ASSESSMENT OF GUIDED AEROCAPTURE AND ENTRY FOR VENUS IN SITU MISSIONS USING MECHANICALLY DEPLOYED AERODYNAMIC DECELERATOR. S. J. Saikia[1,2], H. Saranathan[1,2], J. M. Longuski[2], and M. J. Grant[2], [1]Ph.D. Student, [2]School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907-2045, sarag@purdue.edu.

A mechanically deployed aerodynamic decelerator, known as the Adaptive Deployable Entry and Placement Technology (ADEPT) is a viable entry system alternative to the traditional rigid aeroshells for in situ missions to Venus. ADEPT reduces both the peak deceleration loads and peak heat fluxes as opposed to traditional aeroshell technology. This research assesses the feasibility and advantages of using ballistic coefficient and bank angle modulations to further reduce peak deceleration loads and heat fluxes to benign levels. Optimal solutions-space is obtained for both the entry and aerocapture cases that minimizes the total heat load with a deceleration constraint of under 10 g's. These results further demonstrate the capabilities of ADEPT as a feasible and enabling entry system for in situ missions to Venus.

Introduction: The priority science questions for Venus have been identified in the 2013 National Research Council's (NRC) Planetary Decadal Survey [1]. European Space Agency's (ESA's) Venus Express is currently in orbit observing polar cloud dynamics and composition and is helping in the understanding of the structure, chemistry, and dynamics of the atmosphere. The gaps in the knowledge of the atmosphere to understanding climate evolution of Venus will require in situ measurements of deep atmospheric gas compositions and surface mineralogy that can be obtained using landers that can survive entry in to the dense Venusian atmosphere. As a part of the NRC's Decadal Survey, Venus Intrepid Tessera Lander (VITaL) mission concept, which lands on the tesserae terrain and achieves the New Frontiers science objectives [2].

Challenges of Venus Aerocapture, Entry, Descent, and Landing : Venusian atmosphere represents a harsh entry environment to spacecraft. All the past landers and probes to Venus have employed the traditional rigid aeroshell technology and a thermal protection system (TPS) comprised of fully-dense Carbon Phenolic (CP). For ballistic flight, the properties of CP necessitates the spacecraft to enter the atmosphere at a steep flight path angle. Such an entry trajectory presents high heat fluxes (3–17 kW/cm^2) and high deceleration loads (150-500 g's) [3].

ADEPT for Venus: The shapes and sizes of all rigid aeroshells used in all the past missions to venus were constrained by the diameter of the payload fairings of the launch vehicles. However, use of very low (<30 kg/m^2) ballistic coefficient (β)—entry spacecraft mass divided by its drag area—vehicles permits the use of much shallower entry flight angles, which in turn lowers the peak heat-fluxes and deceleration loads. Figure 1 shows the VITaL lander repackaged in to the ADEPT structure of a 6 m / 70º diameter ADEPT-VITaL configuration. The high ballistic coefficients of rigid aeroshells can be lowered via in-space deployment of a deceleration system. A mechanically deployed aerodynamic decelerator, ADEPT, is a potential candidate. The feasibility, risks, benefits, and limitations of the ADEPT mission (with VITaL lander repackaged into ADEPT) are outlined in [4]. It was shown that a mass saving of 248 kg is achievable compared to the baseline VITaL CBE of 1061 kg [4].

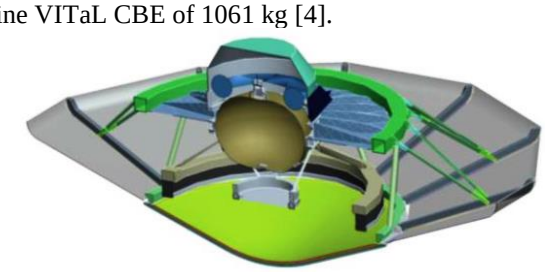

Figure 1. VITaL shown repackaged in the 6 m dimater / 70º sphere-cone ADEPT-VITaL configuration [5].

Baseline Mission Concept and Science Goals: In the baseline mission concept, the lander concept in a tessera region (study baseline is Ovda Regio, 3.7º E longitude, and , 25.4º S latitude) carries the same instruments as VITaL lander and fulfil the same scientific objectives. The mission concept provides measurements of: (a) surface chemistry and mineralogy (b) important atmospheric species that can answer fundamental questions about the evolution of Venus. (c) noble and trace gases (d) potential crustal dipole magnetic field [5].

Guided Aerocapture and Entry Using ADEPT: Low ballistic coeffcient and shallow entry flight angle (γ) combinations for ADEPT help in order of magnitude reduction (to 10s of g) of peak deceleration loads and peak heat fluxes to less than 100 W/cm^2. The analysis of ADEPT for the ADEPT-VITaL in [4] is done for ballisitic entry case. However, ADEPT configuration presents attractive options of precision control of spacecraft. A gimbaled aeroshell [6] and movable ADEPT aerodynamic surface presents ways to control the bank angle, angle of attack, and ballistic coefficient to provide precision control of the vehicle for any stage

of the mission. Controlling the lift using bank angle modulation is well understood and has been done for the Apollo and Mars Science Laboratory spacecraft.

Control Using β Modulation Only: β is defined as entry spacecraft mass divided by product of reference area (A) and drag coefficient (C_D) (this product is also called drag area). Changing the angle of attack also changes β (via C_D); however ADEPT presents a way to change β by changing the reference area which does not affect the angle of attack. The reference is changed by opening and closing the ADEPT outer structure akin to opening and closing of an umbrella. Fully deployed configuration represents minimum-β (Figure 1), and closing-in to make a 30º-cone represents maximum-β (Figure 2). The peak deceleration load for ADEPT-VITaL was found to be 30 g's or more [4]. Controlling the beta during entry can further reduce the peak deceleration to less than 10 g's and limit the peak heating to less than 110 W/cm^2. These advantages provides additional reduction in the structural and instrument mass (free up mass for more instruments or thermal control masses) to enhance longetivity for a landed mission. For ADEPT, shallow-γ and low-β reduces the peak deceleration loads and heat fluxes. But, shallow-γ increases the probability of skip-out of the spacecraft due to various perturbations (atmospheric) and uncertainties in the states, the ability to control the deceleration mitigates this problem.

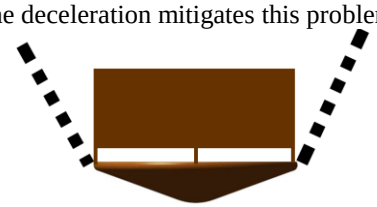

Figure 2. Schematic of the 6 m diameter/ 70º sphere-cone ADEPT-VITaL β-modulated configuration—maximum-β case.

Control Using Both β and Bank Angle Modulations: The advantages of β and bank angle β modulation can be combined to provide improved (precision) control of the spacecraft from entry to landing. This will help in reduction of target (or landing) error in the presence of uncertainties. Therefore, it will guarantee that the lander lands precisely where it is intended to i.e. scientifically important landing sites.

Aerocapture Using β Modulation: β modulation can be used for the ADEPT-VITaL to deliver the lander on to the surface. The same control can also be used for aerocapture of the spacecraft prior to direct entry, or for circular orbit insertion. While the idea of aerocapture for Venus is not new for its advatage over propulsive capture [7], β modulation provides added advantages to account for perturbations. The peak deceleration during aerocapture to a 500-km circular orbit is less than 5 g, although the total heat load increases. If the spacecraft now enters from this 500-km circular orbit to land on the surface, the peak deceleration load is limited to less than 10 g. Thus, an aerocapture followed by entry using guided-ADEPT can present very gentle deceleration loads as opposed to the direct entry case [8].

Optimal Solutions: For the entry case, optimal solutions-space have been found for the entry-γ, and history of β-control that carry the spacecraft from entry conditions to subsonic parachute deployment altitude of around 60 km. The solution minimizes the total heat load by constraining the peak heat flux to under 120 W/cm^2, and peak deceleration to less than 10 g. Similarly, for aerocapture case, the optimal solution-space has been found that minimizes the total heat load which carries the spacecraft to a capture altitude of 500 km such that the terminal circular speed is attained constrained by a peak deceleration of under 5 g. Figure 4 shows an optimized baseline trajectory for entry using β modulation.

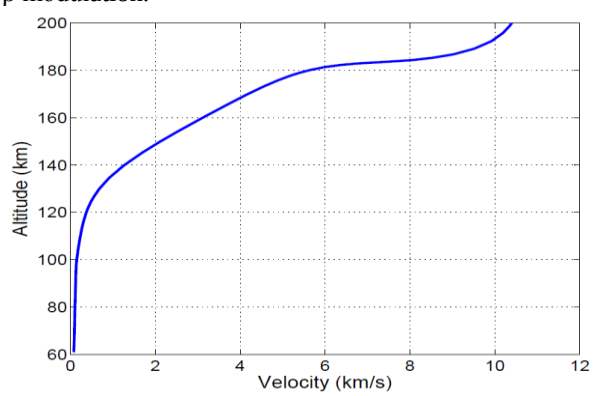

Figure 4. Baseline trajectory of the entry system from 200 km altitude to subsonic parachute deployment at 61 km altitude that minimizes total heat load and constrains the g-load to under 10 g's using β modulation.

Summary: Use of active control during aerocapture and entry will increase the accessibility of Venusian surface, atmospheric, and orbital targets for scientific investigations. It will help to make the entry system design more robust to uncertrainties and perturbations. Precision control of the spacecraft during all mission phases wil enable the delivery of scientific payloads right at the interesting targets.

References: [1] Squyres, S., et al. (2011), NAP Press, pp. 111-132. [2] Gilmore M. S. et al. (2010) NASA [3] Dutta S. et al. (2012) IEEE AC, 10.1109 [4] Smith B. et al. (2013) IEEE 978-1-4673 [5] JPL (2014), VEXAG pp. 3-5 [6] Venkatapathy E. (2011) AIAA 2011-2608 [7] Munk M. M. and Spilker T. R. (2008) 6th IPPW. [8] Beauchamp P. (2013) VEXAG.