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Performance of the Z-2 Space Suit in a Simulated Microgravity Environment

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The Z-2 space suit is the product of the last fifty years of NASA's space suit research and testing experience. The suit was originally built as a prototype exploration space suit to evaluate advances in suit design and technology for use on a planetary surface. After the delivery of Z-2, however, NASA shifted focus and sought to evaluate the feasibility of using design features of the Z-2 suit to inform the design of the xEMU Demo space suit, which will be demonstrated on the International Space Station (ISS). Aside from being developed primarily to evaluate the overall architecture of the xEMU space suit, the xEMU Demo may also supplement or replace the existing Extravehicular Mobility Unit (EMU). To evaluate the microgravity performance of the Z-2 architecture for compatibility on the ISS, the suit was tested in NASA's Neutral Buoyancy Laboratory (NBL), which is the primary microgravity testing environment for space suits. The Z-2 NBL test series began in the fall of 2016 and concluded in the fall of 2017. Five astronauts performed various tasks that are representative of the tasks performed on the ISS. Test subjects performed tasks in the Z-2 suit and the EMU so that relative comparisons could be drawn between the two suits. Two configurations of the Z-2 space suit were evaluated during this test series: the ELTA configuration and the ZLTA configuration. The ELTA configuration, which was the primary test configuration, is comprised of the Z-2 upper torso and the EMU lower torso. The ZLTA configuration is comprised of the Z-2 upper torso with the Z-2 lower torso, which contains additional mobility elements. This paper discusses the test results from the Z-2 NBL test series.

Nomenclature

ABF	=	Anthropometry and Biomechanics Facility
APFR	=	articulating portable foot restraint
BRT	=	body restraint tether
CCA	=	communications carrier assembly
CCE	=	critical contingency extravehicular activity
CM	=	crew member
cm	=	centimeter
CO_2	=	carbon dioxide
DCU	=	display and control unit
DTO	=	development test objective
DVT	=	design, verification, test
ELTA	=	extravehicular mobility unit lower torso assembly
EMU	=	extravehicular mobility unit
EVA	=	extravehicular activity
EVVA	=	extravehicular visor assembly
FHRC	=	Flexible Hose Rotary Coupler
HUT	=	hard upper torso
ICS	=	Integrated Communication System
IFHX	=	Interface Heat Exchanger

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in	=	inch
ISS	=	International Space Station
JSC	=	Johnson Space Center
LTA	=	lower torso assembly
MBSU	=	Main Bus Switching Unit
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
SAFER	=	Simplified Aid for Extravehicular Activity Rescue
VTD	=	vertical trunk diameter
ZLTA	=	Z-2 lower torso assembly

I. Introduction

THE Extravehicular Mobility Unit (EMU) was originally developed by the National Aeronautics and Space Administration (NASA) in the 1970s to enable astronauts to perform extravehicular activities (EVAs) in microgravity during the Space Shuttle Program.[1] The EMU has been successfully used for several decades and it continues to be used today to perform EVAs on the International Space Station (ISS).

The Z-2 prototype space suit was delivered to NASA in 2016 and is the culmination of several decades of space suit development work.[2] The rear-entry suit was originally developed as a prototype exploration space suit for use on a planetary surface. However, there were programmatic changes at NASA after Z-2 was delivered and NASA sought to use design features of the Z-2 suit to inform the design of the xEMU Demo space suit. The xEMU Demo is a Development Test Objective (DTO) space suit that NASA plans to demonstrate at the ISS by 2025. Design features of the xEMU Demo will feed into the design of the xEMU space suit, which will support NASA's future exploration missions. Aside from primarily evaluating the overall architecture of the xEMU space suit, the xEMU Demo may also supplement or replace the existing EMU. To refine the xEMU Demo architecture design (Z-2) and optimize it for microgravity, it is necessary to evaluate the microgravity performance of Z-2 on the ground. Previous tests with the Z-2 space suit have been limited to 1-g evaluations. Tests have included carbon dioxide (CO_2) washout evaluations[5] and fit checks in a laboratory environment.

The Neutral Buoyancy Laboratory (NBL) is NASA's primary simulated microgravity testing environment for space suits. This location was used to evaluate the Z-2 space suit in a simulated microgravity environment. The Z-2 NBL test series ran from September 2016 through October 2017 and the test included 19 manned runs. This paper presents the results associated with this test series. Ref. 3 presents the methodology associated with the test. Ref. 4 provides a more thorough description of the methodology and results.

II. Test Plan

A. Test Objectives

To understand the microgravity performance of the xEMU Demo suit architecture, it is informative to compare the performance of the suit to the current state-of-the-art, which is the EMU. As such, the high-level objective of this test series was to evaluate the performance of the rear-entry Z-2 space suit in simulated microgravity as compared to the EMU. This test series was separated into six specific test objectives. Additional details for each objective are provided in Ref. 3 and Ref. 4.

1. Evaluate ability of Z-2 in the ELTA suit configuration to perform microgravity tasks, such as the ISS Critical Contingency EVA (CCE) tasks, relative to the EMU
2. Evaluate EMU tools with the Z-2 upper torso architecture
3. Evaluate Z-2 with the advanced portable life support system (PLSS) package volume (PLSS 2.5) for use on ISS
4. Evaluate suit usability with subjects who span the size range of Z-2

5. Evaluate added performance from a highly mobile LTA (ZLTA)
6. Evaluate capabilities of Z-2 suit with a highly mobile LTA (ZLTA) at 8.0 psid

B. Test Methodology

The Z-2 NBL test series consisted of 3 development runs and 16 primary runs. Two engineers participated in the development runs, and five astronaut test subjects (crew members (CMs)) participated in the primary runs. This was the largest practical number of astronaut test subjects considering facility availability, schedule, hardware availability, and astronaut availability. Results in this test report reflect feedback from the astronaut test subjects. Because the test series was constrained to 16 primary runs, priority was given to evaluating the EMU lower torso assembly (ELTA) configuration of Z-2. All five astronauts performed runs in the ELTA configuration of Z-2. Four of these astronauts also performed runs in the ZLTA configuration of Z-2. Attempts were made to schedule the test subjects' runs such that the runs were performed over as short of a time frame as possible. A summary of the Z-2 NBL runs is provided in Table 1.

Each subject's first run in Z-2 in the NBL was a familiarization run in the ELTA configuration of Z-2. A subject's second run was the CCE run, which was the primary data collection run. The CCE runs were broken into two parts: a run in the ELTA configuration of Z-2 and a run in the EMU. Subjects performed the same tasks in the ELTA configuration and the EMU so that relative comparisons could be drawn between the two suits. The runs with the ZLTA configuration included some of the CCE tasks, in addition to other tasks that were not evaluated in the CCE run. Ref. 3 and Ref. 4 provides details on these runs.

Table 1. Summary of Z-2 NBL Runs

Run	Date	Test Subject and Suit Configuration	Run Description
1	9/20/16	Engineer #1 (ZLTA)	ZLTA Engineering Run
2	9/27/16	Engineer #1 (ELTA)	ELTA Engineering Run
3	10/07/16	Engineer #2 (ELTA)	ELTA Engineering Run
4	11/14/16	CM1 (ELTA)	ELTA Familiarization Run
5	11/08/16	CM2 (ELTA) & CM2 (EMU)	CCE Run
6	11/18/16	CM1 (ZLTA)	ZLTA Run
7	12/01/16	CM2 (ELTA)	ELTA Familiarization Run
8	1/05/17	CM2 (ELTA) & CM1 (EMU)	CCE Run
9	3/10/17	CM2 (ZLTA)	ZLTA Run
10	1/31/17	CM3 (ELTA)	ELTA Familiarization Run
11	2/07/17	CM3 (ELTA) & CM4 (EMU)	CCE Run
12	2/14/17	CM3 (ZLTA)	ZLTA Run
13	2/23/17	CM4 (ELTA)	ELTA Familiarization Run
14	3/23/17	CM4 (ELTA) & CM5 (EMU)	CCE Run
15	3/30/17	CM5 (ELTA)	ELTA Familiarization Run
16	4/06/17	CM5 (ELTA) & CM1 (EMU)*	CCE Run
17	6/22/17	CM5 (ZLTA) & CM2 (EMU)	xEMU Demo Volume Assessment^
18	9/26/17	CM1 (ELTA & CM6 (EMU)**	xEMU Demo Volume Assessment
19	10/6/17	CM2 (ELTA) & CM5 (EMU)	xEMU Demo Volume Assessment
-	11/21/17	CM3 (EMU)	ABF Motion Capture Task

*CM3 was originally scheduled for Run 16, but she was replaced with CM1 due to schedule constraints
**CM6 filled in for CM3 during this run. Data from CM6 were not considered in this paper.
^Data from xEMU Demo Volume Assessment runs are discussed in Ref 4.

C. Space Suit Descriptions

Two configurations of the Z-2 space suit were evaluated during this test series: the EMU lower torso assembly (ELTA) configuration and the Z-2 lower torso assembly (ZLTA) configuration. (See Figure 1)

1. Z-2 - ELTA Configuration

The ELTA configuration of Z-2 is comprised of the Z-2 HUT and the EMU LTA. Specifically, the ELTA configuration consists of: Z-2 HUT, EMU arms, EMU Phase VI gloves, and EMU LTA. EMU arms were used instead of Z-2 arms because more sizing options are available with EMU arms. Z-2 was not originally designed to connect to an EMU LTA, but an interface adaptor was built to enable this configuration. The ELTA configuration was the primary configuration for this test series. This configuration was exclusively evaluated at 4.0 psid.

2. Z-2 - ZLTA Configuration

The ZLTA configuration of Z-2 is comprised of the Z-2 HUT and the Z-2 LTA. Specifically, the ZLTA configuration consists of: Z-2 HUT, EMU arms, EMU Phase VI gloves, Z-2 waist/brief assembly, EMU legs, and EMU boots. The EMU boots were used instead of the Z-2 boots so that the suit could interface with the articulating portable foot restraint (APFR). The Z-2 boot bearing was not designed to connect to an EMU boot, so an adaptor was built to enable this configuration. As with the EMU arms, the EMU legs were used instead of the Z-2 legs because more sizing options were available. This configuration was evaluated at 4.0 psid and 8.0 psid.

3. EMU

In addition to performing tasks in two configurations of the Z-2 space suit, test subjects also performed tasks in the enhanced EMU space suit. All test subjects evaluated tasks in the planar EMU HUT, and all subjects used a medium-sized EMU HUT. The EMU was exclusively evaluated at 4.0 psid.

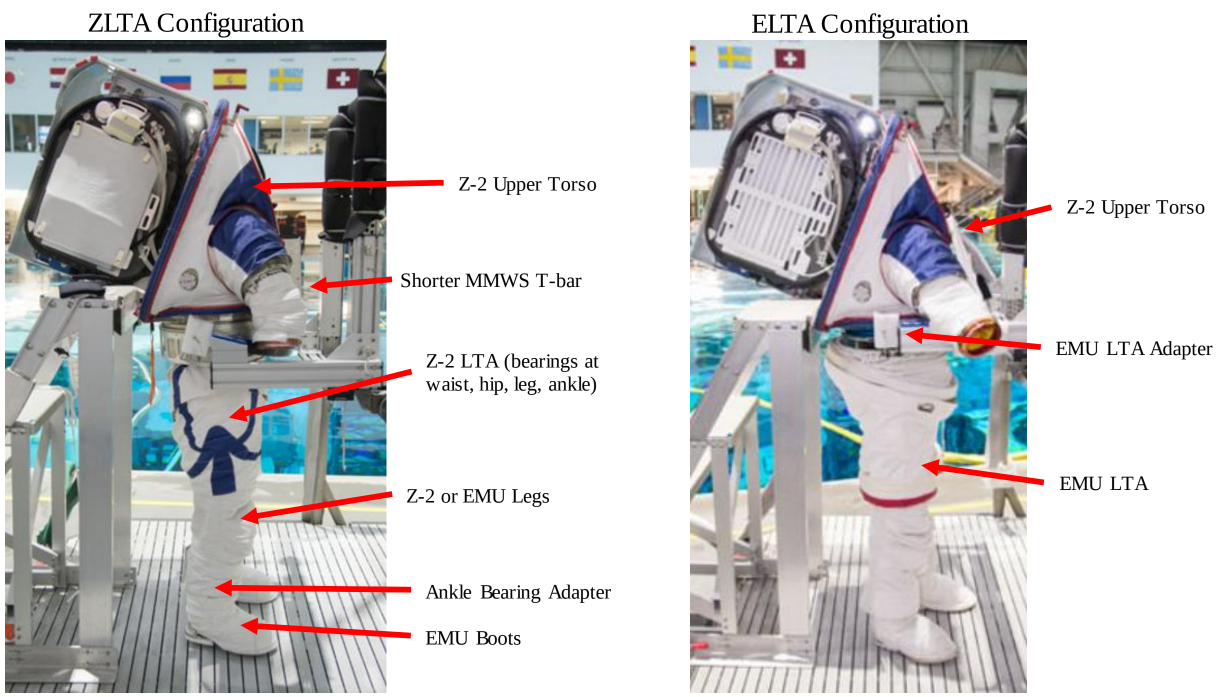

Figure 1. Comparisons of ZLTA and ELTA configurations of Z-2 space suit.

D. Evaluation Metrics – Subjective Data

1. Data Scales

Throughout their runs, test subjects rated acceptability, simulation quality, rate of perceived exertion, discomfort, and muscle fatigue. The specific questions for these ratings are listed below. Descriptions of the scales referenced in this paper are shown below. More detailed descriptions of all of the scales are provided in Ref. 3 and Ref. 4.

- Rate the acceptability of completing the task.
- Rate your perceived exertion while completing the task.
- Rate your muscle fatigue while completing the task.
- Rate the simulation quality of the task and explain the rating.
- Rate discomfort while completing the task.

Table 2. Acceptability Scale

Rating	Description	Value
Totally Acceptable	No improvements necessary	1
Acceptable	Minor improvements desired	2
	Major improvements desired	3
Unacceptable	Minor improvements required	4
	Major improvements required	5

Table 3. Discomfort Scale

Rating	Description
1	No discomfort
2	Low discomfort
3	Moderate discomfort
4	Extreme discomfort

Table 4. Muscle Fatigue Scale

Rating	Description
1	No muscle fatigue
2	Low muscle fatigue
3	Moderate muscle fatigue
4	Extreme muscle fatigue

Table 5. Rate of Perceived Exertion Scale

Rating	Description	Value
No Exertion	You do not feel tired	1
Light Exertion	You feel a little tired, but you can continue this task	2
Moderate Exertion	You feel moderately tired, but you can continue this task	3
Hard Exertion	You feel very tired, and you cannot continue this task without a break	4

2. *Subjective Questions*

In addition to rating scales, test subjects responded to the following questions after performing tasks:

- Was completing this task easier, harder, or the same as completing it in the EMU, and why?
- Was completing this task easier, harder, or the same as completing it in the ZLTA configuration of Z-2, and why?
- Did the suit's field of view affect your ability to complete the task or change how you completed the task?
- Did the suit's shoulder mobility affect your ability to complete the task or change how you completed the task?
- Did the suit's volume affect your ability to complete the task or change how you completed the task?

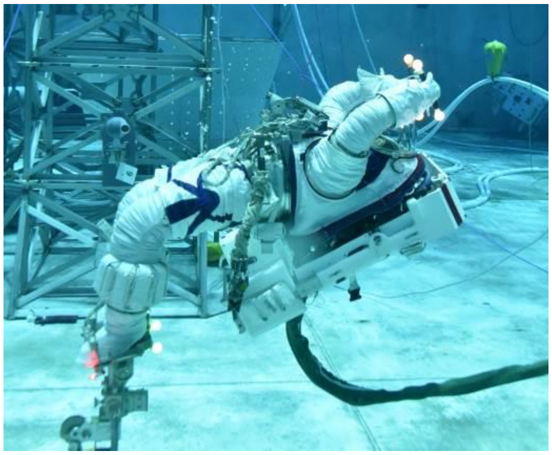

Figure 2. Z-2 subject performing ABF task.

E. Evaluation Metrics – Objective Data

Throughout the test series, subjects provided feedback about the mobility of the Z-2 suit configurations and the EMU so that relative comparisons could be made between the suits. However, subjective data can be difficult to interpret and compare, so the team also sought to obtain objective reach data.

1. Anthropometry and Biomechanics Facility (ABF) Motion Capture Data

The ABF developed a system to capture the reach envelope of the suits in the NBL.[6] The suit was placed in an APFR at the bottom of the NBL. Three underwater cameras were positioned around the suit and the cameras recorded video as the subject performed a series of standardized motions. The subject's motions consisted of arm-isolated vertical/horizontal motions and full-body vertical/horizontal motions. Video from these cameras was post-processed to create a 3-dimensional dynamic model from which a reach envelope was generated. Detailed results from this task are provided in Ref. 6-9.

2. Metabolic Rate

Metabolic rate data were collected for each test subject so that general workload could be compared across suits. The flow rate to the suit and the carbon dioxide (CO_2) output from the suit were measured using the NBL's gas flow system. Metabolic rate was calculated from these data using the Weir equation[5] assuming a constant respiratory exchange ratio of 0.85.

3. Contact Points

Contact points between the space suit and ISS structure and tools were recorded during this test series. During the runs, a team member observed the run from the NBL control room and recorded the severity, location on the suit, and location on the ISS structure for each contact point. The NBL safety divers and test subject also reported observed contact points. Descriptions for the contact points are provided in Ref. 3 and Ref. 4.

III. Test Results

A. Objective 1: Evaluate ability of Z-2 with ELTA to perform microgravity tasks, such as the ISS CCE tasks, relative to the EMU

Subjects evaluated several tasks in simulated microgravity: translations, advanced APFR operations, Flex Hose Rotary Coupler (FHRC) Repair and Replace (R&R), Main Bus Switching Unit (MBSU) R&R, Interface Heat Exchanger (IFHX) R&R, and Airlock ingress/egress. Ref. 3 and Ref. 4 provides detailed descriptions for these tasks. Results for all of these tasks are not discussed in this paper, but the results can be found in Ref. 4. Translations, IFHX R&R, and Airlock Ingress/Egress provided the most interesting data, so only data for these tasks are discussed in this paper.

1. Translation

Subjects generally translated between each task, but the most common long translation path was from the Airlock to the P1 FHRC location (via Rats Nest). Table 6 summarizes the test subjects' responses to questions about task performance, mobility, and field of view. Subjects' comments related to mobility and field of view are also provided below. The ratings for this task in the EMU and Z-2 are provided in Ref. 4. Due to schedule constraints, CM2 did not provide translation ratings for the EMU.

Table 6. Summary of Z-2 test subject responses to questions regarding Translation

Task	**CM1**	**CM2**	**CM3**	**CM4**	**CM5**
Was **completion of this task** [in Z-2 ELTA] easier, harder, or the same as completing it in the EMU?	Easier	Easier	Easier	Easier	Easier
Did Z-2's **shoulder mobility** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	No	Yes	Yes	Yes
Did Z-2's **field of view** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	Yes	Yes	Yes	Yes

Table 7. Ratings for Translation

	Acceptability		Muscle Fatigue		Exertion	
	EMU	Z-2 ELTA	EMU	Z-2 ELTA	EMU	Z-2 ELTA
CM1	2	1	3	1	3	2
CM2	2	1	2	2	3	2
CM3	-	1	-	2	-	2
CM4	1	1	2	2	2	2
CM5	1	1	2	2	2	2

Crew Comments Related to Mobility

- CM1: You can reach far and not have to swing the suit to reach something [in Z-2]. You can move your arm and move it in a normal way. Seems like there is less programming.

- CM3: Able to take a different/more efficient route [in Z-2]; I have better reach [can reach things she normally cannot reach in EMU]. I could reach farther with less effort. It is easier to re-orient body because I can get a wider grip.
- CM5: You can abduct your shoulders better in Z-2 as compared to the EMU. I can translate with an arm in front and behind me [in Z-2], as opposed to side-side-side [EMU]. Overhead translation is easier in Z-2 because overhead reach is much easier in Z-2 than the EMU.

Crew Comments Related to Field of View

- CM1: Field of view is what I like the most [in Z-2]. There's a perception that you can move your head around in the EMU a lot. You can't in the EMU. In Z-2 you can, and it saves so much time and effort to be able to look around and see what's around you and what's ahead of you.
- CM3: The suit's [Z-2] field of view made it easier to translate in Z-2 because it was easier to see where I am going and to identify hazards [didn't have to count on memory alone].

Discussion of Data

All subjects said that translation was acceptable in Z-2 and that no improvements were necessary. Most subjects provided similar muscle fatigue and exertion ratings for the EMU and Z-2. Subjects consistently commented that it was easier to translate in Z-2 than the EMU because Z-2 had improved shoulder/arm mobility and/or because Z-2 had improved field of view over the EMU.

All subjects said that Z-2's field of view was better than the EMU and this was due to two factors: 1) A greater ability to move their head inside the helmet and 2) Z-2's larger helmet bubble. Three subjects said that improvement in overhead visibility was the most noticeable improvement in field of view. Subjects generally said that the geometry of the helmet bubble contributed to improved longitudinal visibility, while improvements in lateral field of view were caused by the subject's ability to move their head inside the helmet, not necessarily the helmet geometry. Some subjects said that improved visibility led to improved situational awareness during translation and during plane changes, particularly in areas where subjects have to anticipate structure, like around the Airlock and under the mobile transporter. Additionally, some subjects said that they could see their translation path easier without stopping and repositioning, which is something that they have to do in the EMU. Subjects said that this reduced the physical and mental fatigue associated with translating. Subjects said that these factors made it faster and more efficient to translate in Z-2. Although the increased helmet bubble size improved field of view and situational awareness, several subjects commented that they had an increased number of contacts between the helmet bubble and ISS structure. These subjects had to actively try to avoid making helmet bubble contacts, which increased the mental fatigue associated with translating.

It is important to note that Z-2 did not include an Extravehicular Visor Assembly (EVVA) during this test series, and this likely contributed to test subjects' positive feedback regarding field of view. However, feedback from subjects during this test series will be incorporated into the design of a future EVVA. Future EVVA development will attempt to maintain the field of view benefits identified during this test series. Visor mockups were evaluated during a few runs from this test series to inform the design of a visor design that is compatible with the Z-2 architecture. Results from these evaluations are discussed in Ref. 4.

2. IFHX R&R

Subjects performed IFHX R&R tasks at the zenith and nadir sides of the IFHX worksite. Subjects reported that the tasks at the nadir side were more difficult than the tasks at the zenith side because the nadir side had a smaller workspace. In the interest of brevity, only results related to the nadir side are presented in this paper.

Table 8. Summary of Z-2 test subject responses to questions regarding IFHX R&R (nadir side)

Task	CM1	CM2	CM3	CM4	CM5
Was **completion of this task** [in Z-2 ELTA] easier, harder, or the same as completing it in the EMU?	Easier	Same	n/a	Harder	Same
Did Z-2's **shoulder mobility** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	Yes	Yes	No	No
Did Z-2's **field of view** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	No	n/a	No	Yes
Did Z-2's **volume** affect [hurt] your ability to complete the task or change [negatively] how you completed the task compared to the EMU?	Yes	Yes	Yes	Yes	Yes

Table 9. Ratings for IFHX R&R for EMU and Z-2 ELTA (nadir side)

	Acceptability		Muscle Fatigue	
	EMU	Z-2 ELTA	EMU	Z-2 ELTA
CM1	2	3	3	3
CM2	3	3	3	4
CM3	-	3	-	2
CM4	3	4	2	1
CM5	1	1	2	1

Crew Comments Related to Mobility

- CM1: You can move arms in small space easily [in Z-2]. There is more room at the worksite with the EMU, but the mobility of the hands with Z-2 is very helpful.
- CM3: I am able to reach more things due to shoulder mobility and come at things from a different angle that may not have been an option in the EMU.

Crew Comments Related to Volume

- CM2: Suit [Z-2] bubble volume created contacts. Mobility helps, but volume hurts.
- CM4: The PLSS volume made it more difficult to complete the task [in Z-2].

Discussion of Data

All subjects, except for CM4, said that it was acceptable to perform the IFHX R&R task in Z-2 and the EMU at the nadir side. CM4 said that it was unacceptable to perform this task in Z-2 (rating of "4"), while he gave a borderline acceptable rating (rating of "3") for the EMU. CM4 gave an unacceptable rating for Z-2 because the increased volume of Z-2 wedged him into the worksite and he did not think that he would have enough space in the worksite to configure everything by himself. There was mixed feedback from subjects related to exertion; some subjects provided higher exertion ratings for the EMU and other subjects provided higher ratings for Z-2. Subjects reported that exertion at this worksite was primarily due to volume constraints.

3. Airlock Ingress/Egress

Test subjects evaluated Airlock ingress/egress as EV1 and EV2 in both the EMU and Z-2 suits. Z-2 subjects said that completing this task as EV1 was more difficult than completing the task as EV2. In the interest of brevity, data are shown only for ingress/egress with Z-2 as EV1. Ref. 4 provides results related to ingress/egress with Z-2 as EV2.

Table 10. Summary of Z-2 test subject responses to questions regarding Airlock Ingress/Egress as EV1

Task	CM1	CM2	CM3	CM4	CM5
Was **completion of this task** [in Z-2 ELTA] easier, harder, or the same as completing it in the EMU?	Harder	Harder	Harder	Harder	Harder
Did Z-2's **shoulder mobility** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	Yes	No	No	No
Did Z-2's **field of view** affect [help] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	Yes	No	No	No
Did Z-2's **volume** affect [hurt] your ability to complete the task or change how you completed the task compared to the EMU?	Yes	Yes	Yes	Yes	Yes

Table 11. Ratings for Airlock ingress/egress for suits as EV1

	Acceptability		Discomfort		Exertion	
	EMU	Z-2 ELTA	EMU	Z-2 ELTA	EMU	Z-2 ELTA
CM1	2	2	2	2	2	3
CM2	1	3	2	2	2	3
CM3	-	2	-	1	-	2
CM4	2	3	2	2	2	2
CM5	1	3	2	2	2	2

Crew Comments Related to Mobility

- CM2: Shoulder mobility helps to compensate for some volume constraints (overhead reach for hatch ops and reaching under you, as well).
- CM3: I have more arm mobility [in Z-2] which helps, but it is kind of canceled out by the position you are in, which is at the limit of the arm mobility, to get vertical and perform the task.

Crew Comments Related to Field of View

- CM1: Increased Z-2 visibility helps, but volume still challenging.
- CM3: Z-2's field of view may have helped [ingress/egress], but helmet volume is large

Discussion of Data

All test subjects could ingress/egress the Airlock with Z-2 as EV1 and the EMU as EV2 without diver support. All subjects rated this task as acceptable for Z-2 and the EMU, and both suits could simultaneously fit inside the Airlock. Once inside the Airlock, all Z-2 subjects could reach the hatch keeper, and all EMU subjects could reach the manual isolation valve and UIA panel. All subjects said that it was harder to perform EV1 ingress/egress in Z-2 as compared to the EMU. All subjects said difficulties in ingressing/egressing the Airlock in Z-2 were due to the increased depth of the Z-2/PLSS system as compared to the EMU. Some subjects also said that Z-2's larger helmet bubble made it more difficult to access the hatch and manual isolation valve. Several subjects commented that additional training may address some of the challenges associated with Airlock ingress/egress.

4. Fatigue and Soreness

During and after the Z-2 NBL runs, subjective and objective data were collected from test subjects regarding mental/physical fatigue and soreness. These data are shown below. Subjects compared their Z-2 NBL runs to their EMU CCE run and to their general experiences in the EMU in the NBL. It is important to note that the subjects' general EMU NBL runs are more difficult than the Z-2 runs performed in this test series. The Z-2 NBL runs had several breaks during which subjects provided feedback on suit performance, while normal EMU NBL runs do not have these breaks.

Mental Fatigue – Subjective Data

Crew comments related to mental fatigue are provided below.

- CM2: Mental fatigue was less [in Z-2] because of field of view; I could relax and just translate. Definitely the frustration level is a little less.
- CM3: You can't over-estimate the value of no comm. cap [in Z-2]. I'm more comfortable which makes everything seem easier. You normally spend a lot of time fighting your mic booms [in the EMU].
- CM4: Z-2 is less mentally fatiguing than the EMU because arm mobility is more natural in Z-2.

Soreness – Subjective Data

Crew comments related to physical fatigue are provided below.

- CM1: My hands don't hurt [in Z-2]. Usually my hands are sensitive and in pain at the end of the 6 hour run. My left trapezius muscle is pretty sore [from Z-2 run]. It usually isn't after my EMU runs. However, most of my body is usually pretty sore after EMU and it isn't now.
- CM3: My shoulders are usually a lot more tired in the EMU. My neck is usually very sore in the EMU. The back of my head is usually sore as well. I have none of that in the Z-2.
- CM4: Ease of don may be especially helpful, especially at the beginning of run [shoulders not traumatized and ready to work]. I'll probably have bruises on my ribs from the Z-2. I definitely don't have any soreness or pressure on my shoulder with these shoulder harness.

Physical Fatigue – Subjective Data

Crew comments related to physical fatigue are provided below.

- CM1: It is less work to do the same tasks [in Z-2] than in the EMU. In the EMU, it seems like keeping your arms straight out in front of you is tiring. In Z-2, it was more comfortable to work up higher up, straight in front of you.
- CM2: Physical exertion was about the same [in Z-2 as compared to EMU].
- CM4: I think this test was a little below average on intensity overall, but I had spurts where I was working as hard as ever. I felt less fatigued at the end of the run as compared to my [CCE] run in the EMU. I felt really tired at the end of my EMU CCE run. Lots of little fatiguing things add up in the EMU to make things generally more fatiguing. Examples are: shoulder mobility is more natural in Z-2, my back is more comfortable in Z-2, it is easier to access dead space in Z-2, indexing in the gloves is better in Z-2, and ability to look around in the helmet is better in Z-2. With respect to mobility, there are dead spaces in the EMU that are hard to get to or hard to reach. Z-2 eliminates some of these dead spaces, making it easier to reach. All of these little things add up to make it less fatiguing to use Z-2.
- CM5: Raising your shoulders takes effort in the EMU, but it takes very little effort in Z-2.

Physical Fatigue – Objective Data

In addition to subjective feedback related to workload, metabolic rate data were collected during each run in the Z-2 and EMU suits. The metabolic rate data showed no consistent differences between the two suits when comparing individual task workload and average workload over the entire run. A more detailed set of results is presented in Ref. 4.

Discussion of Data

Subjects generally said that they had less overall mental fatigue in Z-2 than the EMU. Subjects said that increased field of view reduced their mental workload because it was easier to maintain situational awareness. Some subjects also said that the Z-2's shoulder programming felt more natural than the EMU. However, subjects said that the increased size of the Z-2 helmet bubble and the suit/PLSS system increased their mental fatigue because they had to actively avoid contacting the suit while performing certain tasks. Except for CM2, all test subjects commented that they felt overall less physical fatigue in Z-2 or they used less effort in Z-2 to perform the same tasks in the EMU. Subjects said that small improvements in shoulder mobility, the use of an integrated communication system, and increased field of view reduced the physical workload of Z-2. Subjects consistently commented that they felt less sore after their Z-2 run than their EMU run. Specifically, subjects said their hands and shoulders felt less fatigued in Z-2. This was likely due to the perceived higher mobility features of the Z-2 shoulder joints as compared to the EMU.

The metabolic rate data did not show any clear differences in workload between the Z-2 and EMU. This may have been because energy differences were small or because the test series was not set up in a way to reliably infer metabolic rate differences. A controlled methodology was not used to ensure that subjects completed tasks in the same way or without breaks. Other limitations included: some tasks were too short for subjects to develop a steadystate metabolic rate, the task start/stop times were not consistently recorded because data takers interpreted the task start/stop times differently, some subjects did not complete certain tasks due to scheduling constraints, subjects were not as familiar with performing tasks in Z-2 so they may have performed tasks more metabolically efficient in the EMU, and subjects sometimes repeated a task multiple times in one suit but not the other suit.

5. ABF Motion Capture – Reach Envelopes for Z-2 ELTA and EMU

Arm-Isolated Reach Envelope Data

As discussed in Section II of this paper, the ABF measured the reach envelopes of both suits while the suits were affixed in an APFR in the NBL. Figure 3 shows a subject-averaged parametric plot of the arm-isolated motion capture data (top, rear, and side views). Table 12 shows the differences in total cross-reach for the subjects in Z-2 and the EMU.

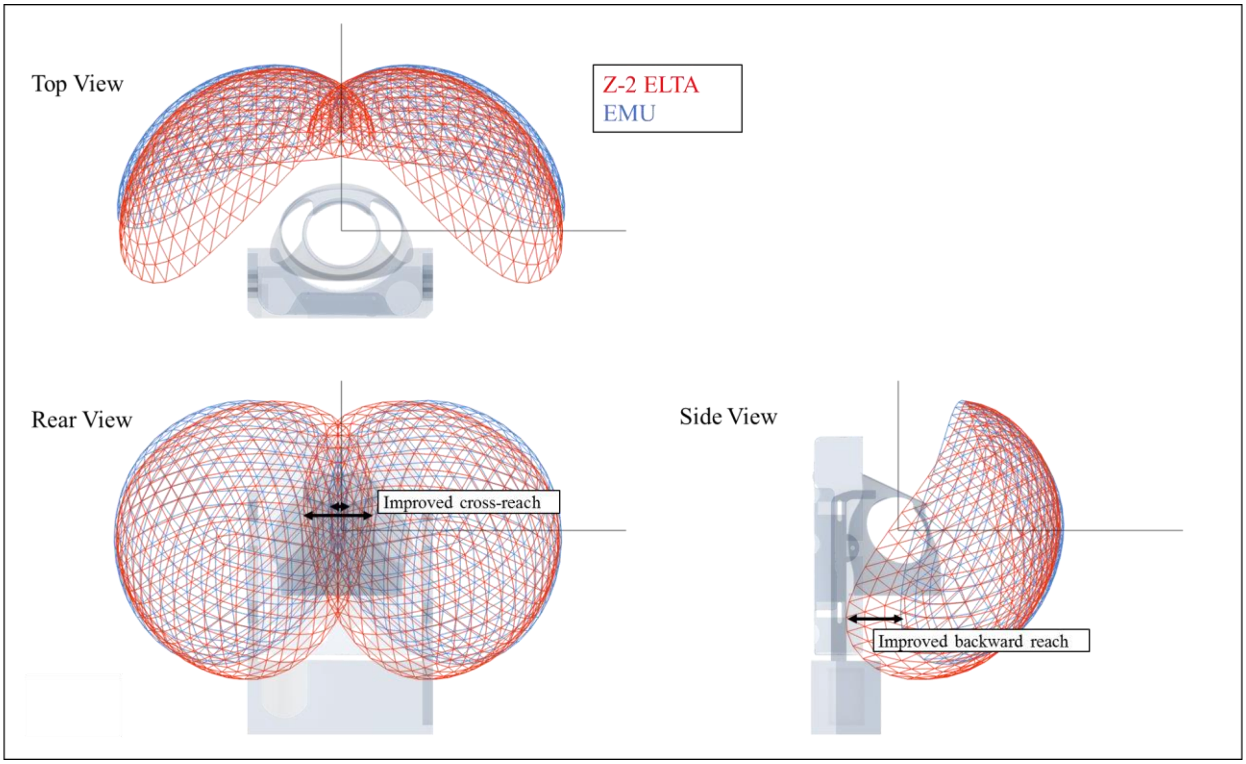

Figure 3. Arm-Isolated Reach Parametric Data for EMU and Z-2 ELTA – Subject Average

Table 12. Total Arm-Isolated Cross-Reach Distance for Z-2 ELTA and EMU

Subject	Z-2 ELTA	EMU	Increase in Cross-Reach
CM1	23.1 cm	7.8 cm	196%
CM2	29.1 cm	12.3 cm	137%
CM3	21.1 cm	11.4 cm	85%
CM4	23.0 cm	-3.7 cm	Enabling
CM5	23.4 cm	11.0 cm	112%

Discussion of Data

Figure 3 and Table 12 support the feedback from subjects that Z-2 provides increased cross-reach. This is likely because Z-2 has an increased scye horizontal angle, relative to the EMU, and a smaller front inter-scye spacing and DCU[3]. Table 12 shows that CM4 did not have cross-reach in the EMU, but Z-2 enabled cross-reach. Improved cross-reach enhances a subject's ability to use both hands when handling tools or interacting with a worksite, which was noted by several subjects. Figure 3 also shows that Z-2 provided increased backward reach, relative to the

EMU. This was unexpected because the Z-2's increased scye horizontal angle biases the arms forward. The increased backward reach is likely because subject's shoulders were better indexed in Z-2 than in the EMU. Increased mobility from the Z-2 rolling convolute shoulder joints could have also contributed to improved backward reach in Z-2.

B. Objective 2: Evaluate EMU tools with Z-2 suit (ELTA and ZLTA)

Various tools were evaluated with both configurations of the Z-2 suit: Modular Mini Workstation (MMWS), Pistol Grip Tool (PGT), right-angle PGT drive, Body Restraint Tether (BRT), retractable equipment tether, trash bag, nominal T-bar, short T-bar (built for Z-2 ZLTA testing), local tether, safety tether, APFR with ingress aid, wire ties, round scoop, ratchet wrench, Quick Disconnect (QD) bail drive lever, and QD release tool.

Subjects performed a variety of tasks to evaluate the tools. During the ELTA familiarization run, subjects evaluated the tools at the Z1 Toolbox and they performed an RPCM R&R. Subjects also evaluated tools during the CCE tasks. Subjects evaluated tools in both configurations of the Z-2 suit.

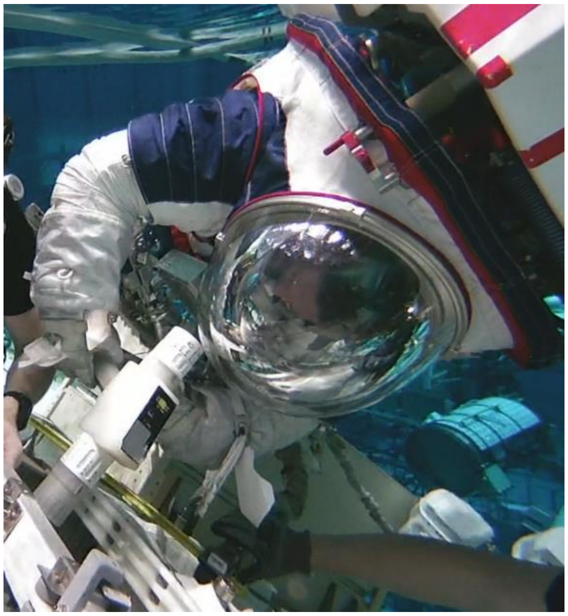

Figure 4. Z-2 Helmet bubble interference with PGT.

1. Subjective Data

Subjects provided general comments on the acceptability and usability of the tools in comparison to the EMU. Comments related to tool use with Z-2 ELTA are provided below.

- CM1: Tools are entirely compatible with Z-2. Tools were really easy to see and easy to reach. I can see the joints at the connection to the MMWS. Visibility gave me the ability to see and push the joints the way I wanted to.
- CM2: BRT affected [hurt] Airlock ingress more because of suit volume [in Z-2]. You could see the BRT better. Transitioning hardware between hands is easier. I can see the adjustment knobs on the BRT. There's no way I can see them in the EMU.
- CM3: Z-2 enables me to get two hands on the PGT in a larger work envelope, which is a big challenge for me. PGT is now hitting my visor [in Z-2]. Easier to get PGT out. I can do a PGT swap using the swing arm and it's easier than a socket swap on the EMU. I can see the front tether points on the dual tether point. I don't normally use them, but I might now because it seems easy. I can reach across MMWS easily.
- CM4: There were a few times when my visor interfered with tools when I was on my back [in Z-2]. The visor is a bigger target. The visor took up space in my workspace, so this made the right-angle drive hard to use. APFR setup was a lot harder because of the increased visor mockup depth. In the EMU, the MMWS is the first thing to interfere with APFR setup. The Z-2 visor is a problem with performing routine tasks, not just hard ones. There are a lot of thing I do by feel - things when it comes to PGT, BRT joints, or anything else down low, because you can't see it. With Z-2, you can just look down and see what's going on. I can see the extremes down lower on the work station. I can use both hands to assist on activities.
- CM5: No issues with the tools that I evaluated. I thought there would be interference problems between tools and the visor, but I didn't have any issues. It was easier to use the BRT in Z-2 than in the EMU due to better reach and access in Z-2. Better downward visibility. I feel like I have a better view behind the MMWS (trash bag, etc.).

2. Discussion of Data

All test subjects said that the tools were compatible with the tasks that they evaluated during this test series, in both configurations of Z-2. Additionally, subjects did not identify any significant interface problems between the suit and the tools. In both configurations of Z-2, subjects said that they had better visibility of the tools that were located on the MMWS; this helped them reach and access the tools. Subjects said that this contrasts with the EMU, where they have limited visibility of their tools - subjects sometimes have to rely on “feel” to access tools on the MMWS while in the EMU. All subjects said that it was easier to use the BRT in Z-2 because they had better visibility of the tool; this made it easier to manipulate and stow the BRT. Several subjects commented on interferences between the tools and Z-2 helmet bubble, due to the increased size of the Z-2 helmet bubble, relative to the EMU bubble. In particular, subjects said that APFR setup was more difficult due to inadvertent contact between the APFR and the helmet bubble. Some subjects also had difficulties using the PGT with the right angle drive at tight worksites, like the IFHX.

C. Objective 3: Evaluate Z-2 with advanced PLSS package volume (PLSS 2.5) for use on ISS

During each run, test subjects provided feedback on if the volume of the Z-2/PLSS system affected their ability to perform tasks. The advanced suit and PLSS development teams did not optimize the shape of the Z-2/PLSS system prior to this test. However, data from this test will inform how much volume optimization is required.

1. Subjective Data

Table 13 summarizes the subjects’ responses to the question of if the Z-2 system volume affects (hurts) their ability to complete a task.

Table 13. Summary of Z-2 test subject responses to the question: “Did Z-2’s <u>volume</u> affect [hurt] your ability to complete the task or change [negatively] how you completed the task compared to the EMU?”

Task	CM1	CM2	CM3	CM4	CM5
Airlock Ingress/Egress with Z-2 as EV2	Yes	Yes	Yes	Yes	Yes
Airlock Ingress/Egress with Z-2 as EV1	Yes	Yes	Yes	Yes	Yes
FHRC R&R (zenith side)	Yes	Yes	Yes	No	Yes
MBSU R&R	-	-	-	-	-
Advanced APFR Operations	-	-	-	-	-
IFHX R&R (zenith)	No	Yes	Yes	Yes	Yes
IFHX R&R (nadir)	Yes	Yes	Yes	Yes	Yes
Translations	-	-	-	-	-

Below are a few subjects’ comments related to how the Z-2/PLSS system volume affected task performance.

- CM2: I couldn't get close enough [to FHRC worksite] because of the PLSS. Didn't seem like helmet was in the way.
- CM3: Visibility is great, but that visor sticks out really far. I have a hard time reaching past that visor.
- CM4: The visor depth and PLSS/suit system volume should be reduced [for Z-2]. Volume is a problem at the Airlock. The SAFER [Simplified Aid for Extravehicular Activity Rescue] seems to be the biggest problem. It [Airlock ingress/egress] felt much more EMU-like when we removed the SAFER. APFR setup was a lot harder because of the increased visor mockup depth.
- CM5: Mentally fatiguing in tight spots due to volume constraints [for Z-2].

2. Contact Points

One metric for assessing volumetric differences between Z-2 and the EMU is the number of unintended contacts that the suits make with ISS mockups and tools during subjects’ runs. Figure 5 shows the contact points for Z-2 ELTA and the EMU during the CCE runs.

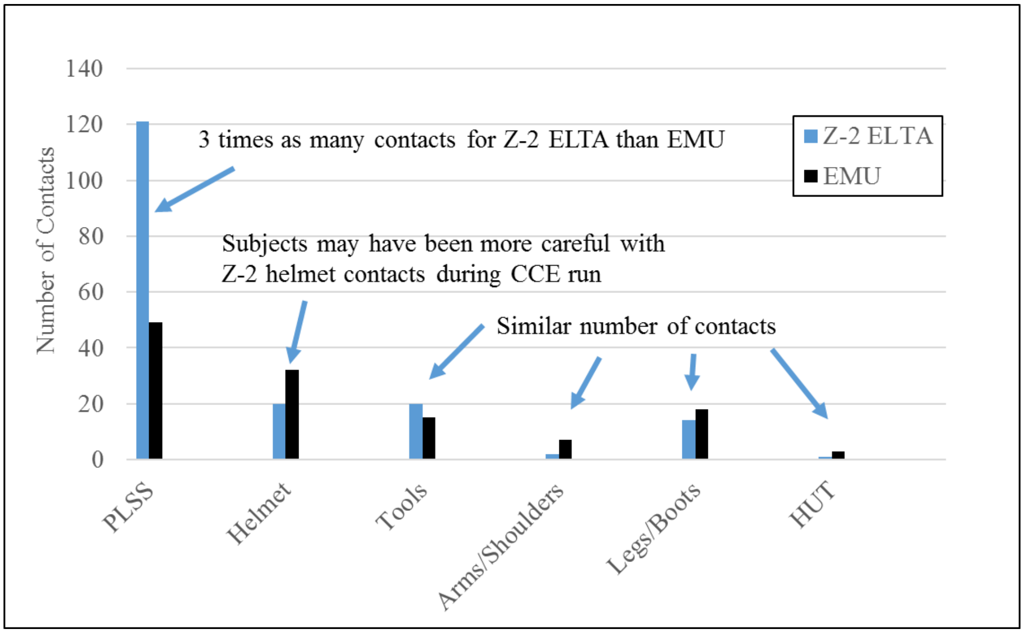

Figure 5. Contact points for Z-2 ELTA and EMU during CCE runs. Excludes CM3 data because she did not complete CCE run in EMU.

3. Discussion of Data

Except for CM4 at the nadir side of the IFHX and CM1 at the zenith side of the FHRC, all Z-2 subjects were able to acceptably complete the tasks evaluated in this test series. Although subjects were able to complete most tasks in Z-2, subjects consistently said that it was easier to perform tasks in the EMU at worksites where volume was restricted. These worksites included the Airlock, IHFX, and FHRC. At these worksites, subjects said that the front-to-back depth of the suit/PLSS system and the outward depth of the Z-2 helmet bubble were the primary volume issues.

Regarding contact points, Figure 5 shows that test subjects had about twice as many total contacts in the ELTA configuration of Z-2 than the EMU during the CCE runs. Subjects had a similar number of contacts for the helmet, tools, arms/shoulders, legs/boots, and HUT. For the PLSS, however, subjects had about twice as many contacts in Z-2 as compared to the EMU. Subjects consistently commented on difficulties performing tasks due to the front-to-back depth of the suit/PLSS system, and this is supported by the increased number of contacts on the PLSS. Although subjects consistently commented on interference with the Z-2 helmet, Z-2 did not appear to have more inadvertent contacts with the helmet than the EMU. This could have been because the subjects were more careful with the Z-2 helmet. It is important to note that experience in a suit can play a large role in reducing the number of unintended contacts. Subjects in this test series had significantly more experience in the EMU than Z-2, so this may have contributed to more contacts in Z-2.

D. Objective 4: Evaluate suit usability with subjects who span size range of Z-2

1. Task Acceptability Data

The subjects in this test series spanned the size range of Z-2. Subjects rated most tasks in this test series as acceptable for Z-2 and the EMU. Z-2's increased system volume was the reason that some subjects rated some tasks as "unacceptable" in Z-2. In addition, the discomfort and muscle fatigue ratings were consistent across the test subjects.

2. Weigh-out Data

All test subjects reported acceptable weigh-outs in both configurations of Z-2. CM1 and CM3, who were the female test subjects and had smaller torsos than the other subjects, provided more positive comments on their weigh-outs in Z-2 (as compared to the EMU) than the other test. This was likely because the smaller subjects were better indexed in Z-2 than the EMU; moving around inside an EMU during an NBL run can cause the weigh-out to change.

Some comments from CM1 and CM3 related to weigh-out are provided below.

- CM1: Weigh-out seemed really good [in Z-2]. But it was a little different because I was so well indexed in the suit.
- CM3: Weigh-out was solid [in Z-2]. In the EMU, I move around so much that my weigh-out is terrible. They [divers] are always trying to fix it. It was rock solid in the Z-2 today. I didn't even have hip pads today and I normally do in the EMU. Feels like the Z-2 weigh out stays better through more orientations.

3. ABF Motion Capture Data – Comparison of Subject Mobility

Table 12 in Section III, A, 5 shows the arm-isolated cross-reach data for the subjects in the Z-2 ELTA and EMU. Table 14 in Section III, E, 5 shows the whole-body cross-reach for the subjects in each suit. There are no consistent differences in mobility improvements for large vs. small subjects between the ELTA and EMU; all subjects consistently exhibited greater range of motion (arm-isolated and full-body reach) in ELTA as compared to the EMU. Table 14 shows that both of the smaller subjects (CM1, CM3) had a greater improvement in mobility in the ZLTA as compared to the EMU than the other subjects. However, it is unclear if this is the result of subject size variations; other inconsistencies highlighted in the motion capture data were likely caused by day-to-day variations, differences in weigh-out, or other factors.

4. Fit Data

All test subjects reported the fit as acceptable in both configurations of Z-2. The highest (worst) reported discomfort rating in Z-2 was "2" (low discomfort). CM1 and CM3 provided more positive comments related to the fit of the Z-2 suit as compared to the EMU. The larger subjects (CM2, CM4, and CM5) provided more negative comments about discomfort between the scye carrier ring and the chest. Comments from subjects related to fit are provided below.

- CM1: I like that my hands indexed in my gloves throughout the entire run [in Z-2]. My hands don't hurt at the end of runs. During IFHX R&R: In the EMU, my hands are coming out of the gloves. I never had a problem with my hands coming out of the gloves during my Z-2 run.
- CM3: My fingers were indexed in the gloves and have good visibility in the relaxed position. Hands - In the EMU, I think I jam my hands in the gloves a lot to try and reach farther. Seemed like I could reposition and get to where I want easier. My hands didn't seem to come out much, but I wasn't on my back much. It felt a lot easier to move my arms [in Z-2]. Rotations felt easier. Plane changes were a lot easier.
- CM4: I have discomfort due to bearings on my chest wall.
- CM5: In regards to mental fatigue, the only mentally fatiguing things about Z-2 was the chest discomfort. Chest padding should be addressed.

5. Volume Data

Subjective Data

CM1 and CM3 provided more negative comments about the size of the Z-2 helmet bubble than the other subjects. CM1 and CM3 had smaller vertical trunk diameters (VTDs) and chest depths than the other subjects and this may have prevented them from being fully indexed forward in the suit. CM3 also had shorter arms than the other subjects, so this could have impeded her ability to reach past the helmet bubble when performing tasks in her work envelope. Some comments from test subjects are provided below:

- CM1: Bubble sticks out farther than is useful. Decrease bubble size, you don't use it.
- CM3: Visibility is great, but that visor sticks out really far [in Z-2]. I have a hard time reaching past that visor. I had tools resting on the visor. PLSS volume - Only time it bothered me was at the Airlock. I bumped it once or twice in a few other areas, but it didn't really seem to impede me. If having to work slightly overhead, that area is not usable (ratchet hit helmet)

E. Objective 5: Evaluate added performance from highly mobile LTA (ZLTA)

Four of the five test subjects in this test series (CM1, CM2, CM3, and CM5) evaluated the ZLTA configuration of Z-2 in the NBL. General comments from subjects during the ZLTA runs are provided below.

- CM1: Weigh-out: As good as it is going to get with the suit [ZLTA]. Suit [ZLTA] moves [more than ELTA], so it makes the weigh-out hard, but mobility allows you to compensate.

- CM2: The primary benefit of the mobile lower torso in the ZLTA configuration of Z-2 was ease of ingress/egress of the APFR. The ZLTA waist also provided better visibility when I was in an APFR because I could rotate my waist more than in the EMU or Z-2 ELTA.
- CM3: The primary benefits of improved mobility in the lower torso were:
  - Improved mobility made it easier to ingress/egress the APFR.
  - Improved mobility made translation feel more natural by enabling me to use my legs.
  - Improved mobility enabled me to crouch down in worksites where reach is a challenge (ex: MBSU bolt removal).
  - The mobile lower torso did not make me feel unstable over the course of the run.

1. Advanced APFR Operations

All subjects who evaluated Z-2 ZLTA could ingress/egress the APFR in free space at the U.S. Lab with a local tether and with an ingress aid. All subjects reported that it was easier to ingress/egress the APFR in ZLTA, as compared to the ELTA configuration of Z-2 and the EMU. All subjects rated the acceptability of performing this task as “1”. Subjects said that the ankle bearing was the primary benefit of the ZLTA regarding APFR ingress/egress; the ankle bearing helped subjects rotate their heels, which improved ingress/egress. Comments related to APFR operations are provided below.

- CM1: Ability to take advantage of the flexibility of the legs [is benefit over ELTA]. Also lets you take advantage of the visibility. Bearings allow mobility to be effortless (ankle and hips), some aiming is still required. So, even if you miss you can do it two times and not feel like you’re making it hard.
- CM2: It takes an intentional action to remove my heel from the APFR. I don’t think the extra mobility in the ankle would cause my feet to inadvertently come out of the APFR. I didn’t notice the mobility of the hips. The added benefit is primarily the mobility of the ankle.
- CM3: That was awesome [in ZLTA]. That was way too easy. I usually hate APFRs. Overall it is easier because I can look. I have so much control over my legs. I can move knee, hips, foot. It is really easy to rotate my heels.
- CM5: Your visibility is better and you can bend your knees. You can step up onto the APFR like a step. The ankle bearing helps.

2. Translations

Comments related to translation in the Z-2 ZLTA are provided below.

- CM1: As compared to ELTA, nominal translation is about the same in ZLTA. But being able to move legs to get over a tether or objects makes getting around obstacles is easier. I don't have to move my whole body just to move legs.
- CM2: The added mobility in the LTA did not change my ability translate, although it is more comfortable to be able to move my legs. The added LTA mobility does not hurt you when translating, but it also does not help that much.
- CM3: I could move my legs easier in ZLTA during translation and this made it easier to get untangled from a tether or structure. In general, I did not use the LTA mobility when translating, although I did use the LTA mobility during plane changes.
- CM5: I feel like a rock climber when I have to translate over objects. I can “scramble” over objects.

3. ABF Motion Capture Data – Reach Envelopes for Z-2 ZLTA

Figure 6 shows the average parametric surfaces of the raw motion capture data for all three suits for CM1, CM2, CM3, and CM5. Data were generated for the left and right hands, but only the right hand data are shown for clarity. Figure 6 and Table 14 show that ZLTA provides better whole-body cross-reach than the EMU or ELTA. All subjects had a significant increase in whole-body cross-reach in ZLTA. It is important to note that the APFR limited the downward reach of the suits because the APFR did not allow the legs to move. For example, a subject in ZLTA can bend down and touch their toes in 1-g, but this range of motion is not shown in Figure 6.

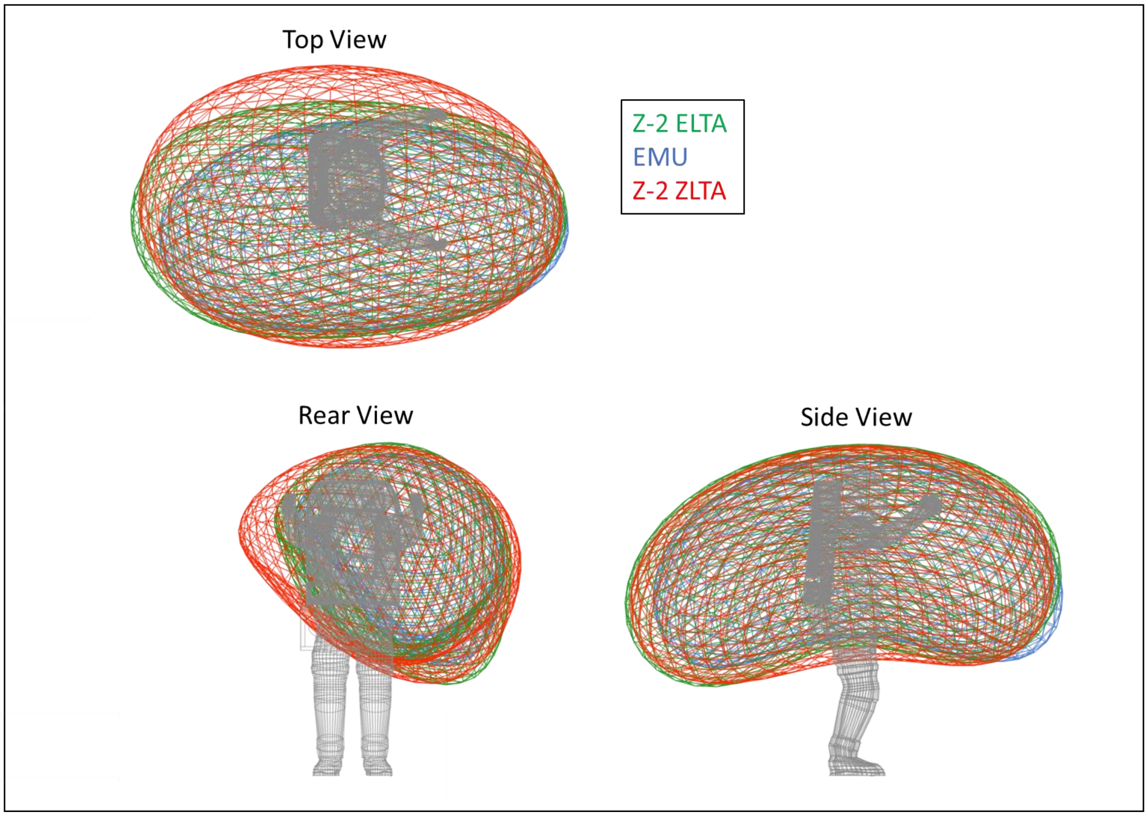

Figure 6. Full body reach envelope parametric data for Z-2 ZLTA, Z-2 ELTA, and EMU. (Right hand only)

Table 14. Whole-body cross-reach distance for all suits

Subject	Z-2 ZLTA [cm]	Z-2 ELTA [cm]	EMU [cm]	Increase Relative to ELTA	Increase Relative to EMU
CM1	148	78.2	56.3	89%	163%
CM2	140.	91.3	66.0	53%	112%
CM3	124	62.7	48.3	98%	157%
CM5	138	81.2	73.9	70%	87%
Average	137	78.4	67.2	77%	104%

F. Objective 6: Evaluate performance of Z-2 suit with highly mobile LTA (ZLTA) at 8.0 psid

CM1 and CM2 performed tasks in Z-2 ZLTA at 4.0 psid and 8.0 psid. The subjects spent the first two hours of the NBL run pressurized at 8.0 psid and the last four hours of the run at 4.0 psid.

1. *Subjective Data*

Comments from subjects during the 8.0 psid tasks are provided below.

- CM1: The gloves [at 8.0 psid] feel like space when the gloves are pressurized to 4.3 psid. I think the 8.0 psid gloves would be harder in space. Hands are okay, but would not want to do this task for a long time. Even at 8.0 psid, I still have cross-reach, so worksite set up [APFR settings] could still be done well.
- CM2: 8.0 psid did not hurt my ability to perform tasks as compared to 4.0 psid. It would probably be acceptable to do tasks for a couple of hours at the beginning of an EVA at 8.0 psid. I had a hard time telling that the suit was pressurized to 8.0 psid. The gloves were a little stiff, but the gloves are normally stiff at 4.0

psid, so I am not sure that the gloves feel any different. I am pleasantly surprised by how little of an impact 8.0 psid is.

2. Discussion of Data

Both subjects acceptably completed all tasks at 4.0 psid and 8.0 psid. However, subjects provided increased (worse) acceptability and muscle fatigue ratings at 8.0 psid because of increased glove stiffness at 8.0 psid as compared to 4.0 psid. Subjects said that the higher pressure in the gloves made hand-intensive tasks more difficult to perform. Specifically, it was harder for subjects to move their fingers in the gloves, and their forearms were more fatigued when doing tasks. CM1 also said that the Z-2 arms had more of a tendency to straighten out at 8.0 psid as compared to 4.0 psid, and this contributed to differences in ratings for acceptability and muscle fatigue.

IV. Discussion

A. Favorable Feedback on Z-2

1. Mobility

All of the test subjects said that Z-2 provided better upper torso mobility than the EMU, for the tasks that were evaluated in this test series. Specifically, subjects said that Z-2 provided improved cross-reach and improved access in the lower portion of work envelope. This feedback was supported by the ABF motion capture data. Improved cross-reach enabled subjects to handle tools more easily and make better use of both hands at worksites, which could improve task efficiency.

2. Field of View

All subjects in this test series said that that Z-2's field of view was better than the EMU and this improved subjects' abilities to perform tasks. Specifically, subjects said that Z-2 provided better overhead visibility, better lateral visibility, and better longitudinal visibility. Test subjects said improved field of view this was due to two factors: 1) A greater ability to move their head inside the helmet and 2) Z-2's larger helmet bubble. Subjects said that the improvement in overhead visibility was the most noticeable improvement in field of view. Subjects generally said that the geometry of the helmet bubble contributed to the improvement longitudinal visibility, while improvements in lateral field of view were caused by the subject's ability to move their head inside the helmet, not necessarily the helmet geometry.

3. Mobile LTA Performance

Four subjects evaluated the microgravity performance of the ZLTA configuration of Z-2, which includes bearings in the LTA. The test subjects said that ZLTA mobility does not appear to hurt microgravity operations at ISS, and it may help performance.

4. Integrated Communication System

All subjects preferred the Z-2 ICS to the EMU CCA. Although subjects did not evaluate the CCA in Z-2, subjects had a significant amount of experience with the CCA in the EMU and the subjects drew on this experience when comparing the two communication systems. Subjects said a benefit of the ICS is that it does not have microphone booms, unlike the CCA; it can be mentally fatiguing when the microphone booms interfere with the subject's mouth, drink bag, or Valsalva. Reducing this mental fatigue with an ICS could make an astronaut more efficient during EVAs.

B. Opportunities for Improvement for Z-2

1. Reduced Suit/PLSS Depth

The front-to-back depth of the Z-2 suit/PLSS system was approximately 5 inches larger than the EMU suit system, and test subjects consistently reported that the depth of the suit/PLSS system should be reduced. Test subjects said that the depth of Z-2 made it difficult to perform tasks at worksites where volume is limited, including the Airlock, FHRC, and IFHX. Some subjects said that the improved upper torso mobility of Z-2 was able to overcome some of the volume-related issues in some worksites. However, most subjects said that the volume-related challenges cancelled out or exceeded the mobility benefits. While volume did not impede most subjects' abilities to acceptably perform any tasks in this test series, it could have contributed to higher mental fatigue, higher physical fatigue, or greater risks of hardware damage.

2. Reduced Helmet Bubble Depth

Several test subjects said that the outward depth of the Z-2 helmet bubble should be reduced due to interference with task performance. Subjects reported that the outward depth of the helmet made it more difficult to perform tasks because subjects could not get adequately close to the worksite without contacting the helmet bubble with structure or tools, as shown in Figure 4.

3. Reduced Shoulder Bearing Profile

Several test subjects reported discomfort due to hard contact between the Z-2 scye bearing and the subject's pectoral region and/or rib cage. In response to this feedback, test subjects wore various types of chest pads to distribute and mitigate contact from the scye bearings. However, this did not completely eliminate discomfort, especially for subjects with larger chest depths.

4. Integrated Communication System

Although subjects generally preferred the Z-2 ICS over an EMU CCA, subjects said that the audio quality of the ICS speakers should be improved. Subjects said that the speakers sounded "tinny" and that it was sometimes difficult for the subjects to understand the test conductor or test director. Based on this feedback, changes should be made to the ICS to improve the audio quality.

C. Limitations of Test Data

1. Suit Sizing

Because there was only one size of the Z-2 suit HUT, it was not possible to evaluate Z-2 suit performance for all possible anthropometries of astronauts. This potentially limits the applicability of the test results to the anthropometries that were evaluated in this test series. However, subjects in this test series spanned the size range of Z-2 for key anthropometric parameters, and the subjects generally provided acceptable feedback for task performance, fit, and comfort. The xEMU Demo space suit will likely consist of just one size of suit, but the overall xEMU architecture will consist of at least two HUT sizes.

2. Limited Number of Crew

Due to overall run limitations, this test series was limited to five astronaut test subjects. Feedback from five astronauts certainly does not capture the opinions of the entire astronaut office and it may have improved the test if more test subjects evaluated Z-2 in the NBL. However, the mix of astronauts in this test series likely adequately represented future astronauts who may use a xEMU Demo space suit in space. During the test planning process, the team sought to diversify the test subject pool as much as possible: inclusion of males and females, mix of relatively large and small astronauts, inclusion of astronauts with spaceflight EVA experience, inclusion of astronauts who were medical doctors, and all subjects had extensive EMU experience in the NBL.

3. Test Environment

The Z-2 space suit was evaluated in an environment that was optimized for the EMU, and this environment may not fully evaluate the potential of the xEMU architecture. However, the ISS environment is the near-term operational environment for the xEMU Demo, so it is the best representation of how the suit will perform in that environment.

4. Learning Effects

All of the test subjects in this test series said that learning effects played a role in defining their task performance in Z-2. While all astronaut subjects had extensive experience in the EMU in the NBL, none of the astronauts had experience in Z-2 in the NBL. The test team sought to minimize this learning effect by providing each subject with a familiarization run in the ELTA configuration of Z-2. Schedule constraints prevented subjects from performing a familiarization run in the ZLTA configuration of Z-2. The team also tried to schedule subjects' NBL runs close together to minimize knowledge loss between tests. Several test subjects said that some difficulties in Z-2 (Airlock ingress/egress, inadvertent boot disconnect in APFR), would likely be mitigated with additional training. Therefore, it is likely that acceptability ratings for Z-2 would improve if the test subjects had additional experience in Z-2.

V. Conclusions

This paper describes the data associated with the Z-2 NBL test series. Results identified favorable improvements from the EMU to Z-2, which include improved indexing for smaller subjects, increased reach envelope, improved shoulder mobility, and improved field of view. Results also highlighted areas of improvement for the Z-2 space suit, which include reducing the overall suit system depth, reducing the helmet bubble depth, reducing the shoulder bearing profile, and improving the audio quality of the ICS. Test subjects said that the mobile lower torso configuration of Z-2 ZLTA did not hurt microgravity operations, and it may help task performance in microgravity. Subjects also said that it would probably be acceptable to perform preliminary EVA operations at 8.0 psid.

VI. Forward Work

Design changes identified in this test series will be incorporated into the next iteration of the xEMU Demo development suit, which is the Z-2.5 space suit. Z-2.5 will be a research and development suit that is aimed at improving the design of the xEMU Demo space suit. Design changes are targeted at improving the microgravity performance of xEMU Demo.

Issues that were identified with the Z-2/PLSS system and the associated design changes from Z-2 to Z-2.5 include:

- Reduced suit/PLSS system depth
  - Increased hatch angle (more vertical) to reduce depth of HUT
  - Reduced PLSS depth
- Helmet bubble interference
  - Improved positioning of test subject’s head inside helmet
  - Reduced helmet bubble workspace interference by changing the angle of the neck ring interface
  - Reduced helmet width.
- Chest discomfort due to shoulder bearing contact
  - Reduced shoulder bearing profile
- Audio Quality of ICS Speakers
  - Design changes to the ICS to improve audio quality of speakers
- Development of flight-like EVVA

The Z-2.5 suit will be completed in the summer of 2018. Z-2.5 will be evaluated in the lab environment and at the NBL in the fall of 2018 to evaluate the performance of the suit in a simulated microgravity environment. Following Z-2.5 testing in the NBL, the design, verification, test (DVT) unit of the xEMU Demo space suit will be designed and built. A flight version of the xEMU Demo is planned to be evaluated on the ISS by 2025.

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