the ADEPT-VITaL mission. These tests demonstrate the viability of woven carbon cloth as a structural-TPS material for the ADEPT-VITaL mission. Figure 18 compares the margined entry environments with recent carbon cloth arc jet test conditions achieved at NASA's Test Position 2 (TP2) arc jet and Interactive Heating Facility (IHF) arc jet. In this figure, the margin is achieved through an entry mass (2100 kg) and velocity (11.5 km/s) that are higher than expected for the ADEPT-VITaL mission (1621 kg and 10.8 km/s). The entry flight path angle is -8.25º, the same as predicted in flight.

In Figure 18, the heat flux vs. pressure plot (part a) and the heat load vs. time plot (part b) can be used compare the demonstrated woven carbon cloth capability with the margined aerothermal environment and margined thermostructural environment, respectively. Arc jet testing has focused on showing the viability of the woven carbon cloth to survive the thermostructural environment (simultaneous structural load and heat load – heat flux multiplied by exposure duration). Excellent material performance was achieved during the Bi-Axially Loaded Arcjet Mechanical (BLAM) test at conditions exceeding the margined ADEPT-VITaL thermostructural environment. Bounding aerothermal conditions (simultaneous heat flux, pressure, and shear stress) have not been achieved in test, although initial test results are promising. Readers should refer to Arnold [5] for a detailed description of the test articles, test conditions, model design, and results.



(a) Heat flux vs. pressure (clockwise from origin)



(b) Heat load

Figure 18. Woven carbon cloth environments at the highest heating location for the 2100 kg entry mass / 11.5 km/s entry velocity / -8.25 entry flight path angle / 6 m diameter / 70º cone angle ADEPT-VITaL vehicle compared with arc jet test conditions.

8. Future Work

The work presented in this paper demonstrates the feasibility of ADEPT as a viable alternative to a rigid aeroshell with the potential for game-changing mission benefits. A key product of this effort is a list of identified technology risks. The work required to mitigate these risks will guide further investments of the ADEPT project.

In order to address manufacturability and mechanism reliability risks, a subscale 2 m diameter ground test article (GTA) will be fabricated with a mixture of breadboard and flight-like components. Additional high priority risk is associated with the carbon cloth attachments and transition from hot structure (ACC) to metallic structure. This will be accomplished through a radiant heat test of the top cloth-to-rib and cloth-to-nose attachment schemes. Together, the GTA testing and radiant heating component tests will provide further confidence that ADEPT is a viable decelerator technology for the VISE mission.

Some aerodynamic and aeroelastic risks remain to be mitigated. There are three aspects to the aerodynamic problem: (1) static, which deals with placement of the center of gravity of the system and the sensitivity of this location due to static flexural loads; (2) dynamic, which deals with pitching/yawing motion of a flexing structure and the stability of the vehicle; and (3) the response of the carbon cloth to aeroacoustic loads (primarily from vortex shedding at supersonic and subsonic freestream Mach numbers). Static aerodynamics and dynamic stability were studied in earlier work [3] and used as part of a larger trade study to select the ADEPT-VITaL ballistic coefficient and skeleton geometry. Dynamic stability risks are addressed primarily through leveraging key results of the inflatable reentry vehicle experiment (IRVE) flight tests, which have shown that flat-base aerodynamic decelerator geometries may provide improved dynamic stability at low supersonic Mach numbers compared to classical rigid aeroshells with a large backshell. This remains to be verified for the ADEPT-VITaL geometry, and is the focus of ongoing 6DOF trajectory simulation sensitivity studies and validation of computational tools with the IRVE flight data. Current efforts are also focused on understanding fluid-structure interaction due to aeroacoustic loads. While static deflection of the ADEPT ribs and woven carbon cloth is expected, dynamic aeroelasticity (flutter) due to fluid-structure interaction will be avoided through appropriate fabric pre-tension and stiffening features at the shoulder end of the gore. Ongoing efforts involve focused tool development and validation of fluid-structure simulation capabilities.

Finally, modeling and simulation of the woven carbon cloth requires additional material testing to better characterize thermal and structural properties. Additional material testing in an arc jet of the woven carbon cloth is needed to characterize its thermal response in a bounding aerothermal environment.

9. Summary

The objective of this study was to develop a variant of the VITaL Decadal Survey concept that replaces a conventional rigid aeroshell with ADEPT, a mechanically deployable aerodynamic decelerator. The science payload and mission operations are unchanged, and the ADEPT decelerator is designed around existing mission requirements and operations concepts. The study checks that the new technology has no adverse effects on other mission elements, can survive all mission phases without compromising its operation during atmospheric entry, and assesses its performance relative to the rigid aeroshell.

A range of shapes and sizes of decelerators were investigated, and several configurations appear viable. A forebody with a diameter of 6 m, and a 70º cone angle, was chosen as the baseline because it can sustain the aerothermal and mechanical loads with relatively low structural mass.

The basic structural arrangement for ADEPT-VITaL has been defined, and suitable materials for each component are selected. A finite-element model has been used to size all the parts and generate mass estimates. The level of pre-tension in the membrane required to mitigate fluid-structure interaction has not been fully assessed, but structural sizing assumes pre-tension loads that are of the same order as flight loads. Several mechanisms for deployment have also been considered, and preliminary sizing of promising candidates has been performed. Mass estimates for the decelerator are less than those for a rigid aeroshell with conventional TPS. Structural response has been checked for loads throughout the mission, and the folded configuration also shows adequate structural margins.

The shallow entry angle, long-duration trajectories flown by ADEPT provide significant advantages for payload delivery. The primary benefit is the reduction in peak deceleration loads, which opens up the option space for adding mission science capability or reducing component masses. ADEPT as an entry system revolutionizes what can be done in a Venus lander by providing opportunities in the following areas:

- Inclusion of sensitive instruments that could not be used in the rigid aeroshell architecture due to very high entry loads
- Reduced cost of VITaL lander system due to lower structural requirements and reduced cost of verification
- Reduced launch vehicle requirements (if mission mass permits use of smaller vehicle)
- Increased launch mass available for the payload suite
- Increased thermal mass of system to increase time on the surface
- Increased overall instrumentation providing more context and or more in-situ sample locations
- Added mass to landing ring and landing system to enable landing on steeper slopes
- Reduced complexity and risk of the lander components

ADEPT does not compromise function of the cruise stage. The interface between the entry vehicle and the cruise stage is essentially unchanged. It is preferable to delay deployment until just prior to separation and entry to assure that there is no interference with solar panels and communications.

The size of ADEPT complicates parachute deployment, but a system that combines features previously flown on Mars and Venus missions can be developed. Fully relevant parachute deployment tests can be performed by dropping test articles from low-cost balloons from moderate altitudes in Earth's atmosphere. Design of the descent system can be addressed through conventional engineering approaches.

There are still a number of issues to be worked. This design effort produced a list of technical risks that will be tracked in the ongoing ADEPT technology program. The most pressing concerns are transonic stability and fluid-structure interaction (flutter). Development of high fidelity coupled fluid and structural response tools is in work, and tests to provide validation data on relevant configurations should be pursued within two years. None of the identified risks appear insurmountable.

Feasibility of the ADEPT concept for the VITaL mission is established at a preliminary design level. Opportunities for more efficient integration have been identified, particularly with respect to packaging and structural load paths. It is expected that even greater mission benefit will be achieved as the mission design is advanced.

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BIOGRAPHIES

Brandon Smith *is an Aerospace Engineer in the Entry Systems and Technology Division of NASA Ames Research Center. He received his Bachelor's and Master's degrees in Aerospace Engineering from Georgia Tech. Brandon's interests are in system design of atmospheric entry vehicles and development of heat shield instrumentation technologies. Brandon is lead system engineer of the ADEPT project and is deputy lead system engineer of the Orion Exploration Flight Test 1 heat shield instrumentation project.*

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Charles Baker *has been involved with the NASA GSFC Mission System Design in the Planetary area for 3 years. He has lead 2 Planetary Decadal Studies, lead planetary mission proposals, and planetary instrument proposals. Destinations for those proposals have been Venus, Mars, Jupiter System, asteroids and comets. He has also performed studies on Landers and Orbiters.*

APPENDIX A

ADEPT-VITaL Master Equipment List

Item	CBE [kg]	Composite Mass Growth Allow. [%]	Element Mass with Margin [kg]
Probe *(Lander + Aeroshell)*	**1620.5**		**2100**
VITaL	**813.5**	**30%**	**1058**
Lander Science Payload	**36.9**		**48**
Mass Spec	**8.3**	**30%**	**11**
TLS	**3.4**	**30%**	**4**
Atmospheric Package	**1.5**	**30%**	**2**
Magnetometer	**0.9**	**30%**	**1**
Descent Camera	**1.6**	**30%**	**2**
LIBS / Raman Context Camera	**1.8**	**30%**	**2**
LIBS / Raman	**9.8**	**30%**	**13**
Panoramic Camera	**2.3**	**30%**	**3**
Science Payload Accommodation (including Mechanisms)	**7.5**	**30%**	**10**
Lander Subsystems	**777**		**1010**
Mechanical/ Structure	**212**	**30%**	**276**
Landing System	**452**	**30%**	**588**
Thermal	**65.5**	**30%**	**85**
Power	**12.3**	**30%**	**16**
Harness	**10.0**	**30%**	**13**
Avionics	**6.8**	**30%**	**9**
Mechanism Control Electronics	**8.5**	**30%**	**11**
RF Comm	**9.0**	**30%**	**12**
ADEPT Aeroshell	**807**		**1042**
Heat Shield	**484**		**629**
Main Body	**233**	**30%**	**303**
Nose cap & Lock Ring	**61**	**30%**	**79**
Ribs & Bearings	**46**	**30%**	**60**
Struts & End Fit	**42**	**30%**	**55**
Joint Hardware	**10**	**30%**	**13**
Carbon cloth	**92**	**30%**	**120**
TPS	**71**		**85**
Nose TPS	**50**	**20%**	**60**
Ribs TPS	**12**	**20%**	**14**
Aft cover TPS	**9**	**20%**	**11**
Backshell	**30**		**39**
Payload backshell	**30**	**30%**	**39**
Mechanisms & Separation	**205**		**267**
Overall Deployment System	**54**	**30%**	**70**
Stowed/Deployed Latches	**19**	**30%**	**25**
Aeroshell separation ring	**30**	**30%**	**39**
Separation guide rails	**45**	**30%**	**59**
Backshell sep	**7**	**30%**	**9**
Parachute system	**50**	**30%**	**65**
Avionics & Power	**17**		**22**
Avionics unit	**4**	**30%**	**5**
Harness	**5**	**30%**	**7**
Power unit	**8**	**30%**	**10**
Spacecraft	**797.2**		**970**
Probe Separation System	**30**	**30%**	**39**
S/C Mechanical, Structural	**300**	**25%**	**375**
HGA Gimbal System	**7.0**	**25%**	**9**
GN&C	**40**	**15%**	**46**
Propulsion Hardware	**137.7**	**20%**	**165**
Thermal	**50**	**20%**	**60**
Power	**67.0**	**15%**	**77**
Harness	**40.5**	**25%**	**51**
RF Comm	**70.0**	**15%**	**81**

Avionics	**25.0**	**15%**	**29**
Launch Vehicle Separation System SC side	**30.0**	**30%**	**39**
Satellite *(S/C + Probe)* Dry Mass	**2417.7**		**3069**
Propellant Mass	**1035.6**	**1%**	**1046**
Satellite Wet Mass	**3453.3**		**4115**
LV Throw Mass available to lift Wet			**5310**
Atlas V 551 Small Fairing Contractual Throw Mass, C3 = 7.0			**5360**
3302 Truss PAF stays with L/V			**50**
Separation System LV Side			**0**
Mass Margins			
Project Margin (Wet Mass Growth, MEV to LV Limit) [kg]			**1195**
Wet Mass Growth (Wet Mass Growth, MEV to LV Limit) [%]			**29%**