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LUNAR EXOGENIC PROCESSES POSING HAZARDS TO LONG-TERM LUNAR INFRASTRUCTURE

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Abstract: *Humanity's transition from short-duration lunar sorties to the establishment of a continuous human presence on the lunar surface in the context of NASA's Artemis program, the International Lunar Research Station (ILRS), and ESA's Argonaut lunar lander program requires ensuring long-term operational reliability within the harsh lunar environment. This review paper consolidates into a unified framework the numerous exogenous hazards identified to date by the aerospace community. It analyzes ongoing impact cratering processes, their morphological features and mechanisms, cosmic ray flux, electrostatic regolith mobilization, and drastic diurnal temperature swings. Ultimately, this review details the specific risks and structural impacts that these phenomena pose to lunar infrastructure and instrumentation.*

ЛУННИ ЕКЗОГЕННИ ПРОЦЕСИ СЪЗДАВАЩИ ОПАСНОСТИ ЗА ДЪЛГОСРОЧНАТА ЛУННА ИНФРАСТРУКТУРА

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Ключови думи: *Лунна среда, Екзогенни процеси, Опасности, Образуване на ударни кратери, Космическа радиация, Електростатична мобилизация на прах, Лунна температурна амплитуда*

Резюме: *Преходът на човечеството от кратковременни мисии до Луната към установяването на постоянно човешко присъствие на лунната повърхност – в контекста на програма „Артемида" (Artemis) на NASA, Международната лунна изследователска станция (ILRS) и програмата за лунни спускаеми апарати Argonaut на ESA – налага да се гарантира дългосрочната надеждност на системите в суровата лунна среда. Настоящият обзорен доклад консолидира в единна рамка множеството екзогенни опасности на лунната среда, идентифицирани до момента от аерокосмическата общност. В него са анализирани текущите процеси на образуване на ударни кратери, техните морфоложки особености и механизми, потокът от космически лъчи, електростатичната мобилизация на реголита, както и драстичните денонощни температурни амплитуди. Посочени са конкретните рискове за лунната инфраструктура и апаратура, както и последствията от тях.*

Introduction

Humanity's contemporary return to the Moon represents a major operational transition from the transient, short-duration sorties of the mid-20th century Apollo era to a long-duration and sustainable infrastructure footprint [1]. While the legacy of the Apollo and Luna programs demonstrated the fundamental feasibility of lunar transit, orbital descent, landing, and surface operations, their limited mission profiles masked the cumulative, long-term degradation mechanics driven by the lunar environment. Specifically, the lunar exogenic surface processes external forces that shape the landscape in the absence of atmospheric or magnetospheric buffering pose severe operational challenges to long-term infrastructure and operations. Today, major international initiatives are driving toward this long-term presence. These include NASA's Artemis architecture for sustainable habitation, the International Lunar Research Station

(ILRS) targeting extensive surface networks, and the European Space Agency's (ESA) Argonaut lunar lander program providing heavy logistics delivery. This array of planned engineering infrastructure must endure, adapt, and operate within the lunar harsh exogenic environment. To support this collaborative international framework, this review consolidates the primary environmental hazards currently identified by the aerospace community into a concise, unified overview, as summarized in Table 1.

Table 1: Lunar Exogenic Hazards and Engineering Infrastructure Risks

Hazard Category	Exogenic Mechanism	Environmental Parameter	Engineering Risk & Infrastructure Impact
1. Impact Cratering	Micro-impact bombardment	~ 1.4 metric tons day^{-1} global mass influx; velocities ~ 9 km s^{-1}	Surface micro-pitting, shock-induced melting, and long-term erosion of exposed structural alloys.
1. Impact Cratering	Small & macro impacts	~ 180 annual primary craters with diameters D ≥ 10 m	High-energy kinetic events leading to catastrophic structural failure.
2. Geotechnical Risks	Regolith overturn	Regolith mixing depth of top 2 cm over a timescale of 81,000 years	Regolith accumulation, structural burial, and secondary low-velocity ejecta bombardment.
2. Geotechnical Risks	Substrate heterogeneity	Simple craters (D < 15 km) featuring interior unstratified breccia lenses	Lateral variations in substrate density driving differential foundation settling.
2. Geotechnical Risks	Seismic slumping	Complex craters (D > 20 km) with terraced walls; multiring basin faults (D ≥ 410 km)	Seismic displacement, mass-wasting events, and structural fatigue from seismic wave propagation.
2. Geotechnical Risks	Asymmetric ejecta flux	Oblique trajectories with impact angles < 6° relative to the horizontal	Asymmetric kinetic loading and focused directional hypervelocity ejecta streams requiring targeted shielding.
3. Radiation & Plasma Charging	Space radiation influx	Continuous unattenuated ion, proton, and heavy nucleus energy spectra	Total Ionizing Dose (TID) degradation and Single-Event Effects (SEEs) within avionics.
3. Radiation & Plasma Charging	Electrostatic discharge	Microsecond-scale transient current pulses driven by rapid dielectric charge decay	High-amplitude ESD-induced EMI coupling into shielding seams, causing component latch-up or gate breakdown.
3. Radiation & Plasma Charging	Hemispheric divergence	Unshielded farside solar wind plasma velocities anchoring at ~ 400 km s^{-1}	Accelerated dielectric charging and accelerated cumulative dose metrics for farside hardware.
4. Particulate Dynamics	Dust levitation	Terminator electric fields ≥ 40V m^{-1}; surface potentials scaling to several kilovolts (kV)	Particulate deposition on optical surfaces and photovoltaic arrays; radiator occlusion driving thermal runaway.
4. Particulate Dynamics	Triboelectric abrasion	Highly abrasive, glass-rich, comminuted regolith fragments	Triboelectric charge accumulation on dynamic interfaces, leading to sealing track degradation and solar array obscuration.
5. Thermal Dynamics	Cyclic thermal shifts	Equatorial diurnal cyclic temperatures shifting from ~ 397 K down to ~95 K	Pronounced cyclic thermal deformation inducing mechanical joint fatigue and weld micro-fracturing.
5. Thermal Dynamics	Polar deep freeze	Cryogenic thermal floor of polar PSR crater interiors consistently down to ~ 50 K	Glass transition cryo-embrittlement of elastomeric seals, lubricant freezing, and irreversible battery capacity degradation.

Materials and Methods

A systematic literature review was executed across the NASA Astrophysics Data System (ADS), Scopus, Web of Science, and Google Scholar to synthesize exogenous hazards facing long-term lunar infrastructure. The search window captured peer-reviewed baseline data and operational observations published through 2026. Search queries utilized Boolean intersections combining environmental mechanism variables ("impact cratering", "cosmic ray flux", "electrostatic regolith mobilization", "diurnal temperature") with lunar asset classes ("lunar infrastructure", "instrumentation", "habitats", "solar arrays", "radiators", "rovers"). The compiled literature was systematically structured into five distinct exogenic hazard vectors based on their physical mechanisms and targeted infrastructure systems: Impact Cratering and Geotechnical Risks, Radiation and Plasma Charging, Particulate Dynamics, and Thermal Dynamics.

Impact Cratering

Impact cratering is a major exogenic mechanism driving large-scale structural disruption, landscape degradation, and mechanical reorganization of the lunar crust. Lunar impact structures span a continuous spatial spectrum from 0.1 μm microcraters to the South Pole–Aitken (SPA) basin exceeding 2000 km in diameter [2]. For the purposes of this review, impact features are classified into three operational scales micro, small, and macro which correspond directly to crater dimensions.

Micro-Impacts

In interplanetary space, moving solid natural objects with a size spanning from 2 mm to 1 m are categorized as meteoroids, whereas the smaller sub-population restricted to dimensions below 2 mm represents micrometeoroids [3]. As projectile dimensions decrease, the corresponding impact flux increases. On planetary bodies lacking an atmosphere, such as the Moon, this continuous influx of hypervelocity particles presents the dominant threat to anthropogenic surface assets, delivering a contemporary mass flux calculated at approximately 1.4 tons per day [4]. Because there is no atmospheric column to ablate this incoming debris, these projectiles strike infrastructure entirely unimpeded, subjecting solar arrays, pressure vessels, and optical components to relentless particulate pitting [5].

The localized physical reaction of engineered materials or native substrates to microscale strikes depends on target material density and shock impedance (4, 6, 7). At highly elevated energy thresholds, hypervelocity micro-impacts drive target shock melting, vaporization, and complete ionization, generating transient, reactive plasma columns directly above the impact zone [4, 8]. On solid materials (bedrock, metals, ceramics), these impactors produce distinct microcraters defined by central glass-lined pits, severe shock-induced fracturing, localized spallation zones and high-albedo structural halos [7]. Over multi-decade timelines, this causes micro-scale mechanical abrasion and structural degradation of exposed anchors, seals, and structural alloys. Due to orbital flux geometry, equatorial regions experience three to five times higher impact rates than polar regions, exposing equatorial infrastructure to significantly accelerated rates of microscale mechanical wear and surface erosion [4].

Hypervelocity projectiles encountering the Moon typically possess a characteristic velocity distribution that peaks at 9 km s^{-1} for standard asteroidal and Jupiter-family comet populations. The architectural lifespan of long-term lunar assets is strongly dictated by the latitudinal geometry of the incoming micrometeoroid flux, creating distinct vulnerability profiles for equatorial and polar installations. Conversely, while polar infrastructure benefits from this reduced cumulative flux, it is uniquely vulnerable to highly energetic, high-latitude cometary impactors arriving from the zenith at average velocities of roughly 15 km s^{-1}. Within deep polar depressions like Shackleton crater, retrograde and high-eccentricity cometary impact velocities regularly exceed 40 km s^{-1}, with the broader cosmic distribution scaling up to 70–72 km s^{-1} [4]. The mechanical hazards of lunar regolith buildup on surface infrastructure stem from its physical nature of highly jagged, glass-rich, and razor-sharp fragments shaped by billions of years of impacts. Upon accumulating on mechanical components, it acts as a highly abrasive medium that accelerates friction and mechanical wear. This deposition induces the failure of seals and mating interfaces, compromises thermal management systems, and drives the degradation and obscuration of solar arrays [9].

Small-Impacts and Macro Impacts

Although the flux of the impactor size spectrum decreases significantly as projectile diameters exceed 1 m, the hazard to localized engineering infrastructure increases disproportionately. Guided by the non-linear planetary scaling laws established by Holsapple (1993), these meter-scale bodies generate hypervelocity, high-energy kinetic events that typically yield final crater diameters characteristically 10 to 20 times the physical dimensions of the projectile, depending on the specific impact velocity and target regime properties [6]. Consequently, these impacts carry sufficient kinetic energy to induce catastrophic, total destruction of assets in a direct strike.

While the traditional Neukum Production Function (NPF) predicts a steady-state background production of ~ 140 impact craters with diameters ≥ 10 m annually, modern orbital observations reveal a 33% more hazardous environment [10, 11]. Multi-year before-and-after image pairs from the Lunar Reconnaissance Orbiter Camera (LROC) empirically detect an elevated contemporary flux of ~ 180 annual craters within this same size threshold. This active population spans up to a maximum observed diameter of 43 m a discrete, high-energy event expected only once or twice a year globally. On decadal scales, this accelerated primary bombardment drives secondary cratering processes that turn over the top two centimeters of regolith in merely 81,000 years, compounding mechanical wear and abrasion risks for long-term engineering infrastructure [11].

Extrapolated over geological periods, hypervelocity bombardment generating craters with dimensions (10–100 m) acts as the primary agent of lunar landscape degradation and surface erosion. This process gradually rounds prominent rims, fills interior depressions, and on sloped terrain drives a continuous mass-wasting mechanism. Because ballistic ejecta travels 40% farther downward, this mobilization creates a net transport of native regolith from topographic highs to gravitational lows, forcing older structures to fade into the background terrain. At a macroscopic scale, these evolving features exhibit distinct morphological variations that introduce unique geotechnical and engineering hazards [7].

Simple craters (< 15 km) feature a bowl-shaped depression with a sharp-crested rim and an internal, unstratified breccia lens accumulated via wall failure. Siting infrastructure on these unconsolidated lenses introduces high risks of differential foundation settling due to the extreme heterogeneity of the underlying shocked and impact-melted rocks. Furthermore, primary strikes blanket adjacent features with a continuous, hummocky debris field of ejecta and scoured regolith, posing threats of structural burial, mechanical abrasion, and heavy kinetic loading. Beyond this perimeter, simple craters are surrounded by extensive secondary crater fields and bright, high-albedo ray systems of pulverized ejecta. Because these rays extend several crater diameters, surface architecture positioned far outside the primary excavation zone remains vulnerable to secondary bombardment and severe dust contamination [12, 13].

As structural scales increase, complex craters (> 20 km) introduce severe engineering challenges defined by terraced walls, central peaks, and flat interior floors. Terraced walls represent unstable zones susceptible to seismic shifting and localized landslides. Concurrently, the flat interior floors are covered by irregular impact melt sheets and localized pools, inducing extreme lateral variations in substrate density and hardness that complicate excavation or drilling. At the largest scale, multiring basins (≥ 410 km) exemplified by the 930 km diameter Orientale basin with its four concentric rings present severe macro-structural risks. These systems introduce deep, crustal-scale fault networks that can propagate seismic energy and complicate safe foundation. Finally, highly oblique impacts striking at entry angles under approximately 6° deviate from these standard circular trends, yielding elongated, elliptical geometries. These occurrences pose a focused directional hazard, projecting asymmetric, “butterfly-wing” ejecta patterns that concentrate hypervelocity fragments along a specific downrange vector requiring targeted structural shielding [2, 12, 14].

Solar radiation and galactic cosmic rays

Spacecraft materials and lunar infrastructure are inevitably exposed to severe environmental stressors driven by the solar wind, solar energetic particles (SEPs), and galactic cosmic rays (GCRs). These dynamic charged particle fluxes comprising protons, electrons, and heavy ions collectively induce material degradation and radiation damage, manifesting as total ionizing dose (TID) effects, single-event effects (SEEs) within microelectronics, and spacecraft charging followed by electrostatic discharge (ESD). These phenomena degrade structural materials and compromise systemic reliability, dictating the overall operational lifespan of space missions [15].

The transient energy released during an ESD event poses severe risks to onboard electronic infrastructure. The rapid dissipation of stored charge generates high-amplitude transient currents and high-intensity electromagnetic interference (EMI) within microsecond timescales. This EMI can directly penetrate hardware enclosures or electromagnetically couple into sensitive signal lines, power distribution networks, and telemetry cables through structural gaps, slots, or shielding seams. This coupling induces false commands, component latch-ups, or catastrophic permanent damage to critical command, control, and payload electronics [15]. Furthermore, data from the Chang'e-5 and Chang'e-6 missions reveal a hemispheric divergence in solar wind interactions, indicating that approximately 25% of the total solar wind influx at the lunar nearside undergoes deceleration from ~ 400 km s^{-1} to ~ 200 km s^{-1} during crossings of the Earth’s magnetotail, whereas the farside remains exposed to the unshielded, high-velocity solar wind [16].

Electrostatic Dust Mobilization and Transport

On the lunar dayside, solar ultraviolet (UV) radiation and X-rays irradiate the regolith, eliciting photoelectron emission through the photoelectric effect, which imparts a mild positive electrostatic potential onto the surface. These emitted electrons hover in a thin, dense photoelectron sheath extending approximately 1 meter above the local terrain. On the nightside and inside permanently shadowed regions (PSRs), where solar irradiation is absent, interaction with the solar wind electron plasma drives the accumulation of a high negative charge. During solar storms or when the Moon crosses the Earth's magnetotail, this surface potential can intensify to thousands of volts [17]. At the terminator boundaries,

sharp spatial gradients in surface potential generate intense localized electric fields (exceeding 40 V m^{-1}) that can electrostatically interact with cross-boundary operational assets.

The resulting electrostatic charge levitates sub-micron and fine particles of lunar dust, causing them to migrate within a dynamic dust cloud that can coat solar panels, optical lenses, and camera shields [18]. When rovers traverse or astronauts walk on this charged, highly resistive regolith, frictional contact induces accelerated triboelectric charging. On the sunlit surface, the ambient photoelectron plasma and plasma current environment facilitate safe dissipation of this net charge. Conversely, in the dark polar regions, the charge builds up continuously on rover locomotion components and extravehicular activity (EVA) suits, posing a constant risk of electrostatic discharge (ESD) that can induce catastrophic damage in onboard electronics [19].

Thermal Dynamics of the Lunar Environment and Implications for Infrastructure

The complex and extreme lunar surface thermal environment imposes severe engineering constraints on anthropogenic infrastructure, including habitats, rovers, and photovoltaic arrays. The high-amplitude cyclic temperature shifts, which at equatorial latitudes peak at ~387–397 K (~114°C to 124°C) during the 14-diurnal-Earth-day lunar daytime and plummet to ~ 95 K (~ −178°C) during the lunar night, trigger pronounced volumetric changes through thermal expansion and contraction [20]. This thermal gradient is further exacerbated within permanently shadowed regions (PSRs), primarily inside polar crater interiors, where environmental temperatures consistently settle as low as 50 K (−223°C). Over extended deployment lifetimes, this continuous physical deformation induces structural fatigue, threatening the integrity of structural joints, accelerating the degradation of welds, and potentially leading to catastrophic mechanical failures. Over geological timescales, this diurnal cycle drives
micro-mechanical fracturing and the progressive breakdown of surface lithologies and boulders. Operational survivability during the lunar night spanning 14 Earth days presents a reciprocal engineering challenge. Subsystems must endure prolonged dark periods without dropping below critical operational temperature thresholds, beyond which mechanical seals undergo glass transition, lubricants degrade, and rechargeable cells suffer irreversible battery capacity loss [21]. When electrostatically charged fine regolith particles adhere to external surfaces and accumulate on reflective radiators or optical solar reflectors, the high-absorptance, low-albedo dust increases solar absorption, accelerating thermal degradation and compounding the risk of system-wide overheating. Furthermore, thermal management of operational systems is severely restricted by the vacuum environment, which eliminates convective heat transfer and isolates thermal radiation as the exclusive mechanism for external heat rejection [22].

Conclusion

In summary, this review demonstrates that the lunar surface is far from a geologically static and inactive environment; it is a highly volatile, interconnected environmental frontier that demands specialized, environmentally tailored engineering approaches across structural materials, electromechanical mechanisms, thermal control systems, and microelectronics. The future operational reliability of planned infrastructure envisioned under NASA's Artemis architecture, the International Lunar Research Station (ILRS), and ESA's Argonaut program will be rigorously tested by this harsh cross-section of external stressors. Enduring multi-year operations requires these systems to simultaneously withstand unattenuated hypervelocity micrometeoroid fluxes, localized macro-impact ejecta dynamics, extreme diurnal thermal cycling and sharp spatial gradients down to 50 K, ionizing radiation, electrostatic charging and subsequent discharge processes, and dynamic dust mobilization. Developing engineering solutions to tackle these interconnected degradation mechanisms represents the foundational baseline required to transform the Moon into humanity's premier deep-space laboratory. Ultimately, the operational durability metrics validated through these upcoming deployments will serve as the direct technological stepping stone for humanity's subsequent expansion toward Mars and beyond.

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