

Some Thoughts on the Architecture of a Planetary Extravehicular Space Suit

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Abstract

For a return to the moon or voyage to Mars the extravehicular space suit will take on an importance that it has never had before in piloted space flight. While EVA space suits were looked upon in the past as only ancillary hardware, they will be a pivotal technology to the success of a lunar return or Mars mission. With a possibility of as much as half of surface time being taken up by extra-vehicular activity, the Martian surface space suit is not going to be just an afterthought, it will be the focus of much of the mission. Likewise, EVA systems may even be a pacing technology for a manned Mars landing. A planetary surface suit will have to meet standards of safety, ruggedness, and low mass that no present system can provide.

This paper will address the technical choices and trade-offs the authors have found most appropriate, given the present SOA (State-Of-The-Art) for the architecture of an early Lunar EVA space suit design that also might be evolvable to the Martian environment. These choices and trade-offs have been arrived at from open literature, personal studies, proprietary research performed by Weaver Aerospace Inc. in the middle 1990's, and latter studies undertaken by De Leon Technologies LLC personnel in cooperation with the University of North Dakota's Space Studies Department's NDX-1 Space Suit Demonstrator program.

Accordingly, in this paper, we will explore candidate SOA spacecraft cabin/planetary space suit pressure/atmospheres, planetary suit enclosure subsystem architectures and related don-doff methods and a cursory look at candidate planetary EVA life support subsystems.

Introduction

The Polish author Stanislaw Lem noted: “there are no answers, only choices.” When it comes to space suit engineering, a more accurate maxim could not be found. There are, and will be, many different approaches to lunar and Mars surface EVA investigated in the years to come. In systems engineering there is seldom one precise solution for a problem, especially if engineering for human physiology. Instead, there are a succession of technical trade-offs that must be studied and compared in order to ascertain what is the most appropriate solutions available to the designer/engineer, given the requirements and limitations s(he) must address. Since we are dealing with human anthropometry it must also be born in mind that space suit enclosure design, and especially fabrication, is as much an art as a science. Accordingly, design approaches will draw from a history of technical choices and skilled design arts that have evolved in the United States and Russia since the 1960s. In addition, we must also draw from the most recent discoveries in materials sciences and processes (1).

Space Vehicle/Habitat EVA Suit Atmosphere

While there are other theoretical approaches to early Lunar-Mars EVA, such as MCP (Mechanical Counter Pressure) space suits, the present, quantifiable, SOA would seem to indicate that an anthropomorphic gas pressurized enclosure be considered.

This type of approach is nominally understood, a fairly mature technology and, due to a near revolution in pressurizable fabric and materials sciences since the 1970s, able to be made more robust, acceptably mobile, lighter and far safer than present and past EVA space suits. Those who espouse the use of alternative space suit approaches, such as MCP and APVs (Articulating Pressure Vessels), etc., for planetary surface applications often note that gas pressurized EVA space suits (A) lack flexibility (mobility) (B) are unsafe because they are essentially anthropomorphic balloons and (C) have unfavorable mass issues.



Figure-1 NDX-1 EVA suit during field trials

Our research has found such sentiments are viable only if one takes a cursory look at present, operational orbital EVA suit systems. However, upon closer analysis, the most mobile EVA space suit ever built was the AiResearch EX-1A and AiResearch AES (Advanced Extravehicular Suit). These two experimental hybrid lunar prototype

suits, built by William Elkins and the AiResearch Corp in the early 1970's could perform with nearly the same range of motion and human dexterity as if in a shirt sleeve environment (1). During this same time frame, Litton Industries also fabricated a series of lunar semi-rigid and hybrid EVA space suits that were highly mobile, comfortable and robust (2).

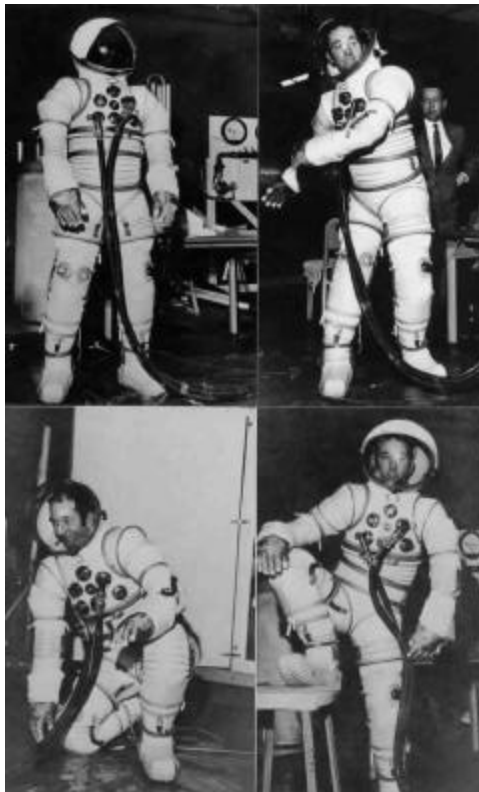


Figure-2 1970s era AiResearch EX-1 IEVA suit.

More recent efforts, such as ILC Dover's "T" Suit and the ILC/Hamilton Sundstrand/NASA "H" or Hybrid suit (once called the ZPS Mk-III) have demonstrated superb mobility, comfort and motion range for lunar applications. All of these past and present prototype EVA suit enclosures have exhibited positive features that enhance mobility, lessen joint moment (torque) forces, and increase comfort and motion range to varying degrees (3). But what features,

based on present knowledge and even Apollo experience are applicable to early lunar and Mars EVA?

Space suit and LSS (Life Support System) design is heavily influenced by candidate space vehicle and habitat atmospheres. For example, it makes sense for an orbital space station to have an Earth equivalent sea level atmospheric pressure. Sea level pressure is composed primarily of oxygen and nitrogen at 14.7 psi (101 kPa) with oxygen composing 21%, or 3.08 psi partial pressure (21.25 kPa) and nitrogen making up about 78%, or 11.5 psi Pp (79 kPa) of the whole. The nitrogen is inert and takes no part in metabolism, acting primarily as a carrier for the oxygen, though it can cause decompression complications.



Figure-3 ILC "T" Suit Prototype with rear entry closure

The oxygen, at about 3 psi Pp, is the minimum partial pressure needed for metabolism. Earth orbital stations use sea level atmospheric pressures so as to interfere the least with on board experiments, to lessen fire danger, increase avionics cooling, and to conform to well known human physiology parameters, etc. The tradeoff to this high mixed-gas cabin pressure, however, is that the station/vehicle hull must be built stronger, thus heavier, to stand the pressure load. In addition, EVA space suits deployed from such a station must either use a low suit pressure, combined with a time consuming and complex decompression regime, or use a higher suit pressure to avoid, or moderate, the decompression penalty. This last point means that the EVA suit must also be built stronger (and heavier), and that the suit's glove mobility will be even more inadequate than is now the case.



Figure-4 Hamilton Sundstrand/ILC NASA "H" Suit

In contrast, a lunar or Mars space vehicle will be divorced from Earth's atmospheric conditions for weeks, months or years; therefore, a spacecraft/habitat cabin pressure of 5 psi (34.5 kPa) may be an acceptable alternative. This cabin pressure would consist of 70% oxygen at 3.5 psi Pp and 30% nitrogen at 1.5 psi Pp (or 24.15 kPa and 10.35 kPa respectively). This was the same cabin pressure that NASA's 1970s era Skylab Space Station utilized and adequate data exist that suggests it may be a safe, viable approach to lunar/Mars (4). This cabin pressure also has the accrued benefit of making the space vehicle/habitat lighter, decreases hull leakage, and most importantly, allows the EVA space suits to benefit from a lower suit pressure of 3.5 to 3.7 psi (24 - 25.5 kPa) of pure oxygen. This beneficial cabin/suit pressure profile means that the EVA astronauts will not be subject to a decompression penalty; as such, crew members will be able to move in and out of the surface habitat with no physiological induced delay. Low pressure EVA suits will, as well, have a simpler, lighter LSS (a mixed-gas suit pressure is not required) and suit mass and mobility, especially in the gloves, will be enhanced.

Planetary EVA Suit Enclosure

With a lower space-vehicle/habitat to suit pressure combination, fewer rigid components need be utilized in the space suit enclosure. This has the benefit of allowing much of the enclosure to be built from modern, rugged fabrics and possibly light carbon composites rather than metals. From our studies we have found that a space suit enclosure using a restraint (shaping) layer of Zylon and a

para-aramid shows promise. This type of textile, which has emerged just in the last few years, was used in the enclosure of the NDX-1 Mars Surface Suit Demonstrator fabricated in cooperation with the University of North Dakota's Space Studies Department. It was chosen because it has high tensile strength and flexibility, is resistant to abrasion and displays good bias elasticity. It also is cut resistant (high trapezoidal strength of the warp and fill fibers), has excellent resistance to rip propagation and is thermally stable. Zylon/para-aramid is as well easy to join with readily available bonding adhesives and is commercially available. Its tradeoffs are that it is onerous to shear by common mechanical methods and in moderate deniers it is relatively thick and can be arduous to stitch. Moreover, it forms thick seams once sewn, requiring creative methods to attach it to hard elements such as wrist rings, etc. Additionally, its vacuum stability and hypobaric off-gassing potential are as yet to be fully quantified.



Figure -5 NDX-1 Demonstrator

Zylon/para-aramid fabric was also chosen, over many other fabrics tested, in view of its capacity for construction of all enclosure components of an EVA suit (flexible and non-flexed layers). Indeed, one prime goal of the NDX-1 Program was to find an extremely rugged textile that could also be used in mobility joint fabrication that did not exhibit the detrimental characteristics displayed by present EVA suit materials like Nylon, Polyester, etc. After comparative construction and analysis it was ascertained that Zylon/para aramid blends could be used to build acceptably mobile flat panel convolute joints for shoulders, elbows, wrists, waist, hips, straddle, knees and ankles.

The type of convolute joints used in the NDX-1, called "Isolated Asymmetrical Convoluters" (or just IAC joints), were created at Weaver Aerospace in the middle 1990s by one of the authors of this paper. They were incipiently to be used in an emergency pressure suit for the Roton (Rotary Rocket) launch vehicle. Weaver Aerospace, which had a contract to develop an escape capsule for the manned Rotary Rocket, sought to be in a position to win any pressure suit contract that might have come out of the now defunct Roton Program. IAC joints borrowed the best qualities of flat pattern joints, as invented by Buck Scott of Litton Industries and enhanced by ILC Dover, and now used in the Shuttle EMU (1). IAC joints were also influenced by the fabric convolutes used in the Russian Orlan EVA suits. IAC convolutes demonstrate excellent range of motion (included angle), acceptable joint moment (torque), absence of static torque (no neutraling/spring return) and extensive cycle life. To further reinforce all of the stitched seams of the joint,

each was bonded, then sewn, then made redundant by the addition of stitched-on Nylon or polyester restraint and circumferential webbing. This ability to be fabricated in a redundant fashion suggests the fabric convolute joint's applicability to a lunar or Mars suit that may have to be used for many months on the planetary surface.

Besides rendering satisfactory mobility, fabric convolute joints can be made more repeatable in their construction by a skilled fabricator using a technique explored for space suits at De Leon Technologies LLC called "Stressed Fabric Construction" and latter used throughout the UND suit program. While this technique is proprietary, essentially it can be expressed in this way: In most past pressure and space suit enclosure fabrication, repeatability was difficult to achieve. It was nearly impossible for two fabric suits, or suit textile parts, to be made exactly alike. Sewing fabricators worked from patterns, and due to the non-linear characteristics of textiles they often could not cut the fabric to the exact shape or sew it in the exact manner. An onerous characteristic of fabric is that it is difficult to predict how much it will "shrink" once cut, or the fabric will not display the same shape when cut on the bias as opposed to the warp or fill. On the other hand, this detrimental shape feature can be circumvented, using some modern textiles, by stressing them into the proper dimensions akin to that of aircraft skin.

Upper Torso Assembly (UTA) and Don/Doff Closure

As might be expected, there is disagreement within the space suit community on the type of don/doff closure (entry seal) a planetary EVA suit should need. This disagreement may seem, to the uninitiated, to be merely tertiary; however, the don/doff configuration used in an EVA suit affects the entire enclosure design and interrelated component geometry, especially in the Upper Torso Assembly. In many respects the don/doff entry seal system, and the UTA it inspires, can be viewed like the footing of a house: all components array out from it. The suit is literally built-out from the entry seal and UTA foundation (see Figure-6).

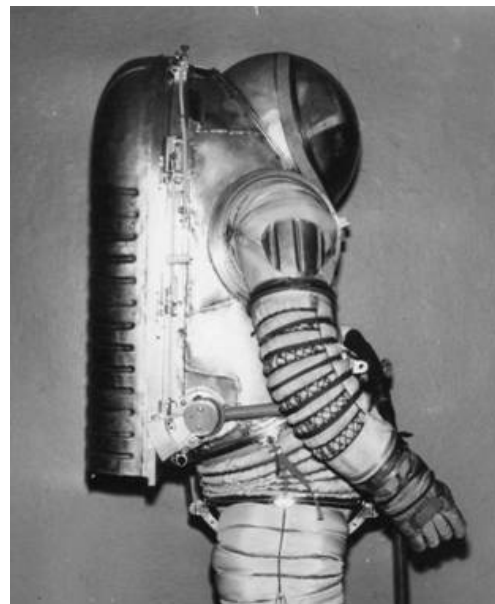


Figure-6 SK-2000 Hard Upper Torso

It is generally agreed, however, within De Leon Technologies that a back-entry, or dual-planar mechanical seal closure is desirable. While a few within the space suit engineering community have importuned to use slide fasteners (akin to pressure tight zippers, as were used during Apollo) for EVA suit entry closures, we wholeheartedly agree that a rigid mechanical seal appears safest, due

to the mechanical seals ability to be made redundant. A mechanical seal also can be equipped with dust mitigating barriers, an obvious advantage. Even NASA's own safety requirements demonstrate a predilection for mechanical seals over slide fasteners (1). In this same light, De Leon Technologies and University of North Dakota NDX-1 mock-up studies have found the single planar closure, as is used in the Shuttle Extravehicular Mobility Unit (EMU, Shuttle EVA suit), to exhibit too many detrimental tradeoffs.

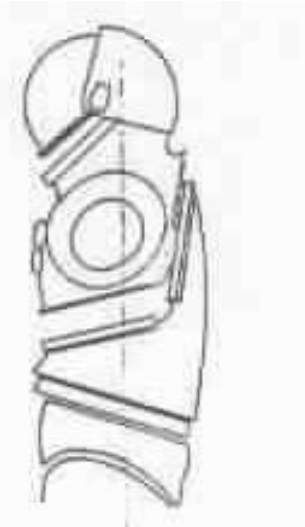


Figure-7A Litton RX-3 Dual Planar Closure

The most desirable feature of the single planar closure (like that used in the Shuttle EMU) is its relatively low cost of manufacture. It is just cheaper and simpler to machine any mechanism on a single plane, especially in comparison to the complexity of a dual-plane closure ring. However, this questionable frugality is offset by the single plane closure's difficulty in donning. Indeed, one astronaut complained that to don the Shuttle EMU took "help from two of your best friends and your dog (1)." A single plane closure also creates a wide, unnatural cross section of the UTA (see

Figure-8). This wide, oval cross section, combined with the poor geometry of the shoulder scye bearings (created by the wide resultant UTA) forces the astronaut's arms to hang out away from the body thus adversely affecting comfort and walking gait.



Figure-7B Orlan Back Entry

Prior to the NDX-1 program, mock-up studies at Weaver Aerospace and De Leon Technologies LLC (and the open literature) had conclusively demonstrated to us that a single planar body seal closure was not optimal for an orbital EVA system and was impractical for a walking EVA suit. All NASA astronauts, who had been allowed to test the Russian Orlan EVA suit (which uses a rear-entry closure), had remarked how easy the suit was to don/doff as compared to the Shuttle EMU (5).

For the NDX-1 surface suit demonstrator, a single plane body seal was unacceptable and machining a dual planar closure was simply beyond the modest funding available. Machining a dual plane closure ring, or even an accurate mandrel, would have required

an aluminum billet (large block) of unaffordable dimensions. So in an effort of compromise, a shallow dual planar closure was manufactured in-house. If anything, this shallow dual planar UTA has reinforced these authors conviction that a full dual plane closure or a back-entry closure seal is required on any future dedicated EVA suit system.



Figure-8 ILC “T” Suit with single plane closure

The full dual planar closure has the advantage of rendering a highly mobile yet compact waist joint. Fore and aft bending (flexion-extension) is possible with such a waist joint as are side-to-side motion. In contrast, with a rear entry closure seal, as is used by the Russians, only a fore and aft flexion joint is possible, due to the length of the UTA caused by the long back-entry aperture. Nevertheless, the back-entry closure has many features that recommend its use. For instance, the back-entry hatch will allow most or all of the life support components to be contained within the pressurized volume of the suit enclosure.

Containment in the suit volume means that any leakage of gaseous oxygen will be into the suit, rather than overboard (as is now the case with the Shuttle EMU’s LSS). Russian EVA suits have always taken advantage of this feature with a good safety record. As noted, the Shuttle EMU’s LSS is a separate component from the suit enclosure volume (its internal components are exposed to vacuum). This arrangement forces all of the LSS gaseous and fluid connectors to meet stringent leak requirements testing before the suit is sent up to the space station. In other words, the EMU is a ground-based system, rather than space based. These ground-based checks are so strict as to preclude on-orbit change out of oxygen bottles, etc. or even limited repair, thus the EMU must be brought down to Earth for servicing. In contrast, with the Russian system of having the oxygen bottles, etc. contained in the back entry hatch (in the suit volume) any leakage at connectors will simply be into the suit, rather than overboard. If a large connector leak should occur the Russian Orlan suit has a large pressure relief valve to protect against excessive suit inflation loads. This allows the Orlan to be a more versatile space based system. The back entry hatch also has another major advantage: the LSS components are easy to reach and service on-orbit (or in a planetary habitat for that matter).

The base structure of the Upper Torso Assembly is also still open for debate. In recent Mars suit studies, the Russians have opted for an evolution of their semi-rigid design: the Orlan EVA space suit family. In this concept the UTA utilizes a Hard Upper Torso (HUT) of stressed aluminum married to soft arms and soft Lower Torso Assembly (waist joint and pants section). Of course the

term “soft” here is misleading. When suit fabric components are pressurized to even 3.7 psi (25.5 kPa) they become as firm as footballs. Flexibility is rendered to the soft arms and legs only through specially designed mobility joints. A rigid HUT has many advantages other than its ruggedness. It provides a solid fixture on which to mount the scye bearings, rear entry closure/LSS, and waist pressure ring (HUT to LTA interface), etc. This rigidity also gives stable geometry (constant volume) to the suit structure. Likewise an advantage of a rigid HUT is that a redundant pressure barrier can be literally painted onto the inside of the aluminum structure in the form of a polymer. Modern carbon fiber composites can also be used to build HUTs that are as strong and durable as metal, but lighter. There is even a company now that has innovated a process for stressing carbon fiber sheets into HUT shapes.



Figure -9 Russian Mars EVA Suit Study

On the other hand, a Hard Upper Torso has some tradeoffs. Because it is rigid, the HUT is less stowable. Moreover, the HUT can not change the position of scye bearings or the interstitial distance between bearings, helmet, waist ring,

etc. to fit differing anthropometry (though some contractors have investigated the idea of HUT scye bearings that can be vernier adjusted). The American firm of ILC Dover has constructed a prototype planetary suit that uses an all-fabric upper torso. Called the “I” suit, this very creative UTA has a conventional fabric restraint layer and inner, separate pressure bladder of urethane bonded onto nylon (similar to the soft parts of the Shuttle EMU). This soft UTA concept may allow for sufficient rigidity (when pressurized) to give stable suit geometry and yet still limit the EVA suits stowage penalty.

In order to create a UTA that is light and can be relatively stowable and still utilize a back-entry hatch/LSS, De Leon Technologies personnel have begun an in-house investigation of what we term a MUT, or Malleable Upper Torso, sometimes called a Morphing Upper Torso. There is nothing revolutionary in this innovation, just an attempt to apply understood suit sizing adjustment to a fabric layered torso structure. Fabric was chosen for the UTA over rigid metal or fiber composite, due to reasons of weight. Whether an all fabric arrangement is best, or a fabric/carbon fiber aggregate, has yet to be discerned.

Generally speaking, the soft mobility components of a Lunar or Mars UTA, such as shoulder, elbow and wrist joints, can be essentially the same as those used in present orbital EVA suits. Present orbital EVA suits have the majority of their mobility built into the shoulders, arms, wrists and gloves. This is because the majority of work performed in orbit is done with the arms and hands; the legs performing only the function of anchoring the upper body (such as in the

Space Shuttle robotic arm). That said, perhaps the greatest challenge for any future EVA suit will be glove mobility.

Glove Mobility

In recent years, spurred on by the complexity of space station assembly, NASA, ILC Dover and RD&PE Zvezda have begun attempts to improve glove mobility. This effort has bore fruit and the present SOA of glove technology has reached a relatively successful Phase-VI level. The NASA/ ILC Dover Phase-VI, EVA glove has shown mobility and fit improvements of a magnitude over that of gloves used during the Apollo era and ILC Dover's excellent engineering staff deserves credit for this. Still, there is much room for improvement and NASA has stated as much through its Centennial Challenge Program. Presently De Leon Technologies has begun negotiations with outside specialists so that we can bring new eyes to bear on this rather intractable problem. As yet any progress is, however, proprietary to the company.

Taking a less conventional tact, Honeywell International working with Dr. Paul Webb and the University of California and Clemson University has undertaken studies to ascertain whether a mechanical counter pressure glove is possible (6). These studies have shown some promise, but three difficulties come to mind. First, what is the solution to mating an MCP glove to a gas type suit while avoiding a disbaric condition arising between the suit gas pressure and the glove mechanical pressure; the two have to be perfectly balanced? Second, MCP gloves still do not exert uniform pressure over all parts of the hand and

wrist. If this condition would contribute to interstitial edema or subcutaneous gas (when combined with a gas pressurized suit), is a question yet unanswered. Regardless, there is a third element here that has not been well thought out: one of the greatest impediments to glove mobility is not merely the gas pressurized glove restraint/bladder assembly of present glove concepts, but rather the thick thermal micrometeoroid garment cover (TMG).

Today's operational glove TMGs rob the hands of flexibility and tactility. Past lunar glove TMG covers certainly did as well. And it does not matter if an MCP glove is used or a conventional type glove, the TMG will still make the astronaut feel like s(he) is working in boxing gloves. One Hamilton Sundstrand study even indicated that a Martian EVA glove cover might be thicker than a lunar TMG glove cover, due to the cold environment. Many who are not truly versed in the intricacies of the Martian environment simply note that "Mars is cold." But what does that mean? Yes, Mars does have a cold environment, but it is also a near vacuum (7 to 10 torr atmospheric pressure, or less). On an average spring, summer or fall day the suit occupant will likely build up metabolic heat inside the suit. At rest humans emit metabolic heat equivalent to about a 100 Watt light bulb. During physical activity we can produce ten to fifteen times as much. On Earth our primary method of metabolic heat regulation is convection and conduction to the surrounding air. We also emit a negligible amount of heat through radiation on the infrared side of the spectrum (1).

In the Martian near vacuum a suited crewmember will not be able to conduct or convect adequate heat out of the suit shell; though s(he) will lose some by infrared radiation. On Mars the trick to keeping the astronaut within tolerable thermal limits (during the day) appears to be the creation of an aggregate heat loss from the suit, while at the same time insulating the hands and feet. Or, at the minimum, the redistribution of heat away from the torso to the hands and feet. This requirement is going to need a thick glove insulation material. As an aside: the Martian surface, due to near vacuum conditions, is thermally decoupled from the atmosphere. The surface soil is -58 degrees Fahrenheit (-50 C) planet wide and this also means a boot with sufficient insulation is required, or a boot designed to break the thermal outflux (outflow of heat), through physical separation from the ground will have to be developed. And this does not even consider the problem of how to keep someone alive if they are stranded on the Martian surface at night when the atmospheric temperature drops to -193 degrees Fahrenheit (-140 C) (7). An emergency thermal pup tent might be one answer.

An old glove idea that could stand a reexamination, in our view, is that of end effectors. These are pincers, tools and the like attached at the end of the wrist. The hand remains bare inside a pressurized, heavily insulated housing (usually just the left hand) and works a simple manipulator. William Elkins and Accurex Corp. performed studies of end effectors in the 1970's for applications in high Earth orbits (HEO). End effectors were thought necessary for work in HEO as the radiation shielding required at such altitudes would have made the

glove TMG covers too thick to be practical (8).

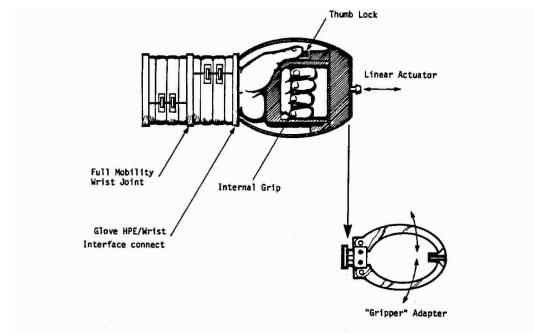


Figure-10 End Effectors

Lower Torso Assembly (LTA)

It is self-evident that with a planetary walking suit, the mobility and comfort of the Lower Torso Assembly (LTA) is a design drive that supersedes all other mobility considerations, with the possibly exception of glove improvement. As was noted earlier in this paper, fabric convolutes were found to be the most applicable mobility joint system for the NDX-1 program. One of the prime reasons for this was due to the fabric convolute joints ability to create predictable and stable, waist, hip, knee and ankle joints for the LTA. With an EVA suit that employs multiple bearings in the hips (such as the NASA "H" suit), the UTA of the suit will tend to sag onto the shoulders of the astronaut, when the suit is worn in a gravity field. Multiple hip bearings make for an excellent "walking suit" design, with natural hip motion, but the hip joint instability accompanying this multi-bearing arrangement requires the upper torso of the suit to use a shoulder harness to support its weight. This shoulder harness places most of the suit and LSS mass (as defined by its weight) onto two narrow point load areas of the suit occupant's

shoulders: like a rucksack. S(he) is thus carrying the whole suit mass. Alternatively, if the hip and waist joints of the walking EVA suit are made from fabric convolutes, with a single thigh bearing placed horizontally between the hip and straddle joint, then the inherent nature of the convolute joints will “push-up” the UTA and help support most of the upper suit and LSS mass.

To further illustrate this phenomena: during human locomotion in a walking type space suit the forces that have to be overcome are, first, resting inertia: That is, to get one’s own mass and the suit’s mass into motion from a resting stop. Second, to support the combined suit’s mass and ones own mass while in motion. Lastly, to overcome or re-vector the combined inertia of the suit’s mass and your own mass once in motion (such as changing direction or stopping). Of course we can’t lessen, or reengineer, the mass of the astronaut, but we can reengineer (manage) the EVA suit system. From this we see that the greatest “manageable” expenditure of energy is to get the suit’s mass inertia into motion and bring it to a stop once moving. Much less energy is spent once one is up to speed and walking. It is obvious that the planetary suit mass must be minimized to minimize inertia. What is less obvious is that if the weight of the suit and LSS can be removed from the astronaut’s shoulders (taking advantage of the “push-up” of the convolute hip and waist joints). Then his or her primary expenditure of energy will be to get the suit’s mass in motion and alter its motion inertia once moving. Only minimal energy will be spent to hold up the suit.

The before mentioned explication hints that the EVA surface suit can be somewhat heavier than some engineers have expressed (9), that is if the UTA and LSS mass can be removed from the astronauts shoulders. As such we can more intelligently distribute (manage) the suit and LSS mass around the astronaut’s body rather than just as a point load on the shoulders. Of course the UTA and LSS mass must be engineered as such to contribute to a “friendly center of mass,” that is, near to the astronaut’s natural, nude-range center of mass (1).

The tradeoff is that the convolute hip joint may be somewhat less flexible than the multi-bearing supported hip. Besides the hip joints, a fabric convolute waist joint can also help support the UTA and can be designed so as to contribute supplementary vernier length adjustment for suit sizing. Moreover, the fabric convolute waist joint, like the convolute hip joint, displays acceptable motion range and stability (10).

Boot and Ankle Assembly

The mobility of the ankle joint and fit of the EVA suit boot will be critical as the astronaut traverses the undulating topography of the moon or Mars. As former Army infantry soldiers who have spent our share of time covering rough ground, these authors knew how critical good boots are. In the NDX-1 EVA suit demonstrator, the boot core (lower boot) was an off-the-shelf, base polymer cold weather boot. To this we bonded and sewed a sophisticated gimbal ring and flexion/extension joint interfaced with a adduction/abduction joint. This ankle mobility concept was influenced by the very creative work of engineer Nikolay

Moiseyev of RD&PE Zvezda of Russia. Lessons learned from this approach have shown that a lunar, and especially Mars style boot, must have a means of external fit adjustment, and custom boots must be used for each astronaut. Limiting adduction/abduction motion range is also important for the ankle joint. This is done to keep the ankle from undue stress during stride over uneven terrain. Adduction/abduction motion range is limited through limitation of convolute geometry.

Another lesson, from earlier studies, is that the tread patterning of the boot's sole is important. During the Apollo program it was recognized that astronaut's slipped sideways during lunar walking. This side slippage was allowed by the Apollo A7L and A7LB boot's simple, striated tread pattern. Lunar regolith is imbedded with tiny volcanic glass beads. These beads act like ball bearings when stepped upon. During the latter 1960s AiResearch Corporation undertook limited studies to develop a boot tread that kept good footing in lunar soils, but, the boots were never tested on the moon (1). We suspect, however, that today extensive knowledge has emerged from the hiking boot industry to deal with this problem.

Bearings

A possible benefit to having the previously noted horizontal LTA thigh bearing (for pronation/supponation of the lower leg and foot) placed just below the hip joint is its separation from the dust stream kicked up by walking. Most past EVA walking suit studies have envisioned a bearing at the ankle. But the human foot does not fully rotate at

the ankle, it rotates as well in the upper leg and hip; in other words in the general area of the thigh/straddle joint. By using a single horizontal bearing in the lower thigh, placed in the general area of the hip convolute and the straddle convolute, we also minimize the number of bearings in the Lower Torso Assembly. Minimizing the overall number of bearings in the planetary suit will lessen suit mass (bearings are the major contributor to suit enclosure weight) alleviate maintenance, lessen expense and complexity and increase safety (1). Safety, in the matter of bearings, is a unique concern, after all, bearings are literally an interruption of the space suit's pressure bladder integrity; as such they are another potential failure point. Though what is the minimum number of bearings a lunar suit might have and still be coincident with human/suit kinematics is not entirely known. Subjectively, scye bearings (for omnidirectional shoulder rotation), upper arm bearings and wrist bearings along with the before mentioned thigh bearings might be a candidate minimalist arrangement. This is an area begging further study.

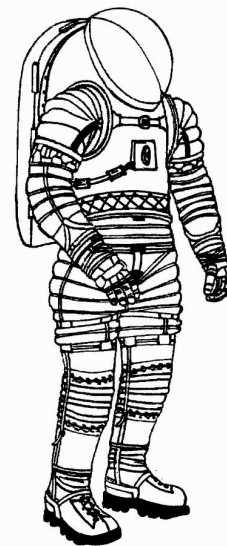


Figure-11 Potential Lunar/Mars Suit architecture

Beyond the number and placement of bearings, basic bearing design is going to be an engineering challenge for a planetary surface suit as well. Past experience during Apollo surface activities has shown that bearings (and suit seals) will rapidly degrade from dust intrusion. The moon and Mars both contain deep, very fine dust layers. Mars soils and lunar regolith contain dust particulates that apparently range in size from medium sand (40 – 130 micrometers) to a medium silt (20 micrometers), with an average grain size of around 70 micrometers. Encouragingly, oil impregnated felt seals and labyrinth traps have been suggested to alleviate the dust hazard (9).

Pressure Integrity

It goes without saying that pressure integrity of the EVA suit is the prime and overriding design driver. The EVA astronaut has about 15 seconds of consciousness following total suit pressure loss (depending how aware s(he) is of the impending loss). While it is highly unlikely that a space suit would suffer catastrophic pressure failure, mechanisms can be put in place, however, to limit loss of pressure integrity and or to react during pressure integrity interruption. The Russians, for instance, use two pressure bladders in their Orlan family of EVA suits. In the Orlan, the outer bladder (the primary bladder nearest the restraint layer), is a universal style rip-stop Nylon with a Latex membrane pressure barrier. The secondary (redundant), or “hot standby” bladder, is similarly composed, but remains uninflated unless the outer bladder is breached. In the case of a pressure breach of the primary outer

bladder, three aneroid valves react and automatically inflate the inner pressure bladder. If both bladders are penetrated, the inner bladder will still generally seal as the hole though both bladders will misalign when the inner bladder inflates (11).

The Shuttle Extravehicular Mobility Unit (Shuttle EVA suit) uses a tough polyurethane coated nylon layer as its pressure bladder. The polyurethane membrane is very durable, but as a tradeoff has no self-sealing qualities, or redundancy. In contrast natural Latex, as used by the Russians, while an older, less durable material (membrane shelf life is only about 3 years), has some self-sealing ability. Still, using two bladders, as the Russia do, adds to the Orlan suit being less mobile and contributes to suit weight and complexity (1).

In recent months De Leon Technologies LLC has identified new, commercially available textiles with bonded-on membranes that exhibit surprising self sealing qualities, with a high trapezoidal tear strength and excellent thermal stability. Further study in this area is paramount but dependent on the limited funding available to the company and university.

Helmet

Strong candidates for planetary space suit helmets are a 13 inch (330 mm) diameter hemispherical design, otherwise known as a half-spheroid or, less accurately, a half-bubble. The other strong candidate is an oval helmet as is employed on ILC Dover’s “T” suit. The optimized geometry of both of these

helmet styles is interdependent upon a rear entry suit closure.

The narrowness of an oval helmet has the advantage of allowing an upper torso that has less interstitial distance between the shoulder scye bearings as compared to a 13 inch hemispherical helmet. This favorable interstitial scye bearing spacing allows the suit subject a greater overhead reach and natural shoulder motion. Because it shares general geometry with the hemispherical helmet, the oval helmet also has favorable optical qualities, acceptable expired gas washout, has acceptable emulsification (is large enough to keep carbon dioxide from concentrating in interspersed pockets in the respiration cavity), and exhibits low flow turbulence (12).



Figure-12 ILC Dover's "T" Suit.
Note Oval Helmet

Further, if the seeing area of an oval helmet is scratched or mired, the helmet can be rotated around 180 degrees to the clean side (1).

The 13 inch diameter hemispherical helmet shares many qualities with the

oval helmet except that, if it is scratched or mired, the suit user can simply rotate it a few degrees to find a clean seeing area. This implies that the helmet can be used longer in an abrasive environment than an oval before replacement. Both of these helmet candidates must be placed on an approximate 50 degree angle (50 degrees to the horizontal, give or take) in order to allow the planetary astronaut to see his or her feet. The Russians consider an acceptable viewing range from a helmet to be 120 degrees in the vertical and 200 degrees (side-to-side) on the horizontal. The hemispherical and oval designs easily meet these criteria (13). Additionally, the 13 inch hemispherical helmet will fit the majority of astronaut/cosmonaut anthropometry.

Conclusion

This paper addresses only some of the top-level considerations for future EVA suits used on the moon and Mars. Even from this initial examination presented here, it is readily observable that future planetary suits must be considered as part of a larger, mutually influencing system of vehicles and habitats. Moreover, the design of both EVA systems and vehicles must be holistically considered in context to an overarching mission architecture.

The design and engineering of operational planetary EVA suits will benefit enormously from continued experimentation on all the various suit components. As presented in this paper, there are some approaches derived from the history of orbital suits that are directly applicable to planetary suit research. However, the unique aspects of

surface environments and the physical separation from Earth require that planetary suits be enormously robust and maintainable. The authors believe that these suit qualities primarily derive from a solid understanding of suit design trade-offs that is gained through numerous iterations and hands-on experimentation. Nuances of space suit mechanics, such as supporting suit mass with the lower torso, go against the grain of initial assumptions of maximum

mobility. Thus, even though highly-mobile walking suits were demonstrated four decades ago, such an approach may not be the most appropriate solution in reduced gravity fields. An initial appraisal of the state-of-the-art in space suit technology indicates that continued research and investigation is required to better identify the materials, methods and concepts that will enable human exploration beyond low-Earth orbit.

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