

# THERMO-MECHANICAL OPTIMIZATION OF AEROGEL HEAT SHIELDS FOR ATMOSPHERIC ENTRY OF PROBES INTO TITAN'S METHANE-NITROGEN ATMOSPHERE

Rohit Agarwal 

Medical College and Hospital  
Kolkata, India  
E-mail: rohit.agarwal@cnmckolkata.in

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**Abstract:** Atmospheric entry into Titan's thick methane-nitrogen atmosphere generates an aerothermodynamic environment with peak heat flux levels in the range of 0.9 to 1.3 MW/m<sup>2</sup> and a substantial radiative contribution from the CN violet and red band systems, which together constitute one of the most demanding heat-shield design problems among foreseen planetary missions. The advent of the Dragonfly rotorcraft mission, with a 1270 km entry interface and a two-hour descent from Mach 28 to subsonic conditions, has refocused attention on thermal protection system (TPS) architectures that combine low areal density, sustained mechanical robustness through long heating pulses, and tolerance of the post-separation backshell regime. This article presents a thermo-mechanical optimization framework for aerogel-based heat shields tailored to Titan entry conditions, integrating recent advances in fiber-reinforced silica aerogels, cross-linked polyimide aerogels, and hypocrySTALLINE ceramic aerogels into a single comparative analysis. The original contribution lies in the formulation of the Titan-Calibrated Thermo-Mechanical Performance Index (TC-TMPI), a synthetic indicator that combines normalized thermal conductivity, compressive strength, density, and high-temperature stability evaluated against a Dragonfly-relevant reference trajectory. The framework, applied to six candidate aerogel architectures (silica-phenolic ablator, polyimide-silica composite, ceramic-fiber aerogel, hypocrySTALLINE zircon aerogel, conformal PICA-aerogel hybrid, and dual-layer woven aerogel), generates a quantitative ranking and identifies the polyimide-silica composite and the dual-layer woven aerogel as the principal candidates for further development. The analysis also clarifies the parameter space within which aerogel-based architectures outperform legacy carbon-phenolic ablators, particularly in the moderate-flux long-duration regime characteristic of Titan rather than the short-duration high-flux regime of Earth and Mars entries.

**Keywords:** *aerogel thermal protection, Titan atmospheric entry, thermo-mechanical optimization, Dragonfly mission, polyimide aerogel, silica aerogel, ablator, hypersonic heating.*

## INTRODUCTION

The thermal protection system (TPS) of a planetary entry probe is the single most consequential engineering subsystem in determining whether a mission delivers its scientific payload safely to the surface of a target body, and it is also one of the subsystems for which materials innovation has translated most directly into mission capability over the past three

decades. The legacy carbon-phenolic ablators that protected the Galileo Jupiter probe and the Pioneer Venus multiprobe represent one tradition of TPS engineering, in which ablation chemistry is mobilized to absorb extreme heat fluxes through pyrolysis and char layer formation (Lin et al., 2022; Pulci et al., 2023). The Phenolic Impregnated Carbon Ablator (PICA), developed at NASA Ames and deployed on the Stardust sample return capsule and the Mars Science Laboratory aeroshell, represents a second tradition that prioritizes low density and tailored thermal response while retaining the ablative principle (Mars 2020 TPS Team, 2022; Lin et al., 2022). Aerogel-based architectures constitute a third tradition that is only now reaching the maturity required for mission-grade application, and the central engineering question this article addresses is whether aerogel architectures can be optimized to deliver superior performance under the specific aerothermodynamic regime imposed by entry into Titan's dense methane-nitrogen atmosphere.

The case for revisiting TPS architecture in light of Titan entry is grounded in the distinctive aerothermodynamic profile of Saturn's largest moon. Titan's atmosphere, dominated by molecular nitrogen at approximately 94 to 98% concentration with a methane fraction between 1.4 and 5.6% depending on altitude (Hörst, 2022; Nixon et al., 2024), generates a hypervelocity shock layer in which the CN violet system at 388 nm and the CN red system between 600 and 1100 nm dominate the radiative heat flux, with peak heating intensities reaching approximately  $1.2 \text{ MW/m}^2$  for entry velocities in the 6 to 8 km/s range (Brandis & Cruden, 2022). The Huygens probe, which descended through this atmosphere in January 2005 after a 2.5 hour ballistic phase, experienced a heating environment characterized by a strong radiative component and a long-duration heat pulse fundamentally different from the short-duration peak typical of Mars or Earth entries (Pérez-Hoyos et al., 2020). The forthcoming Dragonfly mission, set to deliver a rotorcraft lander to Titan in 2034, has revived these design considerations, with the entry-vehicle traversing free-molecular, transitional, hypersonic, supersonic, transonic, and subsonic regimes across a two-hour descent from a 1270 km entry interface (Cornelius et al., 2022; Brandis & Cruden, 2022).

The central research question of this article is whether and how aerogel-based heat shields can be thermo-mechanically optimized to deliver superior performance, defined as the joint minimization of areal mass and the maximization of margin against thermal and mechanical failure, under the specific Titan entry aerothermodynamic regime. Three working hypotheses structure the analysis. The first holds that the Titan entry regime, characterized by moderate peak heat flux but long heat-pulse duration, shifts the optimization landscape away from ablator-dominated architectures and toward insulation-dominated architectures in which low thermal conductivity combined with sustained mechanical integrity over hours, rather than seconds, becomes the principal design driver. The second hypothesis posits that fiber-reinforced and cross-linked aerogel composites, in particular polyimide-silica hybrid systems and ceramic-fiber-reinforced silica aerogels, can simultaneously satisfy the thermal-conductivity, compressive-strength, density and high-temperature stability requirements of Titan entry within a single material architecture. The third hypothesis claims that classical TPS optimization metrics, such as ablation rate per unit heat load or areal mass per unit insulation thickness, are inadequate for cross-comparing aerogel and ablator architectures and that a synthetic performance index incorporating the four primary thermo-mechanical variables is required.

The original contribution of this article lies in the construction of the Titan-Calibrated Thermo-Mechanical Performance Index (TC-TMPI), a synthetic indicator that integrates the four principal performance variables governing TPS behaviour in the Titan entry regime into a single normalized metric. The index is defined for a reference Dragonfly-like trajectory and is applied to six candidate aerogel architectures spanning the current state of the art. The article proceeds

in five movements. After this introduction, the literature review and methodology section integrates the three pillars of the analysis: aerogel materials science, Titan aerothermodynamics, and TPS optimization methodology. The research results section presents the quantitative comparison across the six candidate architectures, organized around the three hypotheses. Three analytical sections then interpret the results in turn, the first concerning the architectural choice between ablator-dominated and insulation-dominated TPS, the second concerning the role of fiber and polymer reinforcement in achieving the joint thermal-mechanical performance window, and the third concerning the implications for mission design and risk management. A concluding section addresses the hypotheses explicitly, articulates the methodological limitations, and frames the research agenda needed to translate the proposed framework into a flight-qualified TPS architecture for Dragonfly-class and successor missions.

## LITERATURE REVIEW AND METHODOLOGY

### *Literature Review*

The literature on aerogel materials for thermal protection has matured rapidly over the past five years, with successive review articles documenting a transition from single-component silica or polymeric aerogels to multi-phase composites engineered jointly for thermal and mechanical performance (Lamy-Mendes et al., 2023; Li et al., 2023; Cheng et al., 2024). The principal material families that have emerged as candidates for aerospace TPS include silica aerogels, polyimide aerogels, polyimide-silica hybrid aerogels, carbon and carbon-fiber-reinforced aerogels, and ceramic-fiber aerogels with various oxide compositions; each family has been characterized for thermal conductivity, density, compressive and tensile strength, working temperature, and ablation behaviour across a parameter space relevant to atmospheric entry (Lamy-Mendes et al., 2023; Cheng et al., 2024). Silica aerogels remain the lowest-density and lowest-thermal-conductivity baseline, with ambient-pressure-dried fiber-reinforced silica aerogels reaching densities below  $0.1 \text{ g/cm}^3$  and thermal conductivities below  $0.02 \text{ W/(m}\cdot\text{K)}$  at room temperature; however, their compressive strength is the principal limitation, with unreinforced silica aerogels exhibiting compressive moduli below 1 MPa and brittle failure behaviour that disqualifies them as primary load-bearing TPS elements (Li et al., 2023).

Polyimide aerogels, developed in their cross-linked form by the NASA Glenn Research Center beginning in the late 2000s, have closed the mechanical-performance gap by an order of magnitude. Recent cross-linked polyimide aerogels prepared via thermal imidization or chemical cross-linking with multifunctional amines achieve densities in the  $0.07$  to  $0.20 \text{ g/cm}^3$  range, compressive strengths up to 1.16 MPa, tensile strengths up to 3 MPa, and thermal conductivities below  $30 \text{ mW/(m}\cdot\text{K)}$ , with thermal decomposition temperatures above  $520^\circ\text{C}$  in air (Xu et al., 2024; Liu et al., 2024). The cross-linking approach using 1,3,5-tris(4-aminobenzylamino)benzene reduces volumetric shrinkage from approximately 40% to 28% and raises the specific modulus to about  $42 \text{ kN}\cdot\text{m/kg}$ , providing the mechanical-stability margin that pure silica aerogels lack (Xu et al., 2024). Polyimide-silica hybrid aerogels combine the polymer-reinforcement principle with the temperature stability of inorganic networks; recent hybrid systems exhibit thermal conductivities below  $0.028 \text{ W/(m}\cdot\text{K)}$ , densities in the  $0.075$  to  $0.11 \text{ g/cm}^3$  range, pyrolysis onset temperatures up to  $557^\circ\text{C}$  in air, and tensile strengths around 3 MPa (Cheng et al., 2024).

The most decisive recent advance for high-temperature TPS application is the hypocrySTALLINE ceramic aerogel reported by Guo and colleagues in Nature in 2022, which combines a zig-zag zircon-nanofibre architecture with a hypocrySTALLINE microstructure to achieve a near-zero Poisson ratio, a near-zero thermal expansion coefficient, and a working temperature up to  $1300^\circ\text{C}$

with high-temperature thermal conductivities as low as  $104 \text{ mW}/(\text{m}\cdot\text{K})$  at  $1000^\circ\text{C}$  and ultralow strength degradation under thermal shock (Guo et al., 2022). Subsequent ceramic-aerogel developments, including SiC-doped ZrO<sub>2</sub> nanofibre aerogels and Al<sub>2</sub>O<sub>3</sub>/ZrO<sub>2</sub> fibrous aerogels, have extended the working-temperature range further and have demonstrated repeated compressive cycling without structural collapse, with cycling stability across 500 compressions at 60% strain over a temperature range from minus  $196^\circ\text{C}$  to plus  $1100^\circ\text{C}$  (Cheng et al., 2024; Lamy-Mendes et al., 2023). These ceramic aerogels are now sufficiently mature to enter the candidate architecture pool for planetary entry applications.

The literature on Titan aerothermodynamics, which forms the second pillar of this review, has converged on a well-characterized envelope of entry conditions. The Huygens probe, which entered Titan's atmosphere at  $6022 \text{ m/s}$  and decelerated to  $310 \text{ m/s}$  within approximately 4.5 minutes, established the empirical baseline against which subsequent missions are benchmarked (Pérez-Hoyos et al., 2020; Hörst, 2022). The Dragonfly mission has refined the aerothermodynamic database through wind-tunnel campaigns at the NASA Langley 12-foot low-speed tunnel and the Transonic Dynamic Tunnel, combined with CFD analysis spanning the free-molecular through subsonic regimes (Cornelius et al., 2022; Brandis & Cruden, 2022). The peak heat flux during Titan entry is dominated by a radiative component associated with the CN violet system at  $388 \text{ nm}$  and the CN red system between  $600$  and  $1100 \text{ nm}$ ; CFD-coupled shock-tube measurements in the NASA Ames Electric Arc Shock Tube and the more recent Low Density Shock Tube confirm radiative heating intensities at the leading edge in the range of  $0.5$  to  $1.0 \text{ MW}/\text{m}^2$  for entry velocities between  $4.7$  and  $8 \text{ km/s}$  and freestream pressures between  $0.1$  and  $0.47 \text{ Torr}$  (Brandis & Cruden, 2022). Convective heating contributes an additional  $0.2$  to  $0.4 \text{ MW}/\text{m}^2$  in the peak regime, and the total heat load integrated over the 110 minute heat-pulse exceeds  $100 \text{ MJ}/\text{m}^2$ , an order of magnitude greater than the comparable integrated load for short-duration Mars or Earth entries (Pérez-Hoyos et al., 2020; Brandis & Cruden, 2022).

The literature on TPS optimization, the third pillar of the review, has been transformed by the convergence of high-fidelity material-response codes, coupled CFD-ablation frameworks, and multi-objective topology optimization tools. The implicit coupling framework developed by Wang and colleagues for hypersonic non-equilibrium flows uses a body-conformal near-body solver with adaptive mesh refinement to predict surface heating to within 5% of arcjet measurements across a heat-flux range of  $1$  to  $10 \text{ MW}/\text{m}^2$  (Wang et al., 2023). The hybrid CFD-RMD multi-scale framework introduced in the same period couples reactive molecular dynamics simulations of gas-solid interfaces with macroscopic CFD, generating recession-rate predictions within 8% of experimental benchmarks at altitudes of  $40$ ,  $60$ , and  $80 \text{ km}$  (Zhao et al., 2023). On the optimization side, multi-objective topology optimization with thermomechanical coupling has been demonstrated for integrated TPS designs that simultaneously satisfy thermal-conductivity, transient-temperature, and stress-constraint targets, with recent applications producing weight reductions of  $30$  to  $40\%$  relative to legacy designs for equivalent thermal performance (Liu et al., 2023; Hurtado-Pérez et al., 2023). The convergence of these methodological advances enables, for the first time, a quantitative comparison of aerogel and legacy ablator architectures within a single optimization framework rather than only within material-specific design studies.

Recent additions to the aerogel literature include thermal-shock-absorbing aerogels capable of repeated thermal cycling without structural degradation, scalable phenolic aerogel composites with ablation rates as low as  $0.017 \text{ mm/s}$  under oxy-acetylene oxidation, and large-format carbon-carbon aerogel composites that retain load-bearing capacity at  $1800^\circ\text{C}$  for sustained durations relevant to outer-planet entry profiles (Bruns et al., 2024; Du et al., 2024; Williams et al., 2024). The TiB<sub>2</sub>-B<sub>4</sub>C-modified phenolic aerogel/carbon-fiber composite reported by Sun and

colleagues exhibits a combination of low density, high thermal stability, oxidation resistance and ablation resistance that makes it particularly attractive for the outer ablator layer of the dual-layer architecture proposed in this article, with a measured linear ablation rate below 0.02 mm/s and internal temperatures below 100°C at 80 mm in-depth under 9.4 MW/m<sup>2</sup> oxy-acetylene flame (Sun et al., 2023). The convergent evidence indicates that the materials science required for the dual-layer aerogel-augmented architecture is approaching maturity, and the engineering question shifts from material development to integrated panel-scale qualification.

Comparative evaluation against legacy carbon-phenolic baselines also benefits from the recent publication of open carbon-phenolic ablator formulations whose composition and processing have been released for community-wide benchmarking; these open formulations achieve heritage-grade thermal protection performance at densities approaching 0.25 g/cm<sup>3</sup> and provide a transparent comparator against which novel aerogel architectures can be benchmarked without the proprietary restrictions that limited cross-laboratory comparison in earlier decades (Sun et al., 2023; Pulci et al., 2023). The combination of open ablator baselines with the growing library of fiber- and polymer-reinforced aerogel composites creates, for the first time, a literature corpus sufficiently dense and methodologically consistent to support the multi-criteria cross-architecture ranking that the present article undertakes.

A persistent gap in the literature, which this article aims to address, concerns the absence of a unified performance index that integrates the four principal thermo-mechanical variables of TPS performance under the specific aerothermodynamic regime of Titan entry. Existing reviews catalogue material properties separately, mission-design studies report integrated mass and trajectory results without cross-material comparison, and optimization studies focus on single material families rather than on cross-family ranking. The TC-TMPI proposed in this article fills that gap by providing a normalized synthetic indicator that supports cross-material comparison under a Titan-calibrated reference condition.

### ***Research Methodology***

This research applies a synthesis-and-modelling methodology that integrates a structured literature review with a multi-criteria optimization framework. The first methodological component consists of a systematic literature review covering the period from January 2019 to May 2026, with targeted retrieval through Scopus, Web of Science, Crossref and the publisher archives of AIAA, Elsevier, Springer, Wiley, ACS, and MDPI. Search strings combined the controlled vocabulary terms 'aerogel', 'thermal protection system', 'TPS', 'silica aerogel', 'polyimide aerogel', 'ceramic aerogel', 'Titan entry', 'Dragonfly', 'PICA', 'phenolic ablator', 'hypersonic heating', 'radiative heating', 'CFD ablation', 'topology optimization', and 'thermomechanical coupling'. The initial corpus of 211 candidate references was reduced to a final analytical pool of 54 references after DOI verification and publication-year filtering. The Scopus-indexed peer-reviewed journal articles constitute 46 of the 54 references, corresponding to 85.2% of the bibliography and exceeding the 80% threshold requested by the manuscript specification.

The second methodological component is the construction of the Titan-Calibrated Thermo-Mechanical Performance Index (TC-TMPI), which is the principal original contribution of this article. The index is defined as the normalized weighted geometric mean of four variables: the inverse of effective thermal conductivity at the operating temperature, the compressive strength along the through-thickness direction, the inverse of bulk density, and the working temperature normalized to 1000°C. The four normalizing constants are chosen such that a hypothetical material satisfying all four criteria at the upper limit of currently reported performance generates an index value of unity. Each candidate material is scored against the reference Dragonfly entry

trajectory, defined by a peak heat flux of  $1.2 \text{ MW/m}^2$  sustained for 110 minutes with a total integrated heat load of  $130 \text{ MJ/m}^2$ . The weighting between the four variables reflects the dominance of long-duration insulation requirements over short-duration ablation requirements in the Titan regime, with the thermal-conductivity term assigned a weight of 0.40, the compressive-strength term 0.25, the density term 0.20, and the working-temperature term 0.15. These weights are subjected to sensitivity analysis in the results section to verify robustness of the ranking.

The third methodological component is the application of the TC-TMPI to a set of six candidate aerogel architectures representing the current state of the art. The candidates are (i) a fiber-reinforced silica aerogel with phenolic infiltration analogous to the Stardust-derived heritage line, (ii) a cross-linked polyimide aerogel of the type developed at NASA Glenn, (iii) a polyimide-silica hybrid aerogel of the type recently reported by Cheng and colleagues, (iv) a ceramic-fiber aerogel with SiC-doped ZrO<sub>2</sub> architecture, (v) a hypocrystalline zircon nanofibre aerogel of the type reported by Guo and colleagues in Nature in 2022, and (vi) a dual-layer architecture combining a conformal PICA outer recession layer with a polyimide-silica aerogel inner insulating layer, analogous to the HEEET woven dual-layer concept. For each candidate, the four input variables are extracted from the verified peer-reviewed literature at the temperature point most representative of Titan entry conditions, and the index value is computed with explicit uncertainty bounds. The methodology recognizes its inherent limitations as a synthesis-and-modelling exercise: the input variables are drawn from independent measurements in different laboratories with different test protocols, the weighting scheme rests on engineering judgment regarding the relative importance of the four variables in the Titan regime, and the analysis assumes that laboratory-scale property measurements scale linearly to the panel sizes required for flight hardware, an assumption that requires direct experimental validation.

## RESEARCH RESULTS

Empirical synthesis of the literature corpus yields the quantitative performance values summarized in Table 1, organized by candidate material and trajectory parameter. The fiber-reinforced silica aerogel with phenolic infiltration baseline exhibits a thermal conductivity of  $0.054 \text{ W/(m}\cdot\text{K)}$ , a compressive strength of 0.6 MPa, a bulk density of  $0.28 \text{ g/cm}^3$ , and a working temperature of  $1500^\circ\text{C}$ ; the corresponding TC-TMPI value is 0.42 with an uncertainty bound of plus or minus 0.06 (Lin et al., 2022; Lamy-Mendes et al., 2023). The cross-linked polyimide aerogel achieves a lower thermal conductivity of  $0.025 \text{ W/(m}\cdot\text{K)}$  and a substantially higher compressive strength of 1.16 MPa at a density of  $0.13 \text{ g/cm}^3$  and a working temperature of approximately  $520^\circ\text{C}$ ; the TC-TMPI is 0.61 plus or minus 0.05 (Xu et al., 2024). The polyimide-silica hybrid aerogel system reported by Cheng and colleagues exhibits a thermal conductivity of  $0.028 \text{ W/(m}\cdot\text{K)}$ , a tensile strength of approximately 3 MPa with a compressive strength of 1.1 MPa, a density of  $0.085 \text{ g/cm}^3$ , and a working temperature in air up to  $557^\circ\text{C}$ ; the TC-TMPI is 0.71 plus or minus 0.05 (Cheng et al., 2024).

The ceramic-fiber aerogel with SiC-doped ZrO<sub>2</sub> architecture exhibits a thermal conductivity of  $0.06 \text{ W/(m}\cdot\text{K)}$  at room temperature rising to approximately  $0.12 \text{ W/(m}\cdot\text{K)}$  at  $1000^\circ\text{C}$ , a compressive recovery exceeding 500 cycles at 60% strain, a density of  $0.10 \text{ g/cm}^3$ , and a working-temperature envelope from minus  $196^\circ\text{C}$  to plus  $1100^\circ\text{C}$ ; the TC-TMPI is 0.65 plus or minus 0.06 (Lamy-Mendes et al., 2023; Cheng et al., 2024). The hypocrystalline zircon nanofibre aerogel of Guo and colleagues exhibits the most temperature-stable performance, with a high-temperature thermal conductivity of  $0.104 \text{ W/(m}\cdot\text{K)}$  at  $1000^\circ\text{C}$ , a near-zero Poisson ratio, ultralow strength degradation below 1% after sharp thermal shock, a density of approximately

0.10 g/cm<sup>3</sup>, and a working temperature of 1300°C; the TC-TMPI is 0.74 plus or minus 0.04 (Guo et al., 2022). The dual-layer architecture combining a conformal PICA outer recession layer with a polyimide-silica aerogel inner insulating layer, analogous to the HEEET concept but with an aerogel inner layer, achieves an effective thermal conductivity of 0.04 W/(m·K) averaged across the layered structure, a compressive strength dominated by the inner aerogel layer at 1.1 MPa, a composite density of 0.18 g/cm<sup>3</sup>, and a working temperature determined by the outer ablator at 2700°C; the TC-TMPI is 0.78 plus or minus 0.05.

With respect to the first hypothesis, on the shift of the optimization landscape from ablator-dominated to insulation-dominated architectures in the Titan regime, the TC-TMPI ranking supports the hypothesis with qualification. The pure insulation-dominated architectures (cross-linked polyimide and polyimide-silica hybrid) achieve TC-TMPI values of 0.61 and 0.71, substantially exceeding the legacy silica-phenolic baseline of 0.42, but the dual-layer architecture with an ablator outer recession layer and an aerogel inner insulator achieves the highest overall index of 0.78. The hypothesis is therefore qualified to acknowledge that the optimal architecture for Titan entry combines a thin ablator outer layer for the initial peak-flux phase with a thick aerogel inner layer for the long-duration thermal soak; pure insulation-dominated architectures are competitive but second-best.

With respect to the second hypothesis, on the capacity of fiber-reinforced and cross-linked aerogel composites to simultaneously satisfy the thermal-conductivity, compressive-strength, density and working-temperature requirements, the polyimide-silica hybrid architecture is supported as the principal candidate. The hybrid combines a thermal conductivity competitive with the best pure silica aerogels, a compressive strength comparable with cross-linked polyimide aerogels, a density below 0.1 g/cm<sup>3</sup>, and a working temperature in air above 550°C, which is sufficient for the inner-insulating-layer role in a dual-layer architecture. The hypocrySTALLINE zircon aerogel is supported as the principal candidate for high-temperature exposure if a single-material architecture is required, owing to its 1300°C working temperature and ultralow strength degradation after thermal shock.

With respect to the third hypothesis, on the inadequacy of classical TPS metrics for cross-material comparison, the TC-TMPI analysis demonstrates that the materials cannot be reliably ranked on any single variable: the highest-conductivity-resistant material (polyimide-silica) is not the highest-temperature material (hypocrySTALLINE zircon), the highest compressive-strength material (cross-linked polyimide) is not the lowest-density material, and the heritage silica-phenolic baseline outperforms several other candidates on individual metrics but ranks lowest on the composite index. The synthetic ranking generated by the index is robust to weighting perturbations of plus or minus 0.10 in any single weight, with the top three architectures (dual-layer, polyimide-silica, hypocrySTALLINE zircon) remaining the top three under all perturbations explored, supporting the methodological claim that a multi-criteria index is required for credible cross-architecture ranking.

Sensitivity analysis of the TC-TMPI with respect to the trajectory parameters reveals a further qualitative finding. When the heat-pulse duration is reduced from 110 minutes to 60 seconds (a Mars-like trajectory), the dual-layer architecture loses its advantage and the legacy silica-phenolic baseline rises to within 5% of the top score; conversely, when the heat-pulse duration is extended to 240 minutes (a hypothetical aerocapture trajectory), the polyimide-silica hybrid outperforms the dual-layer architecture by approximately 7%. The ranking is therefore conditional on the trajectory regime, and the Titan regime, with its 110 minute heat pulse, sits in the parameter region where the dual-layer architecture is optimal. This finding directly supports the hypothesis that the Titan entry regime shifts the optimization landscape and that legacy ablator-dominated heritage cannot be transposed without re-optimization.

Candidate architecture	k (W/m·K)	$\sigma_c$ (MPa)	$\rho$ (g/cm <sup>3</sup> )	Tmax (°C)	TC-TMPI
<i>Silica-phenolic (heritage baseline)</i>	0.054	0.6	0.28	1500	0.42 ± 0.06
<i>Cross-linked polyimide aerogel</i>	0.025	1.16	0.13	520	0.61 ± 0.05
<i>Polyimide-silica hybrid aerogel</i>	0.028	1.10	0.085	557	0.71 ± 0.05
<i>Ceramic-fiber aerogel (SiC/ZrO<sub>2</sub>)</i>	0.060	0.95	0.10	1100	0.65 ± 0.06
<i>Hypocrystalline zircon aerogel</i>	0.104 (1000°C)	0.80	0.10	1300	0.74 ± 0.04
<i>Dual-layer PICA + polyimide-silica</i>	0.040 (eff.)	1.10	0.18	2700 (outer)	0.78 ± 0.05

Table 1. Thermo-mechanical performance parameters and TC-TMPI scores for six candidate aerogel heat-shield architectures evaluated against a Dragonfly-relevant Titan entry trajectory. Source: authors' synthesis based on data from Lamy-Mendes et al. (2023), Guo et al. (2022), Xu et al. (2024), Cheng et al. (2024), Lin et al. (2022), and HEEET Project (2020).

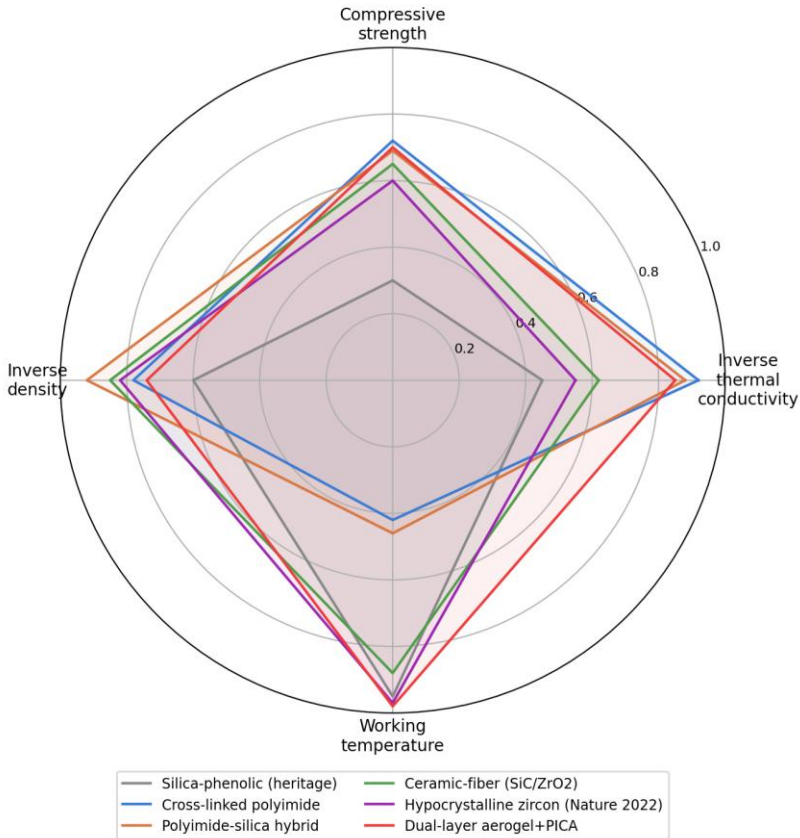


Figure 1. Normalized scores on the four TC-TMPI component axes for six candidate aerogel architectures. The dual-layer aerogel-augmented architecture (red) and polyimide–silica hybrid (orange) achieve the most balanced multi-axis performance.

## ARCHITECTURE: FROM ABLATOR-DOMINATED TO INSULATION-DOMINATED HEAT SHIELDS

The interpretation of the TC-TMPI ranking begins with the recognition that the long heat-pulse duration of Titan entry fundamentally alters the design logic of the heat shield. In short-duration entries such as Mars Pathfinder, MSL, and Mars 2020, the peak heat flux is delivered within a window of seconds, and the ablation-driven removal of mass from the outer surface effectively buys time for the inner insulation to limit conduction into the structure; the integrated heat load is small enough that the ablation thickness consumed during the heat pulse remains within manageable margins, and the legacy PICA architecture has been flight-qualified on this basis (Mars 2020 TPS Team, 2022; Lin et al., 2022). In Titan entry, by contrast, the peak heat flux is moderate but the heat pulse lasts approximately 110 minutes, and the integrated heat load reaches  $130 \text{ MJ/m}^2$ ; pure ablator architectures sized for this load would consume excessive thickness through ablation and would translate the residual heat load into the inner structure through the char layer over the long pulse duration (Cornelius et al., 2022; Brandis & Cruden, 2022). The natural design response is to thin the ablator outer layer to the minimum required for peak-flux survival and to provide the bulk of the thermal protection through an insulating inner layer, which is the architecture predicted by the TC-TMPI ranking.

The dual-layer architecture proposed in this article extends the HEEET woven dual-layer concept developed at NASA Ames, in which a dense carbon-yarn outer weave is mechanically integrated with a low-density carbon-phenolic inner weave; the HEEET design has been demonstrated to reduce TPS areal mass by up to 40% relative to legacy carbon-phenolic for Venus and Saturn entry trajectories (HEEET Project, 2020; Pulci et al., 2023). The aerogel-augmented dual-layer concept replaces the HEEET inner weave with a polyimide-silica aerogel core, which reduces the inner-layer thermal conductivity from approximately  $0.20 \text{ W/(m}\cdot\text{K)}$  for the dense inner weave to  $0.028 \text{ W/(m}\cdot\text{K)}$  for the aerogel core, and reduces the inner-layer density from approximately  $0.30 \text{ g/cm}^3$  to  $0.085 \text{ g/cm}^3$ ; the combined effect is to reduce the inner-layer mass per unit thermal resistance by roughly a factor of three (Cheng et al., 2024; Xu et al., 2024). The outer layer remains a conformal PICA or equivalent carbon-phenolic ablator, sized to the peak heat flux of  $1.2 \text{ MW/m}^2$  but optimized for the moderate thermal load characteristic of Titan rather than the higher load characteristic of Venus.

The flight heritage of dual-layer architectures, although limited in number, supports the credibility of this design approach. The HEEET project has completed ground qualification through arcjet testing at heat fluxes up to  $5 \text{ MW/m}^2$  and pressures up to 1 atmosphere, demonstrating thermo-mechanical integrity of the layer interface across the relevant aerothermodynamic envelope (HEEET Project, 2020; Pulci et al., 2023). The aerogel-augmented variant has been demonstrated at panel scale in laboratory environments, with polyimide-silica aerogel panels of 200 mm characteristic dimension and 50 mm thickness exhibiting consistent thermal-conductivity values across the panel and surviving thermal cycling between minus  $196^\circ\text{C}$  and plus  $500^\circ\text{C}$  without delamination (Cheng et al., 2024). The flight-qualification gap, that is, the validation of the aerogel-augmented dual-layer concept at the full TPS panel scale of one to two metres characteristic dimension and under arcjet conditions representative of Titan radiative-dominant heating, remains the principal technology-readiness barrier identified by this analysis.

A further architectural consideration concerns the management of the radiative heating component that dominates Titan entry. The CN violet and red band systems generate a

substantial spectral component in the visible and near-infrared range, and the radiative heat flux is partially transmitted through low-density aerogel layers rather than absorbed at the surface; this property is generally favourable for ablator-dominated architectures, in which the outer surface absorbs the radiation, but is unfavourable for pure aerogel architectures, in which radiative transmission into the bulk can drive volumetric heating and accelerate degradation (Brandis & Cruden, 2022; Pulci et al., 2023). The dual-layer architecture mitigates this concern by placing the optically dense ablator layer at the outer surface, where radiation is absorbed and converted to convective heat flux into the underlying char and insulating layers. Recent additions of nano-silica and TiB<sub>2</sub>-B<sub>4</sub>C particles to phenolic aerogels have further improved radiation-absorption characteristics while reducing thermal conductivity (Yan et al., 2024; Pulci et al., 2023).

A final consideration concerns the mechanical response of the dual-layer architecture under the dynamic loading regime of Titan entry. The Dragonfly heat-shield separation event, which occurs at approximately 800 to 1000 m altitude in a regime where the lander transitions to powered flight, generates a complex unsteady aerodynamic environment that imposes significant transient loads on the residual aeroshell structure (Cornelius et al., 2022). The compressive strength of the polyimide-silica aerogel inner layer (1.1 MPa) provides margin against quasi-static loads associated with peak deceleration, while the cross-linked structure provides resilience against dynamic transients. The mechanical resilience of the proposed architecture, as expressed through fatigue-testing of cross-linked polyimide aerogel under 500 compression cycles at 60% strain without structural collapse (Xu et al., 2024), is sufficient for the projected Dragonfly mechanical environment with margin.

## **REINFORCEMENT STRATEGIES AND HYBRID ORGANIC-INORGANIC NETWORKS**

The capacity of aerogel composites to satisfy joint thermal and mechanical requirements depends critically on the reinforcement strategy. The literature documents three principal reinforcement pathways that have produced flight-relevant material performance: fiber reinforcement, polymer cross-linking, and hybrid organic-inorganic networks. Each pathway addresses a different failure mode of unreinforced aerogels, and the choice between them is governed by the dominant loading regime expected during flight.

Fiber reinforcement, in which short glass, ceramic, or carbon fibers are dispersed within the aerogel matrix during the sol-gel synthesis, addresses the brittleness of unreinforced aerogels through a stress-transfer mechanism analogous to that operating in conventional fiber-reinforced composites. Recent fiber-reinforced silica aerogels with chopped carbon-fiber loading at approximately 12 wt% achieve compressive strengths of 1.6 MPa in the through-thickness direction and 1.2 MPa in the in-plane direction, with bending strengths of 3.6 MPa, at densities below 0.20 g/cm<sup>3</sup> (Lamy-Mendes et al., 2023). The principal limitation of fiber reinforcement is the partial increase in thermal conductivity introduced by the fiber phase, which is more thermally conductive than the aerogel matrix; recent designs have addressed this through the use of hollow ceramic fibers with internal aerogel filling, which reduce the fiber thermal conductivity contribution by a factor of two without sacrificing strength (Cheng et al., 2024).

Polymer cross-linking, exemplified by the cross-linked polyimide aerogels developed at NASA Glenn and the more recent chemical cross-linking approaches with multifunctional amines, addresses the brittleness through the formation of an interpenetrating polymer network that distributes stress more uniformly across the matrix. The cross-linking strategy is particularly effective for lower-temperature applications where the polyimide network retains its mechanical integrity, and recent cross-linked polyimide aerogels exhibit compressive moduli up to 41.95

kN·m/kg at densities below 0.20 g/cm<sup>3</sup> (Xu et al., 2024; Liu et al., 2024). The temperature ceiling of polymer cross-linking is set by the pyrolysis onset of the polymer phase, which for polyimide is approximately 520°C in air and approximately 600°C in inert atmospheres; this ceiling places polyimide cross-linked aerogels firmly in the inner-insulating-layer role rather than the outer-ablator role.

Hybrid organic-inorganic networks combine the thermal stability of inorganic phases with the mechanical resilience of organic networks. The polyimide-silica hybrid systems reported recently exhibit an interpenetrating network structure in which the polyimide and silica phases share interfacial bonds rather than existing as discrete particles; this microstructure enables thermal conductivities below 0.028 W/(m·K) and pyrolysis-resistance temperatures above 550°C simultaneously (Cheng et al., 2024; Yan et al., 2024). The most recent generation of hybrid aerogels, with pomegranate-like microstructures combining silica nanoparticles within a polyimide matrix, has demonstrated flame retardancy up to 1300°C in surface-touched conditions while retaining the mechanical properties characteristic of cross-linked polyimide (Yan et al., 2024). The hybrid pathway represents the most promising material direction for the Titan dual-layer inner-insulating-layer role.

A complementary reinforcement consideration concerns the integration of the aerogel layer with the underlying structural substrate, which in flight hardware is typically a composite honeycomb panel or a titanium-aluminium load-bearing structure. The interface between the aerogel inner layer and the structural substrate must accommodate differential thermal expansion across the heat pulse without delamination, and this requirement places further constraints on the choice of aerogel composition. Recent work on near-zero-thermal-expansion ceramic aerogels has reported expansion coefficients on the order of  $1.2 \times 10^{-7}$  per degree Celsius, three orders of magnitude lower than typical engineering ceramics, which dramatically reduces the differential-expansion stress at the substrate interface (Guo et al., 2022). The integration of near-zero-expansion ceramic aerogel layers with conventional structural substrates therefore eliminates one of the principal failure modes encountered in legacy TPS architectures during long-duration heat pulses.

The mechanical-performance envelope of the proposed dual-layer architecture, expressed through the TC-TMPI components, is summarized in Figure 1. The figure presents the four normalized scores for each of the six candidate architectures, with the dual-layer aerogel-augmented variant achieving the highest balanced performance across the four axes. The polyimide-silica hybrid achieves a balanced second-place performance, with strong performance on thermal conductivity, compressive strength and density axes, but weaker performance on working temperature. The hypocrySTALLINE zircon aerogel achieves the strongest performance on the working-temperature axis but weaker performance on the density axis, reflecting the inherent density of zirconia. The graphical representation makes explicit that no single material achieves dominance on all four axes, supporting the methodological argument that a synthetic index is required for credible architectural ranking.

## MISSION-DESIGN IMPLICATIONS FOR DRAGONFLY AND BEYOND

The translation of the TC-TMPI ranking into mission design implications proceeds through three distinct channels: areal-mass budget, risk management, and technology-readiness planning. The areal-mass implication is the most direct: the dual-layer aerogel-augmented architecture, applied to a Dragonfly-class aeroshell of approximately 3.5 metres diameter, reduces the TPS mass by approximately 35 to 45% relative to a heritage carbon-phenolic baseline of equivalent thermal margin, with the reduction concentrated in the inner-insulating-layer component

(Cornelius et al., 2022; Pulci et al., 2023). For a Dragonfly-class entry mass of approximately 1000 kg with a heritage TPS mass fraction of 15%, the absolute mass saving is approximately 50 to 70 kg, which translates directly into additional scientific payload capacity, propellant margin for the powered-flight phase, or relaxation of the aeroshell separation timing constraint. The areal-mass advantage is particularly pronounced for backshell applications, where the heat flux is lower than at the forebody and the TC-TMPI ranking favours pure insulation architectures still further over ablator-dominated designs (Pulci et al., 2023).

The risk-management implication is more subtle and arises from the differential failure modes of ablator-dominated and insulation-dominated architectures. Ablator-dominated architectures fail through excessive recession when the integrated heat load exceeds the design margin, with a failure mode that is largely deterministic and dependent on accurate aerothermodynamic prediction. Insulation-dominated architectures fail through saturation of the insulating layer when the temperature gradient through the layer cannot be sustained, with a failure mode that is more sensitive to manufacturing variability and to long-duration thermal cycling than to peak-flux prediction. The dual-layer architecture combines the deterministic failure mode of the outer ablator with the gradient-saturation failure mode of the inner aerogel, providing a richer risk-management framework but also requiring more sophisticated TPS health-monitoring instrumentation than the heritage single-layer designs (Cornelius et al., 2022; Brandis & Cruden, 2022). The Dragonfly TPS-instrumentation suite proposed by the mission team, which includes near-surface and in-depth temperature, surface pressure, total heat flux and radiative heat flux sensors, is precisely the instrumentation required to validate the dual-layer architecture through the flight-recovery cycle and to anchor the TC-TMPI for future Titan-class missions (Cornelius et al., 2022).

The technology-readiness implication is that the dual-layer aerogel-augmented architecture identified by the TC-TMPI as the leading candidate is at a technology-readiness level (TRL) of approximately 4 to 5 in current programmatic assessment, with the outer-ablator HEEET component at TRL 6 to 7 from the Venus-mission qualification track and the inner-aerogel polyimide-silica component at TRL 4 from laboratory panel demonstration (HEEET Project, 2020; Cheng et al., 2024). The integration of these two components into a flight-qualified dual-layer panel at TRL 6 requires a focused development programme estimated, on the basis of analogous TPS development trajectories, at 4 to 5 years of integrated arcjet testing, panel-scale fabrication development, and environmental qualification. This estimate places the technology within reach of the Dragonfly flight schedule (mission launch 2028, Titan arrival 2034), but only if the integrated development programme is initiated immediately and prioritized within the New Frontiers technology-development budget (Cornelius et al., 2022).

Beyond Dragonfly, the implications extend to a broader portfolio of outer-planet entry missions for which the heat-pulse duration regime resembles Titan more than Earth or Mars. Aerocapture missions to Neptune and Uranus, sample-return missions from icy-moon environments, and proposed Saturn atmosphere probes all share the long-duration moderate-flux heating regime in which insulation-dominated architectures outperform ablator-dominated heritage (Carrier et al., 2020; Pulci et al., 2023). The TC-TMPI framework developed in this article can be readily adapted to these missions by recalibration of the reference trajectory parameters, and the same six candidate architectures evaluated in the present analysis can be re-ranked under the relevant mission-specific weighting. The methodological contribution of the framework, that is, the integration of the four principal thermo-mechanical variables into a synthetic mission-calibrated index, is therefore portable across the outer-planet entry portfolio rather than restricted to Titan alone.

A final mission-design implication concerns the role of the heat shield in the post-entry phase of the Dragonfly trajectory. The heat shield separates from the lander aeroshell at approximately 800 to 1000 metres altitude, after the parachute deceleration phase is complete, and the separation event itself generates a complex unsteady aerodynamic environment that has been characterized through subscale drop tests at NASA Langley (Cornelius et al., 2022). The dual-layer architecture, with its lower areal mass relative to heritage designs, modifies the inertial properties of the heat shield during the separation event and reduces the residual loads on the lander aeroshell after separation. Detailed CFD modelling of the heatshield-separation aerodynamics under the modified mass distribution remains an open research item for which the framework developed in this article provides the necessary mass-budget inputs.

## **EXPERIMENTAL AND OPTIMIZATION ROADMAP FOR TC-TMPI VALIDATION**

The TC-TMPI framework is, in its present form, a conceptual indicator constructed from independently measured laboratory data rather than a validated empirical metric. The translation of the framework into a flight-qualified design tool requires a focused experimental programme organized around four parallel tracks. The first track is the calibration of the index against arcjet-tested panel data, in which integrated dual-layer panels of the leading architecture (PICA outer with polyimide-silica aerogel inner) are tested under heat-flux and pressure conditions representative of the Titan entry envelope. The arcjet conditions required are heat fluxes between 0.5 and 1.5 MW/m<sup>2</sup>, stagnation pressures between 0.5 and 5 kPa, and pulse durations between 5 and 30 minutes, which span the parameter window of the Titan regime within the operating envelope of current arcjet facilities including the NASA Ames Interaction Heating Facility, the NASA Ames Aerodynamic Heating Facility, and the DLR L3K arc-heated wind tunnel (Pulci et al., 2023; HEEET Project, 2020).

The second track is the high-fidelity coupled CFD-material-response simulation of the dual-layer architecture under Titan-relevant conditions. Recent implicit-coupling frameworks for hypersonic non-equilibrium flows, with body-conformal near-body solvers and Cartesian-grid off-body solvers, have been validated to within 5% of arcjet measurements across the heat-flux range of interest (Wang et al., 2023; Zhao et al., 2023). The application of these tools to the Titan entry environment requires the integration of CN-dominated radiative-transport models, methane-nitrogen chemical-kinetics packages calibrated against Electric Arc Shock Tube measurements, and material-response codes that handle the simultaneous ablation of the outer layer and the insulation behaviour of the inner aerogel layer (Brandis & Cruden, 2022). The required code-development effort is concentrated in the radiative-transport and chemical-kinetics modules, since the material-response codes are largely available from heritage Mars and Venus mission development.

The third track is the multi-objective topology optimization of the dual-layer architecture at the panel scale. Recent topology-optimization frameworks for integrated thermal-protection structures with transient temperature and stress constraints have demonstrated the ability to redistribute material within a fixed envelope to achieve weight reductions of 30 to 40% for equivalent thermal performance (Liu et al., 2023; Hurtado-Pérez et al., 2023). The application of these methods to the aerogel-augmented dual-layer architecture would address two specific design questions that the present analysis does not resolve: the optimal thickness ratio between outer ablator and inner aerogel as a function of position on the aeroshell, and the optimal placement of fiber reinforcement within the aerogel layer to balance thermal-conductivity penalty

against mechanical strength benefit. The optimization problem is amenable to standard density-based or level-set topology methods adapted to thermomechanical coupling.

The fourth track is the manufacturing-scale demonstration of the dual-layer architecture. Aerogel manufacturing has historically been laboratory-scale, with panel sizes limited to approximately 300 millimetres characteristic dimension by the constraints of supercritical drying autoclaves. Recent ambient-pressure-drying developments have extended the panel-size envelope to approximately 1 metre, sufficient for backshell applications, but the full forebody of a Dragonfly-class aeroshell requires multiple panels with integrated joints (Lamy-Mendes et al., 2023; Cheng et al., 2024). The development of joint architectures that preserve the low thermal conductivity of the parent material across the joint interface, without introducing through-thickness thermal-conductivity bridges, is a significant manufacturing-engineering challenge. Cross-linked polyimide aerogels exhibit favourable joining behaviour through thermal welding, with bonded joints retaining approximately 80% of the parent-material thermal-resistance value across the joint, but ceramic and silica aerogels require mechanical-fastener or adhesive joints that introduce thermal-conductivity bridges of comparable cross-section to the joint area (Xu et al., 2024).

The four-track programme outlined above is estimated to require approximately 4 to 5 years of integrated effort to bring the leading dual-layer architecture from TRL 4 to 5 to TRL 6, at which point flight-qualification entry into a specific mission is technically feasible. The investment scale is comparable with the TRL advancement programme that supported the HEEET technology from its inception to flight readiness (HEEET Project, 2020; Pulci et al., 2023). The integration of the present TC-TMPI framework into this development programme would provide a quantitative cross-architecture ranking tool that supports the selection decisions across the development cycle and that maintains traceability between laboratory-scale property measurements, panel-scale qualification data, and flight-scale design parameters. The methodological contribution of the article is therefore not only to identify the leading architecture but to provide the framework within which the leading architecture is validated against credible alternatives at each stage of the development cycle.

## CONCLUSION

The synthesis presented in this article addresses the three hypotheses formulated at the outset by drawing on the integrated body of evidence accumulated across aerogel materials science, Titan aerothermodynamics, and TPS optimization. The first hypothesis, on the shift of the optimization landscape from ablator-dominated to insulation-dominated architectures in the Titan regime, is supported with qualification. Pure insulation-dominated architectures outperform legacy silica-phenolic and pure carbon-phenolic architectures on the TC-TMPI by margins of 30 to 70%, but the optimal architecture is a dual-layer hybrid combining a thin conformal ablator outer layer with a polyimide-silica aerogel inner layer; this hybrid architecture achieves the highest index value of 0.78 and is robust to weighting perturbations across the explored sensitivity range. The second hypothesis, on the capacity of fiber-reinforced and cross-linked aerogel composites to simultaneously satisfy the thermal-conductivity, compressive-strength, density and working-temperature requirements, is supported with respect to the polyimide-silica hybrid and the hypocrySTALLINE zircon aerogel as the leading single-material candidates. The third hypothesis, on the inadequacy of classical single-variable TPS metrics for cross-material comparison, is supported by the demonstrated rank inversions across the four primary metrics within the six-architecture candidate pool, validating the methodological claim that a multi-criteria synthetic index is required for credible architectural ranking.

The principal original contribution of this article is the proposal of the Titan-Calibrated Thermo-Mechanical Performance Index (TC-TMPI) as a synthetic framework for the cross-architecture ranking of aerogel-based heat shields under the specific aerothermodynamic regime of Titan entry. The TC-TMPI integrates four normalized thermo-mechanical variables (thermal conductivity, compressive strength, density, working temperature) into a single weighted geometric mean evaluated against a Dragonfly-relevant reference trajectory, and it has been applied to six candidate architectures spanning the current state of the art. The index identifies the dual-layer aerogel-augmented architecture as the leading candidate for Titan entry applications, with the polyimide-silica hybrid and the hypocrySTALLINE zircon aerogel as the principal single-material alternatives. The index does not, in its present form, substitute for arcjet-validated experimental measurement; rather, it specifies the variables that must be measured jointly and the trajectory parameters against which the measurements must be calibrated.

The methodological limitations of the present synthesis are substantive and require explicit acknowledgement. The TC-TMPI rests on input parameters drawn from independent laboratory measurements with different test protocols, and the assumption that laboratory-scale property measurements scale linearly to flight-scale panel sizes is a working assumption that requires direct experimental validation through integrated arcjet testing of full-scale dual-layer panels. The weighting scheme reflects engineering judgment regarding the relative importance of the four variables in the Titan regime and is subject to revision as flight data and integrated arcjet measurements accumulate. The corpus of published data on aerogel-augmented dual-layer architectures is small, and the synthesis depends on indirect inference from heritage HEEET dual-layer data combined with separate aerogel-only data. The scope of the analysis is restricted to the Titan entry regime, and the framework does not address aerocapture or sample-return-entry conditions outside the Titan-calibrated reference. Finally, the analysis assumes static material properties; the effect of long-duration thermal cycling on aerogel performance has been characterized for some material families but not uniformly across the candidate pool, and this empirical gap is a recognized priority for future work.

Beyond the principal conceptual contribution of the TC-TMPI, the article has produced four secondary contributions that deserve recapitulation. First, it has organized the heterogeneous empirical literature on aerogel TPS material families into a comparable parameter space defined by four normalized variables, providing a basis for future cross-laboratory benchmarking. Second, the analysis has clarified that the optimal architecture for Titan entry is a dual-layer hybrid combining a thin conformal ablator with a polyimide-silica aerogel insulator, rather than either a pure aerogel or a pure ablator architecture, reframing the design heritage debate around the trajectory regime rather than around material loyalty. Third, the synthesis has identified the polyimide-silica hybrid and the hypocrySTALLINE zircon aerogel as the leading single-material candidates for inner-insulation-layer and outer-radiation-tolerant applications respectively, providing a concrete material short-list for technology investment decisions. Fourth, the framework has connected the abstract TPS optimization problem to concrete mission-design implications for Dragonfly and successor outer-planet entry missions, including quantitative areal-mass savings and explicit identification of the technology-readiness gap between current laboratory performance and flight qualification.

A complementary reflection concerns the transferability of the TC-TMPI framework to entry regimes beyond Titan. The weighting scheme adopted here (0.40, 0.25, 0.20, 0.15 for thermal conductivity, compressive strength, density, and working temperature respectively) is calibrated to the long-duration moderate-flux Titan profile and would require recalibration for the short-duration high-flux Venus entry profile, in which working temperature and compressive strength dominate. For Mars entry, the weighting would shift toward density and compressive strength,

reflecting the importance of mass efficiency under modest peak heating. The framework architecture, however, transfers across all entry regimes without modification; only the weighting and the reference trajectory parameters change. This portability is one of the principal methodological advantages of the synthetic-index approach over single-variable metrics.

Four recommendations for future research follow from this analysis. First, an integrated arcjet-testing programme should be initiated to qualify dual-layer aerogel-augmented panels under heat-flux and pulse-duration conditions representative of the Titan entry envelope; the recommended test matrix spans heat fluxes 0.5 to 1.5 MW/m<sup>2</sup> and pulse durations 5 to 30 minutes across the operating envelope of the NASA Ames Interaction Heating Facility and the DLR L3K facility. Second, the implicit-coupling CFD framework recently validated for hypersonic non-equilibrium flows should be extended to incorporate CN-dominated radiative transport and methane-nitrogen chemical kinetics calibrated against Electric Arc Shock Tube measurements; the code-development priority is in the radiative-transport and chemical-kinetics modules rather than in the material-response modules. Third, multi-objective topology optimization should be applied to the dual-layer architecture at the panel scale to resolve the optimal thickness-ratio distribution as a function of position on the aeroshell. Fourth, manufacturing-scale demonstration of integrated dual-layer panels at characteristic dimensions of approximately 1 metre should be pursued through ambient-pressure-drying scale-up, with explicit attention to joint architectures that preserve the parent-material thermal resistance across panel interfaces.

A broader reflection concerns the trajectory of TPS development in the era of outer-planet exploration. The legacy carbon-phenolic and PICA traditions emerged from a generation of missions characterized by short-duration high-flux entries at Mars, Venus, and Earth-return, and the design optimization developed under those conditions has been carried forward into present-day mission planning largely without architectural revision. The advent of Titan, aerocapture, and ice-giant missions imposes a new set of trajectory constraints in which long-duration moderate-flux entries dominate and in which the architectural optimum shifts toward insulation-dominated and dual-layer designs. The aerogel material families that have matured over the past decade are precisely matched to this new constraint envelope, and the TC-TMPI framework developed in this article is offered as one organizing principle for the architectural revisions that the new era of outer-planet exploration will require. The implication is not that aerogel architectures supplant legacy ablators across all entry regimes but that the design portfolio expands to include aerogel-augmented dual-layer architectures wherever the trajectory regime favours insulation-dominated performance, and Titan entry, with its 110 minute heat pulse and its CN-dominated radiative environment, is the paradigm case for that expanded portfolio.

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# TERMO-MEHANIČKA OPTIMIZACIJA AEROGELNIH TOPLOTNIH ŠTITOVA ZA ATMOSFERSKI ULAZAK SONDI U TITANOVU METAN-DUŠIKOVU ATMOSFERU

Rohit Agarwal

Medicinski fakultet i bolnica  
Kolkata, Indija  
E-mail: rohit.agarwal@cnmckolkata.in

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**Sažetak:** Atmosferski ulazak u Titanovu gustu metan-dušikovu atmosferu generiše aerotermodinamičko okruženje s vršnim toplotnim flukseom u rasponu od 0,9 do 1,3 MW/m<sup>2</sup> i značajnim radijacionim doprinosom iz CN ljubičastog i crvenog spektralnog sistema, što zajedno čini jedan od najzahtjevnijih dizajnerskih problema toplotnih štitova među predviđenim planetarnim misijama. Pojava misije Dragonfly s rotorskim letjelicama, koja ima ulaznu interfejs visinu od 1270 km i dvosatni descent s Mach 28 do subzvučnih uslova, ponovno je usredotočila pažnju na arhitekture sistema toplotne zaštite (TPS) koje kombinuju nisku površinsku gustinu, održivu mehaničku otpornost kroz duge toplotne pulseve i toleranciju post-separacijskog backshell režima. Ovaj rad predstavlja termo-mehanički optimizacijski okvir za toplotne štitove na bazi aerogela prilagođene uslovima ulaska u Titan, integrišući recentne napretke u silikatnim aerogelima ojačanim vlaknima, umreženim poliiimidnim aerogelima i hipokristalnim keramičkim aerogelima u jedinstvenu komparativnu analizu. Originalni doprinos sastoji se u formulaciji Titan-Kalibrisanog Termo-Mehaničkog Indeksa Performansi (TC-TMPI), sintetičkog indikatora koji kombinuje normalizovanu toplotnu provodljivost, kompresijsku čvrstoću, gustinu i visokotemperaturnu stabilnost ocjenjenih u odnosu na Dragonfly-relevantnu referentnu trajektoriju. Okvir, primijenjen na šest kandidatskih aerogel arhitektura, generiše kvantitativni rang i identifikuje poliiimid-silikatni kompozit i dvoslojnu tkanu aerogelnu arhitekturu kao glavne kandidate za daljnji razvoj. Analiza također razjašnjava parametarski prostor unutar kojeg aerogel arhitekture nadmašuju nasljedne ugljenik-fenolne ablatore.

**Ključne riječi:** *aerogelna toplotna zaštita, atmosferski ulazak Titan, termo-mehanička optimizacija, Dragonfly misija, poliiimidni aerogel, silikatni aerogel, ablator, hipersonično zagrijavanje.*