53rd International Conference on Environmental Systems
21-25 July 2024, Louisville, Kentucky

Establishing a Standardized Test Method for Evaluating the Cut Resistance of Space Suit Glove Fabrics

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

Morgan B. Abney[2], Tim Brady[3], Danielle Morris[4]
NASA Engineering and Safety Center, Langley Research Center, Hampton, VA 23666

Richard Rhodes[5],
NASA Johnson Space Center, Houston, TX 77058

Shane McFarland[6], David Cox[7]
Aegis Aerospace / KBR HHPC / NASA Johnson Space Center, Houston, TX 77058

Joe Settles[8]
Jacobs / NASA Johnson Space Center, Houston, TX 77058

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

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 against the continual threat of inadvertently cutting the fabric of the glove. Second, there is insufficient data on state-of-the-art glove cut performance at lunar temperatures 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 glove fabrics can meet new, challenging cut requirements. This paper focuses on the development of a test procedure to characterize the cut resistance of lunar EVA glove fabrics at cryogenic temperatures using a modified ASTM standardized test method. The results of testing on Phase VI glove fabrics are presented.

Nomenclature

ASTM	=	American Society of Testing and Materials
C	=	Celsius
COTS	=	Commercial Off the Shelf
CPPT	=	Cut Protection Performance Tester

[1,5,6,7] 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, EVA and Human Mobility Deputy, Marshall Space Flight Center, AL.
[8] Advanced Materials Laboratory Lead, NASA Johnson Space Center, Houston, TX
[9] Senior R&D Laboratory Manager, Wells Lamont, Skokie, IL

EPG	=	Environmental Protection Garment
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
F	=	Fahrenheit
gf	=	gram-force
in	=	Inch
IRSST	=	Institut de recherche Robert-Sauve en sante et en securite du travail
j	=	waypoint index
K	=	Kelvin
LN2	=	Liquid Nitrogen
MLI	=	Multi-layered Insulation
mm	=	Millimeter
RTV	=	Room Temperature Vulcanized
TDM	=	Tomodynamometer
TMG	=	Thermal Micrometeoroid Garment

I. Introduction

THE performance of extravehicular activity (EVA) on the lunar surface, which could require handling sharp edges on tools or other hardware combined with the dust and sharp rocks of the lunar environment, poses a distinct hazard to astronauts navigating and conducting activities on the Moon. Because of these hazards, EVA gloves are required to provide a level of resistance against being cut. Cuts can open holes allowing excess dust to easily breach to the more delicate under layers. Deep cuts can cause significant damage to the underlying pressure retaining layer potentially causing a suit leak. Understanding and mitigating the cut risks inherent in the space suit glove fabrics is paramount to ensuring the safety and functionality of lunar missions.

Fabric strength properties are typically influenced by environmental conditioning at the time of use[1]. For this reason, standardized tests call for fabric test specimens to be preconditioned to defined temperature and humidity[2] ranges. In actual use, the fabrics will undergo a wide variety of property changes as they are exposed to the extremely variable lunar conditions. One condition that is relatively unexplored is fabric performance at cryogenic temperatures. Therefore, NASA has undertaken an effort to develop several new test methods for evaluating the performance of these fabrics in the context of their use. This paper provides the background of one such test exploring the cut resistance of fabrics and then details a NASA led effort to devise a cut test that includes the ability to chill specimens to cryogenic temperatures. The data gathered from this study is part of a larger suite of data that is intended to provide information to NASA and its suit vendors about the impact of the lunar environment on various suit materials.

II. Cryogenic Cut Test Method and Materials

A. Approach Overview

Because mission temperature limits for lunar exploration are more extreme on the lower end and limited fabric performance data are available in this regime, efforts were focused on devising a method for evaluating cut resistance while at cryogenic temperatures. No literature could be found describing the cut performance of fibers at cryogenic temperatures. However, research into the topic revealed that, in general, fabrics lose pliability and display increased stiffening when exposed to decreasing ambient temperatures[3]. Additional research[4] suggests that stiffening of carbon fiber yarns and fibers causes the breaking strength of carbon fiber composites to *increase* in varying amounts depending on the properties of the given fabric. Based on this literature, two initial theories were formed: either the cut resistance would increase similar to the carbon fiber breaking strength as a result of fiber stiffening from becoming cold, or the cut resistance would decrease due to the fibers becoming brittle and being less resilient to the applied force of the blade moving across the fibers. To determine the effect of cryogenic temperatures on materials of interest for gloves, a systematic approach was taken to devise the test methodology.

ASTM F2992-23 "Standard Test Method for Measuring Cut Resistance of Material Used in Protective Clothing with Tomodynamometer (TDM-100) Test Equipment" is a recognized standard for testing the cut resistance in commercially available safety gloves (at ambient temperatures). Industry wide, this standard is replacing the previously used ASTM F1790-21 due issues with the test apparatus called out in that standard. Therefore, F2992-23 was chosen for adaptation to meet NASA cryogenic test needs, as described in Section II. It was adapted to include a feature to chill the fabric specimen to cryogenic temperatures. After reviewing available resources in the NASA Johnson Space Center (JSC) Advanced Materials Laboratory (AML) where testing was conducted, the decision was made to locally chill the fabric holding portion of the TDM-100 with a lab supplied liquid nitrogen (LN2) feed system. Tasks included the design and fabrication of a custom clamp and specimen holder (or mandrel) for use with the TDM-100 to provide LN2 to cool the test specimen to cryogenic temperatures (-250F/116K) and the pre-testing of the specimen holder to study the effects of frost buildup and humidity on the components.

To evaluate the effectiveness of the newly developed Test Procedure, after blade calibration at ambient condition, multiple cut resistance measurements at ambient and cryogenic temperatures were conducted on pristine versions of fabrics in the Phase VI Glove and the Extravehicular Mobility Unit (EMU) thermal micrometeoroid garment (TMG). Sufficient data were collected (45 cuts per specimen type per temperature) to perform a regression analysis. Results are presented in this paper.

B. Terrestrial Cut Testing Background

ASTM F2992-23 is the current revision of a standard test method that pertains to evaluating the cut performance of materials used in protective clothing. This standard is specifically focused on gloves used for protection against cuts in various industries, such as manufacturing, construction, and automotive. The purpose of ASTM F2992-23 is to provide a consistent and reliable method for testing the cut resistance of materials. ANSI/ISEA 105-2016 is the standard that outlines the testing procedures and requirements that gloves must meet to be classified into different cut resistance levels. These levels are categorized as ANSI/ISEA 105-2016 Cut Level A1-A9. See Table 1.

Table 1. Standard Cut Resistance Ratings. *In the context of cut resistance, gloves are rated on a scale from A1 to A9, with A1 being the lowest level of cut resistance and A9 being the highest. This allows users to choose gloves that match the level of protection required for their particular work environment.*

Gram-force	Rating	Range	Common Applications
200	A1	Low	General, Warehouse, Maintenance
500	A2		Construction, Injection Molding
1000	A3	Medium	Metal Stamping, Oil-gas
1500	A4		HVAC, Food Prep
2200	A5		Glass or Sheet Metal Handing
3000	A6	High	Machining, Paper Handling
4000	A7		Recycling, Movement of Sharp Objects
5000	A8		Metal Assembly, Waste Management
6000	A9		Food Processing

The TDM-100 test apparatus, shown in Figure 1 is used to perform the cut testing in ASTM F2992-23. The TDM-100 is considered the standard cut resistance test machine in much of the world[5]. It is the primary cut resistance test machine for both ASTM F2992 (used in ANSI/ISEA 105-2016, the American Hand Protection Standard), and EN ISO 13997 (used in EN 388:2016+A1:2018, the standard cut resistance test method in the European Union). It has several key components that provide a controllable and repeatable way to measure cut resistance. These components are shown in Figure 2.

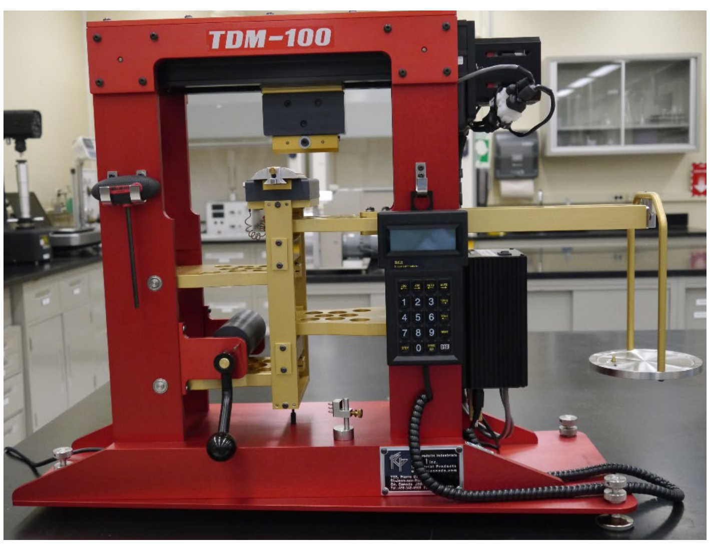

Figure 1. Tomodynamometer. *IRSST developed the Tomodynamometer test apparatus to address issues seen in previous textile cut resistance test methods. This device was utilized to perform the cut testing summarized in this report.*

The test method calls for the TDM-100 to apply a constant force to a standardized blade which is maneuvered using a motor and lead screw in a straight line across the work area of the machine frame. The blade is moved across the surface of a material specimen to create a cutting motion. A lever system, beam balance, and weights are used to apply a known force under the material specimen pressing it into the moving blade. The length of travel of the blade to cut cleanly through the specimen at different forces is recorded and the resulting data are used to determine the cut resistance level of the sample.

The material specimen is prepared by cutting the fabric into approximately 2”x4” rectangles which are cut on the bias for a woven fabric (cut at a 45° angle to the fill and warp yarns). It is then mounted over a curved aluminum specimen holder (or mandrel) supported on a mechanical lever system that can maneuver the sample vertically into a blade. A cantilevered beam connected to the specimen holder has a weight bearing platen. Laboratory calibrated weights are added to the arm to produce the lifting force. The sample is positioned on the specimen holder and secured with a clamp that fastens onto the top of the specimen holder providing a downward clamping force on the material holding it in place.

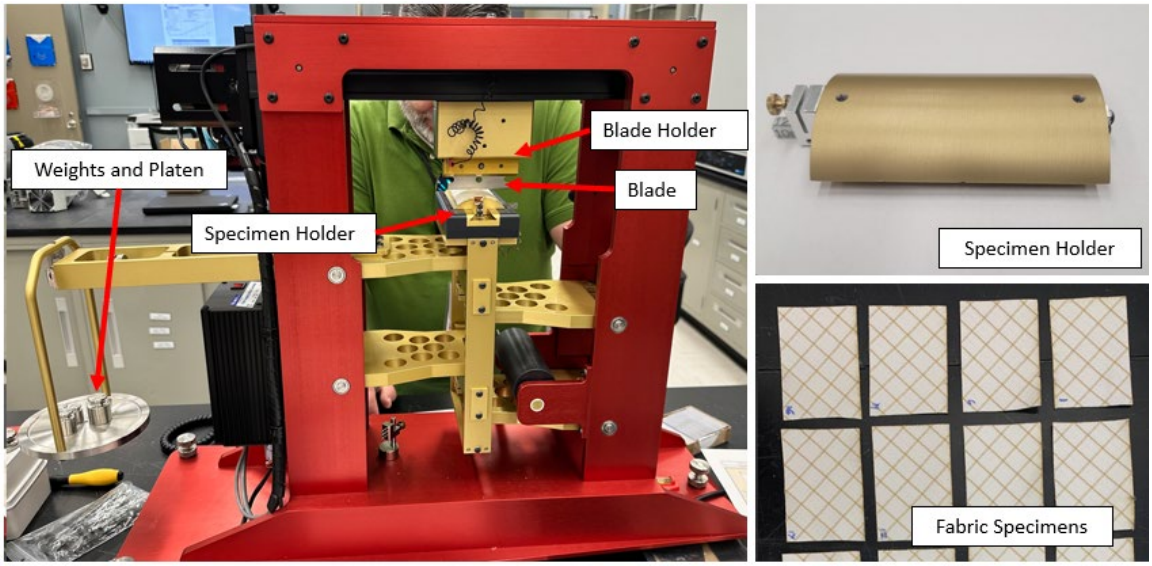

Figure 2. Illustration of the TDM-100 Components. *The TDM-100 has several key components that provide a controllable and repeatable way to measure the cut resistance of materials.*

The blade is mounted into a moveable clamp positioned over the top of the work area. The clamp and blade are moved horizontally via a lead screw turned by a stepper motor as shown in Figure 3. When the blade contacts the metal specimen holder after cutting through the fabric, a circuit is completed, and the test apparatus stops reporting the distance the blade has traveled. This distance is used to calculate the cut resistance.

Per ASTM F2992-23, five tests at each of three different loads are required to calculate the cut resistance at a standard distance. Loads are selected to produce five data points in each of three cut-through distance ranges: 5 to 20 mm (0.2 to 0.8 in.), 20 to 33 mm (0.8 to 1.3 in.), and 33 to 50.0 mm (1.3 to 1.97 in.). ASTM F2992-23 provides additional details about the test setup and load selection. The machine uses mechanical leverage such that the resulting load applied to the specimen against the blade equals twice the total weight placed on the platen.

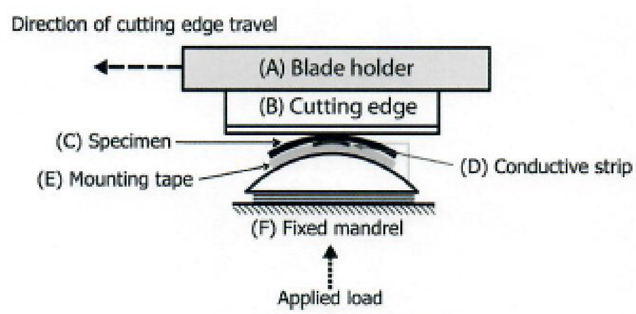

Figure 3. Illustration of the Cross Section of the TDM-100 Test Area (credit: ASTM F2992-23). *The edge of the blade is slid horizontally across the fabric mounted to the top of the specimen holder.*

C. Cryogenic Test Method Development

In order to evaluate glove material cut resistance at cryogenic temperatures, ASTM F2992-23 was used as a basis. Four key changes were made for this purpose. Details of these changes are provided below. This allowed NASA to quickly provide glove vendors with clear and standardized information regarding the cut resistance of fabrics while conversely planning for vendors to use the same procedure to vet the capabilities of any newly selected fabrics and ply-ups (representation of a cross section of layers through the TMG) they choose to use in their gloves.

Cut length values and weights measured for this effort were recorded on a datasheet provided by the ASTM entitled "WK85995 Cut Resistance Template". It uses a regression calculation to determine the weight needed to cut the material to a standard reference distance (20mm). The averaged resulting weight after three repetitions of the test on a single fabric is reported as "gram-force" cut resistance level on the ANSI/ISEA 105-2016 scale. A gram-force (gf) is a unit of force in the centimeter-gram-second (CGS) system of units. It is defined as the force exerted by one gram of mass under standard gravity (9.80665 m/s²). So, one gram-force is equal to the force exerted by gravity on a mass of one gram, which is approximately 9.80665 millinewtons (mN). Gram-force is often used in engineering contexts, particularly in areas like material strength testing, where smaller forces are involved.

1. LN2 Modification to Test Apparatus

To add the capability of cooling the test specimens to cryogenic temperatures Technifab, LLC was contracted to design and manufacture custom components for the TDM-100. Technifab specializes in designing equipment to be used with LN2. Several approaches were considered but ultimately the specimen holder and its base were modified to allow LN2 to flow through, super chilling the fixture and the attached fabric. The LN2 specimen holder was designed to receive LN2 from and vent gases to facility LN2 plumbing. This was selected over a standalone system because of the capacity to continuously flow LN2, thereby reducing manpower. In addition, the lab already used a similarly designed heat exchanger, so the integration of this new system took minimal effort.

The sample holder receives supplied LN2 from a facility valve which diverts a portion of the main flow through a commercial off the shelf vacuum jacketed Teflon™ lined flex hose. The hose plumbs into a ¼" male AN fitting (covered with black caps in Figure 4) welded to an aluminum inlet tube on one end of the custom-made specimen holder. The inlet tube flows LN2 to a machined hole through one side of the aluminum specimen holder, which then exits the specimen holder to a second welded, u-shaped aluminum tube and is routed to the opposite, return side of the specimen holder. A welded-on outlet tube with a second ¼" male AN fitting is plumbed to a second vacuum jacketed flex hose which is connected to the facility LN2 exhaust system and is then vented from the lab.

In ASTM F2992-23, the fabric specimen is affixed to the specimen holder using double-sided tape and a copper strip is added to improve the conductivity of the circuit which detects when a cut has occurred. However, due to concerns regarding the potential loosening or brittleness of the tape under cryogenic conditions, the copper strip was eliminated and the anodization on the top of the specimen holder was removed, allowing for a completion of the circuit between the blade and specimen holder. A modified clamp serves as a viable alternative to the tape, addressing the concerns associated with tape integrity and ensuring a reliable and secure attachment of the specimen to the specimen holder during testing. The clamp can accommodate material thicknesses up to 20 mm.

To expedite the time required to perform all the cut tests at cryogenic conditions, a custom top clamp was fabricated that included 10 slots for samples to be cut rather than the standard 7 provided by the nominal TDM-100 clamp. Technifab also fabricated a custom specimen holder mount out of G10 fiberglass to provide some insulation between the super chilled specimen holder and the other temperature sensitive components of the TDM-100.

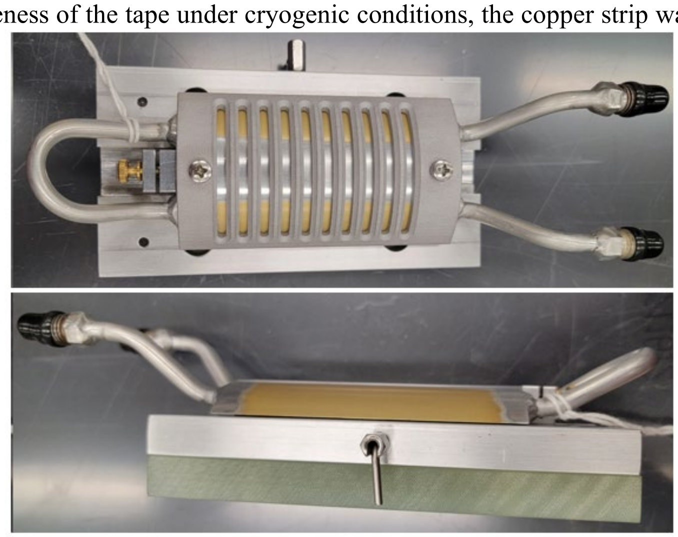

Figure 4. Custom LN2 specimen holder, Clamp, and Base. *LN2 is routed through tubing connected to drilled thru holes in the specimen holder. A 10-slot clamp holds the test specimen during cutting.*

2. Adjustment to Cut Length Ranges

The TDM-100 can move the blade a total of 60mm and therefore has a total range of 0-60 mm. However, due to a risk of catching the corners of the blade on the fabric normal operation range is set to 2-56 mm which provides a safety margin for corner clearance. The usable cut length set forth in ASTM F2992-23 more conservatively sets the operating range to 5-50mm defined by three unequally spaced subranges of cut length set to 5-20, 20-33 and 33-50mm.

During this effort, the full operating range of the machine was used to maximize data collection (less discarding of useable data that falls between 2-5mm and 50-56mm). This allowed the cut ranges to be evenly divided at 18mm each (2-20mm, 20-38mm, and 38-56mm) to allow for a greater range of results. Any data outside of the 2.0 mm-56.0 mm range was recorded separately as "No Cuts".

This information was shared with the designer of the machine IRSST, who concurred with this change.

3. Combination of Data Points

In the original cut standard, five replicated tests at each of three different loads are conducted resulting in 15 total cuts per specimen type to make a determinization of the cut resistance. The Team discussed conducting 3 repetitions of the 15-cut test to assess within-test and between-test variability. However, the Team elected to collect the equivalent amount of data within a single 45 cut total test, combining all data points into a one set.

This change was made for two reasons. First, it makes the calculation of the standard deviation and confidence interval for the entire data set easier to calculate and compare which is difficult because of the regression analysis computation. Second, the Team felt it made a stronger statistical analysis to have at least 30 data points in the set. As a general rule of thumb, a sample size of at least 30 is considered to be sufficient for the Central Limit Theorem to hold true and for the mean of the data to approximately follow a normal (Gaussian) distribution. Therefore, the procedure was written to preform 45 cuts as one data set in the assertion that their normalized sum would be more accurate.

4. LN2 System Balancing

The addition of the cryogenic specimen holder, holder base, and filled LN2 hoses required some additional care in balancing the weighted platen of the TDM-100 and a few items of support equipment to help offset the added weight. The procedure was updated with steps to balance the beam with the sample prior to adding weights to the platen. This can be done by adjusting the calibration weights or by adding half of the weight of the cryogenic system (to be determined by the Test Operator) to the platen.

In addition to system balancing using the weights and beam, a simple rolling hanger system was implemented to support the weight of the LN2 hoses hanging from the back of the machine.

D. Test Material Selection and Justification

To evaluate the effectiveness of the newly developed test procedure, multiple cut resistance measurements at ambient and cryogenic temperatures were conducted on pristine versions of fabrics in the Phase VI Glove TMG. This test article was selected because it is the current, certified for flight, EVA glove and therefore it was desirous to collect "reference" cut values for comparison to candidate lunar fabrics. It should be noted, however, that the Phase VI glove was designed for use in low Earth orbit and not a lunar environment.

The TMG has three main components: the palm, the finger/hand back and the gauntlet. Each has its own unique ply-up (cross section) of highly specialized fabrics performing a function. Four outer materials (Ortho Fabric, Teflon T-162, Turtleskin 816A, and Room Temperature Vulcanized (RTV) 157 silicone rubber) and two unique fabric ply-ups (gauntlet and EMU TMG) were selected and tested per the newly adapted procedure. See Figure 5 for a reference of where each fabric and ply-up appear on the glove TMG. These fabrics comprise the primary outer surface of the glove and thus would be the most susceptible to receiving cuts.

Ortho Fabric was developed for use on the Shuttle and then eventually the ISS EVA suit. Teflon T-162 was used on the Apollo suit as well as on the Phase VI glove. RTV silicone rubber pads comprise the palm, finger/thumb fronts and finger caps of the gloves. Turtleskin Vectran T9-816A was added to the Phase VI glove in high-risk areas to increase cut protection from metal edges found on the ISS[7]. The ply-ups were included to determine if multiple layers of unique fabrics could be tested at the same time. The ply-up of the gauntlet area of the glove was chosen because surplus glove gauntlets were made available for testing. The gauntlet plyup includes Teflon, three layers of MLI, and Ortho Fabric.

Figure 5. Phase VI TMG Fabric and Ply-up Locations. *Teflon T-162 is located on the outside of the hand back and wrist portion of the glove, RTV 157 is the compound used to form the palm and finger pads, Ortho Fabric is located in the wrist and is also the outer fabric of the EMU, Turtleskin is used as a cut resistant layer on the fingers and palms. The glove gauntlet is a ply-up of fabric (Teflon, multilayered insulation (MLI), Ortho) that covers the suit lower arm.*

The EMU TMG ply-up was included because of its relevance to the cut protection of the entire suit. It is comprised of pristine layers of Ortho Fabric, 5 layers of MLI, and a layer of neoprene coated nylon liner fabric. The fabrics and ply-ups are further detailed in Table 2.

Table 2. Fabrics and Layups selected for Ambient and Cryogenic Cut Testing. *The location and details of each are included for reference.*

Material	Location	Notes
Ortho Fabric	Phase VI; Outer layer of gauntlet	14.5 oz/yd², 3D basket weave, Gore-Tex, Nomex and Kevlar fibers
Teflon™ T-162 Fabric	Phase VI; Outer layer of hand back and fingers	9.3 oz/yd², plain weave, Teflon fibers
RTV 157 Pads	Palm, finger/thumb fronts and finger caps	3/16" thick, light grey
Turtleskin T9-816A	Palm side of the Thumb and first finger	6.9 oz/yd², tri-knit, Vectran fibers
EMU TMG ply-up	EMU suit TMG layup	Ortho Fabric, 5 layers of Aluminized Mylar, Neoprene coated Nylon
Phase IV Gauntlet TMG ply-up	Below hand of glove, covers suit wrist bearing	Teflon™ fabric, 3 layers of Aluminized Mylar, Teflon™, Ortho Fabric

E. Test Procedure and Test Matrix
The detailed test procedure was captured as a new document entitled "CTSD-ADV-2116 Tomodynamometer LN2 TDM-100 Cut Tester Operating Procedure". It closely mimics the ASTM 2992-23 standard with the included steps of how to setup and perform the testing with the newly developed LN2 specimen holder and clamp. The test matrix was generated by referencing the ASTM standard for the specified number of cuts at each range of distance as detailed in Table 3.

Table 3. Ambient and LN2 Cut Testing Matrix. *This matrix details the quantity of cuts performed in each distance range at both ambient and cryogenic temperatures.*

Sample	Ambient Cut Through Distance (mm)	# Of Cuts	Cryogenic Cut Through Distance (mm)	# Of Cuts
Ortho Fabric	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15
Teflon Fabric	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15
Turtleskin	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15
RTV-157	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15
P6 Gauntlet TMG Ply-up	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15
EMU TMG Ply-up	2.0-20.0	15	2.0-20.0	15
	20.0-38.0	15	20.0-38.0	15
	38.0-56.0	15	38.0-56.0	15

III. Test Results

A. Frost Accumulation
During development of the cryogenic test procedure, there were concerns that ambient humidity around the test apparatus would accumulate as frost on the chilled faces of the specimen holder and fabric samples. It was speculated that the excess frost/ice could impede the blade movement across the fabric altering the test results as compared to a dry material sample.

Exploratory testing of the frost accumulation and the potential effects of the frost on the cut testing process was conducted by submerging the LN2 specimen holder, a specimen of Vectran™ fabric and the clamp into an LN2 filled pan. Initially, the assembly was cold soaked for 5 minutes, removed and observed. Immediately after removal, it was noted that almost no frost had formed on the assembly as shown in the upper image in Figure 5. However, after approximately five minutes of sitting on the lab counter, a layer of frost began to form. It was determined that the boiloff of the LN2 in the pan caused dry, nitrogen gas to surround the assembly which prevented contact with the humid, ambient air. After removal from the bath, the nitrogen gas was no longer present, so the humidity began to condense as frost on the surfaces. Longer duration exposures were conducted at 15 and 20 minutes to determine the severity of frost build up. The accumulation after 20 minutes is shown in the bottom image in Figure 6.

A small, metal spatula was used to investigate the stiffness of the frost. It was easily removed from the clamp and was observed to be an amorphous, powdery texture rather than solid ice. The spatula was used to remove frost from one of the slits in the clamp. Very little frost was observed on the material specimen itself.

From this exploratory testing, it was determined that frost buildup from ambient moisture was not a significant concern due to the softness/texture of the ice particles. Frost buildup was deemed unlikely to significantly affect the TDM blade or cut force. As long as the specimen holder was kept cold, the frost would not melt and wet the fabric. Further, the material samples tested were highly hydrophobic and not susceptible to water entrainment. Therefore, cut testing was conducted without mitigating frost buildup during testing. During data collection, cumulative frost buildup was found to be more substantial than during exploratory testing.

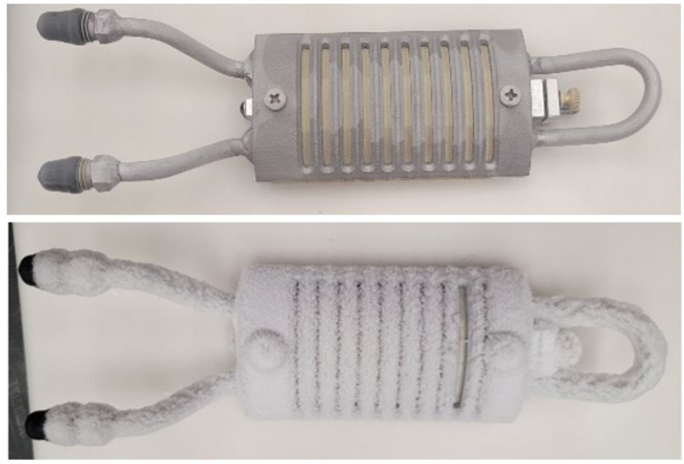

Figure 6. Frost Accumulation Testing. *(Top) Specimen holder directly after being removed from LN2 cold soak (Bottom) Specimen holder after exposure to humid air for 20 minutes after LN2 cold soak.*

During data collection, it was observed that the frost build-up on the LN2 specimen holder exceeded the thickness of frost witnessed during exploratory testing as shown in Figure 7. However, the additional frost did not impede testing or impact the overall operation of the machine. When needed, it was easily brushed away. The configuration of the system allowed the efficient swapping of fabric specimens while the specimen holder remained cold by simply wiping off the frost from its surfaces using a towel. Notably, when the specimen holder was allowed to return to ambient temperature, the accumulated frost melted, resulting in an excess of water on the machine. This required the excess water to be removed before proceeding with further operations or shutting down the test at the end of a day.

B. Teflon Fabric

The Teflon™ fabric presented difficulties which forced its elimination from cut testing. A valid cut length could not be obtained. Even with the beam of the TDM-100 properly balanced as per the ASTM protocol, it was not possible to keep the blade properly engaged on the specimen holder during testing. A possible explanation is that low cut resistance fabrics that are easily sliced through are outside the bounds of what the machine can detect with its beam balance offsetting the load of the LN2 components. Future testing will need to consider that fabrics similar in cut resistance to Teflon (approx. 100 gf) may require a different test method for evaluation at cryogenic temperatures.

C. Temperature Limits of System

A thermocouple affixed to the side of the specimen holder allowed its temperature to be observed during testing. The measurements indicated that the specimen holder and materials reached steady state at approximately -250F (116K) which was consistently achieved within 10 minutes. The time to temperature was captured in the Testing Procedure for future use.

Figure 7. Frost Accumulation During Data Collection. *The specimen holder and surrounding components collected more than expected frost during testing but did not affect the function of the machine.*

There was some concern that a room temperature blade would locally heat the fabric specimen causing the results to not reflect the coldest conditioning possible. Therefore, a thermocouple was also affixed to the blade to monitor its temperature during testing. In an effort to mitigate the effects, the side of each blade was brought into contact with the chilled fabric clamp allowing it to pre-condition before each cut. Each blade consistently reached steady state temperature in approximately 2 minutes. However, because the blade was not thermally isolated from its clamp, its temperature reached steady state at 25F (269K). While this did have some effect and brought the blade temperature to below freezing, it was still significantly higher than the specimen holder temperature. Future improvements to the test could consider better blade isolation to achieve even colder temperatures.

D. Cut Test Results

Cut test data was collected for each type of material and ply-up at ambient and cryogenic conditions. Contrary to the speculation of the Team, all tested fabrics and ply-ups were found to exhibit *increased* cut resistance at cryogenic temperatures. A summary of the test results is provided in Table 4 and Figure 8. Fabric or ply-up type is listed along with the temperature condition at which the data in each line was collected. Forty-five measurements were taken of each type and the cut distances were entered into the ASTM supplied worksheet which has embedded formulas to determine the reported values (calculated load, standard deviation, 95% confidence interval, and R2). The calculated load represents the *theoretical load required to cut through the fabric or ply-up in 20mm* and it was determined by using the Annex A1 from the draft standard. The % increase column was calculated using the formula:

$$percent\ increase\ (\%) = \frac{|Final - Start|}{|Start|} X\ 100$$

where "Final" in formula is defined as the calculated load at cryogenic temperature. "Start" is the calculated load at ambient temperature.

Table 4. Ambient and Cryogenic Cut Testing Results. *This matrix summarizes the cut data collected at both ambient and cryogenic temperatures.*

Sample	Temperature Condition (F/K)	Calculated Load (gf)	Est. Cut Rating	Standard Deviation (gf)	95% Confidence Interval (gf)	R^2	% Increase
Ortho Fabric	70/294	356.3	A1	7.5	±15.2	0.6874	126.8
	-250/116	808.0	A2	24.3	±48.9	0.5158	
Teflon Fabric	70/294	*Removed from Test Series*					
	-250/116						
Turtleskin	70/294	742.3	A2	18.8	±37.8	0.4441	117.1
	-250/116	1611.6	A4	38.6	±77.8	0.4871	
RTV-157	70/294	496.3	A1	23.2	±46.8	0.5337	358.1
	-250/116	2273.6	A5	52.1	±105.1	0.536	
P6 gauntlet TMG Ply-up	70/294	698.1	A2	9.0	±18.2	0.8057	118.8
	-250/116	1527.7	A4	43.5	±87.7	0.4883	
EMU TMG Ply-up	70/294	737.3	A2	16.0	±32.2	0.6622	604.3
	-250/116	5192.8	A8	56.7	±114.3	0.3605	

The percent increase of cut resistance for the Ortho Fabric, Turtleskin® T9-816A, and Phase IV Gauntlet TMG Ply-up materials at cryogenic temperature ranged between 117.1% - 126.8%. This raised the estimated cut rating, as shown in Table 1, one to two levels depending on the fabric. The RTV-157 and EMU TMG ply-up obtained significantly larger cut resistance increases of 358.1% and 604.3%, respectively. This raised the estimated cut rating four to six levels. For comparison, a common A1 or A2 glove for terrestrial use might be used for small parts assembly or packaging. An A4 glove might be used for carpet installation, dry walling, or bottle and light glass handling. An A8 glove might be used is metal stamping, metal fabrication, and glass and window manufacturing.

Figure 8 shows the calculated loads for each fabric and ply-up for both ambient (blue bars) and cryogenic conditions (red bars).

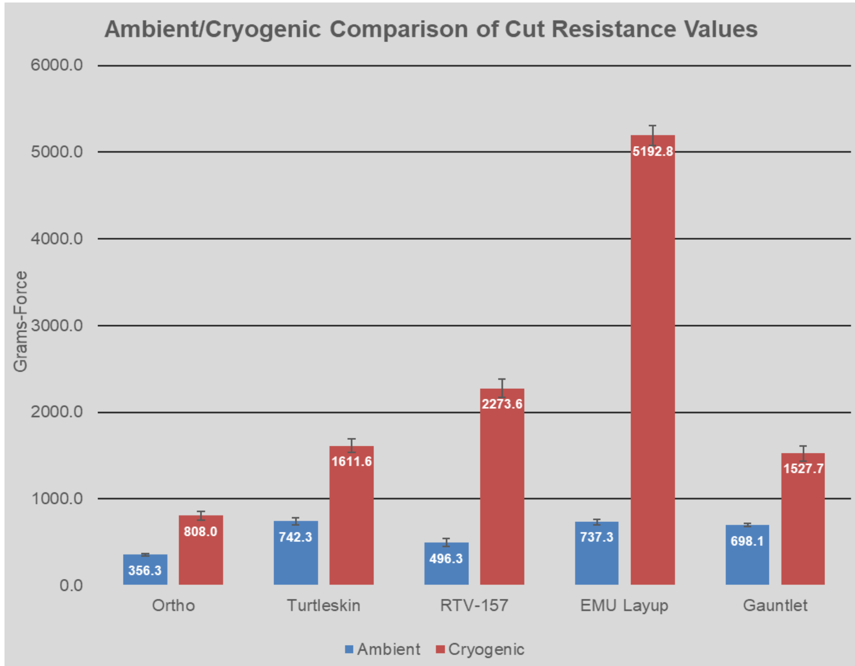

Figure 8. Ambient and Cryogenic Cut Testing Results. *The calculated cut resistances from ambient testing are shown as blue columns. The cryogenic results are shown as red.*

IV. Analysis of Results

A. R^2 Values

A regression model is a statistical model that attempts to establish a relationship between one dependent variable and one or more independent variables. In this test the independent variable is the load applied and the dependent variable is the cut length. The goal of regression analysis is to understand and quantify the relationship between variables, predict the value of the dependent variable based on the values of independent variables, and assess the statistical significance of the estimated relationships.

In simpler terms, regression analysis helps to identify and understand the patterns in data, allowing for the prediction of outcomes based on input variables. The basic idea is to find the best-fitting line (or curve) that minimizes the difference between the observed values of the dependent variable and the values predicted by the model.

Figure 9 is an exponential regression graph produced by the ASTM Worksheet after populating it with the cut data for Ortho Fabric at ambient temperature. A best fit line is drawn through the data. This line is then used to determine the load in gf corresponding to a 20 mm long cut (blue reference lines).

The R^2 value, which is also calculated for each data set on the worksheet, represents the "goodness of fit" in a regression mode and ranges 0-1. Zero indicates that the model does not explain the variability in the dependent variable. One indicates that the model explains all variability. This value is influenced by various factors and for textiles may often be lower compared to other types of tests. For textile cut resistance testing, several specific factors contribute to lower R^2 values. Textile cut resistance is a complex property influenced by various factors such as fiber type, weave structure, finishing treatments, and more. Textile materials can exhibit inherent variability in their properties and cut resistance may be influenced by subtle variations in the manufacturing process.

The relationships between these factors and cut resistance is complex and may result in more variability than some other types of testing. The complexity of these relationships can make it challenging to achieve higher R^2 values. Anecdotal evidence from ASTM consultants provided that historically a range of 0.3 to 0.7 is considered acceptable for textile values given the inherent complexity, in particular with fabrics designed for higher cut resistance. This new test method produced R^2 values in the range of 0.36 to 0.81 making its results in line with other textile tests.

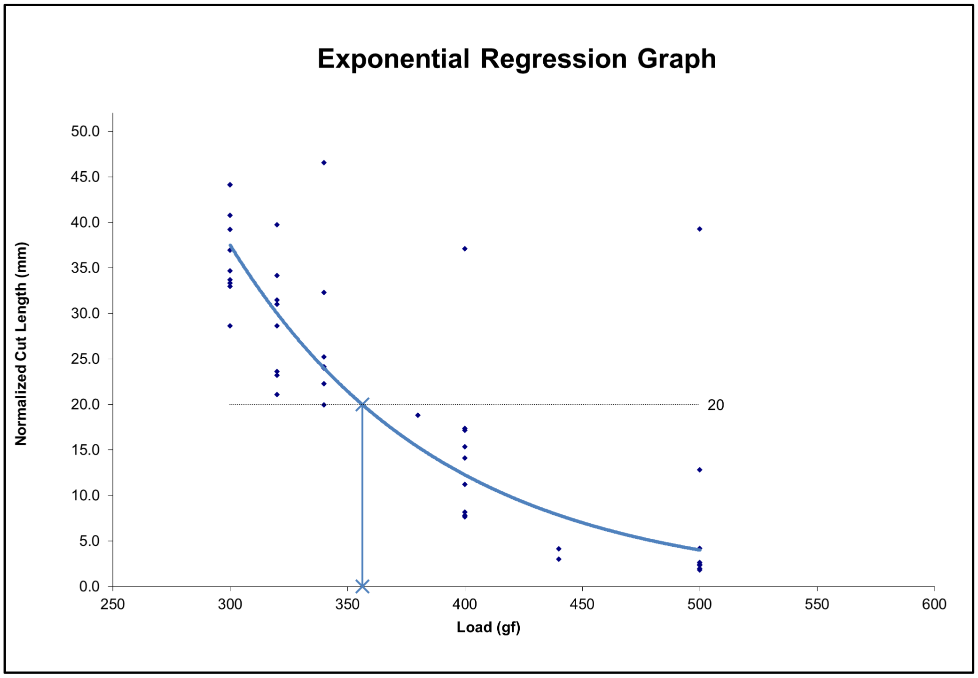

Figure 9. Regression Analysis of Ortho Fabric at Ambient Temperature. *This graph shows the test data (dots) and the analysis for the best fit line through the data. This is then used to determine the load in gf corresponding to a 20 mm long cut.*

B. Increase in Cut Resistance

As previously mentioned, prior to data collection the Team speculated that due to stiffening of the fibers at cryogenic temperatures, the cut resistance of the fabrics and ply-ups would increase. Substantial evidence was produced in this effort to support that theory as every fabric and ply-up experienced a significant increase in cut resistance.

This is further evidenced by the observed stiffening of two of the samples (EMU Ply-up and RTV 157) which after being removed from the specimen holder at cryogenic temperature, retained the curvature of the specimen holder for several minutes as shown in Figure 10 before warming and softening. The individual fabrics did not exhibit this same tendency. It is theorized that the polymer structures in the RTV and the neoprene coated nylon layer of the EMU ply-up significantly stiffened at cryogenic temperatures which resulted in the significantly larger increase in cut resistance of those samples. Glove designers will need to be aware of the stiffening of fabrics so that they can be accommodated for in the architecture of the glove assembly (i.e. how the fabrics are segmented, positioned etc.).

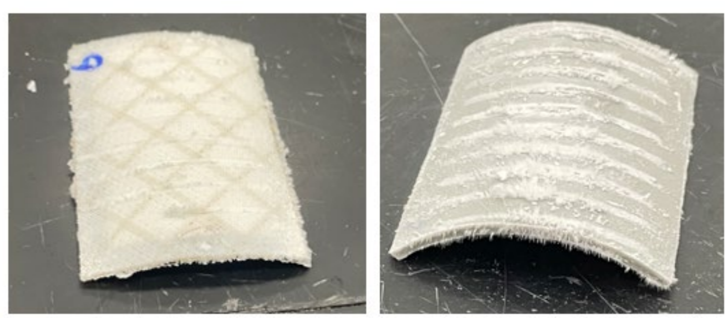

Figure 10. (Left) EMU Ply-up and (Right) RTV Pad. *Photograph taken directly after removal from the cryo specimen holder which shows the observed stiffening.*

V. New ASTM Standard Formation

Similar to the other tasks in this effort, NASA intends to release this newly adapted method as a formal ASTM standard. The implementation of a standardized method is crucial for enabling government organizations and manufacturers to systematically assess new designs, materials, and coatings. Such a method ensures that results obtained can be compared with those of others who utilized the same standardized approach, fostering a reliable basis for evaluation. Furthermore, these results could potentially serve as integral components of performance requirements if deemed necessary.

A proposal to formulate the standard was presented via the cross-cutting subcommittee within the ASTM F47 committee on commercial spaceflight. The absence of any objections within this subcommittee led to the creation of an ASTM work item. This item, designated as ASTM WK85995, titled "Standard Test Method for Measuring Cut Resistance of Materials used in Spacesuits and Spacesuit Gloves under Cryogenic Conditions with Tomodynamometer Test Equipment," is now sanctioned for development and submission through the ASTM process.

Upon the completion of the method's full development and balloting, members of the ASTM F47.05 subcommittee on crosscutting will cast votes on the technical content within the standard. Following the subcommittee ballot approval, the method undergoes balloting throughout the entire ASTM F47 committee, following the same process as at the subcommittee level. If the standard's ballot passes without any negatives or with all negatives found non-persuasive, the standard is deemed approved and sent to the Standards Council for final approval. The Standards Council's role is to ensure adherence to all processes before officially issuing and publishing it as an ASTM standard.

VI. Conclusion

This task was aimed to create a new standard for evaluating the cut resistance of fabrics at simulated lunar conditions, namely extreme cold temperature. The Team elected to adapt the TDM-100 cut test apparatus and the test method ASTM F2992-23 to allow for a portion of the machine holding the fabric to be chilled using lab supplied LN2.

A vendor, specializing in cryogenics containment and handling, was contracted to design and fabricate a custom LN2 specimen holder to use in conjunction with the machine. To assess the efficiency of the recently devised Test Procedure, various cut resistance assessments were carried out on pristine fabric samples within the Phase VI Glove TMG, encompassing both ambient and cryogenic temperatures.

In general, all examined fabrics and ply-ups demonstrated heightened cut resistance when exposed to cryogenic temperatures. The percentage increase in cut resistance for Ortho Fabric, Turtleskin® T9-816A, and Phase IV Gauntlet TMG ply-up materials ranged from 117.1% to 126.8%. The similarity in percentage increase is attributed to the likely resemblance in fibers or fabric structures.

Notably, RTV-157 and the EMU TMG ply-up exhibited significantly greater increases in cut resistance, reaching 358.1% and 604.3%, respectively. The Team speculated that the polymer structures in RTV and the neoprene-coated nylon liner material of the EMU ply-up experienced substantial stiffening at cryogenic temperatures, leading to the pronounced surge in cut resistance. This theory gained support when the specimens, upon removal from the specimen holder after cryogenic exposure, retained the specimen holder's curvature for several minutes before gradually warming and softening.

From an ASTM test perspective, this test series resulted in a relatively limited data set to validate the data or comment on the repeatability of the adapted test method. No precision and bias testing was performed. However, initial results indicate that it appears to be an effective process that generates consistent data within the expected variability of this test apparatus.

The regression analysis performed on the data produced R^2 values in line with expectations. A broader range of R^2 values are common in textile cut resistance testing because of the intricate relationships between various material properties, the inherent variability in textiles, and the complex nature of cut resistance itself. These factors contribute to the challenge of developing highly predictive models, resulting in R^2 values that might be comparatively lower than those obtained in tests with more straightforward relationships between variables. In over 20 years of cut resistance testing, the regression model as published in ASTM F2992, ISO 13997, and related standards has shown to provide consistent results that have been able to inform PPE selection of gloves, sleeves, and other protective clothing.

Future testing should explore the impact of elevated temperatures on cut resistance as well. By employing the same apparatus, hot oil circulation through the tubing in the sample holder could be utilized to heat the fabric specimens to levels mimicking lunar maximum extremes. This adaptation allows for a comprehensive examination of the fabric's performance under a spectrum of environmental conditions, covering both extreme cold and elevated temperatures. The data collected from these hot temperature experiments, in conjunction with the cryogenic data, will form a holistic narrative on the fabric's resilience and efficacy across a broad range of use cases.

Future testing endeavors using the apparatus developed in this effort could be adapted to define objective cut resistance requirements. A cut test with the ability to simulate lunar temperatures presents a valuable tool in defining an objective cut resistance requirement. Given that dust causes abrasion and tools are engineered to avoid sharp edges, the primary concern lies in safeguarding against potential injuries while manipulating lunar rock samples. Initially, Artemis requirements will be established by referencing cut resistance ratings from industries accustomed to handling similarly sharp items. However, future efforts could involve adapting the TDM-100 with a modified mount to accommodate lunar rock simulants or actual returned samples, enabling precise determination of the cut threat. This empirical data would then inform and refine the cut resistance requirement, ensuring optimal safety measures are in place for lunar exploration missions.

Additionally, a more nuanced exploration of the temperature effects on the blade could be undertaken, delving into the effects of the blade's temperature on the cut resistance measurements. One potential avenue for improvement lies in redesigning the blade clamping system to enhance insulation from the rest of the testing apparatus. This modification aims to create an environment that minimizes heat transfer between the blade and the surrounding machinery, thereby fostering the conditions for achieving blade temperatures in line with the target test temperature. By isolating the blade with a more insulated system, glove designers can gain better control over the thermal variables, ensuring a more accurate assessment of cut resistance under varied temperature conditions.

Acknowledgments

The authors would like to thank all the various people who contributed significantly to this NESC effort, without which would not have been successful. Special thanks to Bryan Kanne (JSC-AML), for his behind the scenes work of getting so much testing completed and to William Spenny (NESC Affiliate), for his years of experience and mentorship.

References

1. Iqbal, Mansoor, Sohail, Munazza, Ahmed, Aleem, Ahmed, Kamran, Moiz, Arsheen, Ahmed, Khalil, “Textile Environmental Conditioning: Effect of Relative Humidity Variation on the Tensile Properties of Different Fabrics”, Journal of Analytical Sciences, Methods, and Instrumentation, 2012, 2, 92-97.
2. ASTM D1776 “Textile Standard Atmosphere for Conditioning and Testing” 1998
3. ATA, “5-Part Series (Part 4): Cold Resistance” Geosynthetics, Sept, 2022. https://geosyntheticsmagazine.com/2022/09/09/5-part-series-part-4-cold-resistance/
4. Jiayi Liu, Zhengong Zhou, Li Ma, Jian Xiong, Linzhi Wu, Temperature effects on the strength and crushing behavior of carbon fiber composite truss sandwich cores, Composites Part B: Engineering, Volume 42, Issue 7, 2011.
5. Standard Test Method for Measuring Cut Resistance of Materials Used in Protective Clothing with Tomodynamometer Test Equipment, ASTM F2992-23 (West Conshohocken, PA: ASTM International, approved March 1, 2023), https://doi.org/10.1520/F2992-23 for Figures 6-2 and 6-3.
6. Jones, R., et al, “Establishing Standardized Test Methods for Evaluating Space Suit Gloves” ICES-2023-37.
7. NESC-RP-07-074 “Extravehicular Mobility Unit (EMU) Glove Thermal Micrometeoroid Garment (TMG) Damage Mode Investigation – Vol I”, and Vol II Appendix A, and Vol II Appendix B. 2009. R. Piascik, D. Shockey, J. Zheng, B. Jensen, J. Sutter, and R. Dasgupta.