

Aerothermal and TPS Analysis of ARRIVAL, an Aerocapture Demonstration at Earth

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Aerocapture, a method of exploiting a planet's atmosphere using re-entry vehicle technology to insert a satellite into a desired orbit, has long been studied and analysis has shown it to reduce propellant mass and interplanetary travel durations[1–3]. This spacecraft flight maneuver is an enabling technology for missions targeting outer planets with critical objectives around time of arrival, such as the decadal survey's Uranus flagship mission [4]. To reduce implementation risk, the Aerocapture to Reliably Reduce Inertial Velocity With Aerodynamics and Lift (ARRIVAL) project aims to complete an Earth-based demonstration of aerocapture while placing a payload into a target orbit. This paper presents analysis conducted in support of ARRIVAL, evaluating the merits of both geostationary transfer orbit (GTO) and Lunar return trajectories for a sphere cone capsule approximately one meter in diameter. Specifically, this paper will show predicted aerothermal environments and describe the thermal protection systems (TPS) required to protect the spacecraft from re-entry heating. Computational fluid dynamics (CFD) calculations and radiation are performed by NASA's LAURA and HARA software while the TPS material sizing is performed by NASA's FIAT software. Calculations of forebody and aftbody heating and the resultant TPS material selection and sized thickness are the primary delivered product.

I. Summary

Aerocapture presents a unique way of interfacing with planetary atmospheres. The spacecraft remains in the hypersonic regime of flight traversing from the rarefied atmosphere down into the upper atmosphere and back out. Despite staying out of the thicker atmosphere, heating is still estimated to be in the hundreds of W/cm^2 range [5] and the extended flight time required to reduce spacecraft energy in the relatively low drag environment (compared to traditional re-entry con-ops) generates heat loads greater than trajectories that end on a planet's surface. Ultimately, the aeroheating calculations and subsequent thermal protection systems (TPS) design are critical components to the success of aerocapture and the Earth demonstration design detailed in (Dutta et al., 2026) [6].

The first section will introduce the two mission concepts under consideration; the geostationary transfer orbit (GTO) and Lunar Return orbit, and then contrast the predicted aerothermal environments. Anchoring design points and interpolation computation methods will be presented enabling the construction of an aerothermal database which addresses phases of flight (continuum and rarefied), heating sources (convective and radiative), and induced heating multipliers such as turbulence and surface roughness. Alongside mission con-op sensitivities and bounding control cases described as Lift-Up and Lift-down trajectories, shown in Fig. 1, conclusions from trade studies on the geometry of the vehicle will be presented. These studies explore impacts of vehicle half cone angle, shoulder radius, and nose radius. Finally, the best estimate forebody and aftbody aerothermal predictions will be provided.

The second half of the paper turns to TPS solutions to insulate the aerocapture vehicle from the re-entry heating beginning with identifying appropriate material systems which are robust to the predicted environments. Based on GTO

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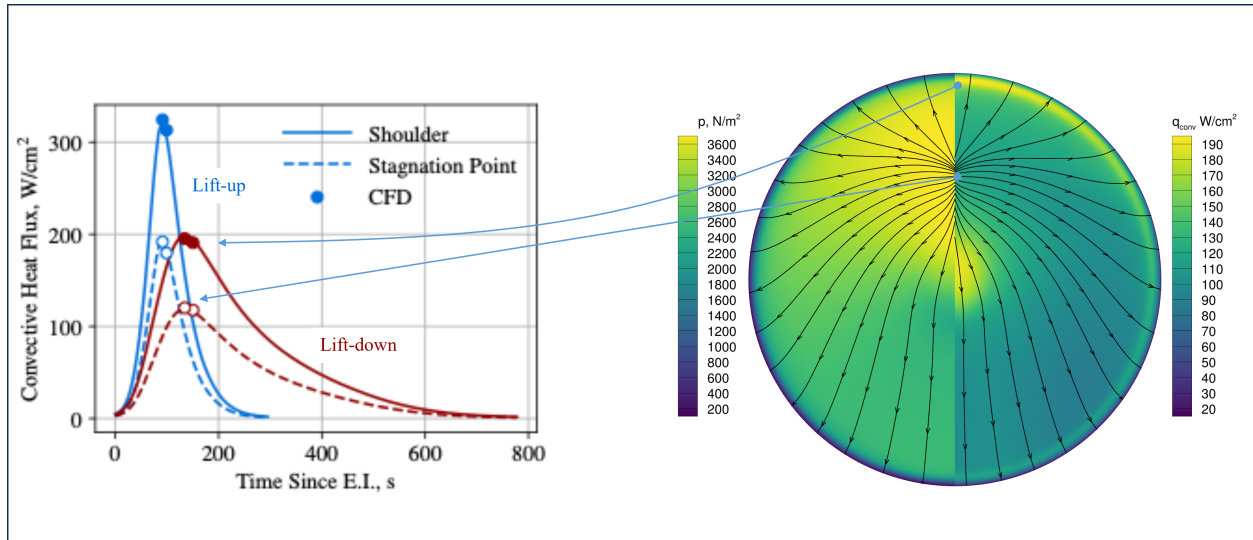


Fig. 1 Convective Heating Predictions from a 70° sphere cone on a GTO trajectory.

solutions completed to-date, Conformal Phenolic Impregnated Carbon Ablator (C-PICA), is a system well suited as the forebody TPS on the ARRIVAL mission. The anticipated aftbody environments open the possibility of flying several different backshell TPS materials. Sizing of these various materials including the Materials Engineered for Re-entry using Innovative Needling Operations (MERINO) family, Super Lightweight Ablator (SLA-561V), and C-PICA will be presented in the paper along with explanations of the benefit of each system. Scaling C-PICA to a flagship sized vehicle requires tiled parts. Adopting tiles in ARRIVAL would reduce risk for future tiled applications of C-PICA operating at these higher environments that necessitate a more robust gap-filler. To this end, a tile implementation strategy of forebody seams will be discussed. Simplified thermal analysis will review the ability of TPS design to support a trim tab as a method of vehicle control. The final version of this paper will comment on TPS sensitivity to GTO and Lunar return trajectories.

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