**Heat Shields for Aerogravity Assist Vehicles Whose Deceleration at Titan**

**Saves Mass for Future Flagship Class Exploration of Enceladus**

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**Brief Presenter Biography:** Dr. Arnold has worked in the field of atmospheric entry technology for 59 years, starting with his study of radiative heating for the Apollo Command Module under the leadership of Alvin Seiff. His experimental work involved the use of ballistic ranges, shock tubes and arcjet facilities while his theoretical work included the development and application of line-by-line radiative transfer codes and the introduction of computational chemistry to determine the properties of shock-heated gases. He served as the chief of NASA Ames Space Technology division for 14 years. Arnold has received many awards: From **NASA** including medals for Outstanding Leadership, Exceptional Scientific Achievement and Distinguished Service, from the **Senior Executive Service** (Both Meritorious and Distinguished Executive), from the **AIAA** (Fellow) and from the **IPPW** (Alvin Seiff Award).

**Introduction:** A mission of great Astrobiological interest is one that would search for life signatures associated with the oceans and geysers of Enceladus [1]. Spilker et al., [2] have shown in a 2009 paper that use of an Aerogravity Assist (AGA) maneuver with a blunt body in Titan’s atmosphere could enable a Flagship Class Mission to Enceladus within reasonable cost

($3 B) and mission duration (14 years). This paper will summarize the 2023 Decadal Survey (DS) Whitepaper by Arnold, et al. [3] that estimated heat shield masses for an AGA vehicle whose deceleration in Titan’s atmosphere saves mass for future missions to explore Enceladus. This study focused on Titan AGA for an Enceladus landercorresponding to mission “E” in the Spilker, et al. paper [2]. The analysis is the first reported for heat shield requirements for an AGA aeroshell that accounts for the convective and radiation heating arising from flight in Titan’s atmosphere.

A companion 2023 DS Whitepaper by Tackett, et al., [4] studied Guidance, Navigation and Control (GN&C) for a Mars Science Laboratory (MSL) aeroshell flying an AGA maneuver in Titan’s atmosphere. Their results demonstrated that an AGA maneuver could be successfully accomplished by the use of modern GN&C technology. They reported [4] that the use of Titan AGA could reduce propellant load for Enceladus missions by 99.5 percent, not accounting for the requirement for an aeroshell for the maneuver.

There have been previous studies e.g., [5,6] of Titan AGA and all of these have demonstrated the benefits of the maneuver for the exploration of Enceladus.

The “Orbilander” Study by Mackenzie, et al. [7] did not include the use of Titan AGA. The mission studies by MacKenzie, et al. and Spliker, et al. both used “moon tours” as an element of the deceleration to Enceladus orbits. That by Spilker, et al. lasted 2.25 years while that in the MacKenzie et al. study lasted for 4.5 years. The difference in moon tour durations suggests that the use of Titan AGA could reduce the transit time to the start of science exploration from 11.42 years to 9.17 years for the Orbilander mission concept.

There is concern that flight in Titan’s atmosphere could contaminate the spacecraft and sensitive instruments with tholin-like organics that would compromise measurements at Enceladus later on. Ref. [3] acknowledged this problem and offered a suggestion to address the issue, but more work is required for a satisfactory solution.

The DS process allowed for endorsement of submitted Whitepapers. This Whitepaper [3] received 79 endorsements from the Entry, Descent & Landing (EDL), IPPW, Astrobiology and Space Science communities.

**Key Results:** Figure 1 illustrates a Titan AGA maneuver and defines the required boundary conditions in the Titan inertial reference frame - which. They are the hyperbolic excess velocities during Titan approach (V∞ in), and departure (V∞ out) and the angle ∆\_AGA in the Titan inertial reference frame (the hyperbolic turn angle is π - ∆\_AGA).

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Figure 1: A schematic of a Titan AGA maneuver that results in orbit capture with a periapsis near Enceladus. For this example, on 2/11/43, the spacecraft approaches Titan at a hyperbolic excess velocity (V∞ in) of 11.3 km/s nearly perpendicular to Titan’s orbital velocity direction and then enters Titan’s atmosphere. After executing the AGA maneuver with a hyperbolic turn angle of 180° – 23° = 157°, the spacecraft leaves Titan with a hyperbolic excess velocity V∞ out of 1.64 km/s and is targeted for the 2.25-year moon tour and the first gravity assist at Rhea.

Six AGA maneuvers were considered in [3]. Arrival dates were all in February of 2043, based on the team’s interplanetary trajectory design with a launch C3 of 16.2 km2/s2, and a 10 year transit time of flight that includes two Earth and one Venus Gravity Assist. Each case is identified using the arrival date followed by the type of transfer to Enceladus: those using a ~2.25-year long moon tour (MT) by targeting first gravity assist at Rhea, or a direct propulsive transfer (D) that targets Enceladus orbit radius as the capture orbit periapsis altitude. Direct transfers typically take several days. Cases considered were those that approached Titan at hyperbolic excess velocities V∞ in of 7.3, 11.3 and 14.8 km/s in the Titan-centered frame. This set of hyperbolic excess approach speeds depends upon the orbital location of Titan when the spacecraft initiates the AGA maneuver. None of these AGA trajectories dipped below 200 km so flight in methane rain or the condensate haze is not a concern. Atmospheric flight times range from about 800 to 1200 seconds.

To be consistent with the notional blunt body and “Mission E” reported in [2], the entry mass for the TRAJ simulations was chosen to be 3,800 kg. For this heatshield feasibility study, the body was assumed to be a simplified 60° sphere-cone with a base diameter of 5 m, a nose radius of 2.315 m (ballistic coeff. 128 kg/m2 at zero angle of attack) and a nose-to-base-radius ratio tuned to match the Huygens [8] aeroshell. The entry interface altitude was assumed to be 1,000 km. The estimated AGA forebody heat shield mass fractions depended on the values of V∞ in and ranged from 5 to 26 percent. A “sweet spot” in terms of heat shield mass was found to be for the case with a V∞ in value of 11.3 km/s where the Technology Readiness Level (TRL) 9 Phenolic Impregnated Carbon Ablator (PICA) forebody heat shield mass was estimated to be 200 kg. PICA was first flown on the Stardust Mission with a heat shield mass fraction of 22 percent [9]. Table 1 displays the results for the four lower V∞ incases where PICA was an excellent heat shield material. As can be seen, the mass fractions of the forebody heat shield ranged from 5.03 to 6.45 percent. The MT case with   
V∞ inof 14.81 km/s required a heavier heat shield (mass fraction of 26.1 percent) that could be made from the TRL 6 Heatshield for Extreme Entry Environment Technology (HEEET) [10]. The 26.1 percent mass fraction for the 14.81 km/s case is not unreasonable, since that for Stardust was 22 percent [9].

Table 1. Heat shield stagnation point sizing results for the Titan AGA vehicle using a Phenolic Impregnated Carbon Ablator (PICA) forebody heat shield as on the Stardust and MSL missions. Heat shield mass estimates assume constant stagnation point thickness over the entire wetted vehicle frontal area.

Table

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The TRAJ code [11] was modified so that it can simulate the Titan AGA maneuvers for specified boundary conditions as described above. The code iterates on the Entry Flight Path Angle (EFPA) and Lift over Drag (L/D) until the V∞ out and the angle ∆\_AGA match the AGA boundary conditions. Outputs from the simulations include the computed L/D, EFPA, trajectory and aerothermodynamics along the trajectory. Ref. [3] provides detail on the processes and approximations used to determine the aerothermodynamics and estimated heat shield masses. Details of the modifications to the TRAJ code and results of validation studies will be presented in [12].

**Contamination Control**: Contamination control of the AGA vehicle surfaces following flight through Titan’s atmosphere is important because the presence of complex, tholin-like organics [13] could possibly confound sensitive measurements at Enceladus later on.

A hypothesis for cleansing mechanisms during the AGA maneuver by aerothermal processes was discussed in [3]. The bow shock wave formed over the forebody heat shield and the extremely hot gases there (5,000 - 11,500 K depending on flight speed) will almost certainly dissociate any organics present in the free stream atmosphere of Titan, *before* they contact the surface of the AGA vehicle. While sterilization by the said aerothermodynamic processes will certainly occur at lower altitudes and higher speeds during the AGA maneuver, those processes might be too benign to be effective at the higher altitudes and lower speeds at which the AGA vehicle exits Titan’s atmosphere. More work is required to find a satisfactory method of contamination control of Titan AGA aeroshells.

**Summary**: The proposed paper will summarize the 2023 Decadal Survey (DS) Whitepaper by Arnold, et al. [3] that estimated heat shield masses for an AGA vehicle whose deceleration in Titan’s atmosphere saves mass for future missions to explore Enceladus. Ref. [3] is the first paper discussing heatshield masses for Titan AGA aeroshells and demonstrates that high TRL heat shield materials can provide solutions. The research is relevant in the context of the IPPW and the study of EDL since AGA flight at Titan involves analysis of aerothermodynamics and heat shield sizing. Exploration of Enceladus with the Orbilander involves landing, plume control and hazard avoidance [7].

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