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Dust Mitigation Solutions for Lunar and Mars Surface Systems

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ABSTRACT

Dust mitigation has been identified as a major obstacle to lunar and Mars surface operations for space suits, robotics, and vehicle systems. Experience from the Apollo program has demonstrated that lunar stays of limited duration will be difficult and dangerous if dramatic measures are not taken to mitigate the impacts of dust contamination. Numerous mitigation approaches have been studied in the past including electrostatic materials, cleaning techniques, and suit-locks. Many of these approaches are effective in operation but are challenged by the trend of returning to a single space suit system, similar to Apollo, which is used for launch/entry as well as surface and contingency extra-vehicular activity (EVA) operations. Bringing the surface suit inside the vehicle after surface EVA will transfer surface material in the vehicle. Studies are currently ongoing to identify containment methods of isolating the space suit or robotics elements from the surface dust during EVA operations through the use of removable covers. This approach not only protects the underlying components from dust contamination but also precludes the transfer of dust into the vehicle or habitat. Similar containment analogs are employed everyday throughout the world when using chemical, biological, or radiological protective equipment in the military and various industries. Prototype covers for the space suit have been designed and tested to create robust durable covers that protect the suit from degradation without encumbering mobility, while also being simple to don & doff. Accompanying procedures, such as removing the covers just outside the airlock, will keep the dust off the underlying space suit and therefore prevent it from entering the vehicle. The covers may also include any dust mitigating materials advances such as lotus-effect coatings as they evolve, simplifying certification and life-cycle impacts of the underlying space suit. First order system level trades have been conducted on various technical approaches. Results of the trade studies, discussion of the analogs that are in existence and prototype testing will be presented in the paper.

INTRODUCTION

Based on the experience gained from project Apollo, there is no doubt that considerable attention must be given to dust mitigation if long term missions are to be attempted on the lunar surface. The space suits and equipment used in Apollo were quickly covered in lunar regolith (Figure 1), and the transport of exposed regolith into the Lunar Excursion Module (LEM) was a nuisance as well as a hazard to the crew and vehicle [1].

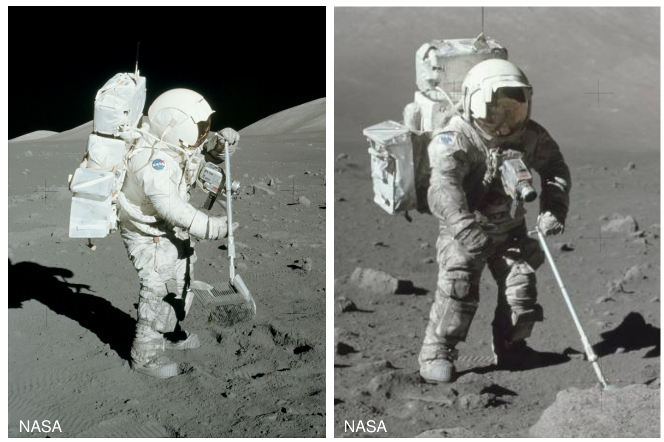

Figure 1 – Astronaut Harrison Schmitt, Apollo 17 EVA #1 (left), and EVA #3 (right), color photographs [2]

Dust incursion caused mechanical and wear issues with space suits and mechanical systems on the lunar surface. The abrasive and chemical reactive nature of regolith in the form of micron sized angular silica oxide particles, created problems for the space suits after only one EVA. Numerous procedures were put in place during Apollo to attempt to mitigate the problem but with limited success.

This paper discusses potential solutions that are extrapolated from existing paradigms where Personal Protective Equipment (PPE) used. These include military nuclear, biological, and chemical (NBC) war fighting, high-potency powder pharmaceutical processing, mining, semiconductor manufacture, and in handling deadly biological materials such as the Ebola virus. Dust mitigation component concepts and processing procedures are also drawn from Protective Equipment (PE) such as deployable NBC military shelters, flexible powder pharmaceutical process containment systems, and flexible isolation chambers used in many industries [3]. There is a vast compendium of knowledge in practice for military and industrial operations, which have direct applicability to the issues encountered in exploration regarding dust effects mitigation as well as planetary protection. A number of these approaches have been developed and practiced by ILC Dover, and have become the basis of several concepts under consideration for the return to the lunar surface.

The issue of dust mitigation has been studied since project Apollo and numerous approaches have been considered [4, 5, 6]. Often these centered on enhanced materials for dust rejection, dust seals, and processing techniques for dust removal from exposed items. Each of these concepts has something to offer with respect to dust mitigation. However, the overarching motivation for the studies described within this paper focus on a higher principal, which is to prevent dust exposure to critical components in the first place.

The space suit is a good focus area for technology application because it is the single greatest transport mechanism, and requires protection itself in order to survive numerous Extra-Vehicular Activities (EVA's). Employing removable covers on the space suit that are only worn during surface EVA will not only prolong the life of the suit and reduce crew maintenance, but will stem the transport of material into vehicles (airlocks, habitats, rovers, etc.). Approaching the issue in this manner creates an adaptable solution which can be immediately applied to exploration activities, and be amended over time to enhance performance further through the inclusion of independent technologies such as dust repellant materials, cleaning techniques, etc. Not only does this approach have a positive impact on the space suit, but also it has a broad systems level impact on vehicle performance, maintenance, logistics, and crew safety.

The application of removable covers to the space suit is one use of what is broadly known as "containment" in various industries, but many other possibilities exist for application of containment technologies in exploration systems architecture. Flexible covers for robotics assemblies would extend the life of mechanisms in a similar way as the space suit. Covers for containment of dirty items being brought in-vehicle for repair would also have a positive systems impact. Covers can be made clear and incorporate arm/glove sleeves to allow work to be conducted while the item is contained. Deployable isolation chambers could also be used in the lander/habitat to act as a dirty work area if needed, and then repacked or discarded as necessary.

Looking further in time toward Mars exploration, containment technologies will be critical for planetary protection. Containment can be used to keep material from being expelled by space suits and robotics onto the surface, and thus maintain the cleanliness of the area with respect to organic materials brought from earth [7].

It is worth noting that the study of solutions for dust mitigation must be approached holistically in order to be effective. Identifying solutions, which can be immediately applied and can be modified to match the needs of the evolving surface architecture is important. For instance, some experts in the industry have concluded that the use of an EVA dedicated space suit is the solution to keeping dust from entering the vehicle. This may be an acceptable solution in future for a well established surface camp with a large infrastructure, but early missions are planning for a single space suit more in line with the Apollo paradigm [8]. This suit will be used for Intra-Vehicular Activity (IVA) as well as EVA, and will probably exhibit similar dust transfer issues as were experienced on Apollo. In a similar fashion, many people identify the airlock, where the dirty suits can be stored between EVA's, as a solution. This hypothesis is constrained by the single suit issue, but also puts a considerable burden on the airlock seals and life support systems, and certainly increases the modes of transfer into the lander/habitat during suit doffing in a confined space through contact between the "clean" wearer and the dirty airlock. Work discussed in this paper attempts to take the exploration timeline into consideration as well as deeper systems issues such as crew time, logistics, and mass when discussion options for dust mitigation.

Limits for levels of containment (or dust exposure limits) for surface space suits, landers, and habitats have yet to be established by NASA [9]. Practically speaking however, it is likely that some level of dust transfer into the vehicle will be acceptable, and somewhat unavoidable. Industrial Operator Exposure Limits (OEL's), which dictate quantities of particular substances humans can be exposed to over a prescribed time, provides well-established guidance into these issues. Concepts for lunar dust containment are being developed which can span the gamut of OEL's as required.

HISTORICAL PERSPECTIVE

The Apollo experience with respect to dust exposure and mitigation has been chronicled extensively [1,2,6]. Many statements were made by the Apollo Astronauts, which prove that more effective dust mitigation measures must be taken in future endeavors [6].

Dust related hazards and transport mechanisms have been sorted into categories based on the Apollo mission experience [1]. Dust related hazards have been sorted into nine categories. These categories are: vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion of materials, thermal control problems, seal failures, and inhalation and irritation. Mitigation methods, which address multiple categories, would be favorable. This categorization was used for guidance in the development of containment solutions for exploration activities.

There are two general classes of dust transport mechanisms, natural and anthropogenic [1]. Natural transport mechanisms include secondary ejecta from meteor and micrometeoroid collisions with the surface, and electrostatic levitation of dust at the terminator. Three anthropogenic mechanisms were analyzed and are, in order of increasing importance; astronaut walking, rover wheels spinning up dust, and landing and take-off of spacecraft [1]. Many more anthropogenic mechanisms may be introduced with the planned level of exploration. It is possible to look at this classification and observe that the definition of “transport” is confined to the localized movement of material. However, if a broader definition were adopted for transport of material, than its adherence or entrapment in material or components would dictate that the space suit and other components become the transportation vehicle and humans or robots the transport mechanism. Since it is impossible to alter the natural mechanisms, solutions were developed to emphasize impacts of the anthropogenic mechanisms and their subsequent transport vehicles.

Perhaps the most important reason for developing dust mitigation methods for exploration is crew health. There have been many terrestrial occupations where workers are exposed to dust, and this experience can be used in guidance for setting physiological limits as well as mitigation solutions. There is more than 200 years experience in mining. Of the typical maladies that occur, silicosis is perhaps the most representative model to the lunar environment because of the particles size distribution, shape, and chemical reactivity [9]. Other well known diseases such as coal miner’s lung or asbestosis are unlikely in the lunar environment because of the limited volume of exposure and particle type respectively [9]. Advances in PPE have done much to reduce occurrences of these diseases in industry. Protecting the crew from significant dust exposure will be of paramount importance for lunar return, to prevent immediate complications or long-term medical effects.

SYSTEM NEEDS & REQUIREMENTS

NASA is currently developing comprehensive system requirements for dust mitigation [10]. Until they are available, only assumed needs and requirements can be developed from the large body of knowledge available, particularly Apollo technical data. This paper will therefore only describe several overarching needs and requirements, which have been critical in guiding the development of concepts to date. Requirements discussed will include technical needs as well as program issues, such as anticipated implementation timelines for various operational procedures.

Some of the common overarching themes guiding concept development are mass & volume reductions, crew safety, logistics impact, reducing crew burden, life-cycle cost, and adaptability. The mass and stowage volume of any approach to dust mitigation will be of critical importance because of up and down propellant mass impacts and vehicle configuration impacts. A platform approach from which derivative solutions can be created offers the potential to exploit commonality of materials, reduce training, and logistical impacts. From an operations standpoint, stemming the transmission of lunar material from the surface into components, and then from components into the vehicle is critical.

SPACE SUIT REQUIREMENTS

Beginning with the function of the space suit itself, mobility, thermal protection, soundness of the gas barrier, and structural integrity must be maintained for a significant lifetime of the suit. Joint mobility and torque correlate directly with fatigue, comfort, and crew efficiency. The suit or anything attached to the suit should not hinder mobility or joint torque. Bearings and mechanisms in the suit need to be protected from exposure and must maintain performance over time. Optical properties of the exterior of the suit, and the thermal insulation, such as Multi-layered Insulation (MLI), cannot be allowed to degrade appreciably because of the subsequent burden on thermal control systems. Maintenance of the gas barriers integrity and joint/closure seal integrity is critical to preventing loss of precious consumables, and protecting life. Structural performance must be maintained after many flexure cycles and impacts. The effects of abrasion, thermal impacts, and loading must be considered.

The above structural and performance requirements are well understood by those in the community. Perhaps more interesting though, in the development of dust mitigation concepts, are operations issues dealing with the suit and system architecture. At this time the lunar return architecture is not well defined. However, some system impacts are apparent in early trips back to the lunar surface. A suit platform with capabilities, which exceed the Apollo suit, but minimize mass and volume impacts on the Crew Exploration Vehicle (CEV) and Lunar Lander (LL), will be critical [8]. Currently, a single modifiable/adaptable suit is baselined, with operational aspects similar to that of Apollo. Therefore, the suit used for EVA on the lunar surface will also be brought back in the LL for the return to earth. This is a critical point in developing dust mitigation concepts. It is also important because of the alternate space suit approaches impact on vehicle mass and stowage volume if numerous secondary components are required to support EVA. Crew-down operations where medically incapacitated suited crew are brought back into the vehicle while suited also need to be considered. The space suit will need to function for many EVAs between maintenance intervals, to reduce crew burden. The suit must also be simple to accommodate rapid maintenance. Apollo literature indicates that in some instances suit performance deteriorated from dust contact to a point where further EVAs would not have been possible [1].

INTRA-VEHICULAR REQUIREMENTS

Anything used in the vehicle must be compatible with the environment, be simple to use, and be intrinsically safe. Materials must be non-flammable, non-toxic, low outgassing, and acceptable for human contact. Mobility and adaptability to use in various areas may also be of importance in extending the useful life of components. Power minimization is also important because of overall system mass impacts.

ROBOTICS REQUIREMENTS

The requirements for dust mitigation for robotics follows a similar path as for space suits. Mobility joints and critical components must be protected from contact with the abrasive lunar materials, and not have their mobility hindered. Consideration of maintenance operations is critical and must be accounted for.

OPERATIONAL CONCEPTS

Most dust mitigation studies to date have focused on enhancements of materials (electrostatics, lotus effect or superhydrophobic coatings, etc.), physical removal (brushing, vacuuming, etc.) or processing techniques (airflow control, suit-port, leaving suits in airlocks, etc.). All of these approaches have merit and warrant consideration. They have been studied extensively and are well understood to the reader and are not discussed in detail here. An alternate approach to the above is proposed in this paper, which has synergistic benefits with the other approaches. Through the use of containment technologies, the transfer of dust can be significantly mitigated and a first line of defense can be established to keep dust away from components and locations. This tactic is preventative in nature and deals with the threat upstream of when it has impact on systems. Several approaches are discussed here including EVA suit covers, IVA suit covers, deployable IV rooms, isolation chambers with glove-sleeves, and robotic covers. These technologies can also be expanded to medical isolation and sample isolation/containment, and can also be extended to planetary protection.

SPACE SUIT COVERS

The concept of applying donnable/doffable protective covers is commonplace in many industries. Perhaps the most well known use of covers of this sort are common DuPont Tyvek® suits (Figure 2) which can be purchased at hardware stores and used for protection while painting, working with fiberglass insulation, etc. The 9 mil thick suit comes in a very compact package. It is opened, donned for use, then doffed and discarded or reused, depending on the application. It protects the wearer from significant contact with the external threat. Extensions of this approach are commonplace in many industries and in more robust and complex protective equipment. The military use personal protective equipment (PPE) in the form of hoods, masks, and suits, to protect the wearer against nuclear (dust), biological and chemical threats (Figure 2). PPE of this nature are reusable, can be decontaminated and robust enough to stand-up to military use without hindering function. Materials are typically 20-30 mils thick and provide excellent barrier properties.

Chemical Biological (CB) suits are also used in many commercial and government installations (Figure 3). As with the military NBC suits noted above, Level A CB suits are used repeatedly and methods of cleaning are implemented between uses. Procedures are developed to protect the user from exposure to life-threatening material on the exterior of the suit while doffing a contaminated suit. This kind of suit is used in high potency powder pharmaceutical processing in thousands of facilities worldwide. In many instances where ingestion or inhalation of micrograms of dust can be life threatening. It is also used by the US Center for Disease Control when working with deadly viruses (such as Ebola and HIV), *Bacillus anthracis* (the bacteria causing Anthrax), and various antibiotic- resistant agents (*staphylococcus & mycobacterium spp.*).

Figure 2 – DuPont Tyvek™ suits being used for disaster clean-up operations, and an Army M3 TAP CB suit

These suits are constructed of impermeable chemically resistant materials, which are typically 20-30 mils thick. They are slightly pressurized to prevent internal contamination even if the suit has a penetration, and are oversized to fit a wide range of users. Although fairly bulky in nature, they don't restrict motion of the user enough to impact performance. These suits are used in commercial operations where efficiency is critical. NASA also uses similar suits for fueling launch vehicles with propellants such as hydrazine. They are known as Propellant Handlers Ensembles (PHE's), and have been in use for decades.

Figure 3 – ILC Dover Chemturian® Level A suits used in high-potency powder pharmaceutical manufacturing (left), and at the US Center for Disease Control (right)

Other industries such as semi-conductor manufacturers, nuclear materials manufacture and power-plant operators also wear similar equipment and use extensive procedures for proper use of protective equipment. It is interesting to note that PPE used in the semi-conductor industry protects the materials being processed from worker contamination, as well as protecting the worker from materials used in the manufacturing process [12]. Solvents used in the process (such as 2-Methoxyethanol, 2- Ethoxyethanol and Their Acetates - Glycol Ethers) are carcinogenic and highly toxic [13]. Exposure limits are highly controlled.

Given that many of these suits were used in ways, which were similar to the challenges astronauts will face with lunar dust, space suit covers were considered a logical path for investigation. At this time the space suit configuration and operations are not well defined so the progress made in these studies is considered first order. A basic operational concept would have the astronaut launch in the suit, traverse to the moon (unsuited), and descend to the lunar surface suited. The potential exists for contingency or planned EVA in space, which drives the need for a highly mobile suit. Until the crew goes EVA on the lunar surface, the suit is uncontaminated. When the crew does go EVA for the first time, they would don their covers in the airlock (See Figure 4). They would then go EVA and establish a simple doffing station at the foot of the ladder consisting of a slightly elevated grating and a bench. After the EVA (covered in lunar soil), they return to the grating, stomp their feet and brush-off as required. They then remove their covers and stow them. The suits are clean at this point and they can proceed inside the vehicle. Procedures, donning aids, and support tools can be developed to reduce contamination further if required.

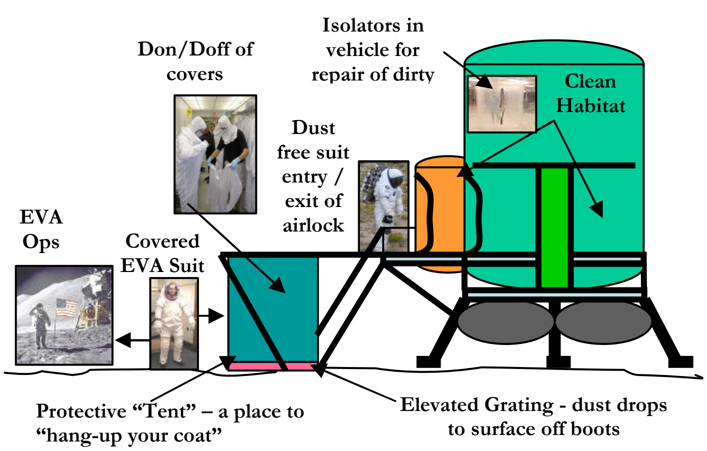

Figure 4 – Operational scenario for reusable space suit covers on the lunar surface

Several general operational approaches are possible and require further evaluation and trade. Questions surrounding reusability vs disposability must be considered. At the heart of the question are the simplicity of donning and doffing and how much material might be transmitted to the space suit from the cover. This is related to OELs as the suits are brought in the vehicle, which have yet to be defined. Single use covers might be one way to help alleviate this issue as you would only don clean covers, but as EVA numbers rise, so does consumable mass. Also, the covers must be engineered to be highly puncture & tear resistant in use which will work against supporting disposable covers.

Another option for covers would be to cover the dirty suit for the return flight. This assumes that covers are not required to bring longevity to the suit in the first place. Something along these lines was done on Apollo 15 when Astronaut Scott used a jettison bag to contain dust on the legs of his suit in the LEM prior to docking with the CM [6].

Space Suit Cover Configuration Options & Test

Numerous configuration options are possible for a cover garment. In considering options, the first question is whether the cover will be a single piece or multiple pieces. Although most anthropomorphic protective covers (described previously) are single piece, preliminary tests have shown that multiple pieces may be more advantageous for lunar suit covers. The decision principally becomes one of trading ease of donning and the potential for transfer of lunar material to the suit (and ultimately into the vehicle). It is likely that the small amount of material that might be transferred to the suit could be removed prior to entering the vehicle, or in the vehicle, through cleaning practices. Split covers (coat and pants) can be slightly less bulky without restricting mobility, and also ease the burden on sizing the garment and will facilitate better fitting of a larger population with less discrete sizes because of mid-torso overlap. Split garments will also be more conformal in fit and thus have lower snag potential.

Another important item in developing the configuration is determining what portions of the suit will be covered with an integral and contiguous cover. Gloves and over-boots could be integral or separate from the main cover. Experience tells us that the gloves should not be encumbered in any way because of the negative impacts on hand mobility and tactility. Therefore, the termination of the sleeve will likely occur at the wrist, over the glove gauntlet. The gloves may require an over-cover to be applied during suit cover doffing, or the glove TMG may need to be temporarily removable, to prevent transporting lunar material inside the cover. It is possible that this may be possible by inverting the glove gauntlet itself, if oversized. Boot over-covers are more likely to be integral with the suit cover, as the amount of exposure on the lower legs is significant and continuity in the barrier must be maintained in this area according to Apollo experience. The lunar EVA suit will likely have tools, displays, and controls that must be accessed, and must be accommodated. Pockets and sealed access openings in the outer cover may be required depending on the final suit design. The PLSS mounted on the back of the suit could have a separate cover to improve donning of the outer cover. Cover concepts currently do not include helmet visor protection, but this may be possible in future if a suitable interface to the Extra-Vehicular Visor Assembly (EVVA) can be developed.

ILC Dover fabricated and tested two cover mock-ups to begin understanding the potential for creating a cover that could be easily donned and doffed (Figures 5 and 6). Other aspects of the covers that were studied included mobility impacts, suit to cover interface, sizing/fullness, and closure methods. Both covers were full piece assemblies assembled using 9 mil thick DuPont Tyvek®.

In the initial test, an extra-large commercially available Tyvek® cover garment (~1 lb) was modified to interface with the I-Suit. This version of the I-suit is rear entry, and no life support system was attached. The cover terminated at the wrists, ankles, and around the helmet. The Tyvek® suit was tight in numerous locations, and the material has relatively low elongation, but mobility was not significantly affected once the cover was properly positioned. It seemed to match the contours of the suit well and the low friction material (flash spun & bonded very fine, high-density polyethylene fibers) allowed the required translation at the bearing interfaces. Areas where easements were needed and other desired modifications were noted and a second garment was constructed for test.

Figure 5 – I-Suit with a modified DuPont Tyvek® cover garment in first order interface test

The second garment was manufactured from the same Tyvek® material, but was patterned and assembled with easements to facilitate donning and doffing. The single piece unit had integral over-boots, and a fastener tape closure mechanism in the front. The garment was donned and doffed by the unaided suited subject (at 4.3 psid) while in the I-Suit. Donning operations were evaluated in the seated and standing positions. The splay of the legs due to the motion of the hip/thigh mobility joint motion was found to require greater easement for the seated position. The high range of motion of the I-suit aided in donning the cover, and is an important component of the symbiotic nature of the cover and suit. The lack of stiffness of the very thin material complicated donning. It is thought that a stiffer material may help the wearer, but may also have a negative effect on mobility. Elastic straps are needed to make the cover more conformal and to decrease snag potential. Strategic locations for placement of the straps were evaluated. Integral distensible bands in the arms, legs, and torso may aid donning as the cover will grip the suit when positioned, and will be added in future studies.

Figure 6 – I-Suit with a patterned cover mock-up made

from DuPont Tyvek® in don/doff test

Issues with a blind operation such as moving the cover around a back-mounted Life Support System (LSS) may necessitate use of donning aids or the "buddy-system" in donning. Several types of donning aids have also been considered to simplify the process. Detachable hoops, which maintain the garment's opening geometry, are one option. Something similar to a rear entry space suit donning stand has also been considered. Donning aids have the potential to reduce contamination from the covers exterior to its interior or to the space suit itself.

Future testing will include versions with stiffer, more durable materials (discussed later), integrated over-boots, integrated conformal bands, donning/doffing aids, and more elaborate closure mechanisms. A split configuration of pants and a jacket will also be tested for fit/sizing and ease of donning/doffing. Eventually simulant testing will be conducted to establish modes of material transfer from the cover to the suit in repeated use and quantification thereof. ILC Dover has conducted simulant testing of pharmaceutical containment systems to quantify OEL's [13]. In these tests (Figure 7) a fluorescing dust was added to the powder simulant and the final item was inspected with a black light after trials to assess contamination sources. The same approach could be used in testing the dust cover if a visual signature is not enough.

One of the greatest challenges in designing the cover is to make it conformal. Conventional wisdom would indicate that elastic materials could be added to strategic locations to make the cover "hug" the suit. This may be possible if low temperature silicone rubber is used, but most materials will not be able to flex in the low temperature environment, which may be encountered (approximately -250F). Other options exist though, such as using special knit materials, which have the ability to deform through fiber shifting in the weave while being manufactured from inelastic fibers. This is possible with warp-knit materials such as tricot weave patterns used in hosiery. Large deformations are possible with these materials. A more robust option may be to add linear extension springs (in sleeves) and cords to the cover at the desired locations. This approach would yield a predictable uniform tension under a wide range of temperatures with little degradation over time as compared to elastic materials or specialty woven components.

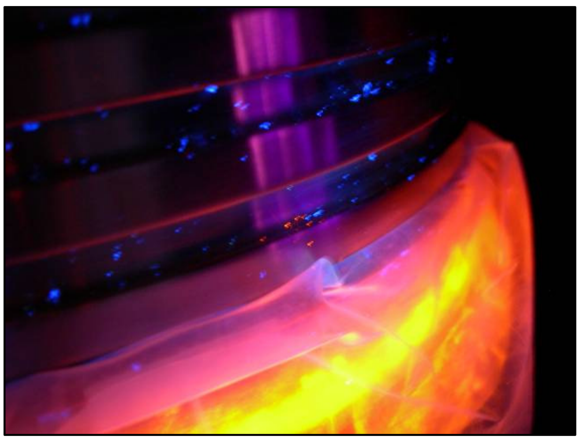

Figure 7 – Pharmaceutical Containment Systems Being Inspected After Test with a Fluorescing Powder

Space Suit Cover Materials

Apollo space suits were constructed from 21 independent layers of material [14]. The exterior surface consisted of either a woven Beta-Cloth (fine denier fiberglass) shell, Beta-Cloth made with Teflon coated fibers, or a woven Chromel "R" fabric (typically on the gloves and boots). Below the surface layer were a series of interleafed Beta-Cloth, vapor deposited Aluminum (VDA) coated polyimide, VDA coated Mylar, and lightweight polyester fabrics. Together, these layers were called the Thermal & Micrometeoroid (TMG) layer. Below the TMG was the bladder/restraint that was a neoprene coated nylon laminate. Lunar dust permeated the outer woven layers and entered the MLI because the Beta-Cloth & Chromel "R" were a woven material with fine intestacies. No contiguous coating was present. Regolith caked in the intestacies and was difficult to remove because of its surface topography.

Gaps in the TMG were part of the design to enable mobility of the joints, which were fabricated from and covered by non-distensible materials. This was true particularly in the area of bearings and disconnects because the rotation of the joints required large localized translation. These gaps became an entry point for lunar material and allowed it to become entrapped in the suit as well as impact rotary and other joint mechanisms (bearings, zippers, pulleys, etc.).

Steps can easily be taken to reduce this mode of transport in future space suits. The materials used in the cover as well as the space suit outer garment should be coated fabric. The fabric component would be a lightweight, high strength material such as Vectran®. The continuous coating would be a material such as silicone, and would act as a robust flexible dust barrier. A material of this nature was used in the Pathfinder and Mars Exploration Rover airbags, which landed probes on the surface of Mars [15]. In this case the silicone coated Vectran® (40 x 40, 200d) had to be able to be tightly packed, cold soaked to –250F in Transit to Mars, and then rapidly deployed in under one second during the landing event. This material is highly abrasion resistant and the silicone coating is consistent with that used in the Apollo overboots, which survived well during Apollo without significant abrasion degradation [16]. The exterior surface of the dust cover material could either be smooth or textured in some way to reduce surface tension and adherence of dust. The coating may also be filled with a small percentage of titanium dioxide to make it white for thermal control. Other materials such as FEP or PTFE cloth laminated with a film of the same material are also candidates, but may not exhibit as much strength or low temperature flex capabilities.

ROBOTICS COVERS

Covers for articulated robotic joints may be approached in a similar fashion as the space suit covers. The fine mechanisms used in robots such as Robonaut or ATHELETE must be protected from dust incursion. Highly flexible conformal covers can be added to the joints for protection. This approach is employed in automotive CV-joints, spray-paint robots (Figure 8), and industrial robots which function in dirty environments.

Figure 8 – Articulated Paint Spraying Robots with Protective Covers

IN-VEHICLE PROCESSING TECHNIQUES

Many of the previously mentioned industries use special processing techniques to manage contamination transfer during operations with PPE. Airflow management, air showers, and staging areas are some of the more typical methods used. Military shelters used in the NBC battlefield environment are a good example of the effective use of procedures. In the M28 Transportable Collective Protection System (TCPS), all of these approaches were used (Figure 9) [17]. The contaminated user in PPE would enter the airlock (green triangular box in center) and would be exposed to a down-flow air-wash. After a prescribed period of time, they enter an interior chamber, which is kept at a slightly higher pressure than the airlock, and flows into the airlock. Contaminated PPE is doffed in this area, and the soldier moves into the clean area through another pressure sealing door. The clean area is kept at the highest internal pressure. A recirculation filter is used in the clean area to continuously recirculate and filter the air in case any contamination is brought in accidentally.

Figure 9 – The US Army M28 Transportable Collective Protection System Developed by ILC Dover

Similar techniques can be applied to lunar landing vehicles and habitats to mitigate dust, perhaps in conjunction with in-vehicle isolators.

IN-VEHICLE ISOLATORS

It is possible to deploy “mud” or “work” rooms within habitat structures to aid in dust mitigation. These rooms, or isolators, can be used adjacent to airlocks for staging in and out of the habitation space, for maintaining dirty or contaminated components, for washing, etc. Rooms can be manufactured from very thin films, can be freestanding (supported by inflatable tubes), and can be quickly re-packed making a space easily reconfigurable. Depending on the use, positive or negative pressure isolation can occur. Air filtration in the form of HEPA filters can be added to facilitate use. An example of an isolation room manufactured for terrestrial medical isolation by ILC Dover can be seen in Figure 10. Here, inflatable tubes support the thin-film walls of the chamber to create an isolated space.

On a smaller scale, isolation bags were used during Apollo to bag samples and dirty items brought in the LEM. Isolation techniques of this nature worked well [6]. In this case, items were bagged prior to transfer into the Command Module to maintain cleanliness. Similarly, EVA items that require maintenance may be loaded into flexible isolators and moved into a controlled work area without contaminating it. The isolators can be constructed with integral sleeves and gloves to create a glovebox, which allows manipulation of the item inside with the potential for contaminating the vehicle. An example of a component with this functionality is a flexible isolator used in powder pharmaceutical manufacturing (Figure 11) [3]. With equipment such as this, OELs on the order of 10-20μg/24hr can be expected. The exposure limits are established by the method of closure of the isolator, in this case being twist tie and cut.

Figure 10 – ILC Dover deployable self-standing 7.5 ft cube isolation chamber made from thin films

Figure 11 – ILC Dover transparent thin film flexible isolation chamber with integral glove sleeves used in high potency powder pharmaceutical manufacture

CONCLUSION

Numerous options exist for employing lightweight flexible materials for dust mitigation in lunar and Mars surface exploration activities. Many industries such as pharmaceutical, nuclear, and semi-conductor, have stringent standards for operator exposure during manufacture operations, and extensively use protective equipment and procedures to limit exposure to hazardous substances. Similarly, the military and civilian first responders use protective equipment and shelters to protect military personnel and civilian personnel from nuclear, biological, and chemical threats on the battlefield and in emergency situations. Information gathered from this equipment has been applied to dust mitigation for the return to the lunar surface. Protective covers for use on the space suit and robotics have been developed and tested to prove the efficacy of the approach. Simple reusable covers, which are worn over the clean space suit, can protect the space suit from the deleterious effects of dust contamination and prevent transfer of dust into habitats.

Flexible isolation chambers and rooms made from thin films developed for medical isolation and high-potency powder pharmaceutical manufacturing can be adapted for dust mitigation inside lunar vehicles. Lightweight deployable vessels can be used as reconfigurable "mud" rooms, and facilitate the repair of dirty equipment without transmitting material in the vehicle.

Protective elements of this type prevent vehicle contamination thus protecting crew health, prolonging the life of components, reducing component mass and thus the logistics chain. They also open up system architectural options for exploration. They can be implemented immediately and serve near-term and long-term system needs well, such as a single-suit architecture which is used for EVA and IVA operations for the entire mission. Covers can also be improved independently of certified equipment independently as technologies emerge for enhancing dust shedding.

Apollo 17 Astronaut Harrison Schmidt noted "you need a long-term layered defense against lunar dust". Containment solutions in the form of suit covers, robotics covers, and in-vehicle isolators may be a part of that defense in future lunar exploration

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CB: Chemical-Biological

CEV: Crew Exploration Vehicle

CM: Command Module

EVA: Extra-Vehicular Activity

EVVA: Extra-Vehicular Visor Assembly

ILC: ILC Dover LP Company

IV: Intra-Vehicular

IVA: Intra-Vehicular Activity

LEM: Lunar Excursion Module

LL: Lunar Lander

LSS: Life Support System

MLI: Multi-Layer Insulation

NASA: National Aeronautics & Space Administration

NBC: Nuclear, Biological and Chemical

OEL: Operator Exposure Limit

PPE: Personal Protective Equipment

PE: Protective Equipment