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System Considerations for an Exploration Spacesuit Upper Torso Architecture

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ABSTRACT

NASA's Exploration Architecture announced in September 2005, calls for development and flight of a Crew Exploration Vehicle (CEV) no later than 2014 and return to the moon by 2020 with a goal to reach and explore Mars. Intra-Vehicular Activity (IVA) suit systems will need to comfortably protect the crew during launch entry and abort scenarios. Extra-Vehicular Activity (EVA) suit systems will need to provide the capability to perform contingency zero-gravity EVA from the CEV as well as surface EVA to explore the moon and Mars. Studies currently underway to begin definition of the IVA and EVA suits point to a two suit architecture, the first being a launch, re-entry, and contingency EVA system used from CEV, the second and later being a lunar surface mobility suit only. An important consideration, yet to be determined, is the level of commonality between the early CEV and late Lunar suits. One concept is to have maximum commonality beginning with the architecture of the spacesuit upper torso.

The upper torso is the foundation of the spacesuit. The upper torso supports the life support system, displays and controls, the opening for entry and closure, the helmet, and the shoulder and waist mobility joints. Upper torso architecture therefore, has a great affect on life support configuration, don/doff capability, mass and volume, suit sizing, and suit performance particularly in terms of visibility, mobility and comfort. Of prime consideration, is the upper torso material. Historically, hard upper torsos (HUTs) have been made of aluminum or composite, and soft upper torsos (SUTs) have been made of dual layer coated and noncoated fabrics. Architecture concepts have included waist entry, rear entry, and zipper closures. Upper Torso architecture is a key driver for the early CEV and late Lunar exploration spacesuit systems definition.

This paper provides a review of probable Constellation Program requirements, existing upper torso architectures, and material candidates. Recent developments in the ILC Dover I-Suit fabric upper torso are discussed in relation to meeting program goals. Trade assessments suggest that fabric upper torsos, common to both Constellation Program spacesuits, provide the best advantage to meet the goals of the program.

INTRODUCTION

NASA has established the Constellation Program to accomplish the goals of the Vision for Space Exploration (VSE). The path for the Constellation program is to have a manned flight of CEV to the International Space Station (ISS) by 2012. The CEV will return to land (contingency water landing only) and crew will remain aboard the CEV in case of abort. This first phase of the Constellation missions is termed Block 1. By 2018, the CEV will be integrated with the Lunar Surface Access Module (LSAM). This is the earliest date for the first lunar landing; the goal is to have a manned mission land on the Moon no later than 2020. Four crewmembers can be carried to and from the Moon. Landing locations on the Moon are not limited by the vehicle return capabilities and the poles are possibilities for Lunar sorties. A minimum of two missions per year, starting with the first landing, will help establish a Lunar Outpost by 2022. This second phase of the Constellation missions is termed Block 2. Lunar outpost missions will help develop the technologies needed to reach Mars. The Mars mission milestone is 2032. See Figure 1.

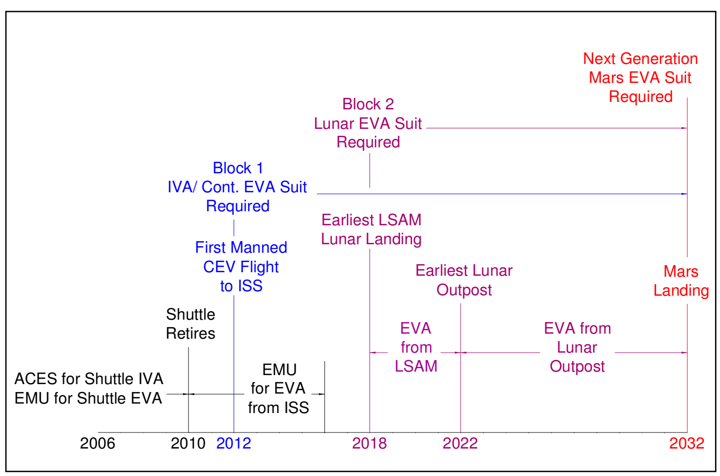


Figure 1. Constellation Program Timeline

The first spacesuit necessary for Constellation will be required to protect the crew during launch, entry, and abort scenarios from the CEV. In addition, the suit will be required to perform contingency EVA from the CEV. This first suit will be required by 2012. By 2018, a spacesuit will be required for lunar surface EVA. Finally, far term needs include modifications or upgrades to the suit for Mars surface EVA.

A Crew, Robotics, and Vehicle Equipment (CRAVE) contract study was undertaken to identify, and assess the feasibility of different suit system architectures. One-suit, two-suit, and three-suit architectures were proposed for study. As an example, Apollo demonstrated the potential of a one-suit reconfigurable system. Currently, two suit architectures, the Advanced Crew Escape Suit (ACES) and the Shuttle Extra-Vehicular Mobility Unit (EMU), meet the IVA and 0-G EVA needs of the Shuttle and ISS programs. To meet the Constellation Program needs, the current paradigm would be a three-suit system, one for IVA, one for 0-G EVA, and one for planetary EVA. However, multiple suit systems have negative impacts including mission flexibility, mass, volume, logistics, and cost. Based on the above timeline and study results, focus has been on a two-suit system. The Block 1 suit would used for Intra-Vehicular Activity (IVA) and contingency 0-G EVA from the CEV. The Block 2 suit would be used for lunar surface EVA only and would be stowed on the LSAM.

The Block 1 spacesuit will be defined in the near term. Design of the Block 2 spacesuit has an advantage of time to allow technological development. Design of the Block 2 spacesuit will be dependent to some degree on the Block 1 suit. The level of commonality between the two suits will greatly influence Block 2 upper torso design.

SYSTEM REQUIREMENTS

Some requirements are known for the Constellation Program. The Block 1 suit must protect the crew from launch, entry, and abort scenarios. The suit will be worn primarily unpressurized and must be comfortable. However, in case of cabin depressurization, the suit could be worn pressurized for up to 96 hours. In case of contingency EVA, the suit must have pressurized mobility to accomplish 0-G repairs, assembly, or vehicle transfer from CEV.

The Block 2 suit must provide surface EVA capability for lunar exploration and eventually habitat maintenance and assembly. The suit must function for long duration without return for ground based maintenance and repair. Dust and cold temperatures will be significant environmental challenges.

System requirements that affect upper torso architecture can be derived from the developing Constellation requirements. Table 1 lists and compares first order derived requirements for the Block 1 and Block 2 suits.

Table 1. First Order System Requirements Affecting Upper Torso Architecture

Requirement	Block 1	Block 2
Mass	As low as possible for comfort and CEV mass, overall space suit assembly (SSA) < 40	As low as possible for comfort and fatigue, overall SSA < 240 lbs.
Volume	As small as possible pressurized volume for seated dimensional envelope. Minimal unpressurized volume for stowage on CEV	As small as possible unpressurized volume for stowage on LSAM. Small pressurized volume for donning area
Comfort	Unpressurized comfort is highest concern, must be acceptable for 3-6 G loads and vibrations	Pressurized comfort for long duration EVA and varied activities
Entry Method, Don/Doff	Must be able to self don/doff quickly in limited CEV area	Must be able to self don/doff. Must manage dust at entry seal and prevent LSAM or habitat contamination
Vehicle Interface	Shoulder width must be minimal. Seat interface must be acceptable to secure crew and suit without harm from vibration and G load. Must be able to egress/ingress hatch.	Must interface with donning stand, and LSAM and habitat air locks, without dust contamination. Must interface with lunar vehicle. Potential for robotic interfaces.
Mobility	Must be able to operate vehicle pressurized. Must be able to egress vehicle pressurized. Must have sufficient mobility for contingency 0-G EVA.	Mobility is highest concern. Must have excellent range of motion and low torque for lunar EVA.
Sizing	Must accommodate broad range of crew sizes (5^{th} to 95^{th}). Must be able to resize on orbit.	Must accommodate broad range of crew sizes (5^{th} to 95^{th}). Must accommodate body changes due to 0-G and partial G. Must be able to resize on orbit
LSS Interface	Pressurized on umbilical.	Autonomous. Must have buddy system and recharge capability.
Structural Integrity	Factor of safety of 2 over nominal 3.75 psi operating pressure. Provide ability for short term, static 8.0 psi use.	Factor of safety of 2 over nominal 3.75 – 5.8 psi operating pressures and man loads. Provide ability for short term, static 8.0 psi use and bends treatment. Must protect from impact.
Protection from Environmental Threat	Must have survival equipment including thermal protection. Removable thermal layer for 0-G EVA	Must protect against thermal, radiation, and micrometeoroid hazards.
Chronological Life, Maintenance Interval	500 days, On-obit inspection, maintenance, and repair	500 days/300 EVAs, On-orbit inspection, maintenance and repair
Safety/ Reliability	High technology readiness level (TRL), proven technologies, design redundancies and fail safe modes	High TRL, proven technologies, design redundancies and fail safe modes

HISTORICAL PERSPECTIVE

Existing spacesuit systems (Figure 2), including flight qualified systems, meet some of the Block 1 suit requirements. Full pressures suits such as the Advanced High Altitude Flight Suit (AHAFS) provide sufficient pressurized mobility for high altitude aircraft operations. ACES and Sokol are currently used for IVA operations and meet requirements associated with IVA such as mass, vehicle seat interface and environment survival equipment. Apollo/Skylab is the only existing suit system that has met both IVA and 0-G requirements. However, Apollo suits did not have the life requirement expected of the CEV suit, nor was it easy to don and doff. The original waist entry I-Suit and the D-Suit, manufactured by David Clark were fabricated for NASA JSC to meet specific requirements for low weight and high mobility.

All of these suit systems have in common a fabric upper torso. ACES, Sokol, Apollo, and AHAFS have a one-piece torso with a slide fastener closure, while the I-Suit and D-Suit have a waist entry Body Seal Closure (BSC). The waist entry I-Suit is the only example with scye bearings. All of the suits have umbilical connections on the front torso for life support. Helmets vary between the suits, however the upper torso interface commonly includes a neck ring tie-down. The long vertical slide fastener closure limits waist mobility joint performance. Only Apollo/Skylab had a slide fastener and a fabric mobility waist joint.

Figure 3 shows past and present spacesuit systems that provide perspective for the Block 2 suit. Apollo met many of the Block 2 requirements although it was not designed solely for planetary EVA and was used for a limited number of EVAs. The Shuttle EMU and Orlan, designed for 0-G EVA, currently meet some Block 2 requirements for upper torso mobility, structural integrity, and safety and reliability, but significantly exceed mass requirements. The NASA JSC H-Suit was originally developed by ILC Dover as the ZPS Mark-III for Space Station. It was designed to have a longer cycle life and to meet higher structural loads than the Shuttle EMU, operating at a zero pre-breathe pressure of 8 psi. The H-Suit has since been reconfigured with lighter weight elements and has been used extensively in simulated planetary trials. The second generation ILC I-Suit was designed as a planetary suit and has been configured both with a waist entry and a rear entry upper torso.

The suits shown in Figure 3 demonstrate a wide variety of upper torso architectures with few similarities. All of these suits support an autonomous life support system (LSS), although Apollo could interface with the vehicle LSS. All of the upper torsos, with the exception of Apollo, have scye bearings. However, scye bearing size and orientation varies. Apollo has a slide fastener closure. Shuttle EMU is waist entry. H-Suit and the Orlan are rear entry suits.

Figure 2. Block 1 Suit Perspective

The material selection for the suits shown in Figure 3 also shows great variation between upper torso architectures. Both Apollo and the I-Suits have a coated fabric bladder and fabric restraint patterned upper torso. Shuttle EMU and the H-Suit have molded composite upper torsos. Orlan has an aluminum upper torso shell.

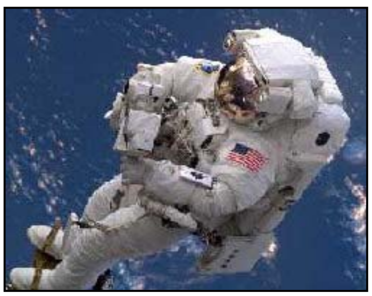
The Shuttle EMU and Apollo helmets are basically the same although Apollo had a small flexible joint in the upper torso at the neck ring that allowed slightly better visibility. The bubble shape has been replaced by the H-Suit and I-Suit hemispherical shapes. This hemispherical shape yields a larger interface with the upper torso but eliminates the need for a neck bearing or flexible mobility joint while improving visibility.

Orlan

H-Suit

Apollo A7LB

Rear Entry I-Suit



Shuttle EMU

Figure 3. Block 2 Suit Perspective

I-SUIT FABRIC UPPER TORSO DESIGN

The ILC waist entry and rear entry I-Suit SUT architectures are discussed in support of understanding their potential in the Constellation Program. I-Suit design and structural analysis are reviewed. Experience with the I-Suit SUT includes rapid resizing to fit 5th percentile female to 95th percentile male and unassisted don/doff.

DESIGN DATA

The waist entry I-Suit has a single layer polyester fabric structural restraint and underlying urethane coated nylon bladder. A composite wedge element separates the SUT from the helmet and provides for backpack attachment and pass through of air, water, and electric lines. Three sizes of SUTs have been manufactured, all using a 16-inch BSC. The BSC and neck ring closure mechanisms are a snap ring controlled by a locking handle. See Figure 4.

Figure 4. Waist Entry SUT

The rear entry I-Suit has a double layer polyester fabric structural restraint and underlying urethane coated nylon bladder. The composite wedge is eliminated. The upper portion of the rear closure provides for backpack attachment and pass through of air, water, and electric lines. The lower portion of the rear closure is fabric for mass reduction. The entry closure is a snap ring closure common with the I-Suit BSC and neck ring. See Figure 5.

Figure 5. Rear Entry SUT

The BSC ring, scye bearings, helmet and neck ring are interchangeable between the rear and waist entry I-Suits. The weight of comparable size rear entry and waist entry I-Suit SUTs is shown in Table 2. The comparison assumes a rear entry neck spacer ring used for attachment of forward facing displays, lights, etc., and a waist ring for shape retention in place of a BSC. The rear closure is approximately 9 pounds heavier than the BSC closure. Neither the rear closure nor composite wedge weights include the gas and water connectors. Neither the rear entry or waist entry weights include the neck ring disconnect. The fabric SUT structure weight is similar between the two SUTs. For comparison, the large size Shuttle EMU fiberglass pivoted HUT weighs 9.8 lb. without neck ring, Body Seal Closure (BSC), or scye bearings. However, embedded water lines, and Portable Life Support System (PLSS) and Display and Control Module (DCM) attachment points are included.

Table 2. Rear Entry and Waist Entry I-Suit SUT Weights

	Rear Entry I-Suit (lbs.)	Waist Entry I-Suit (lbs.)
Closure (Rear vs. BSC)	13.7	5.0
Composite Wedge	---	4.0
Attachment Rings (Neck Spacer and Waist Control)	3.3	---
Fabric	0.4	0.3
Total	17.4	9.3

STRUCTURAL ANALYSIS

The waist entry and rear entry I-Suits are manufactured using the same Dacron fabric as used on the Shuttle EMU restraint layer. The fabric is a plain weave with a yarn count of 52 x 46. The fabric strength is 300 lbs/in minimum in the warp direction and 250 lbs/in minimum in the fill direction. Seam construction has been established that is as strong or stronger than the fabric.

In developing the rear entry, a prototype single wall construction was built and tested to determine the pressure and geometry at failure. The SUT was pressurized to 16 psi before failure of a seam at the front of one of the scye bearings. The mean strength of the seam is known to be 387 lb/in. The hoop load for a cylinder is calculated as pressure times radius. Although the SUT is not a cylinder, an effective radius at the front of the SUT is determined to be 24 inches. New seam construction was established for double layer Dacron. The mean strength of the new seam is determined to be 620 lb/in. Assuming the same effective radius, it is estimated that the rear entry SUT would fail due to hoop load in the fabric at a pressure of 25.8 psi.

In comparison, the Shuttle EMU fiberglass Planar HUT is certified to meet a maximum operating pressure of 5.5 psi and a proof pressure of 15.8 psi with a factor of safety of 2. The proof pressure induces the equivalent of pressure plus man induced loads and accounts for the EMU being used for bends treatment. ILC has also manufactured a flexible textile hyperbaric chamber for bends treatment. The chamber is 31.5 inches in diameter and 6.9 feet long. The chamber has a factor of safety of 3 over the operating of 29.4 psi.

A concern for the rear entry was elongation of the fabric section of the rear door. The fabric section is two layers of Dacron restraint and a urethane coated bias ply bladder. Excessive elongation or “ballooning” of the fabric could cause interference with PLSS. A finite element model was created using ABAQUS to analyze the mechanical strength and deformation of the door structure under a pressure load normal to the door. At 4 psi, a maximum deformation of 1.37 inches occurs at the center of the fabric section of the door. See Figure 6A. A maximum stress of 3891 lb/in2 occurs at the perimeter of the fabric at the mounting flange, a factor of safety of 7.7 over the material strength. See Figure 6B.

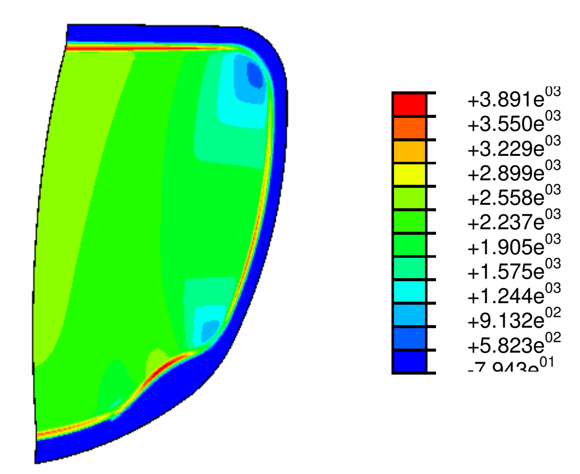


Figure 6A. Rear Entry I-Suit Fabric Door Deflection

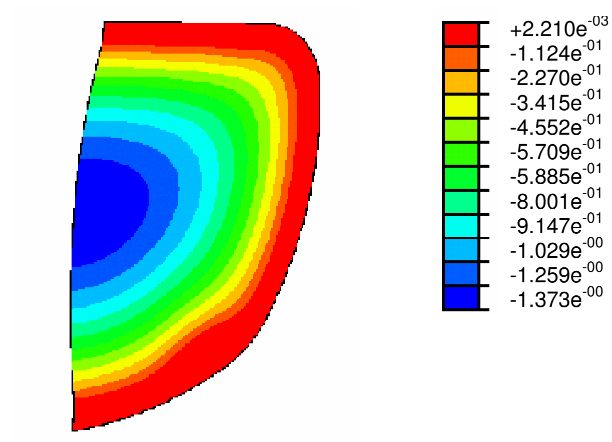


Figure 6B. Rear Entry I-Suit Fabric Door Stress

SIZING

The approach to sizing the I-Suit is based on use of common neck ring, scye bearings, and entry closure between all sizes. The smallest size waist entry SUT was designed to fit a female crewmember with stature near the 5th percentile. The largest size waist entry SUT was designed to fit a male subject with anthropometric torso measurements near the 95th percentile. Figure 7 shows the small waist entry I-Suit next to the large Shuttle EMU.

Currently, there is one size rear entry I-Suit SUT sized to fit large subjects. It will be possible to reduce the inter-scye distance and breadth of the SUT to fit smaller crewmembers. However, there will be some limit to minimizing the torso length to fit the 5th percentile female torso length without making a smaller entry.

Figure 7. Small Size Waist Entry I-Suit and Large Size Shuttle EMU

DON/DOFF

Don/Doff capabilities include the ability to self-don, the ease of donning/doffing, the ease of alignment in sealing the closure, and emergency extrication capability. The waist entry I-Suit has been donned both with and without a donning stand. Without a backpack, it is relatively easy to donn the waist entry I-Suit like a shirt and pants. With a backpack, a donning stand is used. In both cases, the subject is able to connect internal harnesses and water lines and latch and lock the waist entry BSC unaided. Umbilicals can be connected by the subject on the front of the suit.

Manned evaluation of the rear entry I-Suit found little to no difficulty in donning using a donning stand. Harnesses and water lines are routed to fasten in the rear and were secured by a technician after the subject had donned the suit. The subject is able to latch the rear door unaided. Likewise, when doffing, the subject is able to unlatch the rear door unaided. Doffing is slightly more difficult than donning due to the lack of resistance in the lower torso. The rear entry donning stand includes a “pull up” bar and foot stand to facilitate don/doff.

MATERIALS CONSIDERATIONS

Material selection affects a majority of the system considerations listed in Table 1. The following review provides a comparison of material concepts.

MASS AND STRENGTH

Table 3 shows a relative comparison of weights and strength of some textile, metal, and composite materials at comparable thickness. The textile thickness was calculated for a standard 1000 denier yarn, in a nearly maximum yarn count plain weave construction. Metal material properties are based on a thickness comparable to the textiles. Tensile strength for the textiles is based on the fabric construction and yarn properties. Strength is the same in the warp and fill directions for these balanced fabric constructions. Textile weights assume the specific restraint material and a urethane coated nylon bladder, similar to the Shuttle EMU bladder, for gas retention. Tensile yield strength is provided for the metal materials.

Table 3. Material Physical Property Comparison

Construction	Material	Tensile strength (ppi)	Weight (oz/in^2)	Thickness (mil)
1000 denier 55 x 55 plain weave	Polyester Fabric	1042	0.015	43
1000 denier 45 x 45 plain weave	Spectra Fabric	3968	0.015	51
1000 denier 55 x 55 plain weave	Vectran Fabric	2788	0.015	43
1000 denier 55 x 55 plain weave	Kevlar Fabric	3152	0.015	43
15-5 stainless PH1100 sheet	Stainless Steel	4800	0.194	43
7075-T73 Sheet	Aluminum	2019	0.070	43
6AL-4V	Titanium	2320	0.110	43
Epoxy impregnated Fiberglass	Epoxy impregnated Fiberglass	1920	0.098	43

The strength of metal and composite materials is comparable to the strength of textiles at the same thickness. However, flexural stiffness and impact resistance also dictate metal and composite thickness and construction. Therefore the thickness and weights listed in Table 3 are not representative of actual upper torso properties. Upper torsos made of Dacron fabric, aluminum and fiberglass reinforced epoxy materials do exist and can be compared. Table 4 lists the typical thickness of several upper torso constructions: ZPS Mark III, Shuttle EMU and the I-Suit.

Table 4: Material Thickness and Weight Comparison of Upper Torso Constructions

Suit	Material	Material Thickness (mil)	Weight (oz/in^2)
Shuttle EMU HUT	Fiberglass reinforced epoxy	90	0.205
Rear Entry I-Suit SUT	Double layer 440 denier Dacron with urethane coated nylon bladder cloth	33	0.016
ZPS Mark III	Aluminum	80	0.130
ZPS Mark III Brief Transition	Fiberglass reinforced epoxy	60	0.137

Strength and weight comparisons can be performed on these materials to some degree. As shown in the table, fabric offers a considerable weight savings over the use of metal or composite materials on an areal density basis. This weight savings remains despite the need for multiple fabric layers, restraint and bladder, whereas the hard upper torso design functions to both carry man loads and provide gas retention. However, the unique characteristics of the materials must be considered in addition to strength and weight comparisons.

The use of textiles offers flexibility in material design. A myriad of possibilities can be achieved by using fibers specifically targeting tenacity, elongation and other physical property characteristics, different yarn sizes and material constructions. Material construction alone can change cut, tear, and puncture characteristics. Lightweight material possessing low strength can be coupled with reinforcing materials, such as webbings, in high stress areas. This affords the designer the ability to minimize mass through fiber orientation using structure only where needed.

High tenacity textile fibers like Spectra, Kevlar, Vectran and Polybenzoxazole (PBO), posses low elongation. Therefore load sharing between yarns in a fabric construction is reduced. This can result in seam windowing and failed fibers. Kevlar and PBO are susceptible to flex fatigue and abrasion and therefore are poor candidates for components that are highly flexed (such as joints) or that are folded (such as for stowage). Polyester and Vectran are much less susceptible to flex fatigue and in general are better candidates than Kevlar or PBO for applications that require folding or flexing. Creep rupture must also be addressed. All polymeric materials exhibit this characteristic to varying degrees. Spectra, particularly susceptible to creep rupture, may be limited in its use, especially at elevated temperatures. Seam windowing, flex fatigue, and creep rupture can be mitigated through proper fabric construction design. Products, such as Pathfinder airbags, that utilize fabrics made from high tenacity fibers, demonstrate that these materials can be integrated into high pressure structural designs.

Due to textile's flexible nature, impact does not deform the material. Unless tensile loads are exceeded, there is no catastrophic failure of the material. However, the flexural stiffness of metals and composites makes them susceptible to damage or permanent deformation due to impact loads and therefore must be considered during design. Figure 8 shows the affects of stiffness on impact failure modes of aluminum, carbon fiber reinforced epoxy and fiberglass reinforced epoxy. As shown, the aluminum deforms and the fiberglass reinforced epoxy delaminates but neither fails catastrophically. The carbon fiber reinforced epoxy composite, the stiffest sample, failed catastrophically.

CHRONOLOGICAL LIFE AND MAINTENANCE

Life considerations consist of both cycle life limitations and chronological limitations. Wear, abrasion and cyclic loading are among the factors that dictate cycle life limitations. Chronological life is dictated by susceptibility of the materials to degradation mechanisms present in the use and storage environment. These degradation mechanisms include, but are not limited to UV degradation, hydrolysis, oxidation and corrosion. Maintenance interval requirements can be driven by either chronological limitations or by use limitations. An example of chronological limitations could include the replacement of seals due to degradation by hydrolysis. Requiring relubrication due to wash out is an example of use driven maintenance.

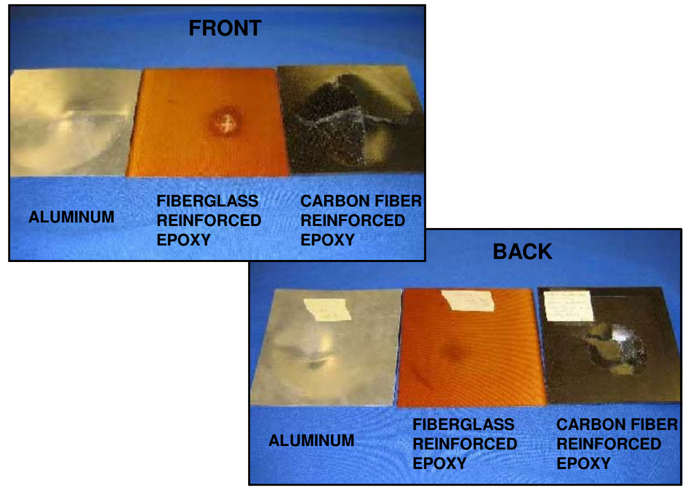


Figure 8: Results of Impact Testing at 300 ft-lbs

Polyester materials are currently limited to a 10 year chronological operational life in the EMU. Polyester materials are susceptible to UV degradation. They possess excellent resistance to oils, moisture, acids and bases. The susceptibility to UV degradation would not be characterized as severe.

Spectra is a linear low-density polyethylene (LLDPE) and as such possesses excellent chemical resistance. Spectra is resistant to oxidation and hydrolysis but is susceptible to UV degradation. Supplier literature lists Spectra as being more UV resistant than polyester. The chronological operational life of Spectra for EMU uses is 10 years.

Vectran, Kevlar and PBO materials are extremely susceptible to UV degradation. Kevlar is limited to a 6 year chronological life in the EMU due to poor UV resistance. Vectran, also extremely susceptible to UV degradation, is currently limited to 5 years in the EMU SSA. PBO is not currently used in the EMU but it is anticipated that life limitations would be similar to Kevlar.

Epoxy impregnated fiberglass composites are susceptible to UV degradation and hydrolysis. The hard upper torso of the EMU SSA, an epoxy impregnated fiberglass, possesses a chronological life of 15 years.

The use of thermal covers protects upper torso materials from direct UV exposure. The use of thermal covers allows textiles and composite materials to be used with an acceptable chronological life. However, the chronological life of these materials will be significantly less than metals.

Metals, degraded by corrosion and stress corrosion, possess a chronological life of 40 years for EMU applications. This life is predicated on a non-corrosive environment using materials that are not susceptible to corrosion or stress corrosion. Exposure to corrosive environments significantly reduces the life of these materials.

The use of metal or composites would most likely necessitate fracture control of the HUT. As a fracture critical item, the HUT would be required to conform to programs that include initial safe life analysis and test to certify the design, and subsequent non-destructive evaluation (NDE) testing for pre-delivery acceptance. NDE testing including microscopic inspection, structural pressure tests, and/or dye penetration tests would probably also be required throughout its life to ensure structural integrity.

Maintenance of a SUT is expected to be similar to the maintenance requirements of the EMU. Periodic visual examinations are performed on softgoods during pre-flight inspection or at 50% of the certified manned pressurized time. This inspection includes inspecting bladders for lifting reinforcement tapes, punctures, cuts, abrasion, delamination or cracking of the urethane and stress marks. The restraints are inspected for tears, cuts, snags, broken stitching, fraying abrasion and proper alignment. The inspection of a SUT could be easily performed on-orbit.

Maintenance of a composite HUT would also be expected to be similar to the current EMU composite HUT. This inspection, performed both during pre-flight inspection and at 50% of the certified manned pressurized time, also requires a visual examination of the HUT for scratches, deterioration, deformation, sharp edges, foreign matter and security of components. However, in addition to a visual inspection, the HUT requires a 10X inspection to detect cracking and degradation of areas where the HUT shell interfaces with hardware such as the BSC and neck ring as well as a structural test. NDE testing would be difficult to perform on-orbit.

It is anticipated that a metal HUT would be made primarily of aluminum due to weight. Most likely a metal HUT maintenance program would be similar to a composite HUT maintenance program. However, corrosion control of aluminum is dependant on anodize and damage to the anodize must be identified and repaired to maintain corrosion resistance. A maintenance program for a metal HUT would have to incorporate inspection and repair of anodize.

PROTECTION FROM ENVIRONMENTAL

Protection from the environmental threats such as radiation, thermal extremes, micrometeoroids, dust, and puncture is critical for the upper torso architecture since it covers the body's major organs. Protection is afforded primarily by an outer multi-layer fabric cover. Material candidates for the upper torso can also affect protection.

Radiation protection has been shown to be most effective with the use of highly hydrogenated materials such as LLDPE. Aluminum, although a shielding material, creates secondary radiation, thereby creating an additional radiation hazard. From this perspective, textiles provide the most potential to decrease radiation hazards. Materials with higher hydrogen content can be incorporated into either the bladder or restraint layer. The epoxy impregnated fiberglass materials also provides radiation protection without secondary radiation but provides limited ability to incorporate materials that would enhance protection.

The thermal cover, additional dust covers, and the protocol for don/doff, will protect the upper torso from lunar dust. The electrostatic charge of dust particles will cause it to "cling" to most materials. If the dust mitigation techniques still allow exposure of the underlying upper torso to dust, a fabric structure is more easily penetrated and damaged by dust particles than composite or metal.

On the Shuttle EMU, the thermal micrometeoroid garment (TMG) protects from micrometeoroid, puncture, and temperature extremes. The TMG maintains the restraint and bladder layer between approximately 50°F - 170°F when exposed to –169°F (for 10 minutes) to 325°F for the duration of an EVA and incidental contact of -244°F - 320°F. One area of concern for designs using Spectra is its performance at elevated temperatures. Spectra materials will exhibit creep at elevated temperatures and begins to lose strength at temperatures exceeding 250F. However, use of thermal covers prevents Spectra materials in the EMU from reaching unsafe temperatures. One of the positive attributes of Vectran and Kevlar is their flammability resistance and performance at elevated temperatures.

SYSTEM CONSIDERATIONS

Based on the first order Constellation Program requirements, historical perspective, and material considerations, the Block 1 and Block 2 upper torso architectures can be considered.

BLOCK 1 SUIT UPPER TORSO ARCHITECTURE

In order to meet mass and comfort requirements, it seems certain that a fabric upper torso will be needed for the Block 1 suit. Trade analyses of on back comfort, seat interface, and contingency EVA mobility requirements will likely show that risks outweigh the benefits of scye bearings. Umbilical connections will likely be on the front of the upper torso. The entry method may however be a point of departure from historical IVA suits.

Two options for entry/closures are slide fasteners and waist entry through a hard ring. Table 5 shows a trade assessment of entry types. Entry types were rated on a scale of 1 – 6 as to how well they meet first order system requirements. Low ratings of 1 and 2 are color-coded red and yellow respectively. A high rating of 6 is color-coded green. Ratings were weighted according to the perceived criticality of the requirement

Table 5. Block 1 Upper Torso Entry Method Trade Assessment

Requirement	Weight Factor	Slide Fastener	Waist Entry
Mass	0.9	5	2
Volume	0.9	4	3
Comfort	1.0	4	3
Don/Doff	0.9	2	4
Vehicle Interface	0.7	5	3
Pressurized Mobility	0.8	4	5
Sizing	0.6	3	4
LSS Interface	0.7	5	5
Structural Integrity	1.0	2	6
Protect from Environmental Threat	0.6	3	3
Chronological Life, Maintenance Interval	0.8	2	4
Safety/Reliability	1.0	1	5
Total		32.3	39.1

Slide fasteners have the advantage of lower mass. Although the entry method does not affect the shoulder width, which is the primary concern for seat envelope, slide fasteners could result in lower stowage volume. Unpressurized comfort is intuitively better with a slide fastener. A hard ring has greater impact to the vehicle in accommodations for securing the suit in the seat. The hard ring must be fixed in position in the seat and the crewmember must be secured inside the suit. However, it is possible that seat and suit design provide acceptable comfort for waist entry. Waist entry has the advantage of strength and reliability. Slide fasteners alone will not withstand an 8 psi load requirement. Slide fasteners fail open and cannot be repaired or replaced.

Entry method has the greatest impact on don/doff. Don/doff was reportedly difficult with the Apollo suit. Slide fasteners can be difficult to operate, particularly if not cleaned and lubricated often. Sokol is reportedly easy to don/doff partially because of two long slide fasteners that are oriented to form a triangular flap. However, shorter slide fasteners and circumferential orientation will be necessary to afford a waist flexion joint.

The Block 1 suit can be assumed to be a soft fabric construction with no scye bearings. The initial trade assessment shown in Table 5 suggests the use of a waist entry. However, comfort, vehicle interface, and don/doff require further study to make more conclusive ratings to define the entry method. A final consideration for the Block 1 upper torso architecture is extensibility to the Block 2 suit. Besides a common fabric structure, both the waist entry and neck ring helmet disconnect are potential areas for establishing commonality.

BLOCK 2 SUIT UPPER TORSO ARCHITECTURE

An important consideration for the Block 2 suit upper torso architecture is the material. The options exemplified in the suits in Figure 3 and in the materials review can be generalized as SUTs and HUTs. Table 6 shows a trade assessment of SUT versus HUT. Ratings are based on a scale of 1 – 6 and are weighted according to the perceived criticality of the requirements for the Block 2 suit.

Table 6. Block 2 SUT versus HUT Trade Assessment

Requirement	Weight Factor	SUT	HUT
Mass	0.9	6	4
Volume	0.7	4	3
Comfort	1.0	3	3
Don/Doff	0.9	5	4
Vehicle Interface	0.8	4	4
Pressurized Mobility	1.0	4	4
Sizing	0.7	5	2
LSS Interface	0.7	3	5
Structural Integrity	1.0	5	5
Protect from Environmental Threat	0.8	3	3
Chronological Life, Maintenance Interval	0.8	3	4
Safety/Reliability	1.0	4	4
Total		41.5	39.1

As previously discussed the mass of a SUT is one advantage over the HUT. Assuming a fabric restraint and coated bladder with a weight of .016 oz/in^2, a large size SUT I-Suit shell (no bearings or disconnect) weighs 0.4 lbs. The same area shell fabricated from fiberglass epoxy composite with a weight of .205 oz/in^2 is 5.1 lbs and from aluminum with a weight of .130 oz/in^2 is 3.3 lbs. The difference is only 2% of an overall SSA weight of 240 lbs. However, the 3-5 lbs weight savings might better be spent on a safety redundancy or advanced technology.

The stowed volume of a SUT depends on architecture. A rear entry SUT without life support can be folded flat as shown in Figure 9. A waist entry SUT will require less volume.

Figure 9. Stowed Rear Entry SUT

When a SUT is pressurized, it becomes hard. There is no difference between the pressurized mobility and comfort of a SUT versus a HUT. In addition, for a Block 1 suit, there is no difference between vehicle interfaces for a SUT and HUT. Vehicle interfaces are more dependent on other aspects of upper torso architecture such as entry and the helmet.

Regardless of architecture, the unpressurized flexibility of the SUT is advantageous for donning. If the scye openings can re-orient slightly, akin to a gimballed scye opening, then donning is easier. For a waist entry SUT architecture, the BSC can rise slightly during donning , shortening the length of the upper torso and making the scye openings more accessible. For both a waist and rear entry SUT, the scye bearings can have a smaller diameter than typical HUT designs. The use of smaller scye bearings, also allows a shorter torso length.

Both the SUT and the HUT could be developed in sufficient sizes to meet the 5^{th} to 95^{th} percentile population. There are two aspects of SUTs that offer sizing capabilities not available with HUTs. First, the SUT fabric patterns can be rapidly redesigned and fabricated, The time and cost to produce multiple and custom sizes is therefore better for a SUT than a HUT. Second, a SUT can be resized on-orbit. Several options are available. A mechanical static lacing, similar to the baseline Shuttle EMU sizing strip, can take up fabric length or width. Active systems such as “nastics” have been studied to identify potential actuators and methods for force multiplication to reposition the SUT scye angles. Upper torso sizing can also improve donning by allowing SUT breadth to open before donning and returning to nominal configuration prior to pressurization.

The Block 2 suit upper torso must support an autonomous life support system. The LSS interface is affected by the entry method and the upper torso material. A HUT allows for direct structural attachment of LSS components and mounting of pass-thrus. While umbilical connectors and single pas-thrus are successfully and securely flange mounted to SUTs, structural attachment of a LSS or today’s Shuttle EMU Display and Control Module (DCM) requires mounting to the closure hardware. This limits location of LSS components and could require additional mounting hardware.

HUTS are often perceived to be structurally superior to SUTs. In fact, textile restraints and bladders compare favorably with metals and composites. A SUT is more resistant to blunt impact damage than a HUT, as previously discussed. A SUT can be designed with adequate tensile strength for use of a Block 2 suit at 8 psi or higher for bends treatment.

Fabric structures will not provide as uniform load distribution to hardware interfaces as hard structures. Therefore, bearings and disconnects need to be rigid enough to prevent torsional deformation that can cause leakage or high torque. This is true throughout the SSA and is not specific to the upper torso. A HUT therefore has an advantage in ability to reduce the mass of scye bearings and entry closure. However, it is noted that molded HUTs typically have added mass due to rigid inserts at these interfaces.

Cuts and punctures are considered external threats, as are extreme temperature, micrometeoroids, and dust. The block 2 suit TMG can be assumed to provide adequate protection against cut and puncture throughout the SSA. Protection from environmental threat is not considered a detriment of a SUT versus HUT.

As previously described, HUTs typically have a longer chronological life than SUTs. However, the requirement for Block 2 suit longevity also includes time between ground based inspection and maintenance. The SUT offers an advantage in ability to inspect for damage and reduced maintenance.

The Shuttle EMU provides a history of safety and reliability for both the composite HUT and the softgood SSA. There is no difference between the SUT and HUT in terms of safety and reliability.

In addition to material selection, the Block 2 suit upper torso architecture is defined by the entry method. Waist entry and rear entry are the two leading concepts for entry/closure for the Block 2 suits. The trade assessment shown in Table 7 is based on initial assumptions of weighting factors for requirements that affect entry method.

Table 7. Block 2 Upper Torso Entry Method Trade Assessment

Requirement	**Weight Factor**	**Waist Entry**	**Rear Entry**
Mass	0.9	5	3
Volume	0.7	4	3
Comfort	1.0	3	3
Don/Doff	0.9	3	6
Vehicle Interface	0.8	3	5
Pressurized Mobility	1.0	4	4
Sizing	0.7	4	3
LSS Interface	0.7	4	4
Structural Integrity	1.0	4	4
Protect from Environmental Threat	0.8	3	3
Chronological Life, Maintenance Interval	0.8	3	3
Safety/Reliability	1.0	4	4
Total		37.8	38.9

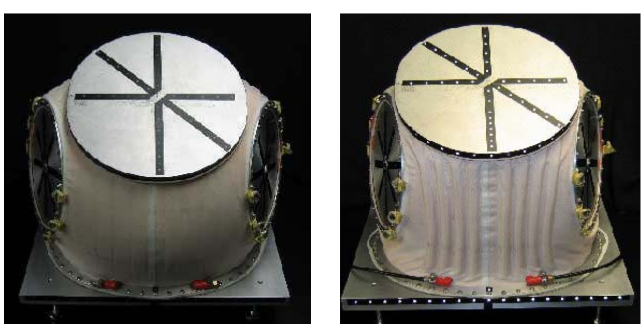
The rear entry has slightly more mass due to the size of the opening and the strength of the closure required to manage higher pressure loads. The waist entry requires less volume for donning which may be critical to the LSAM. Self donning has been demonstrated on-orbit with both methods in the Shuttle EMU and Orlan. ILC subjects find donning the rear entry I-Suit easier than the waist entry. In waist entry spacesuits, the inter-scye distance must be large enough to allow donning. In rear entry, there is less restriction on inter-scye dimension, although the orientation may be tilted forward so that the rear of the scye openings spans the rear entry. In rear entry designs there is less length available for the waist component of the lower torso which may affect sizing for smaller crewmembers. Restrictions on scye placement and waist length can have a minor impact on mobility. Finally, for lunar missions, dust management will be a significant challenge. One concept for lunar outpost is to have a rear entry spacesuit attached to the habitat wall, acting as the air lock. While more research is required to develop dust mitigation strategies, a rear entry suit appears to be the best candidate.

A strong case is made for a Block 2 suit rear entry SUT. To meet pressurized mobility requirements it will undoubtedly have scye bearings. The helmet will likely be elliptical in order to provide the best visibility. A Block 2 SUT could have the advantage of commonality with the Block 1 suit material and helmet disconnect. In addition, a rear entry torso could maintain a BSC common with the Block 1 suit. Commonality provides advantages for mass, volume, vehicle interfaces, maintenance, and safety and reliability.

ADVANCED TECHNOLOGY

Several advanced technologies are currently being developed that may bolster the performance capabilities of SUT based architectures. Nastics, self-helaing bladders, health monitoring, and antimicrobial materials are at TRLs that could be matured to meet the needs of the Block 2 suit.

A NASA funded study is being conducted to identify methods for reshaping the SUT and repositioning scye angles during use. One example of actuator technology, a “fluidic muscle”, is a braided pneumatic tube that contracts in length with increasing internal pressure. Another actuator technology, “nastics’, uses air retaining bladder cells that draw up length when pressurized. Figure 10 shows a “nastic” extra large size waist entry I-Suit SUT in pressurized and relaxed positions. This technology has potential for improving sizing and donning of the I-Suit SUT as well as increasing mobility for specific tasks such as hammering on the ground versus overhead work.



UNPRESSURIZED NASTIC SUT **PRESSURIZED NASTIC SUT**

Figure 10. Nastic SUT

Self-healing technologies that seal small penetrations in a bladder have been developed at ILC Dover. Technologies include visco-elastic gels, compressed foams, and micro and macro encapsulation of reactants. A lower arm bladder manufactured with a visco-elastic gel was successful in sealing 2 mm penetrations at 4.3 psi. See Figure 11. This technology adds weight and decreases mobility. However, for the non-mobile area of the I-Suit SUT, the increase in areal density of .029 oz/in^2 is still less than half the areal density of fiberglass and may be an acceptable trade for a safety redundancy.

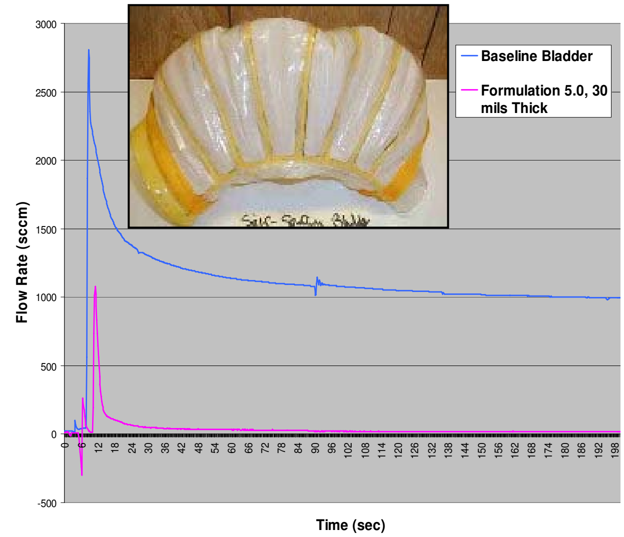


Figure 11. Self-Healing Bladder

Health monitoring of textiles can be achieved by distributing sensors in the textile that can identify damage. ILC Dover has used several technologies in textile and film constructions. Conductive pathways can be sewn or deposited on fabric and films for breakpoint detection. Figure 12 shows the ILC Dover Sensate Liner, silk screened traces on film, and sewn traces in Vectran fabric. This technology provides an opportunity for reduced maintenance and inspection and improved life for textiles, which will be particularly important during long lunar outpost missions.

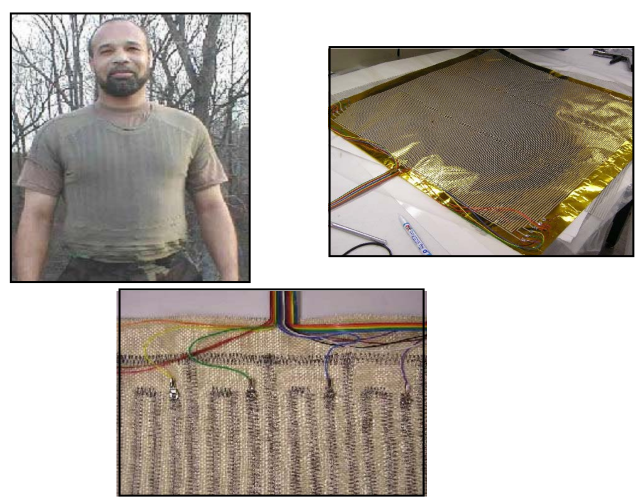


Figure 12. Sensate Liner, Traces on Film and Fabric

Antimicrobial materials can reduce microbial growth on textiles, thereby reducing cleaning intervals and promoting a more sanitary suit. Technologies include the use of inorganic materials, like silver, with innate bacteriostatic properties, and incorporation of organic materials like antibiotics into films or fabrics. A silver dyed nylon knit is currently used in the Shuttle EMU comfort gloves. An added benefit for lunar outpost missions could be a reduction in planetary contamination from suit-born microbes.

CONCLUSION

The Constellation program will require new spacesuits to accomplish the goals of the Vision for Space Exploration. This paper assumes a two-suit system. The Block 1 suit, required by 2012, will be an IVA and contingency 0-G EVA suit used on the CEV. The Block 2 suit, required by 2018, will be a lunar EVA suit stowed on the LSAM.

The upper torso is the corner stone of the spacesuit and it affects system sizing, performance, vehicle interfaces, and safety. The first order requirements that affect upper torso architecture are derived from developing Constellation Program requirements. Historical perspectives point to advantages and disadvantages of previous concepts used to meet similar requirements, such as Apollo, ACES, and Shuttle EMU.

A strong case is made for a fabric upper torso for the Block 1 suit as well as the Block 2 suit. Textiles offer lower volume, superior weight savings on an areal density basis, and proven reliability. Textile architectures can be tailored to meet required pressure and man induced loads, in multiple, custom, and flexible sizes. Protection from external risks to the restraint, such as puncture, thermal damage, and UV damage, is provided by fabric outer covers, as is the case with the Shuttle EMU. Inspection, repair, and replacement of SUTs extend their useful life on-orbit and are more feasible than maintenance of HUTs.

Comfort and mass are two of the most critical requirements for the Block 1 suit. The suit mass and seat interface must provide upressurized, seated comfort for loads up to 3-6 Gs. Crewmembers must be able to don the suit quickly in a limited area. Initial assessments suggest a fabric upper torso architecture with a waist closure and no scye bearings. However, studies are ongoing to obtain further data.

A lightweight upper torso with scye bearings will be necessary to meet the most critical requirements of comfort, mass, and mobility for the Block 2 suit. SSA mass, including the self supported LSS, will affect comfort and fatigue. Don/doff strategies will be important to prevent dust contamination of the LSAM and lunar habitat. Initials assessments suggest a rear entry upper torso. Additional studies are necessary to evaluate don/doff in the LSAM and dust mitigation strategies.

Pursuit of a Block 1 configuration with commonality and adaptability to the Block 2 configuration is recommended. The benefits of commonality to the Constellation program include lower cost, mass, and volume, and improved logistics for vehicle interfaces and maintenance. Safety and reliability can be gained by reducing the complexity of multiple systems. The ILC waist and rear entry I-Suit SUTS provide a good starting point for the Block 1 and Block 2 upper torso architectures. The waist entry I-Suits have been in service for 7 years and the rear entry I-Suit has been in service for 1 year, including 2 weeks continuous use in simulated planetary trials. These suits will be used in on-going evaluations to support and define Constellation program requirements.

Advances in materials and technologies such as “nastic” cells, self-healing bladders, health monitoring systems, and antimicrobial materials are being pursued by ILC. These technologies provide a further advantage to textile upper torso architectures for reduced maintenance, improved life, and improved safety.

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