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Space Suit Concepts and Vehicle Interfaces for the Constellation Program

D. M. Klaus
University of Colorado Boulder

J. Metts
University of Colorado Boulder

R. Kobrick
University of Colorado Boulder, kobrickr@erau.edu

M. Mesloh
University of Colorado Boulder

T. Monk
University of Colorado Boulder

See next page for additional authors

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Authors
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University of Colorado at Boulder

ABSTRACT

In carrying out NASA's Vision for Space Exploration, a number of different environments will be encountered that will require the crew to wear a protective space suit. Specifically, four suited mission phases are identified as Launch, Entry & Abort profiles, Contingency 0g (orbital) Extravehicular Activity (EVA), Lunar Surface EVA and Martian Surface EVA. This study presents conceptual design solutions based on a previous architecture assessment that defined space suit operational requirements for four proposed space suit configuration options. In addition, a subset of vehicle interface requirements are defined for enabling umbilical and physical connections between the suits and the various Constellation spacecraft in which they will be used. A summary of the resultant suit and component concepts and vehicle interface definitions is presented. This work was conducted during the fall semester of 2006 as part of a graduate aerospace engineering design class at the University of Colorado.

INTRODUCTION

NASA's Vision for Space Exploration (VSE) presents a wide variety of operational environments in which astronauts will need the protection of a space suit, both inside the vehicle and during Extravehicular Activity (EVA), which can be under either orbital or planetary surface conditions.

The initial mission phase entails launch, entry and abort (LEA), during which a pressure garment will be worn to accommodate potential emergency depress scenarios, while enabling vehicle operations and rapid emergency egress by foot, via parachute, or into water. Contingency EVA during orbital flight introduces additional demands on suited operations, mainly driven by the weightless, vacuum and radiation environments encountered in space. Finally, lunar and Mars excursions present added space suit design requirements for enabling surface mobility and addressing dust contamination.

Given that some form of protection will be necessary for the crew to operate in each of the aforementioned environments, various architectures have been proposed ranging from using a different suit for each unique operational environment to designing one suit that is capable of functioning in all environments encountered, perhaps with some level of modularity expected.

Previous analysis concluded that two unique design architectures provided the most feasible options. They are defined as *Architecture 1*, using one suit for LEA and 0g EVA and another for planetary surface EVA, either lunar or Mars, and *Architecture 3*, using a single suit for all activities [1]. At the level of detail addressed by this prior study, the two remaining candidate architectures could not be further down-selected. However, it was suggested that if the dust concern could be adequately controlled, *Architecture 3* would be superior in terms of overall logistics and total cost. One of the recommendations from the architecture study was to begin defining conceptual suits that could be included as design options in subsequent trade studies. This recommendation formed the basis for the current effort.

CONCEPTUAL MULTI-USE SPACE SUIT

Since *Architecture 3* appeared to have an overall advantage if dust contamination could be handled, this project was aimed at examining concepts that could enable a single suit to be used for all mission phases defined above. In order to carry out the study, one team was aligned with each of the four suited mission phases and tasked with reviewing requirements and generating conceptual design solutions within each category of use. From this pool of ideas, an integrated suit concept was established that, in principle, could allow a single pressurized garment to be worn for the entire mission, with modular elements incorporated to meet unique environmental demands during extravehicular use. Essentially, the LEA suit must be designed to provide the underlying pressure garment function to be used inside various outer layers needed for thermal, radiation and dust control. This uniquely integrated, modular single suit concept is described as follows.

BACKGROUND

Our conceptual design process began with a review of previous and existing operational suits. The various suit capabilities and design parameters were examined for compatibility with the Crew Exploration Vehicle (CEV) requirements. The functionality provided by the early 'capsule-based' suits, in particular the Gemini G4C, is similar to what is expected to be needed during the initial CEV missions requiring EVA without an airlock. During the early US Apollo program, the primary spacesuit was the A7L model. The A7L provided a backpack-style Portable Life Support System (PLSS) capable of a 7 hour EVA on the lunar surface. Improvements made for the A7LB version included increased mobility in the waist and joints for sitting on the lunar rover and bending during geology-focused EVAs. The A7LB was modified to operate at 34 kPa (5 psi) via umbilical for Skylab.

NASA's Shuttle Launch and Entry suit had a heritage based on suits worn by US Air Force pilots flying the SR-71 and U-2 in the 1970's, as well as the suit worn by the Gemini astronauts. The design underwent modifications prior to use on the early shuttle flights that included attachments for a parachute harness, inflatable rubber bladders in the legs to prevent the astronauts from blacking out during reentry and an escape harness (NASA, JSC-19450, 1989). This suit remained basically unchanged from the early shuttle flights until the introduction of the Launch Entry Suit (LES) for STS-26. The LES was worn by shuttle astronauts after 1988. Its primary purpose was to protect against rapid decompression at high altitude, hypothermia in cold water, high temperature during reentry and toxic gasses emitted by the orbiter after reentry [2].

The original LES design did not incorporate a provision for cooling or ventilation and as a result the crew experienced elevated body core temperatures that increased the effects of orthostatic intolerance. The suit was then modified to allow for ventilation via cabin air but that proved to be ineffective and ultimately a liquid cooling undergarment was incorporated. The LES also incorporated pressure bladders in the legs as well as zippers (as opposed to lock rings) for attaching the gloves. The LES was worn by the shuttle astronauts until 1995 when NASA introduced the Advanced Crew Escape Suit (ACES).

The ACES suit is currently worn for shuttle flights. It was altered from the earlier LES suit to simplify the design, minimize overall weight, reduce overall bulk and optimize self-don/doff operation [3]. It is a one-piece full pressure suit with locking rings for the glove attachments and laced boots. The ACES suit is worn with a nonintegrated anti-G suit for reentry. The anti-G suit has inflatable abdominal bladders and partial leg bladders. A manifold located on the left thigh that is attached to the orbiters oxygen system controls this suit. A knob on the thigh that allows the bladders to be inflated up to 17 kPa (2.5 psi) controls the inflation. They are inflated to 10 kPa (1.5 psi) per the entry checklist. A survival backpack is also donned by the astronauts prior to entering the orbiter and is not integrated with the suit. The suit weighs approximately 35 kg (77 lbs) and is individually fitted to the astronaut. It provides protection up to 15,240 m (50,000 ft) for bail out and up to 30,480 m (100,000 ft) for loss of cabin pressure or oxygen [4].

The Russian Berkut spacesuit, worn on the first human EVA by Aleksei Leonov during Voskhod 2, was a modified version of the Russian Launch, Entry, and Abort (LEA) suit, Sokol SK-1. The Russian Yastreb spacesuit was the first suit designed for use specifically during EVA. With input from Leonov, the spacesuit was designed to be much more rigid to prevent "ballooning" at the joints that he experienced during the first spacewalk on Voskhod 2. The Russian program began utilizing suits for launch and entry after the June 1971 flight accident when the Soyuz 11 depressurized upon reentry and three cosmonauts were killed, with the Sokol aviation rescue suit initially identified as a candidate for enabling cosmonauts to function in environments encountered in the event of an abort, including vacuum [5]. Many modifications to the Sokol suit were made over the years [6].

The Russian Orlan spacesuit consists of flexible limbs attached to a rigid torso and helmet assembly. It is a "rear-entry" suit, meaning that a cosmonaut enters the suit from the rear and then closes the PLSS backpack for full enclosure. When first used on Salyut 6, the PLSS allowed for a 3-hour duration EVA with an umbilical providing power and telecommunications. Subsequent improvements have increased the maximum EVA duration to 9 hours and eliminated the need for an umbilical. Additional improvements on the DMA model consisted of improved gloves, an improved PLSS, and incorporation of lighter and more flexible fabrics in the arms and legs. The most recent iteration, Orlan M, is currently used on ISS.

NASA's Space Shuttle Extravehicular Mobility Unit (EMU) features a hard upper torso and a backpack-style PLSS capable of supporting a 9 hour EVA with a nominal operating pressure of 30 kPa (4.3 psi). It utilizes Multi-Layer Insulation (MLI) for pressurization and thermal and micrometeoroid protection. The EMU is modular in design with several different limbs and torso sizing options to allow for custom fitting. It is comprised of an upper and lower torso assembly that requires help from another crewmember to don and doff. Improvements over the Shuttle EMU for use on ISS included certification for 25 flights without on-ground maintenance required and improved sizing and mobility capabilities.

A review of prior space suits and the related operational complexities described above provided an appreciation for the daunting task of meeting all requirements for the Constellation Program with a single suit. The following sections present a select subset of our conceptual design suggestions proposed as a starting point toward enabling this goal to be achieved.

LAUNCH, ENTRY AND ABORT

One of the elements required for the initial phase of the Constellation Program missions to the International Space Station (ISS) is a space suit system providing at least intravehicular launch, entry and abort capability. Crew protection and survivability during LEA scenarios, including spacecraft depressurization, egress mobility, and water survival are primary design drivers for the LEA suit. Zero gravity (and possibly Lunar and Martian surface) contingency Extra Vehicular Activity (EVA) capabilities are also desired. With Earth's atmosphere comprised of approximately 21 percent oxygen and 79 percent nitrogen at sea level and total pressure decreasing with altitude, humans must wear spacesuits that supply oxygen for breathing and maintain a pressure around the body to keep fluids in the liquid state. Other requirements that drive the LEA suit include high altitude protection, rapid decompression protection and thermal protection [7].

LEA SUIT REQUIREMENTS

The specific environments that the LEA suit could potentially encounter are variable pressure conditions in suits and vehicles; vacuum exposure during cabin depressurization; fire, smoke, or other hazardous materials in the case of an emergency; variable g-loads such as 0g, 1g, or greater than 1g during launch and reentry; thermal extremes in the cabin or on terrestrial surfaces; variable surface characteristics on the Earth, moon, or Mars; and water in the case of a water landing.

Furthermore, the largest driver for LEA suit is the requirement to provide sustained life support in the event of long-term cabin depressurization [1]. The amount of time that the suit must provide life support is dependent upon where in the mission the loss of cabin pressure occurs. In designing for a worst-case scenario, it is assumed that the loss of CEV cabin pressure occurs just after the trans-Lunar injection burn from LEO. If the CEV suffers a non-repairable failure that causes a loss of pressure, the mission would have to be aborted. However, this would require the vehicle to complete the trans-lunar coast and return to the Earth on a free return trajectory and would require the crew to remain inside the LEA suit for the entire 144 hour duration.

Key functional, operational, and interface requirements for the LEA suit needed for the Constellation Program are microbial control for long-term use and provision of life support consumables, and operational capability in a vacuum. Additionally, other requirements such as waste management become more crucial since the astronaut has the potential to spend 144 hours in a suit. For the single suit architecture proposed here that utilizes the LEA suit as the underlying pressure garment for all the suit configurations, dexterity and mobility at vacuum becomes an especially critical parameter. To a large extent, the success of our proposed conceptual single suit, modular architecture hinges on the design of the LEA pressure garment.

Some of the difficulties associated with designing a LEA suit are the wide ranges of atmospheric and gravitational parameters encountered. During launch, the shallow breathing that can result from high-g loading may also dictate a higher oxygen concentration or an increased ventilation rate. In the space environment, rotational accelerations encountered during LEA maneuvers are approximated at ±10 deg/s^2 (omnidirectional), which is much greater than typically experienced on Earth and during reentry, astronauts may experience accelerations up to 4g's in the ±Gx direction, 1g in the ±Gy direction, and 0.5g's in the ±Gz direction [4].

LEA SUIT CONCEPTS

In order to meet the required 144 hour in-suit abort scenario in a depressurized cabin, the astronaut will need to be able to get food, drink, or medical supplies into the space suit and waste out. A conceptual drawing of the suit-access airlock in its deployed open position is shown in Figure 1. When not in use, the airlock would be removed or collapsed in a manner such that it will not interfere with nominal operations or restrict suit mobility.

Figure 1. Suit-Access Airlock Concept

Internal access would require that the astronaut be able to remove their arm(s) within the suit sleeve and reach into the internal opening of the airlock to retrieve the transferred article (illustrated in Figure 2). This becomes a major design driver of the pressure garment.

In consideration of the demanding design requirements, these design concepts provide a starting point for further analysis and preliminary engineering design to follow. The requirements were defined mainly by determining parameters that need to be met for crew protection and survival. The primary drivers for the LEA suit are vacuum functionality for use as the base pressure garment configured for EVA operations and the NASA defined 144-hour suited abort scenario for lunar polar missions. The primary LEA suit concepts proposed here involve incorporating a suit-access airlock to allow exchange of items (e.g., food, water, medicine or waste) to/from the suit interior coupled with an expandable suit design that permits one hand (at a minimum) access within the suit to address the potential for wearing the suit for 144 hours. These concepts are intended to permit the LEA suit to function as an individual suit inside the spacecraft and as the core pressure garment to be worn beneath add-on components to meet the integrated needs of a modular, single-suit architecture.

Figure 2. Internal Suit-Access Airlock Concept

CONTINGENCY ZERO-G EVA

The potential for conducting contingency Extravehicular Activity (EVA) on orbit must also be considered. For the single-suit architecture, the focus of this conceptual design effort was placed on what would be needed to adapt the LEA suit for contingency zero-g EVA use.

CONTINGENCY 0G EVA SUIT REQUIREMENTS

NASA's Vision for Space Exploration (VSE), dictates that the suit must provide contingency EVA capability during the course of LEO operations in the immediate future with the option of extensibility to Lunar/Martian transit, orbital, and surface operations. These objectives, in the short term, intrinsically define the envelope of operation for contingency EVA suit as that encountered outside the spacecraft in free space. Because the CEV will not have an airlock, the LEA suit must be vacuum-rated to provide protection from vacuum in the event of cabin depressurization upon orbit insertion or continuing operations in which the LEA suit will be worn. With this in mind, the relevant environmental parameters that the 0g contingency suit must provide in addition to those already addressed by the LEA suit are as follows: thermal extremes, micrometeoroids and radiation.

While free space can be extremely cold, the insulating properties of the space suit, combined with the metabolic heat given off by the occupant and absorption of incident solar radiation, generally cause the suited crewmember to be too warm rather than too cold. In fact, the outer temperature of a suit with approximately 60% surface area exposed to incident radiation can climb to as high as 394 K depending on properties the outer material. The suit must either actively and/or passively maintain thermal equilibrium at a temperature appropriate for human physiology.

In addition to providing thermal protection, the 0g contingency suit must provide mobility and dexterity in microgravity. Micrometeoroid protection must also be provided. This is typically accomplished by layering fabrics in the suit for energy dissipation. Radiation protection is a similar environmental consideration. Outside of the Van Allen belts, the daily DNA effective irradiance is typically 3100 W/m2, or about 1500 times the value at the equator on Earth [8]. However, it is important to keep in mind that contingency EVAs are expected to occur infrequently, if at all, thus radiation protection during flight is assumed to be primarily considered in the design of the vehicle.

A contingency EVA involves the crew exiting the vehicle, getting to a desired location, performing a task otherwise unachievable, and re-entering the vehicle. Examining events that could potentially require a contingency EVA, two scenario types were identified as design drivers in this analysis. These include the repair of the CEV during translunar or low planetary orbits and a vehicular transfer due to a rendezvous/docking malfunction. Potential situations could involve external repair of a micrometeoroid or orbital debris (MMOD) impact or a Lunar Lander/CEV rendezvous and docking malfunction upon return from the lunar surface. In both scenarios, some or all of the crew will be exposed to the space environment.

As previously mentioned the single suit architecture proposed requires the LEA suit to be vacuum rated and provide basic functionality in microgravity. The LEA spacesuit concept currently requires an umbilical connection to the spacecraft. The flow of mass and energy from the spacecraft to the LEA spacesuit includes oxygen, power, water and telecommunications. Additional requirements for a 0g contingency EVA would be external vehicular access from an umbilical connection. In addition, the umbilical length will need to be expandable to any portion of the vehicle exterior. The addition of umbilical ports at strategic locations on the spacecraft exterior might be needed to facilitate access to all external surface area.

The spacesuits also need a port to allow for the connection to the umbilical. Preferably, this connection will be located on the front of the spacesuit to allow the astronaut to access it without assistance. If the LEA suit provides this type of access, additional modification will not be required. It may also be advantageous to add an additional umbilical port so that an astronaut can connect another umbilical before disconnecting the first umbilical. This will allow for a "daisy-chaining" that could be achieved by several shorter umbilicals rather than one long one if pressure drops are of concern.

CONTINGENCY 0G EVA SUIT CONCEPTS

In order to accommodate 0g contingency EVA with a single suit, modular architecture, a number of unique design challenges arise. These challenges can be categorized as mobility/stabilization and environmental protection. For the purposes here, mobility is defined as maneuvering and conducting tasks on the exterior of the spacecraft (or to another spacecraft) and stability as the ability to rigidly fix body position to the spacecraft exterior. To this end several conceptual solutions were examined.

Portable Mobility Velcro System

The Portable Mobility Velcro System (PMVS) proposes use of Velcro to enable an EVA crewmember to readily attach and detach restraints to the outside of the CEV. Velcro has been used in the payload bay of the space shuttle, making it a flight proven technology; however, adhesives must be certified for use in this context on the CEV surface over the expected range of temperatures. During EVA, astronauts can apply Velcro-Hook patches to the outside of the CEV to create a path to the desired location. These patches could be cut to pre-determined sizes and stored in cargo pockets in the suit. The crew then could then “apply as they go” and create the specific path to a location. The general concept is shown in the sketch in Figure 3.

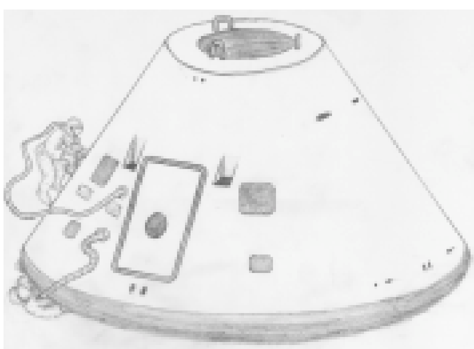

Figure 3: Utilizing the PMVS mobility aid

Velcro-Loop patches can also be sewn to strategic elbow, knee and hip locations on the outside of the astronauts’ suits. Another option is the provision of strap-on Velcro to alleviate the need of sewing pre-located patches onto the LEA spacesuit. Additionally, a Velcro Handle Mobility Unit can be employed (Figure 4). This is a handle-type device with a flat Velcro-Loop base, which will also allow the astronauts to pull themselves from one patch on the outside of the CEV and translate to another.

Force Required for Velcro Separation

Preliminary feasibility assessment of the PMVS design demonstrated that the Velcro patches will be able to provide stability without causing the astronauts undue fatigue. The forces required to separate the Velcro, as well as astronaut force exertions logged from previous missions were quantified. The force required to separate the Velcro is dependent on the type of Velcro, surface area, and the direction of the applied force. Shear strength is the amount of force required to cause a hook to slide over a loop and pull-apart strength is the amount of force required to pull a hook apart from a loop.

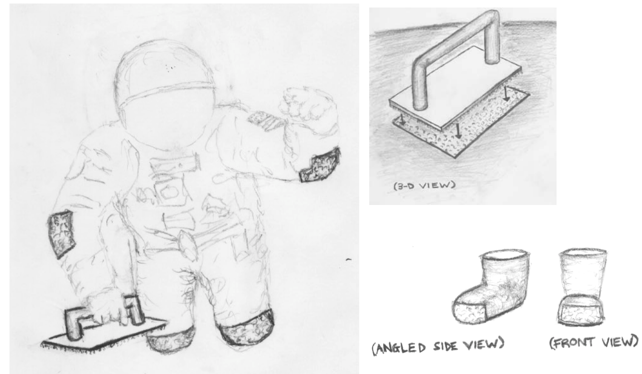

Figure 4: PMVS Interfaces (handhold and suit attach points)

The Enhanced Dynamic Load Sensors (EDLS) space flight experiment took measurements of the forces and moments exerted by astronauts during a long-duration space mission aboard the Mir Space Station [9]. The experiment used active sensing coupled with real-time feedback of the applied forces to quantify astronaut-induced loads in microgravity with 2806 events recorded. It was found that 96% of these events had maximum force below 60 N and 99% of the time the maximum force was less than 90 N. The majority of astronaut motions were recorded between 1-8 N. In order provide sufficient stability to an astronaut during an EVA task, therefore, the Velcro must be able to resist average force loads experienced during an EVA. The median force load recorded during the EDLS experiment was 16.2 N.

Additional considerations are required to implement the PMVS concept. The type of adhesive must be selected to appropriately meet the needs of the PMVS and the requirements of the CEV. Several options for applying the Velcro-hook patches have been discussed; however, a detailed trade-study is necessary. Astronaut fatigue during an EVA will need to be taken into account for the sizing of the Velcro. Finally, the vehicle exterior must be able to accommodate this activity.

‘Turtle Shell’ Concept

External contingency thermal / micrometeoroid protection has been previously used on Skylab. During the launch of Skylab-1 (SL-1), part of the external shielding was damaged causing the spacecraft to lose critical protection against the Sun’s radiation and MMOD. The affected area was near the external hatch for the science airlock, which was intended for several on-board experiments that required exposure to vacuum. In order to save Skylab and enable astronaut crews to live there during the three scheduled manned missions (SL-2 through SL-4), NASA quickly designed and built a protective blanket-like layer to be deployed over the damaged surface. The device resembled an umbrella or parasol and was designed to be deployed through the science airlock and opened in vacuum. In this manner, it could be retracted to within centimeters above the hull. The device consisted of aluminized Mylar, as well as the central support shaft and umbrella-like spokes used to open the device after it exited the science airlock on the vacuum side. The fabric-like Mylar material was similar to thermal/MMOD layers in current EVA space suits. Upon deployment, Skylab's internal temperature dropped from 124 °F to under 100 °F in less than a day. The cabin temperature eventually stabilized below 75 °F and was maintained for the rest of the Skylab missions. The device also gave MMOD protection to the damaged area of Skylab's hull.

The umbrella design used on Skylab would not likely be suitable for EVA because the central shaft and rigid spokes would interfere with an astronaut's movement. However, a very similar design concept dubbed the "turtle-shell" is proposed as a hemisphere of aluminized Mylar layers to provide an astronaut shielding from thermal extremes, radiation and MMOD. This shell effectively modularizes a vacuum-rated LEA suit for use in the external environment.

Aluminized Mylar is highly reflective across the electromagnetic spectrum, including the infrared range. Also, when properly layered, the material is capable of absorbing small MMOD impacts and has been used extensively in space. Its low density, high flexibility, and effective protection against both energetic and physical bombardment encountered in the space environment make it an ideal choice for the shell material. Figures 5 and 6 illustrate the "turtle-shell" concept.

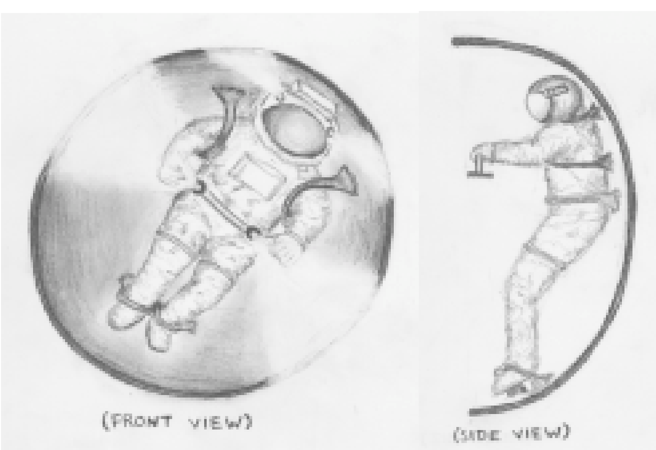

Figure 5: Front and side views of "Turtle Shell" Concept

The shell could be stowed on board CEV in any number of compressed shapes, given the flexibility of aluminized Mylar. Upon deployment for EVA, the shell would fan out into a hemispherical form and be strapped securely to the astronaut's LEA suit. The shell must be sized to have a diameter at least slightly larger than the astronaut's height and full arm span, so that it can wrap around the astronaut to block out 100% of the sunlight and exposed vacuum whenever possible. This coverage enables the shell to provide comprehensive protection against the Sun's electromagnetic radiation (including infrared, a major source of heat in space suits during EVA) and MMOD. Because incident light is also blocked, however, portable electric lights may be necessary to illuminate the work area, as illustrated in Figure 6.

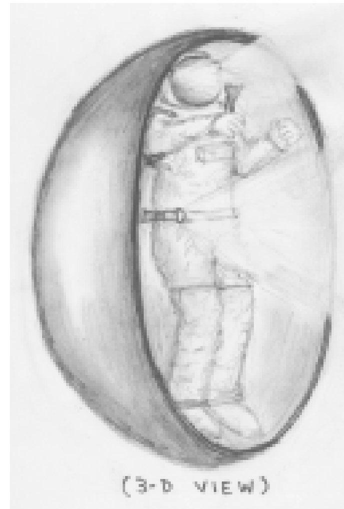

Figure 6: "Turtle Shell" concept with lights activated

Integrated use of the PMVS and Turtle Shell with the umbilical-supported, vacuum-rated LEA suit during a 0g EVA is depicted in Figure 7.

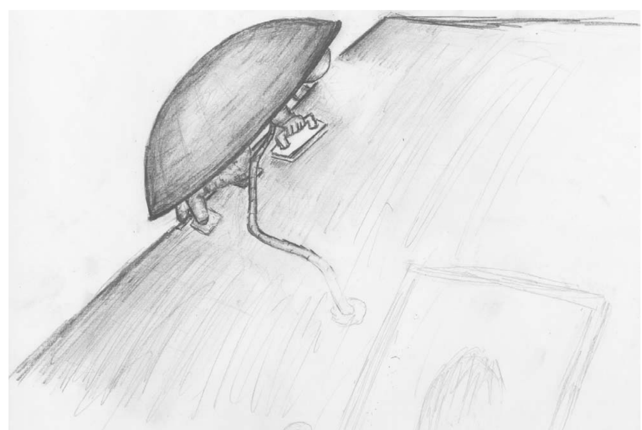

Figure 7: "Turtle Shell" and PMVS integrated concept for modular EVA capability using the LEA suit

LUNAR EVA

The lunar EVA suit is an intricate system of components designed to keep astronauts alive, comfortable, and productive in the harsh lunar environment. More specifically, the suit is required to function in the Lunar Lander, on the lunar surface (rover/walking), and in the Lunar Outpost. Similar to the 0g EVA suit, the LEA suit serves as the underlying pressure garment and is tasked with enabling the primary mobility/dexterity functions. Key assumptions were made based on lunar environmental factors, historical data and the Exploration Systems Architecture Study (ESAS) [10]. These assumptions gave rise to lunar suit requirements and guided our conceptual design considerations.

LUNAR EVA SUIT REQUIREMENTS

Various lunar surface parameters must be considered including atmosphere, radiation, vacuum, temperature, reduced gravity, light scattering, terrain, polar environment, seismic activity, and especially, dust. Lunar dust presents a serious design concern for routine operations. It is made up of mostly extremely fine debris. It is very jagged compared to dust normally found on Earth because there is no water or wind to weather the particles. It is extremely abrasive and penetrates very small openings. It is littered with bonded shards of glass and minerals known as agglutinates [11].

Dust on the lunar surface proved to be more problematic than any of the Apollo astronauts anticipated. It permeated the cabin, covered EVA suits/tools, and soiled the field experiment hardware. It also proved to be a source of respiratory and eye irritation for a number of the crewmembers. Dust got into any unclosed or unsealed volume through almost any size hole, including suit pockets, sample storage bags, nooks and crannies on the Lunar Roving Vehicle (LRV), internal mechanisms of cameras, and onto thermal blankets of experiments and communications systems. The most frequent dust problems encountered during the Apollo missions included: loss of traction, clogging of mechanisms, abrasion, vision obscuration, false instrument readings, dust coating and contamination, thermal control problems, seal failures, and inhalation and irradiation [12]. Basically, the longer a crew was on the lunar surface (including multiple EVAs) and the more intricate a particular mission's EVA tasks were, the more dust-related problems were encountered.

LUNAR EVA SUIT CONCEPTS

For this project, the dust problems encountered by the Apollo astronauts were studied extensively. Conceptual ideas were brainstormed to reduce issues associated with the lunar dust encountered on the surface. Vehicle interfaces also influenced our suit study, specifically the surface access ladder and the lunar module airlock. These factors led to two design concepts presented here referred to as the Auto-Belay/Blocking Device (AB/BD) and the Lunar Dustlock Oversuit (LDO).

Auto Belay/Blocking Device

Based on current design estimates, the ladder from the Lunar Lander habitat to the surface is approximately 25 feet high; therefore, the chance of an astronaut slipping and falling is a concern. The concept of using a handrail attached to each side of the ladder with the proposed AB/BD mechanism was formulated by looking at current technologies in rock climbing gear used to arrest an unexpected fall. However, rather than using a rope for fall stabilization as typical in climbing, the AB/BD concept locks onto the ladder handrail of the Lunar Lander. The device allows movement along the rail in one direction, but inhibits motion in the opposite. Therefore, the device can be oriented in such a way to provide protection while the crewmember climbs down the ladder to the surface and reconfigured for ascending back to the habitat. Attachment points on the suit or a harness will allow the AB/BD to secure the crewmember similar to safety tether protocols used for orbital EVA.

Lunar DustLock Oversuit

The LDO concept is proposed to protect the LEA suit joints from lunar dust, provide thermal and radiation protection during EVA, and reduce dust infiltration into the habitat. While wearing the LEA suit as the pressure garment, the crew will evacuate the airlock section of the habitat and egress the vehicle into a deployed vestibule-type secondary volume already at vacuum. This structure may reside on the top of the descent platform adjacent to the habitat or be erected on the surface at the base of the ladder. In either event, the crew will not come into direct contact with the lunar surface while wearing only the LEA garment. This concept is also readily extensible to the Lunar Outpost era and potentially to Mars as well.

Once in the deployable vestibule structure the crew will then don the LDO. The LDO concept consists of an oversized, baggy, seamless garment that will fit over the modular LEA suit and PLSS. This LDO will keep the LEA suit, joints, and bearings relatively clean, which can minimize the negative effect of lunar dust on the system. The LDO attaches to the outside of the deployable structure, not to be brought into the habitat. Thus, the LDO will stay outside and the crew returns to the habitat only wearing the relatively cleaner LEA suit. Previously described 'suit locks' have been proposed with similar logic [13], however, this variation on that theme is necessary to enable the modular single suit architecture concept to be maintained. The concept is illustrated in Figure 8 showing a rear entry being made into the LDO inside the vestibule, but at vacuum, while wearing the pressurized LEA garment. The LDO is not pressurized.

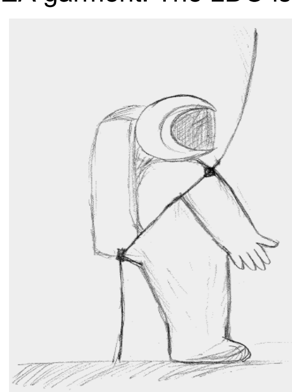

Figure 8. Donning the LDO while wearing an LEA suit

The LDO needs an excess enclosure volume to facilitate ingress and egress while wearing the LEA suit. After the astronaut detaches the suit system from the deployable structure, this excess volume can be taken up by cinching the LDO in key locations (i.e. shoulders, neck, waist, arms, and legs) allowing it to become better form-fitted to the astronaut and less intrusive on operations. Figure 9 shows strategic points suggested for cinching down the baggy LDO onto the underlying pressure garment.

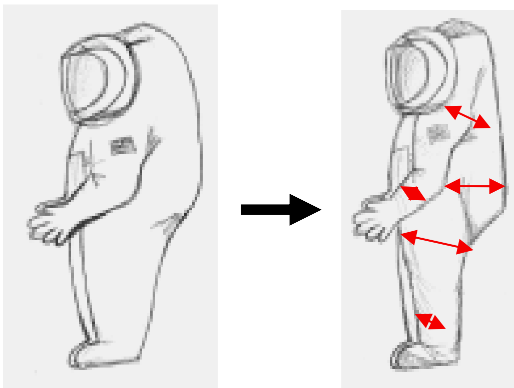

Figure 9. Form-fitting the LDO at strategic cinch points

MARS EVA

Upon examining the lunar and Mars suit requirements, it is plausible to ask whether the same suit can be used in both extraterrestrial environments. It is assumed that the basic functionalities are essentially identical; however, key differences arise from unique environmental parameters encountered on each surface.

MARS EVA SUIT REQUIREMENTS

Like Earth, Mars is a geographically diverse planet. As such, an EVA suit for use on the Martian surface must be designed to protect against a wide range of hostile environmental characteristics that vary dramatically with location on the planet. The high eccentricity of the Martian orbit, which leads to asymmetric seasons in which southern summer is much warmer with a higher atmospheric pressure than northern summer, further complicates matters.

The dangers of radiation exposure associated with interplanetary travel are not eliminated once astronauts land on Mars. While the Martian atmosphere and localized magnetic fields provide some protection, the lack of a global magnetic field results in high fluxes of charged particles from both the sun and cosmic sources. Particulate radiation from the sun originates from both the solar wind and Solar Energetic Particles (SEPs) released during Coronal Mass Ejections (CMEs). The exposure level at any particular time is highly dependent on solar activity. High energy Galactic Cosmic Rays (GCRs) also impinge the surface, exposing astronauts to an estimated effective dose between 20 and 30 REM/yr [14]. The lack of an ozone layer also allows high fluxes of UV radiation to bathe the surface, despite the fact that Mars is further from the sun than the Earth. The worst case daily DNA effective irradiance is estimated to be 3183 W/m^2, about 1500 times the value at the equator on Earth [8]. Furthermore, the radiation environment is highly dependent on the overhead air mass. As such, an astronaut at high altitudes during the vernal equinox will generally be exposed to more radiation than one at lower altitudes during southern summer, when seasonally asymmetric high temperatures cause the southern CO_2 polar cap to sublimate into the atmosphere.

Because both the polar caps and the atmosphere of Mars are mainly composed of CO_2, the pressure on Mars is highly dependent on the seasonal temperature and can vary between ~6.8 mb (aphelion, southern winter) to ~ 10.8 mb (perihelion, southern summer). The pressure decreases exponentially with altitude. Temperature can also vary between -140° C at the northern pole during winter and a warm 20° C at the equator during southern summer [15]. Diurnally, the temperature can swing by as much as 60° C. There also exists a significant vertical temperature gradient that can be 10's of degrees C between an astronaut's head and feet.

As on the Moon, Martian dust will be one of the limiting factors to the lifetime and functionality of the EVA suit. Matters are further complicated on Mars because dust is suspended in the atmosphere as well. Almost all Martian dust is composed of ferromagnetic minerals, about 2% by weight. The suspended particles are < 3μm in size, much smaller than lunar dust, and are ubiquitous across Mars. Global dust storms are common during southern summers. Atmospheric dust can thus present more problems during these events, including visibility issues. Martian soil is composed about 2% ferromagnetic minerals and may be electrostatically adhesive. The Viking Landers also showed that the Martian soil is highly oxidizing, possibly due to the presence of H_2O_2 [16]. This will present additional design challenges for the suit outer shell concept described in the preceding section.

Martian dust can also be easily charged by triboelectric charging (e.g., by dust storms), incident UV radiation, or even the simple act of walking across the surface. The lack of moisture in the Martian soil and its resulting low conductivity decreases the chance of having an electrical ground. This creates a large potential for differential charging and damaging electrical discharge. The dust might also electrostatically cling to the EVA suit [17].

MARS EVA SUIT CONCEPTS

The majority of functional suit requirements between the LEA, 0g, and Lunar and Mars suits are similar; however, there are some fundamental differences primarily driven by environmental parameters. Mars is particularly unique in that there is no precedence for a human mission to the planet. Mars environmental factors, spacesuit functional needs, and mission operational requirements were examined to create a list of conceptual solutions. Since this phase of the VSE is far in the future and largely still undefined, no limits were placed on the scale of these concepts, neither were TRL levels enforced. As a consequence, less comprehensive design concepts are presented here than for the nearer term, better defined mission phases described above. Numerous concepts were evaluated in the process of this semester-long study with three presented here.

Electrical Grounding Mitigation

As discussed, dust on Mars is suspended in the atmosphere and is easily charged by both the wind and motion of an astronaut. Consequently, upon returning to the habitat or rover, the astronaut could be at a different electrical potential and in touching the habitat, a static discharge could occur, possibly resulting in potentially harmful arcing. Two concepts are proposed to mitigate this potentially serious occurrence. First, outside of the habitat a pole or walking mat could be constructed to dissipate built-up charge. The pole would extend sufficiently deep into the dry Martian soil to establish an electrical ground. The astronaut would either stand on the mat or hold onto the pole while it draws the charge out of the dust cover on the suit. Alternatively, the outer dust cover could be made out of the same material as an electro-static discharge material similar to that worn while working on sensitive electronics.

Electronic Assistant

The operations conducted during Martian EVA will require detailed instructions and potentially long periods without communication. Since using printed checklists is impractical and tedious days can result in mental fatigue, a personal user interface/entertainment concept was examined. A programmable wrist-mounted or “heads-up” display could be used to store procedures and checklists. The system could also be used to interface with remote instruments for control and data collection. The system can also include independent audio channel capacity for playing music or other audio programs. This is analogous to the current practice of field geologists often using MP3 players during remote excursions.

Dustlock Oversuit

The basic principle of using an unpressurized dustlock oversuit docked to the habitat and donned externally while wearing a pressure garment as described for Lunar EVA is extendable to Mars surface operations as well, similarly enabling the single suit architecture concept to be continued. The non-pressurized dustlock suit does not enter the habitat; therefore, dust contamination is mitigated and only one pressure garment, the LEA suit, is again for all suited scenarios.

The addition of an airlock is also likely needed for a Mars habitat to provide storage and protection for EVA tools, science equipment and for access to the dustlock oversuits and/or pressurized rovers. The inner segment can be maintained either at Martian ambient conditions, in which the LEA suit is needed, or can be pressurized to provide a shirt-sleeve environment should the astronauts need to conduct complex repairs on the rover, suits or external equipment. This feature becomes increasingly relevant as the longer mission durations and further distance from Earth mandate local maintenance and failure intervention. The integrated Dustlock / Airlock concept offers a compelling solution to challenges of Martian EVA and merits further study as to its design feasibility.

SINGLE SUIT CONCEPT SUMMARY

As the underlying pressure garment for all elements of suited operations required by the Constellation Program, the LEA suit becomes the main design driver for this proposed integrated, modular, single suit architecture concept. The LEA life support system must be able to function independently during a terrestrial emergency egress (on land or in water), interface with the CEV ECLSS via umbilical, as well as be similarly compatible with the (yet to be designed) Lunar and Martian vehicles and respective PLSS designs for lunar and Martian surface EVA. Based on the concepts presented here, the LEA suit must also allow sufficient on orbit EVA maneuverability and interact with the “turtle shell” and Velcro attachment system concepts. For lunar surface EVA, the LDO is proposed as an additional outer garment that an LEA-suited astronaut must be able to don and doff in a protected, but at vacuum, environment. Compatibility with vehicle interfaces such as seats, umbilical ports, the proposed auto-belay mechanism for ascending or descending the lunar habitat ladder, and potentially traversing in pressurized or unpressurized rovers must be taken into consideration. On Mars, the LEA suit will again need to interface with the dustlock oversuit concept, as well as the necessary tools, ancillary equipment and supporting subsystems needed to enable the demanding EVA tasks anticipated for these future missions.

As for the basic life support requirements, the suit must be able to provide the crew with access to food and water in the worst case 144 hour abort scenario for the near term polar lunar missions. This implies that some way of transferring consumables into the suit and removing waste while in a vacuum environment is necessary. Potentially a human-sized inflatable airlock inside the vehicle may offer design relief for the suit. However, this would require the astronaut to be able to access and operate the airlock from inside the suit.

The proposed concepts suggest the development of a series of interrelated suit components built on a core LEA pressure garment that moves toward the design of a modular, single suit architecture for the VSE.

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CONTACT

The contact author, Dr. David Klaus, is an Assistant Professor in Aerospace Engineering Sciences at the University of Colorado, Boulder. (klaus@colorado.edu)