

# Z-1 Prototype Space Suit Testing Summary

Amy Ross<sup>1</sup>

*NASA Johnson Space Center, Houston, Texas, 77058*

The Advanced Space Suit team of the NASA-Johnson Space Center performed a series of test with the Z-1 prototype space suit in 2012. This paper discusses, at a summary level, the tests performed and results from those tests. The purpose of the tests were two-fold: 1) characterize the suit performance so that the data could be used in the downselection of components for the Z-2 Space Suit and 2) develop interfaces with the suitport and exploration vehicles through pressurized suit evaluations. Tests performed included isolated and functional range of motion data capture, Z-1 waist and hip testing, joint torque testing, CO<sub>2</sub> washout testing, fit checks and subject familiarizations, an exploration vehicle aft deck and suitport controls interface evaluation, delta pressure suitport tests including pressurized suit don and doff, and gross mobility and suitport ingress and egress demonstrations in reduced gravity. Lessons learned specific to the Z-1 prototype and to suit testing techniques will be presented.

## Nomenclature

A = amplitude of oscillation  
a = cylinder diameter

[To be completed]

## I. Introduction

A principal role of the Johnson Space Center advanced space suit pressure garment team, herein referred to as “suit team”, is to characterize space suit pressure garment components and full suit architectures. Each mobility joint system and full suit architecture has different capabilities and limitations. The characterization data is used to guide development efforts and in the selection of components and architectures best suited to a specified mission, task, or requirement set. The focus of the suit team’s fiscal year (FY) 12 effort was the test and evaluation of the Z-1 suit.

The Z-1 suit effort was initiated by the desire to provide a pressurizable planetary exploration space suit pressure garment to be used in tests with high fidelity suitport hardware prototypes. The suitport is hardware concept that may replace or augment the traditional airlock function of a spacecraft by providing a bulkhead opening, capture mechanism, and sealing system to allow ingress and egress of a spacesuit while the spacesuit remains outside of the pressurized volume of the spacecraft. The suitport concept may enable three improvements in EVA by providing reductions in: pre-EVA time from hours to less than thirty minutes; airlock consumables; contamination returned to the cabin with the EVA crewmember. The driving requirement for Z-1 was to include a suitport interface plate on the upper torso. The suit team leveraged the effort to include new component designs, allowing the Z-1 to serve as a pressure garment test bed prototype.

## II. Description of the Z-1 Prototype Pressure Garment

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<sup>1</sup> Lead Advanced Space Suit Pressure Garment Engineer, Space Suit and Crew Survival Systems Branch, EC5.

The Z-1, shown in Figure 1, is a planetary walking suit configuration of primarily softgoods construction. The Z-1 suit weighs 154 pounds with the suitport interface plate (SIP) and 126 pounds without the SIP. It is designed for operation at 8.3 psid.



**Figure 1. Z-1 Prototype Space Suit Pressure Garment**

Relevant features specific to the Z-1 include:

- secondary restraints for the soft upper torso,
- a 3-bearing shoulder design,
- a modular dual axis waist,
- a 2-bearing hip with new patterning of the adduction/abduction feature,
- and modified lower leg (knee) patterning.

The secondary restraints on the upper torso addressed a safety requirement to provide failure tolerance. A method for providing this feature in soft upper torsos had not been shown in previous iterations of soft upper torsos and was an open question.

The 3-bearing shoulder design is a new configuration that previously was not represented in the current cadre of prototypes. Between the Shuttle Extra-vehicular Mobility Unit (EMU) scye (shoulder) bearing and the mid-shoulder bearing is a patterned convolute mobility feature. A softgoods wedge lies between the mid-shoulder bearing and the Shuttle EMU upper arm bearing.

The dual-axis modular waist consists of a three components: a flexion/extension joint, an adduction/abduction joint, and a Mark III rotational waist bearing. The waist flexion/extension patterned convolute joint is attached to the bottom on the upper torso. All waist configurations include the flexion/extension joint because it is specifically designed to provide the transition between the angles of the upper torso to the waist control ring, which interfaces with the other joints. The adduction/abduction joint, and then the waist bearing, complete the full dual-axis waist configuration. The waist is reconfigurable in that the adduction/abduction joint and waist bearing can be removed. The typical waist configuration used in most of the testing discussed in the paper is the flexion/extension joint and waist bearing.

The 2-bearing hip has a upper hip bearing located at the brief leg opening and an upper thigh bearing. Located between the bearings is a softgoods wedge and patterned convolute hip adduction/abduction joint. This joint is similar to that of the rear entry I-Suit (REI-Suit), but has been repatterned to allow improved walking motion from the REI-Suit and increased hip adduction/abduction range of motion.

The lower legs are based on the Mark III, Shuttle EMU, and REI suit patterned gore joints. An effort was made through patterning modifications and break lines located on the back of the knee to accommodate a wide and stable range of motion and eliminating a single ‘dive in’ at the back of the knee. The lower legs also included 4.5” of sizing via fabric loops integrated into the axial restraint.

### **III. Test Plan**

The test plan for the Z-1 testing consisted of suit performance testing and interface testing related to the suitport concept.

#### **A. Suit Performance Testing**

Suit performance testing of Z-1 was predominantly comprised of customary methods used to collect data for suit mobility characterization. The standard tests include motion capture of isolated joint and functional motions to determine joint ranges of motion (ROM), and joint torque measurements. A separate evaluation was performed on the Z-1 waist to assess the contribution of the adduction/abduction feature.

However, before any other testing could be performed, the suit had to be approved for use through confirmation of adequate carbon dioxide (CO<sub>2</sub>) washout. A CO<sub>2</sub> washout test was performed for this purpose, and to collect data to use for CO<sub>2</sub> washout computational fluid dynamics (CFD) model accuracy refinement.

Finally, cooperation with and a funding contribution from the Crew Survival team allowed the suit team to include a 3-day series reduced gravity. Objectives for the included both the evaluation of suitport microgravity

ingress and egress using a variety of ingress aids and methods and the evaluation of suit functional mobility at partial gravities. Only the functional mobility test is discussed in this paper.

## B. Suitport Testing

The primary test and the driver for fabrication of the Z-1, was to test suitport operations and the suit-to-suitport interfaces and operation in Chamber B. Chamber B is a human-rated thermal, vacuum chamber, and use of Chamber B allowed the suitport operations to be performed at a delta pressure of 8.0 psid across the suit and suitport. In other words, Chamber B was partially depressed so that the the suit was inflated by atmospheric pressure to a delta pressure of 8 psid. Thus, the suit and the suitport hardware sealing and mechanical system performed under realistic loads.

## IV. Suit Performance Test Descriptions and Results

### A. Z-1 CO<sub>2</sub> Washout<sup>1</sup>

#### 1. Test Description

The primary objective of the CO<sub>2</sub> Washout test was to characterize the workloads and flow rates at which CO<sub>2</sub> is adequately washed away from the suited subject's oronasal area in the Z-1 Suit. The data from the test was used to meet the immediate goal of defining acceptable workloads and flow rates for laboratory-based ground testing with the suits. The data will also be used toward the on-going effort to build a database of CO<sub>2</sub> washout test data that can be used to validate analysis models, as well as, help inform future space suit helmet and ventilation flow path designs.

Three subjects were asked to perform at four metabolic levels; resting, 1000, 2000, and 3000 BTU/hr, and at three different air flow rates, 4, 5 and 6 ACFM. Each subject performed testing on two different days so that the data could be compared for day to day variations. Gas was collected from one fixed sensor located above the subject's head and from two sensors places on either side of an oral/nasal mask worn by the subject, as shown in figure 2.

Resting metabolic rate was obtained while the subject was in the donning stand. 1000 BTU/hr was generated by having the subjects operate a hand ergometer. 2000 and 3000 BTU/hr were produced through walking on a treadmill. Standard air flow for pressurized suited events is 6 ACFM. Lower air flow rates tested are currently used as test termination criteria for pressurized suit events. The lower flow rates were tested because they are of interest in evaluating the future ability to reduced required air flow rates, thus potentially reducing portable life support system (PLSS) size and weight.

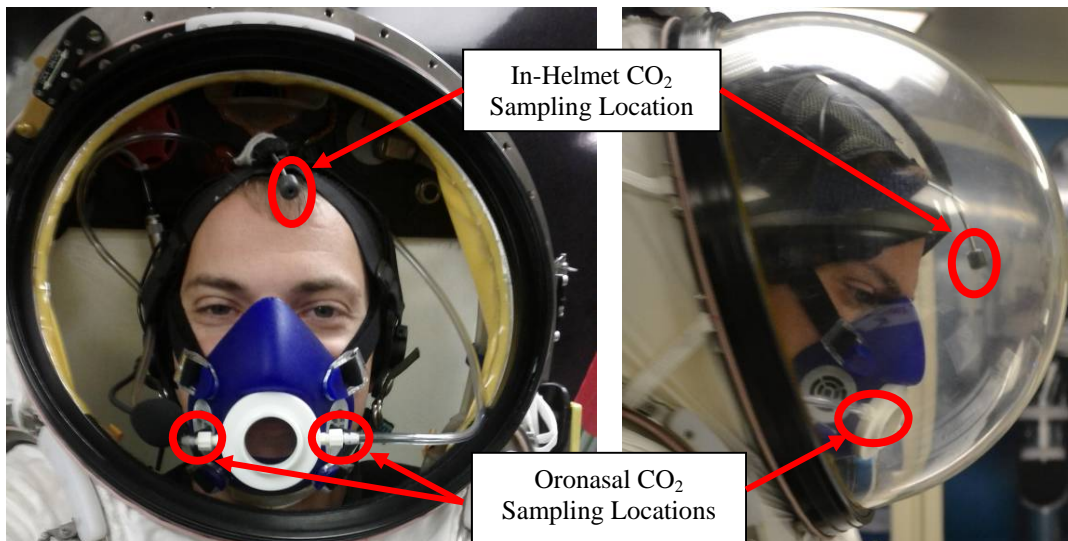


Figure 2. Z-1 CO<sub>2</sub> Test CO<sub>2</sub> Sampling Locations

## 2. *Test Results*

The principle and necessary result from the Z-1 CO<sub>2</sub> washout test was the configuration provides adequate CO<sub>2</sub> washout at the standard test air flow rate of 6 ACFM. This information was included in the Z-1 test readiness review, which allowed the suit to be approved the suit for testing beyond the CO<sub>2</sub> washout test. The second result was confirmation that the computational fluid dynamics (CFD) model of Z-1 predicts CO<sub>2</sub> values consistent with the test results; however, additional model refinement and test data are required to increase the confidence level of the model and improve the predictions, especially at 4 ACFM.

The test revealed additional observations for the improvements of the evolving EVA space suit CO<sub>2</sub> washout protocol. The first is the need to include more fixed sensors. Additional fixed sensors would be helpful in comparing day-to-day test data and in CFD analysis. Another protocol improvement that minimizes the load to the test subject is the suggestion that future testing involving targeted metabolic rates should continue to arrange test points in a way to minimize the changes to treadmill speed during trials to decrease the overall time test subjects spend walking on the treadmill.

## **B. Z-1 Range of Motion<sup>2</sup>**

### 1. *Test Description*

The objective of this test was to capture range of motion (ROM) data using a 3-D real-time motion capture system (Vicon MX) from subjects performing isolated joint and functional tasks. Isolated tasks were intended to move each major joint through its primary axes of motion. An example of an isolated task is elbow flexion/extension. Functional tasks included kneeling to pick up an objects, climbing stairs, walking on an inclined surface, and other common tasks that drove use of suit mobility features. Marker sets that have been developed to allow determination of relative motion between body segments were applied to the outside of the suit. Five experienced test subjects were briefed on task performance so as to limit inconsistencies among the techniques used by the subjects.

### 2. *Test Results*

In the end, the ROM data obtained has not been used because of how it was analyzed. The difficulty lies, in part, with the difference between human ROM and suited ROM. The data was analyzed using classic biomechanical ROM data analysis methods. In general space suit mobility joints do not provide motion in a single plane, and when they do they rarely align with a biomechanical plane of motion. The combination of bearing systems and softgoods mobility features results in an isolated motion such as shoulder flexion/extension moving through the adduction/abduction plane. A strict interpretation of planar motion, as is used in analyzing biomechanical ROM data, does not provide a clear picture of suit mobility. For example, a suit shoulder that can provide superior mobility but whose flexion/extension is not purely planar flexion/extension will look, per the ROM data, to be a lower performing shoulder than a shoulder with less overall mobility, but more purely planar flexion/extension ROM. The suit team utilized observational and subjective evaluations, but not the ROM data in mobility joint selection for this reason.

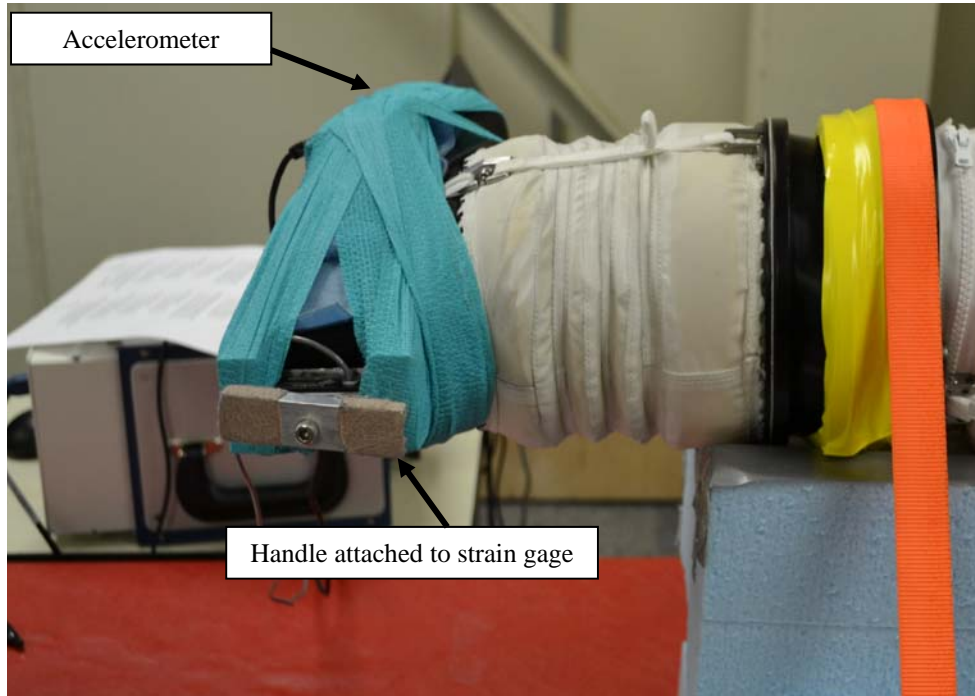
Observationally, the Z-1 lower torso is very mobile. For example, subjects were able to access their boot adjustment from a variety of postures due to the mobility.

Although subjects were selected for suit fit, suit fit continues to be a key factor affecting suit mobility evaluations. The Z-1 shoulder performance is sensitive to subject fit. The 3-bearing shoulder provided good ROM for the subjects who are able to utilize it. However, less than half of subjects had the fit that allowed them to do so.

## **C. Z-1 Joint Torque<sup>3</sup>**

### 1. *Test Description*

Joint torque data was collected for Z-1 using the method described by Valish. In summary, the method uses an accelerometer to track the angle and a strain gage attached to a handle that is, in turn, attached to the suit and used to manipulate a joint through a range of motion, as shown in figure 3. The suit team has been refining this protocol to increase repeatability of results and to understand how the joint torque data can be used. The data represents the torque of the bladder/restraint assembly at the test pressure. Data was collected at both 4.3 psid and 8.3 psid.

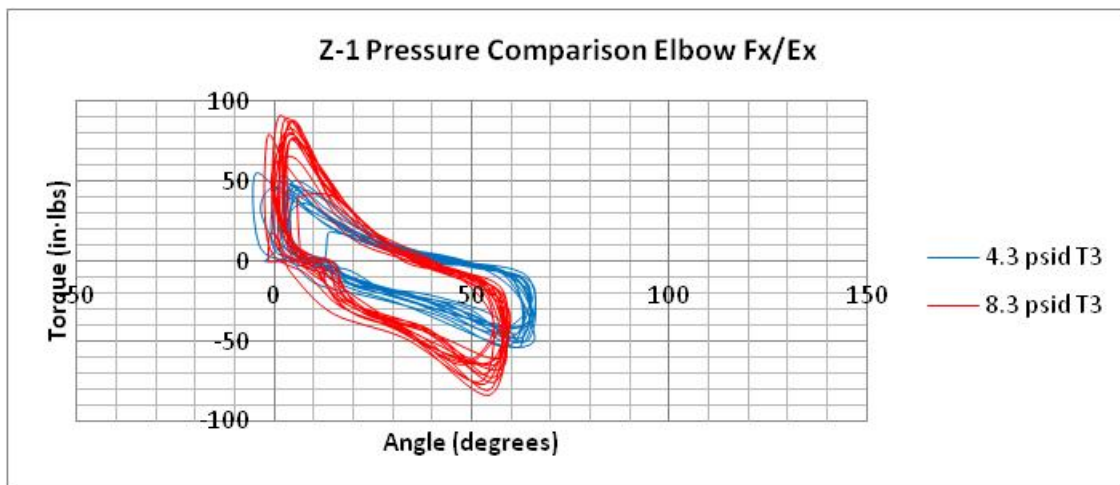


**Figure 3. Joint Torque Test Set Up for the Ankle Flexion/Extension Joint**

## 2. Test Results

In comparison with the Mark III lower arm, the Z-1 demonstrated similar joint torque values, but over a smaller range of motion. For the knee, the joint torque profiles are very similar with an off-set on the angle. The Z-1 maximum flexion value at 4.3 psid occurred at a knee flexion near 140 degrees, whereas the Mark III flexion was around 120 degrees. However, the Mark III total range exceeded that of the Z-1, because it had greater range in extension. Please note that the comparisons being made can ONLY be done so because the data was collected using the same protocol for both suits.

As expected, the range was reduced and the joint torque increased for the lower arm and knee at 8.3 psid as compared to 4.3 psid values. Torque values were affected more than the angles. For example, referring to figure 4, lower arm torque values went from about 50 inch-pounds for both flexion and extension to around 85 in-lb on extension and about 75 in-lb for flexion, while the range for flexion decreased from 65 degrees to 55 degrees.



**Figure 4. Z-1 Pressure Comparison for Elbow Flexion/Extension**

The suit team has determined that the joint torque protocol only provides informative results on single axis joints; therefore, the lower arm and knee flexion/extension results are discussed. Additionally, the angle and torque values are not absolute. The values are useful in comparison, but the team has determined that while joint torque is helpful for internal analysis, the data are not useful as suit design requirements.

#### **D. Waist evaluation<sup>2</sup>**

##### *1. Test Description*

Data was collected while subjects performed both isolated joint and functional tasks for three suit waist configurations: flexion/extension joint and waist bearing, flexion/extension and adduction/abduction joints, and all three components (adduction/abduction was in the middle). Three subjects participated in the waist evaluation. The Z-1 waist is long when all three components are used, which drove the selection of subjects based on torso length, because reasonable suit sizing had to be achieved for the subjects in the longest configuration.

##### *2. Test Results*

The data from the waist evaluation reinforced the observations of and subjective comments on Z-1 waist mobility. The Z-1 waist is very mobile, especially when all three components are in place. The Z-1 flexion/extension joint provides a large ROM. When compared to data from the one subject that also had Mark III waist ROM data, the subject was able to obtain double the ROM from the Z-1 patterned convolute flexion/extension joint over that obtained from the Mark III rolling convolute flexion/extension joint. The flexion/extension joint was highly utilized throughout all test conditions. Unsuit subject data demonstrated that the human body has a large adduction/abduction isolated joint ROM, and subjects utilized more than half of their range for functional tasks. In suited mobility, the adduction/abduction feature provided a good, but lower than human body ROM, so it was utilized through its full ROM for isolated joint and functional tasks. It is interesting to note that the bearing rotation ROM obtained were higher when the full waist joint complement was tested than in the flexion/extension and bearing configuration. The data also demonstrated that the other lower torso joints, such as the hips, ankle bearing and leg softgoods, provided some adduction/abduction and rotation.

#### **E. Reduced Gravity Gross Mobility Evaluation<sup>4</sup>**

##### *1. Test Description*

Two flight days were dedicated to gross mobility evaluations in 1/3-g, approximating Mars gravity conditions. Two subjects participated and performed approximately 20 parabolas in the Z-1 and 20 parabolas in the Mark III. The plan was for the subjects to perform 7 parabolas of functional tasks with the waist bearing active, 7 parabolas of the same tasks with the waist bearing locked out, and 6 parabolas with the waist bearing active and a display and control system mock-up on the chest of the suit. Functional tasks performed included walking on a simulated rock surface, running on a rock surfaces, kneel and recover, and recovery from the supine position. Subjective ratings on a scale of 1 (best) to 5 (worst) for ease of performance, stability while performing the task, and mental workload required to perform the task were recorded following each parabola. A post-test questionnaire was administered, as well.

##### *2. Test Results*

The Z-1 was the preferred suit for walking and running tasks. The preference, per subject comments, was based on a more natural motion and that Z-1 felt lighter when performing these tasks. The Mark III was preferred for the kneel and recover task, but only slightly. The Mark III performed notably better in the recovery from the supine position task. The subjects reported little impact to the walking, running, and recovery from the supine position from the waist bearing being locked out. The subjects did note that the kneel and recovery task was easier with the waist bearing active. With the display and control mock-up size and location tested, there was no negative impact to subject visibility or mobility.

## **V. Suitport Test Descriptions and Results**

### *Z-1 Suit Suitport Chamber B Test*

In 2012, the suitport team evaluated two different high fidelity suitport mechanisms in a delta pressure test in the human-rated Chamber B: the Marmon Clamp and Pneumatic Flipper. The Z-1 Suit was designed to participate in these tests, and the suit results are discussed below. The suit experienced a delta pressure of 8.3 psid during the tests.

## **A. Marmon Clamp Test<sup>5</sup>**

### *1. Test Description*

The suit team objectives was focused on pressurized don and doff performance. The suit team had a secondary objective to assess the adjustable boot feature. The Marmon Clamp test was performed first and lessons learned were incorporated for subsequent subjects and in the Pneumatic Flipper Test. Subjects were asked to provide ratings on the Modified Cooper Harper and Lickert Acceptability scales as they completed tasks. Subject comments and observations also were recorded.

### *2. Test Results*

This test was the first evaluation of pressurized suit don and doff in the history of the human spaceflight program. More difficulties in donning and doffing were encountered than were anticipated. For donning, the primary issue was the geometry of the legs, particularly the knee break of the suit. The Z-1 knee has a natural break that put a bend in the knee, which reduced the leg opening causing some subjects to be unable to don. The suit team responded by evaluating the use of a metal step. The suit legs were propped the metal step in an effort to keep the legs straight for donning. This modification allowed previously unsuccessful subjects to be able to don the suit. In combination with suit geometry, a contributing factor to ease of donning may have been foot length. It is theorized that subjects with longer feet may have had more difficulty; however, this potential correlation has not been tested. A secondary issue was that the ability of the boots to rotate at the ankle bearing which allowed the boot to turn backwards. Although it was a nuisance, subjects were able to manipulate the boot to the correct position for donning. A comment on the upper torso regarded the bladder/restraint of the Z-1 shoulder patterned convolute feature. The patterned convolute folded into the shoulder opening which impacted suit donning. Donning both arms at the same time, versus one at a time, seemed to be a successful technique. This technique is shown in figure 5.





**Figure 5. Z-1 pressurized donning sequence**

DoFFing was more difficult than donning. Only two of five subjects were able to doff the suit in the Marmon Clamp test. The first issue encountered was a large bladder fold at the boot end of the lower leg. The leg, which includes 4.5 inches of sizing at the lower leg, was sized short. This created excess bladder in the area. On subsequent trials, the excess leg bladder was manipulated by technicians so that it laid flat when pressurized which significantly mitigated the issue.

However, as in donning, the more confounding issue was the knee break/bend. As the subject attempted to pull their feet out of the suit the knee bent which formed a hard edge at the back of the knee. A similar situation occurred at the ankle joint. Between the two, the joints acted as a Chinese fingertrap, trapping the subjects. When the subjects attempted to use the small metal step that had improved donning, the angle at the hip became the trap. A modified aid, an angled plate, was built and used by the 5<sup>th</sup> and final subject. However, the design did not aid doffing. A doffing aid that provided some foot restraint was suggested for the Pneumatic Flipper Test.

A final contributing factor to the difficulty of doffing was the waist. Most subjects required that the waist be sized in one of its two shortest settings. Similar to the leg, this caused bladder bunching. The effect of the bunching was heightened by the propensity of the bladder material to stick to the tubing on the liquid cooling garment. To mitigate this effect, a nylon liner was installed in the waist. Test subjects also wore a nylon cummerbund with elastic panels over the cooling garment at the hips to keep the cooling lines from creating additional snag points during Z-1 donning and doffing. These post-delivery additions proved helpful during the Chamber B pressurized don/doff testing, as well as in standard laboratory testing with the Z-1.

## **B. Pneumatic Flipper Test<sup>6</sup>**

### *1. Test Description*

In response to the results of the Marmon Clamp test, a don/doff aid designated the boot jack, shown in figure 6, was fabricated and evaluated in the Pneumatic Flipper Test. The intention for the boot jack was that it would restrain the boots and maintain a straight legged posture to provide an more open path for both donning and doffing.

### *2. Test Results*

The majority of subjects were able to don and doff with greater ease. They attributed the boot jack with securing the legs and feet in place preventing flailing and providing a more open path. The boot jack received very good ratings for effectiveness from most subjects. However, two subjects still reported significant difficulty with don and doff and did not rate the boot jack as effective.

A recurring difficulty from the Marmon clamp test for doffing was the interference at the ankle. At this time it is not clear what combination of variables affects ease of don or doff, but pertinent factors are thought to include subject anthropometry, suit geometry, and technique. Technique and experience played a distinct role in don and doff success.



**Figure 6. Boot jack foot restraint with Z-1 suit installed**

Most subjects rated boot adjustment as having minor but annoying deficiencies. When asked to describe what was challenging about the tasks, the common answer was that it was difficult to manage the weight and the center of gravity of the suit (Figure 7). Suit fit can significantly affect a subject's ability to perform this task. Additionally, multiple subjects commented that the Z-1 thigh bearings began to dig into their inner thighs as they bent over, creating a strong pressure point.



**Figure 7. Subject squatting and adjusting both boots simultaneously**

## **VI. Conclusions**

In the end, pressure garment requirements are meant to result in a suit that allow astronauts to perform specified tasks. The Z-1 testing brought to a head some of the concerns with current suit testing techniques in achieving that effect. Traditionally, suit mobility has been defined by joint ROM and torque. However, the deficiencies and inadequacies of the ROM and joint torques techniques have led the suit team to actively engage in the search for new methods to define suit mobility. For example, the suit team is investigating an energy-based suit mobility evaluation approach in 2013. For all of the Z-1 mobility tests, observational data and subject comments were the most valuable sources of information for the Z-1 mobility test.

The value of observational data and subject comments should not and cannot be underestimated. Each member of the suit team serves as a suit test engineer or test director in order to get a lot of time watching pressure garments move. The suit team also puts a strong emphasis on firsthand experience. By serving as a suit subject, the suit team engineers are more informed, are more empathetic test conductors, and can better translate subject comments. From observations and subject feedback, the following suit team determinations regarding Z-1 joints, and suit architectures in general, were made:

- The Z-1 lower torso provides significant mobility and a natural walking motion.
- The Z-1 3-bearing shoulder performance was fit sensitive.
  - Changes to the implementation of the design may improve performance, but for near-term efforts focused on low risk mobility joint options, the 3-bearing shoulder will not be used.
- The waist adduction/abduction joint will be excluded for near-term suit iterations.
  - Although the waist adduction/abduction joint provided added mobility to the suit, the length of the torso with all three joints limited subject selection to individuals with very long torsos. The waist flexion/extension joint and bearing were prioritized above the adduction/abduction joint.

The pressurized don/doff evaluations were very informative for future suitport compatible pressure garment design. The following are design considerations resulting from the tests:

- Maintain an open pathway in the legs and shoulders

-A don/doff aid may be required and may be the lowest impact design solution. Additional design effort is required.

-Bladder management throughout the sizing range is important to prevent bunching and bladder folds that may obstruct the legs or waist.

-Shoulder joint mobility features should be designed taking the shoulder opening necessary for pressurized donning into consideration.

- Create a friendly interface for donning and doffing
  - Material selection and mitigation of snag hazards must be taken into account.
- Forward work included investigating the potential correlation between anthropometry, suit geometry, and successful pressurized donning and doffing.

## References

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<sup>3</sup>Valish, Dana. "Space Suit Joint Torque Measurement Method Validation." 42<sup>nd</sup> *International Conference on Environmental Systems*. American Institute of Aeronautics and Astronautics, San Diego, CA, July 2012.

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