

An Overview of Technical Textiles for Spacecraft Parachutes

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Materials selection is carefully considered in spacecraft parachute design to ensure parachute objective success, as evidenced by parachute systems used on Orion and the Mars Exploration Rover. Parachutes must be lightweight and flexible for packing, capable of rapid inflation, and strong enough to handle significant tensile loads. Both common and unique materials are used in textile applications on spacecraft parachutes to meet these challenging demands. This paper provides an overview of the technical textiles used on spacecraft parachutes. Materials used as textiles will be identified, with their common industry term noted, chemical composition, and structure explained. Materials reviewed will include polytetrafluoroethylene, aliphatic and aromatic amides, polyethylene terephthalate, and poly(p-phenylenebenzobisoxazole). The steps of manufacturing a textile will be addressed for fibers, yarns, and finished textile products. The textile construction methods to produce finished products will be reviewed including weaving, and cord construction. Finished products and potential applications in parachutes will be considered for woven fabric, cords, and webbing. Specific examples will be given for the Orion and Mars Exploration Rover parachutes to demonstrate the importance of materials science in successful parachute design.

<i>CPAS</i>	=	Capsule Parachute Assembly System
<i>LCP</i>	=	liquid crystal polymer
<i>MER</i>	=	Mars Exploration Rover
<i>MPIA</i>	=	poly(imino-1,3-phenyleneiminoisophthaloyl)
<i>PBO</i>	=	poly-p-phenylenebenzobisoxazole
<i>PET</i>	=	polyethylene terephthalate
<i>PPTA</i>	=	poly(imino-1,4-phenyleneimino-carbonyl-1,4-phenylenecarbonyl)
<i>PTFE</i>	=	polytetrafluoroethylene
<i>UV</i>	=	ultraviolet light

I. Introduction

NASA has used parachutes for many spacecraft programs as early as the Mercury program and most recently the Artemis program on the Orion crew module [1, 2]. A parachute system's design is tailored to its environment and vehicle; parachute systems can be used to return crew to Earth from space but can also be designed for extraterrestrial landings. Examples of NASA parachute extraterrestrial landings include the Viking program, Mars 2020, and the Mars Exploration Rover (MER), all landing on Mars to further scientific exploration and discovery [3, 4]. Human spacecraft rated parachutes and exploration mission parachutes face unique and shared challenges, but ultimately flexible, lightweight, high strength, technical materials are needed for spacecraft parachute applications. Careful assessment of material structure, properties, and processing can help inform material performance in a parachute assembly.

High performance textiles are critical for spacecraft parachute applications. Different materials are selected for specific applications within a parachute assembly. When selecting materials, specific material properties may be maximized or minimized. Strength is often a property that is attempted to be maximized, while mass is attempted to be minimized. Materials selection and evaluation consider the weighted trade between various properties. Specific materials may be particularly suitable for specific applications with a parachute assembly. For example, polytetrafluoroethylene (PTFE) may be selected as a liner material on deployment bags due to the low coefficient of

Trade names are used in this presentation for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

friction associated with PTFE. High strength materials, such as para-aramids are used on suspension lines to withstand heavy loads. Nylon can be used as canopy material for its high strength and high elongation [5].

II. Composition and Structure

A. Materials Tetrahedron

The fundamental materials science tetrahedron can be mapped to materials selection for parachute design. Material structure considers chemical composition and orientation. Examples of material structure include chemical name and relative position of a substituent. Material processing considers methods to alter a material. Examples of processing methods for textiles include heat, plasma, and UV radiation treatment [6, 7]. Material properties are often heavily evaluated and weighed when selecting materials. Material properties can be intrinsic where material properties do not change on sample mass and size, such as density, Young's Modulus, specific heat capacity, and color. Material properties can also be extrinsic, where mass and size do impact properties, such as heat capacity and spring stiffness. For designs involving textiles, material properties of finished textile products are often used to inform materials selection. For parachutes, cord strength and stiffness would typically be evaluated when assessing material suitability with design requirements instead of assessing fiber strength and stiffness with design requirements. Together, material structure, processing, and properties inform material performance and suitability to design requirements. Figure 1 displays the fundamental materials science tetrahedron. Outlined is an example material and how it fits into the tetrahedron. The example material is poly [(4-hydroxybenzoic)-ran-(2-hydroxy-6-naphthoic acid)], trade name Vectran.

- Overview of Vectran [7, 8]**
- **Structure**
 - poly [(4-hydroxybenzoic)-ran-(2-hydroxy-6-naphthoic acid)], a liquid crystal polymer that is highly ordered, aromatic and rigid
 - **Processing**
 - Heat treatment of the fiber increases crystallinity
 - **Properties**
 - Thermal stability, chemical resistance, low elongation
 - **Performance**
 - Strong, stiff, highly resistant to creep

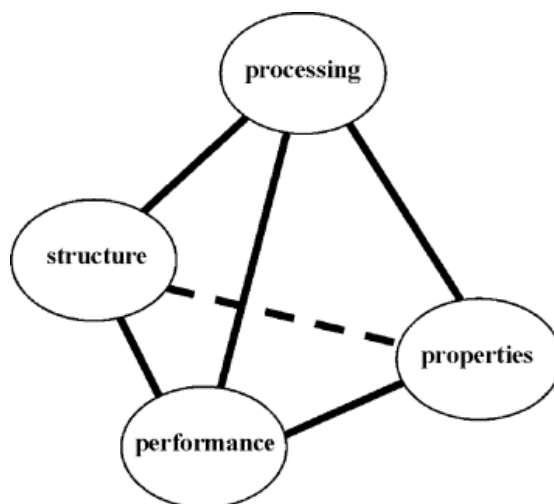


Figure 1: Materials Science Tetrahedron [9]

B. Composition and Structure

An overview of spacecraft parachute textile materials is provided below. Figures 3-8 depict the chemical structure of the materials.

Polyamides

An amide is a chemical functional group, identified by a carbon atom double bonded to an oxygen atom and a single bond to a nitrogen atom. An amide functional group within a monomer for a polymer to be a polyamide. Polyamides can be subsequently divided into groups: aliphatic and aromatic. Aliphatic is a straight chain polymer, aromatic is a cyclic chain with delocalized π electrons [10]. The term aramid is commonly used to describe aromatic polyamides. The structure of a polyamide impacts properties and performance. Aliphatic chains can rotate more freely, resulting in a polymer that has greater elongation and flexibility compared to aramids. The term polyamide is often used to describe nylon, and nylon is an aliphatic polyamide. Specific nylons (for example nylon 6,6 versus nylon 6) will have different properties based on monomer size. Aromatic polyamides are less flexible and more rigid due to the presence

of aromatic rings, resulting in high material strength. Further orientation can impact polymer identity and performance. Figure 4 shows the chemical structure for a meta-aramid and para-aramid. Amide linkages for meta-aramids are on the 1,3 positions of benzene, while for para-aramids, the amide linkages are on the 1,4 positions of benzene. Aramid usage in parachute systems is occasional for meta-aramids and common para-aramids [11]. The International Union of Pure and Applied Chemistry (IUPAC) names for these materials are poly(imino-1,3-phenyleneiminoisophthaloyl) (MPIA) and poly(azanediyl-1,4-phenyleneazanediylterephthaloyl) (PPTA). Trade names referring to these structures are Nomex and Kevlar respectively [12]. The high strength of PPTA makes it an excellent candidate for parachute applications. PPTA is a rigid rod lyotropic liquid crystal polymer (LCP). The high strength comes from the rigid, linear nature of the polymer chain, which promotes π - π bonding between chains, creating a stacked polymer [11]. PPTA also has hydrogen bonding present at the amide linkage, allowing a small degree of rotational freedom, but less than MPIA. Meta-aramids are not as linear, resulting in a lower strength material compared to para-aramids. PPTA and MPIA may be sensitive to ultraviolet light (UV) and discoloration may be observed. Careful assessment of application and storage conditions should be considered prior to implementation.

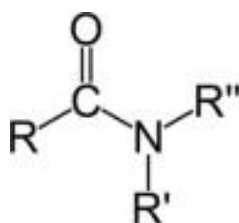


Figure 2: Amide Bond Structure [13]

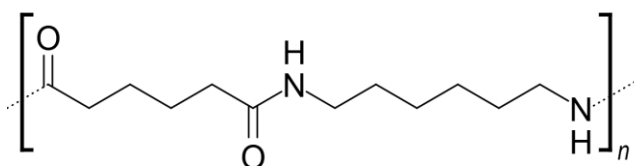


Figure 3: Nylon 6,6 Structure [14]

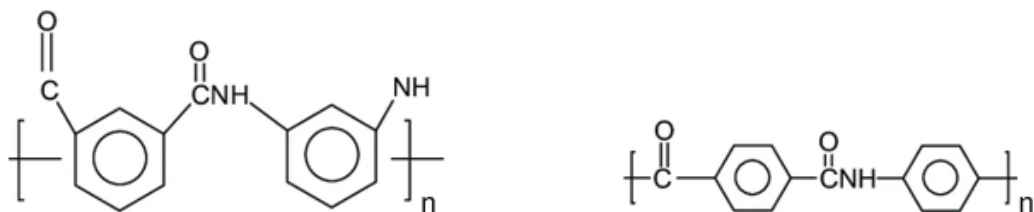


Figure 4: Aromatic Polyamide Structures, Meta-aramid (left) Para-aramid (right) [12]

Poly(p-phenylene-2,6-benzobisoxazole (PBO)

Poly(p-phenylene-2,6-benzobisoxazole (PBO) is commonly referred to as Zylon, the commercial trade name for PBO by Toyobo. It is a synthetic rigid-rod lyotropic liquid crystal polymer heterocyclic aromatic polymer [13]. The benzobisoxazole is bonded to benzene. The aromatic structure results in a highly ordered, planar orientation. Although not fully aromatic (parts of chain are only conjugated), the aromatic components of PBO can allow some extent of π - π bonding, promoting densely packed chains [14]. The highly ordered orientation of the polymer backbone chain allows load to be transferred along the polymer chain, resulting in high strength. PBO has a higher specific strength compared to PPTA due to it having less rotational freedom than PPTA, resulting in a stiffer, stronger chain. However,

it should be noted that PBO is extremely sensitive to UV light, heat, and moisture, more so than PPTA. This is due to the chemical structure. Although PPTA and PBO are both lyotropic LCPs, and both can be sensitive to the acid residuals that remain after fiber manufacture, PBO is more sensitive to hydrolysis than PPTA due to its heterocyclic ring (benzoxazole). Moisture and heat promote the release of residual acidic manufacturing byproducts which acts as a catalyst to hydrolysis of the benzoxazole ring, promoting chain scission of the polymer. PBO is also sensitive to surface photo-oxidation degradation during UV exposure again due to the benzoxazole ring [13]. For these reasons, PBO should be carefully evaluated if selected as a material for use. Strict protocols for storage procedures, assembly operational life, and cycle life may be required to ensure PBO is not significantly negatively impacted by light, heat, or moisture. See Footnote 1 on Page 7 for further discussion.

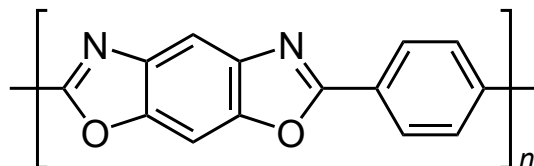


Figure 5: PBO Structure [15]

(Poly)ethylene Terephthalate (PET)

(Poly)ethylene terephthalate is commonly called polyester (example trade name includes Dacron by INVISTA) [16]. It is a synthetic polymer created by the condensation reaction of ethane-1,2-diol and benzene-1,4-dicarboxylic acid linked by an ester bond. [17]. The aromatic portion of the monomer in polymer form imparts strength and thermal stability and the alkylene linkage of the monomer in polymer promotes conformational chain flexibility. Chain flexibility impacts melt processability; PET is a highly melt processible polymer making it a popular material for textile and plastic film applications. PET is susceptible to degradation through the ester linkage via hydrolysis or thermal oxidative, or photo oxidative degradation [13, 17]. For applications where a parachute may be reused multiple times over a long chronological period, performance should periodically be assessed to confirm that the material still meets margin requirements.

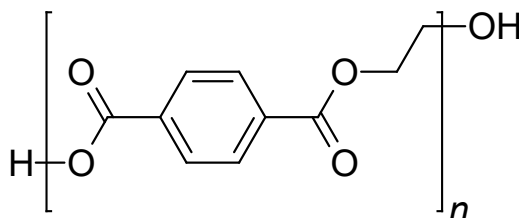


Figure 6: PET Structure [18]

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (PTFE) is commonly called Teflon (trade name specific to The Chemours Company) [19]. It is a synthetic, organic homopolymer. PTFE has a carbon-carbon backbone of pendant groups are carbon-fluorine [20]. Carbon-fluorine bonds are strong and short due to the high electronegativity of fluorine. The highly electronegative nature of fluorine creates a linear polymer; the fluorine acts as a sheath surrounding the carbon backbone resulting in low polymer surface energy and coefficient of friction. The strong carbon backbone and fluorine sheath for PTFE create a slippery, but relatively weak in tension material. The slippery nature of the fluorine sheath allows polymer chains to slide against each other, rather than transferring load [20].

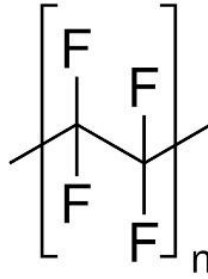


Figure 7: PTFE Structure [20]

III. Manufacturing of Textiles

A. Fiber and Yarns

Raw materials and processing steps are needed to produce fibers. Textile fibers can be produced using multiple methods, including melt spinning, wet/solution spinning, and dry/solvent spinning. The method selected must be compatible with the polymer. Melt spinning is where polymer is melted and extruded through a spinneret. The polymer will cool and solidify, forming fiber. Wet solution spinning is where the polymer is in solution (dope) and extruded through a spinneret into a chemical bath. The desired polymer precipitates out of the solution into the chemical bath, forming fiber. Dry/solvent spinning is where a polymer is in solution and extruded through a spinneret. The product is dried, removing the solvent and leaving behind polymer fiber [21]. PPTA and PBO are both lyotropic LCPs and Vectran is a thermotropic LCP [7, 12, 13].

Fibers are drawn to a specific thickness. The drawing process utilizes rollers to orient the polymer chain within the fiber along a central axis. This process ultimately increases strength of the fiber. Fibers can then be bundled together to create yarn. Yarn may be single ply or multi-ply, such that multiple yarns are twisted together [22]. Degree of yarn and ply twist can impact strength of a material. Significant study has been performed for the effect of twist on polymer performance. Further information can be found in Aramid Yarn as a Tensile Member in Products [23]. Fiber drawing and yarn twisting are examples of how material processing can affect performance.

B. Finished Product Construction

Examples of finished textile products include cords and woven fabrics; both commonly used in parachute system applications. Examples include suspension lines for cords and canopy fabric for woven textiles [24].

Single or multi-ply yarn can be converted into cord using a braiding machine. Different braiding patterns and materials can be used to make a multi-material cord. Figure 9 depicts a diagram of the components that go into a cord. Cord size, twist, braiding pattern and material can be tailored to meet specific performance needs of the cord. In addition to this, cord can be hollow or solid. Hollow cord may have helpful mass and manufacturing benefits, while a solid core could have higher strength. Note that yarn location is typically specified by a carrier number, which is the position of the yarn in relation to the cord on the braiding machine. As such, carrier is also a common term used when discussing cord construction [22].

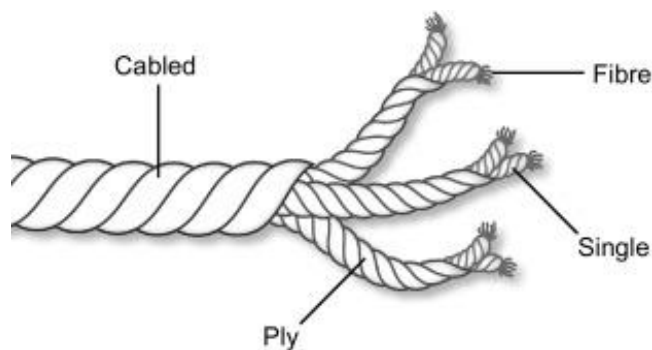


Figure 8: Cord Construction [25]

Unlike cords which are uniaxial in construction, woven fabrics are biaxial in construction. Fabric is woven by interlacing yarns at right angles. The warp direction runs along the length of a fabric; the weft direction runs along the width of a fabric. The biaxial nature of the woven fabric makes it such that it could be constructed to be isotropic or anisotropic. Figure 10 depicts a ripstop weave pattern and a plain weave pattern. Ripstop uses heavier yarns in a grid structure to contain tear propagation if a tear were formed in the fabric [22]. In a parachute assembly, this helps keep damage incurred during flight localized. Plain weave is the simplest weave pattern, with an under-over pattern. Broadcloth is a type of plain weave, using an extremely tight weave to make a smooth and “silk-like” fabric. Nylon ripstop and broadcloth have both been used in spacecraft parachute applications [24]. Material performance for parachute canopies must consider strength, damage tolerance, and porosity. Porosity as a fabric property will not be discussed in this paper, but the Knacke design guide may be consulted for further information of fabric porosity [5].

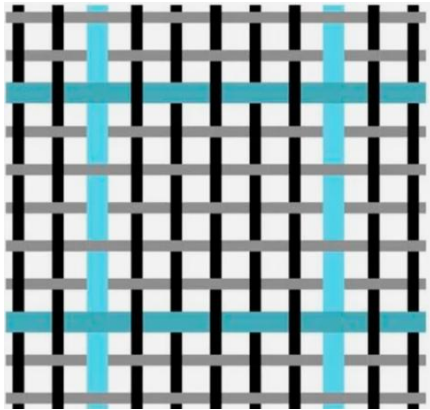


Figure 9: Ripstop Fabric Construction [26]

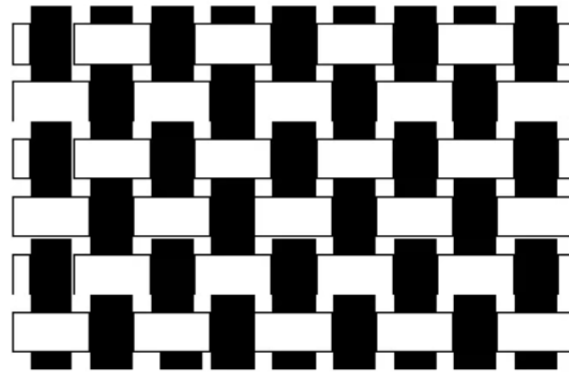


Figure 10: Plain Weave Fabric Construction [27]

IV. Spacecraft Applications

The Orion spacecraft crew module vehicle is part of the Moon to Mars architecture for “long term human led scientific discovery” [28]. The Orion Capsule Parachute Assembly System (CPAS) is designed to safely return the Orion crew module and the astronauts inside it back to Earth from space. Examples of documented textiles used on CPAS are described below [24, 29].

Forward Bay Cover- Kevlar
Drogue Parachute- Kevlar and nylon
Reefing Line Cutter Lanyard- Kevlar
Main Parachute Canopy- Nylon broadcloth



Figure 11: Orion CPAS Drop Test [30]

The Mars Exploration Rover (MER) parachute decelerator system was designed to slow the descent of exploration rovers Spirit and Opportunity [31]. MER. Documented textiles used on the MER parachute are described below [32].

Deployment Bag Canopy-Vent Band Attachment- Kevlar webbing
Deployment Bag Liner- Teflon fabric
Canopy Disk- Nylon, Mil-C-7020 Type I (Nylon 6,6 ripstop fabric)
Canopy Band- Polyester fabric
Suspension Lines- Kevlar cord

PBO was evaluated as a material for MER parachute applications, however it was found that it “appears to exhibit significant degradation due to pressure packing/heat sterilization”.¹ [32]

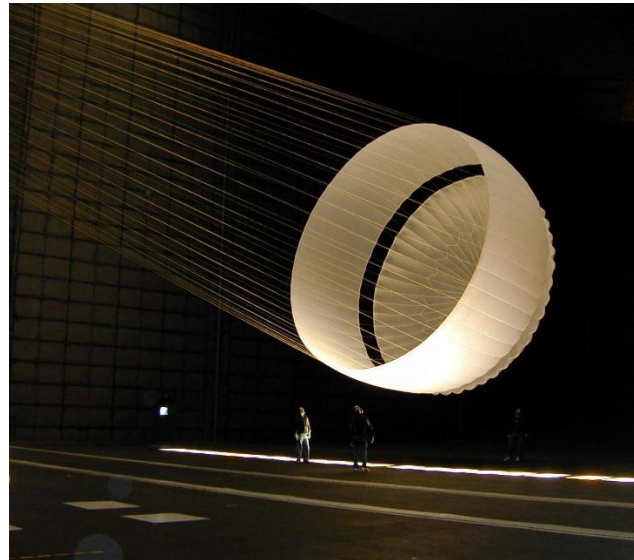


Figure 12: MER Parachute Deployment Testing [33]

V. Conclusion

Textile materials can be evaluated at various levels including chemical composition and structure, material and bulk textile processing and construction, material and bulk textile properties, ultimately impacting material and assembly performance. Materials selection is crucial to spacecraft vehicle parachute design. Technical textile evaluation and selection for parachutes on spacecraft vehicles including Orion and the Mars Exploration Rover ensure system level requirements including strength, mass, and inflation characteristics are met for demanding applications.

¹ At the time of the referenced paper’s publication for MER parachutes, PBO was used in body armor vests for impact resistance. Thousands of vests were recalled due to failure to protect wearers. Failure was attributed to body heat and sweat promoting accelerated degradation of the PBO [34]. Additional materials characterization of PBO has occurred since the recall. Although PBO is rarely used in body armor today, it is used in spacecraft applications, notably on SpaceX Crew Dragon Mk3 parachutes. Refer to Lessons Learned during SpaceX Crew Dragon Main Parachute Development and Testing for further information [35].

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