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Lunar dust: The Hazard and Astronaut Exposure Risks

John R. Cain

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Abstract This paper reviews the characterisation of lunar dust or regolith, the toxicity of the dust and associated health effects, the techniques for assessing the health risks from dust exposure and describes the measures used or being developed to mitigate exposure. Lunar dust is formed from micrometeorite impacts onto the Moon's surface. The hyper-velocity impacts result in communition and the formation of sharp and clingy agglutinates. The dust particles vary in size with the smallest being less than 10 μm. If the chemical reactive particles are deposited in the lungs, they may cause respiratory disease. During lunar exploration, the astronaut's spacesuits will become contaminated with lunar dust. The dust will be released into the atmosphere when the suits are removed. The exposure risks to health will need to be assessed by relating to a permissible exposure limit. During the Apollo missions, the astronauts were exposed to lunar dust. Acute health effects from dust inhalation exposure included sore throat, sneezing and coughing. Long-term exposure to the dust may cause a more serious respiratory disease similar to silicosis. On future missions the methods used to mitigate exposure will include providing high air recirculation rates in the airlock, the use of a "Double Shell Spacesuit" so that contaminated spacesuits are removed before entering the airlock, the use of dust shields to prevent dust accumulating on surfaces, the use of high gradient magnetic separation to remove surface dust and the use of solar flux to sinter and melt the regolith around the spacecraft.

Keywords Lunar dust · Micrometeorites · Chemical reactivity · Exposure · Respiratory disease · Risk assessment · Astronautical hygiene

1 Introduction

In 1969, Neil Armstrong first set foot on the Moon. This was the start of the Apollo missions to explore the Moon's surface. Since Apollo, man's conquest of space has continued with the building of the US space shuttle, the Russian Mir and the European

J. R. Cain (✉)
GeoFind Consultancy, Hookstone Chase, Harrogate, North Yorkshire
e-mail: johncain6@hotmail.com

International Space Station. Today many countries compete in space exploration. China has an ambitious plan to sent astronauts to the Moon.

In 2000, President G W Bush gave an undertaking that the National Astronautic Space Agency (NASA) would land on the Moon and Mars within 30 years. This ambitious programme has recently been downplayed by President Obama (2010) because of the financial crisis within the USA and the need for the American space programme to change direction. Landing on the Moon is now not an aim of NASA though research on manned space travel is expected to increase.

It is expected that the continual exploration of space will see impetus from the private sector as demand for minerals increase and from the public in particular space tourism. It is therefore highly likely that within 20–30 years there will be a space colony on the Moon. The lunar surface is a dusty place and during the exploration of the Moon's surface, the astronauts will need to be protected from exposure to dust and other hazards such as radiation.

Any exploratory activity on the lunar surface for example, digging, walking, sifting will generate airborne dust that will cling to the astronaut's spacesuits. Neil Armstrong's and Buzz Aldrin's spacesuits were heavily coated in dust following their brief excursions on the Moon's surface.

This paper will review the physical characteristics of the lunar dust including its formation. It will discuss the toxicological effects of dust exposure including the associated health effects of acute and chronic inhalation and dermal exposure and eye contact with the lunar regolith. It will also outline how the exposure risks to health will be assessed and then outline the measures that have been developed and are being developed to mitigate dust exposure.

2 Characteristics of the Lunar Regolith

Lunar dust or regolith (Table 1 outlines the definitions of lunar dust, dust and regolith) is made up of very small particles. Over 95% is finer than 1 mm, about 50% is smaller than 60 μm and 10–20% is smaller than 20 μm. About 10% of the very fine particulate component (<10 μm) is in the respirable range. It is this component of the dust that is likely to cause respiratory disease if inhaled.

In addition to its size, the lunar soil particles have a very large surface area that is approximately 8 times that of a sphere of equivalent size (Keller et al. 2000). This results in the soil particles not packing lightly together as efficiently as uniform spheres (Taylor et al.

Table 1 Definitions of Lunar dust (Convention informally adopted at a NESC lunar dust workshop at amesresearch centre, Jan 2007)

Definitions of lunar dust
1. Regolith—General term for the mantle of loose, incoherent or unconsolidated rock material of whatever origin, size or character that is nearly everywhere on the Moon – Most lunar regolith is formed by hypervelocity impact – Lunar regolith is spatially very heterogeneous in composition and particle size distribution when compared to Earth regolith
2. Dust—An informal term—regulatory definition for dust related health concerns set for particle sizes smaller than 10 and 2.5 μm
3. Lunar dust—Particles from the Moon <20 μm in size

2004). Furthermore, Carrier et al. (1991) note that the lunar soil particle-size distribution is very wide and even though it may be highly packed in places, the porosity is about 40–50%.

The lunar rocks contain iron (Fe0). The soil produced from these igneous rocks contains about 10 times more Fe0 than found in the rocks from which the soil was derided (Taylor and Cirlin 1985). Taylor et al. (2004) have postulated that this phenomenon was caused by the auto-reduction of the Fe0 in silicate melts and vapours during micrometeorite impacts on the silicate minerals in the lunar dust.

This caused the Fe0 in the impact melt to be reduced to elemental Fe0. It became supersaturated and nucleated homogeneously to produce the nanophase-sized Fe0 particles (3–33 nm). When the melt was quenched, it formed the glass that now binds the aggregates of soil particles called agglutinates. The agglutinates are highly chemically reactive. If they are inhaled into the respiratory tract, they may cause serious health effects.

3 Lunar Soil Formation

3.1 Micrometeorite Impacts

Micrometeorite impacts onto the Moon's surface are responsible for the main "space-weathering" and erosional factors in the formation of lunar soil (Noble and Lindsay 2007). The lunar surface is exposed daily to hypervelocity meteorite impacts of various sizes and velocities because it contains no protective atmosphere. The hypervelocity impacts result in larger soil particles being comminuted to finer ones. Silicate glass formed by some impacts, welds together soil grains into glassy aggregates called agglutinates.

There is less fusion and vaporization during impact. Keller and McKay (1997) have successfully argued that communition and agglutination are the two competing processes that are involved in the evolution of the lunar soils or regolith. The changing or "gardening" of the lunar surface by repeated hypervelocity impacts causes turn over, mixing and soil aggregation (McKay 1991).

Man's exploration of the Moon will result in communition for example, during module landing when large quantities of regolith are displaced and crushed and when the crew explores the surface and "gardens" the regolith (Khan-Mayberry 2007). Apart from communition and agglutination, there are other processes involved with the weathering of the regolith that cause significant effects. These involve the additional formation of surface-correlated nanophase Fe0 resulting from impact-induced vapourisation and subsequent deposition of Fe-and Si-rich patinas on most soil particles (Taylor 2000b) as well as sputter-deposited contributions (Bernatowicz et al. 1994).

3.2 Nanophase-Sized Fe0 Particles

The amount of nanophase-sized Fe0 particles (np-Fe0) in a lunar soil sample is measured using Ferro Magnetic Resonance (FMR) and is designated as "Is". This value is divided by the total Fe0 content of the soil fraction being investigated to determine the quality of np-Fe0 present. The value of "Is/Fe0" is used as the maturity index for all lunar soils and it indicates the amount of np- Fe0 which has been formed by the weathering processes (Morris 1976, 1978). This index may be useful in assessing the risks to health from exposure to lunar dust; the higher the "Is/Fe0" index, the greater the risks to health.

The agglutinates are easily crushed because they are brittle and fragile. The abundance of agglutinitic glass increases significantly with decreasing grain sizes; the "Is/Fe0" values increase with decreasing grain size. This increase in the size of "Is/Fe0" indicates that there is another source of nanophase Fe0.

This is the presence of nanophase Fe0 in the vapour-deposited patinas (rims) on virtually all grains of a mature soil and it accounts for the increased "Is/Fe0" value as identified by Taylor (2000a) and Taylor (2000c).

3.3 Other Weathering Processes

There are other weathering processes on the lunar surface caused by for example, galactic and solar cosmic rays that will result in vapour and sputter deposits. Cosmic rays cause spallation in which a bombarded nucleus breaks up into many particles other than agglutination (James 2007).

In retrospect, it can be seen that virtually all available lunar soil contains vapour-deposited nanophase-sized Fe0 (np-Fe0) embedded in impact glass and the surface grains are very reactive due to the grain surfaces being etched by solar wind. Such surfaces have a high density of crystal dislocations. In vivo and in vitro experiments will need to be undertaken to determine how toxic the particles are in particular when deposited deep within the lung.

3.4 Lifting of Lunar Particles

The lunar surface is electrically charged due to the interaction with the local plasma environment and the photo-emission of electrons from solar UK light and X-rays (Stubbs et al. 2006). The like-charged surface and dust grains then act to repel each other and according to Rennilson and Criswell (1974) in certain conditions the dust grains are lifted above the surface. Extremely light particles may be lifted to altitudes of up to 100 km above the lunar surface.

Stubbs et al. (2006) have proposed a model to explain the phenomenon i.e. the dynamic fountain model. Criswell (1973) proposed a static levitation concept. In the levitation model, the dust grains find a point near the surface where the electrostatic (Fq) and gravitational (Fg) forces acting on it are about equal and opposite and therefore suspended. In the dynamic fountain model, once the grain has attained sufficient charge to leave the lunar surface, it is accelerated upward through a sheath region with a height of order—the plasma Debye length. The dust grains being so small ($Fq \gg Fg$) leave the sheath region with a large upward velocity (V-exit) and follow a near-parabolic trajectory back towards the lunar surface. Deposits falling on equipment will cause contamination that could result in damage.

4 Physical and Electrostatic Properties of Lunar dust

The lunar regolith is persistently adhesive and abrasive in particular when it interacts with spacesuits and equipment. This is due to the combined electrical and physical properties of the particles. Carrier et al. (1991) quantitatively established the high surface volume ratio (SVR) of lunar particles relative to the smooth spheres of equivalent size.

The relationship between the surface and volume in lunar dust particles as a function of grain size is recognised by Carrier et al. (1991) as a characteristic that controls the interaction between lunar dust and its environment (e.g. dust is dangerous if it covers machinery and/or is inhaled by an astronaut). Particles with sizes in the range of 3 μm or below are inhaled into the respiratory tract and could cause cellular changes leading to a silicosis-type disease.

Average regolith grain size is about 70 μm with about 10–20% by weight <20 μm. Greenberg (2005) found grains as small a 0.01 μm in Apollo samples. Particle shapes are highly variable and can range from spherical to extremely angular; although in general they are elongated. The low electrical conductivity of the regolith allows individual dust grains to retain electrostatic charge. On the dayside of the Moon, conductivity can increase with surface temperature and infra-red and UV radiation.

5 Chemical Reactivity of Lunar Dust

The basic composition and formation of lunar dust is well known, but there is very little information on its chemical reactivity. This could have significant implications for an astronaut's health because reactivity is linked to increased risks to health.

Lunar regolith is formed and modified by continuous micrometeorite bombardment of the lunar surface. High volume impacts induce "shock melting" and cause localised vaporisation of the regolith. This quickly re-condenses resulting in agglutinates with high surface area, complex shapes and sharp, jagged edges.

The bulk composition of lunar dust varies across the surface but it is about 50% SiO_2, 15% Al_2O_3, 10% CaO, 10% MgO, 5% TiO_3 and 5–15% iron with lesser amounts of sodium, potassium, chromium and zirconium. Table 2 shows the major constituents of lunar dust. Trace amounts of virtually all elements ranging from the parts per billion level to the parts per million level can be found in lunar dust. Wentworth et al. (1999) have identified that the iron content consists of both iron oxide and nanoscale deposits of fully reduced metallic iron (nanophase iron), the latter being a form of iron not present in terrestrial minerals.

Minerological studies on lunar rocks from the Apollo era missions show they consist of pyroxene, plagioclase, ilmenite, olivine with rare grains of crystobalite, tridymite, chromite, ramacite, taenite and trolite (Agrell et al. 1970). Analysis of lunar fines to μm size range revealed an increasing proportion of glassy material with smaller particle size, consistent with the understanding that lunar regolith undergoes shock-melting as a result of micrometeorite impact.

The high level of silica oxide in all five samples indicates that exposure to the lunar dust particles over a long time period could result in a progressive silicosis type respiratory disease. An understanding of the reactivity of the lunar dust requires a knowledge of the effects of UV and other radiation on the dust. Exposure to UV light causes changes to the

Table 2 Major constituents (%) of lunar dust from Apollo samples

Samples/comp	SiO_2	Al_2O_3	TiO_2	FeO	MgO	CaO	Na_2O	K_2O	MnO
Lunar 10019	41.1	13.7	8.25	15.7	7.86	11.9	0.93	0.14	0.22
Lunar 10022	43.0	13.0	7.0	16.0	8.0	12.0	0.54	0.12	0.23
Lunar 64501	53.63	12.77	3.47	13.32	3.57	9.2	0.73	1.0	0.2
Lunar 70161	40.34	11.6	8.99	17.01	9.79	10.98	0.32	0.08	0.23
Lunar 14053	48.0	12.0	1.5	16.0	8.4	12.0	0.38	0.14	0.29

optical properties of the dust that are due to changes in the oxidation state of the iron (Hopke et al. 1970). Hopke et al. (1970) observed that solar wind radiation i.e. low energy protons also resulted in changes to the chemistry of the dust following irradiation (observed by changes in the visible and IR reflectance spectrum).

Sample containers with dust from Apollo 11 leaked. This has had an affect on experiments on the chemical reactivity and toxicological nature of the dust due to possible contamination. To understand the chemical reactivity of lunar dust, more work needs to be performed, for example, characterisation of the effects of UV irradiation on the chemical reactivity of the dust (Loftus et al. 2007).

6 Toxicity of Lunar Dust

The toxicity of lunar dust is not fully known. A number of studies have been conducted, mainly by NASA, to elucidate the toxic effects on the body following exposure. Lam et al. (2002) has studied the pulmonary toxicity of lunar dust simulant (JSC-1) and the toxicity of lunar dust in the lungs of exposed rodents. Preliminary studies examining the biomarkers of toxicity in bronchioalveolar fluid (BALF) from mice intratracheally instilled (ITI) with the lunar dust indicate that the dust is more toxic than TiO_2 but less than quartz dust containing silica.

Further examinations of BALF (e.g. for total cells, total protein, cytokines) and lung tissue for histopathological changes e.g. inflammation, fibrosis, necrosis in rodents exposed to the dust by ITI and by inhalation are underway. The results of these studies will be used to set exposure limits on airborne lunar dust for astronauts living and working on the Moon.

Wallace, Hammond and Jeevarajan (2008) have developed methods to activate quartz, lunar simulant and lunar soil and to monitor the levels of activation using a fluorescence assay based on the production of hydroxyl radicals in solution. Ground quartz has been shown in such studies to be less active for the production of hydroxyl radicals than ground lunar simulant and ground lunar soil. As the soil on the Moon will be in an activated form, the results of the experiment yield valuable data on the toxicity of lunar dust and soil. For instance lunar soil produces 2–3 times more hydroxyl radicals than lunar simulant and 10 times more than quartz.

7 Deposition of Inhaled Particles in the Human Lung in Low Gravity

Lunar dust is similar to the respirable crystalline silica that is found in mines, in the quartz used by stonemasons and in foundries where sand is used. Workers exposed to the silica may develop silicosis or related respiratory disease (Cain 2009). Lunar dust contains almost 50% silica. Lam et al. (2002) observed that mice developed mild to moderate focal alveolitis 7 days following exposure to simulated lunar dust and alveolar septal thickening and fibrosis 90 days post-dust exposure.

For particles larger than 0.5 μm, deposition in the respiratory tract is strongly influenced by gravitational segmentation. It is expected to be less in a reduced gravity environment. It has been shown by Darquenne et al. (1997) and Darquenne et al. (1998) that deposition in microgravity is lower than in normal gravity. Both studies conducted by Darquenne et al. also show that there is a non-linear relationship between deposition and gravity level (between microgravity and hypergravity). Deposition by sedimentation is direct.

This makes the prediction of the deposition of particles into the lung whilst on the Moon and in 1/6th gravity difficult.

To determine the effect of lowered gravity on the deposition of particles in the lungs, Darquenne and Prisk (2008) measured the deposition of 0.5 and 1.0 μm diameter particles in six subjects on the ground (1G) and during short periods of lunar activity (1/6th G) aboard the NASA Microgravity Research Aircraft. They concluded that in 1G, deposition in more central airways reduced the transport of fine particles to the lung periphery.

In the fractional gravity environment as on the Moon, the reduced sedimentation rate will enable the particles to penetrate deeper into the lungs and deposit in the alveolar region of the lungs. This will increase the risks of lung damage if exposure is over a long-time period. Furthermore, due to the Moon's reduced gravity and the size of the dust particles in the air, the respiratory system may not be able to remove dust as efficiently as on Earth. This will increase the risks to health (personal communication with Professor Kim Prisk 2008).

A significant fraction of lunar dust that would have deposited in the conducting airways in normal gravity and cleared within 1 day by mucociliary transport will deposit in the non-ciliated regions of the lungs in lunar gravity. Clearance will proceed much slower and particle retention will be much higher in reduced gravity (Lippmann et al. 1980).

8 Effects of Gravity on Chest Wall Mechanics

Gravity affects the shape of the respiratory system. Bettinelli et al. (2002) have found that when subjects go from a low gravity atmosphere of 0 to 1G as on Earth, there is a decrease in rib cage volume. The data suggests that the chest wall does not behave as a linear system when exposed to changing gravity because the effect depends on both the chest wall volume and the magnitude of gravity. Further work is required to determine how low gravity will affect lung function and contribute to the risks of deep lung dust penetration.

9 The Basis for Setting Permissible Exposure Limits

9.1 Background

The Lunar Airborne Dust Toxicity Advisory Group (LADTAG) was formed in 2007 by NASA to set a lunar dust standard or permissible exposure limit (PEL) for lunar dust (Khan-Mayberry 2007). The LADTAG team consists of the World's leading experts on lunar dust, inhalation toxicology, lunar geology, space medicine and biomedicine research; it is taking a multidisciplinary approach to determine a PEL for lunar dust and the measures required to prevent or control exposure from exceeding the limit.

To assess the risks to health of exposure to lunar dust, the PEL will need to be based on the time duration of exposure, on the type of work activity, on the lunar dust physical characteristics e.g. chemical reactivity, on the toxicity of the dust and on the measures used to prevent or control exposure. Multiple standards may need to be set for the different types of lunar dust as well as for dust in its activated and passive form. The activated dust is likely to be more hazardous and pose a greater risk to health. It will therefore require a lower PEL to control exposure.

Short-term and long-term PELs will be necessary to reflect the length of time an astronaut is exposed to the dust and also to reflect the potential for acute and chronic respiratory disease. Acute exposure limits will be set for a few hours exposure and chronic exposure limits will be set for exposures of up to 6 months. Khan-Mayberry (2007) indicates that it may be necessary to develop the setting of other standards and human health criteria for dermal and ocular exposure.

9.2 Dust Characteristics

Prior to the setting of a space PEL, including terrestrial exposure limits (Brook et al. 1997), it is necessary to understand the hazard in particular the compositon of the lunar dust and the particle sizes that may be inhaled. The respirable dust levels are from 10 μm down to 0.1 μm. The inhalation of the smallest particles i.e. <1 μm, can cause oedema, inflammation, fibrosis and possible cancer if exposure is chronic.

Particles or ultrafine particles of <0.1 μm do pose special problems in the lungs in that they have been shown to cause more inflammation in experimental studies than the larger respirable particles (composed of the same material) when delivered at the same mass dose (Donaldson and Stone 2003; Donaldson et al. 2001). Anderson et al. (1990) found that ultrafine particles deposit with high efficiency in the lungs (50%). Inflammation induced by the ultrafine particles is likely to be responsible for exacerbating airways disease and cardiovascular effects. The mechanism of inflammation appears to be via oxidative stress than due to the large particle surface area. The surface area is increased in lunar dust and therefore the inflammatory affects on the lungs are expected to be greater.

The lunar dust particles are also in a reactive state due to solar winds, solar flares etc. Exposure to activated lunar dust particles may be very toxic in particular if inhaled in the pressurised environment of the spacecraft or module.

Other known toxicological effects of exposure to dust are dermal irritation and penetration, ocular irritation and corrosion and upper and lower respiratory tract injury. Some particles less than 0.1 μm are expected to pass through the respiratory tract without causing damage and are exhaled out into the atmosphere (NASA 2005).

9.3 Setting the Limit for Inhalation Exposure

Based on the characteristics of the hazard, the potential toxicological effects following exposure and data from the Apollo missions, LADTAG has recommended a PEL for lunar dust particles of 0.05 mg/m^3 for aerodynamic particle size range of 0.1–10 μm (NASA 2009). This is a mass-based requirement which is independent of particle size in the 0.1–10 μm range and therefore does not discriminate whether there are more particles closer to 0.1 μm (and with more penetration) than at 10 μm in size (Greenberg et al. 2007). The PEL is likely to be based on a six month exposure though it maybe that a limit will be set based on a shorter time period to account for acute inhalation exposure.

Inside the spacecraft module, the internally generated dust, the biological growth and lunar dust will be indistinguishable so therefore the combined load of the lunar dust and generic dust will have to be treated and monitored at the LADTAG PEL of <0.05 mg/m^3 for the particle range of 0.1 μm to 10 μm. Dory (2006) argues that the allowable dust load of lunar dust will be more stringent than the PEL represents.

9.4 Skin and Eye Exposure

Because the lunar dust is highly abrasive, it could irritate the dermal water vapour barrier e.g. dermis and lead to dermatitis and/or sensitisation. Eye contact could result in minor irritation, physical or chemical injury leading to conjunctivitis. To study the effects of skin exposure to lunar dust, in vitro skin modelling and animal studies will be required.

Skin studies will include abrasion studies to determine the permissible limit for entry into the spacesuit. The ocular effects of dust exposure will be studied in vitro and in vivo experimentation systems to assess the risks of damage to the eye and to provide a means to evaluate the effectiveness of treatments following eye contact (NASA 2005).

10 Human Exposure Studies from Apollo Missions and Assessing the Health Risks

There were 6 Apollo missions (11, 12, 14, 15, 16 & 17) between 1969 and 1972 that each landed 2 astronauts on the Moon. During extravehicular activity (EVA) on the Moon, the spacesuits became coated in lunar dust. The dust exposures occurred when the astronauts returned back to the module and removed their spacesuits. The exposures were uncontrolled and brief but sufficient to cause acute health effects (Cain 2010).

There was continual inhalation exposure to airborne dust and there was also skin exposure and eye contact from surface contamination on the return journey to Earth. It is not possible to estimate the levels of inhalation exposure to the dust but it is likely to have exceeded the proposed PEL of 0.05 mg/m^3 because it was mainly uncontrolled. Furthermore, it is not possible to differentiate the active from the passive lunar dust exposures. It was highly likely to be a combination of the two but mostly activated dust with a higher risk of lung damage if exposure was chronic.

According to the Apollo astronauts (Gaier 2005), the lunar dust entered and floated everywhere in the lunar excursion module during the ascent to the Command module under microgravity. The dust was also reported to have given off a distinctive pungent odour like "gun-powder" suggesting that there were reactive volatiles on the surfaces of the dust particles. What were the volatiles? Were they hazardous? Could the volatiles have been identified and monitored? These questions will need to be answered to assess the health risks on future missions.

The dust permeated all areas of the module. On the Apollo 12, when removing their clothing on the return journey to Earth, they discovered that their skin was covered in dust. The dust affected their lungs causing irritation and it also affected their eyes, nose and ears where it produced mild allergic health effects such as sneezing and sore throat. On one Apollo mission, the crew kept their helmets on until the Command module was reached and it was expected that there was no lunar dust.

10.1 Assessing the Astronaut Exposure Risks

The experience of the Apollo missions indicates the continual need to assess the risks to health during a Moon mission and thereby determine whether the measures to prevent or control exposure are effective or will require modification. A suitable and sufficient risk assessment will include determining the characteristics of the exposed lunar dust, determining the length of time of exposure and the type of work activities, determining the exposure routes, determining the levels of airborne dust and the measures used to mitigate dust exposure.

Monitoring the concentration of dust particles will be necessary within the Extravehicular Mobility Suits (EMS), the airlock, the habitat and the spacecraft. Without effective control measures such as the use of effective filtration systems, high dust levels may occur and any chosen PEL may be exceeded.

Any sampling strategy will need to consider all areas where dust may be an issue and to highlight the differences between high exposure risk and low exposure risk areas (e.g. surface dust mapping). It is expected that a real time monitor for example, a tapered element oscillating microbalance (TEOM) will be situated in the module at specific locations to monitor lunar dust particles and enable the particle sizes and quantities to be measured within specific areas over time. The real time monitoring can be used in assessing whether exposure controls have been effective at reducing the airborne dust levels and for assessing the subsequent risks to health.

For most Moon excursions the exposure risks will be reduced considerably because exposure will only be for a few hours i.e. acute. However, Apollo 17 Commander Gene Cernan noted that "……once you get inside the spacecraft, as much as you dust yourself, you start taking off the suits, and you have dust on your hands and your face and your walking in it." (Gaier 2005). Such exposure to high levels of dust as described by Cernan are likely to be significant in particular on the skin and eyes. There is also the potential for ingesting the dust during finger to mouth contact in particular if it contaminates instruments and equipment, with the risks of systemic health effects on specific target organs. Though most dust exposure is likely to be acute, on longer exploration visits to the Moon, the exposure may be chronic with the risks of developing respiratory disease similar to silicosis.

10.2 Other Dust Related Hazards

As part of the overall risk assessment it is necessary to understand other dust related hazards that may occur and cause serious harm. They can be sorted into nine main categories; vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasions, thermal control problems, seal failures, irritation and inhalation problems (Gaier and Creel 2005). These hazards are discussed below. Furthermore, it needs to be understood how the dust is transferred onto surfaces so that effective measures can be implemented to reduce its spread and the subsequent risks of exposure in particular by inhalation.

10.3 Dust Transport Mechanisms

The two general classes of dust transport mechanisms are natural and anthropogenic (Katzan and Edwards 1991). Katzan and Edwards (1991) estimated that natural transport mechanisms for example, from meteor collisions did not transport significant amounts of dust over a 14 day period. However, it will still contribute to the dust load burden of the spacesuit during EVA. The Moon has no appreciable atmosphere so submicron particles do not stay suspended and settle almost immediately.

Most dust is transported by the landing and take-off of the spacecraft but during these activities there is no personal exposure and most of the damage caused by the dust will be to equipment left on the Moon prior to landing, during EVA and after take-off. The 3 anthropogenic mechanisms of dust generation that will contribute to the overall body burden of dust exposure are during walking on the surface and spacesuit contamination, when the rover wheels spin up dust and contaminate the spacesuit and equipment and by falling onto the surface.

During walking, the feet and ankles become coated in dust. On several occasions, Apollo astronauts lost their balance and fell to the surface or they bent down on one knee to observe something. The dust adhering to the spacesuit could not be removed with a brush.

When removed in the space craft, the dust on the spacesuit will be released into the atmosphere with the potential for inhalation and skin exposure and acute health effects.

During the Apollo missions, the lunar dust was noted to cause problems that would have increased the risks to health and also jeopardised the safety of the astronauts during EVA and whilst in the lunar modules. For example, dust was coating the lower parts of the spacesuit and was released inside the Lander Module (LM) (Apollo 15), the lost Lunar Roving Vehicle (LRV) fender extension caused dust to cover the astronauts (Apollo 16) and in Apollo 17, dust coated and contaminated everything.

The contamination caused dust inhalation as the particulate matter floated around the spacecraft. Dust in the LM and in the Command Module after docking contaminated the eyes causing irritation (Apollo 16) and helmets were required to keep inhalation irritation symptoms down in Apollo 17. Dust adhering to the spacesuits was the main means of transporting and releasing the dust when they were removed.

It is highly likely that significant inhalation exposure occurred in all Apollo Missions but because the exposure was a one-off exposure and because of the different objectives of the missions, exposure was likely to vary. There was no accumulation exposure; if this was the case then it is likely that chronic respiratory disease would have occurred. Unless there is effective exposure control to mitigate the effects of lunar dust exposures, then accumulated exposure may occur in future missions where the Moon may be visited several times by the same astronauts.

11 Visual Obscuration etc. and Relation to Exposure

The Apollo missions identified several dust related hazards, apart from exposure, that could have jeopardised the mission e.g. vision obscuration (Gaier 2005). These hazard categories will be considered briefly and related to the potential for increasing the body burden of exposure in particular if they cause an increase in spacesuit contamination or surface contamination that could cause dermal health effects.

Dust causes visual obscuration. There was total obscuration before Apollo 11 and 12 touched down on the Moon (Mullis 1971). This could have caused major problems if the vehicle's feet landed on a boulder. However, the presence of dust and extent of visual obscuration can be used to assess the risks to health during EVA. If there is a high level of dust on surfaces causing blackness, it is expected that the levels of surface dust will be high and therefore likely to coat the spacesuits during EVA. When the dust is removed prior to removal of the spacesuit, uncontrolled dust will contaminate the surrounding environment and the astronauts may become exposed. If the dust coats instruments such as cameras, then the brushing off of excess dust from the lens in particular in the airlock will generate airborne dust with the potential for inhalation exposure.

Instruments may be coated in lunar dust during descent, leading to false readings. The quantities of dust at various land sites will vary and also the potential to settle on instruments and cause false measurements. Such readings may over or underestimate the levels of dust during landing and subsequent EVA. Furthermore, on Apollo 12, temperatures measured at five different locations in the magnetometer were approximately 68°F higher than expected because of lunar dust on the thermal control surfaces.

Gaier (2005) noted that the spacesuits of the Apollo astronauts were affected by lunar dust that quickly and effectively coated all surfaces including the boots, gloves and suit legs. Valuable exploration time was spent on brushing off the dust. Dust on the boot soles was a slip hazard for example, during descent onto the surface via ladders. Kicking excess dust from the boots reduced the slip risks and also reduced the quantities of dust contaminating the spacecraft by removing the excess.

Clogging of the spacesuit zippers, wrist and hose locks, faceplates and sunshades (including lock buttons) were cause for concern during the Apollo missions. Several astronauts remarked that the clogging of suit joints reduced surface activity and even the vacuum cleaners designed to remove the dust became clogged. Lunar dust was also found to be abrasive leading to the wearing away of spacesuit fabric, the outer layers of the boots and the cover gloves. In addition, sunshades were scratched; Harrison Schmitt's sunshade on his face plate was so scratched he could not see in all directions thus impairing his vision. Dust settings on the suit seals lead to suit pressure drops e.g. a leak rate of 0.15 psi/min on first EVA initially leading to 0.25 psi/min on second EVA during the Apollo 12 mission. The safety limit is set at 0.30 psi/min so further EVAs could have caused a serious incident. During unsealing and re-sealing of the EMS in the airlock, dust will be released from the seals into the local environment. More dust tolerant sealing needs to be used in future missions.

12 Lunar Dust Mitigation Methods

12.1 Airlocks and "Double Shell Spacesuit"

There are several means of reducing direct lunar dust exposure by the use of effective astronautical hygiene practice including the prevention of the dust from affecting life support systems and subsequently the health of the crew (see Table 3).

The introduction of dust into the spacecraft or lunar habitat with the potential for subsequent spread is the major potential for the release of dust into the atmosphere with the risks of exposure via inhalation, dermal, ingestion and eye contact. Measures need to be implemented to reduce the quantities of dust that are released and that contaminate the habitat area and life support equipment. Kennedy and Harris (1992) have designed an airlock which will minimise the amount of dust brought into the habitat module/spacecraft.

Briefly, the astronaut removes excess dust from the spacesuit following EVA by brushing, shaking etc. and removes any cover garments within an airlock under negative pressure. The excess airborne dust is vented when the astronaut enters the second airlock chamber. In this chamber, a vacuum is used to clean residual dust from the spacesuit under re-pressurisation. The suit is then removed while a "buddy" further cleans the suit and airlock. Following cleaning, both crew members then enter the pressurised living quarters that is free of dust. The use of an airlock will not remove all the dust and there will still be dust in the atmosphere which may be inhaled. The removal of dust, particular from the air, will be necessary.

Table 3 Astronautical hygiene methods to prevent or control exposure to lunar dust

Measures to prevent or control exposure to lunar dust
1. Eliminating entry of dust into the airlock e.g. use of "Double Shell Spacesuits"
2. Preventing spread throughout the spacecraft or lunar habitat e.g. removing dust from spacesuit
3. Reducing lunar dust exposure by extracting airborne dust particles in the airlock
4. Reducing surface contamination using effective clean-up methods
5. Designing robust equipment which can operate in a dusty atmosphere

An alternative arrangement developed by Leuoth and Weihrauch (2005) may be the use of a "Double Shell Spacesuit" which has been developed at the Institute of Astronautics for use on Mars (and the Moon) to avoid the to and fro contamination by completely separating the contaminated from the clean area. The spacesuit is docked to the habitat like a vehicle and the contaminated areas remain outside and the astronaut can leave the suit through a bulkhead. This will reduce the need to clean the spacesuit within an airlock prior to entering the habitat. The outer spacesuit will be cleaned from the outside without the risks of contaminating the air. The outer suit is composed of a size-adaptable outer shell and a hard frame with the docking mechanism and helmet (Dirlich and Weihrauch 2006).

12.2 Local Exhaust Ventilation and Particle Filtration Systems

Unless the air within the habitat area is changed frequently there will be a build up of dust and the possibility of "dead zones" (poorly ventilated areas) where high levels of lunar dust could accumulate and settle on surfaces. Any air cleaning system should incorporate high efficiency particulate air (HEPA) filters to trap the airborne dust. However, this will require a constant flow of pressurised air. The two most likely approaches to lunar dust removal are the use of cyclones and filters. To aid air extraction and to minimise the impaction and retention of particles on surfaces, appropriate air flow regimes must be selected (Fuhs 1988).

Particle filtration will serve as a primary means for cleaning up the recycled air by removing the generated dust as well as the dust introduced into the habitat and airlock from the contaminated spacesuits. Such a system of filtration will need to be efficient, have a high load capacity, low energy consumption, low mass and volume and the ability to be regenerated (Agui and Stoker 2009). It is expected therefore that any future missions will need to:

- provide high recirculation rate air removal with high speed fans and high efficiency particulate or HEPA filters;
- provide air showers in the airlock;
- provide vacuum cleaners with fans and HEPA filters;
- include sensors with filter to withstand depressurisation and re-pressurisation of the cabin and airlock;
- protect all direct openings to the cabin and provide dust protection on depressurisation/re-pressurisation valves;
- design Environmental Control and Life Support Systems (ECLSS) for dust robustness; and
- use worst case scenarios to determine measures to reduce dust (Dory 2006).

The dust inside the habitat will have to be removed by the on-board elements of the life-support system and there will be a need to maintain clean, breathable air for the crew. For spacecraft revitalisation there will be a need to recover, recycle and distribute the atmosphere gases. For particulates, removal from the stream and filtration will be required whereas physical adsorption will suffice for the gases.

It is proposed by Aqui and Stocker (2009) that a multistage filtration consisting of screen filters (capture particles >800 μm), an internal filter (capture particles >5 μm) and a high-efficiency filter (capture particles <5 μm) will ensure adequate removal of the regolith. Of the lunar dust particles that enter the spacecraft, only particles below 10 μm are expected to become airborne (7% by mass of lunar regolith); but this is a significant quantity to cause disease following exposure.

There will be other particulate matter (e.g. skin, hair) in the spacesuit that will be captured by the filtration system. The combined load of lunar dust and general dust will be included in the PEL of <0.05 mg/m^3 for the particle range of 0.1–10 μm (Dory 2006). To ensure the effectiveness of the HEPA filtration system, an industry best practice of 99.99% capturing efficiency should be the target. The pre-filter will extend the life of the main filter. A fibrous filter media fabric will constitute the filtration system e.g. dry, spin bond, meltdown, glass blanked. Because they are depth filters, the particulates will be subjected to 3 capturing mechanisms; diffusion, interception and impaction (ANSI/ASHRAE 2007).

Particles below 0.1 μm should all be captured because of the diffusional capturing mechanism. There will also be a need to ensure that the filters are cleaned regularly to ensure that a build-up of particulate on the filtration system does not reduce the efficiency and effectiveness of the system. However, over time, the filter efficiency will decrease exponentially with increasing air and face velocities. It is therefore necessary to determine the air flow rates within the spacecraft. For example, increasing the air flow rates will generally increase the capturing efficiency since the volume of air in the cabin is cycled through the filter more rapidly and frequently. In conclusion, the filtration system will need to reduce the quantity of contaminated particulates in the air to ensure that the proposed PEL is not exceeded (0.05 mg/m^3 for the 0.1–10 μm particles).

Screens are typically used for the pre-filters to capture the larger particles. They are cleaned easily using a vacuum cleaner. Sintered metal or ceramic filters will capture the smaller particles that pass through the pre-filter; they provide high loading capacity. Alternatively, an inertial filter may be used such as a cyclone filter, impingement plate or baffle; they will trap particles of a particular size by interception and impaction. However, the dust trapped will need to be removed for example, from a bag physically or by backflow pulsating and venting outside. The final filtration will be provided by the HEPA filter.

12.3 Magnetic Handling of Lunar Soils

A technique designed by Odor and Taylor (1990) is based on the ferromagnetic properties of the lunar regolith and can be used to segregate the particles of the lunar soil i.e. high gradient magnetic separation to mitigate exposure. The moon dust to be segregated is passed through an open matrix of metallic material such as steel wool inside a powerful magnet. The matrix creates locally high gradients in the magnetic field which attracts and traps fine particles while allowing the coarser particles to pass through.

By having different matrices, it is possible to segregate the dust into different fractions. The magnet will be turned off when the matrix material is “saturated”. The dust will need further processing with the use of a liquid to form a slurry. Such a system could form part of an overall air filtration system on a lunar base.

12.4 Dust Removal from Surfaces e.g. Spacesuits

The combined electrical and physical properties of the lunar dust cause it to adhere to the spacesuits. Tools have been developed and designed to remove dust from surfaces based on the natural properties of the dust and the forces affecting them (Clark et al. 2008). One such machine is called SPARCLE (Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment) which is a plasma-based solution. The SPARCLE tool attracts and removes dust from surfaces, such as on a spacesuit, through the use of particle beams.

The excess dust is disposed of in a receptacle through the use of oppositely charged particle beams to control the potential of the tool's surface. The tool will act as a "magic" wand using internal electrons or ion guns to control its surface potential.

An electro-dynamic dust shield has been developed by Calle et al. (2008) to remove already deposited micro-sized particles from surfaces and to prevent the accumulation of such particles on surfaces. The dust shields are based on the electric curtain concept and are activated by three-phase power supplies. This provides a Moesner and Higuchi square signal combined with a single sine waveform (Immer et al. 2006). The shields can be optimised for a specific environ by altering the electrical electrode width and separation by driving the frequency and maximum amplitude and the dialectric coating. The curtain electrodes are excited by a single-phase or a multi-phase AC voltage.

12.5 Dust Mitigation Vehicle

One way that has been tried to reduce the problem of lunar dust contamination on spacesuits and equipment is to remove the source of the dust and by paving the surface around the base. A dust mitigation vehicle uses concentrated solar flux to sinter and melt lunar regolith simulant (Taylor et al. 2004). It thereby provides a hard dust-free area for surface operations.

Cardiff and Hall (2008) have designed a vehicle that consists of a chassis that supports a 1 metre sized lens that can focus the solar flux. The position of the vehicle and the lens is determined by remote control. Three variants of the vehicle have been designed that utilise either a Fresnel lens to direct the solar flux or a single low-mass parabolic reflector with a linear focus.

12.6 Impact of Regolith on Hardware e.g. Instruments, Filters

Contamination with lunar dust may affect equipment and instrumentation and for example, cause degradation of seals and valves and cause a breakdown of lubricants, jam moving parts and create flow blockages. During the Apollo 12 mission, the landing velocity trackers gave false readings. Landing radar outputs were affected by moving dust and debris during landing together with visual obscuration.

In every Apollo mission there was clogging of camera equipment, lock buttons etc. together with thermal control problems due to an insulating layer of dust on the radiator surfaces. It is vitally important that these issues are controlled during a mission by ensuring that little dust enters the craft. This could be achieved by a combination of cleaning suits and equipment whilst on the ladder waiting to return, by using floors with sticky peel, by using magnetic coats to remove any residual dust, by providing suitable airlock decompression and vacuum cleaning within the airlock and near the platform at the top of the ladder, by using more brushing and by providing adequate filtration for 0.1 μm particles in the airlock and cabin.

The measures instigated to protect hardware from dust contamination should protect all direct openings to the cabin, provide protection for depressurisation and re-pressurisation valves and to provide high-recirculation rate air clean up with high speed fans and high efficiency particulate filters (HEPA). Furthermore, the craft should be so designed that there are few cavities and crevices in the floor space where dust could accumulate and later cause a health problem. Also brushing by itself will not be fully effective at removing dust and will be time consuming.

12.7 Effects of Lunar Regolith on Spacesuits

When carrying out EVA, the dust coats all surfaces quickly and effectively because of its size and composition for example, boots, gloves, suit legs and any hand tools. Brushing off the dust was shown to be ineffective by itself. Dust adhering to boots was responsible for loss of traction and the potential for slipping. However, kicking off excess was sufficient during Apollo missions to remove the excess dust and reduce the potential for tripping.

Dust was also responsible for clogging up zippers, wrist and hose locks, faceplates, sunshades and equipment. Due to the abrasiveness of the dust, the spacesuits were liable to be damaged (e.g. the EMS was worn through the outer layer and into the Mylor multi-layer insulation above the boot) and gauge dials and sunshades scratched. The use of a nylon brittle brush was effective for removing the coarse grain material but not very effective for the fine grain. Wet wipes were effective at cleaning the skin and surfaces within the spacecraft, together with a small vacuum. It was essential on Moon missions to weave Chromel-R into the lunar boots and gloves to reduce contamination and abrasion; the boots and gloves used the abrasion-resistant silicone RTV-630 for the soles and finger tips.

13 Conclusions

This paper discusses the characteristics of lunar dust (for example, particle size, chemical reactivity, toxicity), the exposure risks to astronaut health whilst working on the Moon, how to assess the risks of acute and chronic exposure and the measures developed or in development to significantly reduce the dust exposure risks.

Lunar dust or regolith contains very small particles. It is the fine respirable dust component (<10 μm) that is likely to cause respiratory disease if inhaled. Micrometeorite impacts onto the Moon's surface are responsible for the main weathering and erosional factors in the formation of lunar soil. High volume impacts induce "shock melting" and localised vaporisation of the regolith. When it re-condenses, the agglutinates have sharp, jagged edges. This results in the properties of adherence and abrasiveness which can damage spacesuits and equipment.

The dust which consists of over 50% of silica oxide is chemically reactive. Chronic inhalation exposure to the dust particles could result in a progressive silicosis type respiratory disease. The fractional gravity of the Moon will enable the small particles to penetrate deep into the lungs and thereby increase the risks of lung disease. Other known acute toxicological effects of exposure are dermal irritation and penetration, ocular irritation and corrosion and upper and lower respiratory tract injury in particular from ultrafine particles (<0.1 μm).

The experience of the Apollo missions indicates the need to assess the risks to health during lunar exploration to determine whether the measures in use to prevent or control exposure are effective or will need to be modified. This will require careful monitoring of airborne dust levels within the airlock, the habitat and the spacecraft. The results obtained will need to be related to the PEL for example, if the dust levels exceed the PEL then control has not been achieved and will need to be remedied.

Apart from the health effects associated with direct exposure to lunar dust, there are other related hazards that may arise and cause serious harm. These include visual obscuration, loss of traction, clogging of mechanisms, spacesuit abrasions and seal failures. There are several means of mitigating lunar dust exposure using good astronautical hygiene practice to reduce the astronaut health risks. These include initially eliminating the entry of dust into the lunar airlock using solar flux to sinter the surrounding dust, brushing and shaking dust from the spacesuit, and using a "Double shell spacesuit". Inside the airlock, the dust can be removed from the air by using extraction with high air recirculation rates and HEPA filters to trap the dust, by using effective clean-up techniques such as plasma-based SPARCLE to collect and remove dust from spacesuits and by using electrodynamic dust shields to remove deposited micro-sized particles from surfaces.

Future research work will be needed:

- to understand the relationship between lunar dust chemical reactivity and health effects;
- to study the effects of low gravity on the deposition of particles within the lung;
- on the toxicity of lunar dust e.g. in vitro and in vivo studies of the effects of exposure to lunar dust systemically and on the skin and eye;
- on the development of PELs; and
- on specific measures to mitigate exposure to the dust.

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