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Final Frontier Design's EVA Space Suit Enclosure (ESSE)

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FFD is developing a new EVA Space Suit Enclosure with a semi rigid upper torso, integrated helmet, and rear entry design, leveraging components already developed from prior projects. The EVA Space Suit features a single wall laminate pressure garment; glove, arm, and torso assembly prototypes have been built and component-level tested. Component testing has included burst pressure physical testing, range of motion and torque testing of joints, pressurized cycling of joints, and leakage testing. Future system level testing is envisioned.

Nomenclature

AM = Additive Manufacture
DMLS = Direct Metal Laser Sintered
EMU = Extra Vehicular Mobility Unit
ESA = European Space Agency
ESSE = EVA Space Suit Enclosure
EVA = Extravehicular Activity
FFD = Final Frontier Design
HUT = Hard Upper Torso
IVA = Intra Vehicular Activity
LEO = Low Earth Orbit
LCG = Liquid Cooling Garment
MCP = Mechanical Counter Pressure
NBL = Neutral Buoyancy Lab
PLSS = Portable Life Support System
psid = Pounds per Square Inch Differential
ROM = Range of Motion
SBIR = Small Business Innovation Research
sccm = Standard Cubic Centimeters per Minute
SRUT = Semi-Rigid Upper Torso
TMG = Thermal Micrometeoroid Garment

I. Introduction

As the space industry grows, there will be increasing demand for commercial Extravehicular Activity (EVA) space suit systems, both within and beyond NASA. Multiple companies intend to send humans to orbit in the near future, and they will undoubtedly find themselves in need of EVA capabilities for assembly, repair, and maintenance operations. FFD has set out to build, test, and qualify an EVA space suit for the commercial market. This is FFD's EVA Space Suit Enclosure, or ESSE.

The ESSE is designed to be a full pressure space suit operating at 4.3 psid with a rear entry hatch. Our goal is a total enclosure weight goal of less than 75 pounds. A fabric-reinforced Semi-Rigid Upper Torso (SRUT), low-profile backpack closure system, additive-manufactured restraints and ventilation components, along with a single layer pressure garment, help to meet our low mass goal. Safety, reliability, and risk mitigation remain our guiding principles, which we will achieve with appropriate component testing, cycling, pressurization, and fault tolerances for life critical hardware.

The ESSE is based on FFD's extensive experience developing space suit enclosures; our lead designer has personally developed both IVA and EVA enclosures for both Russian and European projects for many decades before co-founding FFD. Multiple important components have been developed and tested at FFD within the last 5 years, including the torso, glove, arm, and TMG.

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II. Design Concept and Background

A. Design Concept

The ESSE incorporates several FFD pre-existing EVA components, in a strategic goal to address the overall space suit enclosure piece by piece. FFD's development strategy is to build and test early, and test often. The ESSE will operate at +4.3 psid, similar to NASA's current flight suit.[2] However, multiple components have been developed for higher operating pressures, creating increased factors of safety in the short term. A long term ESSE design goal is to incorporate as many dual fault tolerant designs as possible. The pressure garment is constructed from single layer, bladder/restraint bonded elements; future iterations of the pressure garment could incorporate a redundant internal bladder for dual fault tolerance. The Liquid Cooling Garment (LCG) design will utilize thin walled flat channels for water flow to allow more efficient cooling than tube based systems and include a redundant loop. The ESSE will use a rear entry system, with a multilock closure capable of limited component failure, and dual seal system.

The ESSE design is broken down into these assemblies:

- Semi-Rigid Upper Torso / Helmet
- Arms
- Gloves
- Lower Torso and Legs / Feet
- Liquid Cooling Garment
- Communications
- Biometrics
- Personal Life Support System (Backpack)
- Thermal Micrometeoroid Garment

B. Background

Since 2010, FFD has been developing a novel Intravehicular Activity (IVA) space suit design.[3,4] The FFD IVA suit utilizes a single layer pressure garment construction, with joints at the shoulder, elbow, wrist, fingers, hip, knee and ankle. The single layer pressure garment integrates the bladder and restraint into a functional joint that has a high range of motion, can hold multiple neutral-torque positions, and is capable of high pressure loads. This IVA suit also utilizes a variety of AM elements including closures and ventilation components; the AM parts are optimized for suit applications, as many shapes are not available off the shelf. Many year testing of the single layer pressure garment concepts have enabled FFD to optimize their design and validate their cycling and functionality. The IVA suits are built to be lightweight, durable, and convenient to operate. We believe these IVA technologies can be utilized in EVA operations, with appropriate operational considerations. A key factor in this development from IVA to EVA will be the incorporation of fully dual fault tolerant systems.

Figure 1. FFD's IVA space suits, 2011-2015

Figure 2. FFD's IVA Suit Sizing

FFD has built several prototype EVA components for NASA's SBIR program since 2011, including gloves, elbow and shoulder assemblies, and a radiation-shielding Thermal Micrometeoroid Garment (TMG). FFD's lead designer also has a background in EVA systems at Zvezda, including EVA gloves originally flown in 1988, Hard Upper Torso (HUT) prototyping for both the Orlan and European Space Agency (ESA). He holds 4 patents on space suit hardware design.[5,6,7] The design of the ESSE is loosely based on research conducted on rear entry advanced exploration prototypes with developed at Zvezda in 1992-1994, and again in 2001-2005. The arms and gloves are more directly derived from FFD's SBIR and contracting research.

Figures 3. FFD pressure garment development background, including HUT (Left) and SUT (Right)

III. Requirements

FFD has developed a preliminary set of ESSE requirements and performance goals. We have picked a relatively low 4.3 psid operating pressure for our suit to reduce initial costs and complexity. Pressure requirements for the ESSE are outlined in **Table 1.** These requirements are based on heritage NASA hardware requirements for safe operation.

Table 1. ESSE Pressure Requirements

ESSE Pressure Requirement	Value
Operating Pressure	4.3 psid ± 0.5 psid
Structural Pressure (1.5 X Max Operating Pressure)	7.2 psid
Proof Pressure (2 X Max Operating Pressure)	9.6 psid
Burst Pressure (3 X Max Operating Pressure)	14.4 psid
Max Leak Rate	500 sccm

To define anthropometric requirements, we have compiled previous suit example ranges of the chest breadth and height, both US and Russian. Multiple EVA torsos and architectures were investigated, including the EMU, Mark III, Orlan-DMA, Orlan-M (MK), EVA-2000 and Z-2, as shown in **Table 2**. Percentile ranges listed in **Table 2** are the "Body Size of the 40-Year-Old Japanese Female and the 40-Year-Old White or Black American Male for Year 2000 in One Gravity Conditions" according to NASA's General Anthropometrics Guidelines.[8]

Table 2. Comparative anthropometric range of EVA space suits[5,6,7,8,9, 10]

Suit	Chest Breadth Min-Max (Inches)	Stature Height (Inches)	Percentile	References
EMU	11.25 - 14.75	68.18 - 74.8	5% to 95%	5,7
Mark III	11.25 - 14.75	68.18 - 74.8	5% to 95%	5
Orlan DMA	11.25 - 13.8	64.57 - 70.87	3% to 87%	6
EVA 2000	11.25 - 14.75	64.57 - 74.8	3% to 95%	10
Orlan MK	11.25 - 14.75	64.57 - 74.8	3% to 95%	6
Z-2	11.5 – 13.5	64-71	5% to 87%	9

Based on the analysis of **Table 2,** FFD has determined to use similar sizing metrics to many prior EVA efforts, with a goal to satisfy a 5 to 95 percentile sizing range. We estimate we must provide at least 3 sizes of upper torsos, in addition to sizable limb mobility elements and a range of glove sizes, to meet this goal. Other ESSE goal requirements have been quantified in **Table 3**, while some requirements are still to-be-determined, such as visibility, range of motion, and relative comfort.

Table 3. Goals for FFD's ESSE EVA space suit

Goal	Value	Notes
Anthropometric Range	5% to 95%	
Enclosure Weight, not more than (torso, limbs, gloves, TMG)	75 lbs.	Without Life Support System, goal
Time for donning	3 mins	Self Donning Capable
max metabolic rate	2500 BTU	Running met rate
Stowage volume, max	8 cubic ft.	Goal volume for enclosure unpressurized
Usage	8 EVAs	Disposable Design for Low Earth Orbit
Low Earth Orbit (LEO) Thermal Range	-200° to +250° F	LCG
Fault Tolerance	2 Fault Tolerant where possible	Several elements of the EMU were not deemed 2 fault tolerant including the pressure garment.

IV. ESSE Modeling and Component Prototype Testing

A. ESSE SRUT

The development of a 3D model of the SRUT was a first step of the ESSE development. Parametric digital models were built to adjust the design based on anthropometric requirements. The sizes, diameters and inclinations of hard elements were evaluated to determine the position of key components of the suit architecture that will fit the desired anthropometric range. A goal to reduce the width of the hatch compared to prior suit designs was implemented. The proper dimensions of the hard elements, as well as the relative position and orientation, were designed into the model in a few iterations to correspond to standard digital human body models.

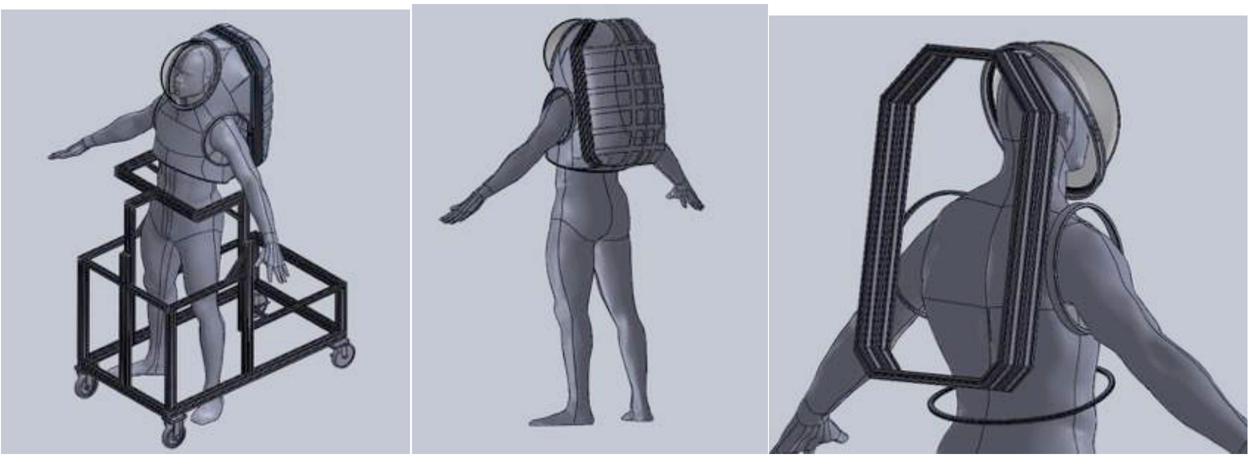


Figure 4. Isometric view of ESSE, showing a cart, backpack, and interface orientation

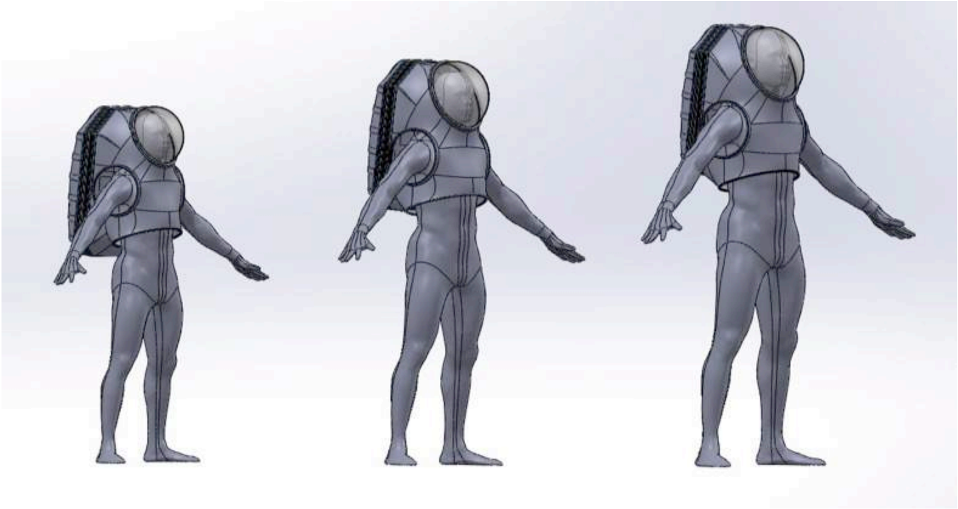


Figure 5 Isometric view of ESSE SRUT in 3 sizes (50% female, 95% female and 95% male)

FFD then developed a physical mock up SRUT for the ESSE that uses a flat patterned, multi-layer, bonded fabric layup. The design elements of the SRUT are broken down to the hatch, visor, shoulder interface ring, waist flange, softgoods, and restraint elements

The SRUT hatch uses two opposing aluminum frames like a door. The hinges and latches are Direct Metal Laser Sintered (DMLS) stainless steel, bolted to the hatch frames. The hatch has a 15" inner width and a 25" inner height. Despite the narrow width, wide-shouldered individuals with shoulder widths greater than 22" are able to don the torso. The softgoods flat patterns connect with the hatch frame using a locking ring system. The hatch seal is inflatable, and includes a redundant second seal. It is opened and closed using a user-operated handle on the right closure side, which operates a circumferential locking mechanism. The locking mechanism opens and closes 6 hatch latches.

The prototype hatch has a fabric enclosure, to house elements of the Portable Life Support System (PLSS) inside the pressurized enclosure, as with the Russian Orlan EVA suit system. The hatch could interface with a flat metal plate, in a similar manner to NASA's Z-suit architecture, to fit an all-external PLSS. However, the hatch is much narrower than the Z-2 backplate.

The SRUT helmet visor is a 13" hemisphere; FFD chose a simple hemisphere because it is a simple shape to manufacture, and it offers little distortion compared to more complex ovoid. Metal restraint rings interlock the mating fabric edge around the helmet ring. The visor is set at 66° above horizontal, for downward visibility. A 3D printed ventilation manifold is attached to the visor for controlled CO^2 washout. The helmet manifold design is based on flow modeling already performed on FFD's IVA space suits.

Figure 6. SRUT Hatch closed (left) and open (middle), showing hinges and latches (right)

The SRUT has a fabric and polymer composite layup, a variation of the Single Wall Laminate approach. Current mockup layups utilize a single layer, off the shelf 10 oz per yard, ripstop, Kevlar – Nomex blend fabric with a Teflon coating for fire fighters. The fabric has a bonded, pressure tight urethane coating on one side and a Teflon coating on the other. This firefighter's turnout gear fabric is inexpensive, has an excellent thermal range and chemical resistance, has high tear and wear strength, and is pressure tight with a thin coating.

Figure 7. SRUT prototype evaluation - pressure, stowage, donning/doffing and range of motion

B. EVA Arm Development

FFD has worked on multiple NASA SBIRS addressing arm assemblies for EVA. In 2015, FFD developed a single layer EVA arm pressure garment assembly, and separately a TMG arm with radiation shielding, under NASA SBIR contracts NNX13CJ28P and NNX13CJ29P.

The pressurized arm assembly utilized a unique approach to the pressure garment: a single layer integrated pressure garment joint, as opposed to a traditional double layer bladder-restraint pressure garment. FFD's single layer design has a host of important advantages over double layer pressure garments. The single layer pressure garment is generally lower mass than a double layer garment because the bladder forms its own restraint system; wall thickness of a single layer pressure garment is generally less than 0.03", while a double layer pressure garment wall thickness including bladder and sewn restraint average 0.07". In addition, friction between bladder and restraint is eliminated in a single layer garment, decreasing joint torque and negating the need for indexing between layers. Because of the reduction of parts, the joint is easier and less expensive to manufacture and maintain. Importantly, the joints are all flat patterned with minimal hard elements and tooling required; flat patterned components are easily scaled for modification and sizing, highly repeatable, more stowable, and less costly than hard-formed elements. The single layer pressure garment also has the capability of adding an unpressurized, emergency internal bladder for full redundancy of the pressure garment, with masses and performance probably similar to a non-redundant double layer garment.

The SBIR EVA arm configuration utilized a stand-in arm bearing, which was simply an aluminum ring with Helicoil fittings matching NASA's EVA arm interfaces. The arm bearing conveniently splits the elbow and shoulder components of the pressure garment for easy component-level testing.

Figure 8. FFD's SBIR EVA Arm

FFD defined 5 major requirements for the prototype arm assembly, with the intention of outperforming the EMU in terms of mobility and joint torque, while advancing our cycling experience:

1. Operating Pressure shall be +8 psid based on burst tests at 3 times operating pressure
2. Leakage shall not allow loss of pressure of greater than 1 psid over 5 minutes, when capped at +5 psid capped to start.
3. Pressurized Range of Motion (ROM) shall be between +10° and +120° shoulder adduction, and between -10° and +170° elbow flexion-extension
4. The elbow joint torque shall not exceed 360 inch-ounces (2.5 newton-meters) at 4.3 PSI in the defined ROM range (0° to 140°)
5. The elbow shall be capable of above 10,000 flexion cycles of at least 90°

Figure 9. FFD's Elbow #16, inflated to +29 psid

Component testing of the elbow and shoulder under pressure confirmed each item's ability to withstand elevated pressures without damage or significant change in shape. Both the elbow and shoulder components were separately held at +29 psid for 5 minutes without issue, exceeding the burst pressure requirement. Leakage was measured by inflating the full assembly +5 psid and sealing it. The pressure of the system did not fall below +4 psid after 5 minutes.

Range of motion of the assembly was assessed visually in component tests. Both the elbow and the shoulder were placed with their range of motion horizontal to the ground plane, and were measured using a large printed protractor. Measured range of the elbow was -30° to + 150°; while hyper-extension of the elbow was possible, the goal of flexion to 170° was not possible given the hardware setup, so these outer limit ranges were not met. High angle flexion of the elbow is generally not possible in any space suit, even unpressurized. For the shoulder, ROM was assessed visually from 10° to 120°, exactly within requirement goals.

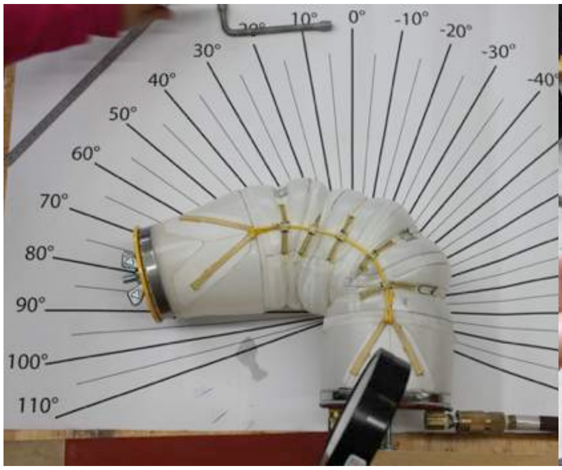


Figure 10. Elbow ROM and Torque Test

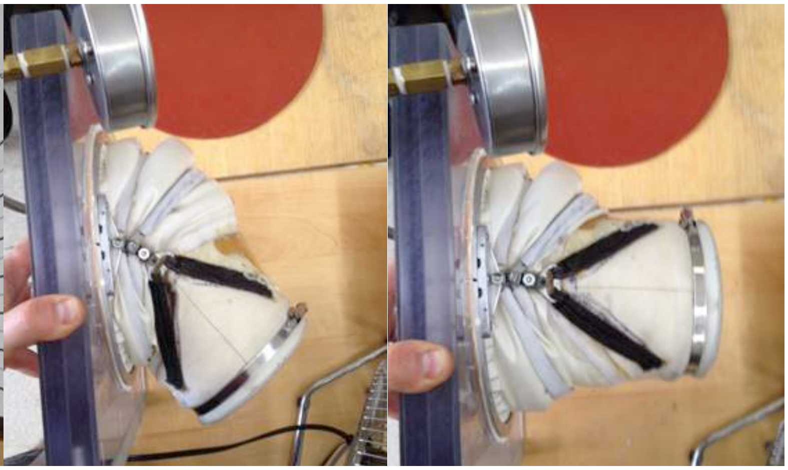


Figure 11. Shoulder component Pressurized Test Setup

Torque of the elbow and shoulder joints was measured with a hand held force gauge, connected to a standardized hook on the plug of each assembly. Multiple measurements were taken by the same operator and averaged, while the component was pressurized to +4.3 psid ± 0.5 psi. Torque measurements over a range of 180° (from -30° to +150°) did not exceed 320 in-oz (2.25 nm) in either direction. While test results can vary widely based on setup, comparisons to measurements taken at MIT in 2001 of the EMU show favorable results.[11] **(Figure 12)**

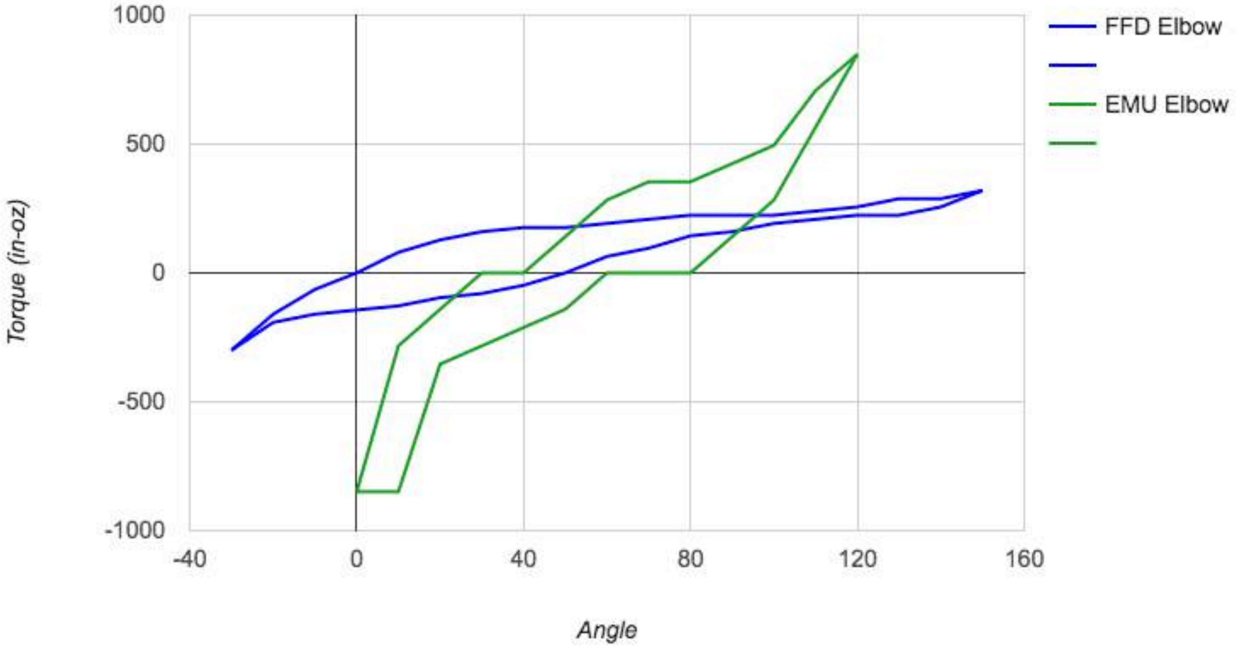


Figure 12. Elbow Torque and ROM, FFD's EVA elbow and EMU Elbow[11]

FFD developed a robotic elbow joint cycler, and tested 2 iterations of pressure garment elbow component to more than 10,000 pressurized cycles, meeting our Phase I requirements for cycling. The joint cycler logs each cycle on a computer processing interface, and can be manually or automatically controlled. The joint cycler is capable of at least 90° ROM under pressure (4.3 psi) inside a pressure garment elbow component. This automatized elbow joint allows us to cycle the elbow several thousand times a day accurately and consistently, and will more accurately model the motion and wear of the joint than an external cycling mechanism. Because the robot sits internally to the enclosure, it more accurately mimics the movement of the human body. Internal components of the arm were covered with padding and buffer tape to reduce mechanical impingement and wear on the pressure garment. (See **Figure 13)** Cycling tests took place after an initial leak test, and were limited in cycles to 500 at a time to prevent servo overheating.

During the cycling testing, we found two wear points on the bladder directly underneath the longitudinal restraint cords, which eventually contributed to leakage, after approximately 9,000 cycles, in the first iteration. FFD has identified solutions to this issue, including introducing wear patches to buffer the friction of the cord, and coatings to the cord to reduce the friction of a cycle. These changes were implemented in subsequent assemblies, and a second attempt at 10,000 cycles was successful without significant change in leakage before and after.

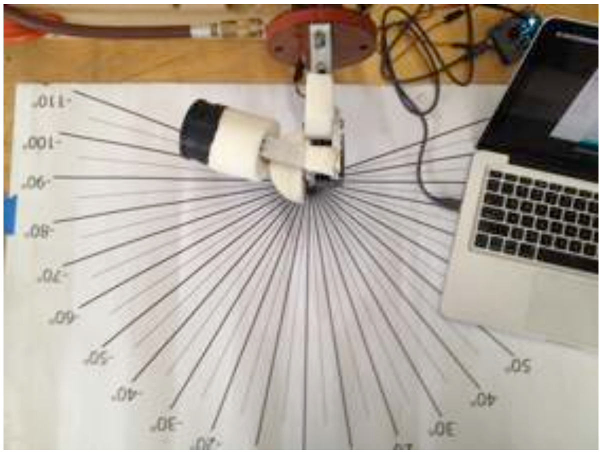


Figure 13. FFD's Robotic Elbow Joint Cycler

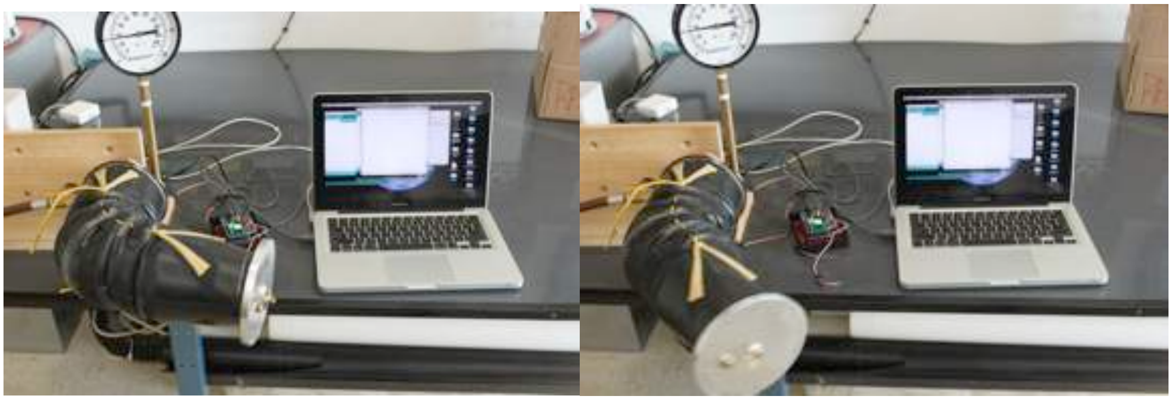


Figure 14. Robotic Arm Cycling of Arm #15. Flexion (R) and Extension (L)

Figure 15. FFD's elbow and shoulder assembly at +4.3 psid

FFD has also developed specific designs and patterning, and conducted materials research, on a TMG for the elbow assembly. This included 4 complete iterations of these 11-layer assemblies, designed to not greatly restrict the motion of the pressure garment below, while protecting the suit and wearer from extreme temperatures, cut and abrasion risks, and micrometeoroid debris. TMG patterning and design requires a specific attention to seam configurations, to avoid very thick overlaps or other manufacturing complications. FFD's TMG includes several multi-functional layers, including reinforced Mylar, and a combination micrometeoroid-liner layer.

Figure 16. TMG Elbow Assembly Iterations

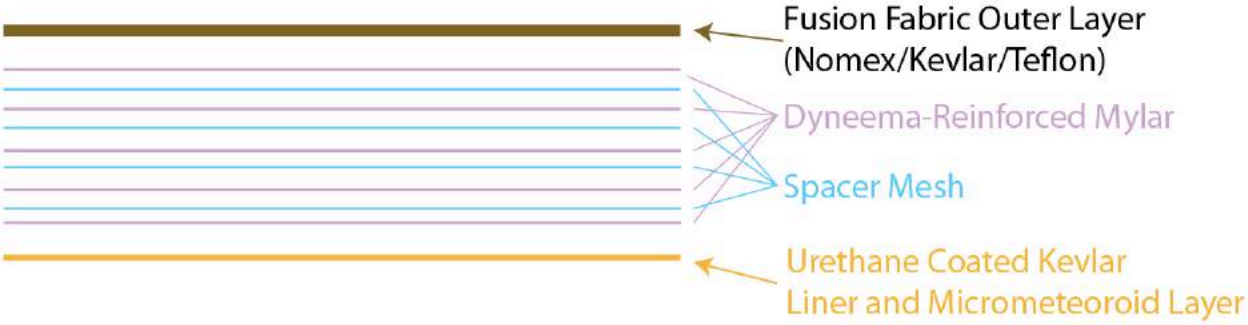


Figure 17. FFD's TMG material cross-section

D. EVA Glove Development

FFD's EVA glove design has roots in NASA's 2009 Astronaut Glove Challenge (AGC), with back of finger (dorsal) pockets, flat patterned, for increased finger ROM. The glove also includes an anthropomorphic wrist design, a customized palmar restraint, and a single layer bladder-restraint design. FFD's EVA glove design has had multiple years and hundreds of thousands of dollars of materials and processes advancements since 2009, including 2011 and 2015 SBIR contracts focused on both glove pressure garment and outer garment development. The pressure garment is a single layer welded fabric design, with AM Titanium restraint components at the palm and wrist, high-strength Dyneema restraint lines, individual finger sizing capabilities, and customized fingertips with fingernails. The outer garment includes an innovative, light weight outer fabric, reinforced Mylar, and customized fingertips. FFD has developed a series of requirements for their EVA space suit glove assembly:

1. Operating Pressure shall be +8 psid based on burst tests at 3 times operating pressure.
2. Leakage shall not allow loss of pressure of greater than 1 psid over 5 minutes at +5 psid to start.

3. Glove ROM shall allow finger thumb opposition to all fingers and the base of the index and thumb. Wrist flexion shall be at least 60°, and wrist extension shall be at least 90°. Wrist abduction / adduction shall be at least 30° each.

4. The glove shall have standard sizing features to adjust for finger length of at least 0.20” and palm circumference range of at least 1”.

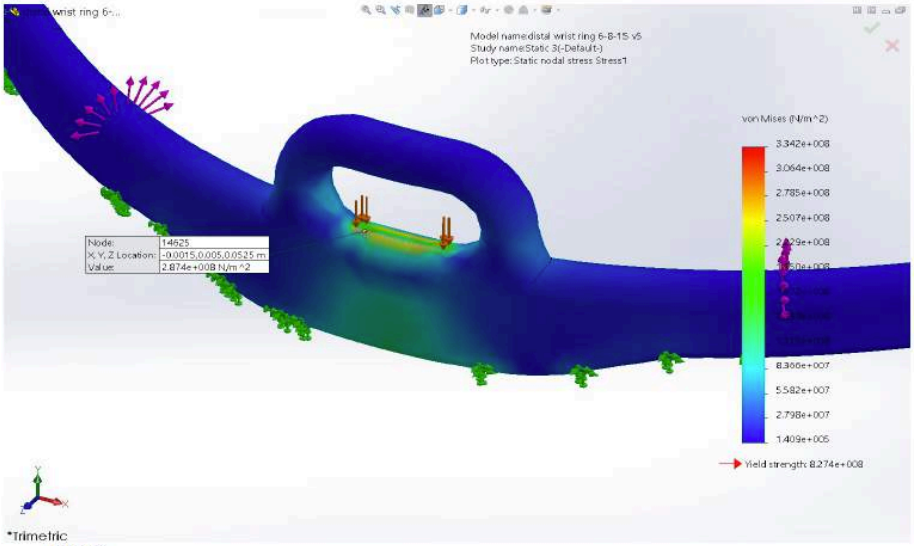
5. The pressure garment and outer garment glove shall have a mass not including bearings or disconnects of less than 1 pound.

6. The glove shall allow the user to blindly detect a gap of at maximum 0.125”

Pressure testing of the glove took place through several iterations. Pressures were slowly increased in incremental tests. Initial high pressure testing showed that while the pressure garment was capable of withstanding high loads at high pressure, the wrist restraint gimbal showed significant deflection. (**See Figure 18)**

Figure 18. FFD’s Pressure Garment Glove at +10.6 psid (left) and +21.2 psid (right).

Because of this initial result of gimbal deflection, FFD performed additional load analysis of the wrist gimbal ring and determined a design change to mitigate the deflection. (**Figure 20, 21)** Further high pressure testing using the reinforced gimbal ring allowed the pressure garment glove to exceed +24 psid and meet our pressure requirement.



Model name:distal wrist ring 6-8-15 v5
Study name:Static 3(-Default-)
Plot type: Static nodal stress Stress1

Node:	14625
X, Y, Z Location:	-0.0015,0.005,0.0525 m
Value:	2.874e+008 N/m^2

Loads:
87 psi pressure
240 lb load on each loop
240 lb distributed load on each side

Figure 19. FEA of the wrist distal ring axial interface

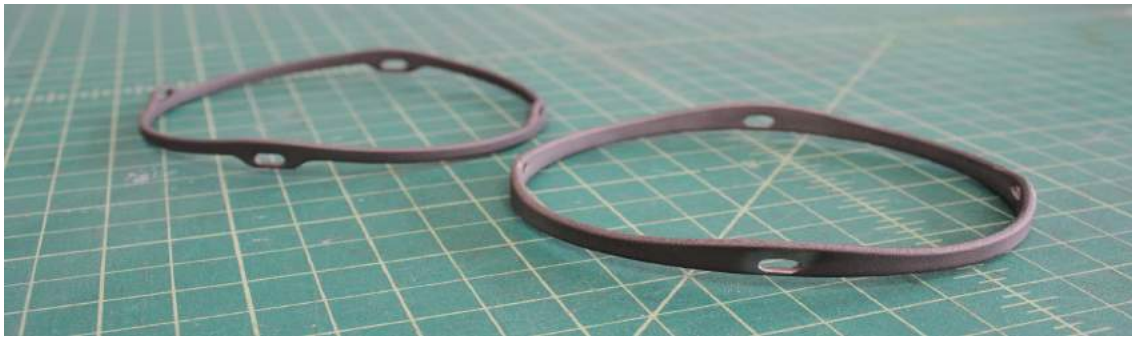


Figure 20. Gimbal Ring Optimization. Original Ring (Left) and Reinforced Ring (Right)

Leakage of the gloves was checked with a cap-and-hold method. The requirement was for the pressure garment to be pressurized to +5 psid and capped. After 5 minutes, the internal pressure should be no less than +4.0 psid. Each glove passed this test, although sealant was required in several areas, especially around the finger crotches, with early prototypes.

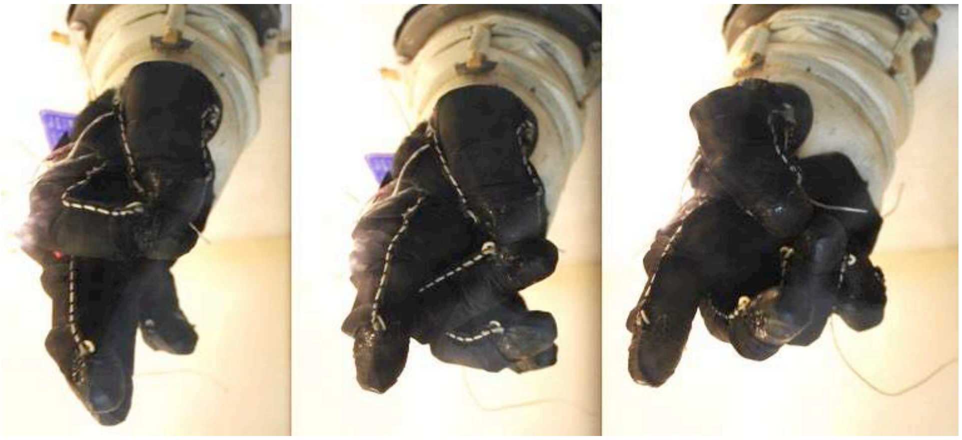


Figure 21. FFD's EVA Glove Finger Range of Motion, 4.3 psid

ROM testing of the glove met all stated requirements, with the wrist joint capable of greater than required flexion ranges. (**Figure 23**) The glove includes a thumb gimbal that allows nearly 20° of thumb ad-abduction.

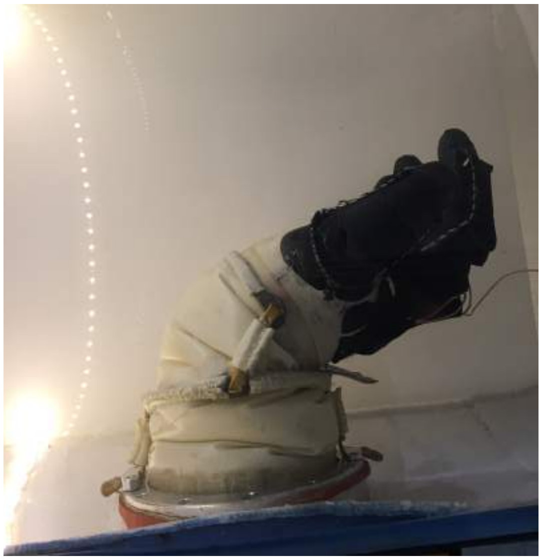


Figure 22. Wrist Extension at 85°

Figure 23. Wrist flexion at 90°

FFD’s pressure garment gloves include individual finger sizing restraints, allowing for finger length adjustments of approximately 0.20”. The palm bar is AM titanium allowing adjustment of the hand body circumference of more than 1.5”. The outer layer TMG is indexed to the pressure garment at the base of the fingertips, using soft fabric tabs as tie-off points.

Glove mass not including the bearing and disconnects was 12.9 ounces, less than our requirement of 16 ounces. (See **Table 4**)

Figure 24. Glove Finger Restraints

Table 4. FFD Glove Assembly Overall Weight

HPEG Component	**Weight (Oz)**	**Notes**
Pressure Garment	**5.25**	**Actual Deliverable Weight**
Outer Garment	**7.65**	**Actual Deliverable Weight**
Disconnect	**8**	**FFD Current Standard**
Clamping Ring	**4**	**Based on current hardware**
Bearing	**14**	**FFD Estimated**
Seals and Fasteners	**2**	**FFD Current Standard**
Total	**40.9 Oz**	**2.55 Lbs**

Figure 25. Fingertip tactility testing to 0.1875” with TMG at 8 psid

FFD's pressure garment glove includes custom formed seamless fingertips with restraint 'fingernails' that force the oval cross section of the finger and allow a very thin walled barrier which enables high tactility. The outer garment fingertip was designed to fit exactly over the pressure garment tip, minimizing drift and added tactility restrictions. In both pressure garment and TMG testing, at 8 psid, the test subject was able to blindly identify the minimum gap of 0.125" in a tactility bar, meeting stated requirements.

The outer garment of FFD's EVA system includes a reinforced mylar composite thermal protective layering, and a ultra-light non-woven Dyneema-coated Vectran composite outer layer. The reinforced Mylar, which was bonded to Dyneema, adds multifunctional materials to the TMG thermal layer, by creating a reflective thermal barrier that is puncture resistant. The outer layer bonded Vectran was tested for weight, strength, and tear, and had strength and tear properties within 20% of Orthofabric, at about one quarter the weight. This outer coated Vectran layer is also dust resistant, as it is covered with a watertight film. The TMG design also includes dust seal concepts around palm bar and wrist disconnect flaps. (See **Table 5)** The outer garment also included a palmar area reinforced with puncture resistant, high-heat silicone Superfabric.

Table 5. Outer Garment Fabric Performance Comparison

Properties	**Orthofabric**	**Bonded Vectran / Dyneema**
Weight (oz/yd^2)	**13.5 - ASTM D3776**	**3.4 - ASTM D3776**
Failure Strength (Lbf / In^2)	**500 - ASTM 5034**	**440 - ASTM D3039**
Trapezoid Tear (Lbf / In^2)	**100 - ASTM 5587**	**81 - ASTM D5587**

Figure 26. FFD's EVA Outer Garment Glove Palm with Superfabric

IV. Conclusions and Future Plans

FFD has identified a need both within NASA and in the commercial space industry for flight-certified EVA space suit technology. We recognize this as a long, expensive, and difficult task, and we intend to approach it with a 'test early, test often' strategy, addressing individual components before undertaking the entire assembly.

Current design trends for future suits mandate dual fault tolerant systems for life critical hardware on EVA; a major lesson learned from the use of the Extravehicular Mobility Unit (EMU) onboard the International Space Station (ISS) is the need for redundant systems.[1] The EMU has several single fault tolerant systems that have proven problematic in heavy operation beyond its original envelope. Final Frontier Design (FFD) has set out to design, build, and validate a competitive EVA architecture that adheres to strict safety and risk reduction standards; moving forward, this includes dual fault tolerance throughout.

Our first goal is to prove out a safe system through unmanned structural tests and cycling evaluation. This will start with component based testing of each element of the suit, and develop to a full suit assembly for evaluation. This paper has identified some key components that will be utilized and an overall design concept. A major design driver for future iterations is to include dual fault tolerant elements for any life critical elements. This will likely include a redundant pressure bladder, a redundant visor, redundant restraint lines, and redundant closures for the pressure garment. Dual fault tolerance represents a major next step hurdle in our EVA plans.

Suit bearings and disconnects also present a particular challenge for FFD. FFD has developed in house and built wrist disconnects for their current IVA suit that are capable of sealed quick disconnect. These disconnects have been tested an optimized over several years and thousands of uses. However, our disconnects are not dual fault tolerant and require further updating for EVA standards. We have also conceptualized and performed initial prototyping of a sealed, low profile bearing for space suits. Initial development at FFD has been focused on wrist bearings, because of their relatively small size and applicability to IVA suit operations as well. Further work is required to validate this concept and scale to larger EVA bearings.

Figure 27. FFD's Glove quick disconnect

Figure 28. FFD's space suit bearing design

Material analysis, identification, and categorization is an early step we have set as a priority. While we have relied on off-the-shelf materials in many instances, controlled lots and known properties are critical for clearly understanding the performance characteristics of each assembly with confidence moving forward.

As we develop our component level designs, we hope to assemble a full suit architecture for human testing sooner rather than later. We plan on performing human testing in a lab environment using umbilical supplied life support and prototype components, to validate basic range of motion, metabolic, and comfort requirements. Preliminary efforts will focus on microgravity configurations, with a concentration on upper body mobility and baseline functionality.

FFD has identified and built prototype EVA suit architecture concepts which we believe can be integrated into a full enclosure. Much work remains for us to fully understand and qualify our designs.

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