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NASA Advanced Space Suit xEMU Development Report – Environmental Protection Garment

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For the past several years, the Exploration Extravehicular Mobility Unit (xEMU) team at NASA's Johnson Space Center has focused on the development and detailed design of the xEMU to support missions to the International Space Station (ISS) and a moon landing in 2024. In that context, this paper examines the development and baseline detailed design of the xEMU Environmental Protection Garment (EPG). This paper will outline the challenging technical requirements, significant architectural trades, technical solutions required to overcome these challenges, and a status of the detailed design. The preliminary results of Design Verification Testing (DVT) as it relates specifically to the EPG are provided, along with a forward strategy for final maturation into a flight-ready design.

Nomenclature

ANSUR = Anthropometric Survey of US Army Personnel
CAD = Computer Aided Design
COTS = Commercial Off-the-Shelf
DCU = Displays and Control Unit
DVT = Design Verification Testing
EIS = End Item Specification
EMC = Electromagnetic Compatibility
EMI = Electromagnetic Interference
EMU = Extravehicular Mobility Unit
EPG = Environmental Protection Garment
EVA = Extravehicular Activity
EVVA = Extravehicular Visor Assembly
GRC = Glenn Research Center
HUT = Hard Upper Torso
ILS = Initial Lunar Surface
ISS = International Space Station
LCVG = Liquid Cooling and Ventilation Garment
LEO = Low Earth Orbit
LETF = Light Environment Testing Facility
MLI = Multi-Layer Insulation
MMOD = Micrometeoroid and Orbital Debris
NASA = National Aeronautics Space Administration
PGS = Pressure Garment Sub-Assembly
PLSS = Portable Life Support System
PTFE = Polytetrafluoroethylene
SEM = Scanning Electron Microscopy
TBD = To Be Determined

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TMG = Thermal Micrometeoroid Garment
VTD = Vertical Trunk Diameter
xEMU = Exploration Extra-vehicular Mobility Unit
xINFO = Exploration Informatics
XL = Extra Large
xEVAS = Exploration Extra-Vehicular Activity Services
xPGS = Exploration Pressure Garment Sub-system
xPLSS = Exploration Portable Life Support System

I. Introduction

THE Extravehicular Mobility Unit, or EMU, was first flown by NASA in 1983 on STS-6. Over the subsequent four decades, the EMU has been enhanced and modified to fit the changing missions that it supports. Today, the Enhanced EMU is still used on the International Space Station (ISS) for American international partner spacewalkers. Supporting a pressure of 4.3 psia (30 kPa), sufficient upper torso mobility for micro-gravity operations, and a 30-minute contingency return in case of a failure, the EMU has and continues to be a reliable and capable Extravehicular Activity (EVA) platform at the ISS. However, limited sparing of critical EMU components, such as the Hard Upper Torso (HUT) and Portable Life Support System (PLSS) has motivated the ISS Program to shepherd resources to develop a replacement for the EMU capable of supporting ISS operations through the end of its life, expected to be 2028 or later. In addition, in 2019 NASA was challenged to accomplish the goal of landing astronauts on the surface of the Moon by 2024. Funding from Congress to develop the necessary infrastructure to accomplish this goal followed the challenge, including but not limited to the launch vehicle, lander, suits, and other surface assets[1].

This paper specifically documents the development of one of the elements for xEMU, the Environmental Protection Garment (EPG). The EPG is a highly integrated component that is used to protect the xEMU system from the environments encountered during EVA. The heritage ISS EMU equivalent was the Thermal Micrometeoroid Garment (TMG). The TMG was designed to protect the pressure suit from the thermal extremes of low earth orbit (LEO), micrometeoroid and orbital debris (MMOD) impact as well as provide a tough and durable abrasion and cut resistant outer cover layer. In addition to the protection provided by the heritage TMG, the EPG must also protect from additional challenges. These include lunar rock and dust, larger thermal extremes, more radiation, and charges built up on the surface of the suit to name a few. The EPG, similar to the heritage TMG, is composed of multiple layers of materials that are combined together to create a multi-functional layup. Due to cost and time limitations, the EPG design for xEMU for the ISS Demo and Initial Lunar missions was specified to use the heritage TMG materials and an initial layup consisting of at a minimum seven layers: Ortho-Fabric, five to seven layers of reinforced aluminized mylar (five in mobile areas to reduce torque), and one layer of neoprene coated nylon as a liner. However, as this paper will highlight, there are many unique features such as patterning and attachments that set the xEMU EPG apart from past designs. Ongoing baseline testing and analysis may determine that additional layers or the addition of surface enhancing applications to the fabric need to be added to meet the more challenging environment on the lunar surface for sustained lunar missions. A sustained lunar suit may necessitate the investigation of alternative options to the EMU TMG materials, but this is not considered in the scope of this paper.

Returning to the Apollo TMG for use on the Artemis missions was not an option. While the Apollo layup construction of the inner layers was similar to the EMU TMG, the outer most layer was comprised of PTFE (Teflon) coated filament Beta cloth. Beta cloth is a fireproof silica fiber cloth and was developed and incorporated after the deadly Apollo 1 fire[2]. While still used in some space applications today, the glass fibers are prone to flex fatigue cracking and are difficult to sew without the edges unraveling[3]. This resulted in added abrasion patches and difficult to manufacture operations that are undesirable and unnecessary for a state-of-the-art solution. Due to a change in oxygen concentration levels between Apollo and Shuttle, textile engineers were able to develop a replacement material called Ortho-Fabric which is a unique combination of Nomex®, Kevlar®, and Gore-Tex fibers[4]. The EMU TMG is somewhat unique in that it has seen very little modification and development over the past 30 years. As part of the enhanced EMU redesign, the HUT TMG was modified to permanently attach the shoulder TMG. This provided a path for a new glove heater cable to run down the length of the arms. Beyond this architecture change, minor modifications were made to the TMG attachments that allowed the suit components to be changed out on orbit, part of the Enhanced EMU design change.

As will be discussed in this paper, the xEMU suit mission requirements drove significant changes to the EPG design. The largest factor needing to be addressed in a new design is lunar dust. Apollo 17 commander Gene Cernan expressed similar thoughts in a technical debrief following his mission, which was the last human sojourn to the moon. "I think dust is probably one of our greatest inhibitors to a nominal operation on the moon. I think we can overcome other physiological or physical or mechanical problems except dust," he said[5]. The lunar regolith is abrasive, it clogs mechanisms, and can cause health issues. The EMU TMG does not include any provisions for dust as it is not required for the environment it was designed. The Apollo TMG was attached to the Pressure Garment Subsystem (PGS) via Velcro, Zippers, and loop tape, which did not fare well in the lunar dust and was not successful in keeping the dust away from the underlying suit. As noted by Apollo astronaut Pete Conrad during his Apollo 12 EVA, that "Velcro doesn't hold worth a hoot."[6] Dealing with dust is going to require an "integrated dust mitigation strategy" but the EPG will certainly serve as a first line of defense for the xEMU.

The xEMU EPG development effort represents not only a significant improvement over the Apollo and EMU TMG design, but also is paving the way for a sustained presence on the moon. Presented in this paper are the detailed driving requirements that differentiate the xEMU EPG from past designs including how they are being addressed by the EPG Team. Also summarized is a novel EPG architecture design aimed at reducing torque while also maximizing dust protection. Finally, a summary of past and current analysis and testing that are helping to define requirements is included.

II. Driving Requirements

The unique, significant driving requirements for the xEMU EPG are enumerated below in Table 1.

Table 1. Significant xEMU EPG Driving Requirements.

Requirement	Specification Summary
Sizing Accommodation	Accommodate xPGS sizes to meet system anthropometric range
Thermal Protection	Thermal Range, Optical, Solar Absorption, Effective Emissivity, Contact Temp
Regolith Permeability	Minimize regolith permeation through materials and attachments
Environmental Exposure	Meet all requirements after exposure to environmental conditions
Regolith Cleaning	Allow for cleaning from surfaces with external items so that the maximum amount of dust liberated from the suit once inside the cabin does not exceed 50 g per crewmember
Attachment Strength	Ensure EPG attachment points are robust enough to handle expected loads during all EVA ops
Replaceable by Crew	Include attachment features that allow on orbit removal of certain EPG components

The requirements stated in this section are derived from the Pressure Garment Subsystem Specification (CTSD-ADV-1231)[7] which has imposed requirements from its parent document, CTSD-ADV-1188, Project Technical Requirements Specification (PTRS)[8] for the xEMU Project. Environmental requirements are found in the EVA Office Exploration EVA System Destination Environments Specification document (EVA-EXP-0039)[9]. These requirements were chosen to be addressed in this paper due to their uniqueness in differentiating the xEMU EPG design from the EMU TMG design. The xEMU suit requirements are being continually refined. While many are defined by previous Apollo or EMU experience, the Artemis missions will push the suit into more challenging, difficult environments. As such, many of the current requirements are stated as "to be determined" (TBD) meaning it is known that the requirement is relevant but the exact value that should be designed to is not yet known. The final definition of all values in the TBD requirements is forward work. Therefore, many parts of the EPG design are considered evolving as they are validated through prototype testing, analysis, and trade studies culminating in a more flight like design that will conclude after this paper is published. The details presented here envelop the current work to date and will detail future work to be completed but it is not to represent the final flight design. The requirements stated in this section are derived the Pressure Garment Subsystem requirements and from the xEMU project environmental requirements

A. Sizing Accommodation

The xEMU project requirements outline a series of critical anthropometric measurements, each with a minimum and maximum value that covers the 1st percentile female to 99th percentile male, each measurement from a forward projected and truncated Anthropometric Survey of US Army Personnel (ANSUR) database. Therefore, each critical measurement includes 98% of the crew-like population. However, when all critical anthropometric measurements are combined, approximately 90% of the relevant population is required to fit. This requirement is directly levied onto the xPGS which drove the suit architecture sizing scheme to accommodate the required anthropometric range.

There are several requirements that address EPG sizing accommodations. Primarily, the EPG design is specified to accommodate all of the xPGS parts and sizes. This includes several derived requirements such as modularity, interface sizing variation, and replacement capability. The intent of these requirements is to lessen a logistical burden from the crew in having to remove large portions of the EPG in order to access the underlying xPGS components as needed to support on-orbit resizing and maintenance operations. There are several noted exceptions to the need of being able to remove the EPG entirely. These include the boot soles, arm to glove interface, and PLSS back covers. Other components will have EPG coverings but will not require any sizing accommodations. These include the Extravehicular Visor Assembly (EVVA) and xINFO band, the Displays and Control Unit (DCU), the xPLSS, the boots, hoses, and electrical lines. The sizing of the xPGS is well defined and thus the sizing requirements that the EPG must be designed to are well defined and detailed in Section III, A below.

B. Thermal Protection

The xEMU is required to maintain its function during and after exposure to extreme hot and cold conditions defined from EVA Office Exploration EVA System Destination Environments Specification document (EVA-EXP-0039)[9]. This document provides a definition of the expected natural and induced environments for the Extravehicular Activity (EVA) hardware, along with rationale and analysis for how those environments were developed. It divides the thermal environment into atmospheric temperature, surface contact temperature, thermal radiation, and solar radiation. At the xPGS requirements level this is quantified as overall system heat leakage (currently a TBD), defined in watts, and crew skin touch temperature exposure. The EPG is expected to protect the pressure garment restraint and bladder, and ultimately the crew member, from these environments.

In the absence of convection, due to no lunar atmosphere, heat will be transferred through the suit by radiation and conduction, either into or out of the suit. Solar radiation occurs both directly from the Sun, and reflected off other surfaces, referred to as albedo. Infrared radiation is transmitted to/from other surfaces including the lunar surface. The optical properties of the outer layer of the EPG play a role in the overall thermal protection afforded by it. In space suit applications, it is typically a requirement that there be a low optical property ratio of absorptivity/emissivity, which means it absorbs less solar (reflecting more) and emits infrared well. This aids in the overall cooling of the interior of the suit and thus less workload on the life support system. Lunar surface temperatures vary greatly as a function of latitude, based on the Sun's illumination angle. At the lunar equator, the lunar surface temperatures can be as high as 255°F (124°C) at noon and as low as -289°F (-178°C) just before sunrise. In comparison, the average maximum temperature in the polar regions is -100°F (-73.3°C) with average minimum temperatures at -370°F (-223°C). In a Permanently Shadowed Region (PSR) at the south pole such as Shackleton Crater, the temperature can be as cold as -388°F (-233°C). Conduction which can lead to heating or cooling of the crew members skin occurs at the knees when kneeling, the boot soles when standing or walking and the glove as objects are touched. The xPGS is required to prevent any surface which contacts the crew members skin from exceeding pain threshold limits of 50°F (10°C) and 111.2°F (44°C)

Space suit fabric sullied by lunar regolith will have changing optical properties as more dust clings to the material and creates an overall darker color. Therefore, requirements and testing must consider the fabrics properties at the beginning of life and at the end of life to ensure that requirements are met in even the worst circumstance. As detailed in Section VI, C, analysis coupled with EPG coupon testing and system level testing of the xEMU in a thermal vacuum chamber during design verification testing will resolve the TBD requirements related to thermal protection. Also, a revision to the EPG specification is being considered to add derived requirements relating to the outer fabrics absorptivity and emissivity properties making it easier to identify potential Ortho Fabric replacements for future missions. This is further discussed in Section IV, C.

C. Regolith Permeability

Per the PTRS, the xEMU must be capable of performing all functions after exposure to regolith so that it can continue to protect the crew. Regolith particles from the lunar environment can cause wear and deterioration to subsystem components if they permeate the EPG and become trapped under it or in-between its layers. Therefore, a proposed EPG requirement was set to minimize the amount of regolith that is allowed to permeate through its layers. Because a quantitative amount is still TBD, then the task becomes baselining how the heritage EPG layers fair and making an informed decision on what, if any, improvements should be made. Permeability is an important property for woven textiles used, in this case, as a barrier and it depends on many parameters of the fabric; mainly its weight and construction. Woven fabrics are produced by interlacing warp and weft yarns. This construction creates voids between yarns and the size of the voids are determined by the diameter of the yarns and how tightly they are woven together. A theoretical determination of permeability is highly complex and difficult in relating the individual parameters to the overall affect. Therefore, this property is usually defined experimentally. NASA has traditionally used tumbler testing to perform this type of test on candidate materials. See Section VI, A for further detail.

D. Environmental Exposure

The lunar environment will bombard the suit with multiple potential damaging conditions. These include exposure to thermal extremes, ionizing radiation, solar irradiance, plasma, sharp rocks, and perhaps the most damaging, regolith dust. As the xEMU's first line of defense, this environment will have detrimental effects on the EPG including decreased thermal performance, abrasion, wear, discoloration, functional interference, etc. The EPG design is required to withstand these effects and maintain necessary functionality following exposure. In other terms, the EPG must meet all of its functional requirements after it has been sullied by the lunar environment. Therefore, it is critical to first baseline the performance of the EPG in a pristine condition to ensure that it does, indeed, meet all of the functional requirements. Because the foundation of the EPG design started with the heritage EMU materials, there is confidence that these requirements will already be met. If not, then additional layers or surface coatings can be explored to improve its performance. In some instances, these requirements are still TBD, and this baseline testing will help the xEMU team to properly define these. Then an agreed upon contamination protocol of the EPG must be performed to simulate the conditions of the EPG in an end-of-life state. This includes performing any cleaning steps that the EPG would be subjected to. Mostly this can be done at the material level in small coupons that are subjected to controlled environments simulating lunar conditions. Finally, verification tests are rerun to certify that the requirements are still met. These include but are not limited to optical measurements, surface resistivity, permeability, and microscopic evaluation of the textiles for wear. This is further discussed in Section IV, B.

E. Regolith Cleaning

As specified in the xEMU project requirements, the xPGS should limit design features that can trap environmental regolith to the most extent possible. Over time environmental lunar regolith particles can abrade and/or embed into surfaces. Also, particle entrainment in the softgoods needs to be limited to minimize how much regolith is brought back into the vehicle which has the potential to release in the cabin environment, foul filters, and create health concerns for the crew. Therefore, a requirement is given that the EPG must allow for cleaning to be performed to remove as much regolith as possible. Specifically, the EPG shall allow for the cleaning of environmental regolith from surfaces with external items so that the maximum amount of lunar dust liberated from the suit once inside the cabin does not exceed 50 grams per crewmember. This is primarily aimed at areas where creases, folds, seams, etc. may entrap or allow accumulation. This is further discussed in Section III, D.

F. Attachment Strength

Several xPGS requirements drive the need for the EPG to be easily removable by the crew for on-orbit operations. This includes needing access to the xPGS to size the suit, for maintenance operations, to replace damaged or worn-out components and for cleaning. Also, because the xPGS can be configured into multiple sizes there is a need for the EPG design to include separable, mechanical attachments that facilitate swapping EPG components to allow for a better fitting garment. Therefore, the EPG has multiple requirements which address these attachments. Notable ones include limiting their impact to mobility and torque, minimizing regolith permeation, providing a positive indication of closure, maintaining fracture control, meeting connect and disconnect cycles, allowing cleaning of regolith, and finally attachment strength. Attachment strength is defined as the resistance to unintentional separation of the EPG components where they are joined. This requirement is currently a TBD and is difficult to quantify. An initial value of 10 lb/linear inch (18 N/cm) was identified. This is further discussed in Section III, C.

G. Replaceable by Crew

Certain components of the EPG are required to include attachment features to allow them to be removed and replaced during a mission by the crew. For both mission architectures these include the arms and legs for resizing purposes. For the xEMU initial architecture, the other components will not include on orbit replaceable features as levying this requirement would add additional mass and complexity to the design and would not be needed on a shorter duration mission. The attachment would still be removable with standard tools which could be done by the crew on orbit or on the lunar surface if required during a contingency. For sustaining lunar, the architecture will include a requirement for tool-less attachment features to facilitate servicing of the xPGS by the crew. This is further discussed in Section III, C.

III. Component Maturation

A. Architecture/Sizing

Preliminary xEMU EPG development started in 2018. The initial EPG architecture was directly influenced by two seemingly opposing design constraints: limit the EPG impact to suit mobility and limit the number of interfaces where dust can penetrate. Options considered included a 1:1 scheme in that for every xPGS component and size, there would be a matching EPG component. This configuration would be ideal for fit and mobility; however, it would result in a costly and large logistical burden to fabricate and maintain so many unique EPG components and it would add additional interfaces to seal against dust. While EMU did somewhat follow this approach, launch mass and volume considerations were made for a solution more acceptable for the logistics and environment of a lunar mission. Another option would be a "coverall" approach where the EPG is designed like a more loosely fitting bunny suit. This would be excellent for dust, but it would result in a very poor fitting solution which would create issues due to excess fabric. A similar approach was considered briefly for Apollo where suit engineers evaluated a two-piece solution via a large overcoat and loose-fitting pants but was later scrapped when NASA relaxed its particle impingement requirements allowing thinner and more conformal garments[10]. The solution for xEMU lay somewhere in the middle of those two options.

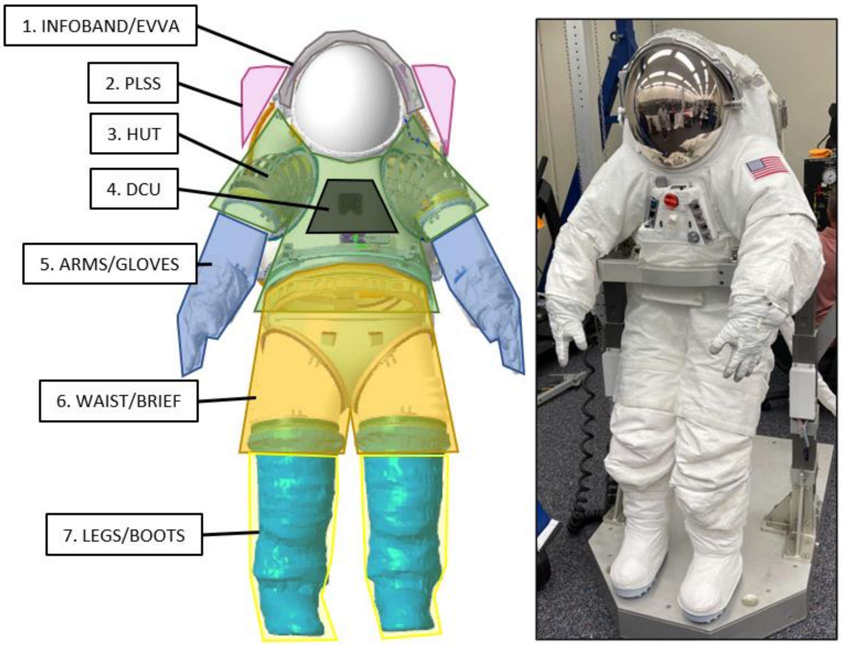

Figure 1. xEMU EPG Architecture 1. *A seven component EPG architecture scheme was evaluated for initial DVT testing. Consideration was given to eliminating breaks to reduce dust intrusion.*

Figure 1 illustrates the seven component EPG architecture that was put forth for initial Design Verification Testing (DVT) assessment which was felt to be the best compromise between the two opposing design constraints. This configuration includes seven unique EPG components: the xINFO band/ EVVA, the PLSS (four separable pieces that are mounted to removable shrouds), a HUT with attached shoulders, the DCU, the arm/glove, a one-piece waist/brief/hip, and the leg/boot. The arm-to-glove and leg-to-boot connections are intended to be sewn interfaces for flight but for DVT, these were mated together via Velcro for easier access to the glove wrist and boot disconnects. For initial DVT only, it was decided to utilize traditional Velcro initially and later zippers for all of the attachments because a flight solution was still being developed and the EPG needed to be delivered for test. A hook and loop down select for a flight solution is discussed in Section VI, B. As more attachment designs were finalized, they were incorporated into EPG components as testing proceeded. EPG attachment design is discussed further in Section III, C. The shoulders, arms, legs, and hips were patterned with some excess fullness to accommodate the range of motion of the xPGS joints they cover to accommodaate flexion, extension, and bearing rotation. It was expected that a one-piece waist/brief/hip design could hinder mobility, but an attempt was made to pattern it to keep it conformal while also loose enough for the hip and thigh bearings to rotate as freely as possible.

To fit the required anthropometrics, the xPGS suit architecture utilizes two HUT sizes, two shoulder sizes that can be adjusted by ½ in. (1.27 cm) relative to their position in the HUT scye opening, waist configurations that include two sizes of brief and four additional sizing rings, one boot size with a cinching mechanism, and the full range of current EMU lower arm, leg, and glove sizes (xEMU utilizes EMU PGS arms, PGS legs, full glove assembly with modified TMG and sizing rings). The short and long brief plus a combination of waist sizing rings can achieve a vertical trunk diameter (VTD) in the required range. The EMU range of lower arms include nine unique sizes with each arm having an adjustable cam bracket on both ends of the axial restraint lines capable of .increment adjustments each. In addition, an arm sizing ring of 1/2 in. (1.27 cm) can be included. Similarly, the EMU range of legs include five (currently only four are in use) unique sizes with each leg having an adjustable cam bracket on both ends of the axial restraint lines including increment adjustments each. In addition, a thigh sizing ring of ½ in. (1.27 cm) and a leg sizing ring of ½ in., 1 in. or 1.5 in. (1.27, 2.54, or 3.81 cm) can be included.

For the EPG to accommodate variations in joint interface dimensions of the xPGS, a detailed sizing analysis was conducted to derive the number of sizes per component as well as how the attachments could be implemented to incorporate incremental sizing similar to the cam brackets in the EMU arms and legs. Initially, a small, medium, and large EPG arm sizing scheme with the additional inch of sizing from Velcro was designed to cover all but the largest xPGS arm lengths. However, it was determined from DVT that an additional arm EPG size of XL needed to be created because the large EPG arm was pulling some tightlines during certain arm positions especially at the wrist attachment where the Velcro separated a few times. The initial attempt to correct the issue was to make a longer arm. However, it was later deduced that the tightness was created by the shoulder which has since been redesigned. Future testing will determine if the shoulder repatterning will eliminate the need for an XL arm size.

It was concluded that built-in incremental sizing would reduce the total number of components needed to fit the full range of the xPGS while the excess material needed to achieve the incremental sizing would be negligible. To achieve this, two rows of 1 in. (2.54 cm) wide strips of Velcro, 1 in. (2.54 cm) apart were added circumferentially inside the bottom of the shoulder. A single piece of Velcro at the top of the arm component could then be aligned with either the bottom or top row of Velcro in the shoulder allowing an additional inch of sizing. The bottom of the brief, similarly, has three strips allowing 2 in. (5.08 cm) of sizing. The legs utilize a two-size scheme designated small and large. With the rows of Velcro in the brief giving two additional inches (5.08 cm), the entire range of xPGS leg sizes could be covered. Early in testing the Velcro was replaced by traditional zippers due to excessive wear. Traditional zippers used for DVT will be replaced by more flight suitable attachments as discussed in Section III, C below.

Early familiarization runs determined a tightness in the brief which limited mobility rather severely when squatting. It was surmised that this was caused by the grippy Neoprene liner creating excessive drag on the outer housing of the hip bearings possibly exacerbated by the incorporation of the zippers in the thighs which caused a lot of take-up from the sewing operation. Several attempts were made to relieve the issue including raising and lowering the crotch of the EPG in relation to the xPGS. Due to the mobility issues in the shoulders and the brief, an alternate EPG architecture was assessed detailed in the following section.

B. Hybrid Segmented Joints

A second EPG architecture in development is referred to as the "hybrid segmented" design as shown in Figure 2. It is an attempt at a hybrid solution to address the dust and mobility paradigm and is not a solution that has been attempted on any flight spacesuit outer coverings of the past. In mobility areas such as the shoulder and arm, the EPG is separated into two subassembly layups each uniquely patterned. The outer subassembly is Ortho-Fabric backed by a tightly woven but lightweight slip layer. The slip layer acts as a second dust barrier to the Ortho-Fabric and also a friction reducing "slip" layer to the moving components underneath. The outer subassembly is patterned such that it is looser fitting and spans over the bearings as explained in Section III, A. The inner subassembly contains a second slip layer of Teflon, the multi-layer insulation (MLI), and the neoprene coated nylon liner. The Teflon layer in this case acts as a second slip layer and a liner to prevent the MLI from being abraded and damaged. The inner subassembly is patterned more like the EMU TMG with breaks at the bearings and a 1 in. (2.54 cm) overhang to ensure total thermal protection. In this way, a dust barrier is maintained over the bearings, but the entire bulk of the EPG layup is not having to twist as the bearings are rotated which reduces torque. Also noted is that the entire heritage TMG materials are still present with only the two slip layers being added. Teflon was chosen because of its availability during fabrication and its low friction characteristic. Planned testing will determine the optimal material to use as a barrier

Figure 2. Segmented Arm EPG Concept. *A second EPG architecture put forth in DVT where there are two subassembly layups, an outer Ortho-Fabric layer for dust, and an inner, conformal layer for mobility. Left: a photograph of the segmented arm with the outer layer pulled down to the glove; Center: Line drawing showing layers of left arm. Purple lines-outer covering, blue-inner shoulder, and green-inner arm; Right: Line drawing showing layers of left leg. Purple lines-outer covering, orange-inner brief, blue-inner hip, green-inner leg.*

and slip layer. The outer subassembly still incorporates incremental sizing and the sizing scheme developed initially is still valid for the outer layer arms and legs. However, the inner subassembly is more conformal and will drive the need for more sizes to fit the range of xPGS arms and legs. This is a trade that must be considered moving forward. The segmented concept has also been incorporated into the brief, hips, and legs as well.

As noted, the heritage EPG architecture was reducing range of motion in the hips as well as the shoulder. Several attempts were made to repattern to allievate tightlines. But in switching to the hybrid segmented architecture, an immediate and large improvement were made in both range of motion and torque reduction with every test subject who had a suited run in both architectures remarking on the notable difference. After this positive feedback, the EPG team began making plans to produce fully hybrid segemented EPG components in preparation for cycle testing.

C. Attachments

As previously stated, the EPG is required to have a method to attach/detach from the xPGS as well as itself. Over 30 attachments are required to connect the EPG to the xEMU and ancillaries such as a tool holster as shown in Figure 3. There are many requirements related to the EPG attachments but two of the most prevalent ones are that they must mitigate dust intrusion and structurally support the EPG so that it does not become inadvertently disconnected during use. Multiple methods of achieving this have been investigated over the course of the xEMU development and include extruded zipper tracks, felt seals, and sealing zippers to name a few. Final attachment selection is forward work as testing is not yet complete.

As previously mentioned, Apollo suits utilized loop tape, metal and sealing zippers and Nomex Velcro for attachments. Loop tape, while perfectly acceptable for the ISS EMU, is labor intensive. Traditional plastic or brass zippers are prone to failure because the slide and teeth can become jammed and worn by lunar regolith. Also, they can separate unintentionally depending on their design. Traditional hoop and loop Nomex Velcro, while developed for NASA and is excellent in many applications, also did not fare well in the lunar dust. It is difficult to clean, and dust becomes trapped in it degrading its mating strength.

Multiple factors can cause loading on the attachments. Any scenario that the suit must endure during ground or EVA operations can cause loading on the EPG attachments and must be considered. Movement of the suit such as when walking or swinging a tool, impacts from external objects or crew either in cabin or during an EVA, the gravity

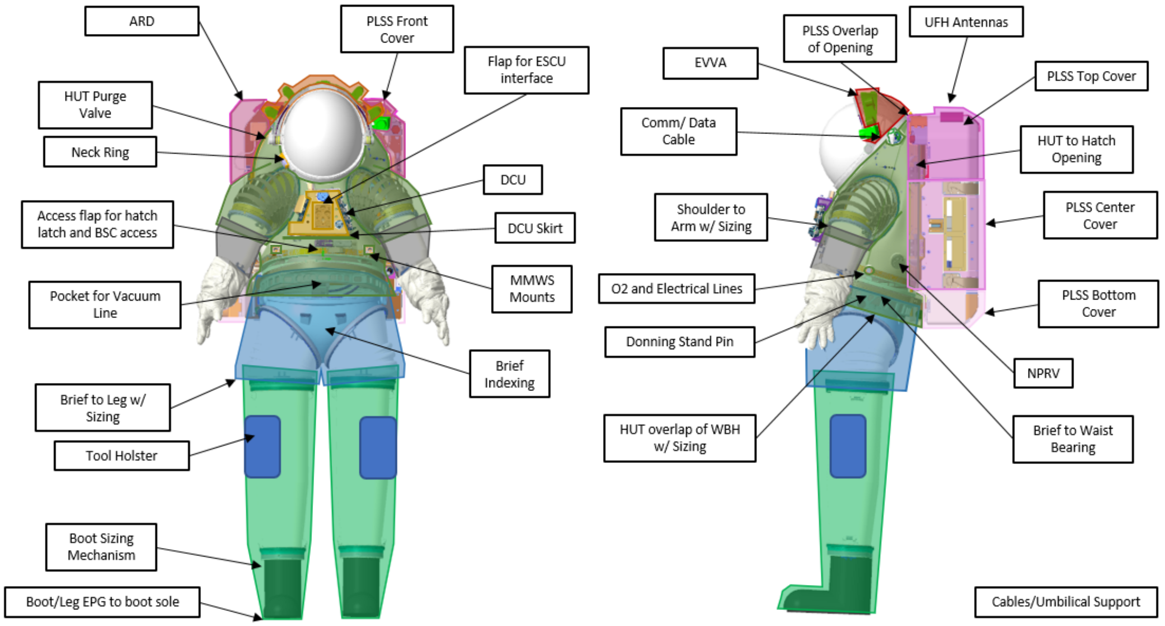

Figure 3. Attachment locations. *Over 30 attachments are required to connect the EPG to the xEMU. A unique design for each location was considered.*

field which pulls the EPG components downward, unintentional falls which can cause drag, and tugging caused by kneeling, pulling a tool off of a holster mounted to the thigh, or cleaning.

While these scenarios are in themselves difficult to quantify, it is also challenging to anticipate how the loads will be distributed to the attachments since they are attached to softgoods. In the case of utilizing 5-6 discrete attachment points around an arm or leg connection, an isolated tug load may result in all of the force driving through only one or two attachments rather than the load being distributed uniformly. This could drive the mass, bulk, and strength of one individual attachment to be very large which could negatively impact suit mobility or torque. A trade must be made to establish a load requirement that reduces the risk of the EPG unintentionally detaching in a worst-case scenario but also considering a realistic value so not to overdesign the attachments. Initially an analysis can be performed to estimate a worst-case load but ultimately this requirement will need to be verified in a system level test where the suit is subjected to a bevy of conditions that will challenge the attachments. As flight like EPG attachments are incorporated, the EPG team will observe how they perform during testing.

A tiger team was formed to specifically focus on the attachment designs. Only a few highlights of their efforts will be detailed here. First, an industry wide search was performed of all Commercial Off-The-Shelf (COTS) solutions for closing or sealing textiles together. This included studying fire and rescue clothing, wet suits, artic expedition wear, Army apparel, biohazard suits and Pharmaceutical softgoods used to contain powder. Closure mechanisms were then compiled into a trades matrix and the tiger team solicited input from experienced softgoods designers to rank the attachments across a range of categories derived from the EPG requirement specification. They included: ease of use, dust tolerance, load bearing ability, security of attachment, mobility impact, flight heritage, compactness, bulkiness, mass contribution, ease of integration and compatibility with sizing. The tiger team met with xPGS leads to apply a weight factor to each category on a scale of 0-1.0 based on how critical each seemed to the overarching requirements. Those filling out the matrix used a 1, 3, 5 scale to subjectively rank each closure mechanism against the others. Results were tabulated and the closures fell into two categories: load bearing ability and dust tolerance.

While the two lists had a few overlaps, the top contenders from the dust sealing group were not structural solutions. It became clear that the solution would most likely require a combination of attachments to provide full functionality. An example of this would be an extruded zipper track combined with structural webbings and buckles spanning over the track to react to loads. Top structural choices were drawstring, toggle fasteners, clasps, and buckles. Top dust seals were drawstring, felt seals, and extruded zipper track.

As mentioned several times previously, traditional Nomex hook and loop “Velcro” used on past missions has gained a reputation of being a non-starter in regard to dust. It fouls as the dust becomes trapped in the pile and quickly degrades. However, many advances have been made in hook and loop fastening systems over the past 60 years and the Tiger Team decided to engage industry to understand if any new styles have been developed that would reinstate it as a potential attachment method. A vendor, Aplix, was found that conceives, produces, and commercializes innovative hook and loop fastening systems. They provide hook and loop fastening systems for the personal care, automotive, aircraft, healthcare, cleaning, and military technical markets. Consulting with them produced several styles of their self-gripping fasteners that they felt would be suitable for a dusty environment. Upon receipt of nine versions, several test plans were generated involving exposing various types of hook and loop to lunar simulant and gathering peel and sheer strength data from pristine, contaminated, and cleaned samples. Results were compared to traditional Nomex Velcro and the results, summarized in Section IV, B, are very promising but still need to be finalized.

Several novel solutions have been developed for the attachment of the HUT EPG to the neck ring as well as to the hatch opening that provide both a structural connection and a dust seal. See Figure 4. A thin, stainless steel snap ring was embedded into a fabric tunnel at the neck opening of the EPG. The snap ring is sized to tightly index inside of a groove on the HUT neck ring. The snap ring can be spread open enough to allow it to pass over the outer edge of the neck ring until it snaps into the groove. A small clasp secures the ends of the ring. The groove, snap ring, and fabric of the EPG create a tortured path for the dust which makes it more difficult to pass through. Similarly, a segmented clamping ring that bolts around the front side of the hatch opening captures the edge of the HUT EPG which has a cord captured in a fabric tunnel. The cord prevents inadvertent pullout of the fabric. This is similar to the design of the restraint flanges on the EMU arms and legs. Several test fixtures will be used to characterize the attachment strength and dust sealing ability of these interfaces.

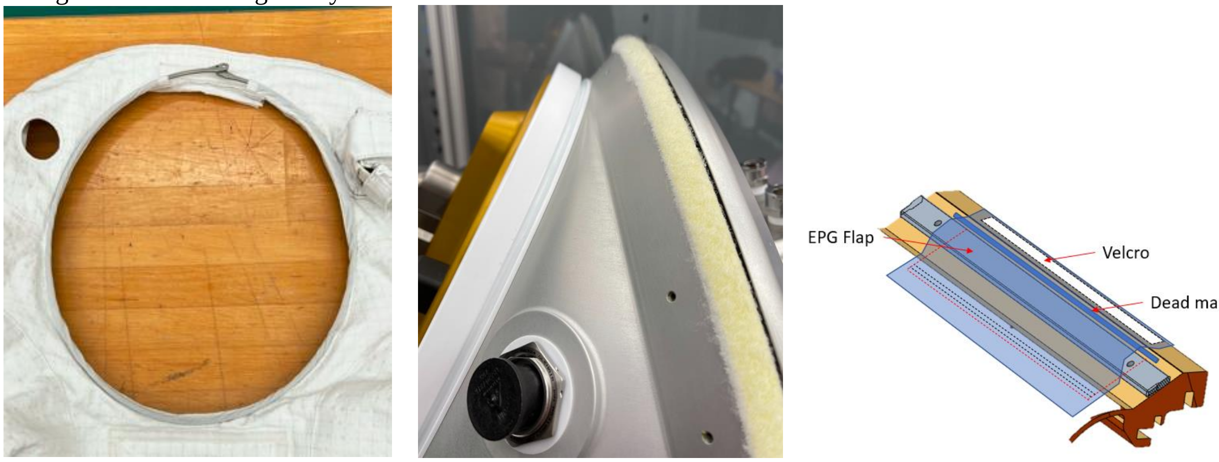

Figure 4. Attachment detail of neck ring and hatch opening. *(Left) An embedded snap ring in the neck opening of the HUT EPG indexes to a groove around the outside of the helmet neck ring (Right) A dead man cord stitched to a structural layer under the edge of the EPG is retained by clamps at the perimeter of the Hatch opening on the HUT.*

In addition to designing attachments internally, the Tiger Team elected to engage an outside vendor who specialize in designing and building technical solutions for water rescue professionals, military elites, and commercial mariners for over 50 years. The vendor, Mustang Survival, has a working relationship with NASA and are viewed as industry leading experts in how to design attachments for extreme survival gear. They were solicited for ideas in how to attach the arms to shoulder, the legs to the brief and how to incorporate integrated sizing. They also were tasked to design the tool holster attachment to the thigh and the HUT skirt overlap to the brief. These areas were deemed by the Tiger Team to be the most challenging and therefore reached out of house for some additional ideas. The vendor proposed several novel design solutions that the Tiger Team is currently vetting. One concept utilizes a roll top closure like the top of many dry bags used in boating and camping. Figure 5 shows the roll top concept, which is low profile, lightweight, easily cleanable and creates an impenetrable seal. A prototype shoulder to arm connection was fabricated to demonstrate the concept. It includes two lightweight skirts with webbing sewn to the edges. The webbings are aligned, and the two skirts are rolled together. Fasteners and webbings connect across the roll to provide structural support. The roll is tucked under to not create a ledge for dust to collect. One option is to include a snap hook and d-rings to provide incremental sizing. Ultimately this attachment mechanism, while novel, was not selected to use on the components built for cycle testing. It was decided that there were too many unknowns to be able to fully develop the concept in time.

In parallel to engaging the outside vendor, the Tiger Team also elected to investigate the latest advances in dust proof and dust toleant sealing zippers. A zipper vendor, Talon, was found that produced the sealing zippers utilized on the Apollo space suits. They touted a next generation dust proof zipper that was an advancement over what was used 60 years ago. Several zipper samples were procured and the Tiger Team subjected them to some dust exposure and cycling with dust. While the zippers did get difficult to operate after becoming fouled, they did not fail. Additionally, the zippers have two ridges of polymer that are pressed together when the zipper is closed forming a

Figure 5. Attachment concepts under consideration. *Prototype demonstrating a proposed roll top concept for the arm to shoulder attachment. Left: Shoulder prototype above, arm below; Left Center: Two skirts are aligned and rolled together, and structural webbings are secured with clips; Right Center: Outer skirt is lowered covering attachments; Right: Tool holster with molle webbing*

seal over the teeth. This interface creates an easily wipeable surface that could be cleaned prior to opening the zipper. Because of their availability and also cleanability, it was decided to pursue the zippers for the arms, legs and hatch latch opening of the EPG in the components built for cycle testing.

D. Environmental/Dust Protection

Gaining an understanding of how the heritage TMG fabrics will perform in the lunar environment is a main priority of the EPG Team. In regards to dust, it is known that Ortho-Fabric has a relatively course, loose weave. This attribute lends itself well to some of the original requirements that the fabric was designed for, mainly that it has excellent resistance to abrasion, wear, tear, and punctures. However, as a barrier to dust it does not fare as well. As part of this DVT effort, the Tools Team conducted a tumbler test of the heritage TMG layup to access which of several cleaning implements would produce the best results. It was observed from this testing that lunar simulant BP-1 passes fairly easily through Ortho-Fabric. BP-1 simulant has a grain size of 1-10,000 µm with an average grain size of 100 µm.

In a traditional EPG layup, the subsequent layer encountered is an aluminized mylar film. The film is a metal coated PET plastic designed for earthly applications to act as a barrier for gases. Because of this, it does stop dust particles from migrating deeper into the suit initially, but it is not a long-term solution to dust because it tears easily and is not desirable to have dust trapped between Mylar layers of the EPG especially because the aluminized mylar is not abrasion resistant and will begin to break down as the dust slides across its surface.

Therefore, it was determined that an additional layer acting as a dust barrier should be added between the outer Ortho-Fabric layer and the next layer of MLI especially in mobility areas where motion of the suit components will cause wear. The segmented architecture, described in Section III, C, dovetails nicely with this requirement in that it incorporates two additional slip layers that can also double as dust barriers. A tightly woven Teflon was chosen as this layer for the evaluation however further dust testing may reveal the need to search for better option. Gore-Tex in both plain and twill weaves and Tyvek are under consideration. However, the slip layer must be able mitigate dust intrusion and to endure temperature extremes as it will be outside of the MLI, so that will eliminate some options.

Knee pads are being considered for incorporation into the leg EPG for two reasons: improving thermal performance when kneeling and contacting the lunar surface and for increased abrasion and cut resistance in an area that will see more wear and tear than elsewhere on the suit. Comfort will be provided by the xPGS in the LCVG. Several prototype kneepads have been designed and fabricated, although future testing will be conducted focused specifically on the pads to challenge their durability.

IV. Test and Analyses

A. Pre-xEMU Testing

Either internally or through its subcontractors, NASA has been studying space suit materials since before the Apollo missions. This includes exposing current flight fabrics as well as potential replacement fabrics to a bevy of harsh conditions in order to characterize how the material will perform on a given mission. Much of this test history can be found in published papers and results of those evaluations have been considered in the design of the EPG for the Artemis missions as detailed below. As previously stated, the xEMU is constrained to using heritage EPG materials for initial missions. Therefore, previous testing conducted on Ortho-Fabric, aluminized mylar insulation and neoprene coated nylon were of particular interest. Additionally, any testing done on surface coatings to enhance properties or a potential backer material that could be used behind the Ortho-Fabric as a dust barrier were keenly considered however no surface coatings will be incorporated into the DVT components. A few key takeaways relevant to the xEMU EPG design are summarized in this paper.

Over the past 25 years NASA has focused mainly on tumble testing as a means of simulating wear on the outer layer of the space suit fabrics. The tumble test method of abrading materials incorporates a large rotary drum tumbler with rocks and loose lunar simulant material to induce abrasion in fabric test layups to represent what might occur during long term planetary surface EVAs. Typically, test runs are eight hours long to simulate a worst-case EVA scenario. This method is preferred over standard abrasion test methods because it appears more representative of working in the lunar environment with the combination of particle sizes and contact forces. Tumble testing will be utilized for the down select of slip layer candidate materials.

In 1990, Joe Kosmo (NASA) used a tumbler test to screen five advanced suit materials[11]. After tumbling, the fabrics were inspected using SEM. Results were compared to an SEM of Alan Bean's Apollo 12 space suit. The result showed that Gore-Tex fabric with a 2 mil. FEP (Teflon) laminated back face out-performed the other four fabrics against abrasion. The other fabrics were Ortho-Fabric back face coated with 10 mil. Silicone, Gore-Tex front face laminated with 2 mil. FEP (Teflon) and Apollo Test Article Teflon (T162). Due to these results, Teflon will be considered for the slip layer in the EPG design.

In 2008, Glenn Research Center (GRC) developed a second method of evaluating fabrics for abrasion resistance to lunar dust. The objective was to develop a standardized set of procedures by which to compare the relative abrasion resistance of candidate EVA fabrics. Also included was a comparison to Alan Bean's Apollo 12 space suit. The final protocol was based on ASTM D 3884-01 with modifications to introduce loose lunar simulant onto the test apparatus. During development of the test protocol, GRC also evaluated several candidate EVA fabrics, including Apollo plain weave FEP, Apollo twill weave FEP, Ortho-Fabric, Tyvek, silicone coated Ortho-Fabric, silicone coated Kevlar, and silicone coated Vectran material. The final test protocol was only run on the latter four fabrics: Kevlar, silicone coated Ortho-Fabric, silicone coated Kevlar, and silicone coated Vectran. Results of the testing were documented in a test report, as well as published in a 2009 ICES paper (2009-01-2473)[12]. Out of the four fabrics tested using the final protocol, Tyvek reportedly performed the best, sustaining the least abrasive damage and blocking dust from penetrating the fabric. Therefore, Tyvek will be pursued as a candidate for the slip layer as well.

In 2009, a test methodology was developed for establishing comparative abrasion wear characteristics between various candidate space suit outer layer fabrics, characterizing the abrasive wear produced by two lunar simulants and evaluating the ability of heat-sealed seams to prevent dust migration through space suit components. The test incorporated a large rotary drum tumbler with rocks and loose lunar simulant material to induce abrasion, replicating what might be experienced on a long-term lunar EVA. Post-test visual inspections of the various test articles showed that three of the four candidate fabrics lost minimal strength after abrasion. The fabrics that performed well included Ortho-Fabric, the Gore-Tex 4 Harness Satin, and the Gore-Tex 3x1 Twill materials. One fabric, Tyvek, performed very poorly in comparison with the other candidate materials. However, it was difficult to characterize dust migration through the materials and the results were inconclusive[13]. It will be forward work for the EPG Team to determine why Tyvek tested well in 2008 but poorly in 2009 and will utilize that information to guide additional testing and characterization.

In 2014 an effort was undertaken by the High-Performance EVA Glove (HPEG) element of the Next Generation Life Support (NGLS) project to develop a lower cost testing method to evaluate material abrasion performance. Data was collected by visual inspections, pre- and post-test optical imaging and SEM, and un-abraded compared to abraded material strength measurements. Seven materials were tested: Ortho-Fabric, Super Fabric, Twaron, Silver Plated Ripstop Nylon, solution coated Vectran, Teflon and Coated Teflon. Ortho-Fabric demonstrated the highest tensile strength and least amount of elongation after exposure. Also noted was that dust migration through a TMG layup is difficult to evaluate with the proposed process and that the test process needs to be uniform throughout the entire series. Fabrics need to be cut in a consistent manner to ensure the same distribution of threads/materials throughout the samples. Ultimately it was concluded that this test method was found to tell only part of the story for space suit cover layer durability evaluation and should be combined with other tests such as cut resistance, puncture, tear, optical inspection, etc. to establish an overall material comparison benchmark[14]. As a result, the EPG Team will utilize these additional tests to characterize the EPG layup.

B. xEMU Testing

The following tests have or are planned to be conducted through the course of xEMU EPG development.

1. EPG Ply up Thickness Measurements

Several locations on the xPGS such as behind the DCU have tight tolerances and designers needed to verify that the tight areas would be able to accommodate the EPG thickness. A layup thickness characterization test was performed to document accurate measurements of the thickness of a 2-layer, a 5-layer and a 7-layer EPG layup with either basic join, T-join, or cross join seams. Multiple data points were gathered using two different thickness measuring devices. Samples were sewn by two different personnel on different machines to determine if either condition affected the seam thickness. The thicknesses varied from the average of 0.135” (0.34 cm) for a 5-layer EPG with a basic join seam to 0.349” (0.89 cm) for a 7-layer EPG with a cross-seam. The test determined that samples sewn by different personnel had a negligible effect on the seam thickness and that random measurements across the face of the single sheet samples did not change in thickness.

2. Thread Testing

Fabrication of early EPG prototypes and DVT deliverables produced staining on the Neoprene Coated Nylon layer. An infrared analysis performed by NASA M&P revealed that the stains were silicone which was later determined to be from the lubricant on the Nomex thread used to stitch the EPG together. The quantity of silicone contained in all of the thread in an entire EPG was deemed to be an issue for use in the vacuum chamber which the EPG would be utilized in due to off gassing which would foul sensitive components. A large investigation was conducted into sourcing and testing a replacement, non-lubricated thread. Samples of the EPG layup were fabricated, and strength data was collected. The original xEMU thread (Silicone coated, bonded Nomex B and E) pulled at an average of 10% lower from the EMU thread (silicone coated, soft Nomex E). System level evaluations during DVT will determine if the diminished strength is acceptable by verifying the EPG seams do not separate during use.

3. Hook and Loop Testing

As previously discussed in Section III, C, eight combinations of Aplix hook and loop fastener were procured for testing. Also included were EMU nylon and Nomex hook and loop representing “traditional” Velcro used for flight in the past. Testing was conducted to determine for each style how much dust was retained on the hook and loop after separation and the pull strength both before and after contamination from lunar simulant and after cleaning. The simulant chosen for this initial study was NU-LHT-4M. This simulant was chosen for its wide particle size distribution, meaning samples were exposed to a wide range of dust particle sizes that may especially affect the strength of the closure. The highly abrasive nature of NU-LHT-4M is also desirable to replicate potential wear mechanisms flight hardware might experience

For each style, five specimens were tested, and results were averaged which are shown in the graph in Figure 6. Out of the eight, three combinations looked to be the most promising. The candidate loop retained less than 0.08 grams of dust after separation. Whereby comparison, nylon hook and loop retained 1.2 grams and Nomex retained 0.37 grams. The cleaning was done using a Teflon brush and did not remove a significant amount of dust beyond what separating the fasteners had already accomplished. The top cleaned Velcro candidates also had increased peel strength of 18.7% over the “traditional” Velcro. Additional testing was conducted which attempted to repeat that result in the lab and then to determine the new candidate hook and loop’s strength after cycling for comparison. Down selected Velcro candidates were cycled an additional 10 times and their strength was measured. The results showed that Aplix 224/200 fastener tape looses less of its strength than traditional Velcro after 10 cycles. Further testing will examine the effects of cold lunar temperature, its ability to seal out dust, how much debris it generates when separated, and its flammability and toxicity levels.

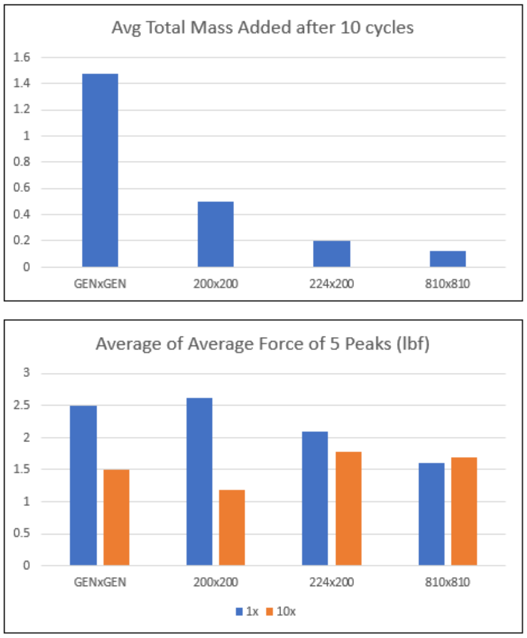

Figure 6. Hook and Loop Peel Test Comparison. *Samples of candidate fasteners were tested against traditional nylon Velcro (Gen). (Top) The generic Velcro retained more dust and lost more strength after 10 cycles than the candidate Velcro.*

4. *Sizing Evaluations*

As detailed in Section III, A, a detailed sizing analysis was conducted to determine what number of sizes of EPG components were appropriate to cover all size variations of the PGS while also attempting to minimize the logistical burden many sizes of components would create. The EPG Team is using the mobility testing portion of DVT to validate the sizing scheme. Of course, the sizing will need to be reconsidered when switching to the hybrid segmented architecture mentioned in Section III, B.

5. *Planned Testing*

There are multiple tests that are planned to fully characterize the performance of the EPG. EPG design specific testing includes determining the strength, durability, and resistance to dust of the attachments chosen at each EPG to PGS interface. Pull strength testing will be performed on the neck ring and hatch opening attachments first followed by the arms, legs, and other structural interfaces that will experience loading during operations.

Environmental testing is planned to expose the EPG material to the lunar conditions specified in EVA-EXP-0039[9] for durations consistent with initial lunar cycles. After exposure, the material will be evaluated for compliance with the material functionality requirements as well as qualitatively for damage, wear, etc. These conditions include thermal, ionizing radiation exposure, solar irradiance exposure, plasma exposure and regolith exposure. Optical measurements will measure and define the specified optical properties both for a beginning of life article as well as an end-of-life test article exposed to representative initial lunar environmental conditions and cycles. These include absorptivity and emissivity. Surface resistance will be measured at various levels of dust contamination to determine how much charge will build up on the surface of the suit from ionizing radiation. Strength measurements will baseline the beginning and end of life of the EPG layup after exposure to dust and cryogenic temperatures. These include tensile, cut, puncture and tear.

A design for integrated knee pads in the legs is being considered for both thermal and cut protection. Several candidate layups have been created and built into strap on kneepads that will be used for data collection from the JSC rock yard. After conducting a prescribed number of kneels, the kneepads will be inspected for wear. The top candidate will be incorporated into the leg EPG layup.

Several xEMU integrated tests will be performed with the EPG installed. These include at the xPGS level: fit, size range, mobility, reach, and cycling. The EPG will be inspected during and after these integrated tests for wear patterns. At the xEMU level, the EPG will be installed for testing of the xINFO band including EMI/EMC, lighting evaluations, and helmet vibration. For the xPLSS the EPG will be considered in interface, antenna, HUT/DCU vibe and PLSS/Hatch vibe. For the entire xEMU, thermal vacuum chamber, system functional and EMI/EMC testing will be conducted.

C. Analysis

As discussed in Section II, B, analysis coupled with EPG coupon testing and system level testing of the xEMU in a thermal vacuum chamber during design verification testing will resolve the TBD requirements related to thermal protection. As part of the xEMU project, a task was performed to develop a more detailed integrated xEMU model used to provide higher fidelity thermal assessments of the EPG performance in regard to minimizing overall suit heat leak. The direct implication for EPG is that this analysis validated the project direction to use 5-7 layers of MLI in the EPG. The following is a summary of several internal reports delivered by the NASA thermal analysis group to the xEMU project on this subject.

To simulate more effectively the complete xEMU spacesuit, two system-level models are used, referred to as External and Internal. The External was primarily designed to determine suit heat leaks and external suit/component temperatures. The Internal model is used for PLSS internal temperatures, cooling and ventilation loops and crew comfort. Each model is intended to provide boundary conditions to the other. This combination is expected to yield more accurate analysis results since the External model has all full radiation exchange with all PGS components. The geometries used in the External model were taken from the xEMU CAD model generated in Creo modeling software. This stand-alone model was used to generate preliminary hardware temperature predictions and subsystem heat leaks for defined lunar surface and ISS environments.

To model the Ortho-Fabric, the optical properties are used. They refer to the ratio of solar absorptivity to infrared emissivity (α/ε), or how much solar is absorbed to the ability of the surface to emit radiation to the environment, which for clean Ortho-Fabric is 0.13/0.787 or 0.17 and degraded Ortho-Fabric is 0.18/.0837. Lunar dust covered Ortho-Fabric is not currently defined but lunar regolith has an optical property ratio of 0.93/0.98, so some preliminary environmental assessments have assumed a ratio of 0.60/0.90 which is a midpoint between clean Ortho-Fabric and lunar regolith properties. The solar absorptivity requirement is part of the previous property but alone states that the outer layer of the EPG must maintain a maximum solar absorption of 0.60.

To model insulation performance, an effective emissivity or ε-star (ε*) value can be used. Multi-Layer Insulation is composed of multiple layers of low emittance film. These layers have a vacuum-deposited aluminum finish on one side. The layers are either embossed or separated by non-conductive spacers or netting. The MLI is designed for use in vacuum environments, where heat transfer occurs via a combination of radiation and solid conduction. Under atmospheric conditions this type of insulation is less effective due to gaseous conduction between layers.

The number of layers of MLI can vary depending on the mission environment. The Apollo suit used 7 layers and the EMU uses 4 to 5 layers. From a modeling perspective, modeling the layers individually can be done, but it becomes cumbersome. Instead, the MLI is modeled using a single value (ε*). This method uses a single radiation conductor through the MLI thickness to simulate the heat transfer through all layers. This method accounts for both the radiation and solid conduction heat transfer modes.

An analysis was performed to assess the usage of ε* for modeling MLI, specifically for the xEMU over the range of expected usage environments. From previous analyses and modeling it is known that there is a potential for underpredicting heat leak in extreme cold environments when using effective emittance to model MLI.

Data taken from an earlier assessment of MLI, which examined both radiation and solid linear conductance through MLI, showed the linear conductance increased with the increase in number of layers. It was theorized that this was due to layer compression, either intentional or due to gravity during testing. For the xEMU application these values are believed to be conservatively high. However, they were acceptable for evaluating the use of effective emissivity as a modeling approach for xEMU.

The assessment was performed based on the number of layers of MLI ranging from 1 to 12. The results showed that for suits with 4-6 layers, using the ε* method is very comparable to using conductance (radiation and linear) through the MLI. At a sink temperature environment of -200°F (-129°C) and an overall suit EPG surface area of 35 ft^2 (3.25 m^2), the results showed a potential underprediction of heat leak of approximately 17.5, 8.75, and 5 BTU/hr (5.2, 2.6 and 1.5 Watts) for 6, 5 and 4 layers, respectively. Given that the linear conduction values are believed to be conservative, these underprediction differences would also be conservative.

Overall, the results show that for the current xEMU EPG configuration and expected environments, that using effective emissivity as a modeling method is acceptable. Historically, the ε* values used for space suits range from 0.05 to 0.1. For xEMU, an ε* of 0.07 was chosen as the baseline for radiation conductance between the EPG and the inner suit wall of the model. This equates to using 4-6 layers of MLI in the EPG. Using the ε* method to represent both the radiation and conduction heat transfer through MLI has shown to be an acceptable practice for the number of layers of MLI used by the current ISS EMU over the range of environment sink temperatures for ISS and LEO applications. It was ultimately decided for DVT testing to build the EPG with 7 layers of MLI in non-mobile areas of the suit and 5 layers in mobile areas like the arms, legs, and waist. Larger flatter areas with less seams and bends, such as the PLSS benefit from more layers. The areas with more bends/seams, such as the arms and legs have less benefit from more layers, since they are driven by the heat leak through the seams and contacting areas created by folds. Also factored into the decision is the impact of added layers on mobility and overall system mass. Results of the thermal analysis showed that for an ε* of 0.07, xEMU suit heat leak was predicted to range from -718.2 BTU/hr (-210.5 W) (into the suit) to 475.3 BTU/hr (139.3 W) (out of the suit) when operating in extreme hot/cold lunar crater and ISS LEO environments.

Figure 7. ARGOS Mobility Testing. *The EPG design will be vetted through ongoing DVT evaluations looking for its ability to minimize impact on torque and range of motion.*

Bare skin and EVA touch temperature evaluations were also covered in this analysis. Due to the length the EMU has been used and the amount of analysis performed on it, the heat transfer rates through the standard TMG layup are well understood and are modelled as a single linear conductor. There are two conditions when evaluating touch temperature limits, incidental contact, and unlimited contact. Incidental contact for a glove analysis is considered brush and bump contact of up to 30 seconds at 0.1 psi (0.7 kPa) of pressure or 3 seconds at 1.0 psi (6.9 kPa) of pressure. Unlimited contact can be used to represent longer duration or repeatedly touching an object such as the handle of a tool. The EVA touch temperature assessment showed serious temperature violations on the EPG external surfaces. However, the contact heat transfer rates of the exposed components were found to be within the allowable limits for both unlimited contact and 3-minute excursions in all analyzed cases. Follow-on touch temperature analyses will be performed to evaluate contact via an undergarment (not direct skin contact) and also alternate allowable touch temperature ranges for contact with non-metallic materials. Ultimately, planned thermal vacuum chamber testing will confirm the results of the analysis looking at the entire EPG layup in both the clean and dirty conditions.

V. Forward Work

As the Artemis program has matured, NASA solicited responses by potential vendor(s) to provide an ISS EMU suit replacement and the Artemis lunar suit as a service, wholly developed, certified, and owned by the vendor(s). This solicitation is known as the eXploration Extravehicular Activity Services (xEVAS) contract. Under the xEVAS solicitation, the complete xEMU design, hardware, NASA testing facilities, and NASA xEMU personnel are available for use by the vendor to leverage how they deem appropriate to meet technical and deliverable requirements.

The EPG has some forward design work required to prepare it for use by the xEVAS contract vendor. Ongoing DVT efforts will evaluate the segmented architecture during mobility and cycle testing shown in Figure 7. Feedback will be solicited on its impacts to range of motion and contribution to overall suit torque. Patterning fixes will be made if required. Regular inspections will be conducted noting wear and tear areas. A confirmation of a proper sizing scheme will be gathered to create a prediction matrix used to assess the final sizing of EPG components. The attachment development will continue both as benchtop testing and by incorporation into cycle testing. This includes the final down select of new candidate Velcro, dust seal evaluations of several snap track designs, zippers and felt. A down select for the proper slip layer material will conclude using tumbler and cryogenic bend testing. Knee pads will be designed, tested and incorporated into EPG legs. A fracture control and hazards analysis related to the EPG attachment hardware will be completed. The EPG specification will be finalized, and drawings completed. Environmental testing will be conducted. The fabricated EPG components will be used for integrated suit testing. Finally, accommodations for the safety tether loop will be included in the design.

VI. Conclusion

The xEMU represents the most comprehensive flight EVA suit development since the Shuttle EMU more than forty years ago. This is due not only to the fidelity of the hardware, but the comprehensive nature of the development. The heritage TMG has seen very little improvement since it was first fielded in 1983 especially in regard to making it capable of providing protection during initial lunar missions. As summarized, the ongoing work to develop and baseline the design of the xEMU EPG encompasses a large volume of work. The design of the EPG includes many challenging technical requirements, significant architectural trades and technical solutions required to engineer a high-fidelity, flight-like solution. This EPG development work has built a platform that will enable the xEVAS contractor to achieve success as humans prepare to return to the moon and go beyond.

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