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Testing the Exploration ConOps (ExCon) Mockup Suit in Lunar Analog Environments in 2022

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Understanding how to effectively train for Extravehicular Activities (EVAs) for Artemis missions is critical. Developing high-fidelity simulation environments is important for Artemis mission preparation. Because the actual Lunar exploration environment cannot be fully replicated on Earth, it is paramount to determine where and how to properly train the Artemis team. The overall focus for this test series was developing the capability to perform Artemis simulated EVAs in high-fidelity, full-scale environments. This test series was broken into three distinct tests titled after the EVA & Human Surface Mobility (HSM) Program (EHP) integrated test team: Joint EVA & HSM Test Team (JETT). The test locations are planned to serve as Artemis training sites and were selected because of their relevance to the expected Artemis Lunar terrain. JETT1 was conducted near Kilbourne Hole by El Paso, Texas and focused on hardware development and checkout. JETT2 was conducted in the Icelandic Highlands and began the transition towards EVA concept of operations (con-ops), risks and technology. JETT3 was conducted near SP Crater by Flagstaff, Arizona and focused on simulating the Artemis III mission including a Houston based Flight Control Team (FCT) and a Science Mission Directorate (SMD) science team. All three JETT tests utilized the Exploration Concept of Operations (ExCon) mockup space suit. The ExCon mockup suit is a lightweight, unpressurized Exploration Extravehicular Mobility Unit (xEMU) simulator. While it cannot replicate the feel of working within a pressurized suit, it does introduce similar volume constraints and some of the mobility programing to simulate the user experience in the xEMU. Overall, the JETT testing was able to create a simulated Lunar EVA and have two subjects perform full scale operations in line with Artemis III mission expectations. Future work is planned to continue to improve the simulation quality of Lunar EVA simulations.

Nomenclature

ASA	=	Acrylonitrile Styrene Acrylate
Con Ops	=	Concept of Operations
EPG	=	Environmental Protection Garment
EMU	=	Extra-Vehicular Mobility Unit
EVA	=	Extra-Vehicular Activity
EVVA	=	Extra-Vehicular Visor Assembly
ExCon	=	Exploration Concept of Operations
HITL	=	human-in-the-loop

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HUT	=	Hard Upper Torso
LTA	=	Lower Torso Assembly
NASA	=	National Aeronautics and Space Administration
PGS	=	Pressure Garment Subsystem
PLSS	=	Portable Life Support System
ROM	=	Range of Motion
xEMU	=	Exploration Extra-Vehicular Mobility Unit
xPGS	=	Exploration Pressure Garment Sub-system

I. Introduction

The Artemis Program will reestablish human presence on the Moon and lead to a new era of scientific discovery and exploration. Led by the National Aeronautics and Space Administration (NASA), the Artemis Program is a collaboration of space agencies and companies from around the world. In support of the Artemis Program a cross-disciplinary effort integrating science, engineering, operations, and human factors is currently being developed to identify methods, facilities, and field locations to test hardware, train astronauts, and evaluate concepts of operations (con ops). Artemis-related test events in 2022 significantly increased in frequency, scope, and complexity across numerous facilities at NASA centers and at remote field locations. This diverse testing portfolio is required to satisfy the variety of conditions needed for hardware, con ops, and training objectives. Integrated testing events and facility developments are coordinated by the Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program, collectively known as EHP, through the Joint EVA & HSM Testing Forum (JETF) and approved by the Integrated Testing & Facilities (ITF) Panel. The JETF consists of numerous stakeholders across the Exploration Extravehicular Activity (xEVA) community, and serves to synchronize test objectives, resources, milestones, and programmatic-level goals. The Joint EVA & HSM Test Team (JETT) is a multi-disciplinary group of subject matter experts from the JETF that plan and execute integrated Human-in-the-Loop (HITL) tests.

By the nature of being on Earth, testing and training for Lunar EVAs presents a unique challenge. There is no single facility or test that can be conducted to perfectly simulate what a Lunar EVA will actually be like. When factoring in the extreme hazards, cost, and complexity of EVAs, it is easy to see why training and mission preparedness are critical to the success of the EVA. The on-going JETT testing serves as a critical stepping-stone to achieve the necessary preparedness for our return to the Lunar Surface. As one of the few opportunities to bring together the largest gathering of critical mission organizations including flight operations, engineering, science, human health and performance, and others in full-scale EVA operations it is imperative to develop the highest simulation quality possible.

While it is preferred to test in as flight-like configuration as possible, that is not always an option. Gravity offload testing can be utilized for testing and training in actual pressurized suits, but that testing is limited in scale by the physical dimensions of the relevant facility. Full-scale EVA operations in NASA's reference design spacesuit, the Exploration Extravehicular Mobility Unit (xEMU), is unrealistic due to its heavy weight in Earth's gravity (1-g). The alternatives are to conduct the testing in either street clothes or in a mockup suit. As with all testing, consideration must be made to ensure the test configuration selected aligns with the objectives. If the testing is not concerned about how the subjects move or physically interact with the test environment, street clothes may be perfectly acceptable. However, achieving a lightweight, volumetrically accurate mockup suit can improve the simulation quality such that the subjects perform in a more realistic way compared to an actual Lunar EVA.

II. ExCon Mockup Suit

Mockup spacesuits are typically developed to be a tool that may be utilized in the appropriate conditions to simulate a real suit but when the real suit can not be used. Typically, factors such as the weight of actual spacesuits and the logistics of providing the necessary life support services can be challenging depending on the desired test environment. The Exploration Concept of Operations (ExCon) mockup suit was created to enhance testing and training events for the Artemis mission. It was designed based on a volumetric shell model of the xEMU spacesuit which is the NASA reference design for Artemis mission, and the ExCon provides some similar volumetric constraints, some mobility restrictions, and some similar tool attachments. This paper is focused on the lightweight ExCon suits which have been utilized for rock yard (a small rock and dirt area for local testing) and field test type activities. Another ExCon mockup suit that has been developed, which was designed for loadable applications including use in the Active Response Gravity Offload System (ARGOS) facility, is outside the scope of this paper.

Maintaining key aspects of the xEMU suit in the mockup suit were critical to ensure that its use would provide value to the testing being conducted and data being collected rather than serve as a potential source of error due to deviations. As mockup suits are inherently different than the flight suit there are some aspects that are missing that can significantly impact both quantitative and qualitative data. This paper will reference xEMU but is more focused on the Pressure Garment System (PGS) portion of that spacesuit system. A full description of the xEMU PGS can be found in the paper by Shane McFarland, et. al. "NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2022".[1]

A. Design

The ExCon mockup suit, originally developed by Atlas Devices and modified by NASA, was primarily designed based on an early surface model of the xEMU. It consists of several of the same major components as its pressure suit equivalent. The suit is comprised of an Informatics band containing lights and a camera, Helmet, Hard Upper Torso (HUT), Shoulders, Waist, Brief, and 2 pairs of Hip segments. A shell of the Extravehicular Visor Assembly (EVVA) is included as it serves as the interface to the Informatics; however, it does not currently have a functional visor or shades. The ExCon mockup suit generally has appropriately placed bearings and joints as compared to the xEMU. The bearings include the scye, arm, waist, and 2 pairs of hip bearings. The Lower Torso Assembly (LTA), which was comprised of the waist/brief/hip portion of the suit was unfortunately designed with little insight into the xEMU LTA design. This is the most significant deviation from the xEMU design. For most testing the LTA was slightly modified to remove the lower hip segment and the upper hip segments interface to the lower hip segment was removed. Although not the exact same as the xEMU design, the updates did make improvements in the simulation quality of making it an xEMU mockup suit. The ExCon mockup spacesuit does not mockup the arms, legs, or boots. Low fidelity glove mockups are used consisting of COTS work gloves with Phase VI spacesuit glove Thermal Micrometeoroid Garments (TMGs) over the top of them. The ExCon mockup suit also has an external cover layer for most parts as well as sleeves for the legs and arms. These cover layers serve mostly as aesthetical and are not representative of an xEMU Environmental Protection Garment (EPG). The cover layers were typically not used during tests. As the lower arm bearing primarily served as the interface to the lower arm cover layer it was also removed for weight savings. This deviation did not result in any significant impacts to the functional performance of the mockup suit. The suit also includes a Portable Life Support System (PLSS) mockup which primarily serves as a volumetric representation but is also used to house the electronics necessary for field testing such as batteries, a computer, radios, and video encoder hardware.

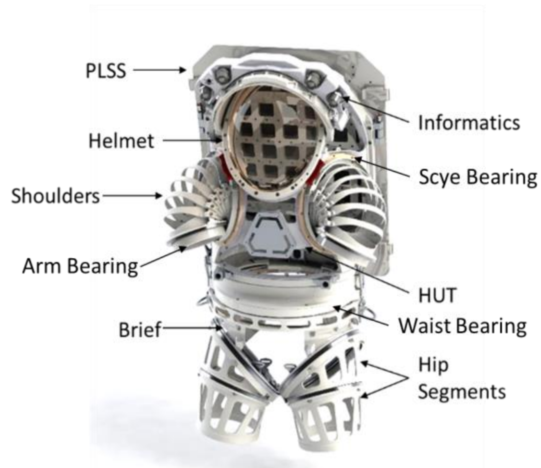

Figure 1: Lightweight ExCon Mockup Suit

1. Hard Upper Torso

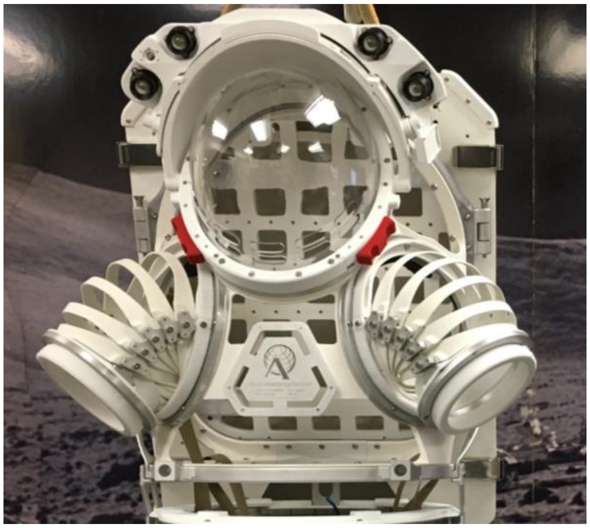
Figure 2: Lightweight ExCon Mockup Suit

The HUT comes in small/medium and large sizes based off the xEMU HUT model, with shoulder spacing resembling the scye-out configuration. Aluminum and 3-D printed materials make up the HUT. All large load bearing components of the HUT are made of 6061 aluminum and smaller load bearing components are made of 7075 aluminum. All 3-D printed parts are made of Acrylonitrile Styrene Acrylate (ASA). There are interfaces for the hatch, helmet, shoulders, and waist. Located at the top of the HUT are two mounting points that are used to mount to the arms of the donning stand and act as lifting points as shown in Figure 3.

2. Hatch

The hatch serves as the entry/exit point for the suit. The hatch attaches to the HUT via four quick-release pins: two pins each on both the left and right sides of the rear HUT entryway. Removing the pins from solely the left or right side of the hatch allows the hatch to swing open, as shown in Figure 4. Removing all four pins detaches the hatch completely. The hatch for the loadable configuration has mounting holes to attach to the ARGOS gimbal and loadable PLSS mockup, whereas the lightweight configuration does not have a separate PLSS/hatch system.

3. Portable Life Support System

The Portable Life Support System (PLSS) mockup is a removable volumetric representation of the xEMU PLSS. The lightweight PLSS mockup has hinges directly on the PLSS for mounting to the HUT via quick-release pins. The loadable PLSS mockup mounts directly to the hatch plate via bolts and through-holes. A removable shell is attached to the PLSS mockup via latches located on the four corners of the PLSS. These latches can be engaged/disengaged by hand without tools.

4. Shoulder

The upper arm assembly (shoulder) is a 6-pivot rolling convolute joint similar to the xEMU. These joints are made of glass fiber reinforced nylon. The ExCon shoulder joint functions in the same manner as the xEMU rolling convolute shoulder.

5. Lower Torso Assembly

The LTA connects to the HUT via three sizing brackets located on the right, left, and rear of the LTA. The brief connects to the waist via four fasteners (two each on both the left and right sides). These fasteners can be removed with the Impact Drill (1/4" ball end driver) that was proved with the suit. The LTA has a waist bearing that allows for rotation at the torso and four hip bearings (two per each leg) that allow for ease of motion when mobile or kneeling.

B. Donning

The suits are integrated into a donning stand for the donning process. The ExCon suit is a rear-entry style similar to the xEMU. To don, the suit is lowered so that the subject may step into it as shown in Figure 3. Then the suit is raised around the subject to the appropriate height as specified by a certified Suit Test Engineer (STE). At that point the suit is secured to the subject via the waist and shoulder straps. Once secured, the subject is able to disengage from the stand. Final prep activities include installing the helmet and PLSS as well as mating the informatics connectors. The doffing process is repeated in the opposite manner.

Figure 3: Suits Installed in Stand for Donning

C. Sizing, Indexing, and padding

The ExCon suit has two primary sizes: small/medium and large. This correlates to the HUT size with the primary difference being in the width of the HUT. It does not have scye positioning like the xEMU and generally represents the scye-out configuration of the respective xEMU HUT. Various waist sizing options are included to accommodate the torso length anthropic range. As the suit does not mockup the arms and legs, no sizing options are included for those aspects. Subjects bear the load of the suit primarily via a built-in waist strap as well as shoulder straps. The waist strap introduces the most significant anthropometric limitation on subjects as it restricts some subjects more than the xEMU primarily based on their hip breadth and waist circumference.

Figure 4: Back Pad and Shoulder Straps

Padding is used for both indexing and comfort. Back and chest padding is added to ensure the subject is appropriately positioned in the fore/aft direction within the suit. Depending on the configuration of the suit, duration of the test, and subject preference additional comfort padding is applied. Typically, this padding is along the iliac crest of the hip bone and lumbar padding for the lower back.

D. Volumetric Performance

While the ExCon mockup suit was designed based on the xEMU there are some differences. The HUT, shoulders, and helmet bubble are reasonably accurate when compared with the relevant external dimensions of the xEMU. There are some slight deviations in areas where design simplicity and weight savings were higher priority but the deviations of these components are minor and inconsequential for the suit's use as a volumetric simulator. The LTA has more substantial volumetric deviations from the xEMU due to its design being completed without knowledge of the xEMU design. After the minor modifications were made, the outer mold line of the LTA became a reasonably good volumetric mockup. As the arms, legs, and boots are not simulated, care must be taken to ensure the lack of those components does not impact the test objectives. Similarly, the low fidelity glove mockups are not volumetrically accurate which can become a factor if performing tasks that require particular tight reach areas. Depending on the specific test objectives, the deviations could be an issue but for the usage in Fiscal Year (FY) 2022, the volumetric deviations have not resulted in significant impacts.

E. Mobility Performance

While the ExCon mockup suit serves well as a volumetric mockup, it is not considered to be an accurate simulator of xEMU mobility. The accuracy varies depending on the specific motion and position. The mobility comparison can be largely characterized by:

1. *Total range of motion*

- Some range of motion limitations imposed by the xEMU are simulated by nature of commonalities such as those imposed by mechanical contact between parts.
    - The amount of roll possible by the shoulder is one example of this.
- Lack of arm and leg components leads to some capabilities that are unrepresentative of xEMU.

- Remaining design differences in LTA result in some suit/subject interactions that are not representative ultimately changing subject's suited capabilities.
- Subject Indexing
    - The subject's shoulders and arms may not be positioned as well as in xEMU leading to some differences in the subject/suit interaction.
    - Hip placement is more limited due to large waist sizing options when compared to xEMU
    - It should be noted that some improvements here are certainly possible; however, based on the current use cases, this would result in negligible benefit.

2. Performing Motions

The most significant delta when moving is the fact that it is an unpressurized mockup. Deviations in the necessary mental bandwidth, programming required, amount of force required, and movement capability due to force limitations all exhibit themselves when moving. These mobility differences are the primary reason that mockup suits are not useful for spacesuit training and can introduce significant challenges with data acquisition. Beyond spacesuit training, testing with mockup spacesuits also introduces a potential pitfall related to validity of data acquired. As critical spacesuit functions are not represented, all data related to those functions is invalidated. Results such as exertion, body positioning, and capability to perform a task in a mockup suit do not correlate directly with the equivalent task in a planetary pressurized suit such as the xEMU.

III. JETT Testing

The FY22 JETT test series was a sequence of three field tests increasing in scale and complexity as the tests went on. The primary purpose of these JETT tests was to develop the hardware and systems required to enable Artemis Lunar EVAs, evaluate and mitigate identified risks and gaps, develop testing capabilities, and provide xEVA stakeholders with an opportunity to evaluate their own objectives.

F. JETT1

JETT1 was conducted in April 2022 in the Potrillo Volcanic Field, NM (vicinity El Paso, TX) to evaluate Artemis related testing/training hardware and instrument concepts of operation to best prepare NASA for near-term Artemis missions to the lunar surface. The evaluation of the ExCon suit in a field test was one of the most significant objectives of JETT1. Over the course of the two days including suit testing, seven subjects of varying planetary pressure suit experience were utilized varying from completely inexperienced to subjects with significant experience. Most subjects ran for 1.5-2 hours without breaks performing various anticipated Lunar EVA activities (such as geological sampling). The test series culminated in a night run on the final day with a mini-EVA being performed. The most significant comments from subjects related to the weight of the ExCon suit. While the mass of the suit system (mockup suit, electronics, and attached tools) was not measured, it is expected to have been ~125lbs. Three of the seven subjects reported medium to heavy inner thigh contact against the interface between the upper and lower hip segment. Two of these subjects had various planetary suit experience and reported that the contact exceeded their experience in actual spacesuits. The inner thigh contact was particularly present during traverse and kneeling tasks and was viewed as equally limiting as the weight of the mockup suit for the three subjects. JETT1 was conducted with the original hip hardware which was updated to the configuration described in section 3 shortly afterwards.

Figure 5: Sampling Operations at JETT1

Ultimately, the test objectives were accomplished as the team was able to successfully deploy and utilize the ExCon suits. Generally, the suits were determined to be effective simulation tools for EVA "station" operations. EVA "Station" operations being the work that happens at a site of geologic interest. The ExCon suits were determined to not be as effective tools for traverse simulations due to the aforementioned issues and the lack of value provided for long distance traverse simulations. It should be noted that a long-distance traverse was not attempted as part of the JETT1 test series.

Figure 6: JETT1 Night Run Shadow's Cast by Test Team

G. JETT2

JETT2 was conducted in July 2022 in the Iceland Highlands to evaluate Artemis III related testing/training hardware, navigation, geology, and concepts of operation (Con Ops) to best prepare NASA for near-term Artemis missions to the lunar surface. Where JETT1 focused on the hardware necessary for Artemis EVA field testing, JETT2 increased the scope to include crew navigation and a heavier focus on both Con Ops and crew geology training. Unfortunately, due to weather events only one run was completed which utilized the ExCon mockup suit. The sole ExCon subject completed a 4-hour Lunar EVA sim which consisted of a full-scale traverse with several stops at geologic stations for sample operations. Another subject participated wearing the NASA Field Backpack, which provides services such as communication but is not a spacesuit mockup. By JETT2 some weight had been reduced with the hip modifications and the arm bearings were also removed. The subject ran in a partially offloaded tool configuration resulting in a total system weight of a little over 100lbs. Although back-to-back EVA days were not possible due to inclement weather, the subject noted a willingness to conduct an EVA the day after the first EVA. The suit weight remained the most significant factor in its usage for full scale EVAs. It was again noted that the suit improved the simulation quality of station operations and EVA tasks but bearing the weight for long traverses and the resulting cumulative fatigue from the full EVA duration was undesirable.

Figure 7: JETT2 Testing

H. JETT3

JETT3 was conducted in October 2022 in the San Francisco Volcanic Field (vicinity Flagstaff, AZ) to evaluate Artemis III related testing/training hardware, lighting, navigation, geology, and Con Ops to best prepare NASA for near-term Artemis missions to the lunar surface. The most significant addition for JETT3 was the inclusion of a Flight Control Team (FCT) and science team based in Houston supporting the EVAs, much like will be done for flight missions. JETT3 saw the completion of the following tests: a day dry run in the ExCon suits, two nighttime back-to-back ExCon suit EVAs followed by a day off and then two more night back-to-back EVA days utilizing the field backpacks. Due to the shipping constraints with the hardware returning from JETT2, no updates were able to be incorporated before JETT3 began. During EVAs with the ExCon suits, both subjects completed ~3.5-hour EVAs and traversed an average of 3.8 km.

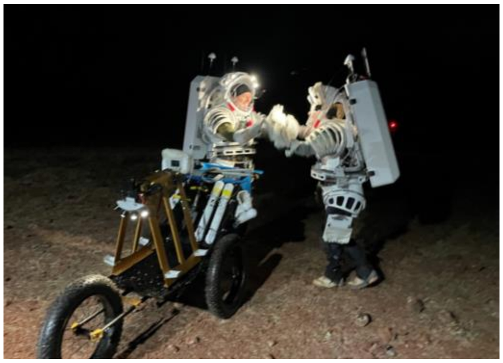

Figure 8: JETT3 Testing

There were several lessons learned from JETT3. Related to the ExCon suits, the weight of the suits was the dominating comment and lead to significant crew fatigue. Contributing to this difficulty was significant terrain and slope that had not yet been evaluated as well as brush; unfortunately, it is impossible to know the relative contributions of each of those components.

Figure 9: JETT3 Testing

From the Artemis Science team, JETT3 made huge strides forward in incorporating a Science Team in pre-mission planning and real-time operations, and it's recommended that any future JETT3-scale tests should include a Tactical Science Team (operating within one EVA) and a Strategic Science Team (working between EVAs) for real-time execution and evaluation. For EVA planning for Artemis EVAs, they noted mission planning should carefully balance EVA objectives with traversable terrain and avoid steep slopes over long distances to maximize successful completion of mission objectives. Although not specifically designed to evaluate crew navigation, it was a consistent challenge for JETT3. Technologies that help crew navigate (GPS, satellite imagery, etc.) would help enable Artemis mission success to meet science objectives, and any position, navigation, and timing (PNT) solution for the first Artemis mission will be worth the investment in order to reduce the penalty in EVA time, consumables, and crew mental fatigue. Overall, the team needs to continue developing field hardware to improve fidelity of full-scale Artemis simulations, including dedicated IT/facility infrastructure support.

Figure 10: JETT 3 Science Team

IV. Conclusion

Mockup spacesuits can be used in mission Con Ops testing and training to serve as a tool to provide some simulation quality improvements of the nature of working in a planetary pressurized suit. Additional mental bandwidth, joint programming, and inertia are all better simulated in mockup suits when compared to shirtsleeve operations. Presently, these benefits are almost entirely based on station operations. For full scale EVAs, and more specifically long-distance traverses it currently actually introduces more negative impacts to the simulation quality than positive due to the weight of the mock-up. However, modifications to reduce the mass of the ExCon suit are already underway to make it a more effective tool. While it is unclear if the weight savings effort will result in sufficient improvements to make it more beneficial for full scale operations, it will continue to provide a useful tool for small scale EVA tasks and geology operations to ensure subjects and crewmembers are training and learning about those operations with some thought as to how they will be conducted in a planetary pressurized spacesuit on the Lunar Surface. While the ExCon, and mockup suits in general, can not replace pressure suit training and testing and must be carefully considered against test objectives and data collection to ensure no invalid data is generated, with the proper considerations they can be effectively used to introduce some aspects of the realities of working in a spacesuit in a way that improves simulation quality. Mission hardware, software, techniques, and capabilities will only be as good as the tests in which they are vetted and stressed; and continued support of these 'forcing function' events like these integrated field tests is necessary to get all relevant teams working together to expose what works (sustains) and what doesn't work (improves) in an operational scenario to continue to improve crew training for Artemis missions.

References

[1]McFarland, S., Campbell II, D., and Rhodes, R., "NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2022." *51st International Conference on Environmental Systems*, 2022.