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# Topical: Electrostatic dust removal from spacesuits

## EXPERIMENTS DESIGNED FOR THE LUNAR SURFACE

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## ABSTRACT

Lunar dust was an unexpectedly large challenge for the Apollo missions. The dust causes problems for both people and machinery, it causes vision obscuration, clogs machine parts and spacesuit joints and causes health problems for astronauts who are exposed to it. The electrostatic and magnetic properties of the dust make it possible to create devices that utilise those same forces to repel or attract dust away from spacesuits. Spacesuit cleaning devices have been tested previously using lunar simulants, however lunar simulants are not able to fully capture the nature of lunar dust. Therefore, experiments used to test the effectiveness of lunar dust cleaning devices for spacesuits should be carried out in the lunar environment itself.

## LUNAR DUST PROBLEMS

The Apollo missions saw humans land on the moon for the first time. With the many dangers of the lunar environment in consideration, it was not expected that dust would be the biggest challenge to overcome. Lunar dust impacted all aspects of the Apollo missions causing vision obscuration, damage to equipment, damage to spacesuits and contaminating the lunar module exposing the astronauts to adverse health effects [1]. Removal of lunar dust from spacesuits before entering into spacecraft or habitats will be essential for future lunar missions to reduce the effects of lunar dust on astronaut health.

### *Effects of Dust on Mission*

A review on the effects of dust on the Apollo missions from mission documentation and transcripts was carried out by James R. Gaier in 2007 [1]. Gaier states that problems caused by dust fall under nine categories: vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation. The effects of the dust on Extravehicular Mobility Suits were so severe that they left some components approaching failure at the end of the mission; the insulation layers of the boots were exposed and the cover gloves had to be discarded. Several astronauts "remarked that they could not have sustained surface activity much longer or the clogged joints [of the suit] would have frozen up completely [1]." The EMS seals were also compromised by the dust causing higher than normal suit pressure decay and further problems arose when the Lunar Module (LM) became contaminated post mission causing eye and lung irritation to the exposed astronauts.

Christoffersen et al investigated the effects of lunar dust on the materials of some of the Apollo 12 and 17 spacesuits and the degree of wear on the sealed wrist rotation bearing from the Apollo 16 intravehicular and extravehicular gloves [2]. Through microscopic and spectroscopic techniques, Christoffersen et al were able to characterise the amount and size distribution of soil retained by the outer materials of the spacesuits, the chemical composition of the soil and the wear and abrasion of the material fibres and the rotation bearing. Christoffersen et al found through SEM imaging of the T-164 Teflon fabric that made up the outermost layer of the Integrated Thermal Micrometeroid Garment (ITMG) that the materials showed progressive and accelerated wear that is most likely due to lunar soil particles. The lunar soil was able to penetrate through outer materials and cause separation of fibres in the fabric weave. The Chromel R fabric of the gloves was also found to demonstrate substantial wear when exposed to lunar soil.

Despite these studies, the effects of lunar dust on exploratory missions are still not completely understood. The '*Lunar Dust and Its Impact on Human Exploration'* Engineering and Safety Centre (NESC) Workshop by NASA sought to provide a set of findings, observations and recommendations identifying the knowledge gaps on the physical nature of lunar dust, its impact on human health, surface systems and surface operations. The findings of the workshop were compiled and summarised by Winterhalter et al [3]. Some of the recommendations from the workshop that were considered of the highest priority included;

- studies on the characteristics of lunar dust at sizes of <45 μm
- studies of the electric charging of particles due to interactions with solar wind plasma, photoemission and secondary electron emissions
- studies of the effect of lunar dust deposition on optical and thermal surface properties
- studies on the potential risks of crew exposure to lunar dust
- development of device cleaning technologies to protect mechanisms, seals, connectors, solar panels, etc
- and the development of an industry-standard for lunar dust simulants.

Some of these recommendations require testing on the lunar surface while others require improved experiments and simulated environments. Precursor landers will need to perform measurements and experiments prior to the Artemis crews landing on the moon. The experts in attendance of the workshop concluded that "the dust problem is an agency and industry concern affecting most mission subsystems, and it must be addressed [3]."

*Properties of Lunar Dust*

The lunar surface is covered in "a wellgraded silty sand that has reached a "steady state" in thickness, particle size distribution, and other properties at most locations on the Moon [4]." Micrometeoroid impacts bombard the moon creating a fine lunar dust. The extremely low conductivity of the lunar soil makes it capable of being charged and holding a charge for a very long time [4], [5]. The vacuum nature of the lunar environment exposes the lunar soil to the solar wind and UV radiation leading to the dust becoming highly positively charged on the lit side of the moon and highly negatively charged on the dark side of the moon [5]. Both the higher surface energy of particles in a vacuum and the highly charged nature of the particles increase the adhesion forces of lunar dust particles when compared to particles made of the same material on Earth. Walton reviewed the force contributions of particle attributes to adhesion in fine lunar particles and notes that "because of the short-range nature of adhesive surface forces, it can be said with some certainty that adhesive surface forces are likely to be a major concern only when attempting to remove particles from surfaces[5]."

Lunar soil also includes agglutinates. Agglutinates are glass bonded aggregates which are formed due to micrometeoroid impacts [6]. These aggregates are "small and contain minute droplets of Fe metal [6]." The presence of Fe metal in the agglutinates is believed to contribute to the magnetic properties of lunar soil [7]. Agglutinates are a unique feature of soils developed on planets lacking in atmosphere and are not found on Earth [6].

*Limitations of Simulants*

A limited amount of lunar soil samples was collected and brought to Earth during the Apollo missions and the properties of the dust have been studied. Lunar soil and dust simulants have been developed for the purpose of replicating lunar soil properties in larger quantities of material for use in experiments which may be destructive or that need to be replicated multiple times [8], [9]. Whilst attempts to standardise lunar simulant production [10] have led to higher fidelity simulants across the market, no simulant has yet to accurately capture all of the major properties of lunar soil and dust. One of the bigger challenges of lunar simulant production is the production of agglutinates on Earth, the inclusion of the metallic iron is particularly challenging [11]–[14].

*Overview of current dust removal devices*

The magnetic and charged nature of lunar dust makes it possible to created devices capable of manipulating the dust via electrostatic and/or magnetic forces. A few different mechanisms of dust removal have been investigated previously both in relation to lunar dust specifically and in relation to dust inside of vacuum chambers.

Onozuka et al designed a system for the removal of dust from vacuum devices, such as fusion experimental reactors, using static electricity [15]. The system consisted of both a collection electrode and a transportation electrode. The collection electrode applied an electric field to the dust which was in contact with the ground and consequently became dielectrically polarised. The dust was then floated by Coulomb forces to land on a collection tray at the inlet of a tube where the transportation electrodes would then apply an electric curtain to the dust using a 3 phase AC voltage to transport the dust. Onozuka et al proved through a simple experimental setup in a previous paper that both metallic and non-metallic dust could be floated and collected using a single electrode [16]. Another device, designed by Saeki et al, utilised an electron beam and collecting electrode for a similar purpose for removing dust from vacuum chambers [17]. The electron beam was used to charge the dust which was then attracted to the highly positively charged electrode. Saeki et al were able to remove 90% of dust using this method. Both Onozuka et al and Saeki et al saw high success rates for dust removal of regular Earth based dust from a vacuum chamber, however neither device was developed with lunar dust in mind. The more complex nature of lunar dust and the variation in surfaces from which it needs to be removed require special attention.

Devices specifically designed for lunar dust have been created by various groups in recent decades. Hiroyuki Kawamoto of Waseda University in Japan has published numerous papers on the designs of devices for removing lunar dust from mechanical seals [18], [19], solar panels [20], [21] and even spacesuits [22]–[24]. Kawamoto's devices used either electrostatic or magnetic forces or a combination of both to clear lunar dust from a surface or material, with one device also incorporating vibration to clean spacesuits. Kawamoto was able to achieve up to a 90 % cleaning rate on a spacesuit by combining electrostatic and vibration forces. Other designs utilising electrostatic and dielectro-phoretic forces using electrodes have also been proposed by NASA and dubbed the Dust Shield [25].

Electron beam technology has also been applied to space applications [26]–[28]. Electron beam technology is not new to space and has been used for decades to control the potential of spacecraft surfaces, such as on the POLAR satellite [29]. However, its application for lunar dust mitigation is fairly new. Clark et al in 2010 proposed the use of an electron beam to charge a surface in an electric field causing dust to disaggregate and reaggregate on a lower potential surface as a means for dust mitigation inside an airlock [26]. The device has been demonstrated to remove dust from a regular surface under airlock conditions. Farr et al designed a similar device utilising an electron beam and were able to demonstrate a cleanliness rating of 83-92% for glass and spacesuit samples in a paper from 2021 [28].

None of the devices were able to demonstrate a cleaning rate of 95% or greater for lunar dust, however the limitations of experiments performed on earth may have affected the cleaning rates of all of the devices. Under lunar conditions, lunar dust displays different properties and therefore it can be expected that the dust will behave differently when exposed to the cleaning devices in its natural environment. Kawamoto designed an electrostatic travelling wave for the collection of regolith for *in situ* resource utilisation (ISRU) and through calculations predicted that regolith would be more readily manipulated by the wave in the lunar condition [30]. The calculations were validated by comparing calculations for dust dynamics under Earth conditions with experimental results.

## SCIENCE THAT CAN BE DONE ON THE MOON

The unique combination of conditions on the Moon is difficult to reproduce in laboratories on Earth. No single facility can achieve a low vacuum, high radiation, low gravity and charged particle surface at once. Each of these conditions can be produced in isolation on Earth, but combining two or more quickly becomes problematic. As we return humans to the Moon, so too must we spend time researching on the Moon. A wealth of experiments should be implemented which utilise – and seek to characterise – the phenomena occurring on the lunar surface. If we are to combat the destructive nature of lunar dust on space suits, then we must conduct experiments into lunar dust on space suits on the moon. Only then can we truly begin to combat the problems it creates. This science must be done in space and will improve the daily working lives of astronauts.

Astronauts returning to the Apollo landers after lunar EVA brought huge amounts of lunar dust back inside the spacecraft with them. This caused breathing difficulties to the crew, equipment to malfunction and irreparable damage to the spacecraft. There is no way to reproduce this on Earth. Large vacuum chambers exist, for the thermal/vacuum cycling of spacecraft qualifying them before travel to space. But placing a large amount of dust inside these chambers, and a human being, is simply not feasible. Vacuum pumps are designed to create a vacuum by removing dust particles from a specified volume. The creation of a vacuum where the dust/particles remain *inside* the chamber is paradoxical to the concept of a laboratory vacuum.

The radiation environment on the lunar surface is incredible. High energy protons, spallation under the near surface, neutrons with wide ranges of energies and electrons all being liberated non-stop makes for a highly-complex particle 'soup' [31]. In principle, we could have crew train close to nuclear reactors or in radiation fallout zones to test suit durability/resistance to radiation, but again, this only represents one of the four conditions found on the lunar surface. Radiation from the solar wind is an important component of the lunar environment as it directly contributes to the mobility of the dust [32].

## METHODS

Lunar dust countermeasure devices for spacesuits can be described as fitting two main types. These are devices that are embedded in the spacesuit design and can be switched on whenever the suit is on the lunar surface to act as a sort of 'dust shield' to prevent adhesion of dust or cleaning devices which are used post EVA to remove dust already adhered to the spacesuit. Both types of devices would require testing in the lunar environment to determine their maximal performance against lunar dust. Two separate experiments are proposed.

1. <u>Autonomous Spacesuit testing – humanoid biped</u>

   Two spacesuits should be placed on the lunar surface. One with an electrostatic device, one without. Motion of the suits, perhaps as autonomous robots, should be implemented. The commercial company 'Agility Robotics' have produced a highly-autonomous humanoid biped called 'Cassie' which could be put inside the lower portion of a spacesuit. The robots could walk around the surface, kicking up dust, and after a period of time, attracting a sufficient coating for analysis. It is assumed that the electrostatic repulsion device could be isolated from operation of the robot. It is also assumed that the spacesuit would prevent shorting out of the robot's electronics due to latent lunar static electricity.

   After a sufficient exposure time, both spacesuit-clad robots should be placed inside sealed containers for analysis. Visual observations and microscopy would be used to establish the level and depth of penetration of dust into the fibres of the various layers of the spacesuit.

   This method could make use of one robot and two spacesuits, such that the robot conducts two EVAs onto the lunar surface at two different times, OR two robots in one spacesuit each, in order to ensure that both spacesuits are exposed to the exact same lunar conditions for the duration of the test.

2. <u>Airlock 'mudroom' concept</u>

   The second option for the testing would involve no personal/suit-integrated electrostatic device. Instead, one robot, with EMU doffed, would conduct a lunar EVA for at least an hour, and then return to a habitat or lander with an airlock. Upon entering the airlock, the electrostatic device would activate and lunar dust would be removed from the suit.

   One possible method for the removal would be to combine a vacuum cleaner style device, with an electrostatic charge. Both would be integrated with the airlock, which would operate whilst still under vacuum i.e. before the robot enters the pressurised side of the spacecraft. The vacuum/electrostatic suction device would extract the small particles inside the volume of the airlock and transfer them outside. Rather than being vented straight back to the lunar surface, the extracted dust could be captured inside a container for weighing and analysis later. If the dust had picked up suit fibres upon removal this could be observed with a microscope.

Until it is possible to realise either one of these options, work continues to replicate some of the conditions of the lunar surface in Earth-based laboratories. Even without charged dust, lunar regolith simulant is still able to penetrate deep into the fibres of spacesuit materials [33], therefore, much work remains to overcome this challenge the Artemis astronauts will face.

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