# INCREASED CONCENTRATIONS OF LUNAR DUST ASSOCIATED WITH A DENSER LUNAR ATMOSPHERE RESULTING FROM HEIGHTENED HUMAN PRESENCE AND ACTIVITY ON THE MOON.

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**Introduction:** With the planned Artemis program bringing lunar exploration back into the public eye, an increased concern has been shown towards lunar dust and the potential dangers it poses towards human exploration and colonization of the lunar surface. Twenty-five missions have landed thus-far on the Moon, with dozens of future missions planned in coming years and decades, from both national and private space programs. NASA plans to send humans back to the lunar surface by 2024, followed by a sustained human presence in 2028 [1]. An ongoing occupancy of the Moon would require regular supply rockets as well as the construction of lunar habitat modules. To make lunar ventures commercially viable, private companies or government organizations will likely mine the lunar regolith for resources such as water, oxygen, hydrocarbons, rare-earth or platinum-group metals, and helium-3 [2, 3, 4]. These processes will inevitably displace large quantities of dust from the lunar regolith, posing a potential danger to any human operations of the Moon.

**Dust Characteristics:** Analysis of dust samples brought back from the lunar surface indicates the lunar dust is typically composed of agglutinitic glass embedded with nanophase metallic iron, with the particles generally 0.1 to 0.25 µm in size [5]. Current theories suggest that lunar atmospheric dust is formed when micrometeoroid impacts melt and vaporize the regolith, leaving behind glass shards when refrozen. [6]. The glass shards contain large reaction surface areas with abrasive, angular, chemically reactive, and electrostatic properties [7]. Due to a small size and electrostatic levitation, lunar dust largely remains suspended near ground-level, where the majority of human operations will take place, often taking days to resettle [8]. The small size and electrostatic attraction of the dust particles likewise caused them to form a thin coating on most surfaces that were exposed to the lunar environment during the Apollo missions. The abrasive nature of the particles wore down seals, clogged valves or moving parts, and caused mild respiratory issues for Apollo astronauts who received dust exposure from limited-duration Moonwalks [9]. Astronauts staying extended periods of time on the lunar surface may expect a multitude of temporary or chronic effects due to lunar dust exposure [10].

**Previous Findings:** The total mass of the lunar atmosphere is approximately $2.50 \times 10^4$ kg, with a surface atmospheric abundance of approximately $2 \times 10^5$ particles/ $cm^3$ [11]. Each of the Apollo missions increased the Moon's atmosphere by approximately 20% due to rocket exhaust and displaced lunar regolith. A return to baseline-level abundances occurred within successive weeks or months [12]. Rates of atmospheric loss due to thermal escape and the solar wind stripping away ions are generally countered by a comparable solar wind deposition rate, outgassing, or sputtering of the lunar regolith [12]. An extended habitation on the lunar surface may offset this restorative force, with dust displacement and exhaust contributing to the atmospheric mass faster than loss processes can restore the balance. An increased density of the lunar atmosphere would raise the exobase - the outermost reaches of the atmosphere - of the moon, significantly increasing the escape time for solar photons and charged particles and therefore creating a recursive feedback loop of increasing lunar atmospheric density [13].

**Contributions to Lunar Atmospheric Density:**

Following an increased human presence on the Moon, the main gas and dust contributors to the lunar atmosphere will likely be artificial, namely in excavation and gas leakage of lunar habitats, displaced dust and vented exhaust from payloads arriving and leaving the lunar surface, as well as any mining operations that disturb the lunar regolith.

*Rocket exhaust.* The first primary artificial supplement to the lunar atmosphere will likely arise from the numerous supply and personnel missions that are sent to the Moon to establish a lunar habitat. Assuming ten flights per year, rocket exhaust would contribute on average 50 g/s to the lunar atmosphere [14]. Large quantities of dust would likewise be displaced due to takeoff and landing, remaining suspended near the surface for hours or days.

*Habitat Leakage.* The second assumed artificial contributor will be habitat leakage and airlock venting. Additional leakage would come from extravehicular activity (EVA) operations. Habitat leakage is estimated from Space Station Freedom data to be $2 \times 10^{-4}$ g/$m^2$s, or approximately 48 g/s for every 240 $m^2$ module [15]. A three-module construction for a crew of approximately four to five astronauts would thus contribute around 150 g/s to the lunar atmosphere. Adding additional modules to existing constructions or establishing other bases would therefore contribute even more to the atmospheric mass density.

*Mining.* The third artificial source of atmospheric mass would arise from future mining or excavation operations on the lunar surface. Large quantities of helium-3 (a potential fuel for fusion power plants), oxygen, water-ice, hydrogen, or rare-earth metals incentivizes mining of the lunar regolith by governmental and private organizations [3]. Lunar dust may also be processed into concrete, also contributing to the outgassing rate [16]. In-situ resource utilization (ISRU) would be beneficial for astronauts or future colonists, due to the high cost of transporting materials to the lunar surface [2]. Large-scale mining of the lunar regolith would likely contribute 1290 g/s to the lunar atmosphere, the majority of which arising from helium-3 mining operations [14, 15].

*Total artificial contributions to lunar atmospheric density.* In total, the additional atmospheric mass from the three artificial sources – supply expeditions to and from the lunar surface, habitat leakage, as well as mining or excavation operations - would likely be over 1500 g/s, assuming a permanent team of four to five astronauts with monthly supply trips. Increased human presence due to improved capabilities and technologies would therefore produce an elevated source rate. With this initial rate, the current lunar atmospheric mass would double in only five hours. Twice the atmospheric mass would approximate a doubling in atmospheric density, thus increasing the time lunar dust particles remain suspended near the surface. This doubling of atmospheric density, along with the increased amount of dust in the atmosphere arising from typical human operations, enables a dangerous situation for any long-term missions on the Moon. In addition, this process is expected to be recurring while a human presence remains on the Moon, causing successive missions to face ever-increasing atmospheric concentrations of lunar dust.

**Implications for Sustained Human Presence on the Moon:** Evidently, the dangers that lunar dust poses to the actualization of humanity's space-faring aspirations must not be underestimated. Lunar dust's abrasive, toxic, and electrostatic properties, coupled with a sub-micrometer size, presents an obvious danger to any long-term missions to the Moon. This danger is not found only in inhalation of the particles, but also to typical lunar operations. Apollo astronauts reported that equipment had malfunctioned or not operated as intended due to the aggregation of dust in joints or seals, hindering movement or causing the degradation of operational capabilities. The electrostatic nature prevents the easy-removal of dust via brushing, so measures must be taken to not track the lunar dust into habitation modules. Some means of mitigating the risk of lunar dust on human operations involve EVA spacesuits that directly connect with lunar habitats or pressurized and electrostatic airlocks that vent dust. Additionally, lunar dust capture-technologies may be used, such as by repurposing existing filtration or carbon-capture mechanisms to mitigate excess lunar dust generated from human operations. This captured dust could be either deposited back into the regolith or repurposed, such as in the construction of lunar concrete. Spacecraft exhaust-scrubbing and less-permeable habitat technologies may also work to decrease the mass of contaminants released back into the lunar atmosphere.

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