Fire-resistant Textile Development for Exploration Vehicles with Enriched-Oxygen Cabin Environments

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Material selection is a key part of the National Aeronautics and Space Administration (NASA) spacecraft fire safety management plan. Non-flammable textiles are necessary to ensure large-scale flame propagation events do not occur inside a spacecraft. An increased use of textiles and other softgood material is crucial to the pursuit of exploration spaceflight to reduce mass and volume. Exploration spaceflight missions benefit from enriched oxygen cabin environments (>21% O_2) by allowing a reduced prebreathe protocol before Extravehicular Activity (EVA). However, materials become exponentially more flammable the higher the O_2 levels become. Recent testing within the agency has revealed the lack of commercial-off-the-shelf (COTS) materials that can meet safety requirements in oxygen-enriched environments. Most of the fibers and textiles developed during Apollo (100% O_2 cabin environment) and Skylab (>70% O_2 cabin environment) are no longer commercially available due to those Programs ending and the discontinuation of raw materials or closure of the original manufacturers. As NASA returns to higher oxygen concentrations inside spacecraft, non-flammable textile development efforts have begun to meet the agency's needs. This paper discusses those efforts including overall fire safety approach, priorities, interactions with industry, flammability testing and expected challenges.

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I. Introduction

IN 2021, a memorandum was issued by the Deputy Associate Administrator, Human Exploration and Operations (HEO) Systems Engineering & Integration to establish a common habitable atmosphere across human exploration atmospheres [1]. The atmosphere for operation on the lunar and Martian surfaces was designated as a total pressure of 8.2 psia and a 33.7% volumetric fraction of O_2. The goal was to reduce flammability risk while minimizing the time needed for prebreathe before extravehicular activities (EVA), considering the short missions planned for the lunar surface. This atmosphere is a significant departure from the current habitable volumes of other current NASA crewed vehicles, which maintain an essentially Earth atmosphere, and has serious implications for flight materials currently in use. In 2024, at the issuance of Revision B to the Moon to Mars Architecture Definition Document, Non-flammable Materials, Additives, Coatings for Habitable Volumes were listed as an architecture-driven child gap and was included in the overall gap of fire safety upgrades for surviving exploration mission environments, indicating that the need for development of fire-resistant textiles persists [2].

It is worth mentioning that Artemis is not the first program with an enriched O_2 atmosphere. Human space exploration in the Apollo Program started in 100% O_2-rich environments and Skylab was operated at >70% O_2-rich environments. In these environments, materials that aren't normally considered flammable will easily ignite and propagate flame much more rapidly than they would do in Earth atmosphere.

Textiles have been historically used in many space applications, commonly known as softgoods, because of their lightweight and flexible nature. However, textiles are known to have a flammability risk due to their inherent construction and material flammability property, as evidenced by the United States (US) Flammable Fabrics Act and the several National Fire Protection Association (NFPA) standards for textile flammability [3, 4, 5, 6, 7, 8]. Nonetheless, fire-resistant textiles are used as a hazard control to protect more flammable materials from ignition. Fire-resistant textiles are also necessary to protect against large-scale flame propagation events.

Historically, the development of fire-resistant textiles for the Apollo Program was initiated after the fatal Apollo 1 cabin fire. The most probable ignition source was identified as electrical arcing of wires carrying spacecraft power. The environment was 100% O_2 atmosphere at 16.7 psia, 2 psia above standard sea-level atmospheric pressure, which is more than five times the 3-psia (21-kPa) partial pressure of O_2 in the Earth atmosphere.

As NASA proceeds toward Artemis missions that will use high-oxygen cabin environments (>30% O_2 volumetric fraction), there is significant need for improved fire-resistant textiles. Advancement in the area of fire-resistant textiles for design of in-cabin softgoods will inhibit flame propagation in high O_2 atmospheres and ensure mission safety in the event of fire. Now, the agency focus is on certifying textiles for use in 34% O_2 plus a 3% margin, resulting in a target of 37% O_2. Nevertheless, the new exploration atmosphere is a significant departure from the current habitable volumes of other current NASA crewed vehicles and other programs like International Space Station (ISS), which maintain an essentially Earth atmosphere and has serious implications for flight materials currently in use. Now, the current ISS mission relies mostly on Kevlar®, Nomex®, Vectran™ and hybrid blends for making nonclothing softgood applications such as acoustic blankets, cargo transfer bags (CTBs), webbings and sleeping bags. On the other hand, for clothing applications, cotton shirts are widely used for next-to-skin shirts. Most of the commonly used fabrics on ISS in their current form may not be usable in the new exploration atmosphere due to the increased oxygen concentration.

In the agency effort to address this technical gap for the first Artemis missions planned for the lunar surface, textile and materials engineers have tested a significant number of textiles, both individually and in material layups that correspond to specific applications. Overall, the testing efforts in the last three years found limited existing commercial off-the-shelf (COTS) textiles that can be certified for use in up to 37% O_2. This can be attributed to the fact that most of the fibers and textiles developed during Apollo and Skylab are no longer commercially available due to those programs ending and the discontinuation of raw materials or closure of the original manufacturers. Moreover, commercial development of textiles with high flammability performance beyond 21% O_2 is not typically economical due to the limited customer base. The fire service market using high-performance textiles spans clothing for firefighters, police and military. It also includes non-wearable applications like fire barriers on commercial airplanes and in batteries. While these markets are strong, textiles for use in the extreme exploration atmosphere is a niche market since the increased performance to 37% O_2 is not required in commercial applications.

Given the fact that fire-resistant textiles are a key part of the fire prevention strategy that includes materials selection and as NASA returns to higher oxygen concentrations inside spacecraft, efforts have begun for the development of in-cabin textiles needed for the exploration atmosphere on the lunar and Martian surfaces. The focus is on reducing the highest risks first and considering the development paths with the highest potential for success in meeting flammability and application requirements. This paper discusses those efforts including overall fire safety approach, priorities, interactions with industry, flammability testing and expected challenges.

II. Experimentation and Testing

NASA-STD-6001 Test 1 (Upward Flame Propagation) is currently being used to evaluate and certify the flammability of materials intended for use in habitable environments of spacecrafts by NASA [9]. In this test, a vertically oriented specimen (typical size 2.5 inch x 17 inch) is exposed to a chemical ignitor flame at its bottom for approximately 25-30 seconds. The test is performed in a closed 1400 – liter chamber with a controlled O_2 concentration and pressure representative of spacecraft conditions. The passing criteria specify that no specimen of the five required test specimens burns more than 6 inches, and no test specimen propagates a flame through the transfer of burning debris. Moreover, the test can be done as a single setpoint test or a maximum oxygen concentration (MOC) test. When performing a single setpoint test, the test specimen is placed at a set O_2 concentration and pressure; five consecutive samples were tested to verify whether the material passes the test at the set atmosphere. This test evaluates whether a material can be certified for flight use at a specific atmosphere. When performing an MOC test, the test chamber pressure is set and the O_2 concentration is incrementally increased until the sample fails the test; the MOC is the maximum O_2 percentage at which the test material can pass the test. A higher MOC value indicates the material is more fire-resistant.

The typical test configuration is Standard Edge Ignition. This is the most conservative method of testing where the sample is oriented vertically and ignited on the bottom edge. This test configuration is suitable for all materials, especially composites or hard panels, but may be unrealistically severe for textile type of material because raw edges of textile typically are not directly exposed in softgoods assembly. In cases like a tether or tie-down strap, where the edge of the textile will be directly exposed to the environment, this test configuration is recommended.

For most of the textile materials, which will be used as part of a softgoods assembly, a “J”-configuration” is more frequently used. In this set up, test specimen is oriented vertically with a “J” shaped bend at the bottom. The ignitor is placed at the bottom of the “J” to ignite surface of the specimen. This set up allows a fully vertical upwards flame propagation without igniting the sample edge. Additionally, a metal fixture can be used to shield the vertical edges of test specimen when materials are not anticipated to have exposed side or bottom edges in use configuration. This test is suitable for non-metallic materials that don’t have any exposed raw edges in usage applications. When using this set up, additional verification on seam configurations is needed.

Interestingly, testing has revealed the complexities of flammability at the exploration atmosphere which have been captured in a memo issued by Dr. Emily Hacopian, NASA Cross Program Flammability Subject Matter Expert in July 2024 [10]. In summary, the memo cautioned that materials may be more flammable in the as-used configuration and care must be taken in interpreting test results. Recent coupon-level flammability testing at 37% O_2 shows a difference in propagation with configuration and layup testing as compared with single material tests (unpublished data). This means the combined performance of textile components (i.e., zipper, thread, hook and loop), rather than just the outermost layer, must have good fire resistance performance. For example, a Polytetrafluoroethylene (PTFE) woven fabric was tested at 36% O_2 and passed the test with less than 6 in char length with no drip or melt but failed in a layup configuration with a cotton fabric as seen in Figure 1. The two pieces of material were placed one on top of the other. It can be seen that both materials burned through even though the PTFE fabric is less flammable than cotton.

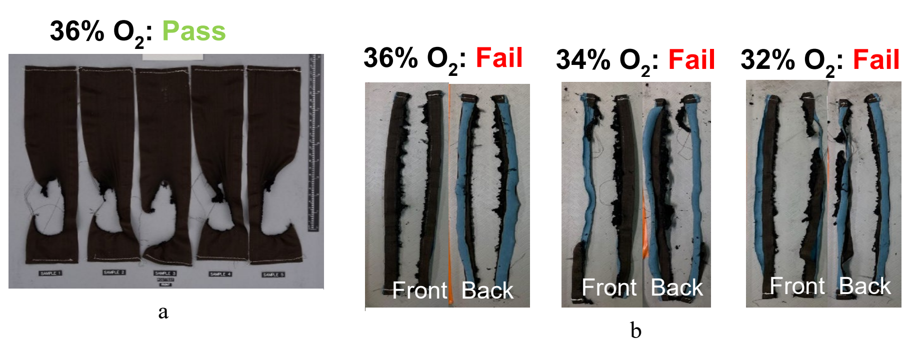

Figure 1. (a) PTFE woven fabric individually tested at 36% O_2 8.2 psia; (b) PTFE woven fabric with cotton (blue color) layup configuration tested at 36% O_2 8.2 psia.

Overall, recent testing revealed very few textiles capable of passing NASA-STD-6001 Test 1, the standard NASA test for flammability, at 37% O_2 and 8.2 psia and even when textiles do pass by themselves, they may not pass in configuration with other textiles as described above. For hardware to be used as a fire hazard control during flight to protect flammable materials from ignition, e.g. CTB, passing Fire Barrier Effectiveness Testing in addition to Test 1 is a mandatory requirement. In this light, it is worth mentioning that the development of Fire Barrier Effectiveness method is currently on going. For the next section, several solutions that have already been developed by the textile engineering and development team to meet NASA-STD-6001B Test 1 at 37% O_2 will be discussed.

III. Results and Discussion

Since the agency has begun to explore and adopt additional materials, new fire-resistant materials have been introduced to crew clothing, sleeping bags and CTBs. These softgood products will be used for the first time on the coming Artemis missions. In this context, the textile engineering and development team has been sourcing existing COTS textile products, modifying COTS textiles and developing custom fire-resistant solutions that meet NASA flammability requirements at 37% O_2 and 8.2 psia. The summary of this effort can be outlined below:

A. COTS products solutions:

1. Crew clothing outer jacket and pants

Crew clothing refers to the specialized apparel and daily attire astronauts wears inside spacecraft cabin during mission. It typically includes jacket, T-shirts, pants, etc. Since the cabin atmosphere is the same as earth atmosphere, current ISS crew clothing use polyester/cotton for daily wear and polyester/nylon for exercise clothing. Crew pants, for example, are composed of 65% polyester and 35% cotton coated in Teflon for stain and wrinkle resistance. They have multiple pockets, both zippered and with hook/loop closures to contain small items on-orbit. Due to the increased oxygen concentration for exploration atmosphere, most of the softgoods currently used on ISS will not be usable for Artemis missions.

The basis for the design and fabrication of the new crew clothing was to produce crew garments that maximize agility, comfort and functionality while meeting flammability standards in a high oxygen environment. The top property of concern after flammability was offgassing which can be problematic for applications in the closed spacecraft interior environment, where low toxicity is critical for crew health. Accordingly, the fabric selected for the fabrication of crew clothing was first tested for flammability and offgassing respectively in accordance with NASA-STD-6001 Tests 1 and 7 where it showed a passing flammability performance at 37% O_2 and low volatile and toxic compounds emission [9]. Besides flammability and offgassing, there are also unique sets of requirements for fabrics used for crew garments such as soft handfeel, comfort and lightweight. These features were deemed critical when different crew clothing fabric candidates were evaluated. The evaluation results showed that a commercially available fabric product made of a blend of para-aramid, meta-aramid and antistatic fibers can be a suitable candidate for developing outer garments like jacket and pants. Moreover, the flammability testing results revealed that the fabric passed NASA-STD-6001B Test 1 at 37% O_2 individually. Afterwards, the same fabric was tested in multiple seam and zipper configurations similar to what to be found in the final garment. An example for passing flammability testing results of a meta-aramid tape / brass teeth zipper configuration made a with commercially available PTFE sewing thread is shown in Figure 2. Although this fabric performed well in flammability testing and is an adequate candidate for short-duration outer garments, for long-duration missions (>9 days) a lighter, softer and more flexible fabric candidate would be desired.

2. Cargo Transfer Bag

CTBs are softgoods containers used to stow, transport and protect hardware and supplies during mission. On the ISS, CTBs have been used extensively for decades and are typically fabricated from meta-aramid and polyester materials.

In oxygen-enriched spacecraft environments, CTBs represent a unique fire safety challenge because they also serve as a fire hazard control to protect flammable content inside the bag from ignition and prevent large fire propagation when exposed to external ignition sources. As a result, in addition to flame propagation testing per NASA-STD-6001B Test 1, fire barrier effectiveness testing is conducted to verify that the CTB materials provide sufficient protection to internal contents when exposed to an external ignition source. Beyond fire performance, CTB materials must also be strong, durable, light weight, and available in multiple color options to support operational and human-factors requirements. This poses unique challenges in finding the suitable textile materials for CTB in oxygen enriched environments. The current CTB construction approach consists primarily of a multilayer construction, including an outer and inner woven fabric layer sandwiching a felt layer. For the woven fabric, multiple fabric candidates are under evaluation, including para-aramid, meta-aramid and antistatic blend fabrics, 100% meta-aramid fabrics, and polybenzimidazole (PBI)/Kevlar® blend fabrics. For the felt layer, a range of materials is being assessed, including oxidized polyacrylonitrile (OPF), polyimide, silica, polyetherimide, and various blended constructions.

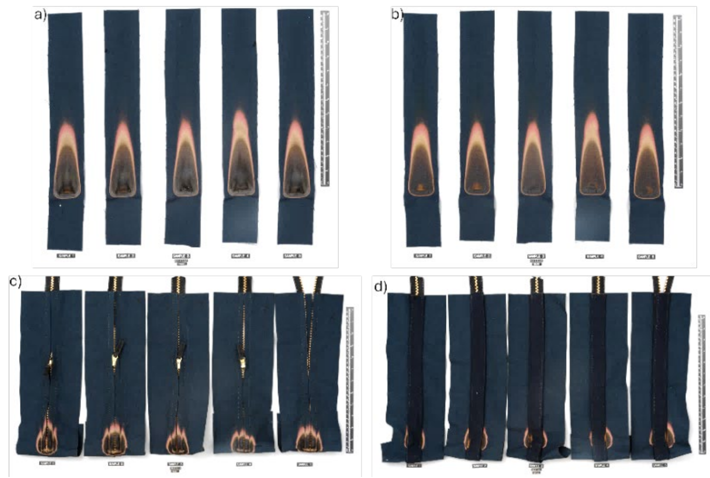

Figure 2. Crew clothing fabric individually tested at 37% O_2 8.2 psia, (a) front side and (b) back side. Crew clothing fabric with zipper assembly tested at 37% O_2 8.2 psia, (c) front side and (d) back side.

It is of prime importance, to emphasize that flame propagation and effective fire barrier performances aren't the only criteria to be taken into consideration during the CTB layup material down selection. Dimensional stability, minimal foreign object debris (FOD) and the final CTB weight optimization are also among the considerations during the development of CTBs. Given the large number of CTBs manifested on certain missions, even modest increases in individual bag mass can result in a significant system-level weight increase. As such, the ongoing CTB material development effort seeks to balance fire safety performance with mechanical robustness and mass efficiency to meet the unique demands of oxygen-enriched spacecraft cabin environments.


Figure 3. ISS 3rd Generation CTB Size 0.5.

3. Sleeping Bag

Similarly, the textile engineering and development team is currently in the process of developing fire-resistant solutions for a sleeping bag that meets NASA flammability requirements at 37% O_2 and 8.2 psia. The current sleeping bag used on ISS has attachment loops made from Nomex® to securely tie-down the sleeping bag to multiple attachment points found inside the cabin using Vectran™ braid cord. Further, the sleeping bag has an outer layer made from Nomex® and the inner layer is made from a replaceable cotton layer that can be secured with hook and loop. Moreover, the ISS sleeping bag has a head strap for head restraining and there is a pillow pocket that can be stuffed with soft items to create support. Additionally, there are arm and foot slits for improved air flow and for allowing excess body heat and moisture to escape.

The fire-resistant sleeping bag fabrication approach mainly focuses on solutions that include a suitable layup with a soft and comfortable interior, a covered COTS narrow woven elastic webbing to be employed as a head restraint, and alternative fire-resistant attachment loops and braid cord. In this context, the textile engineering and development team is currently partnering with different vendors to manufacture a braid cord capable of meeting NASA flammability requirements at 37% O_2. Kevlar® EXO™, Poly-p- phenylenebenzioboxine (PBO), PTFE and Silicone-coated fiberglass are among the braid cord materials assessed in the ongoing material down selection effort. For braid cord, additional properties need to be considered to meet load requirements.

B. Developed flame resistant textile solutions:

4. Crew clothing next-to-skin shirt

Through the ongoing development effort, the textile engineering and development team partnered with vendors to create a custom 100% PBI yarn and knit fabric to be used for next-to-skin crew T-shirt. The selected yarn spinning vendor specializes in high-performance fiber spun yarns used for the fire service and safety protection markets in addition to having a unique capability of worsted spinning. Through various trials, another vendor successfully knitted the 100% PBI spun yarn into a soft, comfortable and relatively lightweight 1x1 rib fabric that was tested and has passed MOC testing at 48% O_2 and 8.2 psia as shown in Figure 4.

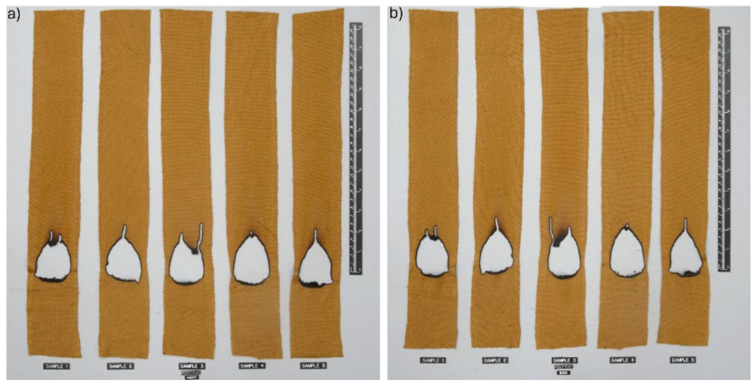

Figure 4. 100% PBI knit fabric MOC testing at 48% O2 and 8.2 psia, (a) front and (b) back.

The new PBI T-shirt is to replace the ISS cotton next-to-skin shirts that are not suitable from flammability standpoint for the coming Artemis high oxygen concentration missions. In addition to the outstanding flammability performance, other reasons that make PBI material a good candidate for next-to-skin clothing are good handfeel, soft touch and high moisture absorption. However, PBI drawbacks are low fiber tenacity and reduced durability, leading to a high tendency for pilling and lower abrasion resistance.

5. Fire-resistant Patches

Special fire-resistant sewn-on patches (e.g. NASA logo, American Flag and crew name tag) were also developed. This effort was deemed necessary as the patches used currently by NASA's different programs are made using a Pellon™ polyester fabric and a thick polyurethane layer. A fire-resistant topical treatment was applied to the existing patches; however, it did not pass Test 1 at 37% O2 and 8.2 psia. Another effort involving printing patches using ink on fire-resistant fabrics was completed but also did not pass the flammability requirement. Custom, fire-resistant patches were developed through a vendor using a multilayer stack of Polyimide felt, 100% meta-aramid fabric and meta-aramid embroidery thread. The patches were sewn to the crew clothing outer jacket fabric with PTFE sewing thread and passed Test 1 at 37% O2 8.2 psia as depicted in Figure 5.


Figure 5. Custom fire-resistant patches sewn to crew clothing outer jacket fabric at 37% O2 and 8.2 psia.

C. Fire-resistant Textile Strategy Approach:

In November 2022, the Exploration Atmosphere Issue Resolution Team (ExAtm IRT) was created after concerns about the challenges of operating at O_2-rich environments were raised to the agency management level. The ExAtm IRT worked on finding the balance between many competing mission variables such as vehicle atmosphere, flammability, decompression sickness risk, suit pressure and EVA duration. As a result, the NASA Engineering and Safety Center (NESC) was requested by the ExAtm IRT to establish an assessment and develop a multi-program strategy for the development of high priority nonflammable textiles for softgoods applications within the cabin at a minimum of 37% O_2 at 8.2 psia. Programs such as Human Landing System (HLS) and Extravehicular Activity and Human Surface Mobility Program (EHP) can use these textiles to design hardware that inhibits flame propagation in enriched O_2 and to ensure mission safety in the event of a fire. The NESC assessment was not completed at the time of the abstract submission therefore it is not mentioned, however, the methodology, findings and strategy are detailed in this paper to provide context for how the fire-resistant textile gaps are being addressed.

Accordingly, the NESC team divided the assessment plan into four main tasks:

- Identify stakeholders that require O_2 enriched environments and collect stakeholder data including key performance and safety parameters/metrics
- Determine material requirements, applications and program priorities
- Comprehensively assess the NASA and industry current state of the art and opportunities for fire-resistant textiles
- Develop a prioritized strategy and implementation plan.

Stakeholders were broadly defined as anyone with input into the priorities of the strategy. The team considered the project and program personnel from the areas of flight operations, health and medical, softgoods, textiles, O_2 and systems engineering. These stakeholders were queried during in-person meetings. Objectives included identifying the possible applications in the cabin, identifying the needed material properties for those applications and discussing top priorities for softgoods and textiles. The data was used to capture the comprehensive in-cabin textile needs at elevated O_2 for NASA. Textile priorities were evaluated by considering how many applications use that textile, how much area or linear feet are used in the cabin, whether an adequate solution already exists, the impact to flammability risk, whether the textile is needed for government furnished equipment (GFE) and whether the textile or the application using that textile was identified as a stakeholder concern. The resulting priority list was divided into Tier 1, a group of higher priority textiles and Tier 2, a group of lower priority textiles.

For the state-of-the-art investigation, it was accomplished by textile subject matter experts (SMEs) who used their own knowledge, a review of Department of Defense (DoD), academic and textile association fire-resistant technology developments, a contracted technology search; trade shows and approximately 30 vendor domestic visits to understand the best-available fire-resistant products for a range of textiles. The textile development that occurred during the Apollo and Space Shuttle time periods was also reviewed to understand the textiles still available today and identify resources used in the past. It is worth mentioning that over 100 vendors were first identified as participants in the supply chain. The NESC assessment team held a discussion with each vendor and followed up with brief interviews of a reduced list to determine initial capability and interest in having a face-to-face meeting. The team down-selected to approximately 30 high potential textile manufacturers in the US for on-site visits. The primary consideration in determining whether a mill was suited for spaceflight textile manufacturing was the textile capability of the vendor. This capability was determined using a combination of the company's market sector industrial scale and their equipment versatility and R&D interests. The ability to provide a low minimum order quantity (MOQ) was also considered.

Finally, the NESC team generated a strategy for developing new fire-resistant textiles in O_2-enriched environments that could be separated into three phases for each individual textile:

- Phase 1: Baseline Testing of Available COTS Products
  - The purpose of baseline testing is to evaluate and confirm whether COTS materials are available that can be certified for use at 37% O_2/8.2 psia for each textile. Certification testing will be performed at White Sands Test Facility (WSTF)
- Phase 2: Incremental Improvement over COTS Solutions
  - Based on Phase 1 testing, if no COTS solution can meet NASA-STD-6001B Test 1, but a relatively low effort can be done to modify the COTS and increase the chance of passing, it is recommended to pursue the incremental improvement/modification on the COTS solution and assess the performance again.
- Phase 3: Custom Textile Development
  - Based on Phase 1 testing, if no COTS solution can meet NASA-STD-6001B Test 1 and it is not possible to do incremental improvement over COTS solutions, a custom major development effort is required with an industrial partner to design and develop a suitable solution that can meet NASA's specific needs.

At the end of each phase, a decision will be made whether to continue to the next phase. All phases will not be executed for all textiles. The first phase may be skipped if there are no COTS products available for the textile or the available COTS products have already been tested. The second phase may be skipped if there is no method known to modify a COTS product to meet requirements or a method has been identified and is in use. The third phase may not be executed if there is no industrial partner willing to work with NASA on a particular textile or the need has been satisfied by the first two phases.

IV. Future Work and Conclusions

Fire-resistant textiles will remain a critical priority for the Agency as NASA seeks to reduce mass and volume in exploration vehicles with enriched oxygen environments of up to 37% O_2 at 8.2 psia. NASA's textile engineering and development team has made meaningful progress by identifying suitable commercial off-the-shelf (COTS) materials and advancing new textile developments to address urgent fire-resistant softgoods needs, including crew clothing, cargo transfer bags and sleeping bags. NASA's textile engineering and development team has made meaningful progress by identifying suitable commercial off-the-shelf (COTS) materials and advancing new textile developments to address urgent fire-resistant softgoods needs, including crew clothing, cargo transfer bags and sleeping bags.
However, further material optimization is required to ensure durability, reliability, and performance for extended-duration exploration missions. To address these gaps, the NESC has recently completed an agency-wide assessment and developed a multi-program strategy for the development of high-priority nonflammable textiles for softgoods applications. The next phase of this effort will be the execution of the NESC's three-phase strategy, beginning with Tier 1, highest-priority textile systems, to systematically mature materials that enable safer and more sustainable human exploration missions.

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