

Advanced Extra-vehicular Activity Pressure Garment Requirements Development

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The NASA Johnson Space Center advanced pressure garment technology development team is addressing requirements development for exploration missions. Lessons learned from the Z-2 high fidelity prototype development have reiterated that clear low-level requirements and verification methods reduce risk to the government, improve efficiency in pressure garment design efforts, and enable the government to be a smart buyer. The expectation is to provide requirements at the specification level that are validated so that their impact on pressure garment design is understood. Additionally, the team will provide defined verification protocols for the requirements. However, in reviewing exploration space suit high level requirements there are several gaps in the team's ability to define and verify related lower level requirements. This paper addresses the efforts in requirement areas such as mobility/fit/comfort and environmental protection (dust, radiation, plasma, secondary impacts) to determine the method by which the requirements can be defined and use of those methods for verification. Gaps exist at various stages. In some cases component level work is underway, but no system level effort has begun; in other cases no effort has been initiated to close the gap. Status of on-going efforts and potential approaches to open gaps are discussed.

Nomenclature

<i>EBM</i>	=	Energy-based Mobility
<i>EMU</i>	=	Extra-vehicular Mobility Unit
<i>EPG</i>	=	Environmental Protection Garment
<i>EVA</i>	=	Extra-vehicular Activity
<i>ft lbf</i>	=	foot-pound force
<i>HPEG</i>	=	High Performance EVA Glove
<i>HRP</i>	=	Human Research Program
<i>lb</i>	=	pound
<i>PLSS</i>	=	Portable Life Support System
<i>SOA</i>	=	State of the Art

I. Introduction

Recent experience in translating requirements into hardware with the Z-2 space suit prototype design contract and on-going efforts to define exploration space suit requirements have highlighted the importance of clearly defined requirements with equally clear methods for verification. This paper reviews lessons learned in the exploration pressure garment requirements development process, including:

- Dangers of adopting heritage requirements
- Limited applicability of using state-of-the-art as a basis for comparison
- Hazards of existing models

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- Troubles with quantifying the qualitative

II. Dangers of Adopting Heritage Requirements

A. Impact Requirement Example

The process of writing the Z-2 requirements and observing the design implications and implementation reinforced the value of good requirements with meaningful verifications. To demonstrate the impact of poor requirements, the example of the Z-2 effort is impact requirement is discussed.

The requirement stated:

“The suit shall meet leakage requirements after impact from a 2” diameter steel ball assuming a 250 lb crewmember, suit and 200 lb PLSS [Portable Life Support System] traveling at 13.9 ft/sec [9.5 mph].

Rationale: The suit must protect the crewmember from catastrophic failure after a worst-case impact. This impact velocity is derived by assuming a 4 mph horizontal velocity component and a simultaneous fall from 2 m of height on the Martian surface; this corresponds to a reasonable worst-case “front running fall” scenario. Note that these values were derived from the Constellation Lunar EVA Falls Table and scaled up for Martian gravity. This requirement applies to suit hardgoods only. The requirement does not apply to the helmet.”

However, as the analysts tested the model of the composite structure against this requirement several questions arose. Generically, these questions were:

- A. “How are we supposed to read this requirement?”
- B. “How do you really want us to verify this requirement?”
- C. “Are you sure you really want to impose this requirement?”

Specifically, these questions came in the following forms:

- A. Is it realistic to treat the system as a rigid body so that the entire system mass is considered in the impact, as the requirement implies?
- A. How is the environmental protection garment accounted for in this requirement?
- A. Is it realistic to apply an impact requirement directly to structure because not all structure is exposed (e.g. covered by display and control module on the chest)?
- B. What analysis cases represent ‘worst case’ in light of not being able to verify the requirement for every location (infinite impact possibilities)?
- C. Do you realize what thickness the structure will need to be to meet this requirement?

Strict interpretation of the requirement treats the combined mass of 620 lbs as a rigid body and generates an impact energy of 1862 ft*lb, driving the answer to this last question to a suit mass that exceeded the mass requirement.

The lack of clarity in the requirement led to weeks of discussions in the attempt to define a usable impact requirement. Discussions included considerations such as the fraction of the suit weight that is to be assumed rigidly attached, the fraction of the crew weight to be included in the mass of the initial impact; realistic impact zones, such as the three impact zones denoted by the green, purple, and red shaded areas in Figure 1; identification of the most severe cases as those in line with the center of gravity; use of realistic surface translation speed (e.g. 4 mph versus 9 mph); and if and how to include a factor for Shuttle-style or Martian-style thermal/micrometeoroid garment in the impact analysis.

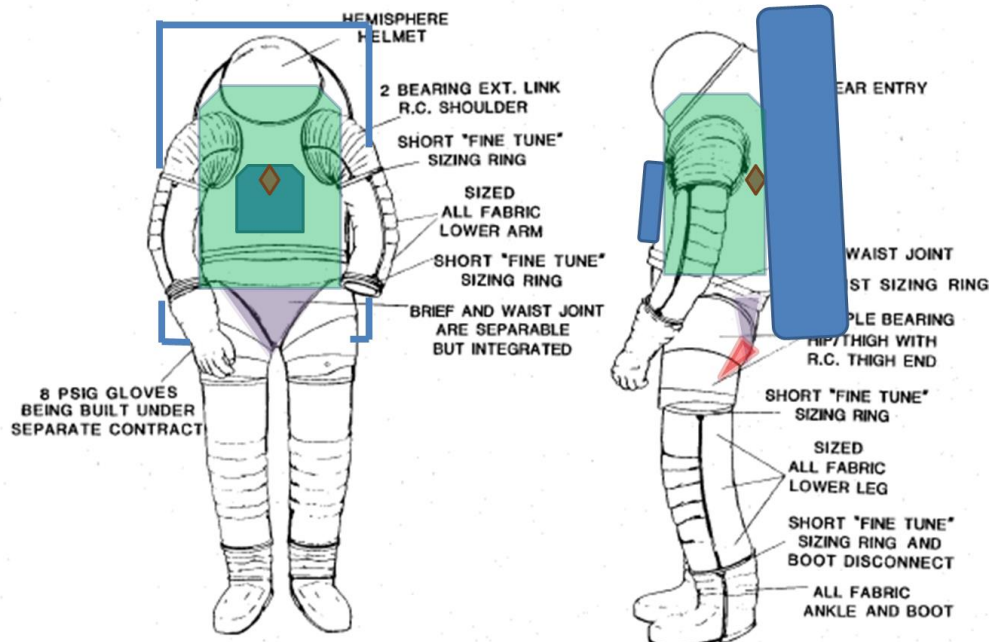


Figure 1: Location of Impact Zones, Credit: Richard Rhodes¹

Various opinions regarding the resolution of the numerous variables involved were voiced. Depending on the assumptions applied new calculated impact energies were in the range from 216 ft lbf to 416 ft lbf for lunar impacts to up to 659 ft lbf for Martian impacts. These numbers looked more realistic, but additional efforts outside the schedule of the Z-2 effort were needed to select and validate which assumptions should be documented in the requirements.

In the face of needing to make a decision for Z-2 design, the next logical question was to review what impact energies that the Shuttle Extravehicular Mobility Unit (EMU) and the most analogous advanced prototype suit, the Mark III, tolerate. For the EMU, the requirement was not applied to the fiberglass structure of the upper torso because, in addition to being mostly covered with the display and control module and the portable life support system, the Shuttle and ISS Programs assume that crewmembers will protect themselves with their hands. Therefore, the EMU offered no comparative data. The Mark III designers considered impact to the brief and hip sections. Tests of candidate hip/brief materials provided data on the energy absorbed by the selected material. The material used in the Mark III represented the most desirable combination of impact energy absorbed (298 ft lbf), thickness/mass, and durability available at the time. Yet, their material's capability did not allow them to meet their original requirement of a fall from a 10 feet high ladder on a Martian lander, which defined a brief impact energy of 622 ft lbf.

Stuck with a lack of data and a potentially unattainable requirement, the overarching question became:

What do you really want for this effort?

The answer was that we wanted a design with similar properties to the Mark III based on the pragmatic knowledge that the Mark III brief and hips sections have been in service since 1992, in rigorous tests including Weightless Environment Training Facility runs, reduced gravity aircraft flights, and over a decade of field testing while needing only recent repair and maintaining structural integrity.

The approach then became to correlate Z-2 candidate material impact results to those of the Mark III and to work within the capabilities of the analytical model to develop a design that creates a durable suit within the required mass. The material properties generated from testing were incorporated into the finite element model to calibrate the model, and analytical impact test results were used to verify that no leakage resulted from the impact.¹ A major lesson learned was that a full suit model was required to address the impact requirements, because the suit geometry and resulting boundary conditions were imperative to the analysis.

We had failed to write a useful requirement. The failure cost us approximately three months of design time, repeated iterations of modeling and materials testing, design of hardware that does not meet a Mars exploration

requirement, and associated budget impacts. We had not done the work to understand what the requirement would drive the designers to do and the effort required to meet and verify.

III. Limited Applicability of Using State-of-the-Art (SOA) as a Basis for Comparison

The very basic specifications, including abrasion resistance, for the environmental protection garments are undefined. While this may seem surprising in light of having had environmental protection garments on space suits since the Apollo program, it isn't when one considers that the primary focus for space suit design has been the relatively pristine low Earth orbit environment for the past 43 years. Until the Constellation Program, there hadn't been a driving need to develop requirements because the pressure garment materials were performing well in the absence of early environmental wear requirements. As NASA has evolved, the requirements conventions of heritage systems have become harder to justify and emphasis has shifted to quantifiably verifiable requirements that drive greater specificity. Additionally, long-duration exploration missions exceed known performance capabilities, which again drives the need for requirements definition.

To generate quantifiable, verifiable requirements for environmental protection garment functions, two general approaches have been used: 1) use of standard test protocols and 2) development of specialized test protocols.

A. Abrasion Resistance Using a Standard Test Protocol Example

This general approach starts with an attempt to understand the materials that were selected for past and current systems and then attempts to extrapolate relevant exploration requirements. One example of this approach was Constellation Space Suit task for the "Outer Layer Cut Resistance" requirement definition.² Current outer layer materials, such as Orthofabric and Polytetrafluoroethylene (PTFE) fabric, were tested using a selected standard, in this case ASTM F1790-05 "Standard Test Method for Measuring Cut Resistance of Materials", to determine the numerical value for the performance of these materials. Once the current fabric performance was quantified against the standard, the value to set for the new suit could be more knowledgeably discussed. Testing against a standard is attractive because there is a clearly defined verification method to a quantitative value. The flaw of this approach is that it doesn't necessarily address the needed performance for the new system because it only quantifies current performance within the specific scope of the test and because extrapolation could be imperfect. The question, "What if the test standard selected does not characterize the attribute of the current material that provides the desired performance?" remains open. Moreover it does not address the question, "What if the test standard does not accurately represent the environment/conditions that the hardware would actually be exposed to?"

B. Abrasion Resistance in a Dust Environment, Development of a Specialized Test Protocol Example

The other principal approach is to develop a test protocol that directly addresses the performance in question. This approach frequently is attempted when no standard protocol is applicable. One example was the 2008 Glenn Research Center's effort to modify ASTM D 3884-01 "Standard Guide for Abrasion Resistance of Textile Fabrics (Rotary Platform, Double Head Method)", see Figure 2. The modification added measured quantities of lunar simulant JSC-1 to the wheel abrasion test. However, when the protocol was tested separately at Glenn Research and Johnson Space Centers, the results did not correlate teaching that the modification of a standard is not a straight forward process. The protocol requires additional definition to be of use.

Another attempt to develop a specialized test was the Johnson Space Center's tumble test development.³ From 1990 through 2009 a tumble test method was developed and used in which cylinders of current and candidate materials were tumbled in a rotary drum with simulated rocks and simulant dust as shown in Figure 3. Before and after testing a visual inspection, material strength (tensile and tear) tests, and scanning electron microscope (SEM) images were performed. The method has been recently revised again for High Performance EVA Glove (HPEG) tests using squares or lay-ups of material secured to the inside surface of the rotary drum in an effort to increase the efficiency of the test. While this method provides significant comparative information, it has not resulted in a clear quantitative requirement. Use and maturation of this method will continue, if not for requirement development, to provide insight into the performance of materials in a dust environment and in mitigating dust penetration.



Figure 2. ASTM D 3884-01 test device



Figure 3: Rotary Drum test device

Thus, the unknown affect and needed performance of dust protection, especially at the level of the sub-system, is a gap that remains and requires significant effort to close. Once the requirement is defined, if a new material is required to meet the requirement a material development effort typically of approximately ten years duration will be needed, which jeopardizes the current 2030 timeline for a human mission to Mars.

IV. Hazards of Existing Models

A. Thermal Model Example

Thermal management is a system level requirement, involving both the suit and portable life support system (PLSS) teams working together to ensure that system level design decisions are made to meet requirements. The pathway to thermal requirements is more straightforward in that correlated thermal models of the human and current space suit in the low-Earth orbit environment exist, along with expert analysts available to use them. However, current models need to be updated and validated if necessary for the Martian conditions. For the pressure garment, the gap lies in the technologies needed to meet the thermal requirements.

New materials are needed on Mars because the currently used thermal protection system of multi-layer insulation depends upon a vacuum to function. A material development effort spanning better than a decade has produced a potential technology, flexible aerogel, to address the gap. A recent High Performance EVA Glove (HPEG; a project funded by the Science Technology Mission Directorate) task incorporated a flexible aerogel into an EPG for an advanced glove, as shown in Figure 4. However, this was the first effort at applying aerogel to a high fidelity space suit component prototype. Before the material can be determined to have closed the gap, this technology must be tested in configuration for continued thermal performance during cycle testing and impacts to mobility.



Figure 4: HPEG glove EPGs that incorporate flexible aerogel

Another gap in thermal protection to address the seasonal thermal variations on Mars persists. Concepts have been suggested and, in some cases, evaluated but only at low fidelities. Models need to be updated with the planetary thermal conditions and exploration pressure garment materials lay-up thermal performance for system-level thermal management requirement compliance to be assessed.

B. Models for Probability of No Penetration

Protection from the ejecta of an impactor on the lunar surface, i.e. secondary impacts, is a gap for lunar missions. Space suit materials have not been tested against these particles. Fortunately, the same approach used to calculate the probability of no penetration (PNP) used for micrometeoroids and orbital debris (MM/OD) in low Earth orbit (LEO) can be used here. An Apollo-era model of secondary impacts is being revised at the Marshall Space Flight Center and a new model has been developed. A model will have to be selected and validated. To feed the model, as EPG lay-ups are selected to meet the other functional requirements, they will need to be tested against secondary impactor energies simulating their speed and mass, to obtain data that will then be used in the calculation of PNP.⁴ Until this test and modeling effort has begun and a program has set a PNP, there is a gap in that we do not know if specific design efforts will be needed to meet this functional requirement.

V. Troubles with Quantifying the Qualitative

A. Mobility, Fit, Comfort

Suit performance measurements constrain several aspects of pressure garment design. Suit performance is defined with the triumvirate of fit, mobility, and comfort. However, the current requirements are flawed, or subjective, or both. Traditionally, they have been addressed as follows:

Mobility has been defined as per joint via range of motion (ROM) for a single-axis motion and torque associated with the motion. The requirements have been determined from joints of successful pressure garment prototypes. While this approach is quantifiable, and substantial effort has been invested in attempting to create a repeatable test methodology, there are major flaws (see Figure 5). First, there is no direct tie between range of motion and functionality. Top level requirements dictate that a suited crewmember be able to perform mission enabling tasks such as kneeling to recover a rock or walking over sloped terrain. The ROM and torque from a collection of joints that may or may not have been incorporated into a single prototype configuration give no guarantee that a configuration that meets the individual joint requirements will meet the functional requirements. Second, for multi-axis joints including the shoulder and hip, measuring a single axis ROM is difficult and not very descriptive of the desired joint performance. In the past, pressure garment prototype development has been successful because experienced space suit designers have built on past experience to continue to improve mobility performance, not because they had meaningful mobility requirements.

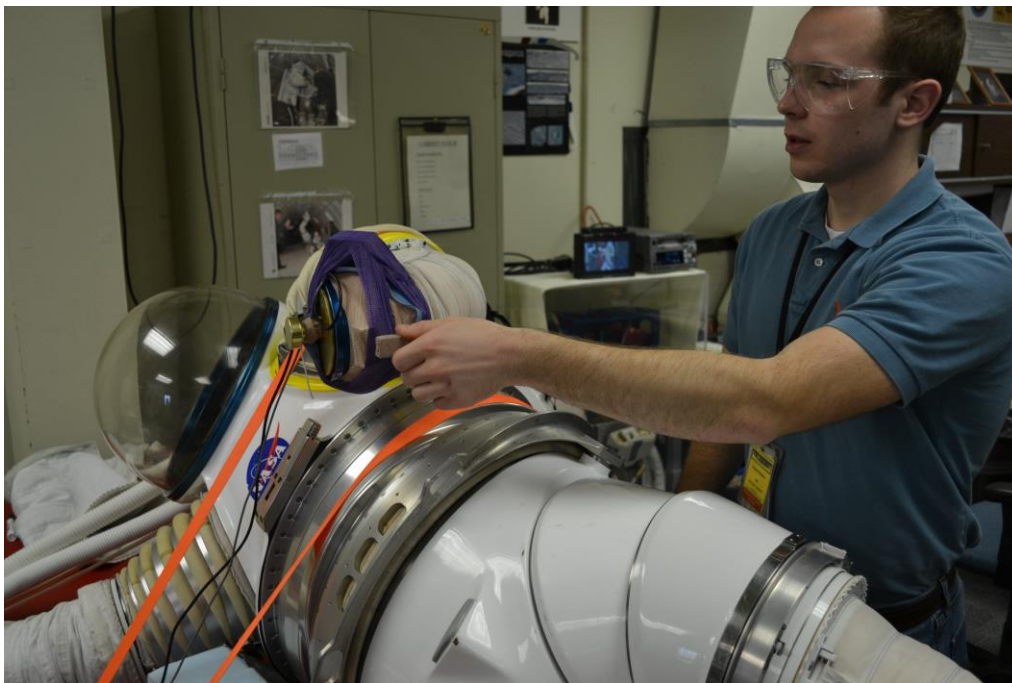


Figure 5: Isolated joint torque testing

Fit has been defined by a set of anthropometry expected to be accommodated within the pressure garment. However, it is clear from fit checks that being able to be accommodated by a suit is a very different criteria from being effective in a suit. Therefore, fit and mobility are linked, and there is no good way to verify fit. In design of space suits, certain assumptions are made regarding fit. For example, the model of the human is centered in the shoulder opening of the suit and given a 1 inch gap between the assumed human crotch and the crotch of the suit (see Figure 6). In the Z-2 design effort, a rapid prototype upper torso and brief were used early in the design to assess fit, as shown in Figure 7. It was found that the 1 inch crotch gap assumption as applied in the model resulted in the predicted sizing from the model to be too long by a waist sizing increment per subject comments during the fit check. Yet the greatest challenge by far to writing a verifiable fit requirement is that the sizing engineer must rely almost exclusively upon subjective user comments to ensure proper alignment within the suit and to guide length adjustments; a suit configured based off poor user feedback doesn't necessarily equate to an ill-fitting suit.

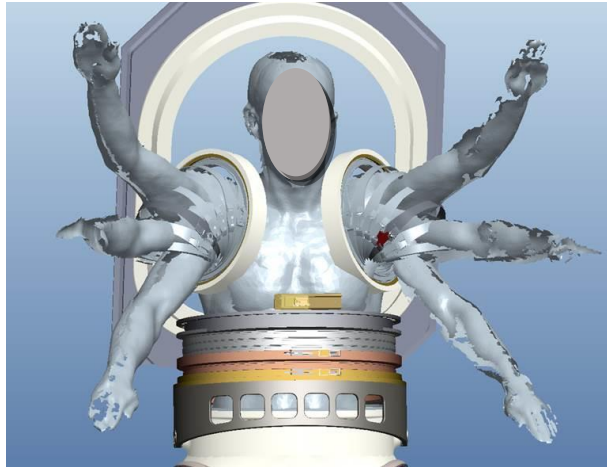


Figure 6: Human scans indexed in suit model



Figure 7: Fit check in 3-D printed Z-2

For long-duration missions with routine EVA, injury mitigation is a major emphasis in pressure garment design. Comfort, which also is the lack of discomfort, is related to fit and thus mobility in that, if a suit applies a pressure point to the body, soon the human will not engage the joint causing the discomfort resulting in reduced mobility. To inform these three related gaps, suit designers need to have detailed knowledge of how the crewmember interacts with the suit and the mechanisms through which acute and chronic injuries occur. While we have SOA techniques such as real-time, three-dimension (3-D) motion capture system to understand how the suit is moving, we have no insight into how the human is moving inside of the suit (i.e. What ROM did the human exercise to obtain a certain suit joint ROM?), nor how the human interacts with the suit to make it move (i.e. Where did the human contact the suit to move it and is that an ergonomic motion?). A suit sensor suite that would allow joint ROM, effort required to move the suit, and pressure point mapping data to be collected in concert with the external motion capture would greatly inform suit design and requirement language. Some progress is being made in this area. Recent work by MIT on their Sensor Garment and by the University of Maryland on their Body Pose Measurement System informed work by the High Performance EVA Glove (HPEG) project on an injury sensor glove. The injury sensor glove is serving as a small scale feasibility prototype for a full suit sensor suite and continues to mature the sensor suit approach. In the meantime, various attempts to address fit/comfort/mobility requirements through suit performance measurements are being explored. One example is Energy-based Mobility (EBM) effort being performed as a collaboration with the Human Research Program. EBM is exploring the insight provided by metabolic data taken as a subject performs a variety of functional tasks in various prototype pressure garment configurations. Early results are interesting, but it is too soon to determine if the methods will be allow pressure garment performance comparisons or definition of quantifiable requirements. Both methods still require complete pressure garments, making in-process requirements verification difficult at the component level. The design cannot be evaluated against mobility, fit, and comfort requirements until the garment is completed.

VI. Conclusion

The gaps and challenges in requirements definition, validation, and verification identified in this paper are a sample of the complete list of gaps faced by the advanced pressure garment team. Opportunities exist for innovative approaches for requirements definition and verification techniques. The team continues to apply lessons learned from these examples and to progress in working toward Z-3 requirements and the refinement of long-range development planning for NASA exploration pressure garments.

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