# Testing of the NASA Exploration Extravehicular Mobility Unit Demonstration (xEMU Demo) Architecture at the Neutral Buoyancy Laboratory (NBL)

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**Following Z-2 space suit testing that occurred from 2016-2017, the Exploration Extravehicular Mobility Unit (xEMU) Project was tasked with building a demonstration unit of the xEMU space suit to test on the International Space Station (ISS) in 2023. This suit is called xEMU Demonstration Suit (xEMU Demo). Based on feedback from astronauts during the Z-2 NBL test series, design changes were made, resulting in a new prototype suit called the Z-2.5 space suit. The design of the Z-2.5 space suit with an exploration Portable Life Support Systems (xPLSS) mock-up represents the architecture of xEMU Demo. The team is testing Z-2.5 in the NBL to evaluate this architecture and validate changes made from Z-2. The results will inform the xEMU Demo design going forward to its Preliminary Design Review (PDR) in the summer of 2019. This Z-2.5 NBL test series focuses on evaluating the microgravity performance of the suit and the ability to complete ISS-related tasks. The series is comprised of 10 manned runs and an unmanned corn-man run. Six test subjects, including four astronauts, will participate. The test objective is to evaluate ability xEMU Demo architecture to perform ISS microgravity tasks. Each crew members will complete both a familiarization run and a nominal EMU EVA timeline run. Qualitative and quantitative data will be collected to aid the assessment of the suit. Preliminary feedback from astronauts who have completed the test series evaluate the xEMU Demo architecture as acceptable to complete a demonstration mission on the ISS.**

## Nomenclature

*APFR* = articulating portable foot restraint
*BRT* = body restraint tether
*CCA* = communications carrier assembly
*CETA* = crew and equipment translation aid
$CO_2$ = carbon dioxide
*DCU* = display and control unit
EHIP = EVA Helmet Interchangeable Portable Light
*EMU* = extravehicular mobility unit
*EVVA* = extravehicular visor assembly
*EVA* = extravehicular activity
*HUT* = hard upper torso
*FHRC* = Flexible Hose Rotary Coupler
*ICS* = Integrated Communication System
*ISS* = International Space Station
*IFHX* = Interface Heat Exchanger
*LTA* = lower torso assembly
*MMWS* = Modular Mini Workstation
*NASA* = National Aeronautics and Space Administration
*NBL* = Neutral Buoyancy Laboratory
*PGT* = pistol grip tool
*PLSS* = portable life support system
*psid* = pounds per square inch delta
*QD* = quick disconnect
*R&R* = removal and replacement
*RPCM* = Remote Power Control Module

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*SAFER* = Simplified Aid for Extravehicular Activity Rescue
*UTA* = upper torso assembly
*WVS* = Water Video System
x*EMU Demo* = exploration extravehicular mobility unit demonstration mission on ISS in 2023

## I. Introduction

Exploration space suit development at NASA has been maturing since 1962 with advanced space suit development for the Apollo program.[1] Many decades of space suit development work since the Apollo space suits culminated in the design of the Z-2 prototype space suit, which was delivered to the National Aeronautics and Space Administration (NASA) in 2016.[2] Z-2 is a rear-entry prototype suit that was originally developed for walking applications on a lunar or planetary surface with a mobile Lower Torso Assembly (LTA). Z-2 could also be interfaced with the Extravehicular Mobility Unit (EMU) LTA to focus on microgravity performance. The EMU is the current space suit used to perform extravehicular activities (EVAs) in microgravity at the International Space Station (ISS). During 2016-2017, the Z-2 space suit completed a test series at the Neutral Buoyancy Lab (NBL).[3] The NBL facility is the primary simulated microgravity environment for space suits at NASA. With this facility, the Z-2 space suit was tested in a simulated microgravity environment using both the EMU LTA (ELTA) configuration and the Z-2 LTA (ZLTA) configuration.[3]

With the crew feedback given during the Z-2 test series, the team made design changes to help mitigate the problems encountered in the microgravity environment. This resulted in the Z-2.5 prototype space suit. Concurrently, the Exploration Extravehicular Mobility Unit (xEMU) project was tasked with flying a demonstration space suit to ISS in 2023. The xEMU Demonstration Unit, henceforth referred to as xEMU Demo, will test the exploration space suit upper torso architecture in the microgravity environment. It will be an exploration Upper Torso Assembly (UTA) and EMU LTA. Z-2.5 represents this xEMU Demo architecture. The team is testing Z-2.5 in the NBL to evaluate this architecture and validate changes made from Z-2. The final results, which are not presented in this paper, will inform the xEMU Demo design going forward to its Preliminary Design Review (PDR) in the summer of 2019. The Z-2.5 space suit test series test plan is described in this paper. Two engineering subjects and four crew members (astronauts) will evaluate the microgravity performance of the suit and the ability to complete ISS-related tasks in a total of ten NBL runs. This paper will present the test plan and preliminary results. Full results from this test series will be presented in a future paper.

### A. Summary of Z-2 NBL Test Series Results

The Z-2 NBL test series included 19 NBL runs, including five crew members as test subjects.[4] The crew members spanned the anthropometric sizes that Z-2 space suit could fit. During the test series, astronauts performed various tasks that were representative of the tasks that could be performed on the ISS. The test subjects performed the tasks in both the Z-2 space suit and the EMU to directly compare the suits. The primary configuration of the Z-2 space suit during the test series was comprised of the Z-2 upper torso and the EMU lower torso assembly (ELTA).[4] This was representative of the xEMU Demo architecture that is planned for use on the ISS. The secondary configuration of the Z-2 space suit was comprised of the Z-2 upper torso and the Z-2 mobile lower torso assembly. This was representative of a planetary, exploration architecture.

Crew members reported three main advantages of the Z-2 space suit design as compared to the EMU: increased mobility of the Z-2 upper torso, improved field of view, and comfort of using an integrated communication system (ICS) versus the EMU Communications Carrier Assembly (CCA).[3] Crew members also reported three main opportunities for improvement in the design of Z-2: reduce the overall suit system depth, reduce the helmet bubble depth, reduce the internal shoulder bearing profile to improve comfort.[3]

### B. Z-2.5 Space Suit Description

The Z-2.5 space suit is a prototype suit that was built to evaluate the architecture of the xEMU Demo space suit. Z-2.5 is an iteration of the Z-2 upper torso architecture, which incorporates design changes learned from the Z-2 NBL test series. Z-2.5 is a rear-entry space suit that utilizes a mix of hard goods for the Hard Upper Torso (HUT) and hatch, and soft goods for the remainder of the suit. The design of the Z-2.5 HUT incorporates a rear-entry hatch with a front-mounted close/open lock mechanism for easy donning and doffing of the suit. The Z-2.5 HUT is designed to interface to the EMU lower torso assembly (LTA), which include a waist bearing element and legs/boots. The Z-2.5 suit will nominally operate in a manned configuration at a delta pressure of 4.3 psid. In addition, Z-2.5 includes some components not included in the Z-2 space suit design, such as the Exploration Extravehicular Visor Assembly (xEVVA), EMU LCVG with auxiliary loop mock-up connectors, and a flight-like Environmental Protection Garment (EPG). Figure 1 shows a diagram of the Z-2.5 space suit.

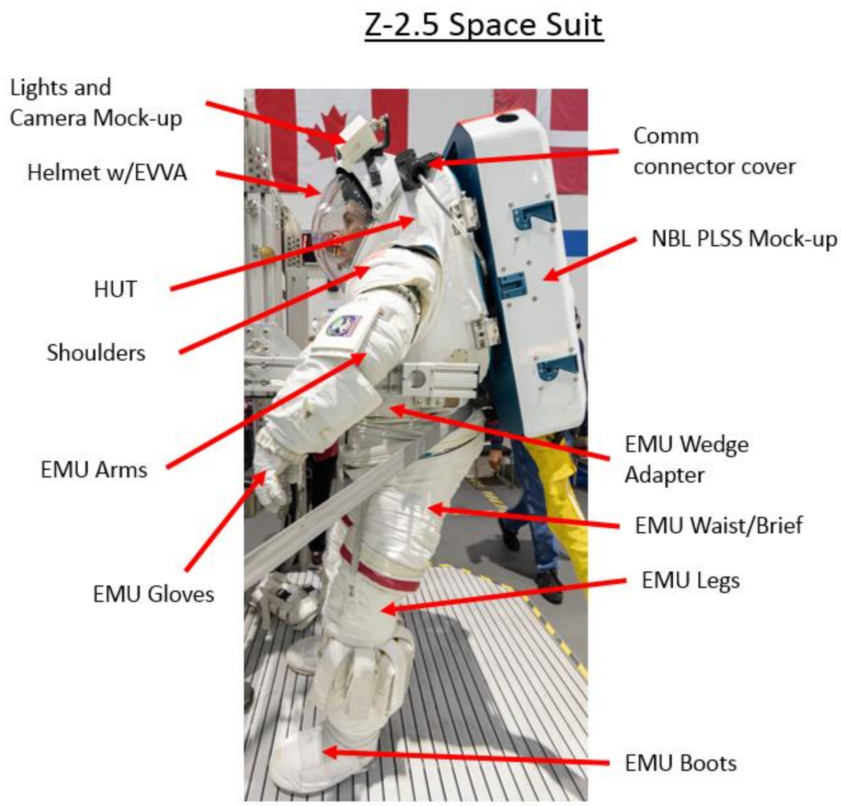


**Figure 1. Diagram of the Z-2.5 NBL space suit configuration which is representative of the xEMU Demo architecture.**

#### *1. Upper Torso Assembly (UTA)*

The Upper Torso Assembly (UTA) Assembly is comprised of the neck ring, scye carriers, hard upper torso (HUT), hatch assembly, hatch lock assembly, vent assembly, shoulder harness assembly, and an EMU wedge adapter element. The EMU wedge adapter adapts the xEMU UTA to the EMU LTA. The hatch and hatch lock assemblies on the back of the UTA serve as the portal to enter and exit the Z-2.5 space suit. The hatch also serves as the entry/exit point for breathing gas and cooling water to the suit. The hatch has an integrated, contoured hatch cover that provides back support to the suited subject and protects various elements located on the hatch. The communications port is located on the side of the HUT. A shoulder harness is integrated into the HUT and includes buckles that are mated/demoted during donning/doffing. The EMU LTA adapter element enables the body seal closure on the EMU LTA to mate to the Z-2.5 UTA.

##### *a) Hard Upper Torso (HUT)*

The Hard Upper Torso (HUT) is the primary element of the UTA. The HUT is the rigid portion of the suit structure over the subject's upper torso. The HUT geometry controls the fit and placement of the mobility joints. It also contributes to visibility through the helmet through the placement of the neck ring. The xEMU architecture for this HUT is designed to fit 1st percentile female to 99th percentile male with two sizes in the xEMU HUT fleet system. xEMU Demo is only planned to incorporate and fly the smaller HUT size; this HUT size was evaluated in the Z-2.5 design. The geometry of the xEMU Demo HUT is designed to be extensible to planetary environments.

The Z-2.5 HUT structure is manufactured from aluminum. The xEMU Demo HUT will be made of a composite material layup to meet impact and low mass requirements. However, to meet the NBL test schedule, the Z-2.5 HUT was fabricated from aluminum because of the shorter manufacturing time required.

The EMU Wedge Adapter for the LTA contains the male passive portion of the EMU LTA body seal closure. The wedge adapter connects the horizontal EMU body seal closure to the angled Z-2.5 HUT. The wedge provides the modular mini workstation (MMWS) square boss interface, which allows tools to be attached directly to the suit. The body seal closure on the EMU wedge adapter offers a secondary egress path in the case of a hatch latch failure. Shoulder harness attachments are built into the EMU wedge adapter structure. The shoulder harness indexes the suited subject in the suit by ensuring the subject is vertically aligned with the mobility joints and maintains good head position.

*b) Hatch*

The hatch is the cover to the portal to enter and exit the Z-2.5 space suit. The hatch also serves as the entry/exit point for breathing gas and water to the suit. The hatch has an integrated, contoured hatch cover that provides back support to the suited subject and protects various elements located on the hatch. Breathing gas and cooling water are routed to the suit via an interface pad. The pad contains four threaded inserts that attach the portable life support system (PLSS) mock-up to the suit. There are also two hitches on the bottom of the hatch that support the PLSS mock-up. The hatch is connected to the HUT via hinges and 2 quick disconnect keeper pins. Four tubing lines transfer water into and out of the suit. A vent line with a plenum on one end connects to the HUT when the hatch is closed and transfer return breathing gas from the suit out an elbow fitting in the top of the hatch.

*c) Helmet*

The Z-2.5 helmet includes a pressure bubble, a protective visor, and a passive male side of the helmet disconnect. The pressure bubble is a hemi-ellipsoid shaped helmet with innermost dimensions of 10 inches by 13 inches. A helmet latch mechanism allows for removal of the xEMU helmet assembly, including the protective visor and EVVA, without the use of tools. The protective visor is made of polycarbonate with a scratch resistant hard coat on the external surface. The pressure bubble is made of polycarbonate and the internal surface of the pressure bubble is coated with a permanent anti-fog coating.

*d) Extravehicular Visor Assembly (EVVA)*

The EVVA is a secondary structure of the Z-2.5 helmet that simulates the xEMU EVVA, which would provide additional Ultraviolet (UV) radiation protection via a sun visor and a rotational opaque eye shade. The EVVA is comprised of an over shell, a center eye shade, two side shades, and a sun visor. The subassembly is attached to the helmet with fasteners. The over shell is made of white polycarbonate with attachment points for lights and cameras. The sun visor is crew-actuated via a mechanical knob on one side of the EVVA. For Z-2.5, the sun visor is made of tinted polycarbonate that simulates the xEMU sun visor, which would be made of silver polysulfone with a gold coating applied to provide the additional thermal and UV protection. The EVVA sun visor design provides tinted shading of the visible helmet area. The EVVA sun shade design includes three sun shades which are crew actuated via tabs on each shade and can be used independently. The EVVA provides three mounting locations design to allow lights and cameras to be installed.

*e) Integrated Communication Systems (ICS)*

The Z-2.5 space suit includes an Integrated Communication System (ICS). This provides headset-free, 2-way audio communication to suited crew members via three microphones and two speakers installed in the HUT. The microphones are a digital microelectromechanical (MEMS) microphone. The speakers are 8-ohm speakers that are mounted on the HUT, behind the crew member’s head. Both the microphone and speaker enclosures incorporate a hydrophobic barrier to protect the components from inadvertent water contact.

*2. Arm Assembly*

The arm assembly is comprised of an upper arm assembly (shoulder), lower arm element, gloves, and optional sizing rings. The upper arm assembly (shoulder) is a 6-pivot, dual layer, rolling convolute joint that is identical to the Z-2 shoulder’s rolling convolute joint. The rolling convolute rings maintain a relatively constant volume throughout the shoulder range of motion, which decreases torque, enhances mobility, and reduces crew fatigue when compared with the EMU’s current gored shoulder design. The Z-2.5 shoulders utilize scye sizing rings that add approximately 1” of adjustability to the scye bearing placement to fit a wider range of crew sizes with a single HUT. The shoulders can be installed at two positions: (1) scye-in for a 10.9” Q-point and (2) scye-out for an 11.7” Q-point. Q-point is a tailor’s term for measuring shoulder width. The arm bearing is located at the lower arm side of the upper arm assembly where it interfaces with the lower arm Fabric Attachment Ring (FAR) quick disconnect.

*a) Lower Arm*

The Z-2.5 suit uses the EMU enhanced lower arm element. When sized along with the shoulder's scye sizing rings, lower arm bracket adjustments, and lower arm sizes, a wide range of sizes for different arm lengths are available.

*b) Phase VI Gloves*

The Z-2.5 suit uses the EMU Phase VI Gloves which are the current gloves used for the EMU. Each glove consists of a bladder for pressure retention, a polyester cloth restraint, gimbal(s) for wrist mobility, a palm restraint to prevent distention, a stainless steel bearing/passive disconnect for wrist rotation and interface with the wrist disconnect on the arm assembly, a detachable Thermal Micrometeoroid Garment (cover), and a tether loop for temporarily attaching wrist tethers.

*3. Lower Torso Assembly*

The EMU Lower Torso Assembly (LTA) connects to the Z-2.5 UTA via the EMU LTA's Body Seal Closure (BSC) and a BSC adapter on the EMU Wedge adapter interface on the UTA. The EMU LTA consists of the EMU waist/brief assembly, EMU legs, EMU boots, and optional thigh/leg sizing rings. The Z-2.5 suit attaches to the EMU waist/brief assembly via the EMU Wedge adapter. Z-2.5 can be used with the -03 EMU brief and a Standard XS or Adjustable 01/02 waist.

*4. Ancillary Support Hardware*

*a. Modified Liquid Cooling and Ventilation Garment (LCVG)*

The Liquid Cooling and Ventilation Garment (LCVG) used for the Z-2.5 testing is the standard EMU LCVG with an auxiliary connector mock-up attached via two lines. For the xEMU Demo, the LCVG will contain both a primary and auxiliary cooling loop to support the xEMU Demo Portable Life Support System (PLSS) design. In case of an emergency, an auxiliary cooling loop built into the LCVG would be utilized. The new LCVG for the xEMU Demo was not available in time for this test series.

For the Z-2.5 NBL testing, an auxiliary water loop connector is used to volumetrically represent the space required for a future connector. This is to assess any potential comfort issues with an additional connector.

*b. Maximum Absorbency Garment (MAG)*

The MAG is a waste containment garment for crewmember use during NBL or other extended test activity. The MAG (if used) is worn under the LCVG and TCU. This is the same MAG used for the EMU space suit.

*c. Thermal Comfort Undergarment (TCU)*

The TCU is a two-piece (top and bottom), crew underclothing. The TCU is worn under the LCVG to improve crew comfort and hygiene. This is the same TCU used for the EMU space suit.

*d. Miscellaneous Undergarments*

Socks, comfort gloves, athletic supporters, sports bras, hair ties, eyeglass retention devices/croakies, moleskin, and mosite can be worn per each crewmember's specific needs. These items are nominally used for crew comfort and/or to alleviate pressure points or "hot spots" associated with Z-2.5 use.

*e. Valsalva*

The Valsalva device is a foam block that is shaped to seal around the nose, enabling suit subjects to conduct a Valsalva maneuver when the suit pressurizes. The Z-2.5 suit uses the EMU Valsalva device.

*f. Disposable In-Suit Drink Bag (DIDB)*

The Disposable In-Suit Drink Bag (DIDB) is the same drink bag used for the EMU. It is a heat-sealed, flexible container made of polyurethane film and has capacity for 32 ounces of drinking water for use during suited activities.

*g. Fresnel Lens*

A Fresnel lens can be used with the suit to assist with vision. This is the same Fresnel lens use for the EMU.

*5. Other Suit Hardware*

*a. DCU Mock-up*

Two Display and Control (DCU) Mock-ups were created for the Z-2.5 NBL test series. They are both volumetric mock-ups of the xEMU Demo DCU design, and they help the suit to achieve neutral buoyancy in the NBL.

The high fidelity (hi-fi) DCU mock-up is made out of anodized aluminum and it has a pocket for Z-2.5 NBL weights or foam. This DCU weighs around 5 lbs. The pocket can be filled with weights (around 5 lbs.) to make it negatively buoyant. It has built in switches and switch guards that mock-up the configuration planned for the xEMU DCU.

The second DCU mock-up for Z-2.5 is the low fidelity DCU Mock-up. It is made out of aluminum, but with no pockets or switches. It weighs 10 lbs. A Z-2.5 custom weight pack which can hold up to nine large tungsten weights may also be used for a total of 37 lbs.

**Figure 2. The NBL DCU mock-up is a volumetric representation with the primary purpose of helping to achieve a neutral buoyancy in the water column. The mock-up on the left (red) is the high fidelity DCU mock-up with representation switches and switch guards. The mock-up on the right (blue) is the low fidelity DCU mock-up. It is a simpler, heavier version of the DCU mock-up. It is shown with a custom weight pack attached to assist with getting more weight on the suit.**

*b. Portable Life Support Systems (PLSS) Mock-up*

The Z-2.5 NBL PLSS Mock-up provides the breathing gas, cooling water, and communication interfaces to the suit via a volumetric xEMU PLSS shell. The Z-2.5 NBL PLSS mock-up is bolted to the Z-2.5 hatch via 4 fasteners and connects to a PLSS hitch that helps to align and support the Z-2.5 NBL PLSS Mock-up.

*c. Simplified Aid for EVA Rescue (SAFER)*

The Z-2.5 NBL PLSS Mock-up has provisions for NBL SAFER attachment using four Airlock Adapter Plate mounts.

*d. Wireless Video System*

The Water Video System (WVS) consists of a non-flight like wired, underwater helmet camera that is mounted to the Z-2.5 Extravehicular Visor Assembly (EVVA). The WVS's housing represents the proposed xEMU Demo camera housing volume. The camera can be mounted on the top or the side of the EVVA through an EVVA band adapter.

*e. xEMU Lights Mock-up*

A mock-up of the xEMU light assembly can also be attached via the EVVA band adapter. A volumetric EVA Helmet Interchangeable Portable Light (EHIP) was built with ability to hold a commercial off the shelf dive light. The two configurations of the band adapter for the EVVA assembly are pictured in the figure below. Configuration 1 was used for the first three NBL runs. Configuration 2 was used for the remaining NBL runs because the project was approved to develop new lights for the xEMU demo. Therefore, the EHIP mock-up was no longer needed.

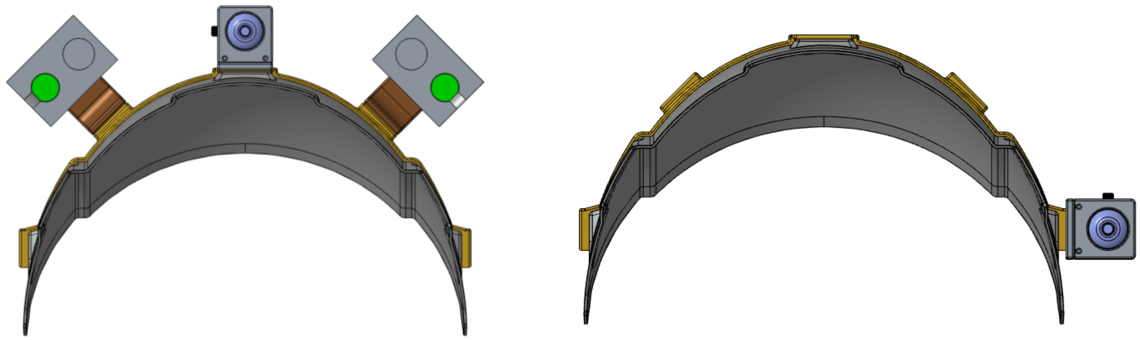

**Figure 3. Two configurations of the xEMU Lights and Camera Mock-up was made. Configuration 1 (left) shows the EHIP lights and the camera mounted directly on top of the EVVA. Configuration 2 (right) represents just the camera being mounted.**

*f. Z-2.5 NBL Donning Stand Attachment*

The Z-2.5 space suit donning stand attachment interfaces the Z-2.5 space suit with the NBL donning stand. Similar to the Z-2 NBL donning attachment design, the space suit faces into the stand to support the rear entry hatch. The donning stand interfaces with the MMWS mounts on the front of the suit and posts on the EMU wedge adapter that help guide the MMWS mounts into place and support the suit.

## II. Test Plan

### A. Test Objective

The objective of the Z-2.5 NBL test series is to evaluate the ability of the Z-2.5 space suit with a mock-up of the exploration PLSS, which represents the xEMU Demo architecture, to perform ISS microgravity tasks. Tasks were selected that are representative of the types of tasks that may be performed during a Demonstration Test Objective (DTO) EVA on the ISS. To evaluate this objective, crew members will complete a familiarization run and an EMU maintenance training timeline run. The test objective will be supported by subjective metrics such as comfort, subject fit, fatigue, volume, field of view, and EMU tool suite compatibility. Following the timeline run of Z-2.5, each crew member will be asked in the post-test questionnaire if the xEMU Demo architecture (simulated with Z-2.5) is acceptable to perform a DTO EVA on ISS (Yes/No/Uncertain). The crew member will also give a confidence rating with their response. In addition to subjective data, objective data is also recorded during this test series: task performance, time to complete tasks, and metabolic rate measured via expired $CO_2$ in the return breathing gas.

After the test series is complete, the results will be recorded in two documents: Crew position memo that summarizes the acceptability of the xEMU Demo architecture for use on ISS for a DTO mission, and test report written by the team in the Crew and Thermal Systems Division (CTSD) that summarizes the test plan, results, and discussion.

### B. Test Methodology

The Z-2.5 NBL test series is broken into four phases. The first phase consists of system checkouts poolside and completing manned, unpressurized emergency extraction drills on the pool deck. This is to ensure all systems perform nominally before completing a run in the NBL environment. The second phase focuses on unmanned checkouts of Z-2.5 in the NBL environment. This run is called “corn-man” because bags of corn are loaded into the suit to simulate the weight of a test subject to practice obtaining neutral buoyancy of the suit in the water column, also known as weigh-out. The third phase will consist of two engineering development runs. These runs are the first manned use of Z-2.5 in the NBL. The engineering runs are used to validate the weigh-out, sizing, and comfort strategy for the suit and complete an initial assessment of the worksites planned for the evaluation of Z-2.5. The final, fourth phase includes eight primary runs using all with crew members. Four crew members will participate in the primary runs. The crew members are selected based on ability to fit into the Z-2.5 Hard Upper Torso, flight EVA experience on the ISS in the EMU, availability to complete both runs of the test series, and their participation in the Z-2 NBL test series.

Unfortunately due to crew schedule, crew members that had completed the Z-2 test series were not available for the Z-2.5 test series. Each crew member will have two NBL runs for them to effectively evaluate the space suit. Details of the two runs, familiarization and timeline, can be found in the sections below. Table 1 shows the schedule of each phase of the test series except for Phase 1 because it did not include a test in the NBL environment.

Before their NBL runs, each crew member will perform two, 1-G fit checks in Z-2.5 in the laboratory environment. The team found this was a valuable practice for the Z-2 NBL test series. The first fit check focuses on the crew member fit and comfort in the suit. During the first fit check, exercises such as laying the subject on their stomach, on their back, and hanging them in the donning stand (if possible) help to simulate the NBL environment to assess fit and if comfort padding is needed. The second fit check verifies the sizing chosen from the first fit check, and focuses on interfacing with the EMU tool suite including the MMWS, PGT, BRT placement, and SAFER reach.

**Table 1: Overview of Z-2.5 NBL Runs**

| Phase | Run | Subject | Suit | Run Description |
|---|---|---|---|---|
| 2 | 0 | Corn man | Z-2.5 | Weigh-out validation with 140 lb. and 200 lb. corn man and diver training |
| 3 | 1 | Engineer #1 | Z-2.5 | Weigh-out, comfort, fit, tools, and volume assessments |
| | | Engineer #2 | EMU | |
| | 2 | Engineer #2 | Z-2.5 | Weigh-out, comfort, fit, tools, and timeline run validation |
| | | Engineer #1 | EMU | Timeline run validation |
| 4 | 3 | Crew Member 1 | Z-2.5 | Familiarization run |
| | 4 | Crew Member 1 | Z-2.5 | Timeline run, post-run evaluations |
| | | Crew Member 2 | EMU | Timeline run, Z-2.5 observations |
| | 5 | Crew Member 2 | Z-2.5 | Familiarization run |
| | 6 | Crew Member 2 | Z-2.5 | Timeline run, post-run evaluations |
| | | Crew Member 3 | EMU | Timeline run, Z-2.5 observations |
| | 7 | Crew Member 3 | Z-2.5 | Familiarization run |
| | 8 | Crew Member 3 | Z-2.5 | Timeline run, post-run evaluations |
| | | Crew Member 4 | EMU | Timeline run, Z-2.5 observations |
| | 9 | Crew Member 4 | Z-2.5 | Familiarization run |
| | 10 | Crew Member 4 | Z-2.5 | Timeline run, post-run evaluations |
| | | Crew Member 3 | EMU | Timeline run, Z-2.5 observations |

### C. Worksite Descriptions

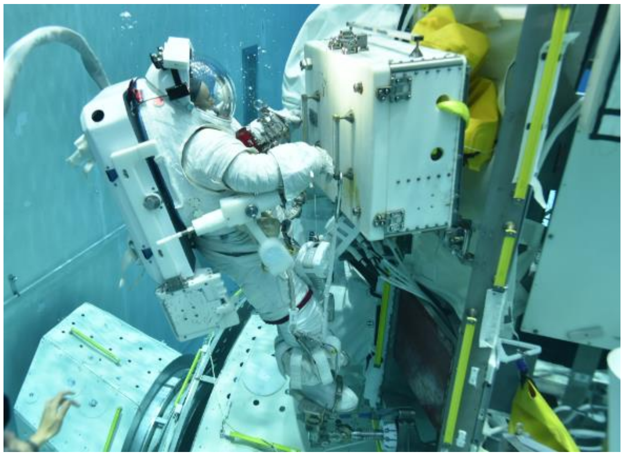

**Figure 4. Z-2.5 subject working at the Z1 toolbox.**

*1. Z-1 Toolbox*

The Z-1 toolbox was chosen to complete the suit familiarization and the basic evaluation for using an Articulating Portable Foot Restraint (APFR). Subjects used this worksite to become familiar with the mobility of each suit joint, the interface with the EMU MMWS and tools such as the BRT and PGT, and practicing ingress/egress of the APFR.

*2. Remote Power Control Module (RPCM)*

The Remote Power Control Module (RPCM) distributes power to parts of the ISS. This worksite was chosen for subjects to complete a basic evaluation of the EMU Tool suite. Using a BRT to stabilize the suit, subjects removed an RPCM with a PGT wobble socket. Then, they attached a round scoop to handle the RPCM after it was uninstalled. Finally, they reinstalled with a ratchet wrench and socket.

3. *Interface Heat Exchanger (IFHX)*
   The Interface Heat Exchanger (IFHX) performs the function of removing heat from the pressurized portions of the ISS. Completing a full remove and replacement (R&R) would require two EVAs. The tasks selected to perform during the NBL series were shortened to focus on the removal of challenging bolts and electrical QDs. This worksite was chosen because of the constrained volume and difficulty of tasks. The same worksite and task was completed in the Z-2 test data. While no crew members are repeating the test series, comparisons can be made of the performance of Z-2.5 in the worksite as compared to Z-2.

**Figure 5. Z-2.5 subject working at the IFHX worksite.**

4. *Flex Hose Rotary Coupler (FHRC) Removal at ESP-2 and Replacement at P1 Truss*
   The Flex Hose Rotary Coupler (FHRC) is part of the Thermal Radiator Rotary Joint. This supports the S1 and P1 Thermal Radiators. Completing a full R&R would require four EVAs. This worksite was chosen because of the constrained volume inside a truss segment and difficulty of tasks. This NBL maintenance run, run number 5 in the ASCAN training flow, highlights important aspects of an FHRC R&R. This task was chosen to be the focus of the evaluation crew members completed for this test series. The tasks are described in detail in section E, Timeline Run Description.

**Figure 6. Z-2.5 subject working at the FHRC worksite in the ISS Truss.**

5. *Adjustable Volume Airlock (AVA)*
   The Adjustable Volume Airlock (AVA) is a mock-up built to validate requirements being developed for the Gateway and Exploration Programs. By having an adjustable hatch size, internal diameter, and axial length, it is possible to evaluate and define functional working activity volume requirements for Gateway Airlock, xEMU, and future exploration programs. The minimum size of each dimension matches the ISS airlock. The diameter can be adjusted from a minimum of 53 inches to a maximum of 72 inches. The axial length can be adjusted from a minimum of 108 inches to a maximum of 128 inches. The hatch can be adjusted from a minimum of 40 inches to a maximum of 44 inches. In addition, a proposed maximum On-orbit Replacement Unit (ORU) mock-up for Gateway was created for the test that is 564 millimeters by 564 millimeters by 1000 millimeters. The Z-2.5 NBL test series has special interest in the AVA because of comments from the Z-2 NBL test series. During ingress and egress of the NBL ISS Mock-up, the crew has to be in the heads down position. The 1-G effects cause this to be consistently more difficult than it would be for flight. With the AVA, it is possible to ingress and egress on the subject's side.

### D. Familiarization Run Description

The focus of the first run for each crew member was to achieve an acceptable weigh out, comfort, and to familiarize the subjects with operating the Z-2.5 suit in a simulated microgravity environment. The format of this run is similar to the Z-2 ELTA Familiarization Run that was completed during the Z-2 NBL test series. This run does not directly support the test objective, but the run gave an opportunity for more specific feedback to be gained as compared to the timeline run. The subject is queried more often throughout the familiarization run than during the timeline run to help receive those particular comments on completing each individual task. The following table describes the task order of the familiarization run:

**Table 2 Description of Familiarization Run**

| Tasks (Z-2.5) | Actions |
|---|---|
| Weigh-out | 1. Complete weigh-out process at the bottom of the pool |
| Suit Familiarization, Basic APFR Operation | 1. Take subject to Z1 Toolbox<br>2. Ingress/egress APFR at the Z1 toolboxes. Remove/replace feet one at a time. Then, egress/ingress from free float.<br>3. Perform isolated joint movement: start with upper torso and move to whole body mobility.<br>4. Evaluate BRT and tool locations and usage.<br>5. Operate door of Z1 toolbox, remove and stow tools<br>6. Operate the EVVA visors: deploy and stow |
| Basic Translation | 1. Subject translates to S0, Face 1<br>2. Translate down CETA rail: hand-over-hand, side-to-side<br>3. When satisfactory distance is travelled, move up towards S0, Face 2 RPCMs. |
| Basic Tool Evaluation | 1. Subject translates to RPCM worksite (P1, Face 1, bay 16)<br>2. Perform RPCM R&R task using waist tether, BRT, RET, PGT. |
| Airlock Operations | 1. Ingress Airlock as EV2 (head first)<br>2. Egress Airlock as EV2 (feet first)<br>3. Ingress Airlock as EV1 (feet first)<br>4. Egress Airlock as EV1 (head first) |
| Advanced Translation | 1. Translate up and over Airlock and Around Z-1 towards the Rats Nest<br>2. Translate through Rats Nest, eventually making way up CETA Spur to CETA Rail. Translate under MT.<br>3. Continue to SSRMS |
| Set up APFR on SSRMS/Advanced APFR Evaluation | 1. Set up APFR on SSRMS<br>2. Ingress SSRMS with ingress aids |
| IFHX (both sides) | 1. Ingress APFR<br>2. Perform reach eval. to QDs and bolts<br>3. Do a selection of QDs/Bolts |
| Hi-Fi SAFER Eval | 1. Install hi-fi SAFER<br>2. Evaluate the reach in Z-2.5 |
| FHRC Familiarization | 1. Demate/mate 2 (of 4) hose box QDs<br>2. Ingress the truss and perform reach eval for the stinger QDs<br>3. EMU does Stinger QD reach eval and then demates the other 2 hose box QDs |
| AVA Airlock Operations | 1. Ingress Airlock as EV2 (head first)<br>2. Egress Airlock as EV2 (feet first)<br>3. Ingress Airlock as EV1 (feet first)<br>4. Egress Airlock as EV1 (head first)<br>Change dimension as needed and repeat. |

### E. Timeline Run Description

Each crew member’s second NBL run is their timeline run, which is similar to the fifth maintenance training flow run (Maintenance Run 5) for the Astronaut Candidates (ASCANs). Maintenance Run 5 is one of the four EVAs required for the Flex Hose Rotary Coupler (FHRC) R&R. This particular run was chosen because it includes many of the tasks that a crew member would need to complete for an ISS EVA. In addition, Maintenance Run 5 is the typical EVA Assessment Team (EVAAT) test for that an ASCAN needs to pass to be EVA-qualified. Because of this, all crew members from the Z-2.5 test series have previously completed the run in the EMU, and metabolic rate data fro each crew member has been recorded for this run in the EMU suit. Finally, this run includes several volumetrically constrained worksites and difficult tasks that stresses the ability to perform an EVA in the Z-2.5 space suit.

During the run, limited subjective questions are asked about the suit performance. Questions are limited to help create a more flight-like EVA experience. This is different than the familiarization runs and the Z-2 test series data collection runs, which would pause after each task to ask questions. The previous Z-2 test method provided opportunities for the crew members to have frequent breaks through the test. This made it hard for them to assess the fatigue related to completing an end-to-end EVA. Hence, limited questions are asked during the Z-2.5 timeline run.

The following table describes the task order of the timeline run:

**Table 3. Description of Timeline Run**

| Tasks (Z-2.5) | Tasks (EMU) | Actions |
|---|---|---|
| Weigh-out | Weigh-out | 1. Complete weigh-out process at the bottom of the pool |
| Airlock Ingress/Egress Evaluations | Airlock Ingress/Egress Evaluations | 1. Ingress Airlock as EV2 (head first)<br>2. Egress Airlock as EV2 (feet first)<br>3. Ingress Airlock as EV1 (feet first)<br>4. Egress Airlock as EV1 (head first)<br>5. EV1 incapacitated crew (get-ahead)<br>6. EV2 incapacitated crew (get-ahead) |
| Airlock Egress | Airlock Egress | 1. Fly subjects to Airlock.<br>2. EV2 (EMU) ingress head first<br>3. EV1 (Z-2.5) ingress feet first<br>4. Nominal egress |
| ESP-2 Spare FHRC Removal | ESP-2 Spare FHRC Removal | Subjects translate to ESP-2 FHRC worksite.<br>Z-2.5<br>1. Release bolts<br>2. Hose box caps<br>EMU<br>1. Stinger caps<br>2. SSRMS Setup<br>3. Release bolts |
| Retrieve camera, translate to P1 FHRC | Maneuver to P1 FHRC | |
| Install spare FHRC in Truss | Assist Z-2.5 subject | |
| Incapacitated Crew Rescue | | Z-2.5 subject rescues an incapacitated EMU subject by returning them to the Airlock. |
| Mate and Open Hose Box QDs | Mate and Open Hose Box QDs | Mating bolts and opening hose box QDs for FHRC |
| Mate and Open Stinger QDs | Mate and Open Stinger QDs | Mating bolts and opening Stinger QDs for FHRC |
| Translate back to Airlock | Translate back to Airlock | |
| EV1 Airlock Ingress/Egress Evaluations | EV2 Airlock Ingress/Egress Evaluations | 1. Ingress Airlock, nominal end of run |

| | | |
|---|---|---|
| AVA Evaluation (Get ahead) | AVA Evaluation (Get ahead) | 1. Ingress Airlock as EV2 (head first)<br>2. Egress Airlock as EV2 (feet first)<br>3. Ingress Airlock as EV1 (feet first)<br>4. Egress Airlock as EV1 (head first)<br>Change dimension as needed and repeat. |
| IFHX R&R (Get Ahead) | IFHX R&R (Get Ahead) | 1. Ingress APFR<br>2. Perform reach eval to QDs and bolts<br>3. Do a selection of QDs/Bolts |

### F. NBL Pool Floor Layout
The layout of the NBL pool floor is shown in the figure below. This shows some of the worksite locations for the familiarization and timeline runs.

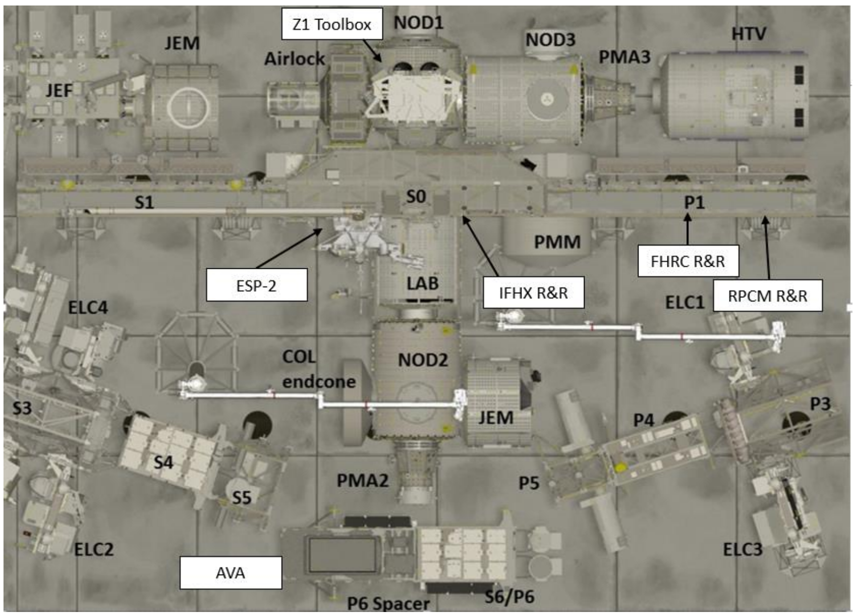


**Figure 7. NBL Pool Floor Layout**

## III. Data Collection

### A. Subjective Data
Subjective data is collected throughout the runs by two team members. One team member performs the role of test conductor, asking questions to the subject through the run. One team member acts as data recorder, writing down the comments subjects make throughout the run. This was a best practice from the Z-2 NBL test series as it improves the quality of the data collected and recorded. Crew members are asked to provide feedback on suit performance, as opposed to feedback on the task itself. Difficult tasks are intentionally chosen to understand the performance of the Z-2.5 space suit architecture. The following sections describe the subjective data that was collected during this test series.

*1. Acceptability*
The acceptability rating scale developed for the Z-2.5 test series is a five-point scale. The scale uses a modified Cooper-Harper model to assess the rating.[5] The acceptability scale is shown in Figure 8. Acceptability is defined as the ability to perform ISS EVA tasks in the Z-2.5 space suit with a tolerable discomfort, exertion, fatigue, avoidable inefficiency and without risk of injury to self or to hardware. Subjects were asked questions starting with the left hand side of Figure 8. When asking these questions during the NBL run, tolerable discomfort, exertion, fatigue, and avoidable inefficiency will be summarized to "tolerable workload." Therefore, an example of this use would be the

second question on the left hand column of the Modified Cooper-Harper Scale would state: "Were you able to complete this task with tolerable workload and without risk of injury to self or damage to hardware?" Using this scale, an acceptability rating of AR4 or AR5 is considered unacceptable. AR4 is unacceptable with improvements required, and AR5 means the task could not be completed and was abandoned. An acceptability rating of AR1, AR2, and AR3 is acceptable. AR1 is acceptable without improvements, AR2 is acceptable with minor improvements desired, and AR3 is acceptable with major improvements desired. If a task was not satisfactory without improvement (AR1), comments were acquired to understand what warranted improvement.

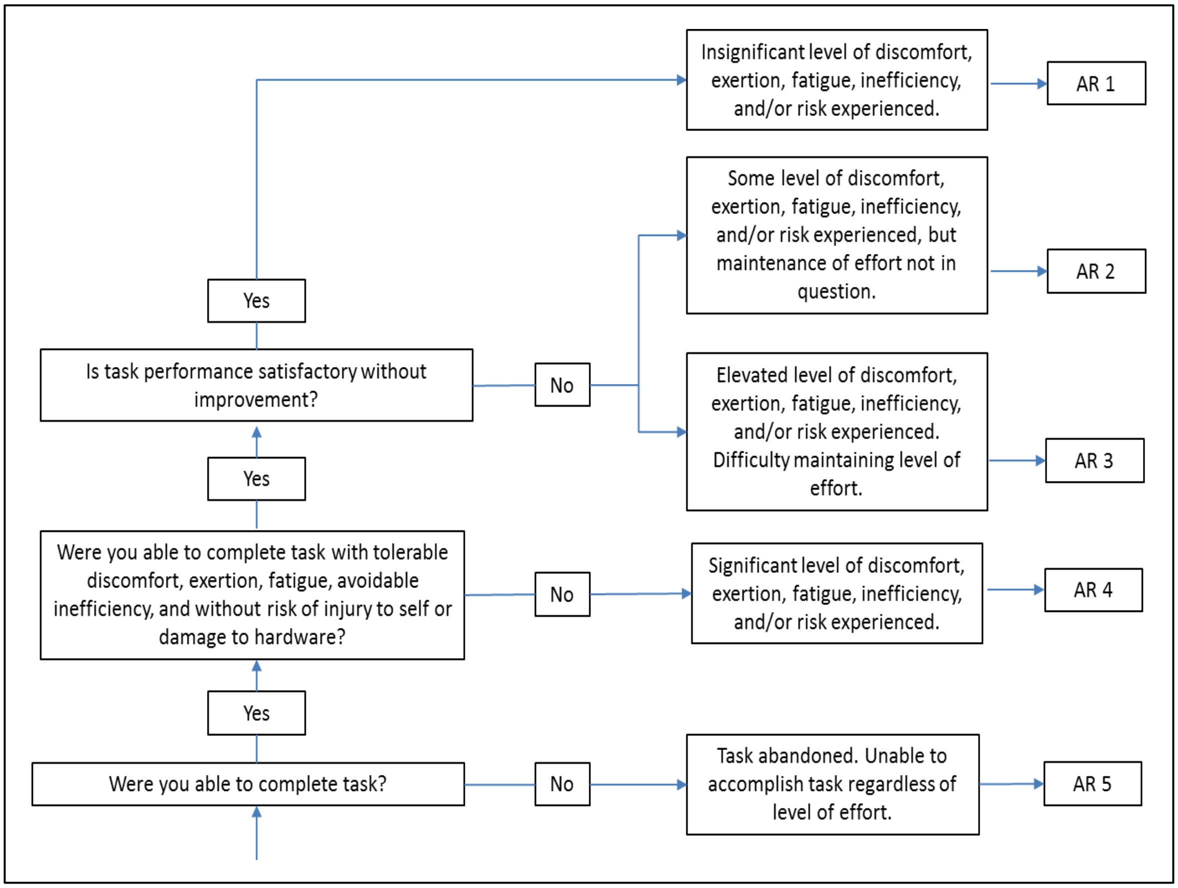


**Figure 8. Acceptability Rating Scale.**

*2. Discomfort and Muscle Fatigue*

The Discomfort and Muscle Fatigue scale, which is shown in Figure 9, is a four-point rating scale that was also used during the Z-2 NBL test series. The scale is used to understand exactly where and to what level the subjects feel discomfort and muscle fatigue during a NBL run. Subjects were queried periodically throughout the familiarization run and at the beginning and end of the timeline run.

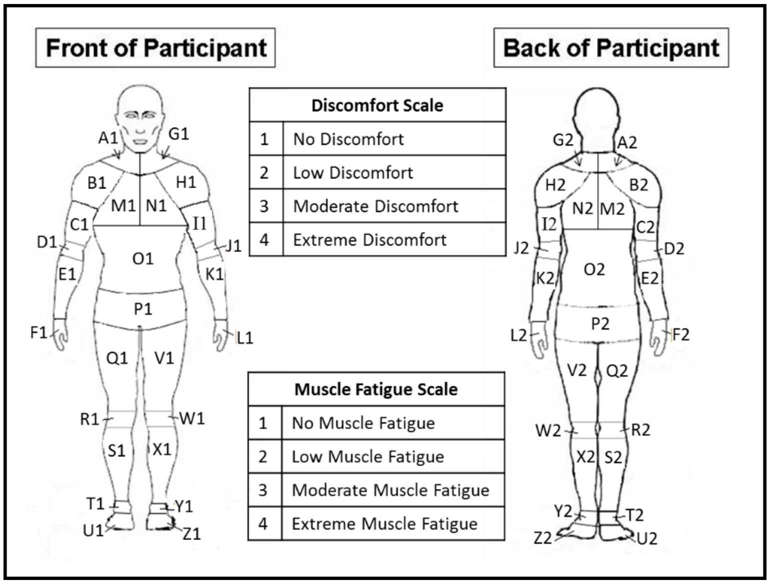


**Figure 9. Discomfort and Muscle Fatigue Scale**

*3. Simulation Quality*

The Simulation Quality scale, which is shown in Table 4, is a four-point rating scale that was also used during the Z-2 NBL test series. The purpose of the simulation quality scale is to assess how well the NBL environment and worksites represent the ISS flight EVA tasks. For the NBL environment, poor simulation quality will often be due to factors such as a bad weigh out for the suit or tools being used.

**Table 4. Simulation Quality Scale**

| Scale Rating | Description | Effects on Data |
|---|---|---|
| 1 | **Excellent** – No limitations/problems | No impacts to validity of test data |
| 2 | **Very Good** – Minor simulation limitations/problems | Minor impacts to validity of test data (describe) |
| 3 | **Adequate** – Moderate simulation limitations/problems | Moderate impacts to validity of test data (describe) |
| 4 | **Inadequate** – Significant simulation limitations/problems | Test data is not considered valid (describe) |

*4. Confidence Scale*

During the Z-2 NBL test series, crew members commented that it was hard to give a direct "Yes" or "No" to some questions. This uncertainty was a result of the limited number of NBL runs and tasks that crew members had completed in the Z-2 suit. Based on that feedback, the Z-2.5 confidence scale was developed. The scale is shown in Table 5. It is a four point system that can help the crew member validate a yes or no reply with their confidence based on what they have completed in the Z-2.5 NBL test series. This is especially important in some of the post-test questions. A rating of 1 means they have a high confidence in their answer (76% or above), a rating of 4 means they have a low confidence (24% or below).

**Table 5. Confidence Scale.**

| High confidence | Moderate confidence | Low confidence | No confidence |
|---|---|---|---|
| 1 | 2 | 3 | 4 |

*5. Comparisons to the EMU*

Throughout the NBL run, crew members were asked to compare if it was easier, harder, or the same level of difficult to complete the task in the EMU. This feedback helped the team to understand how the Z-2.5 space suit architecture was enabling or constraining crew members at worksites based on their past experience. Some crew members could not answer this question for certain tasks because they had not recently completed those tasks in the EMU.

*6. Post-Test Questionnaire*

During the timeline run, the test conductor limits the number of questions they ask the crew member. This enables the crew members to evaluate a more typical flow of an EMU training run. After the timeline run, however, crew members were asked a number of questions, including overall acceptability and benefits/areas of improvement for the suit. The following two questions are asked at the end of each timeline run to provide direct feedback to the test objective for this test series:

- Do you think that it would be acceptable to use the xEMU Demo architecture to perform a DTO mission on the ISS?
    - Rating: YES, NO, or UNCERTAIN
    - What is your confidence rating for your response?
        - Rating: Confidence scale

- Do you think that it would be acceptable to use the xEMU Demo architecture to perform nominal and off-nominal tasks at the ISS?
    - Rating: YES, NO, or UNCERTAIN
    - What is your confidence rating for your response?
        - Rating: Confidence scale

### B. Objective Data

Three pieces of objective data are recorded for this test series. The first piece of data to collect for both the familiarization and the timeline runs is the ability for a crew member to complete a task (yes/no data).

The next two objective pieces of data are only collected during the timeline run: time required for the subject to complete each task and metabolic rate data. By collecting this data, general times to complete tasks and workload can be compared between the Z-2.5 space suit and the EMU. During the Z-2 NBL test series, metabolic rate data was also collected but it was hard to interpret because a controlled methodology was not used to ensure that subjects completed tasks in the same way or without breaks. This made it difficult to draw conclusions about task-specific energy expenditure. With the Z-2.5 test series, by completing an end-to-end standard EMU maintenance run, metabolic rate data should be more consistently recorded. This will help show if the Z-2.5 space suit enables the crew member to perform tasks more/less metabolically efficiently than the EMU.

## IV. Preliminary Results

The Z-2.5 NBL test series is scheduled to be completed in May of 2019, so full results are not discussed in this paper. Preliminary conclusions and feedback from a few of the engineering subjects and crew members are provided below.

Test subjects have reported the Z-2.5 space suit has improved upper torso mobility over the EMU because of the design of the shoulder joint as compared to the EMU. They have reported improved cross-reach and improved upward reach in the new architecture. Subjects have also reported an improved field of view as compared to the EMU. Subjects report that the increased field of view is due to a combination of the new helmet geometry, more room inside the helmet, and the freedom to move their head without a CCA. Subjects have reported improved field of view in both the longitudinal and lateral directions. Subjects have said that the EVVA, which is installed on top of the helmet, does not impact this increased field of view. They have reported improved field of view in both the longitudinal and lateral directions. Subjects have given positive feedback for the operation and design of the ICS system.

Test subjects have suggested areas for improvement for the Z-2.5 space suit. The EMU wedge adapter, which is installed onto the HUT, holds the mounts for the MMWS for the tools. This mounting location is approximately three inches higher on the suit than the mounting location on the EMU, relative to the shoulders. Some subjects have said that the increased height of the tools negatively impacts some of the increased upper torso mobility of Z-2.5, due to interference with the tools.

Areas of improvement consistently seen in the Z-2 NBL test series were that the front-to-back depth of the suit was too large and the outward depth of the helmet was too large.[3] These two areas of improvement were addressed for Z-2.5. Thus far, crew members have provided acceptable ratings for suit volume at all worksites. Comments related to interference have focused on the MMWS and tools. From this initial feedback, the repackaging effort between Z-2 and Z-2.5 may have sufficiently improved the ability to complete tasks in ISS worksites.

## V. Conclusion

The Z-2.5 NBL test approach is described in this paper. The test was designed to focus on evaluating the ability of Z-2.5 space suit with the exploration PLSS to perform ISS microgravity tasks. This configuration is representative of the xEMU Demo architecture. The test series consists of 10 NBL runs and it will conclude in May 2019. Preliminary test subject feedback is the Z-2.5 space suit provides an improved upper torso mobility, field of view, and communications systems as compared to the EMU suit. Areas of improvement would focus on possible repackaging or placement of the MMWS and tools. After the Z-2.5 NBL test series has been completed, a follow-up paper will be written to discuss the results of the test series. The results from this test series will inform the design of the xEMU Demo, which is scheduled to fly to the ISS in 2023. Specifically, results from this test series will inform the Preliminary Design Review (PDR) for xEMU Demo, and the procurement of the Demonstration Verification Test (DVT) hardware.

## References


[1] Thomas, K. and McMann, H. *U.S. Spacesuits,* 2nd ed., Springer, New York, 2012, pp. 17-353.

[2] Meginnis, I., Rhodes, R., Larson, K., and Ross, A. "Testing of the Z-2 Space Suit at the Neutral Buoyancy Laboratory." *47th International Conference on Environmental Systems,* 2017.

[3] Meginnis, I., Rhodes, R., and Larson, K. "Performance of the Z-2 Space Suit in a Simulated Microgravity Environment." *48th International Conference on Environmental Systems,* 2018.

[4] Meginnis, I., and Davis, K. "Testing of the Z-2 Space Suit at the Neutral Buoyancy Laboratory," Crew and Thermal Systems Division Technical Report, CTSD-ADV-1514, 2019.

[5] Cooper, G. and Harper, R., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153. 1969.