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Z-2 Architecture Description and Requirements Verification Results

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The Z-2 Prototype Planetary Extravehicular Space Suit Assembly is a continuation of NASA's Z series of space suits. The Z-2 is another step in NASA's technology development roadmap leading to human exploration of the Martian surface. The suit was designed for maximum mobility at 8.3 psid, reduced mass, and to have high fidelity life support interfaces.

The Z-2 suit architecture is an evolution of previous EVA suits, namely the ISS EMU, Mark III, Rear Entry I-Suit and Z-1 space suits. The suit is a hybrid hard and soft multi-bearing, rear -entry space suit. The hard upper torso (HUT) is an all-composite structure and includes a 2-bearing rolling convolute shoulder with Z-1 style gore lower arms and an elliptical hemispherical helmet. The lower torso includes a telescopic waist sizing system, waist bearing, rolling convolute waist joint, hard brief, 2 bearing soft hip thigh, Z-1 style legs, and walking boots with ankle bearings.

The Z-2 Requirements Verification Plan includes the verification of approximately 200 individual requirements. The verification methods include test, analysis, inspection, demonstration or a combination of methods. Examples of unmanned requirements include suit leakage, proof pressure testing, mass, man-loads, sizing adjustment ranges, internal and external interfaces such as in-suit drink bag, purge valve, and donning stand. Examples of manned requirements include verification of anthropometric range, suit self-don/doff, secondary suit exit method, donning stand self-ingress/egress and manned mobility covering eight functional tasks. The eight functional tasks include kneeling with object pick-up, standing toe touch, cross-body reach, walking, and reaching to the SIP and helmet visor. This paper will provide an overview of the Z-2 design. Z-2 requirements verification testing was performed with NASA at the ILC Houston test facility. This paper will also discuss pre-delivery manned and unmanned test results as well as analysis performed in support of requirements verification.

Nomenclature

CAD	=	Computer Aided Design
CSSS	=	Constellation Space Suit System
DTO	=	Detailed Test Objective
EMU	=	Extravehicular Mobility Unit
ESOC	=	EVA Space Operations Contract
EVA	=	Extravehicular Activity
FAR	=	Fabric Attachment Ring
FOS	=	Factor of Safety
ILC	=	ILC Dover
ISS	=	International Space Station
JSC	=	Johnson Space Center

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LBS	=	Pounds
LSS	=	Life Support System
Mk III	=	Mark III
MMOD	=	Micrometeoroid Orbital Debris
NASA	=	National Aeronautics and Space Administration
ORU	=	On-orbit Reusable Unit
PDA	=	Pre-Delivery Acceptance
DIDB	=	Disposable In-Suit Drink Bag
PGA	=	Pressure Garment Assembly
PSID	=	Pounds per Square Inch Differential
RC	=	Rolling Convolute
ROM	=	Range Of Motion
SSA	=	Space Suit Assembly
SUT	=	Soft Upper Torso
TCU	=	Thermal Comfort Undergarment
TMG	=	Thermal Micrometeoroid Garment
TRL	=	Technology Readiness Level
FSA	=	Feedwater Supply Assembly

I. Introduction

The Z-2 suit is an Advanced Extravehicular Activity (AEVA) System (Figure 1) being developed in support of the Advanced Exploration System (AES) under contract NNJ13437303R. It is a highly mobile space suit assembly (SSA) completing a flexible EVA suit platform that will be ready for NASA's next human exploration mission. Z-2 is a planetary walking suit configuration. This means that it incorporates full upper and lower body mobility required to perform tasks such as walking over rough ground, kneeling and picking an object up with both hands, and recovering from a supine position. The Z-2 consists of a rear-entry composite upper torso with waist bearing, hybrid aluminum and composite hatch, rolling convolute shoulder, and Z-1 style lower arms. The lower torso consists of a composite brief, Z-1 style 2-bearing hip joint, Z-1 style legs, and flexible walking boots. Gloves are not included in the Z-2 contract.

Figure 1: Z-2 Space Suit Assembly

The Z-2 will be used in the following test environments at the NASA-Johnson Space Center:

1. Simulated micro-gravity EVAs in the Neutral Buoyancy Laboratory (NBL) using the NBL environmental control system (ECS) umbilical.

2. Subsequent to NBL testing the suit will be used in a series of tests, including simulated partial gravity EVAs in the Active Response Gravity Offload System (ARGOS) and at the Planetary Analog Test Site (PATS, aka 'Rock pile') , and interface testing with systems such as the PLSS, Power, Avionics, and Software (PAS), and exploration vehicles.

This paper will provide an overview of the Z-2 design. Z-2 requirements verification testing was performed with NASA at the ILC Houston test facility. This paper will also discuss pre-delivery manned and unmanned test results as well as analysis performed in support of requirements verification.

II. Z-2 Space Suit Design Overview

The ILC Z-2 SSA development included Helmet, HUT/Hatch, Shoulders, Lower Arms, Waist, Brief, Hips, Legs and Boots. The design overview will discuss each major suit component progressing down the suit beginning with the helmet and ending with the boots.

A. Helmet Development

The Z-2 helmet (Figure 2) was originally defined by NASA as a 13-inch hemispherical dome similar to that developed for the Mk III space suit. This helmet shape and size was reviewed at the Z-2 Final Design Review on September 23, 2013. At the time of the final design review, it was already known that a delta review would be required since not all designs were complete. After the design review more work was performed on the HUT and Shoulder design leading to a determination that the 13-inch helmet dome shape was unnecessarily too wide for the small scye breadth of Z-2. The overlap of the circular helmet over the shoulders would result in limited shoulder mobility and potential for damage to the shoulder and helmet due to interference when performing mobility exercises. For the Delta Final Design Review, the helmet shape was changed to an elliptical hemispherical.

Figure 2: Z-2 Helmet Assembly.

The approach to the Z-2 helmet architecture is unique in that unlike the ISS EMU the protective bubble covers the entire pressure bubble and sun visor providing complete protection from both impact and abrasions. Due to funding limitations in the Z-2 contract, the development of the full helmet visor assembly was de-scoped and the new approach was to design only the pressure bubble and protective bubbles leaving the appropriate gap between the two bubbles for the sun visor to be designed at a later date.

The pressure bubble was designed with the same polycarbonate bubble to aluminum neck ring interface as the Waist and Rear Entry I-Suits. This includes an outer grove around the base of the pressure bubble potted into groove in the neck ring with an adhesive. This approach has been used successfully since 2000 with several versions of the I-Suit. There is a Z-2 requirement to remove and replace the protective bubble in less than 10 minutes. This is accomplished via four captured pins that interface through holes in the protective visor once it is slipped down into a straight walled groove in the helmet side neck ring. The neck ring is an I-Suit style captured snap ring design with over-center latch that includes two independent spring loaded lock buttons. The HUT side neck ring also has a feature and tapped holes to allow for interface to a heads-free communication system that is GFE from NASA and for future inlet ventilation duct attachment.

B. HUT/Hatch

The Z-2 HUT (Figure 3) is a rear-entry design similar to the Mk III HUT architecture but designed for a smaller population. The only feature that was retained from Mk III was the size and shape of the rear-entry opening and location of LSS pass-throughs in the Hatch. The HUT material choice was driven largely by balancing the impact, strength and mass requirements. A new hybrid composite material was developed for the Z-2 HUT that consists of a few inner and outer layers of S2 glass/epoxy resin prepreg sandwiching a much thicker IM10/epoxy resin prepreg core. This approach provided the best balance between impact resistance, strength and mass resulting in a final HUT shell weight of 17 lbs.

Figure 3: Z-2 HUT Shell

The HUT architecture consists of a Mk III style rear entry, elliptical neck ring interface flange, scye openings sized for a new 9 inch inner diameter bearing, and a circular waist opening flanged to accept a 15 inch inner diameter waist bearing. In order to provide improved sizing for subjects within a given HUT size, the Z-2 design includes two sets of scye insert rings that allow the scye bearing breadth to be moved in or out 0.5 inches per side. This effectively makes two HUT sizes in one when comparing to the ISS EMU HUT sizing scheme. The Z-2 shoulder assemblies attach to the HUT in the same way the ISS EMU shoulders do. The shoulders are installed by sliding the into the scye opening from the inside of the HUT. They are ultimately held in place by the suit pressure but a scye retainer ring that includes three lock tabs and one retention screw is used to maintain shoulder placement during unpressurized operations. The HUT includes an interface to a removable Suit Port Interface Plate. When the SIP is not in use, six of the tapped holes on the SIP flange are used for attachment of two fall protection brackets. The rear entry closure utilizes the same gear box and lock teeth as is used on the Z-1 prototype space suit. The HUT design includes four tapped holes in the chest area to allow for attachment of NBL weights and or display and control mockups. External removable scuff guards have been bonded to the surface of the HUT around the top of the shoulder to mitigate any damage to the HUT shell from the shoulder during operation. The Z-2 design incorporates a pair of removable waist tether brackets and a single BRT interface bracket. All three of these brackets are bolted through the waist bearing flange to the HUT Waist Flange on the front of the suit. The HUT also includes functional interfaces to a GFE Pressure Relief Valve and Multi-Function Purge Valve.

The interior of the HUT includes bonded Velcro that provides attachment for an ISS EMU DIDB. There are two shoulder harness options, one with a self-retracting webbing reel for self- don/doff. The self-retracting webbing reel utilizes a push/pull cable assembly that is actuated to the lock position when the Hatch is closed. A standard shoulder harness similar to that used in the ISS EMU for NBL training was also fabricated for use with the Z-2 HUT.

Figure 4: Z-2 Hatch Assembly

The Z-2 hatch (Figure 4) was originally planned to be a hybrid aluminum and composite assembly but after the kick-off of the Z-2 program both ILC and NASA decided to change the approach to an all composite hatch. The all composite design utilized the same material construction as the HUT. During the demolding portion of the deliverable hatch fabrication process, the hatch was damaged beyond repair. After some investigation, it was determined that a large piece of peel ply was not removed from the lower section of the Hatch during installation of the prepreg layers. This peel ply layer did not allow the composite layers to properly bond together and resulted in significant cracking and delamination during demolding. Due primarily to cost and schedule concerns, the project changed back to the original approach of a hybrid aluminum and composite Hatch. The original hatch mold was utilized again for fabrication of the composite panel. The outer hatch frame with locking teeth and the top portion of the hatch for LSS pass-throughs was machined from one plate of aluminum. After hatch frame machining and anodizing, the composite panel was bonded to the hatch from the inside and clamped around the inside perimeter.

The hatch includes all the interior and exterior LSS interfaces prescribed by NASA. The hatch was designed for the largest planned Feedwater Supply Assembly (FSA) and Aux FSA. A hatch cage was designed to fit over the FSA to protect it and provide a platform for a back pad to aide in indexing the suit subject. The hatch cage was designed to be removable and replaceable without tools. The hatch includes a flight like vent return duct that seals to an interfacing duct on the HUT upon closing the hatch.

C. Shoulder Development

The shoulder design (Figure 5) is an evolution of that developed for the Mk III space suit in the late 1980s. The design consists of aluminum rolling convolute (RC) rings that progressively reduce in diameter from the scye bearing down to the arm bearing. The primary axial restraint is a series of brackets that interface from the scye bearing to the arm bearing capturing each RC ring along the length of the shoulder. The primary axial brackets are fabricated from Titanium and utilize bushing design to last the life of the suit without replacement. The secondary axial restraint is a webbing system similar to the lower arm and leg of the suit that interfaces with a separate secondary bracket at the scye and arm bearings. In order to maintain mobility in the event the secondary was needed, the webbing is routed through slotted brackets attached the outside of the primary brackets.

Figure 5: Z-2 Shoulder Joint

The RC shoulder softgoods consist of a separate restraint and bladder system similar to that used on the all soft joints of the Z-2 suit. The restraint material is the standard polyester used on the current ISS EMU for all of its mobility joints. The bladder utilizes the same single coated bladder cloth as EMU but it is reinforced with a lighter weight single coated urethane fabric. The bladder reinforcement layer is heat sealed to the bladder cloth with the fabric side facing into the inside of the shoulder to act as an abrasion layer, not for pressure retention. The shoulder joint is designed for a range of 90 degrees.

D. Lower Arm

The lower arms on the Z-2 suit (Figure 6) are of the same design as that used on the ISS EMU, Z-1 and Rear Entry I-Suit. This is a flat patterned gored mobility joint fabricated from polyester fabric and Spectra primary and secondary axial restraint webbings. The design includes ISS EMU arm bearing end Fabric Attachment Ring (FAR) and suit side wrist disconnect. The Z-2 primary/secondary brackets are a Titanium single piece cam bracket design similar to the ISS EMU but first used on the Rear Entry I-Suit. The brackets are fabricated from Titanium and utilize the lower portion of the bracket body for the secondary webbing attachment eliminating several parts and features reducing the cost of the bracket.

Figure 6: Z-2 Lower Arm Joint

E. Waist

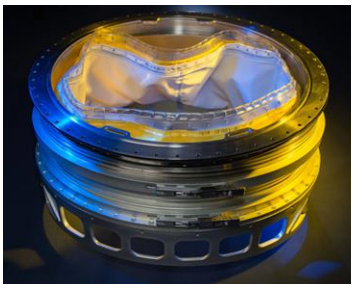

Figure 7: Z-2 RC Waist Joint

Similar to the shoulder joint, the Z-2 rolling convolute waist joint (Figure 7) has its heritage in the Mk III prototype space suit. The design consists of one large aluminum RC waist ring that uses the top portion of the brief effectively making it a two ring rolling convolute joint. The aluminum RC ring attaches to the brief via a large stainless steel pivot pin riding in a roller bearing. The RC waist ring range is limited by rubber coated stops built into the front and back of the brief. The waist softgoods consist of a polyester restraint and bladder cloth bladder fabricated using the same methods as on the ISS EMU. The waist is designed for a range of 40 degrees.

F. Brief

The Z-2 brief (Figure 8) is a hard brief design similar to that utilized on the Mk III suit but it is designed for a smaller population. The only feature that was retained from Mk III is the angles of the hip openings relative to the vertical and horizontal planes. Like the HUT, the brief material choice was driven largely by balancing the impact, strength and mass requirements. The brief uses the new hybrid composite material that was developed for the Z-2 suit that consists of a few inner and outer layers of S2 glass/epoxy resin prepreg sandwiching a much thicker IM10/epoxy resin prepreg core. This approach provided the best balance between impact resistance, strength and mass resulting in a final brief shell weight of 5.5lbs.

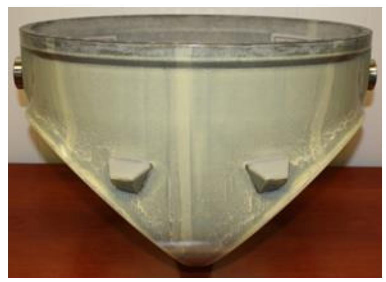

Figure 8: Z-2 Brief Shell

G. Hip

The Z-2 hip joint (Figure 9) is a modified version of the Z-1 hip that is an evolution of the hip joint originally developed for the Waist Entry I-Suit in 1997. The hip joint consists of a hip and leg bearing separated by an all soft fabric cone and torroidal convolute joint. The Z-2 hip bearing diameter is 0.5 inches smaller than the Z-1 hip bearing and the leg bearing diameter is 0.2 inches smaller than the Z-1 leg bearing. Bearing diameters were reduced to accommodate the smaller subjects the Z-2 suit was designed for. The hip wedge angle was reduced from Z-1 to Z-2 to reduce the suit torso length to again accommodate a smaller size population. The Z-2 torroidal convolute section is unchanged from the Z-1 suit.

Figure 9: Z-2 Hip Joint

H. Boot

The Z-2 boot (Figure 11) is an evolution of the boot design first used in the Waist Entry I-Suit in the late 1990s. Unlike previous designs the Z-2 boot is sized to be conformal to the wearer, eliminating the need for internal features to take up excess volume. It consists of restraint and bladder that includes a torroidal convolute ankle joint and foot section. The foot portions of the restraint and bladder are covered by a modified commercial boot outsole and upper/vamp. The upper/vamp is molded to the outsole with primary and secondary webbings routed under the insole at the heal location. The bladder is fabricated from ISS EMU bladder cloth. A rubber cushioning insole can then be used inside the boot bladder if desired.

In order for the boot to stay conformal to the wearer under pressure, a custom Titanium heel clip is fabricated and bonded around the heel portion of the upper/vamp. The commercial upper/vamp is further modified with features for attaching and routing a BOA lacing device over the instep area and at the back of the heel. The two BOAs are tightened to restraint the wearer's foot in the boot during suit operation.

The top of the Z-2 boot ankle is flange-mounted to dual seal Titanium ankle bearing that includes brackets for attachment of the boot primary and secondary axial restraints. The ankle bearing has a female acme thread feature that allows for quick attachment to different size leg joints. The ankle bearing has three redundant locks for attaching the leg FAR.

Figure 11: Z-2 Boot

III. Requirements Verification Test Results [1]

A. Summary

The Z-2 Verification Plan was completed, verifying 24 manned requirements and 175 unmanned requirements. The manned requirements compliance matrix is shown in Table 1 and the unmanned requirements compliance matrix is shown in Table 2 below. Although beyond the scope of this paper, the plan includes verification sign-off blocks by requirement, Tables for verification data recording and appendices A through G with supporting data. Appendix A includes photos supporting almost all manned and unmanned requirements verification. Appendices B through E are structural analysis results data. Appendix F is a corrosion assessment of the Z-2 Suit. Appendix G is the insert fastener failure investigation report.

Of the 24 manned requirements, 9 were determined to not completely fullfil the requirement and DRs were generated defining the reason and providing rationale for closing out the DR with no constraint to delivering the Z-2 to NASA. The first four failed requirements are SM14, SM15, SM23 and SM24 which are all related to self-don/doff. The Z-2 self-don/doff shoulder harness was found to have insufficient spring recoil force to be used and the backup standard harness had to be used for requirements verification testing. A new stronger recoil spring was purchased and installed on the self-don/doff shoulder reel and has been delivered to NASA for evaluation. The self-don/doff waist harness was damaged during emergency egress drill and was not useable for manned testing. The waist harness was redesigned and repaired and has been delivered to NASA for evaluation. Requirement SM23 was to verify that the Z-2 suit assembly was self-don/doff and since the shoulder and waist harness would not provide this ability this requirement was deemed a fail. Requirement SM24 is similar to SM23 but requires the suit to be self-don/doff with an 8.3 psid difference pressure across the suit representing a configuration the suit would see during Suit Port Operations. Since no Suit Port Assembly was available to use for requirement verification this is a fail. It was noted during manned testing the Z-2 legs tend to always want to stay somewhat bent back and this was noted as a potential hindrance to 8.3 psid self-don/doff as noted during actual testing with the Z-1 space suit in NASA JSC Chamber B.

The next manned requirement fail is SM25 which requires the Z-2 suit to have a secondary exit method in the event that the Rear Entry Closure will not open. Of the four verification test subjects only one was able to exit through the waist section of the suit. The other subjects fit so well in the HUT that they could not get their shoulders past the bottom of the scye opening. Requirement SM73 is also a fail. This requirement requires the Hatch Cage to not negatively impact suit sizing or mobility. The as-designed position of the Hatch Cage did not provide sufficient internal volume for all subjects and is therefore deemed a fail. New shorter Hatch Cage attachment brackets are being fabricated and will be delivered to NASA for evaluation. MV1 was also defined as a fail but only as a result of the longest size lower arm being too short for the longest interwrist length requirement. It should be noted that all four NASA test subjects fit the Z-2 and were able to successfully complete Reqirements Verification Testing.

The last two failed manned requirements are DS15 and DS17. Both of these are Donning Stand requirements. DS15 requires each subject to be able to ingress and egress the Donning Stand unaided. The new swing arm style suit capture mechanism designed by NASA for the Z-2 suit did not allow for unaided ingress and egress. A new suit to Donning Stand interface has been designed and is being manufactured to allow the Z-2 suit to be interfaced to the existing Mk III Donning Stand which has been used successfully for many years. DS17 requires that the Z-2 Donning Stand lock mechanism be actuated by the suited subject. The locking mechanism is a commercial pip pin which is not within the suited subjects reach so this requirement is a fail. The new Donning Stand interface will solve this problem as well. All 16 remaining manned requirements were verified as a pass.

Of the 175 unmanned requirements, 4 were determined to be a fail. The first failed requirement is SM21 and it is only a goal and as such no DR was generated. The Z-2 suit is required to be less than or equal to 170 lbs. The goal for Z-2 mass is less than or equal to 140 lbs including the SIP. The Z-2 suit with the SIP is 157 lbs and without the SIP is 143 lbs. The next two failed requirements are helmet related SM56 and SM57. These two requirements deal with the number of pressure bubble imperfections in size, quantity and location. The imperfections were documented on a DR and dispositioned as no constraint to deliver the suit. The scratches on the helmet bubble were most likely due to handling and use before and during Requirements Verification Testing. Requirement SII19 required the Z-2 suit to have 4 threaded inserts in the Hatch for attachment of the communications signal amplifier. During the Delta Hatch Design Review NASA agreed verbally to relieve the University of Delaware of this requirement but this discussion was never properly documented in the design review meeting memorandum. A DR was generated to document the lack of threaded inserts and was dispositioned as no constraint to suit delivery. All 171 remaining unmanned requirements were verified as a pass.

Table 1 [2]
Compliance Matrix
Manned Testing

TRL J.6 VERIFICATION	PRESSURE (psid)	REQUIREMENT DESCRIPTION	VERIFICATION METHOD
PV8	0 - 8.3 +/- 0.5	Z-2 Pressure gauge within crew's FOV	Demonstration
SM10	0 - 8.3 +/- 0.5	Z-2 shall include a boot for a size 10 foot	Test
SM13	0 - 8.3 +/- 0.5	Z-2 Shoulder/Waist Harness shall ensure scye bearings do no contact subjects shoulders	Test
SM14	N/A	Shoulder Harness shall be self-don/doff	Demonstration
SM15	N/A	Waist Harness should be self-don/doff	Demonstration
SM23	N/A	Z-2 shall be self-don/doff	Demonstration
SM24	8.3 +/- 0.5	Z-2 shall be self-don/doff at 8.3 psid	Demo Reach to Rear Entry Latch/Rationale
SM25	N/A	Z-2 shall have an secondary exit method	Demonstration
SM39	N/A	Z-2 Hatch Lock shall provide a way to confirm lock and unlock	Demonstration
SM40	N/A	Z-2 Hatch lock shall be within subject's reach	Demonstration
SM41	0 - 8.3 +/- 0.5	Z-2 Hatch lock is operable with one hand	Demonstration
SM42	8.3 +/-0.5	Z-2 Hatch lock is operable at 8.3 psid	Demo Reach to Rear Entry Latch
SM73	0 - 8.3 +/- 0.5	Z-2 Hatch Cage does not negatively impact MV1 and MV5	Demonstration
MV1	8.3 +/- 0.5	Z-2 shall fit subjects per Table 1-3 dims.	Demonstration
MV5	8.3 +/- 0.5	Z-2 Suit Subject perform repeated circuits of function tests in Table 1-7	Demonstration
MV9	8.3 +/- 0.5	Z-2 shall accommodate a 28.5 in VTD	Demonstration

SEI23	8.3 +/-0.5	Z-2 shall include 2 safety tether points accessible by a pressurized subject	Demonstration
SEI30	8.3 +/-0.5	Z-2 Square Boss Interface shall not interfere with shoulder mobility	Demonstration
SEI31	8.3 +/-0.5	Z-2 Square Boss Interface with BRT shall not interfere with shoulder mobility	Demonstration
SEI32	0 - 8.3 +/- 0.5	Z-2 Square Boss Interface should minimize impact to subjects downward visibility	Demonstration
DS13	N/A	Z-2 Donning Stand shall allow for subject don/doff	Demonstration
DS15	N/A	Z-2 Donning Stand shall allow ingress/egress of suited subject including soft-dock	Demonstration
DS17	8.3 +/- 0.5	Z-2 Donning Stand lock mechanism should be actuated by suited subject	Demonstration
DS24	0 - 8.3 +/- 0.5	Z-2 Donning Stand shall not interfere with the suit umbilical while docked or ingress/egress	Demonstration

Table 2 [2]
Compliance Matrix
Unmanned Testing

TRL J.6 VERIFICATION	PRESSURE (psid)	REQUIREMENT DESCRIPTION	VERIFICATION METHOD
PV1	8.3 +/-0.5	Normal Operating Pressure	Test
PV2	10.6	Maximum Operating Pressure	Test
PV3	13.2	Structural Pressure	Test
PV4	17.6	Proof Pressure	Test
PV5	21.2	Ultimate Pressure	Analysis
PV6	4.3 & 8.3	Z-2 Suit Leakage	Test
PV9	0-15	Pressure Gage Range 0 to 15 psid	Inspection
PV10	N/A	Pressure Gage Shall be Removable	Inspection
SM1	N/A	Rear Opening per Figure 1-1	Inspection
SM2	N/A	HUT Angles per Figure 1-2	Inspection
SM3	N/A	Waist Angle per Figure 1-2	Inspection
SM4	N/A	Z-2 shall use a HUT	Inspection
SM5	N/A	Z-2 shall interface with EMU Wrist Bearing	Demonstration
SM6	N/A	Z-2 shall be compatible with Phase VI Gloves	Test
SM8	N/A	Z-2 shall be compatible with EMU Boots	Test
SM9	N/A	Z-2 shall include boot adjustment mechanism	Demonstration
SM11	N/A	Operational Life of 90hrs post Pre-Delivery Testing	Analysis
SM12	N/A	40hr Maintenance Interval	Analysis
SM16	N/A	Z-2 shall meet isometric manload requirements	Analysis/Test
SM17	N/A	Z-2 shall meet leakage requirements after impact	Analysis/Test
SM19	N/A	Z-2 Softgoods shall be min. 1 fault tolerant	Analysis
SM20	N/A	Z-2 mass shall be less than or equal to 170 lbs	Test
SM21	N/A	Z-2 mass should be less than or equal to 140 lbs	Test
SM22	N/A	Z-2 shall be resizable without tools	Demonstration
SM26	N/A	Z-2 shall maintain min. FOS	Analysis/Test
SM27	N/A	Z-2 Disconnects and Hatch Lock shall be 1 fault tolerant	Insepction
SM28	N/A	Z-2 shall have part and assembly markings	Inspection
SM29	N/A	All hardgoods shall have a min. of .10 radius	Inspection

SM30	N/A	Z-2 shall use NAS fasteners	Inspection
SM31	N/A	All fasteners used during maintenance shall have helicoils	Inspection
SM32	N/A	Z-2 should limit number of fasteners to 4	Inspection
SM34	N/A	Z-2 should limit interior microbial contamination	Goal
SM35	N/A	Z-2 should limit overall microbial contamination	Goal
SM36	N/A	Z-2 should limit interior fungal contamination	Goal
SM37	N/A	Z-2 should limit overall fungal contamination	Goal
SM38	N/A	Z-2 shall contain a Hatch lock mechanism	Inspection
SM43	8.3 +/-0.5	Z-2 Hatch lock torque is ≤ 5 in-lbs	Test Unpressurized
SM44	N/A	Z-2 shall contain removable Hatch Hinges	Inspection
SM45	N/A	Z-2 Hinges shall contain a removable pip pin	Inspection
SM46	N/A	Z-2 Hinges shall support PLSS weight	Analysis
SM47	N/A	Z-2 Hinges shall allow Hatch opening to 90°	Demonstration
SM48	N/A	Z-2 shall include an instrumentation pass-thru	Inspection
SM49	N/A	Z-2 Instrumentation pass-thru per Figure 1-4	Inspection
SM50	N/A	Z-2 Instrumentation pass-thru shall be free from obstructions inside and out	Inspection
SM51	N/A	Z-2 Instrumentation pass-thru located per Figure 1-5	Inspection
SM53	N/A	Z-2 Helmet shall be no-tools removable	Demonstration
SM54	N/A	Z-2 Helmet shall have no visible distortion or optical effects in FOV	Inspection
SM55	N/A	Z-2 Helmet FOV shall be transparent	Inspection
SM56	N/A	Z-2 Helmet imperfections in FOV shall not exceed .03 inch diameter	Inspection
SM57	N/A	Total number of Helmet imperfections in FOV shall not exceed 4, nor more than 1 sq. in.	Inspection
SM58	N/A	Z-2 Helmet color shall be clear UV stabilized Polycarbonate	Inspection
SM59	N/A	Imperfections in Helmet non-FOV shall not exceed twice the size or number of the critical area	Inspection
SM60	N/A	Z-2 suit shall provide a pressure bubble and protective visor	Inspection
SM65	N/A	Z-2 shall have a Polycarbonate Protective Visor	Inspection
SM66	N/A	Z-2 Protective Visor shall have no visible distortion or optical defects	Inspection
SM67	N/A	Z-2 Protective Visor shall be replaceable in less than 10 minutes	Demonstration
SM68	N/A	Z-2 shall provide largest FSA volume	Analysis/Inspection
SM69	N/A	Z-2 FSA should be located near Primary Cooling Lines	Analysis/Inspection
SM70	N/A	Z-2 shall provide interfaces to attach an FSA	Inspection
SM71	N/A	Z-2 shall provide a 32in^3 volume for Aux FSA	Analysis/Inspection
SM72	N/A	Z-2 Aux. FSA should be located near Aux. Cooling Lines	Analysis/Inspection
SM74	N/A	Hatch Cage shall cover FSA and Aux. FSA	Inspection
SM75	N/A	Hatch Cage shall not interfere with any Hatch components	Demonstration
SM76	N/A	Hatch Cage shall provide pass-thrus to allow component routing	Inspection
SM77	N/A	Hatch Cage shall hold a 250lb subject during 2-g pullout without permanent yield	Analysis
SM78	N/A	Hatch Cage shall be removable without tools	Demonstration
SM79	N/A	Hatch Cage should contain padding	Inspection
SM80	N/A	HUT shall provide 3 threaded inserts per Fig.1-6	Inspection

SM81	N/A	All primary and secondary restraints shall be loaded to a 1.0 Limit Load	Test/Inspection
SM82	N/A	All heat seal operations shall have setup and shutdown samples	Test/Inspection
MV2	4.3 +/-0.5	Scye and Arm Bearing starting torque no more than Table 1-4	Test
MV3	4.3 +/-0.5	Z-2 w/Cover shall not exceed elbow and knee torques in Table 1-5	Test
MV4	8.3 +/-0.5	Z-2 w/Cover shall not exceed elbow and knee torques in Table 1-5	Test
MV6	N/A	Z-2 Arm maximum adjustment of .25 inches	Inspection
MV7	N/A	Z-2 Leg maximum adjustment of .5 inches	Inspection
MV8	N/A	Z-2 VTD maximum adjustment of .75 inches	Inspection
SII1	N/A	Z-2 shall interface with an EMU Valsalva	Demonstration
SII2	N/A	Z-2 shall provide a physical interface for a 32oz. of potable water	Inspection
SII3	N/A	Z-2 shall include 20 functional drink bags	Inspection
SII4	N/A	Z-2 should use an EMU DIDB	Inspection
SII5	N/A	Z-2 shall have the PPRV located per Fig. 1-20	Inspection
SII6		Z-2 PPRV interface geometry per Fig. 1-4	Inspection
SII7		Z-2 shall include a PPRV Blanking Plate	Inspection
SII8	13.2	Z-2 PPRV/Hatch Instrumentation Blanking Plates used for testing to 13.2 psid	Test
SII9	N/A	Z-2 shall interface with a MSPV in location per Figure 1-21	Inspection
SII10	N/A	Z-2 shall provide an internal interface for the MSPV per Figure 1-22	Inspection
SII11a	N/A	Z-2 shall be delivered with an MSPV Blanking Plate	Inspection
SII12	N/A	Z-2 shall be provide a removable cover layer	Inspection
SII13	N/A	Z-2 cover layer shall be aesthetically pleasing	Inspection
SII14	N/A	Z-2 shall have keep-out zone in Hatch for speakers per Figure 1-24	Inspection
SII15	N/A	Z-2 Hatch shall provide 4 threaded inserts within the speaker keep-out zone	Inspection
SII16	N/A	Z-2 shall include a mic. keep-out zone per Fig.1-25	Inspection
SII17	N/A	Z-2 HUT shall provide 3 threaded inserts for mics.	Inspection
SII18	N/A	Z-2 suit shall have a place for the signal amplifier	Inspection
SII19	N/A	Z-2 suit shall have 4 threaded inserts for the signal amplifier attachment	Inspection
SII20	N/A	Z-2 shall provide space for electrical cables and connectors per Figures 1-23, 1-24, 1-25	Inspection
SII21	N/A	Z-2 shall have interface to Bendix/Amphenol connectors at least 16 in. up from the hatch bottom	Inspection
SII24	N/A	Z-2 inlet vent duct shall be removable	Inspection
SII25	N/A	Z-2 shall return suit ventilation from EMU MWC	Inspection
SII26	N/A	Z-2 Ventilation-Return line shall be routed from the EMU MWC to the Vent-Return seal interface	Inspection
SII27	N/A	Z-2 shall contain a Vent-Return Seal on HUT per Figure 1-27	Inspection
SII28	N/A	Z-2 shall contain a Hatch Side Vent-Return seal that mates to HUT seal when the hatch is closed	Inspection
SII29	N/A	Z-2 Vent-Return line shall be routed from the Vent-Return Seal (Hatch) to the Hatch Vent-Return connector	Inspection
SII30	N/A	The Z-2 HUT Vent-Return Seal and lines shall be removable	Inspection
SII31	N/A	Z-2 Vent-Return Seal (Hatch side) shall include an Anti-Blockage Cage	Inspection
SII32	N/A	Z-2 Primary cooling lines shall be routed to the EMU MWC	Inspection

SII33	N/A	Z-2 Primary cooling line should be routed back to the Hatch from the EMU MWC	Inspection
SII34	N/A	Z-2 Primary cooling lines shall account for 4in of Hatch translation and then rotation	Demonstration
SII35	N/A	Z-2 Aux. cooling line supply routed from the Hatch across the hinges to ¼" CPC QDs	Inspection
SII36	N/A	Z-2 Aux. cooling line return routed from the CPC QDs across the hinges to the Hatch connector	Inspection
SII37	N/A	Z-2 Aux. cooling lines shall account for 4in of Hatch translation and then rotation	Demonstration
SII38	N/A	Z-2 cooling lines shall be .375ID EVA tubing with min. pressure rating of 22 psid	Inspection
SEI1	N/A	Z-2 shall use GFE Hatch Vent Supply Connector	Inspection
SEI2	N/A	Z-2 Vent Supply Connector location per Fig. 1-30	Inspection
SEI3	N/A	Z-2 shall use GFE Hatch Vent Return Connector	Inspection
SEI4	N/A	Z-2 Vent Return Connector location per Fig. 1-30	Inspection
SEI5	N/A	Z-2 shall have fluid pass-thru similar to Fig. 1-31	Inspection
SEI6	N/A	Z-2 fluid pass-thru dimensions per Fig 1-32,1-33	Inspection
SEI7	N/A	Z-2 fluid pass-thru location per Fig. 1-30	Inspection
SEI8	N/A	Z-2 Hatch shall provide CPC LC ¼" coupling for Primary Fluid Supply	Inspection
SEI9	N/A	Z-2 Hatch shall provide CPC LC ¼" coupling for Primary Fluid Return	Inspection
SEI10	N/A	Z-2 Hatch shall provide CPC LC ¼" coupling for Aux. Fluid Supply	Inspection
SEI11	N/A	Z-2 Hatch shall provide CPC LC ¼" coupling for Aux. Fluid Return	Inspection
SEI12	N/A	No hardware shall be located in zone per Fig. 1-34	Inspection
SEI13	N/A	Z-2 should minimize external chest region hardware	Inspection
SEI14	N/A	SIP shall be removable without disassembly of the pressure garment components	Inspection
SEI15	N/A	SIP shall be thermally insulated from the Z-2 suit	Inspection
SEI16	8.3 +/-0.5	Z-2 SIP shall support 620 lbs at 8.3psid	Analysis
SEI17	N/A	Z-2 shall employ the 2A Pneumatic Flipper Suitport	Inspection
SEI18		Z-2 SIP shall meet the keep out zones per CA2B11900 revA	Inspection
SEI19	8.3 +/-0.5	Z-2 shall have a SIP deflection of less than .02"	Analysis
SEI20	N/A	Z-2 SIP shall have a seal at the suit-to-SIP interface	Inspection
SEI21	N/A	Z-2 shall use PAB bolt pattern per Figure 1-36	Inspection
SEI22	N/A	Z-2 PAB interface shall support 80lbs	Analysis
SEI24	N/A	Z-2 safety tether points shall withstand a static load of 200 lbs in any direction away from the suit	Analysis
SEI25	N/A	Z-2 safety tether points shall have general dimensions per Figure 1-37	Inspection
SEI26	N/A	Z-2 shall have 2 tool harness attachment points on the HUT	Inspection
SEI27	N/A	Z-2 tool harness points should be located in the waist ring are	Inspection
SEI28	N/A	Z-2 shall contain a square boss interface located in general area per Figure 1-38	Inspection
SEI29	N/A	Z-2 square boss interface shall withstand a static load of 75lbs and 300 in-lb moment	Analysis
SEI33	N/A	Z-2 shall one or more suit side structural interfaces that interface with all Donning Stands, ARGOS and Vacuum Chambers in SIP and No-SIP configuration	Inspection
SEI34	N/A	Z-2 suit-side structural interface should be universal	Inspection
SEI35	N/A	Z-2 shall meet structural loads per Table 1-8	Analysis
SEI36	N/A	Z-2 NBL Donning Stand interface should not interfere with BRT attachment	Demonstration

EIF1	N/A	Z-2 will fit in a volume of 35.3"X52.5"X21"	Demonstration
EIF2	N/A	Z-2 suit shall provide data necessary for chamber testing in 100% O2 including MUAs	Analysis/Test
EIF5	N/A	Z-2 stowed should meet launch loads per SSP 50835	Analysis/Test
EIF6	N/A	Z-2 shall be designed for chlorinated water and ambient temps. of +82F to +88F	Analysis/Inspection
EIF7	N/A	Z-2 should avoid using dissimilar metals	Analysis/Inspection
DS1	N/A	Z-2 Donning Stand can support 620 lbs	Analysis/Test
DS2	N/A	Z-2 Donning Stand shall be transportable by maximum of 2 people	Demonstration
DS3	N/A	Z-2 Donning Stand shall use retractable casters	Inspection
DS4	N/A	Z-2 Donning Stand shall be able to be moved through a standard 30" X80" door	Demonstration
DS5	N/A	Z-2 Donning Stand shall be height adjustable without tools while the suit is docked	Demonstration
DS6	N/A	Z-2 Donning Stand should be height adjustable by suited subject in the stand	Demonstration
DS7	N/A	Z-2 Donning Stand shall withstand RGO Take-off and Landing g-loads	Analysis
DS8	N/A	Z-2 Donning Stand shall withstand RGO In-flight g-loads	Analysis
DS9	N/A	Z-2 Donning Stand shall fit in dims. per Fig. 1-39	Analysis
DS10	N/A	Z-2 Donning Stand shall attach to RGO plain floor	Demonstration
DS11	N/A	Z-2 Donning Stand RG Plain Bolt Stress	Analysis
DS12	N/A	Z-2 Donning Stand shall allow access for suit resizing, and component removal	Demonstration
DS14	N/A	Z-2 Donning Stand shall incorporate self-don/doff aids	Inspection
DS16	N/A	Z-2 Donning Stand shall have a locking mechanism once the suit is soft-docked	Inspection
DS18	N/A	Z-2 Donning Stand shall not tip in use	Analysis
DS19	N/A	Z-2 Donning Stand edges are min. 0.01" radius	Inspection
DS20	N/A	Z-2 Donning Stand shall allow Hatch to open 90 degrees with PAB attached	Analysis/Demonstration
DS21	N/A	Z-2 Donning Stand should allow a HUT rotation range of 10º-25° in 5° increments	Demonstration
DS22	N/A	Z-2 Donning Stand shall incorporate a seat	Inspection
DS23	N/A	Z-2 Donning Stand shall incorporate stairs	Inspection
DS25	N/A	Z-2 Donning Stand shall support interface loads	Analysis
DS26	N/A	Z-2 Donning Stand shall prevent contamination	Inspection
SC1	N/A	Shipping container shall clear a 30"X80" door	Demonstration
SC2	N/A	Shipping container shall have multiple latches	Inspection
SC3	N/A	Shipping container shall have multiple handles	Inspection
SC4	N/A	Shipping container shall have removable locking casters	Inspection
SC5	N/A	Shipping container shall be compatible with fork lift	Inspection
SC6	N/A	Shipping container shall include cushioning material	Inspection
SC7	N/A	Shipping container shall be puncture resistant	Inspection
SC8	N/A	Shipping container shall be water resistant	Inspection

B. Pressure and Ventilation Test Results

Pressure and ventilation requirements include PV1 through PV10 as listed in the Unmanned Testing Compliance Matrix shown above. The Z-2 suit successfully passed proof pressure testing to 17.6 psid for 15 minutes encompassing PV1 through PV4. The ultimate pressure requirement of 21.2 psid was met through analysis that is documented in the Verification Test Plan Appendices B, C and E. The Z-2 suit met the PV6 leakage requirement at 4.3 psid (189.3 sccm) and 8.3 psid (280.3 sccm). Post-requirements verification testing leakage at 4.3 psid was 180 sccm and at 8.3 psid was 225 sccm. The remaining ventilation requirements are for the suit pressure gage. These are met because the Z-2 has a small pressure gage mounted to each left lower arm just behind the wrist disconnect.

C. Structure and Mass Test Results

Structure and Mass requirements include SM1 through SM82. SM1 through SM4 refer to the Rear Entry HUT architecture dimensions and geometry. SM6 is about compatibility with the existing Phase VI gloves. This requirement was met by analysis discussing the hardware interface as well as the lower arm sizing. Requirements SM8 through SM10 are boot related. The boot size and adjustment capability was verified through manned testing with 4 NASA subjects. SM11 and SM12 deal with operational life and maintenance interval. Both of these requirements were addressed by analysis and the write-ups are in Table IV of the test plan. SM13 through SM15 are for the shoulder and waist harnesses, and as discussed previously SM14 and SM15 failed but they are no constraint to suit delivery. SM16 and SM17 are for isometric manloads and impact. The isometric manloads were used for calculating all suit hardware and axial restraint webbings and the results are documented in Verification Plan Appendices B, C and E. Requirement SM17 requires the Z-2 suit to meet leakage requirement after impact. The was verified through test and analysis. The requirement was verified in three zones chosen by NASA, as shown in Figure 12. SM20 and SM21 are the suit mass requirements. As previously discussed, the suit does meet the 170 lb requirement but does not meet the goal of 140 lbs. SM22 states the Z-2 suit must be resizable without tools. This requirement was met through the use of lower arm and leg cam brackets, acme thread quick disconnects and a new telescopic sizing element in the waist. SM23 and SM24 are for self-don/doff. As previously discussed in the summary, these both failed since there were functional issues with both the shoulder and waist harness. Secondary crew removal method SM25 was also a fail since only 1 of the 4 test subjects was able to complete this task. The structural analysis results in Verification Plan Appendices B, C and E show that all minimum factors of safety have been met as defined in SM26. All disconnects and hatch-locking features are a minimum one fault tolerant as defined in SM27. This is met by having at least two independent actions that must be performed in order to release a locking mechanism. Part marking per SM28 has been performed where practical on the Z-2 suit. The sharp edge requirement SM29 was supported by analysis rationale and similarity to the ISS EMU. SM30 was met through the use of NAS fasteners throughout the entire Z-2 suit assembly. The use of helicoil inserts was verified by analysis with rationale being documented in Verification Plan Table IV documenting the few places helicoils could not be used and why that is acceptable since those locations are not part of normal 40 hour maintenance. Rationale was provided for SM32, discussing why it is not practical or efficient to limit the number of fasteners to 4 with the major result being increased mass and volume if this requirement was enforced. SM35 through SM37 are for microbial/fungal growth levels. These requirements are goals and therefore verified by analysis and similarity to the ISS EMU. Requirements SM38 through SM43 are for Hatch/HUT lock/unlock mechanisms. Requirement SM39 pertains to visual confirmation of the lock mechanism. This requirement is accomplished with the use of wrist mirrors which are standard equipment on the ISS EMU.

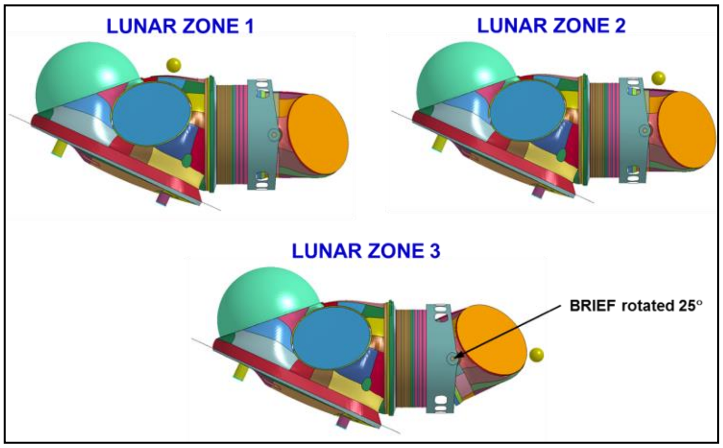

Figure 12: Z-2 Impact Zones to be Verified

SM40 through SM42 were verified through manned testing with 4 different subjects. Requirement SM43 latch actuation torque (5 in-lbs) was verified through measurement and determined to be 4.23 in-lbs. Requirements SM44 through SM47 pertain to the HUT/Hatch Hinges. SM44 and SM45 were verified through inspection. SM46 was verified by analysis and documented in Verification Plan Appendix E. SM47 was verified by demonstration and documented in Verification Plan Appendix A.

Requirements SM48 through SM51 are for the Hatch Instrumentation Pass-through. All of these requirements were verified by inspection and documented with photos in Verification Plan Appendix A.

Requirements SM53 through SM67 pertain to the Z-2 helmet pressure bubble and the protective helmet visor. SM53 was verified by demonstration. Requirements SM54 and SM55 were verified by inspection with NASA Quality Engineering concurrence. Requirements SM56, SM57 and SM59 are considered a fail since the pressure bubble had scratches inside and out that are larger than what is allowable. As previously noted, a DR was generated and dispositioned as no constraint to deliver to NASA. Requirements SM58 and SM65 were both verified by supplying a copy of the polycarbonate vendor CofCs in Verification Plan Appendix A. SM60 and SM66 were verified by inspection with NASA Quality Engineering concurrence. SM67 says that the protective visor should be removable and replaceable in less than 10 minutes without tools. This was verified by demonstration and shown to be replaceable in 20 seconds.

Requirements SM68 through SM80 pertain to Z-2 internal HUT/Hatch interfaces. SM68 through SM72 are for the FSA and Aux. FSA and include requirements like attachment, volume and location. These requirements were verified by inspection and analysis and are documented in the Verification Plan Appendix A. Requirement SM73 is for verifying that the Hatch Cage does not negatively impact subject fit or mobility. As previously noted in the summary, SM73 was deemed a fail since not all subjects could fit in the HUT with the standard length Hatch Cage Brackets. A DR was generated and new shorter brackets have been designed and will be fabricated and delivered to NASA for evaluation. SM74 through SM79 also pertain to the Hatch Cage. SM74 through SM76 were verified through demonstration and inspection. SM77 requires the Hatch Cage to hold a 250 lb subject during a 2-g pullout without permanent deformation. This was verified by analysis and is documented in Verification Plan Appendix A. SM78 and SM79 were verified by demonstration and inspection respectively. Requirement SM80 pertains to threaded inserts in the neck ring that will provide attachment for a future inlet vent duct. SM80 was verified by inspection.

Requirements SM81 and SM82 pertain to manufacturing best practices. SM81 states that all primary and secondary axial restraints shall be loaded to a minimum of 1.0 times the limit load during manufacturing. This was verified by test and inspection. NASA has been provided all the Instron data sheets for all Z-2 axial restraints. SM82 states that all heat seal operations shall include setup and shutdown peel strength tests. This was verified by test and inspection and NASA has been provided copies of all the Instron data sheets.

D. Mobility and Visibility Test Results

This section of requirements includes MV1 through MV9. MV1 states that the Z-2 shall fit individuals within the anthropometric range specified by NASA. This range includes 13 different measurements with a minimum and maximum dimension. As stated previously MV1 is considered a fail since based on the fit of the largest subject in the Requirements Verification pool, the maximum interwrist dimension that was not evaluated would probably not be fit with the longest lower arm made for the Z-2 suit. This is at least in part caused by a known design error that resulted in the largest interwrist dimension being 0.75 inches shorter than required. In order to aid in verifying MV1 each of the 4 NASA test subjects were asked to perform six different exercises and comment on their ability to perform the tasks and any impacts to performance due to sizing (Figure 13).

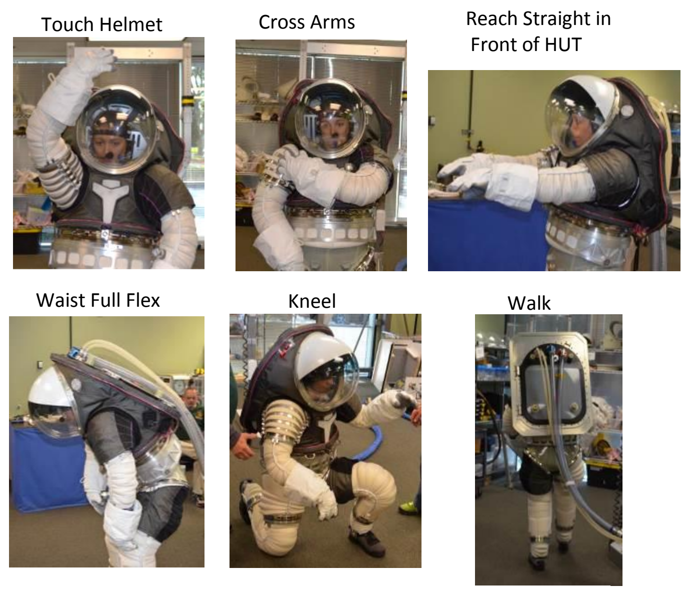

Figure 13: Mobility Exercises for Verifying Suit

Requirements MV2, MV3 and MV4 are for bearing and softgoods joint torques. MV2 requires the scye and arm bearings have a maximum starting torque of 32 in-lbs and 15 in-lbs, respectively. The measured scye bearing torque was 7.2 in-lbs and the arm bearing torque was 1.76 in-lbs. MV3 requires the elbow and knee without cover layer to have a maximum torque of 45 in-lbs and 100 in-lbs, respectively at 4.3 psid. The measured elbow torque with cover layer was 24.6 in-lbs at 90 degrees and 43.4 in-lbs at the maximum range. The measured knee torque with cover layer was 36 in-lbs at 90 degrees and 84 in-lbs at the maximum range. MV4 requires the elbow and knee without cover layer to have a maximum torque of 80 in-lbs and 145 in-lbs respectively at 8.3 psid. The measured elbow torque with cover layer was 33.2 in-lbs at 90 degrees and 55.3 in-lbs at the maximum range. The measured knee torque with cover layer was 66 in-lbs at 90 degrees and 114 in-lbs at the maximum range.

Requirement MV5 is for suit assembly level range of motion at 8.3 psid. Each of 4 subjects were required to perform 8 different functional tasks and comments were recorded in Verification Plan Table III. For each of the 8 functional tasks each subject had to perform at least three circuits. Each subject was able to complete the tasks without any issues. Four of the eight functional tasks is shown in Figure 14.

Requirements MV6 through MV9 relate to sizing components and maximum adjustment increment. MV6 through MV8 were verified by inspection and accomplished through the use of lower arm cam brackets, leg cam brackets and a telescopic waist sizing system that includes both integral sizing as part of the waist bearing inner race and a removable sizing element for subjects with longer VTDs. MV9 was verified by demonstration during the manned portion of testing and focused on one NASA subject with the required VTD.

E. Suit Internal Interfaces

Figure 15: Internal HUT Interfaces

This set of requirements is covered by SII1 through SII39. SII1 was verified by demonstration and states that the Z-2 should interface with an EMU Valsalva device. SII2 through SII4 are for the drink bag. These were verified by inspection to show that the Z-2 suit does interface with a standard EMU DIDB in the same approximate location as that used for EMU operation. SII5 through SII8 pertain to the PPRV and Hatch Instrumentation Pass-through. SII5 through SII7 were verified by inspection and cover the location, interface geometry and need for blanking plates for suit testing. SII8 was verified by test as it requires a blanking plate to be used for 13.2 psi structural pressure testing. This was verified during proof pressure testing as well as daily structural testing during Manned Requirements Verification Testing. Requirements SII9 through SII11a pertain to the Z-2 Purge Valve. These requirements include location, keep out zones and the required blanking plate. These requirements were verified by inspection and test as the Purge Valve blanking plate was used for proof testing as well as all of the manned testing.

Requirements SII12 and SII13 are for the cover layer. SII12 verifies the Z-2 cover layer is removable. This requirement was verified by showing photos of all the removable cover layer interfaces in Verification Plan Appendix A. SII13 states the Z-2 cover layer shall be aesthetically pleasing. This was verified by inspection and concurrence by NASA personnel.

Requirements SII14 through SII20 pertain to electronics keep-out zone interfaces. All of these requirements were verified by inspection and documented with photos in Verification Plan Appendix A. As previously noted in the summary, SII19 is considered a fail since relief on this requirement was not documented during the Hatch Delta Design Review. SII21 requires the Z-2 Hatch to have a feature to allow installation of a single Bendix/Amphenol electrical connector. This was verified by inspection.

Requirements SII24 through SII31 pertain to ventilation interfaces. These requirements are all verified by inspection and documented in Verification Plan Results. Requirements SII32 through SII38 pertain to cooling fluid interfaces. These requirements were verified through inspection or demonstration and also documented in Verification Plan Results. Figure 15 is in internal view of the HUT and Hatch showing the DIDB installed, water line vent tube assembly with purge valve ducting as well as the primary and secondary water lines.

F. Suit External Interfaces

This set of requirements is covered by SEI1 through SEI36. The first subgroup includes SEI1 through SEI11 pertaining to ventilation and cooling interfaces. All of these requirements were verified by inspection and documented in Verification Plan Table IV and Appendix A. SEI12 and SEI13 are for the DCM keep-out zone. These requirements were also verified by inspection and documented in Verification Plan Results. Requirements SEI14 through SEI20 pertain to the Suit Port Interface Plate (SIP). All of these requirements, except SEI16 and SEI19, were verified by inspection and were documented with photos in Verification Plan Appendix A. SEI16 and SEI19 were verified by analysis and the SIP was shown to have a minimum FOS of 4.0 and less than 0.02 inch deflection as documented in Verification Plan Appendix E. Figure 16 shows the Z-2 suit model with SIP attached to the Flipper Suit Port Mechanism that was used in support of requirements verification. Requirement SEI20 was verified by inspection to show that the SIP is sealed to the Z-2 suit via a gasket. SEI21 and SEI22 are for the NASA Portable Air Backpack interface. SEI21 was verified by inspection and documented in Verification Plan Appendix

A. SEI22 verifies the backpack interface features on the Z-2 Hatch will hold the required weight. This was verified by analysis and shown to have a minimum FOS of 3.72 as documented in Verification Plan Appendix E.

Requirements SEI23 through SEI32 pertain to Tool Interfaces. SEI23 was verified by demonstration with 4 NASA test subjects and documented in Verification Plan Table III and Appendix A. No issues were noted in reach to or manipulation of the Tether Hooks to the Tether Brackets. SEI24 pertains to the static load the tether points must hold. This was verified by analysis and shown to have a minimum FOS of 3.92 as documented in Verification Plan Table IV and Appendix E. SEI25 through SEI28 were all verified by inspection and documented in Verification Plan Appendix A. SEI29 pertains to the static load the Square Boss Interface must hold. This was verified by analysis and shown to have a minimum FOS of 3.71 as documented in Verification Plan Table IV and Appendix E. SEI30 and SEI31 were verified by demonstration with 4 NASA test subjects to show the Square Boss Interface with and without BRT does not interfere with shoulder mobility. SEI32 was also verified by demonstration with the 4 NASA test subjects to show the Square Boss Interface does not adversely affect downward visibility.

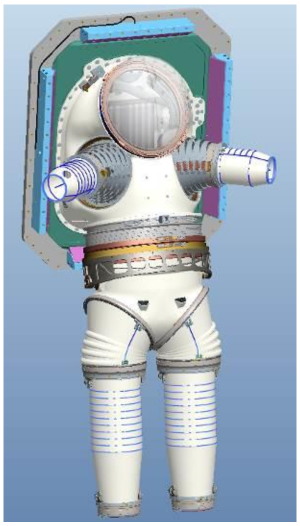

Figure 16: Suit/SIP to Suit Port Interface Model

Requirements SEI33 through SEI35 pertain to the suit side structural interfaces. SEI33 was verified by inspection and documented in the Verification Plan Table IV and Appendix A. SEI34 is for a goal to have on common suit-side structural interface and this was not obtained since it is not practical due to differing suit attachment features for the structural interfaces. SEI35 requires the Z-2 to meet structural load requirements defined by NASA in the J.6 Z-2 Requirements List. This was verified by analysis and documented in Table IV and Appendix E. The lowest factor of safety calculated is 3.53 for the Z-2 Fall Protection Brackets. SEI36 pertains to verifying the NBL Donning Stand does not interfere with the attachment of a BRT. This was to be verified by demonstration but the NBL Donning Stand was not available during Requirements Verification Testing at ILC.

G. Suit Environmental Interfaces

This set of requirements is covered by EIF1 through EIF7. EIF1 was verified by demonstration and refers to the stowed volume of the Z-2 suit (Figure 17). This step was witness by NASA Quality Engineering and involved stowing the Z-2 Suit Assembly in a shipping container of the correct volume. EIF2 pertains to Z-2 suit O2 compatibility. This was verified primarily by analysis but new White Sands testing was performed on the Rubber Boot Inserts and the Composite material resin. The verification is documented in Verification Plan Table IV and in the MUILs provided to NASA materials. EIF3 and EIF4 were originally for Shock Hazard requirements but were removed from J.6 as part of Contract Modification 7. EIF5 refers to a goal for Z-2 to meet launch loads. To fulfill this goal, ILC provided NASA recent launch load analyses for the ISS EMU on new launch vehicles. Requirements EIF6 and EIF7 pertain to NBL compatibility and avoiding the use of dissimilar materials on the exterior of the suit. This was verified by analysis/inspection and documented in Verification Plan Table IV and Appendix F.

Figure 17: Z-2 SSA Stowed Configuration

H. Donning Stand

This set of requirements is covered by DS1 through DS26. For the Z-2 program, NASA designed the Donning Stand in-house and ILC fabricated the components and assembled the stand shown in Figure 18. NASA performed all structural analyses and performed load rating in-house before shipping the stand to ILC Houston in support of Requirements Verification Testing. DS1 was verified by analysis and is documented in the Z-2 Donning Stand Stress Analysis Report

Figure 18: Z-2 Donning Stand

JSC-66796. Requirement DS2, 4, 5 and 6 could not be documented during requirements verification testing. DS3 was verified by inspection and documented in Verification Plan Table IV and Appendix A. Requirements DS7 through DS11 pertain to Reduced Gravity Flight G Loads and were verified by analysis and documented in JSC-66796. DS12, 14 and 16 were verified by inspection and documented in Verification Plan Table IV and Appendix A. DS13 pertains to allowing for subject don/doff. This was verified by demonstration during manned testing. Requirements DS15 and DS17 were considered a fail and have been previously discussed in the Verification Summary. Requirements DS18 through DS20 was verified by analysis in that NASA EC2 performed a Tipping Analysis and determined that in looking at 6 different load cases the righting moment was always greater than the tipping moment by at least a factor of 1.8. Requirements DS21 through DS23 pertain to Donning Stand required features. These were verified by demonstration and inspection and documented in Verification Plan Table IV and Appendix A. DS24 was verified by demonstration during the manned testing and documented in Table III and Appendix A. DS25 pertains to Donning Stand Interface Loads and is verified by analysis and documented in JSC-66796. DS26 refers to the Donning Stand not contaminating the Z-2 Suit. This was verified by inspection and is documented in Verification Plan Table IV.

I. Shipping Container

This set of requirements is covered by SC1 through SC8. They include requirements for size, latches, handles, casters, fork lift interface, padding and resistance to puncture and water. All of these requirements were verified by inspection and are documented in Verification Plan Table IV and Appendix A.

IV. Conclusion

The Z-2 is the most recent advanced flight like prototype EVA space suit produced for NASA. The Z-2 was designed for 100% O2 environments as well as NBL and other ground testing conditions, and it was fabricated as Class II with all material trace data. The suit combines technologies from numerous previous space suits developed by ILC Dover, such as the ISS EMU, Mk III, Rear Entry I-Suit and Z-1 space suits while also including new technologies such as the most advanced composite material ever used on a space suit. Advancements in rolling convolute joint technology were made, providing increased reliability and reduced cost to produce. Internal and external interfaces were designed, fabricated and integrated such as the purge valve, pressure relief valve, DIDB, internal harnesses, SIP, BRT interface and safety tether points. As part of the Z-2 development, new critical requirements such as impact protection were derived collaboratively with NASA, ILC Dover and the University of Delaware. These requirements were then designed through an iterative process of test and analysis, accomplished with expertise provided by the University of Delaware. While 13 of the 199 Verification Requirements were not met in part or whole, the Z-2 passed all critical requirements and was delivered to NASA in March of 2016.

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