DEVELOPING A FLEXIBLE THERMAL PROTECTION SYSTEM FOR MARS ENTRY: SYSTEMS ENGINEERING, MECHANICAL DESIGN AND MANUFACTURING PROCESSES

Thomas J. Hancock[1], John Underwood[1], J. Stephen Lingard[1], Alan Flinton[2], James Merrifield[2], Emma Johnstone[2], Erhard Kaschnitz[3], Thorn Schleutker[4], Heiko Ritter[5]

[1] Vorticity Ltd, Chalgrove, United Kingdom
[2] Fluid Gravity Engineering Ltd, Emsworth, United Kingdom
[3] ÖGI – Österreichisches Gießerei-Institut, Leoben, Austria
[4] DLR – German Aerospace Centre, Cologne, Germany
[5] ESA – European Space Agency, Noordwijk, The Netherlands

ABSTRACT

A flexible thermal protection system (FTPS) is needed to enable the use of deployable and inflatable hypersonic decelerators. These decelerators could increase entry vehicle drag area beyond that of a conventional rigid heatshield, enabling Mars missions with greater landed masses and higher-elevation landing sites than can be currently achieved. An FTPS is essential to protect the hypersonic decelerator and payload from atmospheric entry aerothermal loads; conventional rigid heatshields are constrained by the available space within the launcher fairing. An ESA technology development is ongoing to raise the European FTPS technology readiness level from 2 to 3 and to define an FTPS that may be integrated with a Mars-entry inflatable hypersonic decelerator. This paper presents the FTPS requirements, material selection, mechanical characterisation and manufacturing technique development.

Index Terms — Flexible Thermal Protection System, Layup, Insulation, Inflatable Hypersonic Decelerator, Manufacture

1. INTRODUCTION

A previous ESA study identified that deployable and inflatable hypersonic decelerators could enable Mars landing missions with greater landed masses and/or higher-elevation landing sites than can currently be achieved [1]. Reference entry, descent and landing mission profiles were selected that could benefit from deployable and inflatable decelerators, and concept designs of suitable entry vehicles were completed. As one of the main study conclusions, the flexible thermal protection system (FTPS) was identified as a key enabling technology to use deployable or inflatable hypersonic decelerators on atmospheric entry missions.

The FTPS is an essential part of the entry vehicle heatshield: it prevents the temperature of the payload and the deployable/inflatable decelerator structure from exceeding their maximum operating temperatures during atmospheric entry. The current technology readiness level of FTPS in Europe is low, so a new ESA technology development is underway to advance FTPS design, test and manufacture capabilities.

In this development, an FTPS is being defined that may be integrated with a Mars-entry stacked-toroid inflatable hypersonic decelerator, shown in Figure 1. An accompanying paper at FAR 2022 presents the FTPS thermal design aspects; this paper addresses overall system design, mechanical and manufacturing aspects.

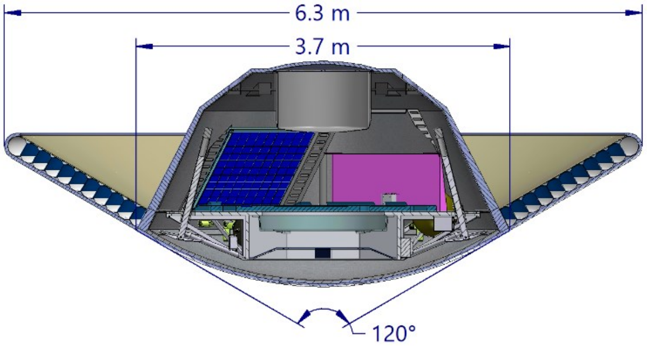

Figure 1 Reference Mars entry vehicle cross-section [1]

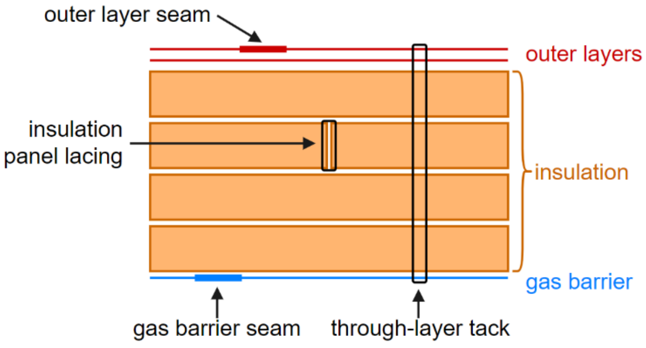

Figure 2 FTPS baseline configuration cross-section

2. FTPS REQUIREMENTS AND BASELINE CONFIGURATION

The FTPS requirements are driven by a reference Mars entry trajectory, which aims to land a 950 kg mass at a site 2 km above the MOLA datum [1]. The FTPS must withstand a reference peak heat flux of 400 kW/m² and a total heat load of 40 MJ/m². This is significantly greater heating than that experienced in previous Earth FTPS demonstrator missions such as IRVE-3 (peak heat flux of 144 kW/m² [2]). The inflatable structure temperature underneath the FTPS must not exceed 200 °C throughout the 400 second Mars entry trajectory, while each layer within the FTPS must not exceed its maximum operating temperature.

The FTPS must be flexible enough when integrated with the inflatable structure to be folded and packed into a small volume. It must remain in its folded configuration during launch and cruise, before deploying successfully when the inflatable decelerator inflates before Mars entry.

The baseline FTPS design concept consists of three functional layers (Figure 2). Each functional layer may consist of one or more material layers. The outer layer must resist direct exposure to the incident flow and so reaches the highest temperatures. The inner insulation must delay the entry heat pulse and keep the underlying gas barrier and inflatable structure below their maximum operating temperature until the heatshield can be jettisoned. The gas barrier prevents any hot gases and FTPS decomposition products from reaching and damaging the underlying inflatable structure. In future developments, this functionality could be fulfilled by the underlying inflatable structure itself. The same three functional layer concept has been developed by NASA over a series of FTPS development studies [2][3]. Four principal joints must be designed: within-layer joints in the outer layer, insulation and gas barrier materials, and a through-layer joint holding the layers together.

The FTPS materials must withstand extremely high temperatures and provide good thermal insulation, while also being flexible. This is a demanding combination of requirements, which is met by a limited number of specialist materials. Following an extended material screening, two candidate materials were selected for each functional layer. These materials were characterised to complete the available material property data.

3. MATERIAL MECHANICAL CHARACTERISATION

3.1. Test methods

Uniaxial tensile tests at room temperature and elevated temperature were conducted at ÖGI for all outer layer and gas barrier materials. Woven fabrics were tested in both the warp and weft directions, using the ASTM D5035 1R-T ravelled strip test method. The ASTM D882-18 test method was used for a non-woven gas barrier candidate, Kapton 300HN polyimide film. Insulation materials are relatively weak and do not carry significant tensile load; the load in the FTPS layup is carried by the outer layer and the gas barrier. This means tensile strength is not a factor in insulation material selection and no tensile tests were needed.

Room temperature tests were performed in a standard ZwickRoell tensile test machine. Elevated temperature tests were achieved by passing the central part of the specimen through a furnace located between the two tensile test machine grips. Once the specimen was installed, the furnace was brought up to the target temperature at the maximum achievable heating rate of approximately 12.5 °C / minute. A maximum test temperature of 900 °C was possible.

Flexibility tests at room temperature were conducted at Vorticity for all candidate materials to assess their relative suitability for packing and deployment. Material strips were bent 180° around mandrels of diameter 0.5 mm, 1.25 mm and 2.5 mm, following the ASTM E290-14 Semi-Guided Bend Arrangement B test method. Strips were also folded in half with no mandrel and creased along the bend line, following the ASTM E290-14 Bend and Flatten test method. Each specimen was visually examined after a single bend held for 10 minutes, and after 25 repeated bending/unbending cycles. The ease of folding, crease line permanence and resulting damage to the material were observed.

3.2. Outer layer candidate materials

The outer layer must protect the underlying insulation from direct exposure to high heat fluxes and aerodynamic shear forces during entry. Insulation materials typically have low strength and would rapidly disintegrate if directly exposed to the incident flow. It is therefore essential that the outer layer material does not fail at high temperatures. Arc-jet tests on similar layups in a previous ESA study reached 1500 °C in the outer layer [1]. Actual outer layer temperatures will depend on the incident heating profile, the outer layer emissivity and the underlying insulation thermal properties. Nevertheless, 1500 °C is a reasonable target operating temperature for initial material selection. The material must also be flexible enough for packing and deployment. A high emissivity is desirable, to increase radiative heat flux rejected to the environment.

Two candidate materials were selected: Nextel 440 BF-20, an alumina-silica-boria ceramic fibre woven cloth manufactured by 3M, and Refrasil C1554-48, a silica ceramic fibre woven cloth with chromic oxide coating manufactured by SGL Carbon.

Nextel 440 BF-20 has a maximum datasheet operating temperature of 1300 °C. The tensile strength of Nextel 440 fibres reduces with increasing temperature; negligible strength is retained at 1400 °C [4]. It was used as the outer layer for the IRVE-3 FTPS [2]. The Nextel 440 ceramic fibres are coated in an organic sizing compound when the fabric is woven. This makes weaving, handling and sewing with the fabric easier, as it reduces fibre breakage and shedding.

Refrasil C1554-48 has a maximum datasheet operating temperature of 1260 °C. As with Nextel, the tensile strength of the fibres reduces with increasing temperature, but no indication of the strength loss is given in the datasheet. Refrasil C1554-48 was also considered as a candidate material during the NASA PAIDAE programme [5].

Neither candidate outer layer material meets the target operating temperature of 1500 °C. Fabrics woven from zirconia or carbon fibres do meet the target operating temperature but are not robust enough to be manufactured into a large flexible blanket. Fabric woven from silicon carbide fibres is the most promising solution: this has been successfully tested in arc-jet tests up to a temperature of 1800 °C [6]. The tensile strength and strength retention after bending of silicon carbide fabrics have been shown to be better than that of Nextel 440 BF-20 [7]. Silicon carbide fabric will be used as the outer layer on the FTPS for the NASA LOFTID flight test [3]. In material screening during this activity, Hi-Nicalon silicon carbide fabric manufactured by NGS Advanced Fibres was selected as the preferred outer layer material. While technically desirable, it could not be tested due to its prohibitively high cost and long lead time.

The outer layer materials were tensile tested at room temperature in both warp and weft directions, then at 900 °C in the weaker direction. Table 1 reports the average failure load and Figure 3 shows typical load vs strain profiles. At room temperature, the average failure load was similar in the warp and weft direction for Nextel 440 BF-20, but Refrasil was more than three times weaker in the weft direction, with a noticeably lower Young's modulus. At 900 °C, the Nextel 440 BF-20 was ten times stronger than the Refrasil C1554-48.

Flexibility tests showed that both materials are flexible enough for FTPS manufacture and packing. Sustained and repeated bending around a 0.5 mm bend radius produced no visible damage to either material. Sharp creases must be avoided, as they fractured fibres perpendicular to the crease line, causing both materials to break (Figure 4).

These tests also showed that Nextel 440 BF-20 is more suitable for manufacturing than Refrasil C1554-48. Fine dust and filaments were released from Refrasil C1554-48 during handling, contaminating tools and work surfaces and requiring protective equipment to prevent inhalation or skin contact. Far fewer fibres were released when handling Nextel 440 BF-20. The microscope images of the two fabrics in Figure 5 show the difference clearly, with many broken Refrasil C1554-48 fibres visible on its surface.

Table 1 Outer layer tensile test failure loads

Material	Average failure load (N/cm)	
	23 °C	900 °C
Nextel 440 BF-20 warp	584	407 (-30%)
Nextel 440 BF-20 weft	639	Not tested
Refrasil C1554-48 warp	248	Not tested
Refrasil C1554-48 weft	73	39 (-53%)

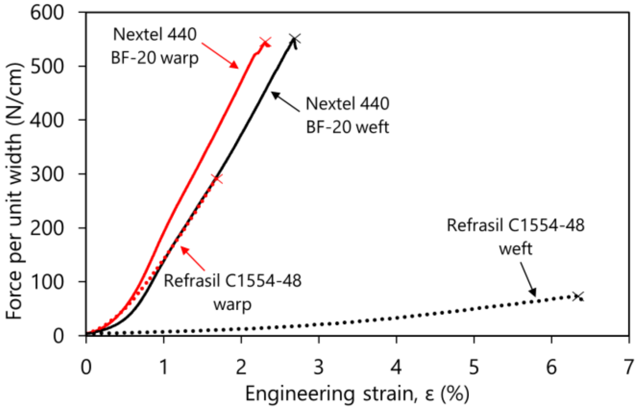

Figure 3 Outer layer uniaxial tensile tests

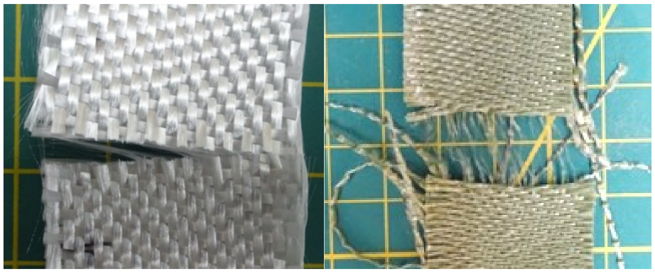

Figure 4 Heat-cleaned Nextel 440 BF-20 (left) and Refrasil C1554-48 (right) after fold and crease

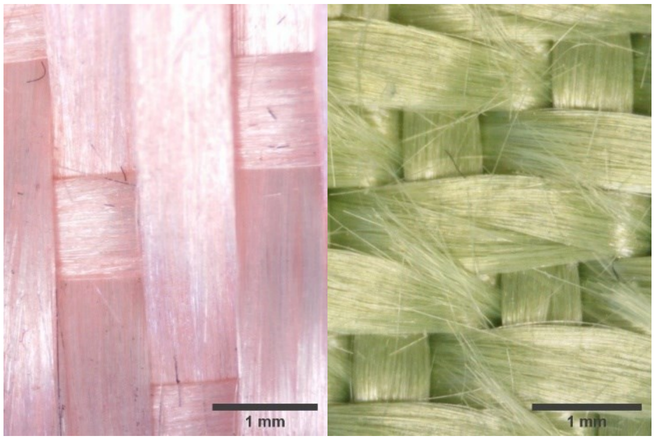

Figure 5 Nextel 440 BF-20 weave (left) and Refrasil C1554-48 (right)

Following these mechanical tests, Nextel 440 BF-20 was selected as the preferred outer layer material. It is significantly stronger than Refrasil C1554-48, with less variability between the warp and weft directions. It is also significantly easier to handle and manufacture.

3.3. Insulation layer candidate materials

The insulation layer must delay the heat pulse caused by atmospheric entry, preventing the gas barrier and underlying structure from exceeding their maximum temperature until after heatshield jettison. Consequently, the main requirement for insulation materials is low thermal diffusivity. As for the outer layer, the insulation materials must also be flexible and allow integration into an FTPS layup.

Two candidate materials were selected: 5.5 mm thick Sigratherm GFA5 graphite felt manufactured by SGL Carbon, and 5 mm thick Pyrogel XTE silica aerogel manufactured by Aspen Aerogels.

Sigratherm GFA5 has the best balance of high operating temperature (more than 2000 °C) and low thermal diffusivity. Similar carbon felts have been used in other FTPS designs, including that to be flown on LOFTID [3]. As Sigratherm GFA5 is made from graphite, it cannot be used in an oxidising environment. Little oxidation is expected within the FTPS layup during Mars entry.

Pyrogel XTE has a much lower datasheet maximum operating temperature (650 °C), but also has lower thermal diffusivity than Sigratherm GFA5. This means that Pyrogel XTE is best used as lower insulation layers, underneath outer Sigratherm GFA5 insulation. Other aerogel products have been used on previous FTPS including IRVE-3 [2].

The thermal properties of the two insulation materials are presented in detail in the accompanying paper; this paper focuses on the mechanical characterisation tests. No tensile tests were conducted as all tensile load is carried by the outer layer and gas barrier.

The insulation material layers form most of the layup thickness and drive the FTPS flexibility. It is critical that the insulation material is sufficiently foldable. Flexibility tests showed that while both materials can be folded, Sigratherm GFA5 is much more flexible than Pyrogel XTE. Sigratherm GFA5 could be folded around a bend radius of 0.5 mm with no visible damage and only minor permanent surface disruption (Figure 6). It readily lay flat after the force imposing the bend was removed, indicating that Sigratherm GFA5 would be compatible with decelerator deployment.

In contrast, the Pyrogel XTE cracked and crumbled along the surface of the fold line, releasing fine aerogel particles for any bend radius less than 2.5 mm. This thinned the Pyrogel XTE locally along the bend line, which could reduce its insulation effectiveness. The bends remained in the material after the bending force was removed (Figure 7).

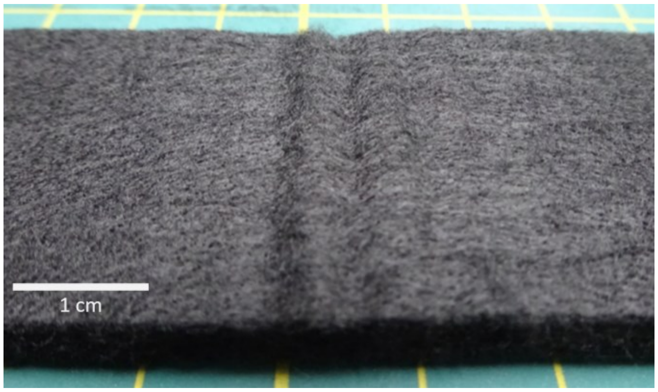

Figure 6 Sigratherm GFA5 surface after bend test

Figure 7 Pyrogel XTE cross section after a bend test

Sigratherm GFA5 is also easier to handle and manufacture. Pyrogel XTE releases significant quantities of fine aerogel dust when handled and its composition is visibly inhomogeneous. Sigratherm GFA5 does release graphite fibres, but less readily, and its composition is more homogeneous. Sigratherm GFA5 can be easily stitched and laced with hand sewing needles; Pyrogel XTE is denser and requires holes to be pre-drilled if stitching/lacing threads are to be passed through.

From a purely mechanical and manufacturing perspective, Sigratherm GFA5 is the preferred material. Nevertheless, both insulation materials were selected for further layup design and testing. The excellent insulating properties of Pyrogel XTE mean that at least one layer may be necessary to achieve the desired overall thermal performance.

3.4. Gas barrier candidate materials

The gas barrier must be impermeable at high temperatures, to prevent hot atmospheric gases or TPS decomposition products from damaging the underlying structures. A gas barrier material with a higher operating temperature limit could allow fewer insulation layers to be used. The gas barrier must also provide a robust backing to the FTPS, holding the insulation in place and securely attaching it to the underlying structure. As for the other layers, the gas barrier material must be sufficiently flexible and manufacturable. The gas barrier does not offer significant thermal insulation, so mechanical and manufacturing properties drive material selection.

Two candidate materials were selected: silicone-coated Kevlar 29 fabric, manufactured by Heathcoat Fabrics, and Kapton 300HN polyimide film, manufactured by 3M.

Kevlar 29 fabric is woven from para-aramid fibres and is widely used in parachute deployment bags. The Kevlar fabric provides strength and flexibility, while the silicone coating makes it impermeable. Silicone-coated Kevlar was used to manufacture the NASA SIAD-R inflatable decelerator torus, with a design maximum temperature of 290 °C [8].

Kapton 300HN is a polyimide film, frequently used in spacecraft multilayer insulation. A Kapton–Kevlar laminate was used as the gas barrier in the IRVE-3 FTPS [2].

The silicone-coated Kevlar was stronger in the weft-aligned direction at 23 °C; the relative strength of warp and weft directions will change with the weave design. The weaker warp direction was also tested at 200 °C and 300 °C. The failure loads (Table 2) show a significant strength loss at 200 °C and near-complete strength loss at 300 °C. At 200 °C only minor specimen discolouration was seen, but at 300 °C the heated part of the specimens was entirely discoloured (Figure 8), showing thermal decomposition.

The silicone-coated Kevlar was significantly stronger than Kapton 300HN at room temperature and at 200 °C; the Kapton 300HN was stronger at 300 °C.

During Mars entry, the heating rate of the gas barrier will be an order of magnitude faster than that achieved in furnace-heated tensile tests. Less thermal degradation and strength loss under rapid heating is expected, as seen in other flash-heating tensile tests of silicone-coated Kevlar [8]. This means a maximum operating temperature of 200 °C (where reasonable strength was retained in these tensile tests) is a highly conservative design assumption.

Flexibility tests showed that both materials are flexible enough for FTPS manufacture and packing. Sustained and repeated bending around a 0.5 mm bend radius produced no visible damage to either material. No visible damage was observed after sharp creases, although they may reduce ultimate tensile strength. Silicone-coated Kevlar has a better drapeability than Kapton 300HN: it will more readily adopt a complex 3D surface curved in multiple directions.

Silicone-coated Kevlar is easier to manufacture into a layup than Kapton 300HN. Kapton 300HN scratches easily during handling and cannot be sewn. Machine-sewn joints used on parachute canopies and airbags/inflatable decelerators may be used with silicone-coated Kevlar. UV radiation exposure must be controlled, as this degrades the strength of Kevlar.

Consequently, silicone-coated Kevlar was selected as the gas barrier fabric. It is more flexible, more suitable for manufacture and stronger at 200 °C than Kapton 300HN.

Table 2 Gas barrier tensile test failure loads

Material	Average failure load (N/cm)		
	23 °C	200 °C	300 °C
Kapton 300HN	166	99 (-40%)	77 (-54%)
Silicone-coated Kevlar warp	331	147 (-56%)	39 (-88%)
Silicone-coated Kevlar weft	453	Not tested	Not tested

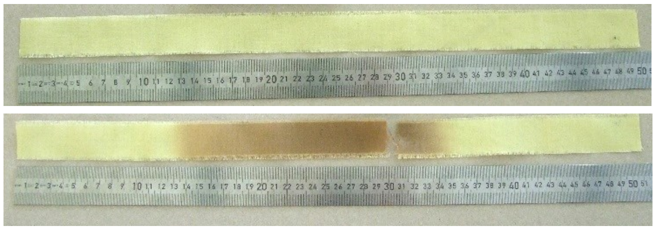

Figure 8 Silicone-coated Kevlar before (above) and after (below) tensile test at 300 °C

4. LAYUP MANUFACTURING DEVELOPMENT

4.1. Outer layer

Nextel 440 BF-20 fabric is procured in rolls 91 cm wide. To form a continuous surface covering a 6 m diameter sphere-cone, multiple panels must be cut and joined together. A pattern consisting of one circular end cap and multiple radial gores was selected (Figure 9). This has no more than two seams intersecting at any point and is relatively simple to manufacture. The gores are warp-aligned so that any length of gore can be cut from the fabric roll.

The separate panels are cut and joined together at the edges using sewn seams. Nextel 440 BF-20 frays easily at cut edges, with threads pulling out of the weave. To avoid this, the cut edge can be stabilised either temporarily with tape, or permanently with adhesive. Fraying is also reduced if each edge is sewn into a joint immediately after it is cut. The free edge of each gore is secured with a double-fold hem.

A 2.5 cm wide double-felled seam with three lines of stitching was selected (Figures 10 and 11). This seam type achieves high strength and encloses any cut edges within the seam, reducing fraying. Nextel 440 BT-30 sewing thread was used to sew the seams. This thread is made from the same fibres as the Nextel 440 BF-20 fabric, so has similar high-temperature performance. Nextel 440 BT-30 thread has a low strength compared to conventional room-temperature sewing threads such as nylon or polyester, and individual fibres can fracture when subject to sharp folds. This makes sewing with Nextel thread challenging: a heavyweight industrial walking foot sewing machine with an oscillating shuttle, low sewing speeds and low thread tension must be used.

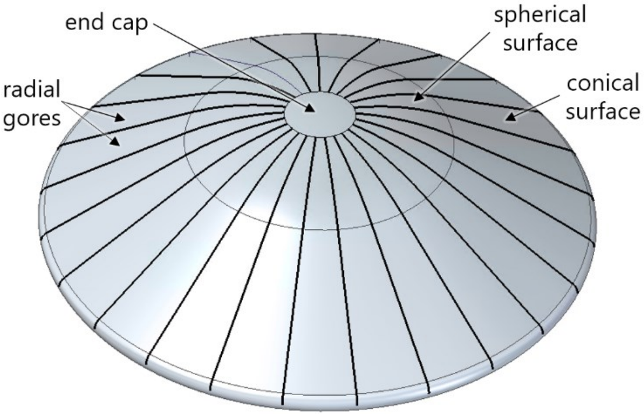

Figure 9 Outer layer pattern

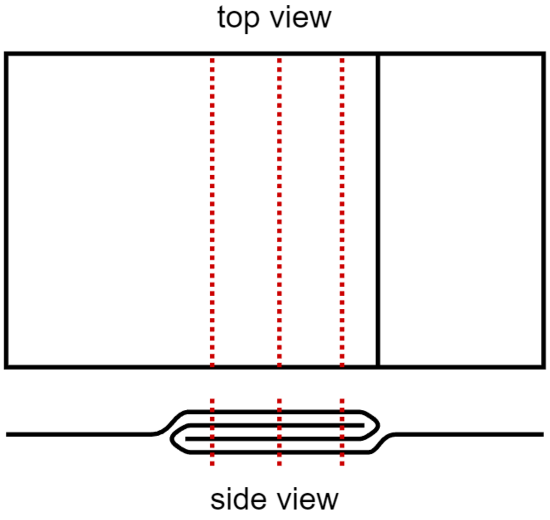

Figure 10 Double-felled seam with three stitching lines

Figure 11 Nextel 440 BF-20 double-felled sewn seam

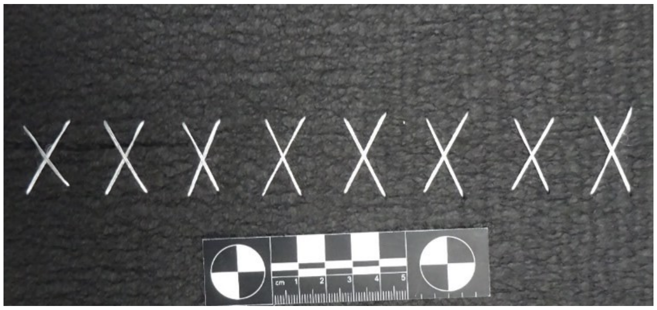

Figure 12 Lacing adjacent Sigratherm GFA5 panels

Fine ceramic fibres can be released when handling Nextel, so protective equipment to prevent skin exposure or fibre inhalation is recommended. After heat-cleaning, fibre shedding and breakage during handling is significantly increased, so it is important to manufacture the outer layer from non-heat-cleaned Nextel. If heat-cleaning is necessary to meet outgassing requirements, the completed outer layer must be heat-cleaned as a finished article, before the gas barrier is attached.

4.2. Insulation layer

Each layer of insulation layer must be made from multiple panels joined together, similar to the outer layer. Sewn seams cannot be used to join insulation panels, as overlapping adjacent seams would create unacceptable local thickness increases. Instead, a manually laced butt seam was trialled and shown to provide a secure, flexible attachment with negligible thickness increase or separation between panels.

Two lacing threads and a needle were used to lace adjacent panels of insulation together in a cross pattern (Figure 12). Nextel 440 BT-30 0.71 mm diameter sewing thread and Vitcas 0.46 mm diameter silica sewing thread were both trialled and found to be suitable.

4.3. Gas barrier

The silicone-coated Kevlar fabric is procured in rolls 1 m wide. The same assembly pattern as the outer layer was selected (Figure 9). Sewn seams are used to join panels; significant seam engineering experience is available from parachute canopy joint design. A 2.5 cm wide double-felled seam with four lines of stitching was selected.

Protos Fil Tex 135 continuous filament Kevlar sewing thread manufactured by Coats was selected as it has a high strength and good manufacturability. The objective for gas barrier seam design is for the seam to fail in the broadloom fabric, rather than at the thread. This minimises strength loss.

The sewing machine needle punctures the silicone-coated Kevlar to form a hole through which the sewing thread passes. This will create some localised permeability along the seam, which has not been assessed in this study. If future tests showed that the gas permeability along the seam was a concern, the sewn seam could be re-sealed with silicone tape.

4.4. Integration

Each material layer of the FTPS is manufactured separately. The layers are then stacked on top of one another to form the complete blanket. It is then necessary to secure the layers to one another with through-thickness joints. These joints ensure that the layers do not separate or become misaligned during packing and deployment.

The through-thickness joints must allow some relative motion of the different material layers, so that the materials can partially accommodate folds by sliding over one another. Quilting was considered, but not considered practical. Quilting using machine-sewn seams would require the entire layup to be passed through a quilting/sewing machine and potentially cause localised compaction of the insulation along the quilting line.

Instead, single stitches were made using a hand sewing needle and Nextel 440 BT-30 sewing thread. The tacks were secured with a surgeon's and lock knot on the inner gas barrier surface. Widely-spaced tacks in a 40 cm square grid were found to provide adequate fixing between different FTPS layers.

Once the layers are joined, fixing points are installed on the FTPS perimeter to allow it to be attached to the underlying inflatable decelerator structure. Several fixing methods were considered and trialled. Adhesives, hook and loop tape, snap fasteners and buttonholes were considered and discarded due to poor high temperature performance and reliability.

The two preferred options are grommets and sewn straps. Stainless steel grommets can be installed in holes punched in the outer layer and gas barrier hems, securing the hole edges and preventing fabric fraying. Sewn straps loops can be made from webbing woven from the same fibres as the outer layer and gas barrier and machine sewn onto the FTPS hem. In both cases, cords can be strung between the loops/holes in the FTPS and the underlying structure to join the two systems.

5. LAYUP MECHANICAL CHARACTERISATION

Flexibility tests were conducted to assess the suitability of different FTPS layups for packing and deployment. 1 m × 1 m square layups with different numbers of internal insulation layers were folded several times, while observing the ease of folding and any resulting material damage. Silica cloth was used as a mechanical analogue for the Nextel 440 BF-20 outer layer.

The maximum insulation thickness feasible for packing and deployment was found to be four layers of Sigratherm GFA5 (22 mm thick insulation), or one layer of 5 mm Pyrogel XTE and three layers of Sigratherm GFA5 (21.5 mm thick insulation). The relatively thin outer layers and gas barrier did not contribute significantly to the folding resistance.

Pyrogel XTE is significantly more resistant to folding than Sigratherm GFA5. At most one 5 mm layer of Pyrogel XTE can be used; any more than one layer, and it is not practical to fold without significant force and material damage. When folded, the Pyrogel XTE layers were observed to release dust and have clearly visible fold lines, where the material had degraded and thinned. No damage or permanent crease lines were observed on the Sigratherm GFA5 layers.

The maximum total layup thickness is limited by the bend accommodation mechanism. At four layers of insulation and above, there is a significant difference in bend path circumference between the outermost and innermost layers. Neither insulation material stretches or compresses sufficiently to accommodate this difference in length, so crumpling and folding are seen on the inner part of the bend (Figure 13).

From a folding perspective, a Sigratherm-only layup is preferable. However, the Pyrogel XTE is a significantly better insulator, so at least one layer is necessary from a thermal perspective.

As well as flexibility testing, tensile tests of the sewn joints in the outer layer and gas barrier are ongoing. These will confirm the suitability of the selected joint designs and provide strength data for future layup development.

Figure 13 Layup bend test of 3 Sigratherm GFA5 layers and 2 Pyrogel XTE layers

6. LAYUP DESIGN SUMMARY

The thickest layup that can be practically packed and deployed is:

- 2 × Nextel 440 BF-20 outer layers
- 4 × Sigratherm GFA5 (or 3 × Sigratherm GFA5 + 1 × Pyrogel XTE) insulation
- 1 × silicone-coated Kevlar 29 gas barrier

Two layers of Nextel are included in the outer functional layer to provide redundancy. If the outermost layer fails, it is important that the underlying insulation is still protected from the external flow, or it will be rapidly destroyed. These layups are undergoing arc-jet testing in DLR's L2K facility to assess their thermal performance in a Mars entry environment.

The thermal design outlined in the accompanying FAR 2022 paper requires more insulation layers than in the thickest practical layup defined here. This means that the heating profile of the reference trajectory is too high for this FTPS design to be used. Nevertheless, it could still be adapted for future Mars entry missions with the following steps:

- Use a silicon carbide fabric outer layer, such as Hi-Nicalon. This can sustain a higher outer layer temperature than Nextel 440 BF-20 and will reject more heat through radiation, as its emissivity is higher than that of Nextel 440 BF-20.
- Use a higher-temperature gas barrier. Increasing the design limit of the gas barrier above 200 °C would allow fewer layers of insulation to be used. A maximum temperature between 300 °C and 400 °C is suggested for the PTFE-coated Zylon fabric used as the gas barrier in the LOFTID FTPS [3].
- Optimise the entry trajectory for FTPS use (a silicon carbide outer layer could enable a steeper entry with higher peak heat flux but shorter overall duration and lower total heat load).

7. FUTURE DEVELOPMENT AND CONCLUSION

A subscale breadboard will now be manufactured, consisting of a 2 m diameter FTPS blanket and stacked toroid inflatable model. This will allow the main challenges of manufacturing a complete FTPS to be identified and possible solutions trialled, leading to an optimised manufacturing process that could be tested on full-scale models. The completed FTPS will be integrated with the inflatable decelerator model and used for basic packing and deployment tests in an ambient ground environment. Possible folding methods will be trialled and compared.

During this project, FTPS candidate materials have been identified and the most promising subjected to extensive mechanical and thermal testing. Manufacturing techniques have been trialled for all materials, allowing an end-to-end FTPS manufacturing process to be proposed. The knowledge gained has increased the capability for FTPS design and manufacture in Europe. The methods developed in the current project may be adapted in the future for the higher-temperature performance materials needed to achieve Mars entry FTPS.

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