

Article

Probabilistic Meteoroid Hazard Analysis for Lunar South Pole Infrastructure Design

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Abstract

The lunar South Pole has emerged as a strategic target for future space exploration due to its potential to host valuable resources and its favorable illumination conditions. However, the absence of a significant atmosphere leaves surface infrastructure directly exposed to meteoroid impacts, creating a critical challenge for long-term operations and mission sustainability. This study presents a probabilistic assessment of meteoroid impact hazard at the lunar South Polar region using version 3.0 of NASA's Meteoroid Engineering Model (MEM 3.0). The proposed methodology integrates site-specific meteoroid flux estimation with probabilistic recurrence analysis to characterize meteoroid mass distributions, relative velocities, directional exposure conditions, and impact frequencies on the lunar surface. The results indicate that the meteoroid flux exhibits a well-defined peak near $25.5 \text{ km}\cdot\text{s}^{-1}$, with maximum values approaching $0.053 \text{ impacts}\cdot\text{m}^{-2}$ per year in the ram direction, confirming a pronounced directional anisotropy in the impact environment. Small particles dominate the cumulative impact frequency within the validated MEM 3.0 mass range ($<10^1 \text{ g}$), whereas probabilistic extrapolation of the mass–frequency relationship suggests that extreme-mass impactors ($\sim 10^6 \text{ g}$) occur far less frequently but generate substantially greater kinetic energies. Power law scaling relationships between impact frequency, particle mass, and return period are further used to define representative impact scenarios for engineering design and hazard assessment. The proposed methodology provides a physically consistent and scalable framework for evaluating meteoroid hazard conditions in localized lunar environments and supports the development of resilient infrastructure for future long-duration exploration missions at the lunar South Polar region.

Keywords: meteoroid impact hazard; lunar South Pole; probabilistic hazard assessment; lunar surface infrastructure; meteoroid flux



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1. Introduction

Renewed efforts toward sustained human presence beyond Earth have positioned the Moon as a central target for near-term exploration and infrastructure development [1,2]. In this context, the lunar South Polar region has emerged as particularly strategic due to its unique environmental characteristics. Permanently shadowed regions are believed to contain significant deposits of water ice, a key resource for future human exploration and in situ resource utilization (ISRU) activities, while adjacent elevated areas may experience extended periods of solar illumination suitable for continuous power generation [3].

In addition, the region exhibits relatively stable thermal conditions and terrain features that are potentially compatible with long-term robotic and human operations [4]. Recent engineering–geology assessments have further identified several locations within the de Gerlache–Shackleton region of the lunar South Polar region as promising candidates for future mining and ISRU activities, highlighting their potential to support resource extraction, infrastructure deployment, and sustained exploration efforts in the lunar polar environment [5]. Consequently, the lunar South Polar region has been identified as a primary target for upcoming missions, including NASA’s Artemis program, ESA’s PROSPECT payload aboard NASA’s CLPS CP-22 mission, and other international exploration initiatives, which collectively aim to establish a sustained human presence supported by surface infrastructure [6–8].

Infrastructure capable of withstanding the extreme conditions of the lunar environment is required to achieve a sustained human presence at the lunar South Polar region [9]. These include vacuum conditions, intense radiation, large thermal gradients, seismic activity, and continuous exposure to meteoroid impacts, all of which represent significant risks to structural integrity and operational safety [10,11]. Among these hazards, meteoroid impacts represent a particularly critical challenge due to their stochastic nature and potentially high energy. In the absence of a protective atmosphere, the lunar surface is directly exposed to a continuous flux of particles spanning several orders of magnitude in both mass and velocity. Typical impact velocities range from 3 to more than $70 \text{ km}\cdot\text{s}^{-1}$, while particle sizes vary from micrometer-scale dust to centimeter-scale bodies [12,13]. This wide variability introduces substantial uncertainty in impact frequency and energy, making it challenging to establish reliable design criteria for lunar surface infrastructure. Beyond exposure frequency, recent studies indicate that micrometeoroid impacts can significantly affect the mechanical performance and damage response of lunar construction materials such as sulfur regolith concrete, thus emphasizing the need to incorporate impact behavior into infrastructure design [14]. In addition to direct structural penetration, meteoroid impacts on the lunar surface also induce transient ground vibrations as well as short-duration, high-intensity localized thermal increases, both of which represent additional risks to the integrity and operational continuity of lunar surface infrastructure [15].

Significant efforts have been devoted to characterizing the lunar meteoroid environment through modeling and observational approaches. Analytical and empirical models have been developed to estimate meteoroid fluxes, velocity distributions, and mass-frequency relationships across the lunar surface [16,17]. In parallel, observational studies based on optical detection of lunar impact flashes have provided valuable constraints on the kinetic energy and occurrence of impacting bodies [18,19]. Together, these approaches have substantially improved the understanding of the global meteoroid environment. Despite these advances, there are still important limitations. Impact flash observations are restricted to the Earth-facing hemisphere and depend on favorable viewing conditions, limiting both spatial coverage and temporal continuity [20]. Similarly, many existing meteoroid environment models provide globally averaged or spatially generalized flux estimates, without explicitly resolving regional variability at sites of engineering interest.

A site-specific characterization of meteoroid impact hazard is required at the lunar South Polar region, which has emerged as a primary target for future surface infrastructure and sustained exploration missions [21]. Although recent studies have begun to integrate meteoroid hazard modeling with structural performance assessment [22], these approaches are generally based on globally averaged lunar conditions and do not explicitly capture local variability at high-priority exploration sites. Consequently, a critical gap remains between global descriptions of the meteoroid environment and the localized, engineering-oriented hazard assessments required to support infrastructure design. Unlike previous studies

focused on globally averaged meteoroid environments or material-scale impact analyses, the present work establishes a regional probabilistic framework that links meteoroid fluxes with engineering recurrence scenarios for infrastructure design at the lunar South Polar region. To address this gap, this study develops a probabilistic assessment of meteoroid impact hazard at the lunar South Polar region using NASA's Meteoroid Engineering Model version 3.0 (MEM 3.0) [23], provides a regionally resolved basis for risk-informed design and contributes to the development of resilient lunar surface infrastructure.

The proposed framework uses MEM 3.0 to derive site-specific meteoroid fluxes, impact velocities, directional distributions, and mass–frequency relationships at the lunar surface from observational and experimental datasets [24,25]. These outputs are subsequently translated into impact energy metrics and incorporated into a probabilistic formulation to evaluate occurrence rates and return periods for representative impact scenarios relevant to engineering design. By linking detailed environment characterization with engineering-relevant hazard metrics, the methodology enables a more realistic assessment of impact risk and supports the design of resilient lunar surface infrastructure.

2. Methods

2.1. Study Area Selection

The study site considered in this work is a candidate location at the lunar South Polar region previously identified through a multi-criteria analysis [21]. The site selection integrates scientific and engineering constraints, including terrain stability, surface slope, thermal conditions, and illumination, which are critical to the safety and operability of future lunar missions [26]. The selected location is situated at $84^{\circ}12'5.61''$ S latitude and $60^{\circ}41'59.61''$ E longitude (Figure 1). This region represents a balanced scenario that combines favorable landing conditions with access to strategically relevant resources, making it suitable for both exploration activities and long-term surface operations [27].

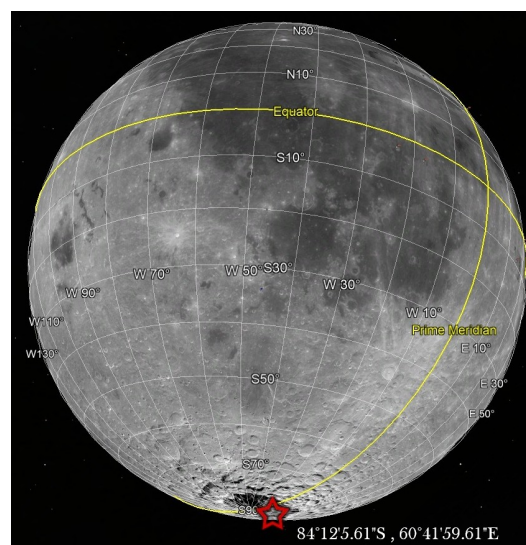


Figure 1. Location of the selected site on the lunar South Polar region.

The environmental conditions at the lunar South Polar region make this region particularly relevant for meteoroid hazard assessment due to the coexistence of permanently shadowed and illuminated areas. These conditions influence local visibility, operational planning, and surface activity patterns, leading to spatially variable exposure of surface assets to meteoroid impacts. Additionally, the concentration of current exploration activities in this region, including NASA's Artemis program and ESA's PROSPECT payload aboard NASA's CLPS CP-22 mission [8,28], makes the lunar South Polar region a high-priority

location for risk-informed assessment of meteoroid impact hazards. In this work, no additional site selection procedure is performed. Instead, the selected location is adopted as a validated reference case, allowing the study to focus on characterizing meteoroid impact hazards and their implications for future lunar surface operations.

2.2. Orbital Data and State Vector Determination

Once the study location is defined, the kinematic information required to describe the Moon's motion relative to that location over time is obtained by determining state vectors. State vectors are defined as the set of position and velocity components that fully describe the states of a celestial body at a given instant. These vectors are expressed in an inertial reference frame and consist of three-dimensional position (u_x, u_y, u_z) and velocity (v_x, v_y, v_z) components, typically given in km and $\text{km}\cdot\text{s}^{-1}$, respectively.

The orbital data required to describe the motion of the Moon relative to the study site are obtained using the NASA Jet Propulsion Laboratory (JPL) Horizons ephemeris system [29]. This system provides high-precision Cartesian position and velocity vectors via a user-defined configuration specifying the target body, observer location, temporal range, and output format. In this study, the Moon is the target body, and the observer is located at the selected South Polar site, which serves as the reference point for the analysis. State vectors are extracted over a one-year period using uniform temporal resolution to capture the variability of the Moon's kinematic conditions at the site. The *Vector Table* output option is adopted, which provides tabulated Cartesian position and velocity components in an inertial reference frame. To express the motion relative to the selected surface location, a translational change of origin is subsequently applied, shifting the reference frame from the lunar center to the local observation point. The resulting transformed state vectors define the kinematic conditions used as input for evaluating meteoroid impact exposure.

2.3. Meteoroid Flux Computation

The meteoroid environment at the lunar South Polar region is characterized using MEM 3.0 [23], which provides engineering-oriented estimates of sporadic meteoroid fluxes based on coupled distributions of particle mass, velocity, and radiant direction. The model integrates observational constraints from radar measurements, spacecraft observations, and meteoroid population studies to predict the meteoroid environment throughout the inner Solar System [25,30]. Although MEM 3.0 was originally developed for spacecraft risk assessment, its framework can be extended to stationary surface targets by appropriately defining the local reference frame and target geometry.

In the present study, the transformed state vectors of the selected lunar South polar site are used to define the instantaneous kinematic conditions under which the meteoroid flux is evaluated. The physical formulation implemented in MEM 3.0 is based on the heliocentric orbital dynamics of meteoroid populations. For a meteoroid orbit with semimajor axis a , the heliocentric velocity magnitude v_h at a radial distance r is obtained from the following equation:

$$v_h = \sqrt{GM_\odot \left(\frac{2}{r} - \frac{1}{a} \right)} \quad (1)$$

where $GM_\odot = 1.327124 \times 10^{20} \text{ m}^3\cdot\text{s}^{-2}$ is the solar gravitational parameter [31].

The direction of motion is characterized by the angle ψ , defined from the radial and tangential velocity components along the meteoroid trajectory:

$$\psi = \arcsin \left(\frac{a^2(1 - e^2)}{r(2a - r)} \right), \quad (2)$$

where e is the orbital eccentricity [23]. The spatial distribution of meteoroids along their heliocentric orbits is represented through the probability density function

$$P(r) = \frac{r}{\pi a \sqrt{(r-q)(Q-r)}}, \quad (3)$$

where q and Q correspond to the perihelion and aphelion distances, respectively. These relationships define the statistical orbital framework that MEM 3.0 uses to estimate the local meteoroid environment.

Meteoroid flux is defined as the number of particles incident on a unit area per unit time. MEM 3.0 resolves this flux using an imaginary cube centered at the analysis point and aligned with the body-fixed coordinate system. The six cube faces correspond to the ram, wake, port, starboard, zenith, and nadir directions (Figure 2). In this study, the cube-based local reference frame is defined as a surface-tangential coordinate system centered at the selected lunar South Polar location ($84^{\circ}12'5.61''$ S, $60^{\circ}41'59.61''$ E). For the selected lunar South Polar site, the zenith–nadir axis is approximately aligned with the global lunar polar direction, while the ram direction is predominantly oriented toward the local east tangential direction associated with the instantaneous orbital motion of the Moon (i.e., the leading-facing direction relative to the incoming meteoroid population), with the wake direction defined as the opposite of the ram direction. This directional discretization enables characterization of the anisotropic nature of the meteoroid environment and allows identification of preferential impact directions.

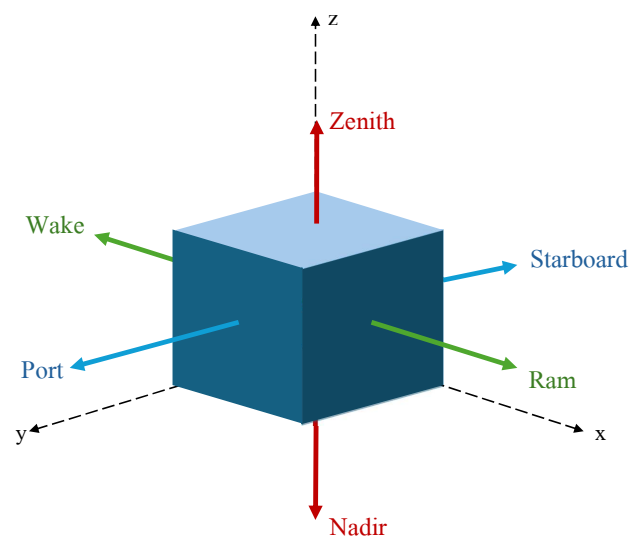


Figure 2. Cube representation used in MEM 3.0 to discretize the directional meteoroid flux.

For each cube face, MEM 3.0 provides the meteoroid flux as a function of particle mass and relative velocity. Due to the anisotropic structure of the sporadic meteoroid environment (i.e., the meteoroid flux is direction-dependent, with certain orientations experiencing higher impact rates than others), the incident flux depends strongly on the relative orientation between the target surface and the incoming meteoroid radiants. Consequently, the ram direction typically experiences the highest impact flux and therefore represents the most critical exposure condition for engineering design.

The Moon is defined as the reference body, and an equatorial coordinate system is adopted to describe the relative geometry between the meteoroid population and the lunar surface. The analyzed meteoroid mass range extends from 10^{-6} to 10^1 g using logarithmic discretization consistent with the model limits. An angular resolution of 5° and a velocity resolution of $1 \text{ km}\cdot\text{s}^{-1}$ are adopted. The high-fidelity mode of MEM 3.0 is

not activated in order to balance computational efficiency and solution accuracy. MEM 3.0 reports cumulative fluxes corresponding to particles with masses greater than or equal to a specified limiting mass. Therefore, differential fluxes for discrete mass intervals are obtained by subtracting consecutive cumulative flux values. This procedure enables characterization of the mass-dependent contribution to the overall meteoroid impact environment.

A representative surface area of $3 \times 10^4 \text{ km}^2$ is adopted to estimate the meteoroid impact frequency over the lunar South Polar region. This value approximates the spatial extent of the operational area considered in recent lunar exploration studies [32]. The analysis assumes that the meteoroid flux is spatially uniform across the selected region and does not account for local shielding effects associated with topographic features such as crater walls or elevated terrain. While crater walls within permanently shadowed regions (PSRs) may provide partial geometric shielding for certain impact trajectories, dynamical studies indicate that meteoroids on highly inclined orbits can still access polar surfaces despite local topographic barriers [33]. Therefore, local topographic shielding is not explicitly modeled in this regional-scale assessment, and uniform exposure conditions are assumed across the study area. Under these assumptions, the total annual number of impacts is obtained by integrating the directional flux over the representative area, yielding a regional-scale estimate of meteoroid impact frequency suitable for preliminary engineering hazard assessment.

2.4. Probabilistic Hazard Analysis

The probabilistic characterization of the meteoroid environment is performed by expressing the impact flux in terms of the return period (T_r), which represents the mean recurrence interval between impact events. In the present study, the return period establishes a direct relationship between meteoroid occurrence frequency and the physical characteristics of potential impactors, thereby enabling a probabilistic interpretation of impact hazard relevant to engineering design. Similar to probabilistic seismic hazard assessment, return periods are considered together with the design life and importance level of a structure to evaluate the likelihood of experiencing a given hazard level over its service life [11,34]. Accordingly, the return period associated with a given meteoroid population or impact condition is defined as the inverse of the annual impact rate and is computed as

$$T_r = \frac{1}{N}, \quad (4)$$

where N is the annual number of impacts associated with a given meteoroid population. The impact rate is obtained from the meteoroid flux predicted by MEM 3.0 according to

$$N = F \cdot A, \quad (5)$$

with F as the meteoroid flux in units of $\text{impacts} \cdot \text{m}^{-2}$ per year and A as the representative exposed surface area considered in the analysis. Combining both expressions yields

$$T_r = \frac{1}{F \cdot A}. \quad (6)$$

This formulation allows the meteoroid environment to be represented probabilistically, in terms of recurrence intervals for different impact conditions. To investigate the influence of particle mass on the impact hazard, a representative velocity of $25.5 \text{ km} \cdot \text{s}^{-1}$ is selected. This value corresponds to the peak of the velocity-dependent flux distribution obtained from MEM 3.0 and therefore represents the most critical kinematic condition for impact frequency. By fixing the velocity at this characteristic value, the effect of meteoroid mass on the return period can be analyzed independently from the variability associated with the full velocity distribution.

At the selected velocity, the corresponding flux values are extracted for each meteoroid mass interval and converted into return periods using Equation (6). The resulting return period–mass relationship exhibits an inverse scaling behavior in which larger particles are associated with progressively longer recurrence intervals. Since the MEM 3.0 dataset is limited to masses up to 10^1 g, the relationship is extrapolated to estimate low-frequency, high-energy impact events associated with larger meteoroids that are not fully represented within the calibrated model range. The extrapolation is based on the power law scaling commonly observed in meteoroid populations and interplanetary dust distributions [16]. The meteoroid flux as a function of particle mass can be expressed as

$$F(m) \propto m^{-s}, \quad (7)$$

where m is the meteoroid mass and s is the mass index governing the relative abundance of particles of different sizes. This relationship reflects the well-established tendency for small particles to occur much more frequently than large particles.

A power law function is fitted to the computed return period–mass relationship and subsequently extrapolated beyond the original MEM 3.0 mass range. This procedure enables the estimation of representative meteoroid masses for selected return periods relevant to engineering design and hazard assessment. Although the extrapolated relationship is physically consistent with observed meteoroid scaling laws, the uncertainty increases outside the model’s calibrated mass range and should therefore be interpreted as a first-order approximation for extreme impact conditions.

2.5. Definition of Representative Impact Scenarios

Representative impact scenarios are defined to establish physically consistent loading conditions associated with different levels of meteoroid hazard. These scenarios link the probabilistic characterization of the meteoroid environment to engineering-relevant impact parameters, enabling evaluation of impact severity across recurrence intervals representative of both operational and extreme conditions.

Six return periods are selected for the analysis: 36, 75, 250, 475, 1000, and 2500 years. These return periods are adopted from performance-based engineering practice, which explicitly links probabilistic hazard levels to structural design requirements by defining multiple recurrence scenarios associated with different expected performance states, ranging from operational conditions to extreme structural demands. This range includes both relatively frequent impact events and rare, high-consequence scenarios that may govern the design of critical lunar infrastructure systems. For each return period, the corresponding meteoroid mass is obtained from the extrapolated return period–mass relationship derived in the previous section.

As mentioned, a representative impact velocity of $25.5 \text{ km} \cdot \text{s}^{-1}$ was considered. The use of a single representative velocity provides a consistent basis for comparing impact severity (i.e., kinetic energy and associated damage potential for a given meteoroid size) across different recurrence intervals while maintaining the analysis focused on the most probable impact condition. The physical dimensions of the impactors are estimated assuming a spherical geometry and a bulk density $\rho = 2800 \text{ kg} \cdot \text{m}^{-3}$, representative of chondritic meteoroids. Under this assumption, the impactor volume V is computed as

$$V = \frac{m}{\rho}. \quad (8)$$

The equivalent diameter of the spherical impactor is then obtained from

$$d = 2 \left(\frac{3V}{4\pi} \right)^{1/3} \quad (9)$$

where d is the equivalent impactor diameter.

The kinetic energy E_k associated with each impact scenario is calculated using

$$E_k = \frac{1}{2}mv^2 \quad (10)$$

where v is the representative impact velocity. This parameter provides a direct measure of the impact severity and constitutes one of the principal quantities governing potential structural damage under hypervelocity impact conditions.

Each representative scenario is therefore characterized by a unique combination of return period, meteoroid mass, equivalent diameter, and kinetic energy. Together, these parameters define a set of probabilistically consistent impact conditions that can support engineering-oriented hazard assessment, preliminary structural design, and risk-informed evaluation of lunar surface infrastructure exposed to meteoroid impacts. Although the proposed scenarios provide a practical framework for impact hazard characterization, they rely on several simplifying assumptions, including a fixed representative velocity, a spherical impactor geometry, and a uniform bulk density. Therefore, the resulting impact conditions should be interpreted as first-order engineering approximations intended for preliminary hazard assessment rather than exact predictions of individual meteoroid events.

2.6. Implementation Details

The meteoroid impact hazard assessment is implemented through a sequential workflow that integrates orbital mechanics, meteoroid environment modeling, probabilistic analysis, and impact scenario characterization. The procedure adopted in this study is summarized as follows:

1. Define the study location where the meteoroid impact hazard is evaluated.
2. Obtain the orbital state vectors using the NASA JPL Horizons ephemeris system.
 - a. Define the ephemeris configuration parameters, including:
 - Ephemeris output type;
 - Target body;
 - Observer location;
 - Time interval.
 - b. Extract the Cartesian position and velocity components ($u_x, u_y, u_z, v_x, v_y, v_z$) as a function of time.
3. Transform the state vectors to the selected study location through a translational change of origin.
 - a. Define the position vector of the observation point on the lunar surface in terms of its latitude, longitude, and the lunar radius.
 - b. Express the position and velocity components relative to the transformed local reference frame.
4. Compute the meteoroid flux using MEM 3.0.
 - a. Use the transformed state vectors as input to the meteoroid environment model.
 - b. Compute the heliocentric meteoroid velocity using Equation (1).
 - c. Determine the meteoroid trajectory orientation using Equation (2).
 - d. Evaluate the spatial probability distribution of meteoroids along their orbits using Equation (3).

- e. Evaluate the cumulative meteoroid flux for limiting masses ranging from 10^{-6} to 10^1 g.
 - f. Compute the differential flux associated with each mass interval by subtracting consecutive cumulative flux values (e.g., $F(<10^{-5}) - F(<10^{-6})$).
 - g. Determine the directional flux distributions for the ram, wake, port, starboard, zenith, and nadir orientations.
5. Perform the meteoroid flux characterization.
 - a. Scale the directional flux to the representative surface area to estimate the annual number of impacts using Equation (5).
 - b. Analyze the variation of impact rate as a function of meteoroid mass and relative velocity.
 - c. Identify the velocity associated with the maximum impact flux.
 - d. At this velocity, extract the corresponding flux values for each mass interval.
 - e. Analyze the relationship between mass and flux, which typically exhibits an inverse correlation.
6. Perform the probabilistic hazard analysis.
 - a. Convert impact rates into return periods as a function of mass using the inverse recurrence relationship in Equation (4).
 - b. Construct return period–mass relationships for representative impact velocities.
 - c. Represent the meteoroid mass distribution using the power law relationship and using Equation (7).
 - d. Fit and extrapolate the power law relationship beyond the calibrated MEM 3.0 mass range to estimate low-frequency, high-energy impact events.
7. Define representative impact scenarios.
 - a. Select a representative return period relevant to the application (e.g., operational, design, or extreme conditions).
 - b. Extrapolate the return period–mass relationship to estimate the masses associated with selected return periods.
 - c. Determine the corresponding meteoroid mass associated with each return period.
 - d. Estimate the meteoroid volume assuming a representative bulk density using Equation (8).
 - e. Compute the equivalent spherical impactor diameter using Equation (9).
 - f. Calculate the kinetic energy associated with each impact condition using Equation (10) and the representative velocity obtained in Step 5c.
 - g. Construct representative impact scenarios defined by return period, meteoroid mass, impactor diameter, and kinetic energy.
8. Use the resulting probabilistic impact scenarios to characterize meteoroid hazard conditions relevant to the preliminary engineering assessment and design of lunar surface infrastructure.

3. Results and Discussion

3.1. Meteoroid Flux Computation

The meteoroid flux as a function of relative velocity for each cube face orientation is presented in Figure 3. A well-defined peak is observed for all orientations at velocities close to $25.5 \text{ km} \cdot \text{s}^{-1}$, where the maximum flux reaches approximately $0.053 \text{ impacts} \cdot \text{m}^{-2}$ per year in the ram direction. This dominant peak indicates that the meteoroid environment at the lunar South Polar region is primarily controlled by particles with moderate-to-high relative velocities, which therefore represent the most probable impact conditions. The predicted velocity range is consistent with the dominant impact regime previously identified in

MEM-based lunar hazard analyses previously reported [22], supporting the validity of the present regional characterization.

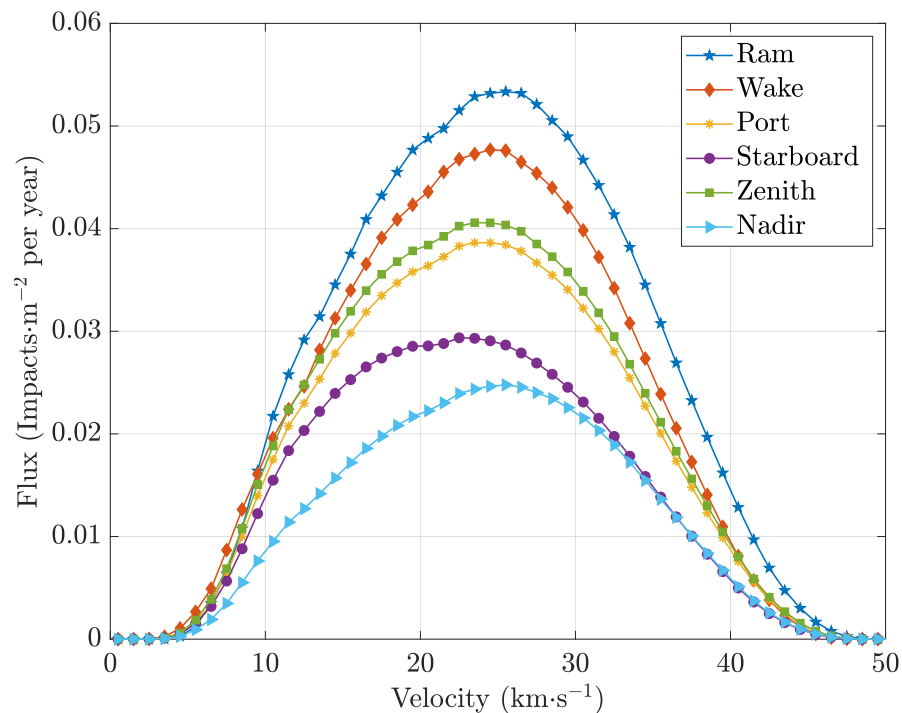


Figure 3. Meteoroid impact flux as a function of relative velocity for each cube face orientation (ram, wake, port, starboard, zenith, and nadir) at the lunar South Polar region, obtained using MEM 3.0 simulations.

The bell-shaped flux distribution observed in Figure 3 reflects the combined effects of meteoroid orbital dynamics and the relative motion between the lunar surface and heliocentric meteoroid populations. Meteoroids intersecting the lunar environment preferentially occupy orbital configurations associated with impact velocities near this range, leading to a concentration of impacts around the characteristic peak velocity. At lower velocities (below $\sim 10 \text{ km}\cdot\text{s}^{-1}$) and at higher velocities (above $\sim 40\text{--}45 \text{ km}\cdot\text{s}^{-1}$), the flux decreases rapidly, indicating substantially lower probabilities of occurrence for these impact conditions.

In addition to the velocity dependence, the results reveal a pronounced directional anisotropy in the meteoroid flux. The ram direction consistently exhibits the highest flux values across the entire velocity range, while the wake, port, starboard, zenith, and nadir orientations experience progressively lower exposure levels. This behavior is directly associated with the relative orientation between the target surface and the incoming meteoroid population. Surfaces aligned with the orbital motion continuously intercept incoming particles, whereas shielded orientations experience reduced exposure.

From an engineering perspective, this directional dependence has important implications for the design of lunar surface systems. Habitat orientation, shielding placement, and operational layouts may significantly influence long-term structural vulnerability. In particular, ram-facing surfaces should be considered critical exposure zones and therefore prioritized in the design of protective layers, shielding systems, and impact-resistant structural components.

3.2. Flux Characterization

Following the characterization of the dominant velocity regime and directional exposure conditions, the meteoroid impact environment is further evaluated to investigate

the influence of meteoroid mass on the resulting impact frequency. The impact rate as a function of relative velocity for different particle masses is presented in Figure 4. Each curve corresponds to a specific meteoroid mass ranging from 10^{-6} g to 10 g; thus, a direct evaluation of the coupled dependence between particle size and impact frequency can be made.

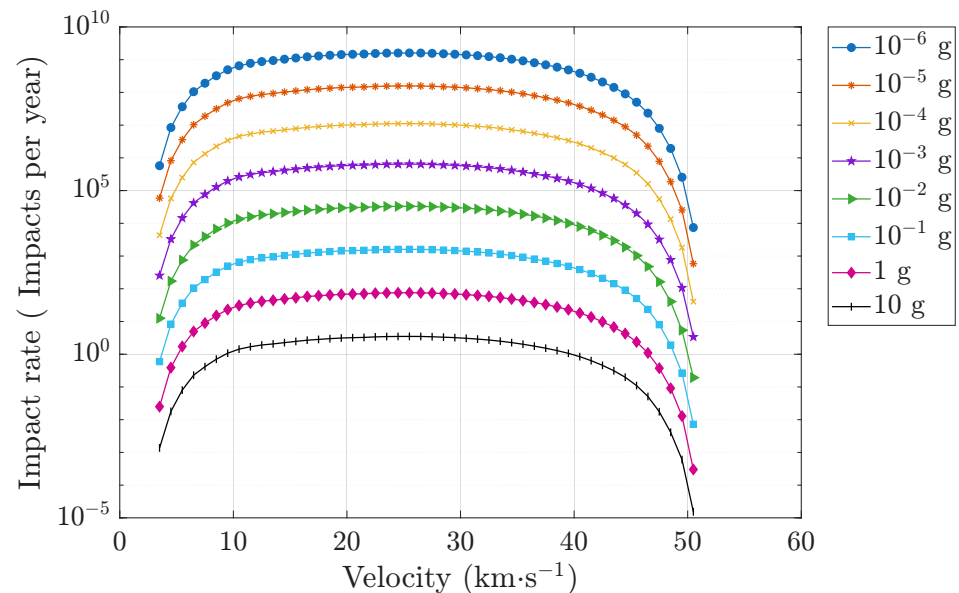


Figure 4. Impact rate as a function of relative velocity for different impactor masses at the lunar South Polar region.

A strong inverse relationship between particle mass and impact rate is observed across the entire velocity range. Small particles, particularly those on the order of 10^{-6} g, exhibit impact rates several orders of magnitude greater than those associated with larger particles. This behavior reflects the well-established dominance of fine particles in interplanetary meteoroid populations and is consistent with collisional cascade processes that govern dust generation and fragmentation in the Solar System.

The approximately uniform vertical separation between curves in logarithmic space suggests a systematic scaling relationship between meteoroid mass and impact frequency. Furthermore, all curves exhibit a similar unimodal distribution, with maximum impact rates concentrated near $25.5 \text{ km} \cdot \text{s}^{-1}$. This confirms that the velocity range previously identified in Figure 3 governs the overall meteoroid hazard environment. At both low and high relative velocities, the impact rate decreases substantially, indicating that the majority of meteoroid impacts are concentrated within a comparatively narrow velocity interval centered near the dominant flux peak. This behavior reflects the combined influence of meteoroid orbital dynamics and the relative motion between the lunar surface and heliocentric particle populations. Consequently, the meteoroid hazard at the lunar South Polar region is governed by a coupled interaction between particle size and impact velocity, in which fine particles dominate the cumulative exposure, while larger meteoroids disproportionately contribute to extreme impact energies.

The return period T_r , computed using Equation (4), is presented in Figure 5 as a function of impact velocity for different meteoroid masses. As expected, the shortest return periods occur near the velocity range associated with the maximum impact rate, while significantly longer recurrence intervals are observed at lower and higher velocities. In addition, the return period increases significantly with meteoroid mass, indicating that large-mass impacts are substantially less frequent and therefore associated with rare but potentially high-consequence events.

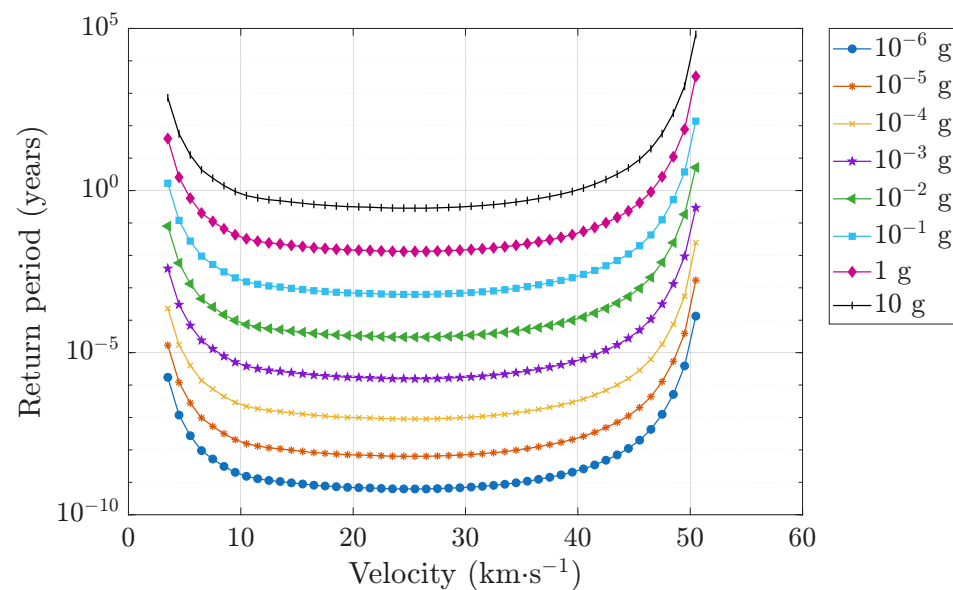


Figure 5. Return period as a function of relative velocity for different impactor masses.

3.3. Probabilistic Hazard Analysis

The variation of impact rate as a function of meteoroid mass for selected relative velocities is presented in Figure 6. The selected velocities span the representative range of the meteoroid environment, enabling evaluation of the combined influence of particle size and impact velocity on the overall hazard conditions.

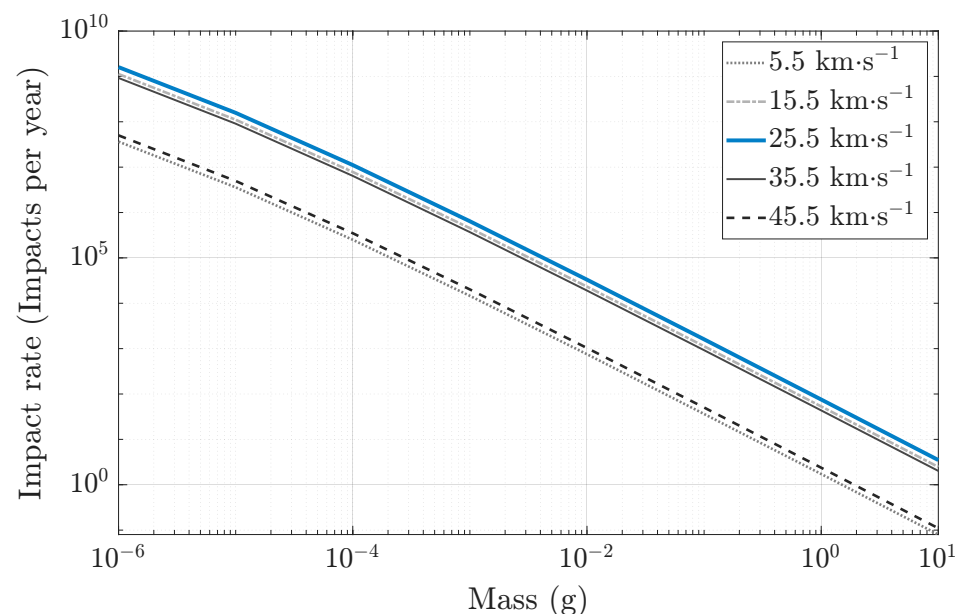


Figure 6. Impact rate as a function of particle mass for different relative velocities.

For all analyzed velocities, the impact rate decreases monotonically with increasing particle mass, spanning several orders of magnitude across the considered mass interval. When represented in logarithmic space, the relationship between impact rate and meteoroid mass exhibits an approximately linear trend, indicating a power law dependence characteristic of meteoroid populations and interplanetary dust distributions. The nearly parallel behavior of the curves suggests that the scaling exponent remains approximately independent of velocity, while the absolute magnitude of the impact rate varies with relative velocity. In particular, velocities near $25.5 \text{ km} \cdot \text{s}^{-1}$ consistently produce the highest

impact rates across the entire mass range, confirming that this velocity interval dominates the meteoroid environment at the study site.

The corresponding return period as a function of meteoroid mass is shown in Figure 7. The return period follows an inverse power law trend with increasing mass, reflecting the progressively lower frequency of large impactors. The log-log linearity observed in both the impact-rate and return-period distributions confirms the scale-dependent nature of the meteoroid environment and supports the use of power law relationships for probabilistic hazard characterization. These results demonstrate that the meteoroid hazard at the lunar South Polar region is governed by a coupled interaction between particle-size distributions and velocity-dependent flux amplification. Although small particles dominate the overall impact frequency, larger particles become increasingly important for extreme loading conditions due to their substantially greater kinetic energy.

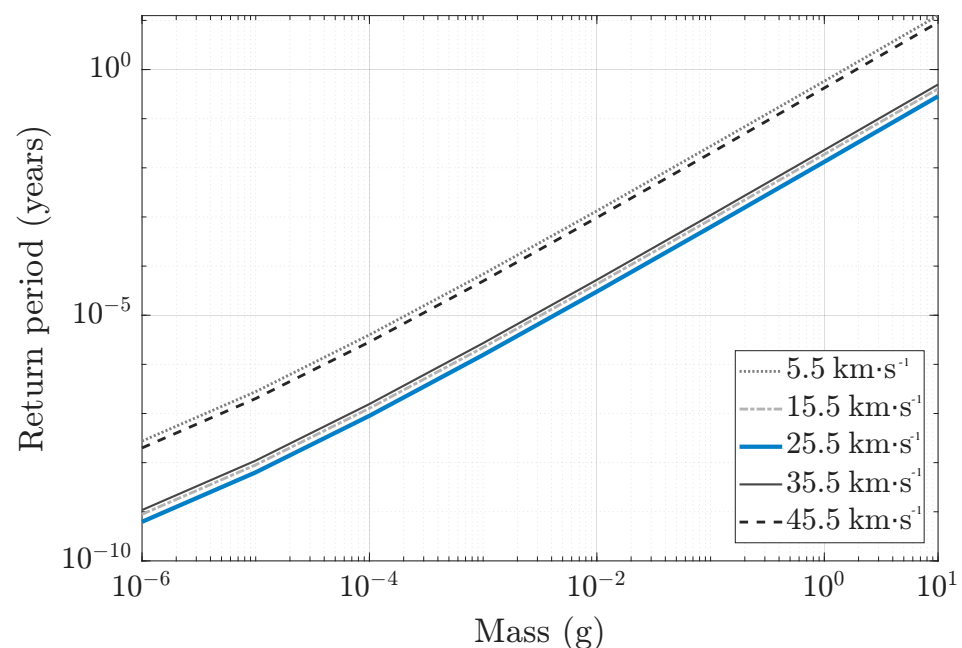


Figure 7. Return period as a function of particle mass for different relative velocities.

3.4. Definition of Representative Impact Scenarios

Based on the previous analyses, a representative velocity of $25.5 \text{ km}\cdot\text{s}^{-1}$ is selected for this scenario, as it corresponds to the maximum impact rate across all mass distributions. This choice provides a conservative yet physically representative basis for engineering-oriented hazard assessment by focusing on the most probable impact regime. The relationship between return period and meteoroid mass for this velocity is presented in Figure 8. When represented on logarithmic scales, the data exhibit a nearly linear trend, indicating a strong power law relationship between recurrence interval and meteoroid mass. This behavior enables extrapolation beyond the calibrated MEM 3.0 mass range, allowing estimation of low-frequency, high-energy impact events relevant to long-duration lunar infrastructure.

The extrapolated relationship is subsequently used to determine the particle masses associated with return periods of 36, 75, 250, 475, 1000, and 2500 years, as shown in Figure 9. Values are obtained by intersecting horizontal lines corresponding to the target return periods with the extrapolated curve, then projecting the intersections onto the mass axis. The extrapolation is characterized by a coefficient of determination of $R^2 = 0.9983$ and a slope $s = 1.2503$, indicating excellent agreement between the power law representation and the computed MEM-based results.

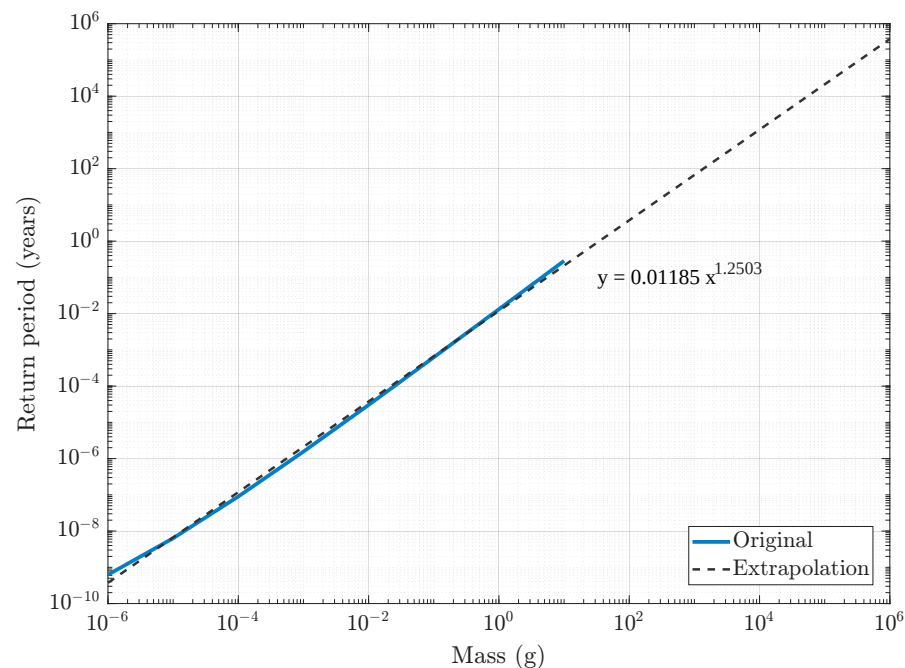


Figure 8. Power law extrapolation of return period as a function of particle mass for a velocity of $25.5 \text{ km}\cdot\text{s}^{-1}$.

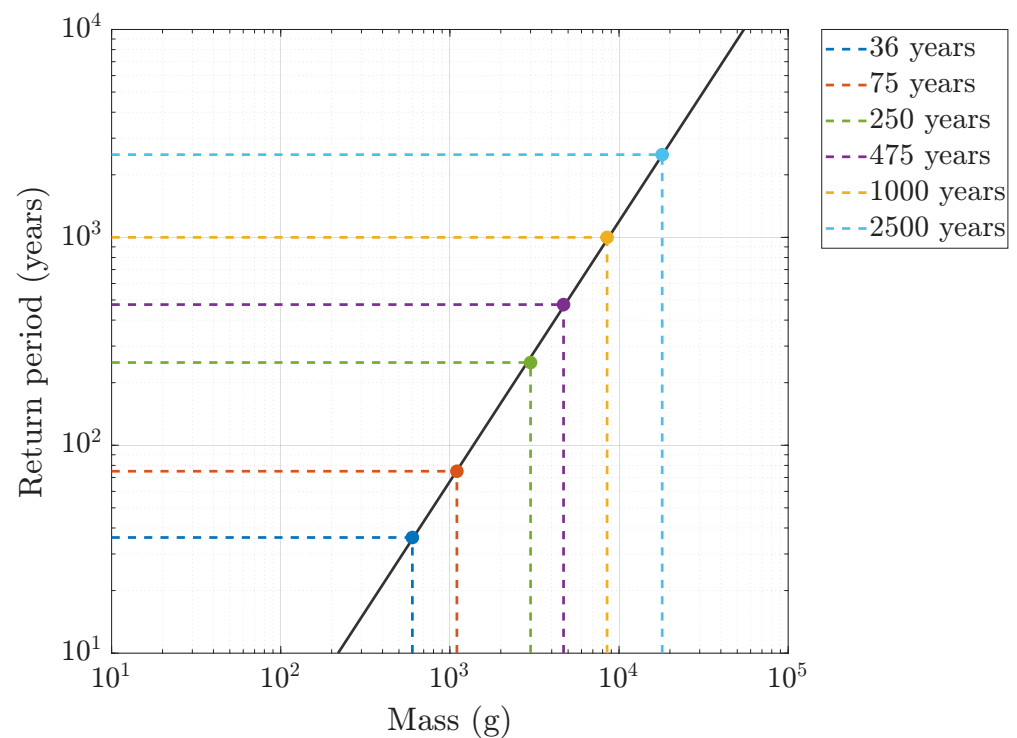


Figure 9. Determination of representative particle masses from selected return periods using the extrapolated power law relationship.

The selected return periods span a wide range of time scales relevant for engineering design, from relatively frequent operational events to rare but potentially catastrophic impacts that may govern extreme design conditions. This range enables a probabilistic characterization of the impact environment under both operational and extreme conditions. Using the corresponding meteoroid masses, the physical characteristics of the impactors are computed, including equivalent diameter, kinetic energy, and TNT-equivalent energy release. The results are summarized in Table 1.

Table 1. Meteorite impact hazard characterization for the selected lunar region.

Parameter	Unit	Return Period (Years)					
		36	75	250	475	1000	2500
Diameter	cm	9	12	18	22	28	38
Mass	kg	1.2	2.5	8.3	15.7	33	82.6
Kinetic energy	MJ	0.39	0.81	2.7	5.1	10.7	26.9
TNT equivalent	kg	93	194	645	1220	2560	6420

The results in Table 1 demonstrate a strong dependence of impact severity on return period. As the return period increases, the associated meteoroid mass and impactor diameter increase substantially, resulting in higher kinetic energies. The estimated impact energies span several orders of magnitude, ranging from moderate operational hazards to high-energy events capable of causing severe structural damage. The increase in TNT-equivalent energy release with return period reflects the nature of the representative impact scenarios: longer return periods are associated with rarer meteoroids of larger mass and diameter, which release greater kinetic energies at the assumed impact velocity. Consequently, these scenarios correspond to increasingly severe impact conditions despite their lower frequency of occurrence. The TNT equivalent provides a practical reference for interpreting the magnitude of released impact energy by expressing it as an equivalent explosive yield, thereby facilitating a more intuitive understanding of the potential destructive effects of hypervelocity impacts. However, the TNT-equivalent values are intended only as comparison energy metrics and should not be interpreted as directly equivalent to terrestrial atmospheric blast effects, since lunar hypervelocity impacts occur in vacuum conditions and involve fundamentally different physical processes. These results highlight the potentially severe consequences of low-frequency meteoroid impacts and emphasize the importance of jointly considering impact frequency, kinetic energy, and equivalent explosive energy in the engineering design of lunar surface infrastructure.

Beyond the variation in impact severity with return period, the results highlight a critical trade-off in lunar impact hazard assessment. Frequent impact events are dominated by relatively small particles, which primarily contribute to cumulative surface degradation and localized material damage. At the microscopic scale, hypervelocity meteoroid impacts may induce localized melting, rapid resolidification, and other thermomechanical effects resulting from the extreme pressures and temperatures generated during impact. Although these processes are not explicitly considered in the present regional-scale hazard model, they may contribute to cumulative material degradation, surface modification, and long-term deterioration of exposed infrastructure components. In contrast, low-frequency events involve significantly larger impactors that can cause severe structural consequences, including penetration, fragmentation, catastrophic failure of exposed infrastructure systems, and severe damage, even when no direct impact occurs, due to the seismicity induced by a nearby impact. Consequently, resilient lunar infrastructure will likely require multi-scale protection strategies that simultaneously address cumulative micrometeoroid exposure and rare extreme impacts. Such strategies may include sacrificial shielding layers, regolith-based protective systems, optimized structural orientation, localized reinforcement of critical components, and assessment of seismic performance of infrastructure against induced ground motion.

Although the proposed methodology provides a physically consistent basis for preliminary hazard assessment, several simplifying assumptions remain. The analysis assumes a fixed representative velocity, a spatially uniform meteoroid flux across the study region, a spherical impactor geometry, and a constant bulk density. In addition, local topographic shielding effects, secondary ejecta generation, and impact-angle variability are not explicitly

considered. These factors may change the effective hazard conditions and should therefore be incorporated in future investigations. Furthermore, extrapolating the power law relationship beyond the calibrated MEM 3.0 mass range introduces increasing uncertainty for extremely low-frequency events. Therefore, the predicted impact scenarios should be interpreted as first-order engineering approximations intended to support preliminary design and risk-informed assessment rather than exact predictions of individual meteoroid events.

Overall, the proposed methodology establishes a scalable framework that translates site-specific MEM outputs into engineering-oriented recurrence scenarios directly applicable to lunar infrastructure assessment. Unlike globally averaged descriptions of the meteoroid environment, the present approach provides site-specific hazard characterization relevant to future exploration activities at the lunar South Polar region and contributes to the development of resilient, long-duration lunar surface structures.

4. Conclusions

This study presents a probabilistic characterization of meteoroid impact hazard at a representative site in the lunar South Polar region using version 3.0 of NASA's Meteoroid Engineering Model. The proposed framework integrates site-specific meteoroid flux estimation with probabilistic recurrence analysis to derive engineering-oriented impact scenarios relevant to future lunar surface infrastructure. The results demonstrate that the meteoroid environment at the lunar South Polar region is strongly controlled by relative velocity and directional exposure conditions. A dominant flux peak was identified near $25.5 \text{ km}\cdot\text{s}^{-1}$, indicating that moderate-to-high velocity meteoroids govern the most probable impact conditions. In addition, the directional analysis revealed pronounced anisotropy in the impact environment, with ram-oriented surfaces experiencing the highest exposure levels, while shielded directions, such as the nadir, exhibit substantially lower fluxes. These findings highlight the importance of structural orientation and localized shielding strategies in the design of resilient lunar structures.

The probabilistic analysis further showed that meteoroid impact frequency follows a power law dependence on particle mass. Small particles dominate the cumulative impact rate, while larger meteoroids have significantly lower occurrence frequencies but substantially greater kinetic energies. This inverse relationship between frequency and impact severity introduces a critical engineering trade-off for lunar infrastructure design, in which both frequent low-energy impacts and rare high-energy events must be considered simultaneously.

Based on the extrapolated recurrence relationships, representative impact scenarios were established for return periods ranging from 36 to 2500 years. This interval was selected to capture a broad spectrum of hazard conditions relevant to lunar infrastructure design, including relatively frequent operational impacts and rare extreme events that may govern critical structural performance and long-term resilience requirements. The corresponding meteoroid masses, diameters, and kinetic energies provide a physically consistent basis for preliminary hazard assessment and risk-informed structural design. Unlike globally averaged descriptions of the meteoroid environment, the proposed methodology translates localized MEM outputs into engineering-relevant recurrence scenarios directly applicable to future lunar exploration activities. Further, the meteoroid impact assessment implemented in the lunar South Polar region can be used to estimate impact hazards at other locations on the Moon. In this regard, the probabilistic impact scenarios derived in this study provide a physically consistent basis for improving confidence in the shielding design of lunar habitats. Future work will use these scenarios to evaluate shielding thickness requirements and habitat structural performance under meteoroid loading through detailed hypervelocity impact analyses.

Although the present methodology provides a robust first-order characterization of meteoroid hazard conditions, several simplifying assumptions remain, including the use of a representative impact velocity, spatially uniform flux conditions, and extrapolation beyond the calibrated MEM mass range. Future work should therefore focus on incorporating additional physical effects such as impact-angle variability, secondary ejecta generation, topographic shielding, and material response under hypervelocity loading. Extending the methodology to time-dependent orbital conditions and additional lunar regions of interest would further support the development of resilient long-duration infrastructure for sustained human presence on the Moon.

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