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Establishing Standardized Test Methods for Evaluating Space Suit Gloves

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

Morgan Abney[2], Tim Brady[3]
NASA Engineering and Safety Center, Langley Research Center, Hampton, VA 23666

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

Shane McFarland[5]
Aegis Aerospace / KBR HHPC / NASA Johnson Space Center, Houston, TX 77058

Joe Settles[6], Chanel Stephens[7], Drew Hoyle[8]
Jacobs / NASA Johnson Space Center, Houston, TX 77058

Andrew Funk[9]
Wells Lamont Industrial, Skokie, IL 60077

Stephanie Rodgers[10]
Textile Made, Inc., Howell, MI 48843

The Artemis space suit glove environmental protection garment (EPG) will be the first line of protection used to shield the crewmember's hands from the environments encountered during extravehicular activity (EVA). As the Artemis missions will include more extreme environments than those experienced on the International Space Station, development, verification, and validation of gloves poses three key challenges. First, there are no standardized tests defined to evaluate the durability of space suit gloves for the extreme lunar environments, particularly the permanently shadowed regions. Second, there is insufficient data on state-of-the-art glove performance in a lunar environment from which to compare new designs. Third, current ISS glove Thermal Micrometeoroid Garment (TMG) fabrics are unlikely to be sufficient to meet Lunar requirements. It is therefore necessary to define tests to evaluate if gloves can meet new, challenging requirements. This paper focuses on the development of a test procedure to characterize lunar EVA glove fabrics using ASTM standardized test methods and the design and validation of a new standardized test procedure for comparing abrasion resistance between fabrics in lunar-like conditions. The results of testing on twelve candidate EVA glove fabrics are presented.

[1,4,5,7] Spacesuit Engineer, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX
[2] ECLSS Technical Fellow, NASA Engineering and Safety Center, C104, Marshall Space Flight Center, AL.
[3] NESC Integrator, NASA Engineering and Safety Center, C102, Johnson Space Center, TX.
[4] NESC Project Co-Lead, NASA Johnson Space Center, Houston, TX
[6] Advanced Materials Laboratory Lead, NASA Johnson Space Center, Houston, TX
[8] Textile Engineer, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX
[9] Senior R&D Laboratory Manager, Wells Lamont, Skokie, IL
[10] Textile Engineer, Textile Made, Howell, MI

Nomenclature

ANSI = American National Standards Institute
ASTM = American Society for Testing and Materials (formally known as)
COTS = Commercial Off the Shelf
EPG = Environmental Protection Garment
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
FOD = Foreign Object Debris
ISS = International Space Station
KPP = Key Performance Parameter
LEO = Low Earth Orbit
LN2 = Liquid Nitrogen
MMOD = Micrometeoroid and Orbital Debris
NESC = NASA Engineering and Safety Center
PPE = Personal Protective Equipment
PSR = Permanently Shadowed Region
TMG = Thermal Micrometeoroid Garment
xEMU = Exploration Extravehicular Mobility Unit
xEVAS = Exploration Extravehicular Activity Services

I. Introduction

NASA's Artemis program plans to return humans to the moon. Phase I includes plans for up to five extravehicular activities (EVA) which include a goal of exploring a permanently shadowed region (PSR) of the lunar south pole for two hours. Regolith samples are planned to be collected from the lunar surface[1]. These extreme environmental conditions will challenge EVA suits and their gloves to achieve new requirements never met before.

Initially, NASA set out to provide an internally designed and fabricated suit to support the Artemis missions. This suit was designated as the Exploration Extravehicular Mobility Unit (xEMU)[2]. However, in the spring of 2022 NASA elected to engage commercial companies for the build and maintenance of a suite of space suits to support space station and lunar EVA activities. This was accomplished through the Exploration Extravehicular Activity Services (xEVAS) contract solicitation. Under the new paradigm, NASA is responsible for providing the technical and safety standards by which the space suits will be built, and the companies have agreed to meet those requirements. NASA plans to provide data to the vendors from any ground or flight experience as well as details of the design of its xEMU suit through the EVA Technical Library[3]. At the time of this writing, NASA plans to send humans back to the moon and conduct an EVA in 2025[4]. Therefore, the suit vendor must design, develop, qualify, certify, and produce the spacesuits and support equipment in less than three years. Many technical design challenges will need to be overcome during this period. Fundamental lessons can be learned from past missions to the Moon, but new developments and testing will be required to meet the even more demanding environments expected to be encountered under the Artemis program.

Due to the short timeline and critical nature of providing lunar EVA spacesuits, NASA has undertaken an effort to address three key obstacles to producing a space suit glove that is sufficiently durable to meet the needs of the Artemis mission. These obstacles include:

1. No consistent/standardized testing defined to evaluate the durability of gloves for the extreme lunar environments.
2. No baseline lunar performance data on the Phase VI gloves from which to compare new designs.
3. Current glove fabrics are unlikely to be sufficient to meet Lunar requirements.

Several tasks were established to answer different aspects of these three obstacles. They focused on finding fabrics with the characteristics for lunar conditions which included high abrasion durability, high cut durability, improved thermal protection at lower temperatures, and that minimize impact to the dexterity of an EVA glove. Ultimately, the results of this effort will be utilized to aid the xEVAS suit vendors in the design and testing of their lunar gloves.

To complete the tasks, a team comprised of NASA space suit engineers, material experts, and test personnel were assembled and are referred to as "Team". This paper details the efforts performed to complete Task 1 aimed at developing a new test procedure to vet candidate glove fabrics, procuring fabrics, and then the use of the procedure to compare the key characteristics of the fabrics.

II. Space Suit Standardized Testing History

There is already a large collection of standardized tests used to characterize the strength of fabrics, coated fabrics, films, seams, and many of the other ancillary components used in the construction of a space suit. They originate from industry and have been developed and published by organizations like ASTM International or the American National Standards Institute (ANSI). These tests have been established to provide engineers with information to select proper materials for applications ranging from personal protective equipment (PPE) to automotive upholstery to inflatable airships. Space suit designs have used these material level tests in conjunction with more complex custom, benchtop level subcomponent, and fully suited, human-in-the-loop (HITL), system level tests since their inception[5].

However, for the past 50 years EVA suit design and testing has focused primarily on developing materials and combining them in a way that is effective for use in low Earth orbit (LEO), a very different environment from the surface of the Moon. Unfortunately, many of the tests that were used for the development of the Apollo lunar suit were either not captured in a way to make them readily available for use today or did not exist as the requirements for the Moon were not well understood. Much of what we know today about how the Apollo suits faired in the lunar environment are from post mission inspection and analysis of the fabrics[6].

A lack of an agreed upon standardized test procedure holds especially true for lunar EVA gloves. Several attempts have been made to create standardized tests to compare glove designs in general. The 2013-2017 High Performance EVA Glove Project (HPEG) made strides in developing ways to measure glove Key Performance Parameters (KPPs), which are objective measurements of performance and served to document and verify the improvement of glove technology across various metrics over time. KPP's were used to compare EVA gloves from multiple vendors and characterized task-based mobility, dexterity, tactility, strength, dust penetration, dust abrasion's impact to strength and elongation, thermal performance, radiation's impact to strength and elongation, measure of task effort, comfort, range of motion and injury potential. Unfortunately, most of these KPPs were found to be unhelpful in characterizing glove performance as they were insufficient in providing quantitative results and often came down to subjective feedback garnered from the HITL, rather than repeatable, consistent test metrics. However, it was noted that material-based KPP's such as strength degradation after environmental exposure or thermal performance showed promise in providing useful analytical data but "require additional development but hold potential as possible metrics in the future to down-select advanced prototype materials."[7]

It is therefore relevant that this effort focused on defining a set of either existing or newly created standardized tests as the go-to method for NASA and its vendors to use for vetting lunar EVA space suit glove assemblies and glove fabrics.

III. Lunar Glove Fabric Evaluation Plan

Fabricating full glove assemblies for system level testing is costly and takes time. Therefore, to reduce program risk it was necessary to develop a vetting process at the fabric level. This allows evaluation earlier in the design process and aids in selecting fabrics that will meet lunar requirements. The Team performed the following:

- Review literature of previous work on evaluation of gloves and glove fabrics
- Define characteristics/requirements of "better" materials for the lunar environment
- Devise a series of standardized tests for evaluating candidate glove fabrics
- Conduct market research to identify alternative materials
- Evaluate alternative materials

A. Literature Review of Previous Work

The Team found many helpful insights in reviewing the historical data that was then used to make informed decisions about the test methodology and fabrics selected for this effort. The information was collected from published papers as well as internal NASA reports available to the Team and included insights into test methodologies and lessons learned that helped to guide the task approach[8].

First, it was noted that due to a lack of relevant Apollo test data, it is prudent to include Apollo PTFE (Teflon) fabric as part of the test matrix for comparison. SEM observations made of the Apollo Teflon that was exposed to lunar regolith during EVA served as a good subjective indicator, or benchmark, to show that abrasion tests performed on Apollo fabric and other candidate fabrics were able to produce similar results. Confirming that the level of wear produced in an abrasion test is accurate and relevant would be difficult to prove without this basis for comparison. Therefore, the Team included the Apollo Teflon (style T-162) in the test matrix for this reason.

Second, the Team found that a custom developed tumbler abrasion test has been the go-to-test for creating EVA-like accelerated wear on space suit fabrics for more than 30 years. The Team analyzed available post tumbler test reports, collecting insight on what went well and what needed further improvement. After carefully considering the alternative abrasion tests, the Team determined to utilize the tumbler test again but with a focus on consistency and repeatability. In addition, modifications were made so that larger fabric panels could be abraded and then segmented for post abrasion strength testing.

The Team examined a similar fabric development study for the NASA rover (VIPER) project and agreed that the format of down select used for it seemed a logical and consistent method for trading the merits of one fabric's performance against another. The approach followed in that effort included soliciting manufacturers for fabrics and coatings that they felt would get close to meeting all requirements. Then the team ranked and compared the fabrics in several bench top level abrasion tests and used air permeability, mass, and thickness to characterize wear. Ultimately, the rover team made a final down select by fabricating several test units that were utilized in subsystem level testing.

Finally, while reviewing historical documents on glove or EPG fabric testing, the Team noted any recommendations made for types of fabrics, fabric construction and coatings that could be brought forward for this effort. It was found that aramid or Vectran fabrics have been used as cut resistant fabrics in space suit glove construction going back decades. These materials are desirable because they can be lightweight and conforming/flexible while also adding a significant amount of cut protection. Also, plain weave fabrics over twill weaves seemed to perform better in both dust mitigation, abrasion and cut protection due to the increased number of crossover yarns creating a tighter construction. It was also noted that multiple efforts considered property enhancing coatings onto the face or backside of a fabric to boost performance.

B. Defining Characteristics of "Better" Materials for the Lunar Environment

After reviewing the literature, the Team sought to define what a "better" glove material would mean for the lunar environment as compared to the state-of-the-art Phase VI gloves used on ISS. The most significant differences in the two applications included those shown in Table 1.

Table 1. Differences in spacesuit glove use-cases for ISS vs Lunar South Pole.

	ISS	Lunar South Pole
Wear Environment	Relatively pristine, low dust	Fine abrasive regolith, sharp rocks
Thermal Environment	144K to 433K (-200F to +320F) Incidental 100K (-280F)	8 hours: 100K to 350K (-280F to 170F) 2 hours: 48K (-390F)
Activities to be Performed	"Light" touch, translation	Heavy activity, high impact tools, frequent handling of "dirty" materials

These differences in environment and use-cases necessitate materials with the following characteristics: Greater abrasion durability, greater cut durability, and better thermal protection at lower temperatures, all while maintaining or improving dexterity of motion during activities. Using these attributes, the Team worked to define the characteristics of glove fabrics suitable for lunar EVA. This led to the creation of a one-page material specification sheet that was later used to solicit input from textile vendors on any fabrics and fabric coatings that they recommended as a potential option. The criteria requested in the sheet are shown in Table 2. Vendors were solicited to provide state-of-the-art fabrics in cut, abrasion, dust, and thermal protection whether they exceled in one category or several.

Table 2. Material specification sheet used to solicit lunar glove fabric recommendations from textile vendors.

Attribute	Requirement/Guideline
Thermal Range	8 hours: 100K to 350K (-280F to 170F) 2 hours: 48K (-390F)
Abrasion Resistance	High (i.e., in a Taber test withstand wear from 150 grit garnet sandpaper)
Cut Resistance	Min rating of ANSI A2 (Ortho); A5 or higher is ideal
Strength	Min strength of 500 lbf tensile (Ortho) for cut/abrasion fabrics
Off gassing/volatiles	Low
UV Resistance	High
Stiffness	Low

C. Standardized Tests for Evaluating Candidate Materials

The following list details the tests selected by the Team for the Test Procedure and provides a brief explanation for its inclusion:

1. **Emissivity** (ASTM C1371 – "Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers") An emissivity value is the measure of an objects ability to absorb, transmit and emit infrared energy. For EPG glove and suit fabrics, this value represents part of the total thermal protection provided. Emissivity measurements are needed for thermal modeling and could be

used as elimination criteria if it was shown to have poor thermal performance or if exposure to the lunar environment caused it to significantly lose thermal performance (color fastness or darkening due to the addition of embedded simulant)

2. **Air permeability** (ASTM D737 – "Standard Test Method for Air Permeability of Textile Fabrics") This test measures the volume of air flow passed through a given area of fabric. This test was included to understand if there is a correlation between a fabric's air permeability value to its ability to resist dust penetration.
3. **Stiffness** (ASTM D1388 – "Standard Test Method for Stiffness") The drapability of a glove fabric, especially those used around finger shafts and palm breaks, contributes to the overall torque of a glove EPG. The drapability of a fabric is a more complex trait and is a combination of stiffness, mass, bending, elasticity, density, and thickness. While drapability will be characterized eventually, stiffness is a simpler metric to use for comparison and down select. For this effort, "Option A" was selected which is a cantilever test that employs the principle of bending a narrow strip specimen under its own mass.
4. **Breaking Strength and Elongation (**ASTM D5035 – "Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method)") Tensile testing is the most applied test method for analyzing the mechanical properties of fabrics. In a strip tensile test, the full width of a test specimen is gripped in the jaws of a universal testing machine. A tensile force is applied until the specimen ruptures. This test was used to provide verification of vendor supplied values (commonly reported) and as one component to evaluate the effects of environmental exposure to a fabric's strength.
5. **Tear Strength** (ASTM D2261 – "Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure (Constant-Rate-of-Extension Tensile Testing Machine)") Resistance to tearing is a metric used to characterize fabric strength. This test measures the force required to propagate a tear through a cut slit or ravel. The cut slit method was chosen to minimize material handling after simulant or cryogen exposure. This test provides another metric to analyze strength degradation due to environmental exposure.
6. **Cut Resistance** (ASTM F2992 – "Standard Test Method for Measuring Cut Resistance of Materials Used in Protective Clothing with Tomodynamometer (TDM-100) Test Equipment") Suit EPG elements are required to protect the pressure garment from contact with sharp lunar rocks or other objects. This is another strength measurement used to study the effects of environment on the fabrics.
7. **Puncture Resistance** (ASTM F1342 - "Standard Test Method for Protective Clothing Material Resistance to Puncture") Puncture resistance is defined as the force required to penetrate the fabric surface with a small tip or blunt instrument. Fabric construction, density, yarn types, and coatings can influence the puncture resistance of a fabric. Pre and post puncture testing on the fabrics was used to compare environmental degradation. In addition, puncture force is an indication of the material's impact protection which translates to micrometeoroid protection, another requirement of EPG systems.
8. **Thermal Conductivity** (ASTM C177 - "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus") Glove fabrics are critical to maintaining safe temperature levels to the hand. This method was selected to evaluate the candidate fabrics thermal conductivity values. Thermal conductivity measurements of Lunar space suit fabrics require a highly engineered test apparatus to create the necessary environmental conditions (vacuum and cryogenic temperatures) to obtain a meaningful value.
9. **Abrasion Resistance** (ASTM D4966 – "Martindale Abrasion Resistance"; NASA mod) To characterize the wear resistance and foreign object debris (FOD) generation of the thermal enhancing fabrics the Martindale Abrasion Tester was used, with a custom particle collection system. It is assumed that in a space suit glove design, the thermal fabrics will be layered under a cut/abrasion fabric and thus protected from most of the external wear. However, internal fabrics are expected to experience some wear as they rub against themselves. This test is meant to simulate that wear condition. It is assumed for this test setup that in a space suit glove, the thermal fabric would be used on the interior of the Glove EPG which is adjacent to the glove restraint (similar to the design of the Phase VI Glove). Therefore, EMU restraint fabric with a sewn seam is used as the abradant in the test.
10. **Tumbler Abrasion** (NASA design) The rotational tumbler test is a custom test developed at NASA as an abrasion test meant to simulate EVA induced wear on space suit fabric test specimens. The test is detailed in Section D.
11. **Cryo Flex** (NASA design) This in-house developed test is designed to characterize a fabric's ability to repeatedly flex and not significantly degrade while at cryogenic temperature. This test was developed during the xEMU development and further modified for this effort to allow the inclusion of more test specimens. The

test is resource intensive due to the required constant monitoring of LN2 and is therefore intended to be used on only fabrics that have been down selected.

D. Standardized Test Development: Tumbler Abrasion

In 1990, NASA began to make plans for a permanent base on the moon and Mars. As EVAs would be required to support continued exploration, this spurred a renewed interest in the space suit group to develop testing for more advanced EVA fabrics. One of the new tests was designed to simulate wear and tear on EPG fabrics due to interactions with lunar regolith at an accelerated rate. This test was originally called "Abrasion Resistance Materials Screening Test"[9] and would later be known more generically as the "tumbler test". Since its inception, NASA has continued to focus on tumbler testing to simulate wear on the outer layer of the space suit fabrics although the details of the test method have evolved over time[10].

The tumbler test method has undergone several key changes since its initial inception including a substantial change during the HPEG glove project which also used the test to compare fabrics in a similar manner[11]. To this end, there were several controllable variables in the setup that the Team identified that did not have a definitive value including: the duration of the test, the rotational speed of the tumbler drum, the type of lunar simulant and rock media, the quantity of lunar simulant and rock media, and the method for the preparation and cleanup of the fabric panels. Further, the test had never been validated to show repeatability of the method.

This effort sought to standardize the method by examining past testing, noting issues that were encountered and updating the method. Updates included: the fabrication of a longer tumbler drum and frames to accommodate longer fabric panels for harvesting specimens for post abrasion analysis, the replacement of previously used fabricated or basalt rocks with commercially available ceramic tumbler media, and the inclusion of polycarbonate plastic backing plates with the fabric frame layup for collecting penetrated lunar simulant. Two sets of testing were performed to define the standardized method: Exploratory Testing (to demonstrate the feasibility of using the approach as a metric for comparing fabrics and to determine parameters for each test factor) and Validation Testing (to demonstrate the statistically significant repeatability of the approach).

1. Rotational Tumbler Exploratory Testing

Exploratory testing was performed by selecting values for the variables, tumbling Ortho and cotton fabric, and comparing their pre and post abrasion tensile strength to determine if the amount of degradation was sufficient to be used as a metric for down select. Two types of fabrics, one high strength and one low strength, were chosen to observe any differences that the strength of the fabric could produce in the results. Ortho Fabric was chosen because it is the outer fabric used in the EMU TMG and its characteristics are well known in the space suit community. A medium weight, woven cotton was chosen for the second fabric because it was readily available, made from a staple fiber, and is therefore commonly known.

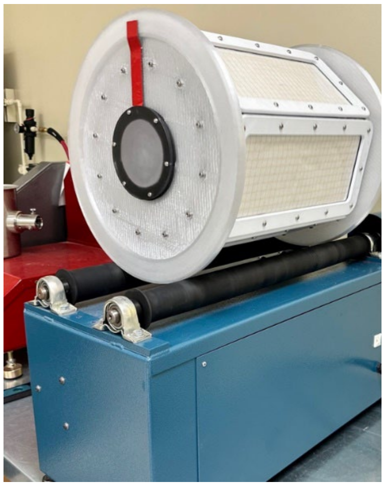
Figure 1. Rotational Tumbler.

The tumbler configuration, as shown in Figure 1, was comprised of six 13" x 8" gasketed clamping frames fastened to the sides of a hexagonal drum. Fabric panels were labeled, weighed, photographed, and then captured under the frames along with clear polycarbonate plastic sheets of the same size. The fabric was mounted so that its face side was to the interior of the drum. For this setup, the fabric was clamped around its edges but not tensioned allowing it to deflect when impacted based on the stretch of the material. The abrasion resistance of the material was not evaluated in a tensioned verses relaxed state which could be considered in future testing. Before the final panel was mounted, a defined quantity of lunar simulant and rock were added to the interior of the drum, as shown in Figure 2. NU-LHT-4M simulant was used as it best approximates the dust regolith found at the lunar south pole. Commercially available ceramic tumbler media (Central Machinery Ceramic Tumbler Rocks) was used to represent lunar rocks encountered during a lunar EVA due to their consistent texture, hardness, size, shape, and weight. It was observed during testing that the rocks held up well during a tumbler run as little was worn away and the overall shapes remained the same. The rotary drum was placed on a powered roller base which provided the rotation at selectable speeds ranging from 10 to 80 rpm.

The tumbler was operated 8, 16 or 24 hours via a countdown timer and was flipped halfway through the duration to ensure that the abradant was equally distributed in case of biasing to one end of the drum. Once completed, the drum was removed from the roller base and the frames were removed. Any simulant that penetrated through a fabric panel was captured between the backside of the fabric and the sheet of plastic. Upon removal of the fabric panel, the penetrated dust simulant was collected and weighed. The fabric panels were cleaned per a prescribed method (brushing and vacuuming in a consistent manner), weighed, photographed, and prepared for tensile tests by cutting into five equally divided strips. The tumbler was then cleaned and prepared for the next run. Tensile test results of the cotton and Ortho Fabric indicated that an eight-hour tumble duration at a spin speed of 80 rpm for the roller base with 453.5g (1 lb.) of NU-LHT-4M lunar simulant and 453.5g (1 lb.) of ceramic tumbler media rocks was sufficient to produce enough wear on various fabrics to serve as a comparison. Ortho Fabric lost 50% of its tensile strength in eight hours and the cotton cloth lost 12.6% of its strength in eight hours.

2. Rotational Tumbler Validation Testing

A validation test was designed to determine the amount of variability in results that the tumbler produces and whether that amount was acceptable to the Team. The tensile strength (ASMT D5035) of test specimens harvested from the worn fabric panels in line with the warp direction was the data used for comparison as there was not enough time to run samples in the warp and weft directions. The warp direction was chosen because it is typically the stronger orientation and would provide a more definitive separation in results.

Figure 2. Interior of Rotational Tumbler (top) and Abraded panel of Ortho Fabric (bottom).

To achieve statistical significance, two test series were devised comparing pre and post tensile strength of two lots of cotton fabric, Ortho Fabric, and a woven Kevlar. Two tumbler drums were used for both test series. Test fabric panels were labeled, weighed, photographed, and then captured under the tumbler frames along with clear polycarbonate plastic sheets of the same size. The fabric panels were mounted so that their face side was to the interior of the drum.

Approximately 453.5g (1 lb.) of lunar simulant, type NU-LHT-4M, and 453.5g (1 lb.) of Central Machinery ceramic tumbler media were added to the drums and then were rotated for 8 hours, each being flipped at the four-hour mark. The panels were removed, cleaned, and processed for cutting and testing. Five tensile specimens were harvested from each fabric panel. The average tensile strength and standard deviation was tabulated for each panel.

Forward work is required to draw conclusions on the variability of the test method. The Team will analyze the data set to understand the test repeatability limits and a coefficient of variability for each test fabric type. Variation from both the pre and post abrasion tensile values will be tabulated and will be compared to values from other fabric abrasion tests to see if they are within reason. Error bars will be added to pre and post tension results to see if strength degradation in the fabrics is significant or not. Results of this validation will be reported at a later date.

E. Cryogenic Flex Testing

For exposure testing, the Team determined that the most severe and unknown performance environmental impact to textiles is the influence of cryogenic temperature exposure. Cryogenic temperature influence is not commonly tested, and limited research is available to understand its effects on traditional woven and knitted materials. The Team found research[13] indicating that liquid nitrogen (LN2) temperature exposure can change the crystallinity density of certain polymer types and in fiber bundles can influence overall fabric strength. Therefore, the Team desired to include a test to characterize a fabric's ability to repeatedly flex and not significantly degrade while at cryogenic temperature. A NASA developed test method using a custom bending apparatus inside a LN2 bath was selected for this purpose. However, the test is highly resource intensive, so the Team elected to utilize it only on fabrics down selected after using the other test methods. As an alternative, a less rigorous pass-or-fail "pre-screen" test was utilized based on ASTM D751 – "Standard Test Methods for Coated Fabrics" to determine if a fabric had significant degradation after being creased one time at cryogenic temperatures. A fabric passing the pre-screen test indicated that there was merit in moving it on to the next assessment.

The Team also elected to collect strength data of the fabric while at cryogenic temperatures. This was accomplished via a thermal chamber that mounts around the Universal Test machine test jaws and can condition the air around the test specimen using LN2 cooled walls. As this exposure testing is also resource intensive, the Team opted to use it closer to the end of the procedure when only down-selected fabrics remained.

F. Alternative Material Candidate Selection

While researching the history of developing EPG cover layers, the Team noted that the cover layer and the yarns that comprise it are combined in highly specialized ways to make a multifunctional fabric. The function of the overall fabric is a summation of carefully selected yarns, yarn construction, coatings, and fabric construction that when cleverly combined, meet all mission requirements. To reduce the layers of the EPG, which reduces mass, torque impact etc., engineers work to implement multiple fabric technologies into one or several layers often in ways that drive to bespoke fabric compositions. The Team reasoned that it was unlikely to find a single, commercial-off-the-shelf (COTS) fabric that addressed all requirements. Therefore, the Team opted to use this effort to characterize the base fibers more broadly (Kevlar®, Nomex, Vectran™, Teflon™, etc.) and coatings to better educate NASA and its suit vendors on the merits of choosing one base fiber or coating over another. This information could feed into an effort to craft a bespoke fabric more tailored to meet the needs of a lunar mission.

Over twenty fabrics were identified as fabrics of interest due to previous experience using them in EVA suits or other applications (other NASA funded projects investigating cover layer softgoods), information garnered from historical suit testing or marketing claims, composition of base fibers, or because of a vendor recommendation. However, due to limitations of availability/cost/schedule and available resources, the Team down selected to a final nine fabrics to be tested.

Several fabrics were included in the testing as reference fabrics. These were Ortho Fabric, a plain weave cotton cloth and a plain weave Teflon™ T-162 fabric. Ortho Fabric, fabricated by FDI, is currently used as the outer layer of the EMU TMG, and is well known in the space suit industry. Therefore, it was included as a reference to use in comparison to the other candidate fabrics. Cotton cloth was used in the tumbler validation process, detailed previously, because it is a staple fiber, has low strength and was readily available to the Team. Teflon™ T-162, produced by Stern and Stern, is a legacy fabric that was used on the Apollo suit outer covering in select locations and is also used on the EMU specifically as the fabric on the outside rear of the Phase VI glove TMGs.

A fiber of interest to the Team was Kevlar®. Kevlar® fiber is a strong, heat resistant fiber and has been used in space suit fabrics in the past. The Team elected to include a fabric to characterize that fiber. The Team sourced JPS Kevlar® 775 KM2®+ which is a Dupont designed product. The KM2®+ fiber is an enhancement over DuPont's previous version, KM2®, which was an evolution of the original Kevlar® fiber having higher strength and better fragmentation protection in military and space applications. KM2® has been used on numerous micrometeoroid and orbital debris (MMOD) shield systems for NASA vehicles. Its attributes include high flexibility, thermal stability at extreme temperatures and has been proven to have improved ballistics performance[14] over the previous version which is a direct translation to improved MMOD protection. The base fiber of Kevlar® is known to have poor abrasion resistance so the Team was interested to test if the new KM2®+ construction would improve this metric.

Another fiber of interest to the Team was Vectran. Vectran is known for its stability at high temperatures, high strength and modulus, low creep, and good chemical stability. Vectran has been used in many space applications including the EMU suit and MER landing airbags. Therefore, the Team selected Vectran "Turtleskin®" as a candidate fabric. Turtleskin® is a marketing name used to describe a family of woven Vectran products that are manufactured by Warwick Mills. Turtleskin® fabrics are designed to be lightweight and puncture resistant. They are marketed for use in COTS protective gloves and a style of it is used in the Phase VI gloves as cut resistant patches. The style selected for this effort, T9-1094, was chosen because it is lighter weight compared to other versions and was readily available. The Team surmised that its high strength coupled with low weight would make for a superior glove fabric.

Of particular interest to the Team was the inclusion of fabrics treated with shear thickening fluid (STF) and super hydrophobic coatings. Other ongoing NASA projects have investigated STF coatings pioneered by the company STF Technologies. STF treatments have been shown to increase certain properties of fabrics such as MMOD protection, puncture resistance and dust resistance. STF is a nanocomposite material which is intercalated in between fibrils in the yarns of a fabric resulting in a dry, flexible textile that can have additional applications applied to it[15]. For this effort, the Team worked with STF Technologies to procure two unique base fabrics, both uncoated and coated (with hydrophobic STF and a COTs superhydrophobic solution) versions, to examine how the additional coatings would affect the fabric properties. The base fabrics were a medium weight, plain weave, woven Vectran™ and a modified Ortho fabric where the Kevlar® ripstop yarns were replaced with Vectran™ yarns. This modification was made because previous testing has shown that Vectran™ yarns have higher strength and abrasion resistance over Kevlar® yarns.

G. Combined Test Procedure

The Team began work to define a combined, overarching procedure for comparing the characteristics of the fabrics with a focus on testing durability for the lunar environment. The Team approached the general test methodology in this way: first, ASTM tests were used to determine the baseline fabric properties, then the fabrics were exposed to several environments simulating lunar surface conditions. Finally, the fabrics were retested during or after exposure (depending on the test) to simulated environments to determine what, if any, impact the environments had on their properties.

Due to a lack of specific glove lunar performance requirements at the time this effort was conducted (i.e., tear, puncture, abrasion, etc.), this procedure was designed to allow a large pool of candidate fabrics to be evaluated in the beginning, with the option to eliminate comparatively poor performers throughout the protocol. This was included so that time and effort would not be consumed testing fabrics that were deemed unfit to continue in the evaluation. The elimination of a fabric was to be considered real-time by the Team at the time the data set was made available.

The full test procedure as envisioned by the Team is detailed below and represents a best approach to material evaluations. However, due to limited schedule and resources for this effort, only a subset of the full test plan, detailed in the results section of this paper, was completed for the reference and candidate fabrics. However, it is the recommendation of the Team that the full test plan, in its entirety, should be carried out in future lunar fabric down-select efforts.

1. Procured fabrics are categorized as "cut/abrasion/dust" or "thermal." These are used to direct each fabric through a subset of tests specific to those categories to eliminate unnecessary testing. Test specimens are cut via a nested layout on a CNC laser cutting machine and each specimen is labeled with a unique identification number.
2. All fabrics are exposed to a "pre-screen" cryogenic exposure evaluation. To expedite the test, the results are observationally collected i.e., visible damage to fibers, a permanent crease in the fabric, or excess fiber debris generated. If any of these conditions occur, the damage is noted and evaluated for elimination.
3. Baseline test values from pristine fabric specimens are collected using both non-destructive and destructive ASTM tests performed at ambient lab conditions and in only the warp orientation, initially. Based on the test results, one or more fabrics may be eliminated. Fabrics are then exposed to several lunar-like environments to induce wear and tear. Degraded fabrics are re-tested utilizing the same ASTM tests to compare pre- and post- test results.
4. For "cut/abrasion/dust" fabrics, eight panels of size 13" x 8" of each fabric are prepared for wear and dust penetration testing in the tumbler test, as detailed above.
    a. After completing the tumbler procedure, the dust on the backside of the fabric panels is collected and weighed. The mass of the dust is a metric used to compare the dust resistance of fabrics.
    b. Specimens are cut from the abraded tumbler panels for post-wear evaluation testing including thickness (D1777/D5729), mass (D3776), emissivity (E408), air permeability (D737), stiffness test (D1388), strip tensile (breaking strength and elongation) (D5035), tongue tear (D2261), cut resistance (F2992), and puncture resistance (F1342).
5. For thermal fabrics, each fabric is prepared for wear and debris generation testing using the Martindale Abrasion Tester with debris collection. The debris is continuously collected and a final weight is noted.
    a. After completing the procedure, specimens are tested for thickness (D1777/D5729), mass (D3776) and air permeability (D737). The debris is weighed and if a fabric generates an excessive quantity of debris comparatively, it is eliminated.
6. After wear testing for both cut and thermal fabrics is complete, fabrics are "passed" or "failed" based on comparative pre- and post- wear and dust penetration resistance performance.

Table 3. Candidate Fabric Information. *A listing of the candidate glove fabrics of interest that the NESC Glove Team investigated and selected for evaluation (highlighted in yellow) using the Lunar Glove Material Test Plan developed during this effort.*

Fabric Tested		Type	Category	Coating	Construction	Weight (oz/yd^2)	Reason for Inclusion
XX	Cotton	Staple	Reference	N/A	plain weave	N/R	*Low strength fabric used for validation testing*
100	Ortho	116	Reference	N/A	2-layer plain weave	14.40	*Baseline fabric used on EMU TMG*
101	PTFE Felt	PTFENF900S	Thermal	N/A	non-woven	26.54	*Used on xEMU EPG around protruding hardware to create a dust seal*
102	Hybrid Shield Thermal Array (single sided)	NSM-HS-TA	Thermal	Elastomer pillars	composite	N/R	*Used on prototype HPEG glove; high temp resistance; flexible fiberglass substrate with elastomer pillars*
103	Hybrid Shield Thermal Array (double sided)	NSM-HS-TA	Thermal	Elastomer pillars	composite	N/R	*Used on prototype HPEG glove; high temp resistance; flexible fiberglass substrate with elastomer pillars*
104	Nomex Nano	Glide Ice	Dust	N/A	composite	6.50	*Nomex nano is used for smoke particle filtration in firefighter garments*
105	Dunmore	TR01447	Cut/Abrasion	Stanet	laminate	7.87	*Fabric selected for VIPER rover suspension cover; VDA/Kapton/Kevlar*
106	Dunmore	Cryoshield	Thermal	aluminum	non-woven	N/R	*Vendor recommended; used for storage of liquid gas*
107	JPS Kevlar	775 KM2 Plus	Cut/Abrasion	N/A	plain weave	6.81	*High MMOD protection; used in other NASA vehicles and military armor*
108	UPT Treated Tyvek	1070D	Dust	ALD-TiO2	spun	2.00	*Dust barrier with coating to enhance UV and abrasion resistance*
109	Uncoated Vectran Ortho	2340	Cut/Abrasion	N/A	2-layer plain weave	20.79	*Included as comparison for coated version of fabric*
110	Uncoated Woven Vectran	2241	Cut/Abrasion	N/A	plain weave	5.63	*Included as comparison for coated version of fabric*
111	Coated Woven Vectran	2241*	Cut/Abrasion	STF	plain weave	9.74	*Shear thickening fluid provides enhanced MMOD, puncture and dust resistance*
112	Coated Vectran Ortho	2340*	Cut/Abrasion	STF	2-layer plain weave	23.83	*Shear thickening fluid provides enhanced MMOD, puncture and dust resistance*
113	Turtleskin	T9-1094	Cut/Abrasion	N/A	plain weave	3.00	*Light weight cut resistant fabric; a version of Turtleskin is used on Ph VI glove*
114	Turtleskin	T9-1391	Cut/Abrasion	N/A	plain weave	5.50	*Light weight cut resistant fabric; a version of Turtleskin is used on Ph VI glove*
115	Mid-Mountain Material	Amatex CF-19	Cut/Abrasion	ceramic	woven	N/R	*Vendor recommended; high strength; high temp range; good flexibility*
116	Superfabric	600d	Cut/Abrasion	guard plates	woven	N/R	*Used in TMG Evolution Task and xEMU kneepads; high op temp; flexible*
117	Sefar Architecture	EL-55-TO	Cut/Abrasion	N/A	woven	N/R	*Fabric evaluated for VIPER rover suspension cover; PTFE fabric; UV resistant*
118	Sefar Architecture	EL-30-T1-UV	Cut/Abrasion	N/A	woven	N/R	*Fabric evaluated for VIPER rover suspension cover*
119	Sefar Architecture	IA-40-CL	Cut/Abrasion	N/A	woven	N/R	*Fabric evaluated for VIPER rover suspension cover*
120	Sefar Architecture	4T40HF	Cut/Abrasion	ePTFE	woven	N/R	*Fabric evaluated for VIPER rover suspension cover*
121	Superfabric	700192	Cut/Abrasion	guard plates	woven	N/R	*Used in TMG Evolution Task and xEMU kneepads; high op temp; flexible*
122	Teflon	T-162	Baseline	N/A	plain weave	8.20	*Used on Apollo suit and EMU gloves*
123	Teflon	T-164	Baseline	N/A	plain weave	9.00	*Used on Apollo suit and EMU gloves*
124	Cormatex	Silica Fiber Felt	Thermal	N/A	non-woven	21.53	*Vendor recommended*
125	Cormatex	Basalt Fiber Felt	Thermal	N/A	non-woven	10.32	*Vendor recommended*
126	Cormatex	Glass Fiber Felt	Thermal	N/A	non-woven	30.97	*Vendor recommended*

7. The evaluation continues for down-selected fabrics by testing each fabric's thermal conductivity in a lunar environment (cryogenic temperature and vacuum). Two specimens are prepared for an ASTM thermal conductivity evaluation (C177) using the Titan Guarded Hotplate apparatus.
8. All fabrics are subjected to destructive testing performed in a LN2 conditioned thermal chamber exposing specimens to a cryogenic environment to characterize strength performance at low temperature.

    a. Strip tensile (breaking strength and elongation) (D5035), tongue tear (D2261), puncture resistance (F1342) tests are conducted. Three specimens are used to perform a stiffness test (D1388) after conditioning the specimens in a LN2 bath for 30 minutes.
9. After cryogenic exposure strength testing is complete, a down select is made based on test performance.
10. A more extensive thermal exposure test is then used to characterize a fabric's ability to resist damage from folding at cryogenic temperatures. Five specimens, are secured to a custom LN2 folding fixture, placed in LN2, cycled 1000 times, and then allowed to return to ambient temperature to perform an ASTM strip tensile (breaking strength and elongation) (D5035) test.
11. For the remaining down selected fabrics, the data set is completed by performing a last round of testing with specimens oriented in the fill direction of the fabric. Specimens are prepared per respective ASTM test guidelines and testing is repeated to create a complete data set.

IV. Candidate Fabric Test Results

As previously mentioned, a reduced-scope version of the Test Plan was completed during this task. The Team evaluated and compared nine fabrics in the "cut/abrasion/dust" category using the pre-screen cryogenic crack test and the pre and post tumbler abrasion strength tests.

1. Pre-Screen Cryo Crack Testing

All nine fabrics were subjected to the pre-screen cryo crack test. Although there were some sounds of cracking heard while folding the fabrics, there were no visible signs of damage, no permanent creases or creation of debris that led to the elimination of any of the fabrics. There are two possible conclusions from this result: either the test is not severe enough to create discernable damage (i.e., damage was caused but the effects could not be determined by only using observation), or all fabrics subjected to the test are capable of being exposed to cryogenic conditions without effect. It is possible that certain fiber types or coatings (i.e., polymers) not included in the nine fabrics would be susceptible to this test. Therefore, future use of this Test Plan should consider either altering this pre-screen evaluation to create more discernable metrics to use for elimination, use microscopy to examine more closely, or running a validation plan on a broader range of fabrics to determine if there is merit in including this test.

2. Tumbler Test Results

The fabrics were "baselined" by collecting data on their tensile/elongation strength, tear resistance, cut resistance, puncture resistance, thickness, mass, air permeability and stiffness properties. The ASTM standards indicated previously were followed for the required quantity, size, and number of measurements to be collected for each fabric.

Following baseline testing, eight 13" x 9" panels of each fabric were subjected to the rotational tumbler wear test. The panels were removed, cleaned, and cut to become specimens used to test their post abrasion strength. The results were averaged. The dust simulant that penetrated through each fabric panel was collected, weighed and results were averaged.

The tensile strength, fabric elongation, puncture resistance, cut resistance and tear strength results will be presented at a later date after the tumbler variation results are understood and can be applied to the candidate fabrics.

Figure 3 summarizes the air permeability (left graph) and the mass of dust that penetrated each fabric (right graph) results. The averaged pre-abrasion, or baseline, air permeability values for each fabric are represented as blue bars. The averaged post-abrasion values for each fabric are represented as orange bars. The mass of dust that penetrated each fabric is represented as green bars. A trend line is shown on both graphs as red arrows. There does appear to be a correlation for fabrics with low initial air permeation such as Kevlar, and the uncoated and coated woven Vectran. They allowed a similarly low magnitude of dust to penetrate. However, for fabrics with a high initial air permeation there seems to be less of a correlation in magnitude to dust penetration such as Ortho, Turtleskin, Teflon, and uncoated Vectran Ortho. There are likely several variables to the fabric construction that would affect these two results such as the denier of the yarn, the coarseness of the weave, finishes, and yarn type which would influence the flow of air particles through the fabric differently than particles of dust which have sharp edges and clump together. Therefore, this is not a 1:1 result but does seem to provide a very basic indication of dust blocking ability for fabrics with low initial air penetration.

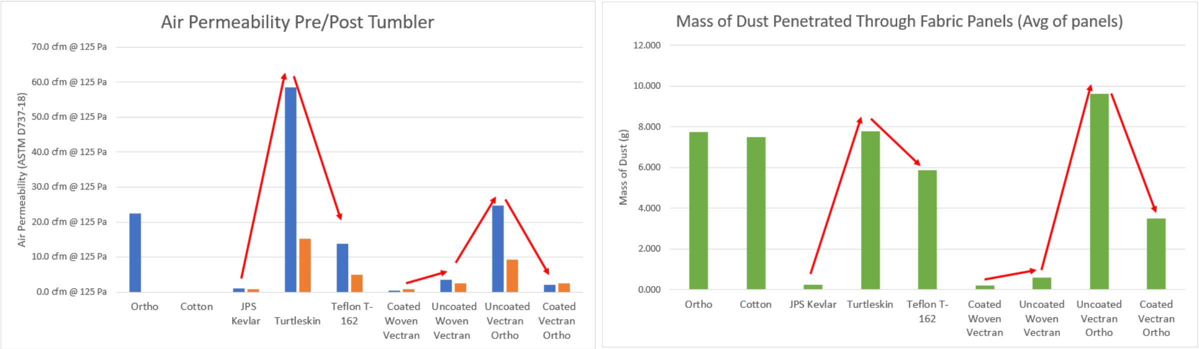

Figure 3. a.) Air Permeability Comparison b.) Mass of Dust Comparison. *Candidate fabrics were tested for air permeability to get baseline values (blue bars). Then they were subjected to abrasion exposure using the rotational tumbler procedure. Abraded specimens were tested, and results are shown (orange bars). The mass of dust penetrated through the panels was collected and weighted and results are shown (green bars). A rough correlation exists between the air permeability and the quantity of dust penetrated (red arrows).*

V. Discussion of Results

Several observations were made about the effectiveness of the subset of tests performed and conclusions about the data gathered on the candidate fabrics and the coatings. The pre-screen cryo test was found to be ineffective at creating a discernable difference between the fabrics. It is possible that all fabrics subjected to the test were capable of being exposed to cryogenic conditions without effect from one-fold. Future testing may consider altering the parameters of the test or eliminating it altogether. One option would be to expand the test to include pre and post cryo exposure tensile testing as a method to better determine degradation.

A tumbler abrasion test method was developed with a focus on inducing consistent, repeatable accelerated wear on fabrics and providing a method to compare dust resistance. The results of the variability of the test on the strength degradation are still under review but the intent is that this test will provide valuable insights into how the performance of the candidate fabrics in various metrics changes as they are worn by the lunar simulants.

Thickness and mass measurements, though very simple to test, did not provide any additional insight into the fabrics abrasion resistance or indicate their ability to not retain dust. These tests could be eliminated in future testing to reduce resource utilization.

The air permeability test does seem to be an indicator of a fabrics ability to resist dust however it is not an absolute equal analogue. The STF coated woven Vectran had the lowest air permeability and the most dust resistance. A possible addition to the test series would be the inclusion of ASTM F2299 which defines a test method for determining the efficiency of materials to resist penetration by particulates which was not feasible to include for this effort.

The Team also used microscopy to investigate how the various fibers and coatings faired from abrasion. In general, it was observed that PTFE yarns (both monofilament [like in Ortho Fabric] and multifilament [T-162]) do not stand up well to dust abrasion. They exhibit a unique shredding effect which ultimately attracts and traps lunar simulant. While this likely has a minimal effect on the strength properties of the fabric, it could be a major cause of concern for thermal performance and prolonged degradation of material even after removal from the lunar environment.

Regarding observations made on fabric and yarn construction, tighter fabric constructions showed less degradation than structures with more openness. This is also true with yarns in that more compact multifilament yarns performed better than both staple yarns (cotton/Turtleskin) and monofilament yarns (PTFE). This correlates to a fabric's susceptibility to dust incursion. The tighter the structure, the less intrusion there is.

In a similar observation, flatter fabric structures generally outperformed more textured fabrics. For example, the woven Vectran fabric had a tightly woven plain (1x1) weave. This type of woven structure minimizes the peaks and valleys seen in woven fabrics, due to its simple over under construction. In contrast, fabric structures like Ortho Fabric have many deep valleys and peaks in its topography, which allows for significantly more dust penetration and thus more damage.

As mentioned previously, the coatings (STF + COTS hydrophobic) were shown to improve dust resistance over the uncoated versions. The reason for this was made clearer when comparing images which showed that the coatings appear to aid in preserving fabric and yarn structure. The coatings appear to bind together the multifilament yarns which prevents deep incursion of simulant and subsequent damage to the fibers in the yarns. The coatings also aided in locking the woven structure in place, whereas the uncoated fabrics showed movement in the fabric structure in the form of widening gaps and shifting yarns.

However, the coatings seemed to have minimal benefits on the monofilament yarns, such as the Teflon in the modified Vectran™ Ortho Fabric. Also, the effectiveness of the coating seemed to be heavily affected by fabric structure as well. This was most obvious between the coated Vectran™ Ortho and the woven Vectran™. As mentioned above the Ortho Fabric structure has many peaks and valleys which allows for deep/quicker dust penetration. In the tumbled Vectran Ortho there was a significant loss of coating, likely due to the early incursion of simulant, whereas the woven Vectran retained much of the original coating.

In summary, the preliminary results of this testing indicate that future efforts should consider tightly woven, multifilament yarn, coated fabrics for the glove EPG cover layer. For this effort, the coated woven Vectran was shown to have the best dust resistance. One caveat to this recommendation is that Vectran is known to degrade from UV exposure (discoloration and some strength loss) which was not captured in this evaluation. Therefore, future testing should examine this effect to determine if the Vectran needs additional UV resistance enhancement.

VI. Conclusion and Future Work

This effort has provided significant value to Artemis EVA glove development by assessing the current state of NASA's ability to test gloves, identifying deficiencies, and setting up the resources necessary to begin tackling a very large effort in standardizing glove testing. This work was divided into three main tasks. Task 1, the focus of this paper, worked to vet a test plan for selecting and testing potential EVA glove fabrics using a bevy of ASTM and NASA developed tests. The resulting test plan is extensive, by necessity, but as a result could not be completed within the resources of this effort. Instead, a small group of candidate EPG glove fabrics selected for their base fiber composition and coatings, were subjected to a subset of the test plan to characterize their performance after exposure to wear testing in the rotary tumbler abrasion test. The collected data will be used for follow-on efforts by NASA and its vendors to design and test more bespoke, engineered fabrics for use on the moon.

Task 2 and Task 3 are still in progress and the results from those efforts will be made available later. Task 2 was established to define a procedure for testing the thermal performance characteristics of a space suit glove assembly in radiation, grasp and high force grasp states in cold temperatures equivalent to the PSR of the Lunar poles. It will develop a standardized test procedure using a custom designed thermal mannequin hand and will utilize a liquid helium vacuum chamber at NASA's Jet Propulsion Laboratory to collect data baselining the Phase VI glove. Task 3 work will focus on developing a standardized method for testing the cut resistance of an EVA glove at cryogenic temperatures. The existing ASTM 2992 cut resistance test will be adapted to use a custom design LN2 fabric freezer on the test apparatus capable of maintaining cryogenic temperatures while the cut test is performed. In this way, fabric performance at very cold temperatures can be compared to baselined Phase VI materials. Lessons learned from these efforts will significantly impact requirements, design, and glove evaluation going forward.

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