Artemis Suit Material Project Overview

Robert J. Jones[1]
Leidos / KBR HHPC / NASA Johnson Space Center, Houston, TX, 77058

Shane McFarland[2]
Aegis Aerospace / KBR HHPC / NASA Johnson Space Center, Houston, TX 77058

Stephanie Rodgers-Ahnen[3]
Textile Made, Inc., Howell, MI 48843

and

Richard Rhodes[4]
NASA Johnson Space Center, Houston, TX 77058

This paper presents an overview of an ongoing NASA technology infusion project aimed at designing, fabricating, and testing a new outer shell fabric for a lunar Extravehicular Activity (EVA) space suit, crucial for sustained lunar exploration. Historically, fabrics such as Beta cloth (Apollo missions) and Ortho Fabric (used on the current Extravehicular Mobility Unit, EMU) have provided essential protection in space. However, both materials have been found to be inadequate for long-duration lunar missions due to challenges posed by the lunar environment, particularly abrasive lunar dust, and cryogenic flexibility. The goal of this project is to develop a more robust and dust-resistant fabric suitable for sustained lunar surface operations as part of NASA's Artemis program. The scope is multifaceted, and a broad overview will be presented here. Detailed results including down selection and test data are planned to be presented in a future publication. The project's methodology includes evaluating commercially available textiles and coatings to better inform the design and development of a bespoke fabric solution to better meet the stringent requirements for lunar EVAs. This paper will focus on the approach taken to develop a set of comprehensive requirements that guide material selection, testing, and validation. These requirements encompass protection against dust infiltration, thermal regulation, durability, and flexibility to name a few. Initial development involves a thorough vetting process of existing, commercially available materials, coupled with the evaluation and evolution of new technologies, to produce a high-performance fabric capable of sustaining prolonged exposure to the lunar environment. The insights gained from this research will inform future development cycles and play a critical role in advancing EVA suit technology for long-term lunar exploration.

Nomenclature

AML	=	Advanced Materials Laboratory
ASM	=	Artemis Suit Materials
BOL	=	beginning of life
COTS	=	commercial off-the-shelf
DOE	=	Design of Experiment
DVT	=	Design Verification Test

[1,2,4] Space Suit Engineer, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.
[3] Textile Engineer, Textile Made, Howell, MI.

EMU	=	Extravehicular Mobility Unit
EOL	=	end of life
EPG	=	Environmental Protection Garment
EVA	=	Extravehicular Activity
GCR	=	Galactic Cosmic Rays
LEO	=	Low Earth Orbit
LOI	=	Limiting Oxygen Index
MMOD	=	Micrometeoroid and Orbital Debris
mSv	=	milli-Sieverts
NESC	=	NASA Engineering and Safety Center
PSR	=	Permanently Shadowed Regions
SEM	=	Scanning Electron Microscopy
STS	=	Space Transportation System
TMG	=	Thermal Micrometeoroid Garment
UV	=	Ultraviolet
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

The overarching goal of the NASA's Artemis Suit Material (ASM) Project conducted by the Crew and Thermal System Division Advanced Suit Team, is to develop enabling technologies and potentially a turnkey solution for the outer shell fabric of a lunar suit environmental protection garment (EPG). Because the EPG is a composition of multiple delicate fabrics and films, the entire assembly is shielded by an extremely durable outer cover shell layer which provides much of the protection. Undoubtedly, the two most challenging EPG requirements answered by the design of the outer fabric involves providing protection from the abrasive regolith and ability to function in an extreme temperature environment. Unfortunately, neither condition has readily available solutions from the commercial market.

During Gemini and before the Apollo 1 fire, NASA began looking at a new fireproof material made by Owens Corning called Beta Cloth.[1] After the Apollo fire occurred, NASA began implementing material replacement tasks to switch to Beta Cloth where possible including the outer covering of the space suits.[2] It was selected because it was believed that it "possessed sufficient durability to last through the mission."[3] However, post inspection of Apollo EVA suits revealed that the Beta Cloth experienced significant damage from abrasion considering the relatively short time it was exposed to the lunar terrain.[4]

After Apollo, NASA began preparing for the Space Transportation System (STS) Shuttle program. Updates included the design of a new extravehicular activity (EVA) space suit made from new materials. After receiving the contract to build the EMU in 1974, Hamilton Standard and ILC Dover delivered the first Extravehicular Mobility Unit (EMU) to NASA in 1982.[5] The EMU is protected by the thermal micrometeoroid garment (TMG) which is constructed with an outer-shell layer called Ortho Fabric. Ortho Fabric has performed admirably throughout its use in various space applications, demonstrating exceptional durability and resilience. To the knowledge of the authors, there have been no reported instances of cuts, punctures, tears, or cracking due to exposure to cold temperatures, highlighting its reliability in the low Earth orbit (LEO) environment. However, while this environment does require high performance textiles to offer protection, the lunar terrain presents new challenges. Previous tests utilizing lunar simulants have shown that Ortho Fabric has significant deficiencies in dust repellency and abrasion resistance, concluding that it will not meet the required dust mitigation and abrasion resistance standards[6].

Because there is not a readily available solution, it is the intent of this paper to outline the essential tools required to select the components of a bespoke fabric in a bottom-up approach specifically designed to meet the demands of lunar exploration. It begins with an analysis of the Apollo Beta Cloth and EMU Ortho Fabric, highlighting their desirable properties and explaining why they fall short for sustaining lunar missions. Next, it continues with an explanation of the methodology followed for this effort for the selection of the raw material, yarn, and yarn systems, which are crucial for the fabric's performance and durability. Finally, it concludes with initial insights into Ortho Fabric evaluations, completed for baselining and requirement definition, and plans for future fabric development and testing. This project is funded by the Technology Integration and Partnerships Office of the EVA and Human Surface Mobility Program (EHP) at Johnson Space Center, mail code DT.

II. Background and Challenges

A. Lunar environment

One of the primary requirements the outer shell fabric must address is to possess exceptional durability against abrasion, wear, tears, punctures, and cuts ensuring its resilience and its ability to protect the pressure garment in the challenging lunar terrain. The most significant hurdle lies in the ubiquitous lunar regolith, which levitates upon disturbance and settles on surrounding objects due to the moon's weak gravity and absence of an atmosphere. The unattenuated effects of solar rays and solar wind create a changing environment which causes the dust particles to become charged[7] and adhere more readily to suit materials. It is ubiquitous in that the entirety of the moon's surface is covered with it. The regolith dust, sharp in nature, remains unweathered by winds and lacks the oxidation process that occurs on Earth[8]. Therefore, it can easily scratch, tear, or pierce fabrics. Consequently, the imperative need for covers that are highly resistant to regolith penetration becomes paramount. Moreover, the lunar environment is scattered with larger rock fragments and debris, posing a significant cut and puncture threat to the space suit if it is not adequately safeguarded.

The second condition that drives the design of the fabric is in its ability to function at extreme temperatures. Due to limited exposure to the sun at the Lunar south pole, Artemis mission temperature requirements are more challenging on the extreme lower end. The Artemis lunar surface requirements state that EVA suits must be capable of withstanding temperatures from 260°F (127°C) to –280°F (–173°C) for 8 hours. Additionally, suits must withstand conditions in permanently shadowed regions of the lunar south pole for up to 2 hours where temperatures can reach as low as -243C (30K). As polymer-based fabrics and coatings become colder, they tend to stiffen, lose stretchability, and become more brittle.[9] A stiff outer fabric could significantly impair suit mobility, making it difficult for astronauts to perform tasks effectively. Similarly, a brittle coating could crack as the suit bends and flexes during movement, potentially compromising the integrity of the thermal and environmental protection layers. Therefore, the outer fabric must not only provide ultra-low-temperature flexibility but also maintain its structural and functional integrity under these extreme conditions to ensure astronauts can move and work effectively in the lunar environment.

Although not as extreme, high-end temperatures (+260°F [126°C]) must be considered as well. When fabrics are exposed to elevated temperatures, several changes can occur depending on the type of fabric and its composition.[10] One synthetic fiber, ultra-high molecular weight polyethylene, which is renowned for its exceptional strength to weight ratio at ambient temperatures, melts at 130°C, which underscores the importance of testing and mitigating fiber exposure to elevated temperature if required.[11]

Other lunar environment hazards include micrometeoroid and orbital debris (MMOD) impacts and extreme exposure to ultraviolet (UV) and ionizing radiation. MMOD refers to tiny particles, such as micrometeoroids (small meteoroids) and orbital debris (human-made debris), in outer space. MMOD protection is crucial because even tiny particles traveling at high velocities in space can cause damage to a space suit or, in extreme cases, harm an astronaut. Therefore, this is an additional design driver for the outer fabric as it generally means it must be tightly woven with a high-end count and high tenacity fibers to mitigate potential MMOD hazards.

The effects of UV radiation on outer suit fabrics are another hazard. Because the Moon has no atmosphere to shield it, it receives unattenuated galactic and solar radiation. This solar radiation does not cause radioactivity. However, long term exposure has been shown to cause significant changes in optical and mechanical properties for various materials.[12] The EPG layers and particularly the outer layer fabric must resist these effects and remain durable over hundreds of hours of UV radiation exposure without a reduction in functionality.

B. Current State of the Art (Beta Cloth and Ortho Fabric)

As previously mentioned, Beta Cloth (reinforced with Teflon) was utilized as the outer shell fabric for the Apollo EVA suits (see Figure 1). Beta fiber, made from glass, was selected by NASA as the primary material for flexible fibrous structures because it was noncombustible in a 100-percent oxygen atmosphere up to 16.5 psia (Apollo capsule environment). It also met requirements for outgassing, toxicity, odor, and crew comfort.[13] Because it is made from high-purity glass, it is classified as an inorganic material (not carbon based) and therefore has dimensional stability through changing temperatures and is resistant to breakdown from solar and ionizing radiation.[14] Additionally, when woven tightly, the glass fibers are capable of resisting degradation due to atomic oxygen which is present in LEO.[15]

In 1974, NASA awarded a contract to ILC Industries for the development of an inexpensive, lightweight, TMG.[16] Part of the effort was to design a new shell layer to replace the Teflon and Beta cloth shell fabric used for the Apollo suits. ILC recommended that the shell layer be a special blend with a goal weight of 10 oz/yd^2, a breaking strength of 180 lbf/in, a tear strength of 20 lbf/in, abrasion resistance better than 7 oz Nylon, a flex life of 100,000 cycles and that it be non-burnable or self-extinguishing. It was suggested that the blend be a combination of Teflon, Kevlar, and Beta fibers in a double, or triple cloth or a French back. The term "blend" was later replaced with Ortho. A Nomex called "Durette" was suggested to replace the Beta because of its flame resistance.

Ortho Fabric is a two-layer fabric with an outer face comprised of 400 denier Gore-Tex (W.L. Gore & Associates) and an inner face of 200 Denier Nomex (Dupont) and 400 denier Kevlar® (DuPont) (see Figure 1). It is a six-harness fabric created using a loom with six harnesses that allows the creation of its intricate "split basket" style weaving pattern. It also utilizes a fancy draw (warp and weft yarns manipulated to create a textured pattern). Ortho Fabric is made by a company called Fabric Development Inc., based in Quakertown, PA.[17]

It was designed to protect the EMU in low Earth orbit, and its constituent fibers were selected because they met LEO requirements (flammability at 30 percent O_2 at 10.2 psi, outgassing, abrasion resistance, temperature resistance). It was designed to provide abrasion, tear and micrometeoroid protection while maintaining the required surface optical properties for space suit thermal control.[18] This fabric can withstand temperatures from −300° to +300°F (−184.4° to 149°C). The outer Gore-Tex layer provides both abrasion resistance (because it has a low coefficient of friction), and thermal protection (because it reflects most of the Sun's thermal radiation due to its bleached white color).

Figure 1. Beta Cloth (Top) and Ortho Fabric (Bottom). Beta Cloth was a single layer fabric made from Beta fibers coated with Teflon. Ortho Fabric is a double layer cloth with a face side composed of Gore-Tex slit film yarn.

C. Need for Innovation

Beta cloth was chosen because it excelled in meeting numerous requirements but proved difficult to work with, required additional finishes for manufacturing and post mission inspect showed that it degraded from regolith abrasion considering its relatively short duration of exposure. First, the fabric was difficult to assemble into a garment.[19] It was difficult to manipulate in the machines because of the fragile glass fibers, which tended to crack when sewn and flexed. Care had to be taken in handling and new manufacturing procedures, such as using a chalk bag to mark patterns verses a pencil, were invented to prevent degrading the fabric.

Next, to weave the cloth, silicone oil had to be applied to the fibers to keep them together. The oil had the unfortunate side effect of making sewn seams in the fabric pull out easily. To overcome this, seam edges were coated with cement to bond the fibers together. Also, the glass fibers were fragile, which drove the need for additional finishes to maintain integrity. The woven fabric surface was initially coated with Teflon to help reduce fiber damage, but this reduced tear strength. This was later resolved by applying the coating to individual yarns before weaving but was costly and required a significant amount of processing to get it into a workable form.

Finally, Beta Cloth was also not durable enough for a sustaining lunar presence. Post Apollo, scanning electron microscopy (SEM) analysis was performed on the outermost soft fabric layers of Apollo 12 and 17 TMGs and the outermost fabrics on Apollo 17 EVA gloves.[20] The dirtiest areas of the suits were examined for contamination, abrasion, and wear or loss of function. It was found that while it was able to meet mission requirements for durability in that the suits did not fail during EVA, it was noted that the duration of exposure was relatively short, and the inspection revealed that the fabric was degraded severely considering length of use. Fibers were frayed and broken, and the lunar dust was embedded in the weave.

Ortho Fabric, while easier to produce than Beta Cloth and more durable, also needs improvement if used on the Moon. It was designed for EVA suit protection in low Earth orbit, a less severe environment than the Moon. As mentioned previously, Ortho Fabric has significant deficiencies in dust repellency and abrasion resistance. This is largely due to the weave's openness, with interstices as large as 70 microns,[21] and the known abrasion issues of its fiber materials, Gore-Tex and Nomex. Testing conducted during this effort has shown that Ortho Fabric loses 40 percent of its tensile strength, 58 percent of its elongation, 48 percent of its tear strength and 17 percent of its thickness when exposed to NASA's custom rotary tumbler abrasion test for 8 hours. It was also found to allow 165 g/m^2 of lunar simulant (NU-LHT-4M) to pass through it in the same test.

The limitations of both Beta Cloth and Ortho Fabric highlight the urgent need for a bespoke fabric specifically designed for sustained lunar surface operations. Such a material must address the deficiencies in dust abrasion resistance, dust infiltration, and mechanical durability while also being compatible with garment manufacturing processes. The ideal solution should combine tightly woven structures with advanced coatings or treatments to improve flexibility, tear strength, and dust mitigation, especially under extreme lunar conditions. This effort represents a critical step forward in developing robust, mission-ready fabrics capable of supporting long-term exploration on the Moon as part of NASA’s Artemis program.

III. Project Goals and Overview

A. Project Goals

The ASM Project aims to develop enabling technologies, and potentially a turnkey solution, for a lunar suit vendor's EPG outer shell fabric. Its goal is to design a durable, flexible, and radiation-resistant fabric that mitigates dust and performs across extreme temperatures, enabling long-term lunar exploration. The project focuses on defining lunar-specific requirements, combining optimal fibers, coatings, constructions, and treatments, and creating a clear roadmap for fabric development. It also addresses supply chain options and scale-up challenges to transition from prototype to full-scale manufacturing.

B. Development Framework Overview

The fabric development framework follows a structured approach to designing a high-performance lunar outer shell fabric. The process begins with identifying commercially available high-performance fiber and yarn options through trade studies, market research, existing test data, and team experience. Past space suit fabric development efforts are examined to determine lessons learned and identify best test practices to incorporate into this effort. A baseline fabric is established and it, along with other high-performance commercial off-the-shelf (COTS) fabrics are subjected to lunar like exposure and tested for degradation. Candidate yarns are procured from vendors and tested for strength, abrasion, and UV resistance. Performance gaps are identified and are addressed by combining yarns, tweaking fabric construction, or adding coatings. These enhancements are then tested to verify performance improvements. Identifying and designing the optimal fabric structure is completed via trade studies and prototype fabric testing supported by a design of experiments (DOE) approach. Potential COTS or custom coatings and laminate layers are evaluated through trade studies and supported by test data. Consultations with industry experts in advanced fabric construction and coatings are leveraged to ensure state-of-the-art practices are applied. Prototype fabric systems are rigorously tested against design requirements, with iterative improvements made as necessary. Finally, the process advances toward replacing COTS fibers and yarns used for prototyping with custom extrusions and blends, scaling up manufacturing, and establishing a robust supply chain to support suit vendors in delivering a final, optimized solution.

IV. Detailed Methodology

A. Trade Studies

Building a custom textile is a non-trivial task, due to the combination of factors that must be considered. Fabric construction has many variables that could be altered to meet the entire set of final requirements. When considering multiple factors, NASA typically utilizes a trade study which is a systematic approach for comparing multiple factors against a set of requirements. A trade study is NASA’s common language for any exploratory research & development exercise and decision making.[22] The development framework put forth in this report utilizes the trade study approach which includes several down-select stages, weighing the priorities at each, testing to confirm, and then iterating to achieve a final best result.

The trade studies for this effort begin with a market survey of available fibers and yarns. This survey identifies potential options and is further refined through testing of selected COTS materials and products, primarily sourced from military or commercial applications and available in fiber or fabric form, with a preference for plain weaves when possible (most commonly available type and allows for more direct comparison). Trade studies 1 through 3 focus on collecting performance data and leveraging research insights to narrow down the top fiber, yarn, and textile options, while identifying performance gaps (e.g., a yarn may excel in strength and abrasion resistance but lack UV resistance) which are carried forward to the next part of the development. Down selects are based on which materials come closest to satisfying all the project requirements. Trade 1 is focused on raw material selection, Trade 2 on yarn selection, and Trade 3 on textile construction.

Trades 4 through 7 address the performance gaps by exploring innovative combinations of yarns and coatings, ultimately fabricating a prototype solution for evaluation. In the development of high-performance fabrics, it's often unlikely that a single fiber type can satisfy all requirements. Each fiber type has strengths and weaknesses, which makes it challenging to find one that offers the necessary combination of durability, UV resistance, abrasion resistance, flexibility, and strength. Consequently, the solution space includes options such as combining different yarns in a single cloth, using a double cloth structure, adding ripstop yarns, blending yarns to mitigate deficiencies inherent to any one yarn type and or adding coatings and film laminates.

For example, Ortho Fabric strategically combines multiple fibers to balance its performance properties. It incorporates Gore-Tex fibers on the surface for UV resistance and optimal optical properties, providing a protective barrier against sunlight and environmental factors. Beneath the Gore-Tex layer, Nomex and Kevlar fibers serve as the core structural components. Nomex contributes strength and heat resistance, while Kevlar, used in a ripstop pattern, offers exceptional tear resistance, reinforcing the fabric's integrity. This strategic weaving and fiber layering in Ortho Fabric serves as a guide for this effort, illustrating the benefits of a multi-fiber, multi-layered approach to meet the rigorous demands of space exploration.

To this end Trade studies 4 through 6 focus on modifying down selected COTs yarns and blending them into prototype fabric structures based on identified gaps in current performance. These modifications and combinations aim to address these gaps, moving closer to a final solution that meets the requirements. The final Trade 7 is conducted to verify that combined yarns and weave structures perform as expected and give consideration for manufacturing scale-up and strategies for strengthening the supply chain.

B. Requirement Development

The ASM project includes the critical task of establishing a requirement set for the shell fabric capable of withstanding the demanding environment. While some flow-down requirements from the Exploration Extravehicular Mobility Unit (xEMU) development were available—such as tolerance to temperature extremes, radiation exposure, and specific optical properties (refer to ICES-2022-265 for further discussion)—other requirements unique to the shell fabric itself had yet to be defined. These include tensile strength, elongation, cut, puncture, tear and abrasion resistance, cryogenic flex fatigue, dust permeability, surface/volume resistivity, absorptivity, emissivity, dust adhesion at vacuum, off-gassing, out-gassing, cryogenic stiffness, thickness, weight, flammability, tribocharging, and MMOD/ejecta.

Given the uncertainty surrounding exact mission parameters, a decision was made to establish a baseline for comparison to set expectations and monitor advancements made by iterative improvements. In cases where flow-down requirements were unavailable, the baseline fabric performance, combined with the performance of other leading COTS fabrics, informed the initial definition of threshold and goal values for performance metrics which can be updated through the duration of the project.

While Beta Cloth was initially included as a benchmark, it failed the NASA rotary tumbler abrasion test, revealing insufficient durability for *sustained* lunar applications making it unsuitable for further comparison. In contrast, Ortho Fabric successfully survived the rotary tumbler test, albeit with measurable degradation. Ortho Fabric was detailed earlier in this paper and will also be discussed further in Section V, where its key merits and weaknesses are outlined. Post-lunarlike environment strength metrics indicate a substantial decline in performance, highlighting areas for potential improvement in future fabric designs. Its selection as the baseline is rooted in its status as a highly established material within the EVA community and its proven track record on the EMU space suit.

Ortho Fabric's performance not only provided a critical reference point for comparison but also heavily influenced the requirement values for the new lunar fabric. Its durability, thermal resistance, and abrasion performance set the minimum thresholds that any new material must meet or exceed. By using Ortho Fabric as a baseline, the trade studies ensure that the next-generation lunar fabric leverages the successes of past materials while addressing their limitations to meet the unique challenges of the lunar environment.

In addition to establishing a baseline, it was recognized that the requirements needed to account for a fabric's condition at both the beginning of its life (BOL) and its end of life (EOL). The EOL condition reflects a degraded state after prolonged exposure to the lunar environment, including abrasion, UV exposure, and extreme temperatures. Therefore, a given requirement also includes the fabric condition that it must be met at (i.e., tensile strength must be met at its EOL condition, or after exposure to 8-hour tumbler abrasion at vacuum, 500* equivalent Sun hours of UV/ionizing radiation and at worst case temperature extreme). This is discussed further in Section V.B.

C. Market Survey and Trade Study 1 Results

The initial market survey and Trade Study 1 are focused on defining potential fiber types. Various types of raw materials can be spun or extruded into yarns for textiles, broadly categorized into natural fibers, synthetic fibers, and inorganic fibers.

Organic natural fibers come from both plant and animal sources, each offering unique benefits and drawbacks. However, plant-based fibers can be prone to wrinkling, shrinking, and, in some cases, lack durability compared to synthetic fibers. A common drawback of animal fibers is their susceptibility to damage from moths, as well as a tendency to require more care in cleaning and maintenance. Additionally, both plant- and animal-based fibers may lack the durability and moisture resistance of synthetic options, limiting their use in high-performance or harsh environments.

Organic synthetic fibers are made from polymers derived from petroleum or natural gas, processed, and spun into versatile, high-performance fibers. Known for their strength and lightweight nature, fibers like nylon, polyester, acrylic, and spandex are widely used in applications ranging from clothing to industrial products. One of the key advantages of synthetic fibers is their customizable nature; during manufacturing, characteristics such as strength, elasticity, and thermal properties can be tailored to meet specific needs. However, synthetic fibers like nylon and polypropylene are more susceptible to UV degradation, which can limit their use in prolonged sunlight without added UV stabilizers.

High-performance fibers like Vectran, Kevlar, and Nomex represent a specialized class of synthetic fibers known for their exceptional strength, durability, and resistance to extreme conditions. These fibers are engineered for specialized environments where conventional synthetic fibers may fall short, providing essential protection, stability, and durability in extreme conditions.

Inorganic fibers are derived from non-living materials, primarily minerals or non-carbon-based compounds. They are recognized for their high strength, thermal stability, and resistance to chemicals, which makes them ideal for high-performance applications. Non-combustible and resistant to heat, these fibers are particularly suited to environments that require flame resistance or high thermal stability. Additionally, these fibers tend to have excellent UV resistance due to the absence of carbon-hydrogen bonds, which are typically susceptible to UV degradation. As a result, they are often used in applications needing structural reinforcement, insulation, or high resistance to UV exposure. However, inorganic fibers are generally more brittle than organic ones and therefore not generally suitable for flexing applications. Each type of raw material brings unique characteristics to the yarns and textiles produced, influencing their application.

For this effort, 83 raw materials were identified, some naturally occurring organic and inorganic and some synthetic. Examples include acetate, bamboo, basalt, carbon, ceramic, hemp, nylon, rubber, and spandex. previous efforts to investigate EPG outer fabrics have focused on a very small list of “space-rated” filament fibers which were included within the list.

A stop light chart was used to conduct Trade Study #1. A stoplight chart is a visual tool used in trade studies to easily disseminate rankings and assess various options using color codes. The three colors–green, yellow, and red–represent different levels of performance or suitability, making it straightforward to interpret the results briefly and easier to communicate decision making verses assigning more detailed levels via numerical ranking. Using this stop light chart approach provides an easy method to quickly convey which fibers are best suited for the project needs, which ones might be acceptable with some reservations or need additional testing, and which can be down selected early narrowing the trade space.

For this project, a separate indicator or notation was used when the performance was unknown, in this instance white. This denoted that further investigation was required. This ensured that stakeholders were aware of the uncertainty and could prioritize actions to fill the knowledge gaps before making down select decisions. For fibers where the performance for a particular requirement was unknown, additional research, consultation, benchmarking, or testing was conducted.

The stoplight chart trade for this effort concluded that the following list of raw materials are likely to meet many of the EPG requirements. High-level pros identified gaps in meeting lunar requirements, and unknowns were noted and are carried into the next trade study. They are divided into two groups, chemical compositions that have been used previously in space suit applications and those that have not. The intent is to convey whether the chemical composition of the fiber type has heritage and is a known entity or is a novel solution that has yet to be included. Note that some fiber types may have been used in other space applications (i.e., radiation blankets, solar sails) but because of the high degree of flexibility required for space suits in particular, the list was divided accordingly.

Fibers currently or previously used in space suit applications:

- Fluoropolymers (FEP/PTFE (Teflon®) /ePTFE (Gore-Tex®)/TFE)
- Aramid (Kevlar® 29/49)
- Liquid Crystal Polymer (Vectran™, PBO/Zylon®)
- Heterocyclic Polymer (PBI)
- Polyimide (P84®/Kapton®)
- Glass (Beta Cloth/Fiber Glass/Silica)
- Ultra-high molecular weight polyethylene (Spectra®, Dyneema®)
- Meta-aramid (Nomex®)
- Metallic/Chromium (Chromel-R)

Novel fibers not previously used in space suit applications:
- Liquid crystal polymer (Tullomer™)
- Aramid (Twaron, Kevlar® KM2+, Kevlar® EXO)
- Natural fibers and Inorganic Minerals (Basalt, Ceramic, Carbon)
- Ceramics (Nextel, Quartzel)
- Electrostatically dissappative (Bekaert, Negastat, Shieldex, Shakespear)
- Carbon Nanotube (Dexmat Galvorn)

D. Testing Framework

Building on a previous fabric evaluation conducted by the NASA Engineering and Safety Center (NESC) (refer to ICES-2023-37, ICES-2024-50, and ICES-2024-52) aimed at identifying suitable replacement fabrics for Artemis EVA gloves, ASM is expanding the protocols established for gloves for use in evaluating fabrics for the entire suit shell fabric. The core objective of the DOE is to expose COTS and prototype fabrics to lunar-like conditions, assess degradation using standard ASTM tests when applicable, compare results to an established baseline, and make informed decisions on the selection of yarn types, sizes, end counts, weave types, and coatings.

Similar to the NESC effort, the ASM team found no existing test capable of simultaneously replicating all lunar conditions—such as abrasion, flexing, temperature extremes, UV exposure, and vacuum—and it was beyond the project's scope to develop one for fabric level testing. Instead, individual tests are conducted to simulate each environmental factor separately, allowing for a more detailed understanding of the effects of each condition in isolation. This approach makes it easier to identify specific vulnerabilities, with the assumption that independent testing is acceptable if certain factors do not significantly interact.

Once a fabric of interest is identified, it is brought inhouse to NASA JSC's Advanced Materials Lab (AML). It is sectioned into specimen sizes and quantities specified in the various ASTM test standards. Once the fabrics have been conditioned to ASTM D1776, baseline strength and physical property testing is conducted via the following: tensile/elongation (ASTM D5035), tear (ASTM D2261), cut (ASTM F2992), puncture (ASTM F1342), thickness (ASTM D1777), mass (ASTM D3776), air permeability (ASTM D737), emissivity (ASTM E408), absorption (ASTM E1775), abrasion (ASTM D4966), thermal conductivity (ASTM C177), and stiffness (ASTM D4032). Resistance

Figure 2. Rotary Abrasion Tumbler (Left), Cryo Cut Resistance Test (Center), Hot Cut Resistance Test (Right). These tests are designed to condition fabrics with abrasion caused by rock and dust as well as temperature extremes to study the fabrics durability.

to abrasion from dust and rock and extreme temperatures have been identified as the two primary requirements that make fabric design for the lunar environment uniquely challenging, so the initial COTS testing has largely focused on these conditions. After baselining, the fabric is then subjected to a custom rotary abrasion test that exposes the face of the fabric to abrasion by continuously moving lunar simulant (NU-LHT-4M/CSM-LHT-1) and ceramic tumbler media (see Figure 2). The tumbled panels are removed, divided into specimen shapes, and again measured for strength and properties. Changes are recorded and compared to reveal trends in durability. The tumbler test also provides a method for measuring the fabrics ability to shed dust and prevent dust from penetration. Before and after mass and optical properties measurements are used to quantify the amount of simulant that remains embedded in the fabric after cleaning with a brush and vacuum.

Cut resistance testing at extreme temperatures is conducted which is also based on work completed during the NESC fabric evaluation previously mentioned (see Figure 2). That effort, detailed in ICES-2024-52, focused on developing a method based on ASTM 2992-23 to cryogenically cool fabric specimens with liquid nitrogen prior to cutting. Building on that premise, the ASM team developed a method to heat the fabric on the cut test apparatus to 120°C prior to cutting allowing the assessment of a fabric's cut resistance and if it increases or decreases because of temperature change.

Out-of-house testing has been established with several specialized facilities to evaluate the performance of materials under extreme conditions relevant to lunar environments (see Figure 3). These facilities provide critical capabilities for testing properties such as tensile strength, flexibility, tear resistance, puncture resistance, and stiffness across a wide range of temperatures, including both elevated and cryogenic conditions.

Precision Measurements and Instruments Corporation (PMIC) is equipped to perform a variety of mechanical evaluations, including tensile, tear, puncture, and stiffness testing. Notably, these tests can be conducted at both elevated temperatures of up to 120°C and cryogenic temperatures as low as –190°C (83K). This capability is essential for assessing material performance under the thermal extremes.

The University of Illinois at Urbana-Champaign's Department of Materials Science and Engineering offers advanced cryogenic tensile testing of fabrics using both liquid nitrogen and liquid helium. They have successfully tested fabrics at temperatures of –190°C (83K), –226°C (48K), and –297°C (30K), providing valuable data on material behavior at temperatures in lunar permanently shadowed regions (PSR). Their expertise in cryogenic testing ensures precise and reliable results, which are integral to material selection and design refinement.

Textile Made is utilizing a custom-built Scott Crease Flex Tester developed by Schap Machine Company. This unique setup incorporates a liquid nitrogen-chilled dry well to test the flexibility of fabrics at both ambient temperatures and cryogenic conditions as low as –170°C. Crosshead clamps bend strips of fabric repeatedly at the same fold line. With a capability of up to 15,000 test cycles, this method provides insight into the durability and flexibility of materials when subjected to repeated mechanical stresses in extreme cold.

These collaborations with specialized facilities allow the project to leverage state-of-the-art testing capabilities, ensuring that materials meet the stringent requirements for lunar applications while advancing the understanding of their performance in challenging environmental conditions.

As the project progresses, fabric testing, and sub-assembly component testing will move toward more comprehensive evaluations. These tests will consider all environmental factors simultaneously to account for their interactions, using higher-fidelity simulations such as testing in a dusty glovebox and a dusty thermal vacuum chamber planned for FY26.

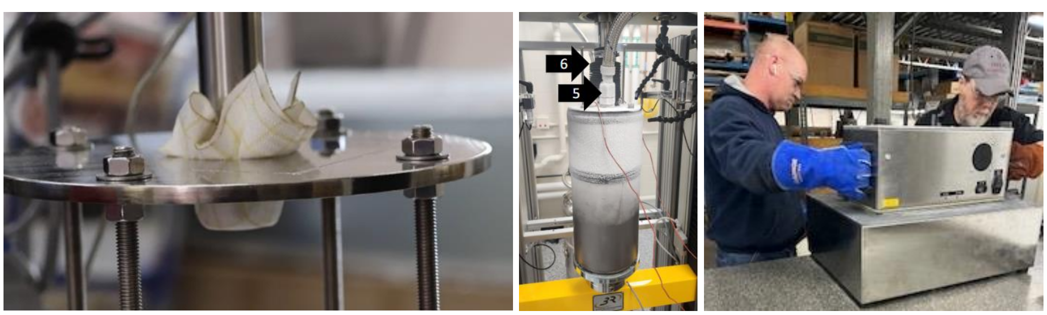

Figure 3. Fabric Stiffness Test at PMIC (Left), Liquid Helium Tensile Test at UofI (Center), Cryo Fabric Fold Test at Schap Machine (Right). Out of house testing has been established with several specialized facilities to evaluate the performance of fabrics at extreme conditions.

V. Initial Insights

A. Material Evaluation

As previously mentioned, due to the uncertainty surrounding specific mission parameters, establishing a baseline for comparison was deemed essential to set performance expectations and track advancements achieved through iterative improvements. Where flow-down requirements from xEMU were unavailable, the performance of the baseline fabric, alongside other leading COTS fabrics, was utilized to define threshold and goal values for critical performance metrics. For this effort, Ortho Fabric was selected as the baseline due to its historical significance in providing protection for the EMU. Measured performance against dust abrasion and temperature will be discussed in this section. The performance of other COTs and prototype fabrics will be discussed in a later publication.

Ortho Fabric was measured for baseline strength and properties and then was conditioned in the rotary tumbler abrasion test for 8 hours with NU-LHT-4M simulant and ceramic tumbler media. Table 1 lists the averaged measured strength values and provides the percent difference in values between pre and post tumbler measurements. The results

Table 1. Pre and Post Tumbler Ortho Fabric Testing Results. This matrix summarizes the strength data collected both before and after an 8-hour tumbler exposure. Negative values indicate a decrease in measurement, positive values indicate an increase. Red shading indicates declining performance, green shading indicates improving performance.

Ortho Fabric	Tensile Warp (lbf)	Elong Warp (%)	Tear Warp (lbf)	Cut (gf)	Puncture (ozf)	Thickness (in)	Weight (oz/yd²)	Air Perm (CFM@125 PA)	Absorptivity	Emissivity
Pre-Tumbler	507	59	229	437	38.8	0.024	14.5	22.5	0.2	0.837
Post Tumbler	302	25	120	637	84.8	0.020	15.49	12.7	0.362	0.866
% difference	-40%	-58%	-48%	46%	119%	-17%	7%	-44%	81%	3%

of the Ortho Fabric tests before and after the tumbler exposure reveal significant degradation in several key properties, indicative of the fabric's lack of abrasion resistance against dust. The tensile strength of the fabric dropped by 40 percent, from 507 lbf to 302 lbf, suggesting substantial weakening of the fabric's ability to withstand pulling forces. Similarly, elongation decreased by 58 percent, highlighting a significant loss in flexibility and an increase in brittleness post-testing. Tear strength experienced a 48 percent reduction, further emphasizing the deterioration of the fabric's structural integrity after exposure to abrasive forces.

Interestingly, cut resistance improved by 46 percent, and puncture resistance increased by an even more notable 119%. These counterintuitive results could indicate changes in the fabric's surface texture or fiber alignment caused by abrasion or more likely incursion of the dust particles which bound the weave together or simply created an additional physical barrier for the blade and probe to pierce through. However, these changes come at the cost of other desirable attributes, such as optical properties and areal weight. While the thickness of the fabric decreased by 17 percent, suggesting material loss or compression during the abrasion process, the weight increased by 7%, most likely due to dust retention. Air permeability dropped by 44 percent, signaling a substantial reduction in the width of the interstices between the yarns, likely caused by fiber compaction or clogging of the weave. Absorptivity and emissivity both increased also likely due to the remaining embedded simulant which is darker in color.

A dust analysis was also completed post tumbling of Ortho Fabric. Table 2 lists the average quantity of dust that was collected from each panel of tumbled Ortho. The exposed area of fabric is 13" × 5" (see Figure 4). On average, 6.9g of simulant penetrated the fabric, standardized to 164.8 g/m^2. For comparison, a tumbled piece of cotton duck cloth averaged 7.49g per panel or 178.9 g/m^2, and urethane coated nylon (used as the EMU bladder cloth) averaged 0g. The "front side dust" metric represents the quantity of dust that was collected off the face of the panel after removal from the tumbler. This number is likely affected by humidity in the air which causes the dust to clump and stick like the caking effect seen in fabric filters used in various applications. The "uptake" metric indicates how much dust was absorbed into the fabric weave, and is an indirect measurement made by weighing the fabric panel before and after tumbling. This value is likely influenced by the loss of fiber mass from abrasion which counteracts

Table 2. Post Tumbler Ortho Fabric Dust Results. This matrix summarizes the dust data collected after an 8-hour tumbler exposure.

Penetrated Dust (g)	Penetrated Dust (g/m²)	Front Side Dust (g)	Uptake (g)
6.9	164.84	11.9	0.8

Figure 4. Dust Covered Ortho Fabric Tumbler Panel (Top), Dust Covered and Abraded Ortho Fabric at 100x (Bottom). Dust coats the face side of the Ortho Fabric after tumbling darkening its color. The abrasion has caused the Gore-Tex® fibers to tuft and discolor.

the effect. Therefore, this value must be considered along with other metrics such as thickness and optical properties to help to better frame true effects from dust alone.

To compliment the strength and dust data, optical microscopy was performed of the fabric after tumbling. Images were taken at 50x, 100x, 150x, and 200x magnification of the front and back side of the fabric panels. The images were analyzed to detect degradation that occurred. Figure 4 shows the face side of Ortho Fabric after the 8-hour tumbler test. The Gore-Tex fibers appear to be shredding. The shredded fibers have embedded simulant making the fabric appear dirty. As mentioned, this effect changes the optical properties of the fabric and would provide a carrier for transporting dust into the vehicle or habitat. The trapped dust makes it difficult to observe how severely the yarns are abraded. The dust appears to form a 'network' on top of the fibers by clumping together. The ePTFE fibers have the appearance of being etched, but it is difficult to discern due to the embedded dust. It was noted that the surface appears to have uniform coverage, but underlying, interlacing yarns appear to have little to no damage.

In addition to tumbling, Ortho Fabric was sent to PMIC for elevated (120°C), ambient (23°C) and cryogenic (–189°C) temperature strength testing. Cut data was collected at JSC's AML. Table 3 summarizes the average values collected. The results highlight the significant influence of temperature on the mechanical properties of the fabric.

At 120°C, both tensile strength and tear strength in both warp and weft directions are reduced compared to ambient conditions, with tensile values dropping to 295 lbf (warp) and 227 lbf (weft). Elongation is notably higher at elevated temperatures, with values of 38.8 percent (warp) and 25.5 percent (weft), indicating increased flexibility. Cut resistance and puncture resistance are significantly reduced, with values of 257 gf and 27.2 ozf, respectively, demonstrating the material's reduced ability to withstand mechanical forces at elevated temperatures. Stiffness is also notably low (1.35 lbf), reflecting a more pliable structure.

Table 3. Changing Temperature Ortho Fabric Testing Results. This matrix summarizes the strength data collected from Ortho Fabric tested at 120°C, 23°C and –189°C. The change in values highlight the significant influence of temperature on the mechanical properties of fabric.

Ortho Temperature Data									
	Tensile Warp (lbf)	Tensile Weft (lbf)	Elongation Warp (%)	Elongation Weft (%)	Tear Warp (lbf)	Tear Weft (lbf)	Cut (gf)	Puncture (ozf)	Stiffness (lbf)
120C	295	227	38.8	25.5	120.7	89.8	257	27.2	1.35
23C	468	379	38.2	13.4	180.3	163	437	59.2	3.08
-189C	437	594	15	7.8	160.4	138.9	808	230.4	14.3

At 23°C, the fabric exhibits balanced performance, serving as the baseline for comparison. Tensile strength reaches 468 lbf (warp) (note the lab-to-lab difference in values from the AML's measured 507 lbf) and 379 lbf (weft), while tear strength is 180.3 lbf (warp) and 163 lbf (weft). Elongation values are lower than at high temperatures, with 38.2 percent (warp) and 13.4 percent (weft). Cut resistance improves to 437 gf, and puncture resistance is 59.2 ozf. The stiffness value of 3.08 lbf suggests moderate flexibility, characteristic of the material's performance at room temperature.

At –189°C, the fabric demonstrates increased tensile strength in the weft direction (594 lbf) but does not increase in the warp direction (437 lbf). Tear strength decreases slightly compared to ambient conditions but remains substantial, at 160.4 lbf (warp) and 138.9 lbf (weft). Elongation drops dramatically to 15 percent (warp) and 7.8 percent (weft), indicating significant embrittlement at cryogenic temperatures. However, cut resistance and puncture resistance improve drastically, reaching 808 gf and 230.4 ozf, respectively, suggesting that the material becomes harder and less susceptible to cutting and puncturing forces. Stiffness increases sharply to 14.3, highlighting reduced flexibility and greater rigidity at extremely low temperatures. However, posttest analysis of the fabric did not reveal any damage from bending through the test apparatus.

Finally, Ortho Fabric was sent to the University of Illinois at Urbana-Champaign's Department of Materials Science and Engineering. Prior to this effort, their team developed a method for tensile testing metallic dog bone specimens at ultra cryogenic temperatures using both liquid nitrogen (LN2) and liquid helium (LHe).[23] The temperature in the environmental chamber can be controlled between the temperature of those two liquids by allowing the canister to fill with gas rather than pure liquid allowing measurements to be taken at –226°C (48K) and –297°C (30K). After establishing contact, their group designed and fabricated new components to be able to grip fabrics at ultra cold temperatures as well.

Figure 5 illustrates the warp tensile strength (measured in pounds-force, lbf) of Ortho Fabric across various temperatures, tested according to ASTM 5035 standards. Data is presented for three testing facilities: University of Illinois (UofI), Precision Measurements and Instruments Corporation (PMIC), and AML to highlight the differences in values obtained from different laboratories. This difference is marginal and within the standard variation of the expected bounds defined in the ASTM standard.

At elevated temperature, the tensile strength is found to be the lowest at 295.2 lbf. However, elongation was at 40 percent. This could be due creep and softening behaviors of ePTFE which begin in the 100-120°C range. Additionally, differential thermal expansion between the differing fibers could be at play.

At ambient, tensile strength reaches its peak with the AML reporting the highest values of 507 lbf. This suggests optimal tensile performance of the fabric will be at room temperature. Elongation was measured to be between 38 and 59 percent.

At –190°C the tensile strength does not drop significantly (roughly 6 percent) but the elongation drops by more than half to 22 percent.

At –226°C, the tensile strength is reduced from 426 lbf to 412lbf, a drop of only 3 percent. However, the elongation drops to 20 percent.

At –297°C, there is a rather significant drop in tensile strength from 412 lbf to 347 lbf. This is a drop of nearly 16 percent from –226°C and a drop of 23.5 percent from ambient. Elongation reaches 16 percent, reflecting some embrittlement or weakening of the fabric at extremely low temperatures.

As previously mentioned, cryogenic flexibility testing has been conducted on Ortho Fabric and over 20 COTS fabrics to evaluate their performance under extreme conditions. While elongation generally decreases at cryogenic temperatures, Ortho Fabric demonstrated remarkable durability, with no visible damage after being flexed for 15,000 cycles at –170°C, as confirmed by microscopic examination. These results highlight the fabric's resilience in cold environments. More detailed findings from this testing are presented in ICES-2025-67.

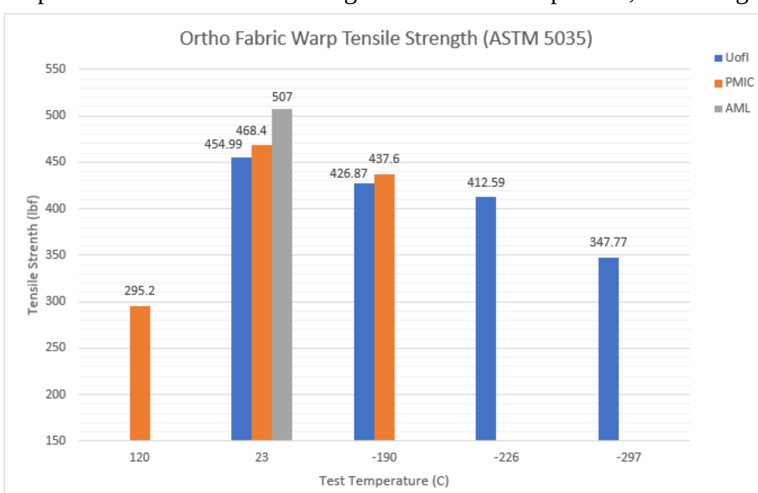

Figure 5. Ortho Fabric Tensile Test Results at 120C, 23C and -189C at different test facilities, PMIC (Orange), AML (Grey), UofI (Blue). Data shows that Ortho Fabric strength is highly temperature dependent and that the hot condition produces the lowest tensile strength.

Overall, the data underscores the trade-offs in material properties across different temperature extremes. While the fabric maintains notable strength and resistance at cryogenic temperatures, its reduced elongation and increased stiffness indicate brittleness. Conversely, elevated temperatures result in decreased mechanical strength and puncture resistance, though flexibility improves. These findings are critical for understanding the fabric's suitability for extreme temperature applications and for requirement definition of a new replacement.

B. Requirement Refinement

Flow down requirements and the baseline performance of Ortho Fabric, combined with the results from testing other leading COTS fabrics, played a crucial role in defining the threshold and goal requirements for the custom shell fabric. These values were carefully determined based on what the team believed was achievable with current technology, while some aspects were designed to push the boundaries and drive technical innovation. To ensure realistic and mission-relevant performance expectations, the team also established fabric conditioning protocols that represent both beginning-of-life and end-of-life conditions. Beginning-of-life is defined as the neat fabric in its as-delivered state to the suit vendor, while end-of-life captures degradation resulting from prolonged exposure to lunar-like environmental stressors. All requirements are expected to be met under the most demanding of these conditions, ensuring robustness across the full operational life of the garment.

The threshold values represent the absolute minimum performance criteria necessary to ensure functionality, while the goal values are more ambitious, providing a margin to mitigate risks associated with unknowns or future challenges. The goal values offer an additional safety buffer to address uncertainties, ensuring that the fabric system is robust enough to withstand the harsh lunar environment.

Encouragingly, based on the data gathered so far, many of the goal values appear to be within reach. However, the challenge lies in integrating all the desired properties—such as strength, flexibility, and thermal resistance—into a single fabric system without introducing new issues. Concerns such as excessive stiffness, bulk, or prohibitive cost could pose barriers to success. Moreover, some risks might not become apparent until the fabric is tested in sub-system or full-system configurations.

To address these challenges, the team emphasizes the importance of continuous communication with all stakeholders, including designers, engineers, and vendors. This collaborative approach ensures that requirements are clearly understood and met at every stage of development, minimizing the potential for unforeseen issues. By maintaining flexibility and staying engaged with the entire supply chain, the team can adapt as needed to meet both threshold and goal values while mitigating risks related to cost, schedule, and performance.

VI. Challenges for Future Work

The ASM team has encountered several significant challenges in establishing a comprehensive test campaign and developing custom fabrics. One key difficulty has been the inability to conduct flammability testing on fibers and fabrics under elevated oxygen and pressure conditions. This limitation is primarily due to the high cost of testing and the restricted availability of resources at NASA's White Sands Test Facility. Limiting Oxygen Index (LOI) is one test that can be performed at the AML and can be used as an indicator of fabric flammability. While some data on LOI and flammability of high-performance fibers is being collected by EC2 for the Gateway program and shared with the ASM team, there does not appear to be a 1:1 correlation between LOI and flammability. Also, flammability testing is not planned until late FY25. This creates a risk, as the planned tests might reveal that top fabric contenders fail flammability requirements, necessitating fallback options. To mitigate this risk, the team is continuously evaluating and updating trade studies, keeping alternative materials in reserve. Additionally, the team is investigating flame-resistant coatings and additives to address potential shortcomings in fabric performance.

UV resistance testing presents another hurdle. While critical for fabric performance in the lunar environment, test chamber cost and schedule constraints limit the number of fabrics that can be processed. Current testing at Marshall Space Flight Center utilizes 6-inch beam spots, allowing for limited area of exposure. Preliminary tests on individual yarns have provided some data, which will be published in future reports. Additionally, insights from other projects, such as Mars 2020,[24] are helping shape the trade space. Mitigation strategies being explored include UV-resistant coatings like titanium dioxide and protecting structural yarns with outer layers of less UV-susceptible, weaker yarns. Comprehensive fabric UV testing is also planned for late FY25, leaving this as an area of ongoing risk and investigation.

Coating development has surfaced as both a challenge and a potential solution to various issues, including dust penetration and UV protection. However, finding a coating that remains flexible at cryogenic temperatures while adhering effectively to the fabric has proven difficult. Challenges such as the coefficient of thermal expansion mismatch between the coating and the fabric, flex cracking, and delamination are concerns. The ASM team is collaborating with multiple coating vendors to address these issues and develop coatings that meet the rigorous requirements of lunar environments. Several coatings and films have been found with early test indications offering promise.

Ultra-cold temperature testing poses logistical and financial challenges. While liquid nitrogen is cost-effective and readily available, it does not achieve the ultra-cold temperatures of liquid helium required to simulate the lunar PSR. This creates a risk, as not every test can be conducted at the desired 30K. To mitigate, the team is analyzing trends in existing data (such as the UofI LHe tensile test) to determine whether extrapolations can provide useful insights. Subassembly testing of a leg EPG in JPL's CITADEL chamber, capable of reaching 48K, is planned for the end of the project, but the high cost and late timing of this test add to the challenges. Despite these hurdles, the ASM team remains focused on identifying innovative solutions and mitigating risks to advance the development of robust lunar fabrics.

Looking ahead, any candidate fabric solution will ultimately need to be vetted through a comprehensive Design Verification Test (DVT) campaign and subsequent qualification testing to ensure it meets the rigorous performance requirements for lunar surface operations. While current testing has provided valuable insights into material behavior under simulated conditions, a full DVT will be essential to validate long-term durability, environmental resistance, and mechanical performance in the context of an integrated suit system. Moreover, it is likely that the final spacesuit design will not rely on a single fabric solution, but rather a combination of specialized fabrics strategically selected for different regions of the suit. For example, thinner, more dexterous materials may be prioritized in areas such as the gloves to preserve mobility and tactility, while high-durability, abrasion-resistant fabrics will be critical for high-wear regions like the knees and lower torso. This tailored approach to material selection will require thorough testing of not only individual fabrics but also the interfaces and transitions between materials to ensure overall suit integrity and performance.

VII. Conclusion

The ASM Project, a 3.5-year initiative, has reached its midway point and is making significant progress toward its objectives. A comprehensive trade study is currently underway to examine state-of-the-art yarns, fabric constructions, coating technologies, and advanced testing capabilities. These insights provide the team metrics to use in a down-selection process to ensure the most promising materials and technologies are prioritized. In conjunction with the trades, fabric and coating development has been structured into three phases: yarn selection and testing, round 1 fabric prototyping, and Round 2 fabric prototyping, with each informing the next.

Accomplishments to date include the successful completion of Phases 1 and 2, drafting of a requirements specification, and the establishment of a comprehensive test campaign. Over 20 yarns of interest have been identified and procured, with extensive yarn-level testing—including UV exposure and yarn-on-yarn abrasion—already conducted. Rotary tumbler abrasion testing has been completed on more than 30 COTS fabrics, and cryogenic flexibility testing has been conducted on over 20 fabrics, with detailed results presented in later Additionally, strong relationships have been established with multiple yarn, textile, and coating vendors to support the project's objectives.

Future work includes completing Phase 3, finalizing the trade study, requirements, and the test campaign, which will culminate in sub-assembly testing of both a leg and glove EPG in cryogenic, dust-filled vacuum chambers. The project will also finalize fabric analysis and specifications while establishing a plan for manufacturing upscale. A series of publications is planned, including ICES papers, three detailed technical reports, a series of technical memorandums detailing findings of interest, and test protocols for custom NASA-developed evaluations. The project is on track to deliver a state-of-the-art EPG shell fabric that meets the rigorous demands of lunar exploration.

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