NASA Advanced Space Suit xEMU Development Report – Waist Brief Hip

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For the past several years, the Exploration Extra-Vehicular 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 history, development, and baseline detailed design of the xEMU Waist Brief Hip (WBH). This paper will outline the challenging technical requirements and solutions needed to overcome these challenges, and a status of the detailed design. Initial results of Design Verification Testing (DVT) as it relates specifically to WBH will also be provided, along with a forward strategy for final maturation into a flight-ready design.

Nomenclature

ABF	=	Anthropometry and Biomedical Facility
ARGOS	=	Active Response Gravity Offload System
BSC	=	Body Seal Closure
CG	=	Center of Gravity
DCCI	=	David Clark Company Incorporated
DVT	=	Design Verification Test
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
EVVA	=	Extravehicular Visor Assembly
FAR	=	Fabric Attachment Ring
FFD	=	Final Frontier Design
Flex/Ex	=	Flexion/Extension
HLS	=	Human Lander System
HUT	=	Hard Upper Torso
ISS	=	International Space Station
LTA	=	Lower Torso Assembly
MAG	=	Maximum Absorbency Garment
NASA	=	National Aeronautics and Space Administration
PDA	=	Preliminary Delivery Acceptance
PIA	=	Pre-Installation Acceptance
PGS	=	Pressure Garment System
PLSS	=	Portable Life Support System
PTRS	=	Project Technical Requirements Specification
VTD	=	Vertical Trunk Diameter
WBH	=	Waist Brief Hip
xEMU	=	Exploration Extravehicular Mobility Unit

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I. Introduction

IN 2019 the acting presidential administration challenged NASA to return humans to the surface of the Moon by 2024. To support this challenge, the Artemis program was formed as NASA's path to the Moon and the next step of human exploration. The Exploration Extravehicular Activity (xEMU) spacesuit will enable astronauts to complete exploration tasks required by the Artemis missions. The xEMU spacesuit will provide enhanced mobility when compared to previous EVA spacesuits. It will provide the capability for astronauts to be able to safely walk, squat, lunge, kneel, and maintain stability during their Extravehicular Activities (EVAs) on the lunar surface with the unique $1/6^{th}$ gravity environment.

The xEMU is a rear-entry spacesuit which uses a mix of polymer, composite, and metallic materials to optimize the mobility and mass of the system. A Hard Upper Torso (HUT), hatch, rolling convolute shoulders, helmet, Extravehicular Visor Assembly (EVVA), EMU arms, and EMU Phase VI Gloves make up the upper torso assembly. A waist, brief, hip assembly (WBH), EMU legs, and planetary boots make up the Lower Torso Assembly (LTA). The WBH is the core component to the LTA which enables complex movements such as walking, lunge, kneel, squat, etc.

II. Background

NASA spent several decades developing and testing planetary prototype space suits. These advanced exploration prototype suits informed the architecture trades which led to the design of the xEMU WBH. Specifically, lessons learned from the Mark III, I-Suit, Z-1, and Z-2 spacesuits have been incorporated into this design. Various tests with these suits have been conducted as far back as the 1980s that document the need for a suit that provides waist rotation, flexion/extenion, and hip mobility. Data from these tests provide the basis for the WBH architecture. These tests have ocurred in the laboratory environment and analog environments, such as the the Desert Research and Technology Studies (Desert RATs), Active Responsive Gravity Offload System (ARGOS), and reduced gravity airplanes. The mobility joints baselined for the xEMU WBH was an architecture trade from these lessons learned. Removal of any part of the joint mobility system does not prohibit all motions, but it would increase the difficulty to complete tasks.

The following sections specifically discuss a test completed on a Mars gravity simulation of a KC-135 flight where the Mark III suit was tested and bearings were locked out to test the capability of the suit with and without the joint for a direct comparison.[1] Reviewing this test data is a good analog to how the different xEMU WBH mobility joints interact with the subject's mobility, and the potential impacts of a spacesuit design that does not use those joints.

A. Waist Bearing

Tests have highlighted the importance of the waist bearing to enable mobility. Achieving natural (unsuited) motions requires the suited subject to control the Center of Gravity (CG). For example, while walking the upper body will shift to compensate for the movement of the lower torso. This keeps the CG within the region of stability. While subjects walk while suited, the upper torso motion is primarily manifested in the rotation of the waist bearing. When kneeling while suited to retrieve objects from the ground, the motion includes rotation at the waist to bring the arm closer to the ground to shift the CG. This was seen on the KC-135 flight when the waist bearing was not locked out.[1]

When locking out the waist bearing, the CG control and consequently stability is removed. Subjects would develop new techniques to compensate. During this test, subjects would obtain rotation from the hip assembly, the Flex/Ex softgoods becoming more active, and the shoulder swing increasing. The gait tended to be wider, stiffer, and required more concentration to maintain stability. All test motions could still be performed while the waist bearing was locked out without excessive effort.

B. Flexion/Extension Softgoods

The Flexion/Extension (Flex/Ex) softgoods, called the waist rolling convolute in the KC-135 report, was utilized in all test motions. It had the most contribution during ingress/egress of a representative rover vehicle seat. The softgoods provided forward waist flexion for the subjects to shift their weight forward as they sat down and stood up. The Flex/Ex softgoods contributed to recovery from supine position as the subjects moved from supine to prone and then got their feet under them to stand up. Loping and walking also utilized the Flex/Ex softgoods to adjust the CG position fore and aft, but the effect was less than the other motions described. When completing a lunge and recover, the Flex/Ex softgoods allowed the subjects to get closer to the floor to retrieve an object more easily. During seat ingress/egress, supine recovery, and kneel, the full range of the Flex/Ex softgoods were used. During a lope and walking, less range of motion was used unless recovery from a stumble or fall.

Locking out the Flex/Ex softgoods, the subject tended to have a more upright position in the spacesuit. The hip assembly than tended to provide flexion. The lock-out of the Flex/Ex softgoods made ingress/egress of the simulated rover seat especially more challenging and required more effort from the legs. The assumption is when the CG cannot be shifted at the waist or start initial motion (such as leaning forward when standing up from a kneeling position), the legs will have to do the additional work to move the body.

C. Hip Assembly

The hip assembly is critical for planetary surface suit feature. The hip is an integral component that is used most frequently to perform activities such as walking, kneeling, recovery from prone, etc. These motions utilize a wide range of motion in both flexion/extension and abduction/adduction. For this test the Mark III style, 3-bearing composite hip was tested. It was tested with a 3-bearings functional, locking one bearing (i.e. 2 bearing hip), and locking out all three bearings. The 2 bearing hip results can be assumed to be like the PGS hip/leg bearing design.

The three bearing hip allowed for the subject to have a very natural walk and lop gait. Kneel and recover was easily performed.

The two-bearing hip (one bearing locked out) was workable, but the subject did note mobility reduction. Flexion/extension while standing was reduced which made the leg not be able to be as lifted as high. The walking and loping gait were also affected. It made the foot rotate outboard when stepping forward.

When locking out all three bearings, the result was crippling to the subjects' mobility. The subject started to use mobility techniques comparable to subjects in the Apollo A7LB suit in Mars gravity. The subject had to rely on compensating mobility features such as the ankles, knees, and Flex Ex softgoods. Most translation came from the subject driving the ankle joint. Most motions could be performed but it was at great difficulty and excessive effort.

III. Driving Requirements

The following section discusses the significant driving requirements for the xEMU WBH as seen in Table 1.[4] Each of the ensuing sub-sections discuss the requirement, and the impacts it drives to the WBH design.

Table 1: Driving Requirements

Section	Requirement	Specification Summary
A	**Anthropometric Range**	The WBH Assembly shall utilize no more than 2 sizes with sizing rings to accommodate the population defined in the Anthropometric Range Table.
B	**Mass**	The short WBH Assembly shall not weigh more than 36.5 lbs, and the long 37.5 lbs.
C	**Mobility Tasks**	The WBH Assembly shall provide acceptable comfort for user task performance as determined by performing the tasks in the EVA Mobility Task Table.
D	**Nominal EVA Operations Pressure**	The WBH Assembly shall have a nominal internal pressure of 4.3 (+/- 0.2) psid.
	Exploration Pressure EVA	The WBH Assembly shall have an internal exploration EVA pressure of at least 8.2 psid (+/- 0.2) psid.
	Maximum Design Pressure	The WBH Assembly shall have a Maximum Design Pressure of 10.6 psid within the pressure garment pressurized volume.
E	**Range of Motion – Abduction/Adduction**	The Hip softgoods shall have adduction of at least 10 degrees and abduction of at least 30 degrees from neutral at 4.3 (+/- 0.2) and 8.2 (+/- 0.2) pounds per square inch differential (psid).
	Range of Motion - Flexion	The Waist flexion/extension softgoods shall have at least 40 degrees of waist flexion forward at 4.3 (+/- 0.2) and 8.2 (+/- 0.2) psid.
F	**HUT Interface**	The WBH Assembly shall interface to the Hard Upper Torso via the Body Seal Closure, Part Number 10591.
	Lower Leg Interface	The WBH Assembly softgoods shall interface to the EMU lower leg via the leg bearing, Part Number 10604.
	Safety Tether	The WBH Assembly shall have two safety tether attachment points.
	Crew Restraint System	The WBH Assembly shall interface with (TBD) Human Landing System (HLS) Crew Restraint System.
G	**Lunar Regolith/Dust**	The WBH Assembly shall be capable of performing all functions during and after exposure to environmental lunar regolith.

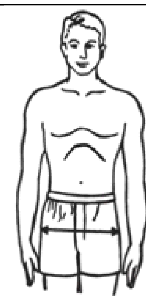
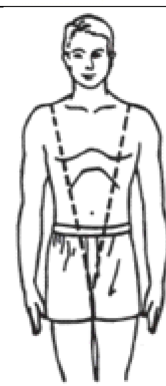
	Dust – Seals	The WBH Assembly shall utilize dust seals that precludes environmental lunar regolith from contaminating primary pressure seals where applicable.

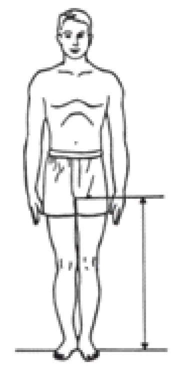
A. Anthropometric Range

The parent requirement for the xEMU, the PTRS (Project Technical Requirements Specification) outlines a series of critical anthropometric measurements and minimum/maximum values which together, represent a practical approach to accommodating the 1st percentile to 99th percentile population (i.e., 90% in total). From that parent requirement, the xEMU WBH Anthropometric minimum and maximum measurements can be seen in Table 2.

A key requirement to note specified that the maximum hip breadth shall be 16 inches. The initial xPGS WBH design for DVT was an iteration based on the Z-2 WBH design with a specific focus on improving the Vertical Trunk Diameter (VTD) accommodations for the smallest VTD subjects for xEMU. This specific focus was chosen as a high region of interest while still meeting schedule for having DVT units to support test events. Therefore, the internal dimension of the brief at the widest point was initially 15.6”. For subsequent xEMU WBH designs, the internal breadth of the brief will be 16” to fully satisfy this requirement.

Table 2: WBH Anthropometric Requirements

Measurement	Minimum (in)	Maximum (in)	Method	Figures
Hip Breadth	11.7	16	Subject stands erect, heels together and weight distributed equally on both feet. Measure the maximum horizontal breadth of the hips. Note: For standing measurements, the largest female hip breadth is larger than the larger male hip breadth; therefore, female	
Thigh Circumference	18.8	28.3	Subject stands erect looking straight ahead, heels together, and weight distributed equally on both feet. Measure the circumference of the thigh horizontally as close to the crotch as possible	
Vertical Trunk Diameter (VTD)	22	29.9	The subject stands erect looking straight ahead, heels far enough apart to insert anthropometer/calipers, and weight distributed equally on both feet. The subject should place one end of the measuring device into the pubis symphysis (male subjects should move scrotum out of the way). Measure the vertical distance from the crotch to the mid-shoulder landmark (have tech or engineer hold calipers). This measurement is done for both the left and right side	

Crotch Height	26.2	37.7	The subject stands erect looking straight ahead, with enough separation between the feet to insert the anthropometer/calipers, and weight distributed equally on both feet. The subject should place one end of the measuring device into the pubis symphysis (male subjects should move scrotum out of the way). Measure the vertical distance from the standing surface to the crotch.	

Two studies focusing on the fleet sizing to meet the anthropometric requirements for the xEMU WBH were performed with the NASA Anthropometric and Biomechanics Facility (ABF).

The first study was described in the paper Davis et. al. (2020).[5] It focused on optimizing the internal geometry of the brief. Using computer aided design modeling, virtual fit checks were performed with body-shaped manikins positioned inside the brief model. The brief-to-body contact and overlap created by these models was quantified and verified via physical fit checks with 3D printed brief hardware. Using the data generated from the body to brief overlap, the internal geometry was optimized. Then a statistical analysis using a logistic regression model was conducted to project approximately 1800 body shapes from the US army to characterize how to overall population would be accommodated by the brief shape.[5]

The second study was described in the work Davis et.al. (2021).[6] The primary purpose of that study was to evaluate the fit, comfort, and mobility of the stack-up of the upper torso, specifically the HUT, with the LTA. It identified potential sizing ring configurations to stack between the HUT and LTA to accommodate different VTDs of test subjects. Subjects performed EVA postures and were asked about fit and comfort while they wore a stack-up of 3-D printed mock-ups. The secondary purpose of the study was to understand if a second, longer size of brief would be more effective for longer VTD subjects than using a taller combination of sizing rings. Subjects performed tests to compare the baseline and elongated brief sizes. Optimal sizing ring and brief configuration as a function of the subject's anthropometry measurements was predicted via a statistical model. The results of the study found that two separate brief types will offer enhanced comfort and controllability for functional movements at anthropometric extremes. From this study, a decision was made for the xEMU WBH to have two brief sizes: a short (i.e. baseline) and long (i.e. elongated). The brief height was increased by two inches to achieve the second size.[6] Four sizes of sizing rings spaced at ¾" increments adequately fit the crew population in conjunction with the two brief sizes.

B. Mass

The WBH mass requirement was self-imposed, and it is based on masses of previous prototype space suits. The requirement drove the selection of softgoods and the number of bearings in the assembly. For example, as referenced in the Background section, a 3-bearing hip does have some mobility benefits over a 2-bearing hip. However, a 3-bearing hip design weighs more so a 2-bearing hip design using hip softgoods was chosen for xEMU. Titanium is used for bearings instead of stainless steel due to the mass savings. A composite brief was considered over an aluminum brief, but it was decided the mass savings were not worth the drawbacks of complex manufacturing and lowered impact strength. The mass requirements are defined in Table 3.

Table 3: Mass Requirements for WBH

Component	**Mass (lbs)**
Waist Brief Hip Assembly (Short)	36.5
Waist Brief Hip Assembly (Long)	37.5
3" Sizing Ring	6.25
2.25" Sizing Ring	5.25

1.5” Sizing Ring	4.5
0.75” Sizing Ring	3.75

C. Mobility Tasks

The Concept of Operations, EVA-EXP-0042, outlines a series of tasks the suited subject must be able to perform while wearing the xEMU. The WBH specification further breaks down the lists of tasks to those in which the WBH will directly impact the comfort of the user while completing those tasks such as walking, kneeling, squatting, laddering climbing, stepping onto and off a ledge, and recovery from prone.

D. Pressure Schedule

The operating pressure and pressure schedule for the spacesuit help to define the load requirements the components are expected to withstand. These are especially important for choosing the strength of the materials used for the softgoods, brief, and fastener selection that connect all the joints. The operating pressures are defined by the xEMU PTRS and the mission. For the xEMU the nominal operating pressure will be 4.3 (+/- 0.2) psid, the exploration EVA pressure could be up to 8.2 (+/- 0.2) psid, and the maximum design pressure will be 10.6 psid.

E. Range of Motion

To allow for the required movement to complete tasks in section C, the hip assembly and Flex/Ex softgoods have range of motion requirements. The hip softgoods requirement is for adduction of at least 10 degrees and abduction of at least 30 degrees from neutral at 4.3 (+/- 0.2) and 8.2 (+/- 0.2) pounds per square inch differential (psid). The short Flex/Ex softgoods requirement state it shall have at least 40 degrees of waist flexion forward at 4.3 (+/- 0.2) and 8.2 (+/- 0.2) psid. The long Flex/Ex softgoods requirement state it shall have at least 40 degrees of waist flexion forward at 4.3 (+/- 0.2) and 8.2 (+/- 0.2) psid. The additional height of the brief allows the long Flex/Ex to have a larger range of motion.

F. Interfaces

The first set of interface requirements for the WBH allow for the connection to the HUT and to the leg softgoods. The HUT connects to the WBH through the HUT’s Body Seal Closure (BSC) to the waist bearing. The BSC is shown in Figure 1 (top). As seen in Figure 1 (bottom), the sliding locking segment mechanism for this interface is based off the design from the Mark III spacesuit since that was found to be a reliable, robust interface. When locked, the latch physically engages a series of locking segments between the BSC and waist bearing. When unlocked, the segments on the BSC will slide over to create space for the WBH to be removed. When used, the sizing ring assembly will be placed between the BSC and the waist bearing. The top of the sizing ring will have the static locking segments to interface with the BSC, and the active sliding segments on the bottom to interface with the waist bearing. The WBH connects to the leg softgoods via an acme thread interface on the leg bearing. This is based off the current EMU leg Fabric Attachment Ring (FAR) design.

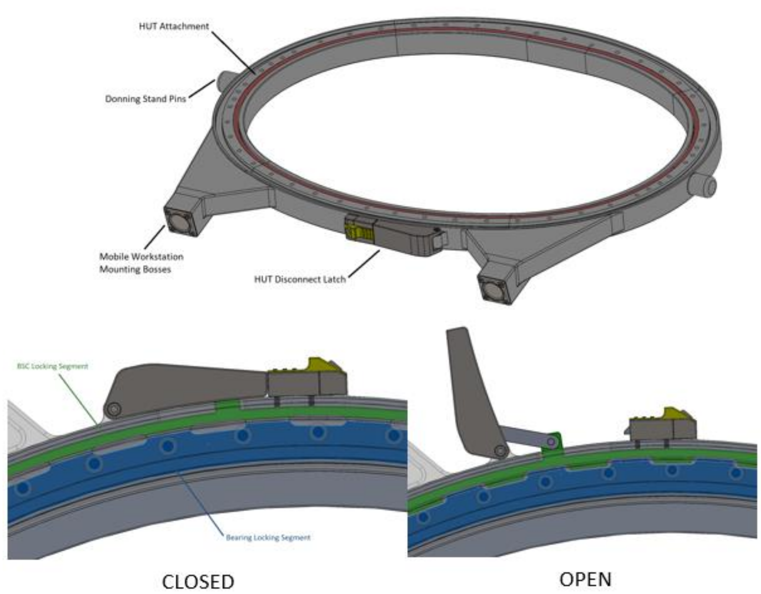


Figure 1: Body Seal Closure (BSC) (Top)
The BSC latch mechanism in the closed and open position (Bottom)

The second set of interface requirements are how the WBH will interact with the ISS and future Human Lander System (HLS). The xEMU could support ISS EVAs as a replacement to the current EMU spacesuit. The xEMU must have an attachment point for safety tethers. Safety tethers are a security measure for crew members to attach themselves to the ISS to prevent floating away as they around the ISS maneuver during a spacewalk. The current EMU spacesuit utilizes D-Rings on the LTA to attach safety tethers. The WBH will have similar D-Rings symmetrically on the left and right side at the pivot of the flex ring. These WBH D-Rings will also need to support an HLS Crew Restraint System which has yet to be designed.

G. Lunar Regolith

Building a robust system to tolerate lunar regolith and dust is a challenge for the xEMU. The WBH is required to be able to perform all tasks in section C during and after exposure to this environment. The main mitigation to prevent dust from damaging the WBH will be the Environmental Protection Garment (EPG) covering the assembly. The secondary mitigation will be a dust seal in each WBH bearing. The design of the dust seal was based off work completed for the High Performance EVA Glove project.[7] The design will use a molded internal wiper seal to prevent dust from contacting the main seal for the bearing races. The design of the bearings using the dust seals was not finalized in time for these bearings to be built and tested for DVT.

IV. Overview of Design

Figure 2 shows the components that make up the WBH. The WBH interfaces to the upper torso via the HUT-side BSC to the waist bearing. Sizing rings can be placed between the BSC and waist bearing depending on the VTD of the subject. Four sizes of sizing rings are available: 0.75”, 1.5”, 2.25” and 3”. The waist bearing enables rotation of the waist. The waist bearing is mounted onto the top of the Flex Ring. The Flexion/Extension (Flex/Ex) softgoods allow for 40 degrees of flexion and extension of the suit for the short brief and 50 degrees for the long brief. The softgoods attached between the Flex Ring/Waist bearing and the top of the brief/brief clamp ring. The brief connects to the flex ring via two pivots on the left and right. As mentioned previously, two sizes of brief are available: short and long. The long is approximately two inches taller than the short to accommodate the anthropometric range for VTD. The four bumpers (two in the front, two in the rear) limit the range of motion respectively for the short and long sizes and protect the flex ring from contacting the brief. Between the hip bearing and leg bearings, the hip is made of patterned softgoods that allow for 40 degrees of total abduction and adduction. The load path for the hip softgoods travel through independent primary and secondary restraint axials that are stitched to the restraint fabric for indexing. The primary and secondary restraint axials interface to bracket assemblies which are attached to the hip and leg bearings. These axial restraint lines and brackets are also represented in Figure 2, but they do not perfectly align in the model.

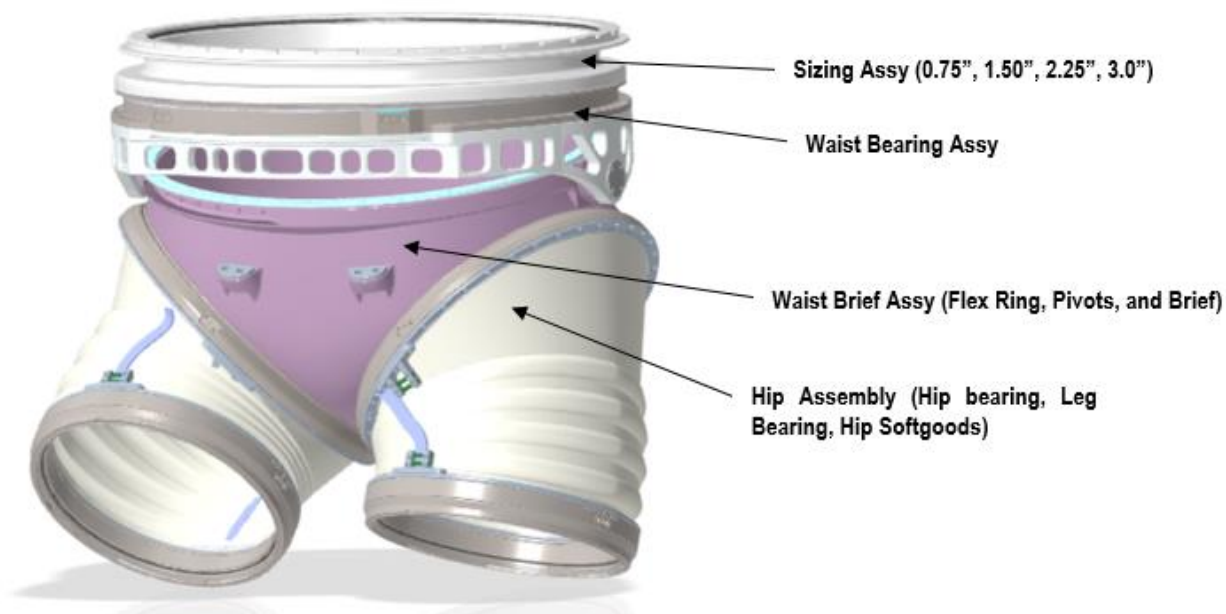


Figure 2: WBH Assembly (Flexion/Extension Bladder not represented)

A. Hardgoods Design

The hardgoods that make up the WBH Assembly are designed and manufactured by Air-lock, Incorporated. The hardgoods are considered all the metallic components: waist bearing, waist brief assembly, hip bearings, and leg bearings. It should be noted deltas exist between the DVT WBH hardgoods and what will be the expected design for Qual/Flight. Those are described in detail in the Forward Work section.

The hip, leg, and waist bearing races are fabricated from Ti-6Al-4V titanium instead of 17-4PH steel that the EMU utilizes to reduce the bearing weight. Aluminum was considered, but not selected because the strength was too low. Previous work on the Z-1 and Z-2 prototype suits considered the work of using titanium bearings to study the unique challenges of the material.[8-9] In a spacesuit's enriched oxygen environment, titanium is considered flammable. However, NASA conduced extensive flammability testing with titanium bearings to demonstrate the bearings cannot create an ignition mechanism with even very high conservative cycling.[8-9] Contact stresses between ball bearings and races was also carefully considered because if it is too high, titanium will experience wear stresses and have subsequently lower life.[9] Originally, it was planned to pulse plasma nitride the bearings races to improve the wear properties and improve oxygen compatibility by isolating the titanium from the oxygen environment. However, the high temperature required to complete the nitriding process caused bearings to warp outside allowable tolerances. To make the hip bearings contact stresses within the acceptable limits without a nitride coating, the ball bearing size was increased to 0.25".[9] The waist bearing and leg bearing contact stresses were considered acceptable, so no changes were made to improve the contact stress performance.[9]

B. Hip Softgoods

Two vendors designed and manufactured two different sets of WBH softgoods: Final Frontier Design (FFD) and David Clark Corporation Incorporated (DCCI). The discussion of each vendor has been anonymized to Vendor 1 and Vendor 2 in the following sections. Two vendors were selected to develop the WBH softgoods to reduce risk for the xEMU project since this was the first time each vendor was building this hardware. Each vendor developed and provided two architecturally different styles of softgoods that accomplish the same goal.

Vendor 1 developed a hip joint like that of the EMU knee or elbow in terms of materials and the gore style pattern as shown in Figure 3 (left). The joint consists of four Polyurethane Nylon fabric patterned gores to allow abduction and adduction, a Dacron cloth restraint layer tabbed to the bladder by tie-ins to stiffen the fabric to create convolutes, and spectra webbing restraint lines for axial loading.

Vendor 2 utilized an Orlan-style orifice system, bonded to an inner bladder layer to equalize flow from bladder to restraint with a flow rate of 500 scc/m at 4.3 psid. As seen in Figure 3 (right), the hip joint consisted of a urethane coated nylon restraint and bladder double layer. The patterning consists of a two-convolute, asymmetric joint. The transversal restraints and axial restraints made of Ultra-high-molecular-weight polyethylene. The restraint layer acts as the nominal pressure tight layer and if the restraint layer suffers a loss of pressure integrity, the bladder will leak at a controlled rate.

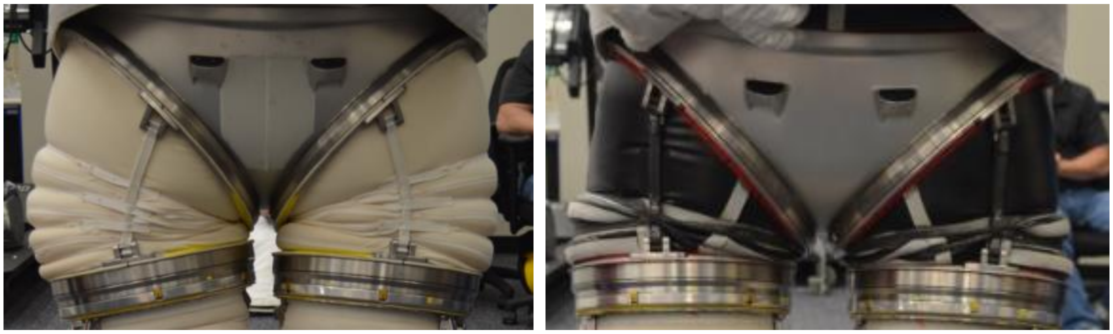


Figure 3: Vendor 1 Hip softgoods (left) and Vendor 2 hip softgoods (right)

C. Flexion/Extension Softgoods

The design of the Flex/Ex joint follows a similar architecture and materials from each vendor as described in the prior section. The routing of the softgoods can be seen in Figure 5. The Flex/Ex joint is clamped between the brief clamp ring/brief, and the Flex/Ex Clamp Ring/waist bearing. The two vendor designs can be seen in Figure 4. Vendor 1 uses a four-piece gore style pattern with radio frequency sealed seam tape and is indexed by four sets of tie-ins to index with the restraint layer. Vendor 2 is a set of two patterned pieces that vary in height to allow range of motion while utilizing the orifice system to equalize pressure. Vendor 2 also requires an additional gasket to be used on the brief/brief clamp ring location to ensure the joint meets leakage requirements.

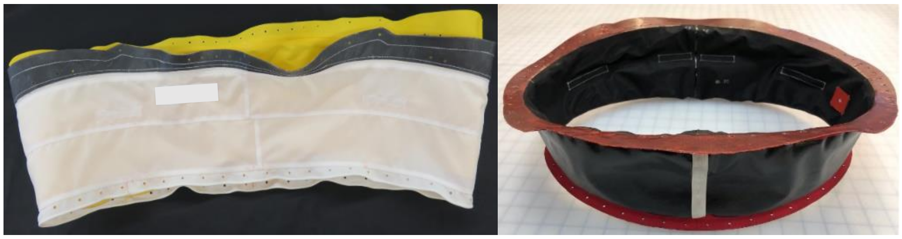


Figure 4 Vendor 1 (left) and Vendor 2 (right) short waist softgoods

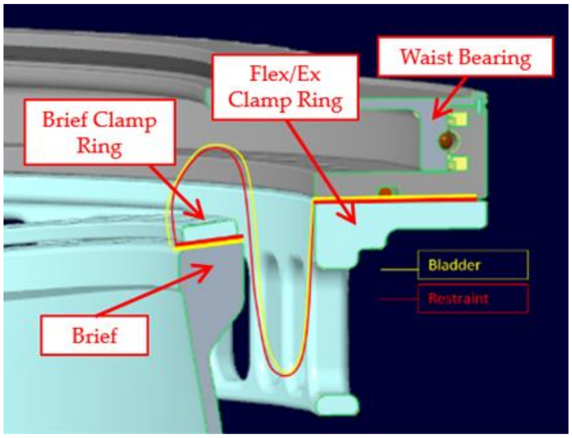


Figure 5 Softgoods Routing for WBH

V. Tests and Analyses

A. Pre-Delivery Acceptance

Prior to accepting the hardware at NASA Preliminary Delivery Acceptance (PDA) testing is the first acceptance test of all flight and qualification hardware, and the first test to be performed following fabrication. PDA is a mandatory end item level test of the hardware to demonstrate its functionality and conformance requirements. Completion of the PDA represents the official "birth" of the hardware. PDA tasks for the WBH include verifications such as weight of the hardware, range of motion of the softgoods, proof pressure testing and leakage testing. The DVT WBH passed PDA testing with no notable issues.

B. Pre-Installation Acceptance

Pre-Installation Acceptance (PIA) testing is a test performed prior to shipment of the hardware for flight installation. Subsystem and Component level PIAs are also performed prior to installation into next higher assemblies, the need for lower level PIAs are dependent on complexity of the flight system. Whereas the PDA is performed once on each flight item, the PIA is performed on flight items prior to each flight use. PIA tasks for the WBH include verifications for a hardware inspection, structural pressure, and leakage testing. The DVT WBH passed PIA testing with no notable issues.

C. Vendor Testing

After completing PDA and PIA testing, the WBH was installed onto the PGS assembly. The team conducted a series of suited tests with subject to identify the best softgoods for the waist and hip design that would be implemented in the final WBH assembly.

Initial fit checks were performed to assess sizing of various subjects throughout the anthropometric range. These fit checks focused on achieving the best fit for subjects. Subjects were asked to comment about suit fit and comfort while performing simple tasks such as isolated joint mobility and walking. Following fit checks, four test subjects with prior suit experience and a variety of anthropometric sizes were chosen to complete further testing. They completed a series of mobility tests in the suit lab under 1-*g* forces to evaluate the functionality of each design. The mobility test series consisted of range of motion, walking, lunging, squat, box steps, and lateral box steps.

When comparing Flex/Ex softgoods performance of the two vendors, subjects experienced excellent range of motion and were able to perform all motions in the mobility test. During these 1-*g* tests, it was commented that both waist softgoods designs experienced bi-stability and an over center force that needed to be overcame to return to a neutral stance after reaching extremes in flexion and extension. Vendor 2 had a higher effort to maintain suit stability related to the bi-stability when subjects were completing isolated flexion/extension or recovering from a lunge. Subjects with more front to back room in the HUT had more concerns with the bi-stability. A tighter HUT fit made the bi-stability easier to overcome.

Similar to the Flex/Ex softgoods results, when comparing the two vendors hip softgoods design subjects had excellent range of motion and were able to complete all mobility tasks. Vendor 1 had a reported inner thigh hotspot caused by the hip bladder diving in. It was noted to be heavier contact on the right hip versus the left. Vendor 2 hip softgoods naturally abduct and caused a reported feeling of having to use a wider-than-natural walking gait. Most subjects noted that Vendor 2 hip softgoods were preferred over the course of the test because they did not have the inner thigh hotspot which made them more comfortable overall.

After the 1-*g* mobility test series, it was theorized that the weight of the suit in 1-*g* could be negatively effecting suit performance and therefore, effecting the evaluations of the two vendors. To verify this wasn't a factor, the Active Response Gravity Offload System (ARGOS) was used to perform a mobility series. ARGOS is a system that offloads the subject and suit weight to simulate a lunar 1/6-*g* environment. The tests performed in ARGOS included the previous tests series with the addition of lunging one hand object pick up, lunging two hand object pick up, boot strap adjustment, neutral treadmill walking, inclined treadmill walking, declined treadmill walking, and lunar lander ladder evaluations.

The results of the ARGOS test series were similar to the results as seen in the 1-*g* lab environment. The Flex/Ex softgoods' bi-stability was improved in ARGOS, but Vendor 1's design was overall preferred over Vendor 2 because there was less bi-stability so subjects felt more stable when completing motions which needed a forward lean such as lunges and box steps. Similarly, the Vendor 1 hip softgoods had improvements to the inner thigh discomfort in ARGOS, but it was still noticeable as compared to Vendor 2. This led to the decision of moving forward into future fiscal year 2022 testing with a configuration of Vendor 1 Flex/Ex softgoods and Vendor 2 hip softgoods.

D. Mobility Testing

The xPGS Mobility Test series will evaluate the performance of the WBH. This test will help to verify the comfort and mobility requirements as listed in Table 4. The selected softgoods for the hips and waist will be used for the evaluations. The testing environment will be in ARGOS. Figure 6 shows a subject completed a hammer and chisel operation in the simulated lunar environment during the Mobility Test series. At the time of publication for this paper, mobility testing has not been completed. Results will be documented in internal xEMU reports.

Figure 6: ARGOS Mobility Testing

E. Cycle Testing

The primary objectives of the xPGS Cycle Testing series are to demonstrate the ability of the xPGS hardware to meet the life cycle requirements, including operational life, operational cycles, and joint cycles for the ISS Demo and Initial Lunar Missions. Following completion of meeting life cycle requirements, the secondary objectives of Cycle

Testing will be to demonstrate the ability of the xPGS hardware to meet all life cycle requirements for the Sustained Lunar Missions and to determine the ultimate life capability of the xPGS Hardware. Cycle Testing for the WBH focus on tasks that involve movement of the hips softgoods in either flexion and adduction/abduction and the Flex Ex softgoods in flexion/extension and rotation. These tasks include walking, ladder ascent/descent, lunge/recover, and squatting. At the time of publication for this paper, cycle testing has not been completed. Results will be documented in internal xEMU reports.

VI. Forward Work

The WBH had gaps in some requirements that will require additional design work to be completed. First, the internal diameter of the brief will be widened to 16". This allows the brief to meet the hip breadth anthropometric requirement. Second, the WBH design does not include ISS safety tether hook attachments. These will need to be added for ISS spacewalks. Figure 7 shows a design concept of adding the D-Ring attachments symmetrically at the pivot on the flex ring. The plan would be to only use the ISS D-Ring Extender on the attachments due to the interferences of the hip bearing and the Portable Life Support System (PLSS) when rotating the waist bearing. Third, the WBH bearings will need to have environmental and dust seals added. The internal environmental seal prevents debris from inside the suit from entering the bearing. The dust seals will be the secondary method of dust protection on the lunar surface.

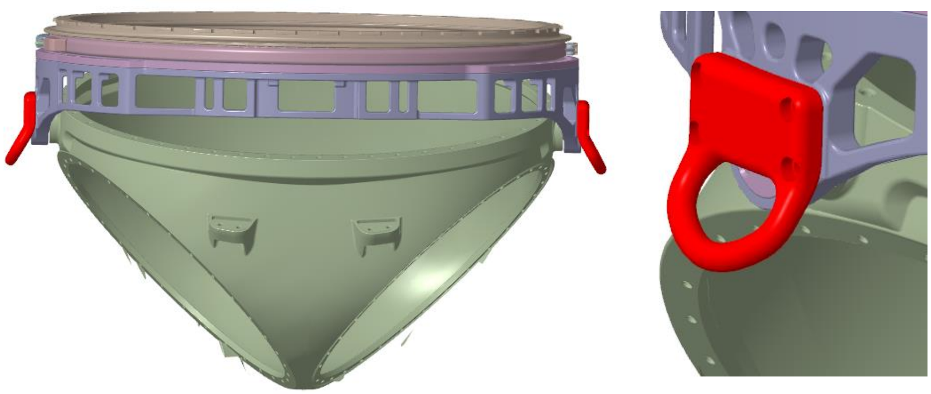


Figure 7: D-Ring Tether Loop Proposed Attachments

VII. 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. Dust-proof outer thermal garments, LCVGs, surface boots, and many other hardware items had not seen devoted development at NASA until the past few years. The xEMU WBH has shown vast improvements in mobility and redundancy throughout the iterations of Advanced Exploration Prototype suits and as shown through Design Verification Testing. This development of the xEMU WBH will hopefully enable NASA's flexibility in the future for development and procurement of advanced spacesuit lower torso architectures.

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