

IN SEARCH OF AN ALTERNATIVE CONFIGURATION OF THE FLEXIBLE THERMAL PROTECTION SYSTEM FOR THE CONTROLLED RE-ENTRY AND SAFE RECOVERY OF 3U CUBESAT-CLASS SATELLITES

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Abstract: This work proposes an alternative conceptual configuration of a deployable, umbrella-like thermal protection system (TPS) for the controlled re-entry and safe recovery of 3U Cubesat-class satellites, incorporating a recently developed flexible aeroshell material manufactured by the filament-winding technique. The methodological approach involved a critical assessment of the existing or those under development flexible systems for reentry missions, focusing on their conceptual design, deployment mechanism, payload configuration, drag modulation, and thermal protection materials. As a result, the classification of the flexible thermal protection systems was proposed. The classification allowed highlighting some characteristics that distinguish the suggested TPS configuration from those subjected to assessment. The principal feature of this TPS was the aeroshell design, which combines rigid surfaces with flexible materials manufactured using the filament winding technique.

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1. INTRODUCTION

The primary purpose of atmospheric re-entry systems is to protect payloads and satellites from extreme aerodynamic heating and mechanical loads during descent through dense planetary atmospheres. As the frequency of low-cost missions and the miniaturization of spacecraft increase, particularly in the context of the expansion of CubeSats applications [1], the development of advanced thermal protection systems (TPS) becomes increasingly essential. These missions require lightweight, compact, and reliable solutions that can maintain thermal and structural integrity under harsh re-entry conditions.

Current flexible thermal protection systems (FTPS), which are folded during the launch phase and deployed at atmospheric re-entry, present trade-offs among thermal resistance, structural simplicity, and packaging efficiency. Over the past few decades, significant progress has been made in the development of such systems, and several materials have been proposed for FTPS [2]. However, there is still limited information on the organization and structuring of existing knowledge and practical know-how gained from various TPS development experiences, as previously reported for the rigid TPS [3-6]. Thus, one of the objectives of the work was to conduct a critical assessment of FTPS for re-entry missions, with the purpose of classifying them, highlighting commonalities, and identifying potential limitations.

Moreover, the feasibility of the filament winding technique for manufacturing a flexible aeroshell with a large half-cone was considered in a previous study [2] for a classical umbrella-like deployable FTPS. It was demonstrated that the filament winding of conical structures poses no significant difficulties, except for limitations in the available fiber paths. The available fiber paths for two configurations of the conical aeroshell were compared with the principal stress distributions expected during FTPS operation. It was demonstrated that the stress distributions did not align with the stiffness distribution of the filament-wound structure. To address the issue, an alternative configuration of the deployable FTPS was considered, aiming to develop a feasible concept that incorporates a recently developed flexible aeroshell material manufactured using the filament-winding technique. In this paper, the emphasis is primarily on reviewing and assessing the FTPS, with a suggested configuration of the FTPS outlined at the end.

2. LITERATURE REVIEW

The methodological approach involved a critical assessment of existing and successfully tested FTPS for re-entry missions, as well as those under development, focusing on their conceptual design, deployment

mechanisms, payload configurations, drag modulation, and thermal protection materials. A number of FTPS were considered in the study, among which were mostly deployable systems; however, non-deployable solutions were also considered, mostly for comparative purposes.

Among the four principal concepts of the FTPS suggested for the classification (Table 1), only the permanent barrier is considered non-deployable. The typical representatives of the concept are the Advanced Flexible Reusable Surface Insulation (AFRSI) and the Fibrous Reusable Surface Insulation (FRSI), which were successfully implemented in the Space Shuttle orbital spacecraft system [7]. The AFRSI and FRSI blankets (Fig. 1a), with a required planform shape, were bonded directly to the orbiter using RTV silicon, creating a continuous thermal barrier in areas with minimal thermal and aerodynamic loads [8]. Although the concept is not directly related to deployable systems, it may potentially find an application as local protection for CubeSat components, as demonstrated, for instance, by the insulation of the engine thrust vector control mechanism [9]. The blankets with relatively low thicknesses (as reported, the minimal values were 4 and 6.35 mm for the FRSI and AFRSI, respectively) could be adapted for deployable FTPS.

The structures of inflatable aerodynamic decelerators (IADs) utilize a thin, flexible insulation material that is folded into small-volume packages during launch and deployed with pressurized gas and/or ram-air during the re-entry phase. The single-volume inflatable structures (IS), or a combination of balloon and parachute, known as ballutes (Fig. 1b), were intended for long-term observation of the atmospheric properties of other planets [10]. For instance, the BVS (Buoyant Venus Station) first deploys a parachute to reduce the speed after the principal re-entry phase, and the balloon envelope inflates only when the dynamic pressure becomes low [11, 12]. In fact, the BVS does not land, as it must float at a particular altitude to collect data on the local atmosphere. The ballutes, over time, have evolved into more efficient multi-chamber inflatable structures with a blunt conical shape (Fig. 1c) that rely on a low aeroshell ballistic coefficient during atmospheric entry. The multi-chamber structures are more robust than single-volume ones, but they require more material, which affects the FTPS mass [13]. Several solutions for the IAD with a blunt body structure have been proposed to date (Table 1). Among the design challenges of such structures is that they must be thick enough to withstand the harsh conditions of atmospheric re-entry, yet thin and flexible to be folded into small volume packages [3]. The aerodynamic analysis of the deployed IADs must rely on the effects of structural deformation [13]. The design of the known IADs does not allow for drag modulation to control the re-entry location aerodynamically. It is believed that the mechanically deployed structures do not have this limitation [14].

The mechanical structures rely on an umbrella-like mechanism comprising a frame covered with a flexible thermal protection aeroshell (Fig. 1d). The frame of the mechanism may consist of metallic ribs supported by struts [15, 16], only ribs made from shape memory alloys (SMA) [17], only ribs supported by cables [18] or a more complex transgrety structure consisting of compression members and cables that comprise the tension network [19]. The aeroshell is deployed by a set of extension-compression springs [20], by SMA components of the mechanism [16, 17], or electromechanical telescopic poles [18]. The aeroshell flexible material is a multilayered woven fabric or a polymeric film that forms a semi-rigid membrane pretensioned by ribs after deployment. This membrane transfers aerodynamic loads to the frame structure [21] and protects it to some extent from heating. An important advantage of the membrane in the mechanically deployable TPS is that it does not require high impermeability, unlike the multi-layered material in inflatable systems. However, the deformation of the membrane may lead to some difficulties in predicting the aerodynamic behavior. During the first flight test, the ADEPT SR-1 experienced increased roll rate and tumbling at speeds below Mach 0.2, which was not predicted in simulations [22]. In reference [23], it was demonstrated that rib flexibility is beneficial in reducing mass and volume, but may result in increased heat flux.

An alternative solution to a flexible membrane is the concept of a mechanically deployable aeroshell with rigid TPS panels whose structure follows origami principles [24]. This structure does not rely on a flexible aeroshell; thus, it can be considered a pseudo-flexible TPS. Among the advantages of the structure are the predictable geometry of the deployed aeroshell, the absence of preloading of the structure due to membrane pretension, and the absence of deformations in the aeroshell material in the stowed state.

In some FTPS, the strategy of thermal protection relies on the development of high-performance material solutions, such as those designed for an aeroshell capable of withstanding heat fluxes exceeding 3000 kW/m². The aeroshell of one of the solutions consists of several overlapping sacrificial tiles (Fig. 1f) made from ethylene-propylene-diene monomer rubber reinforced with aramid fibers [25]. In other FTPS, the heat shielding strategy relies on the re-entry trajectory with minimal aerodynamic heating. For instance, the membrane referenced in [26] is made from a thermoset liquid-crystalline polyoxazole, whose maximum

service temperature is approximately 920 K. Such structures permit the use of relatively simple frames made from SMA, which deploy the aerobraking membrane at a programmed temperature. Another original FTSP concept, which also relies on a less demanding thermal control scenario [27], utilizes inertial centrifugal force generated from autorotation to deploy and stiffen an origami-like flexible heat shield (Fig. 1e).

Worth noting that almost all vehicles considered in this work do not provide mechanisms or structural components responsible for aerodynamic control. These studies have been initiated recently; for instance, aerodynamic flaps attached to the end of the ribs were suggested for steering the ADEPT-like re-entry vehicle [28].

Table 1. Classification of the FTSP for re-entry missions

Deployability	Concept	Conceptual design	Design	Actuation of the mechanism	Examples
Non-deployable	Permanent barrier	Flexible layer	Blanket	-	AFRSI, FRSI [7-8]
Deployable	Inflatable Structure (IS)	Single-volume IS	Inflated ballute	Pressurized gas	BVS [11, 12]
		Multi-chamber IS	Inflated blunt body structure	Pressurized gas	IRDT [29-30], IRVE [31-32], HIAD [33-34], EFESTO [35]
	Mechanical frame	Umbrella-like mechanism	Ribs supported by struts	Mechanical or by smart materials	Brem-SAT2 [36], ADEPT [15, 20, 21], SPLASH [16, 37]
			Frame or ribs only	Smart materials	FEATHER [26]
			Truss-cable structure	Electro-mechanical	IRENE [18], TANDEM [19]
	Rigid aeroshell	Rigid panels in an origami-like structure	Mechanical	Origami-based [24]	
Self-regulating	Reinforced flexible origami-like shell	Inertia force	DESCENT [27]		

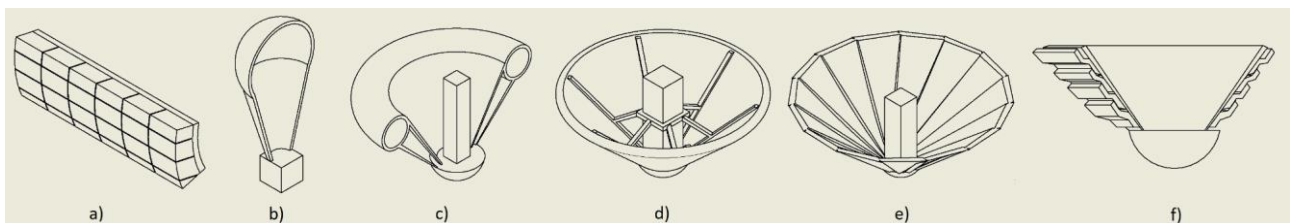


Figure 1. Schematic representation of the FTSP: a) blanket, b) ballute, c) inflated blunt conical structure, d) umbrella-like structure, e) origami-based structure, f) armadillo-like tiles

3. ALTERNATIVE TPS CONFIGURATIONS

As the available winding angles of either geodesic or nongeodesic paths on the conical surface disagreed with the distribution of the expected principal stresses [2], the aeroshell manufacturing process was substantially reengineered without affecting the material composition. In the process, the conical mandrel is replaced with a mandrel whose shape is defined by a combination of a cylinder and elliptical closures. For the winding along a geodesic path, the winding angle is governed by the relation between the diameters of the cylinder and the polar opening at the closure in accordance with Clairaut's relation. After the winding process, the manufactured layup over the cylindrical part is removed from the mandrel and then developed and stretched on a plane surface of a mold. This technological procedure enables the manufacture of angle-ply $[\pm\alpha]_n$ and double-double $[\pm\alpha/\pm\beta]_n$ plane layups with practically any angle-ply configuration, ranging from a few tenths of a degree to nearly 90 degrees.

Table 2. Description of the typical FTSPS

Conceptual design	Mechanism description	Flexible TPS materials	Potential limitations
Continuous barriers	Permanent connection to a protected surface.	Various single-layered or multi-layered solutions in the form of a blanket/felt (fibrous silica felt between glass/basalt cloth; nylon felt coated with silicone elastomer, etc.)	Relatively low temperature limits (~400–650°C); predominantly thick-walled structures; non-deployable.
Inflatable ballutes	Predominantly trailing structures with expanding surface area through their inflation with pressurized gas to increase aerodynamic drag.	Polytetrafluoroethylene insulation reinforced by aramid or carbon fibers; also, polyimide and polybenzoxazole (PBO) films.	Structures feasible for aerocapture and/or aerobraking only; deformability of the structure; low controllability.
Inflatable blunt body	The attached-to-payload structures are made from flexible insulation material, which is folded into small-volume packages and deployed into various shapes or sub-configurations (the isotenoid, the tension cone, and the stacked-toroid blunted cone) by pressurized gas.	Multiple materials with distinct functions: the outer high-temperature fabric (woven ceramic fabric) withstands a harsh re-entry environment; the intermediate thermal insulation layer (reinforced silica aerogel); the inner impermeable gas barrier layer (polyimide-aramid film).	Inflation failure risk exists due to the deformed inflatable structure in the stowed state; a complex inflation system; limited rigidity; no drag modulation.
Classical umbrella-like mechanism	A sliding-ring mechanism with hinged ribs is unlocked by a burn wire and deployed to a predetermined angle by tension or compression springs, with the thermal-protection membrane being tensioned between the ribs.	Woven high-temperature fabrics (carbon or ceramic).	Deployment failure risk; seam vulnerability; unpredictable control due to membrane deformation; non-axisymmetric shape affects the aerodynamic control.
Umbrella-like mechanism with an SMA-actuation	The frame, made of a shape-memory alloy, automatically deploys to a required angle when heated and stretches the TPS membrane.	Thermoset plastics (liquid-crystalline polyoxazole) or woven fabrics (ceramics).	Limited deployment control; low actuation force; limited rigidity.
Origami-based umbrella-like mechanism	Rigid TPS panels with optimized origami folding patterns for compact stowage and predictable geometry upon deployment. The panels are attached between retractable ribs.	Rigid ablative panels (ceramic composites)	Deployment is sensitive to panel geometry; the mechanism exhibits unknown behavior under heat flux; the mass may be higher than that of the membrane.
Origami-based autodeployable shell	The buckled shape of the flexible shell generates aerodynamic roll-torque during atmospheric re-entry. The centrifugal force caused by autorotation deploys and flattens the flexible shell until the roll-torque becomes zero.	Stitched ceramic fabric, locally reinforced with strips of carbon fiber-reinforced plastic.	Uncertain drag modulation; stiffness limited by spin rate; folding complexity; no active control.

Unlike in the wound conical aeroshell [2], the thickness of the flexible laminate with these layups is uniform. This plane laminate can be cut to dimensions that correspond to the aeroshell span between two ribs (Fig. 2a) or between two rigid thermal protection plates (Fig. 2b) in an umbrella-like FTPS. In the later configuration, the rigid TPS panel serves as a structural component supported by a strut. An electromechanical mechanism regulates the length of the strut, which affects the rigid plane inclination angle, thereby providing aerodynamic control. It is assumed that, unlike in a 3D woven fabric, the flexural rigidity of the wound laminate is a non-zero parameter, as it retains its shape in a stationary state under its own weight, as demonstrated in a previous study [2]. Such an effect may be advantageous for a non-fully stretched structure, thus allowing aerodynamic control.

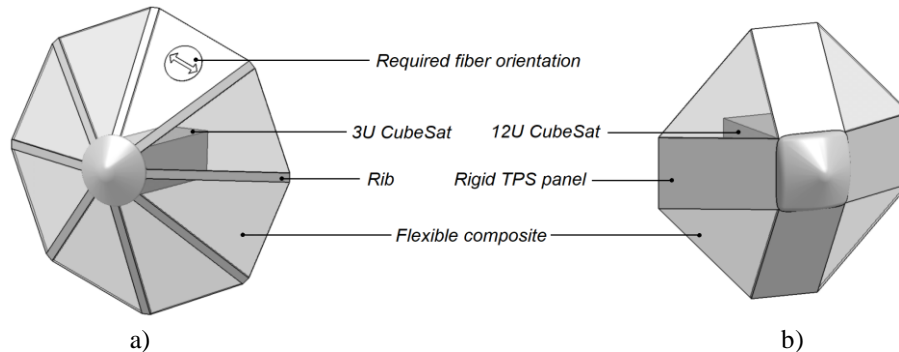


Figure 2. FTSP configurations with aeroshell manufactured by filament winding technique: a) the umbrella-like structure for a 3U Cube-Sat; b) the structure for a 12U Cube-Sat with four rigid panels and flexible laminate stretched between them

4. CONCLUSIONS

From the three principal concepts of the FTSP considered in the suggested classification, only the mechanically deployable umbrella-like structures may potentially enable aerodynamic drag modulation as an efficient method for controlling the re-entry location. An FTSP configuration alternative to those reviewed in the paper combines rigid TPS panels with flexible laminate manufactured by the filament winding technique. The reengineered manufacturing process of the filament winding allows the fibers to be oriented along the principal stress directions in the aeroshell.

4.1. Declaration of Competing Interest

The authors declare no conflict of interest.

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