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Heatshields for Aerogravity Assist Vehicles Whose Deceleration at Titan Saves Mass for Future Flagship Class Exploration of Enceladus

ABSTRACT: This paper reports the feasibility of using mature heatshield materials for an aerogravity assist (AGA) vehicle whose deceleration in Titan's atmosphere is a mass-saving enabler for nine different Enceladus missions (T. Spilker et al. 2009). A geometry for the Titan AGA vehicle is recommended with accompanying high-fidelity flow computations on that shape.

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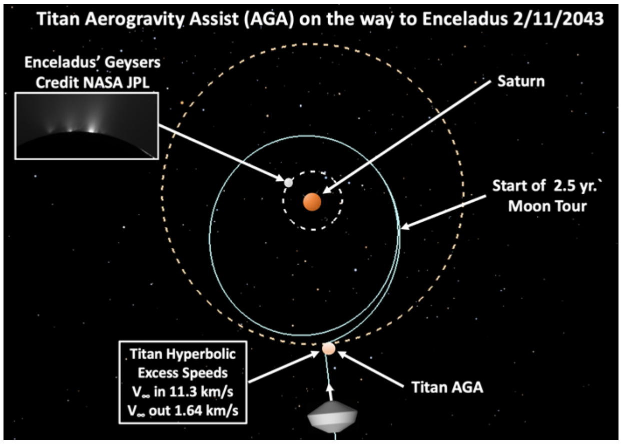

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I. INTRODUCTION

This paper demonstrates that mature materials exist for the heatshield design of Aerogravity Assist (AGA) vehicles that would decelerate in Titan's atmosphere, thereby enabling mass savings required for the exploration of Enceladus. A 2009 paper by T. Spilker et al. [1] described flagship class missions for Enceladus' exploration. Their paper identified technologies needed for the missions including autonomous navigation and radioisotope power, as well as challenges such as third body effects by Saturn on Enceladus orbiters. Given the launch capabilities of a Delta IV Heavy or an Atlas V, Spilker et al. established that a Titan AGA, performed by a blunt body prior to reaching Enceladus, is essential to meet mission mass requirements. The AGA maneuver at Titan would be followed by a mass-saving, standard gravity assist, 2.5-year tour of Saturn's inner moons. Their paper demonstrated that Enceladus exploration missions were achievable within the flagship mission cost cap (~ $ 3 B), realistic mass (6,500 kg spacecraft and propulsion stage), and reasonable duration (14 years including the moon tour) [1]. These missions included landers and low energy plume fly-throughs. They also suggested that the Titan AGA maneuver could be accomplished with a blunt body having a Lift over Drag ratio (L/D) greater than ~ 0.2. Lu considered the Titan AGA maneuver in detail [2] for various entry flight path angles (EFPA) for a 0.4 L/D body at entry speeds from 10 to 20 km/s with exit speeds from Titan's atmosphere ranging from 2 to 5 km/s. Ramsey and Lyne studied Titan AGA [3] with a L/D ~1.0 vehicle at entry speeds of 8-9 km/s into a targeted Saturn orbit that has a periapsis near Enceladus's orbit, allowing repeated close passes.

The present study of Titan AGA is the first that accounts for the radiative heating known to be of great importance for heatshield design of vehicles flying at hypervelocities in Titan's nitrogen/methane atmosphere. Details of this research is planned for submission to a peer reviewed journal [4].

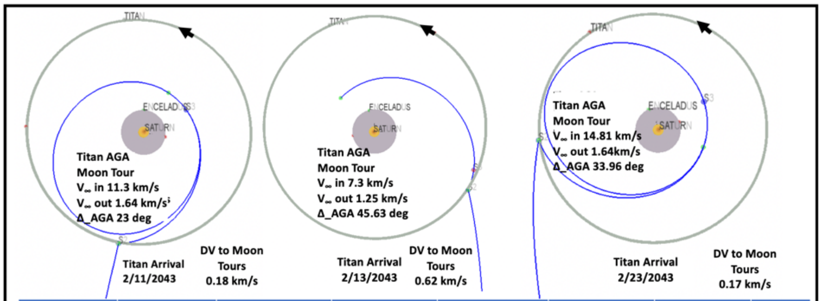
II. RATIONALE FOR THE SCIENTIFIC EXPLORATION OF ENCELADUS

Enceladus is a tantalizing target for astrobiology exploration because it appears to be both geologically active and accessible for sampling. Much has been written about Enceladus since the discovery of a plume there by the Cassini Mission in 2006, and its source—more than 100 jets located along four large fissures called "Tiger Stripes" near the South pole. This observation provides strong evidence for a subsurface liquid water reservoir. Space does not allow here for full referencing of all the research on Enceladus, but much of it is captured in a 2018 book by the University of Arizona Press [5]. Gravity measurements and evidence of libration indicate that this reservoir is not a local sea, but a global ocean. This ocean appears to meet the criteria for a habitable environment—extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy source(s) to sustain putative metabolism. If indeed these habitable conditions have persisted for a significant period of time, Enceladus might contain evidence of extant or past life. The discovery of life on another world, in particular in our own solar system, would revolutionize our perspective of how common life might be in the Universe. Fortunately, Enceladus is unique in terms of access as a mission to sample plume material, either via surface science or low energy fly-throughs. Questions about the composition of the ocean (and whether it might contain biosignatures) could be pursued without the need to dig or drill. Therefore, Enceladus has been ranked among the high priority bodies to target in the near term by the NASA Outer Planets Assessment Group (OPAG) Roadmaps to Ocean Worlds (ROW) group [6]. Finally, the scientific return of Enceladus missions is the subject of current study by Mackenzie, et al. [7].

III. TRAJECTORY TO THE SATURNIAN SYSTEM LAUNCHED IN 2033 AND 2043 TITAN AGA MANEUVERS

A high-fidelity model of the interplanetary trajectory to the Saturnian system was created using

Copernicus https://www.nasa.gov/centers/johnson/copernicus/index.html. The trajectory has a launch C3 of 16.2 km^2/s^2 and reaches the Saturnian system in 2043, 10 years after a 2033 launch via multiple gravity assists by Earth and Venus. The C3 provided by a Delta IV Heavy could enable all nine of the Enceladus Missions discussed in [1], while an Atlas 5 could support a long-lived soft lander (Mission "E") or a low energy plume fly-through Mission "F" [1]. Outbound events are listed in Fig. 1: Two Earth Gravity Assists (EGA), one Venus Gravity Assist (VGA) and two Deep Space Maneuvers (DSM). After the last EGA, a DSM is required for Titan arrival in February of 2043. The 2033 launch date is consistent with the forthcoming 2023 decadal survey. Titan atmospheric entry velocities depend upon the encounter geometry and were chosen to bound heatshield requirements. Six AGA maneuvers are considered herein. Each of them is specified the arrival date, followed by the type of transfer to Enceladus, moon tour (MT) or direct, propulsive transfer (D). Three of these AGA maneuvers are depicted in Fig. 1 in blue where the trajectories are shown in the Saturn coordinate system. After the AGA deceleration, the spacecraft is targeted for the first standard gravity assist at Rhea. Rendezvous with Enceladus occurs after a gravity-assist tour of Saturn's inner moons. The moon tour can take more than two years and requires up to 500m/s ΔV based on previous analyses [1]. The ΔV (DV) values for insertion into the MT trajectories are specified on Fig. 1. The DV values for direct transit to Enceladus (D) are listed in Table 1. Direct transits typically take three days.



Event	Launch	VGA	EGA	DSM	EGA	DSM	Titan Arrival
Date	3/2/2033	8/20/2033	1/25/2035	2/29/2036	10/12/2037	10/25/2038	2/2043
Note	C3=16.2 km^2/s^2	2605 km Altitude	3533 km Altitude	59 m/s	1000 km Altitude	218 m/s	

Figure 1. Outbound Earth⟶Saturnian system trajectory with listing of important events. Zoom-in shows three Titan AGA maneuvers from a suite of six cases considered herein. Trajectory curves are in Saturn-relative coordinates. Dates for the Enceladus-bound AGA maneuvers at Titan are listed on the Figure.

IV. BOUNDING AEROTHERMODYNAMICS FOR TITAN AGA MANEUVERS

Figure 2 (Left) is a schematic of the Titan AGA maneuver that enables mass-saving transits to Enceladus. The AGA boundary conditions are shown in Fig. 2 (Left): hyperbolic excess velocities V_∞ in, V_∞ out and the angle Δ_AGA in the Titan inertial reference frame. The hyperbolic turn angle in the Titan inertial reference frame is π - Δ_AGA. These parameters constitute the boundary conditions for the AGA moon tour maneuvers and their values in Titan inertial coordinates are specified in Fig. 1. For 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 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 first gravity assist at Rhea.

The TRAJ code [8] has been modified so that it can simulate the Titan AGA maneuvers for the boundary conditions specified above. The code iterates on the EFPA and L/D until the V_∞ out and

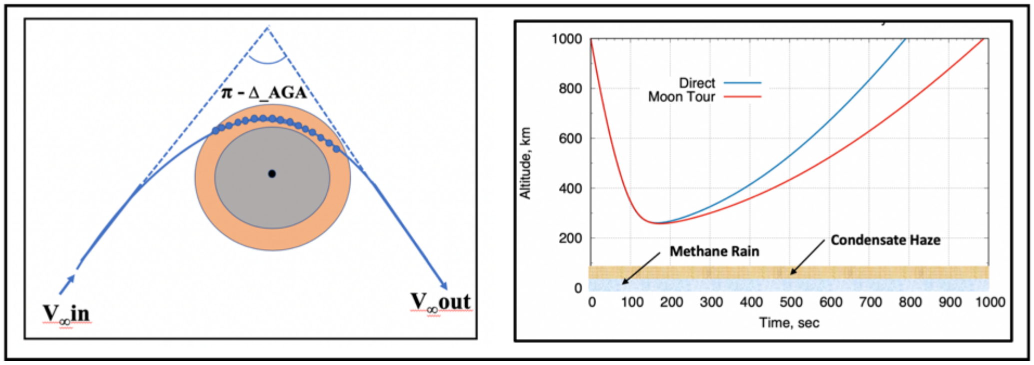


Figure 2 (Left). Schematic diagram for the Titan AGA maneuver in the Titan inertial frame. Figure 2 (Right). Altitude versus time solutions for two cases arriving at Titan on 2/11/43, one for direct transfer to Enceladus (Direct), and another for insertion into a moon tour (MT) terminating at Enceladus.

the angle Δ_AGA match the AGA boundary conditions [4]. Outputs from the simulations include the computed L/D, EFPA, trajectory and aerothermodynamics along the trajectory. The atmosphere used in TRAJ for this work is based on the Titan-GRAM average/nominal model that accounts for Titan's nitrogen/methane composition (~98.7% and 1.3% respectively) and its structure [9]. TRAJ uses an engineering model based on high-fidelity simulations by DPLR (Direct Parallel Line Relaxation) [10] and NEQAIR [11] for *air* [12] as default to estimate convective and radiative heating at each trajectory point, due to the lack of a general Titan heating correlation. These correlations can be scaled based on higher fidelity solutions including those from [13] that better simulate radiative heating for Titan's nitrogen/methane composition and were used to estimate [4] the aerothermal properties listed in Table 1. These results scope the aerothermal conditions for incoming hyperbolic excess speeds ranging from 7.3 to 14.81 km/s. To be consistent with the notional blunt body and "Mission E" reported in [1], 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/m^2 at zero angle of attack) and a nose-to-base-radius ratio tuned to match the Huygens [15] aeroshell. The entry interface altitude was assumed to be 1,000 km. Consistent with practices being used for Dragonfly [13], the following margins were applied to the heating rates: 1.3 for convective heating and 1.67 for radiative heating. Table 1 lists the date and type of maneuver in column 1. Columns 2-4 specify the AGA boundary conditions for each case, and the remaining columns list various values computed by TRAJ that correspond to these boundary conditions. Positive values of L/D are for lift up, while those that are negative are for lift down.

Table 1. Results for six 2/2043 Titan AGA maneuvers created with the TRAJ code.

Arrival Date	V_∞ in km/s	V_∞ out km/s	Δ_AGA Deg.	DV, km/s to Encel-Adus	L/D (Const-ant)	EFPA Inertial Deg.	Peak stag. Press. Pascals	Peak Conv. heat rate, W/cm^2	Peak Rad. heat rate, W/cm^2	Peak Tot. heat rate, W/cm^2	Tot. heat Load, J/cm^2	Atm. Flight Time, Sec.
2/11/43 (D)	11.7	3.3	14.3	3.9	-0.0168	-36.708	1.78^{+4}	200	327	523	35153	738
2/13/43 (D)	7.3	1.197	47.16	5.47	-0.0544	-35.907	6.72^{+3}	98	35	117	21784	1262
2/23/43 (D)	14.80	2.6	18.5	3.8	-0.0114	-37.223	3.22^{+4}	411	2286	2697	119868	792
2/13/43 (MT)	7.3	1.252	45.633	0.618	-0.0534	-35.904	6.71^{+3}	98	34	117	21787	1249
2/11/43 (MT)	11.3	1.64	23.0	0.18	0.0856	-37.786	2.19^{+4}	199	270	461	27990	947
2/23/43 (MT)	14.81	1.64	33.96	0.17	-0.0387	-37.134	3.22^{+4}	410	2276	2686	120538	988

The solutions resulted in very small required L/D values. Higher L/D may be required to counter real-time effects, such as error in the EFPA, discussed by others [16]. The MT and D cases differ significantly in the exit hyperbolic excess speeds and flight duration. The stagnation point heat rates and heat loads span a wide range, important for bounding TPS solutions. Note that there are slight differences between the hyperbolic excess speeds and EFPA in Titan inertial and atmospheric relative coordinates as documented in [4].

Figure 2 (Right) shows that the 2/11/43 MT AGA trajectories never drop below 255 km, the lowest of all six cases considered. Encountering methane rain that occurs below 40 km or the condensate haze that occurs below 80 km [14] are not problems for the Titan AGA cases listed in Table 1.

V. THERMAL PROTECTION SYSTEM (TPS) SIZING FOR A SIMPLIFIED TITAN AGA VEHICLE

The TRAJ code performs TPS sizing based on the FIAT (Fully Implicit Ablation and Thermal Response) program [17]. Results of stagnation point TPS sizing shown in Tables 2 and 3 are for the same simplified body/margins used for the aerothermodynamic solutions in Table 1.

Table 2. TPS stagnation point sizing results for the Titan AGA vehicle using a Phenolic Impregnated Carbon Ablator (PICA) forebody heat shield as on the Mars Science Laboratory (MSL) [18].

Arrival Date	V_∞ in, km/s	V_∞ out, km/s	Atm. Flight Time, Sec.	PICA TPS Thickness, cm	Peak heat flux, margined, W/cm^2	PICA TPS mass, assuming const. thickness, kg	TPS Percent of vehicle entry mass
2/11/43 (D)	**11.7**	**3.3**	**738**	**3.52**	**523**	**215.1**	**5.66**
2/13/43 (D)	**7.3**	**1.197**	**1262**	**4.00**	**117**	**245**	**6.45**
2/11/43 (MT)	**11.3**	**1.64**	**947**	**3.12**	**461**	**191.2**	**5.03**
2/13/43 (MT)	**7.3**	**1.252**	**1249**	**4.01**	**117**	**246**	**6.46**

The maximum heat flux for the MSL entry was 226 W/cm^2, while the tile gap fillers were tested to 323 W/cm^2 in *air* and performed well in terms of differential recession of the fillers compared to that of the adjacent PICA. The sizing results for the Titan atmosphere shown in Table 2 predicted negligible PICA recession (predominantly due to the lack of oxygen in the atmosphere), so differential recession of PICA and the room temperature vulcanizing silicone (RTV) gap fillers may not be an issue for the Titan AGA application. Further consideration of differential recession is included in [4] by the current authors.

The design thickness of PICA for MSL was 2.41 cm [18] as compared to estimates for the lower speed AGA cases that range from 3.12 to 4.0 cm. These PICA thicknesses are manufacturable. Importantly, as shown in Table 2, the tiled PICA forebody TPS mass assuming a constant stagnation point thickness is only 5.66% and 5.03% of the entry vehicle mass, respectively, for the V_∞ in of 11+ km/s direct and moon tour cases. It must be noted that while tiled PICA is at Technology Readiness Level (TRL) 9 for MSL, work to qualify and certify this solution for a Titan AGA vehicle would be required, especially on the relative recession between the RTV gap filers and the PICA tiles. Table 2 omits both of the 2/23/43 missions because the margined heat fluxes exceed the upper limit of even monolithic PICA used on the Stardust Mission [19], so the tiled PICA system is not a candidate for the 2/23/43 AGA maneuvers.

Stagnation point sizing shown in Table 3 was performed for the TRL 6 Heatshield for Extreme Entry Environment Technology (HEEET) [20] for the same body and margins as for the PICA TPS solution. Assuming a constant insulating layer thickness for the entire forebody heat shield, the percentages of the vehicle entry mass would be roughly 15.1% and 26.1% for the 2/11/43 and 2/23/43 cases, respectively.

It is noted that the stagnation point solutions and estimates of TPS mass assuming constant thickness in Tables 2 and 3 are for laminar flow heating. Turbulent flow and effects of surface roughness on the flank of the heat shields could affect TPS mass. The TPS mass estimates shown in Tables 2 and 3 could increase after detailed study, but the conclusions regarding the viability of the TPS materials that could be used for AGA forebody heat shields are not expected to change.

Based on past experience, the Super Lightweight Ablator SLA should work for the aft body TPS. Exceptions might be required at the shoulder seal region, where the shape transitions to the aft body, or at other “hot spots” owing to CN radiative heating (see Fig. 3. below). The solution is to use the forebody TPS material around the shoulder or at hot spots [4].

Table 3. TPS stagnation point sizing results for the Titan AGA vehicle using HEEET [20].

Arrival Date	V∞ in, km/s	V∞ out, km/s	Atm. Flght Time, Sec.	HEEET insul. Layer Thick, cm	HEEET TPS mass assuming const. thickness, kg	TPS Percent of entry vehicle mass
2/11/43 (MT)	**11.3**	**1.64**	**947**	**3.13**	**573**	**15.1**
2/23/43 (MT)	**14.81**	**1.64**	**988**	**5.42**	**992**	**26.1**

VI. RECOMMENDED TITAN AGA VEHICLE SHAPE AND HIGHER FIDELITY AEROTHERMODYNAMICS

The Genesis Sample Return Mission shape [21] scaled to a maximum diameter of 4.5 m is recommended for a Titan AGA vehicle that is similar in size and shape to the notional concept described in [1]. Figure 3 depicts portions of the flow (simulated with the DPLR code [10]) about the smooth outer mold line of this body at the peak heating condition specified on the figure, corresponding to the 2/23/43 MT case. The high concentrations of CN shown to the left are due to non-equilibrium chemistry behind the shock, and subsequent radiative heating in the wake region is significant for two reasons: 1) The aft body TPS needs to withstand this significant heat flux and 2) This heat flux could work in the mission’s favor for contamination control.

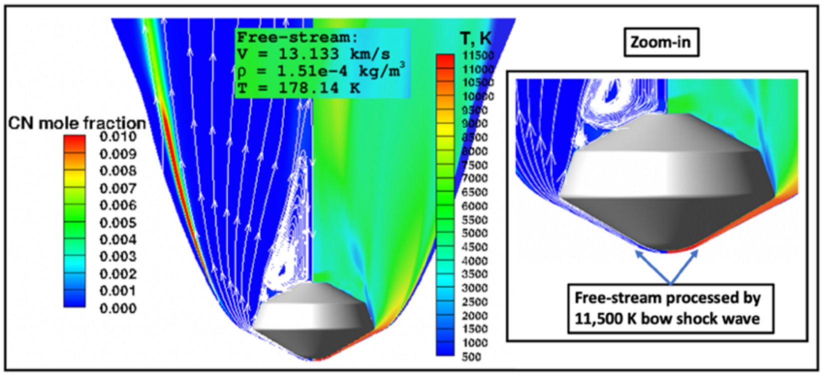


Figure 3. Axisymmetric flow simulation on 4.5 m Genesis shape for the 2/23/43 MT case with V_∞ *in of 14.81 km/s. Free stream conditions are listed in the inset. Shown to the left are CN mole fractions peaking at 0.01 and flow field temperatures ranging from 5,000 to 11,500 K. Velocity vectors are shown in white.*

The Genesis shape is mature in terms of its aerodynamics for flight in air and has been baselined for the Dragonfly mission where the base diameter is 4.5 m. Considerable research will be expended in the future on this shape and associated technologies including TPS for flight in Titan’s atmosphere. This shape should be baselined for the Titan AGA in any follow-on studies.

VII. CONTAMINATION CONTROL OF THE TITAN AGA VEHICLE

Contamination control of tholin-like organics [22] and possibly unknown biotics clinging to the AGA vehicle surfaces following flight through Titan's atmosphere is important because their presence could possibly confound sensitive measurements at Enceladus later on.

Hypotheses for cleansing mechanisms during the AGA maneuver by aerothermal processes are: (1) Referring to Fig. 3. above, the bow shock wave formed over the forebody heat shield and the extremely hot gases (5,000 - 11,500 K depending on flight speed) there will almost certainly dissociate any organics present in the free stream atmosphere of Titan, *before* they contact the surface of the AGA vehicle. This is illustrated by the temperatures and velocity vectors shown in Fig. 3. (2) Short wavelength radiation through the flow field and onto the AGA vehicle's surface provides a second sterilization source. The CN violet and red bands will be major contributors to this radiation. 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. Elimination of contaminants by benign aerothermodynamic environments on the AGA vehicle during its exit from Titan's atmosphere could be evaluated by using existing methods of low-density fluid mechanics codes [23].

VIII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions: Enceladus exploration is of great interest to astrobiologists. Given the launch capabilities of a Delta IV Heavy or an Atlas V, Spilker et al. [1] have shown that a blunt-body Aerogravity Assist (AGA) Maneuver at Titan is a mass-saving, enabling concept for nine Enceladus Exploration Missions. Presented herein are estimates of heatshield masses for vehicles that could execute AGA maneuvers at Titan in 2043 using mature heatshield materials. Specifically, for the lower V_∞ in (7.3 and 11+ km/s) AGA maneuvers, the Mars Science Laboratory (MSL)-style tiled PICA forebody heat shield is a low mass (~200 kg) candidate that requires less than six percent of the vehicle's 3,800 kg mass. This solution would allow the remaining 800 kg of the AGA vehicle's mass allocated for the fore- and aft-body heat shields and associated atmospheric maneuvering system [1] to be used for the aft heat shield and additional instrumentation hardware or propellant for other maneuvers. The HEEET forebody heat shield solutions were shown to be viable for both the (11+ km/s) and (14.8) km/s V_∞ in cases but require a significant fraction of the vehicle mass: 15.1 and 26.1 percent, respectively. These results demonstrate the feasibility for candidate heatshield solutions for future Enceladus missions using the Titan AGA maneuver.

Mechanisms that occur during hypervelocity flight were described that could dissociate tholin-like organics or microbes before they could cling to the surface of the Titan AGA vehicle.

Recommendations: Should NASA decide to undertake future Enceladus missions, these suggestions are provided: (1) For vehicle design, much development and certification on the Genesis shape and its MSL-style, tiled PICA heat shield is forthcoming from the Dragonfly project, so it is recommended that any future work on the Titan AGA vehicle using entry speeds V_∞ in of less than 12 km/s baseline this shape and the PICA forebody heat shield. Study of the precision of the EFPA and resulting dispersions on the exit conditions should be performed as well as effectiveness of the Genesis body's aerodynamics for GN&C during Titan AGA maneuvers. High fidelity, three-dimensional analysis of the flow field should be conducted to understand the aft body TPS design of a Genesis-type vehicle and used to evaluate the effects of turbulence and surface roughness on flank and shoulder heating to estimate their effects on the forebody heatshield.

Arc jet testing should be conducted to evaluate differential recession between the RTV gap fillers and the acreage PICA at conditions simulating the aerothermodynamics expected for the 7.3 and 11+ km/s V_∞ in speed Titan AGA maneuvers. (2) Study of contamination control should be considered in depth. Ideally, this would involve a team with expertise in atmospheric entry technology, astrobiology, instrument design, planetary protection engineering and mission operations. This research should include development of concepts for validation experiments to prove their effectiveness. (3) The performance, reliability and cost of new launch vehicles should be considered to understand their impact on the future of Enceladus exploration.

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