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The Lunar Stairway: An Orbital-Platform-First Paradigm for Lunar Development and Its Engineering Rationale

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Objective: To examine the mainstream premise that lunar development must be based on the lunar surface; to argue the engineering rationale for building long-term residential bases, production facilities, and logistics hubs first in circumlunar orbit rather than on the lunar surface; and to propose a system design for the "Lunar Stairway" (a distributed system of circumlunar platform ports). **Methods:** On the basis of orbital mechanics (the vis-viva equation and the rocket equation), the velocity increments and mass penalties of lunar-surface landing and departure were calculated and compared with those of residence in circumlunar orbit; the success rate of lunar soft-landing missions worldwide from 1966 to 2025 was tallied; scientific assessments of the Apollo moonquake network, the Chang'e-4 in situ radiation measurements on the lunar surface, and the health effects of lunar dust were compiled; and a ballistic delivery and interception–deceleration model for the "circumlunar platform–capsule projectile–cable-net/pit/sponge-lake splashdown" system was established. **Results:** A one-way landing on the lunar surface requires a velocity increment of approximately 1.9 km/s (with I_{sp} = 300 s, propellant accounts for approximately 47.6% of the initial mass), and departure from the Moon requires a further approximately 1.85 km/s. The fully successful lunar soft-landing rate is approximately 50%, with failures concentrated in the powered-descent phase. Apollo seismometers recorded shallow moonquakes of magnitude up to approximately 5, lasting from tens of minutes to several hours, far longer than the tens of seconds of terrestrial earthquakes.

The dose equivalent rate on the lunar surface is approximately 1.4 mSv/d (twice that on the International Space Station), and an extreme solar particle event of the 1972 type could deliver a dose of the order of 3–4 Sv without shielding. Lunar dust is fine, electrically charged, and sharp-edged; it is difficult to remove completely and causes irreversible damage to equipment and to the human respiratory system. With frozen orbits, the annual station-keeping velocity increment in low lunar orbit can be held to 10–50 m/s, corresponding to approximately 3–17 kg/(t·yr) of chemical propellant or approximately 0.6–3.2 kg/(t·yr) with electric propulsion, comparable to or lower than the ISS reboost level (approximately 18 kg/(t·yr)); ballistic delivery requires only an ejection increment of approximately 23 m/s and approximately 10 kg/t of propellant. Near-lunar orbits, although they require more orbit control, maintain closer contact with the lunar surface and receive less galactic radiation because of blockage by the Moon. Different orbits and distributed deployments should therefore be adopted according to actual requirements. **Conclusions:** Circumlunar-orbit platforms are comprehensively superior to lunar-surface residence in energy, safety, environment, astronomical observation, and logistics efficiency. It is recommended that the primary construction layer of lunar development be placed in lunar orbit rather than on the lunar surface, and that low-overload ballistic delivery and electromagnetic ejection be used to open a “lunar orbit–lunar surface” materials corridor (without which construction of the Stairway would be pointless). If a momentum-exchange mode is adopted between platform and cargo, substantial propellant and energy can be saved, coupling the efficient descent of cargo with platform orbit changes and orbit maintenance. The paper also proposes that spent spacecraft hulls be stored in lunar orbit as a reserve of scarce metals.

Keywords: circumlunar orbit; Lunar Stairway; lunar base; soft landing; mascon; frozen orbit; lunar dust; radiation protection; in-orbit manufacturing; lunar development; reuse of discarded hulls; ballistic delivery; electromagnetic deceleration

Introduction

Since the Apollo era, human designs for lunar development have rested on one key premise: almost all engineering and infrastructure for a lasting presence on the Moon are to be built on the lunar land surface. The global space community (including NASA's Artemis and CNSA's ILRS) has envisioned lunar development chiefly as the construction of permanent surface bases, with surface missions as the principal operating layer and lunar space seldom involved. The two current international cooperation frameworks (the U.S.-led Artemis Accords [38] and the memorandum of understanding on the International Lunar Research Station (ILRS) led by China and Russia [39]), as well as the Commercial Lunar Payload Services (CLPS) program, all take "landing – base building – residence" as the standard path for their early testing, development, and verification. However, of the 48 lunar soft-landing attempts between 1966 and 2025, only 24 were fully successful, a success rate of approximately 50% [10–12, 14, 15], and the great majority of failures were concentrated in the powered-descent and landing-control phases; even successful landings frequently ended in "landing with damage," such as tilting or attitude anomalies [13, 15], which greatly reduced mission completion. These facts suggest that making surface landing the precondition for large-scale development is costly and fragile in engineering terms, and whether this collective path lock-in can withstand scrutiny from engineering economics has not been systematically questioned.

Numerous engineering experiences show that the lunar-surface environment is extremely harsh, for example:

1. **High gravity-well penalty:** transporting material from lunar orbit to the surface and back to lunar orbit requires a ΔV of at least 1.68–2.38 km/s for a one-way leg; **once gravity losses and guidance and control margins are considered, the actual powered-landing requirement may exceed this value,** which greatly compresses the payload fraction.

2. **Lunar dust (regolith/lunar dust) poses extremely high engineering risk:** it carries static charge and has sharp particle shapes, and causes irreversible damage to mechanical drives, seals, optical lenses, and the human respiratory system.
3. **Dynamic environmental threats:** moonquakes (shallow moonquakes) last long (up to several hours) and have a strong cumulative energy effect; with no atmospheric protection, direct exposure to micrometeoroids and solar and galactic cosmic radiation (SPE/GCR) is a major threat.

By contrast, spacecraft operations in planetary orbits have decades of mature experience; crew handover and cargo transfer by orbital rendezvous have reached technology readiness level (TRL) 8–9 (e.g., Apollo, ISS, Tiangong), and safety and reliability are orders of magnitude higher than for landing on the lunar surface. Verification already obtained shows that platforms such as the Lunar Reconnaissance Orbiter (LRO) and the Chandrayaan-2 orbiter have operated stably in low lunar orbit for long periods, and the orbit-maintenance requirement is far lower than intuition suggests (for example, at an altitude of 50 km, LRO needs only one station-keeping maneuver every 28 days to keep its orbit within the permitted range of 35–65 km and avoid impacting the lunar surface, and it has operated stably for more than 17 years). The central arguments of this paper are: (1) shifting the center of gravity of lunar development from the lunar surface to high or low lunar orbits is not only more feasible technically but also more reasonable economically; (2) for scenarios such as one-way delivery of materials, in-orbit manufacturing, and orbital observation, moving the front-end focus of lunar development to near-lunar orbit is technically feasible and potentially advantageous economically (see the break-even analysis in Section 3.7). The strategic logic of this shift can be summarized as "space first, surface later": establish a sustainable presence in lunar space first, and then extend progressively to the lunar surface using lunar space as the base. This view also rests on a thought-provoking question: even near-Earth spaceflight verification, including the round trip to Earth, required many years of repeated, expensive, and arduous practice; how much more

so for an unfamiliar world 380,000 km away? The paper also shows that the orbital environment in space is, in both the conditionality and the certainty of construction, much better than the lunar surface (suitably allocated relay bases in orbit can serve as assembly nodes for Earth–Moon transport and lunar-surface missions; whether to use LLO, DRO, NRHO, or another orbit should be determined by trade-offs among multiple objectives such as transportation, maintenance, illumination, and communications).

This paper proposes the theoretical framework of "Orbit-First, Sky-Ground Coupling." It is preferable to establish a large modular "circumlunar platform port" (also called the distributed "Lunar Stairway") in low lunar orbit (altitude 30–200 km) to serve as the center of human production, living, scientific research, and computing, relying on "multi-layer energy-absorption" technology for high-frequency one-way delivery of materials to the lunar surface, thereby avoiding large-scale, high-cost infrastructure construction on the lunar surface in the early stage. The reasons for this opposing proposition fall into five points. First, landing on the lunar surface requires energy for deceleration and departure requires energy for acceleration, so the energy cost per unit mass is far higher than that of orbital residence, and landing technology is difficult and prone to failure (it should be noted, however, that ballistic delivery does not eliminate kinetic-energy dissipation but transfers it to the energy-absorption task of fixed lunar-surface facilities; see 4.2.2). Second, a lunar-surface base must withstand moonquakes and meteorite strikes at all times, whereas orbiting spacecraft run smoothly and can be warned and can evade. Third, viewing angles for astronomical observation from the lunar surface are limited, whereas reconfigurable interferometric arrays of clusters in circumlunar orbit can carry out wide-field sky surveys and, together with Earth, lunar-surface, and deep-space platforms, form very long baselines. Fourth, the lunar surface suffers both cosmic radiation and lunar dust, whereas a metal-hulled orbital module with multi-layer protective liners can shield most radiation and is free from lunar dust. Fifth, establishing a relay

base in high lunar orbit is a natural “aerial harbor” for personnel movement and cargo transshipment. It will also be explained that high-orbit options such as the near-rectilinear halo orbit (NRHO) have advantages in insertion velocity increment and communication continuity[48], but their perilune altitude reaches several thousand kilometers, which cannot support the low-orbit ballistic delivery described in this paper; the high and low options therefore suit different scenarios (see 3.6).

On the basis of the above argument, this paper further presents the design of the “Lunar Stairway” system: a low-lunar-orbit platform port as the transfer and delivery hub; the chain “circumlunar platform – capsule projectile – cable-net/pit/sponge-lake splashdown” to achieve low-cost soft-landing delivery to the lunar surface; electromagnetic ejection for upward transport of materials from the lunar surface; and spent-hull remnants stored in lunar orbit to achieve Earth–Moon material cycling. All numerical calculations in the paper are given with methods and assumptions (see Appendices A and B), and external facts are accompanied by references. The paper seeks to transform “orbit first” from a concept into a calculable engineering system and to give preliminary quantitative models for delivery, energy management, and material cycling. The paper is positioned as a concept study: all conclusions are conditional on the assumptions in the text, and limitations are discussed collectively in Section 4; the break-even analysis (3.7) and the delivery guidance and deceleration analysis (4.2.2) are the key to evaluating the feasibility of this system.

Engineering costs of the lunar-surface residence paradigm

Energy cost of landing on and departing from the Moon

Although the Moon’s gravity well is far shallower than the Earth’s (escape velocity 2.38 km/s versus 11.2 km/s), the characteristic velocity required for “landing and departure” is still considerable. Taking the Apollo missions as the baseline: lunar orbit insertion (LOI) requires

approximately 0.91 km/s [44]; the descent of the lunar module from an approximately 110 km lunar orbit to the surface, including hover and terminal maneuvers, requires about 1.7–2.0 km/s over the whole sequence [43, 45]; and the ascent stage's return from the surface to lunar orbit requires about 1.85 km/s (measured on Apollo 11 as 6,055 ft/s ≈ 1,846 m/s) [43]. Thus a lunar-segment round trip of "going to the surface and coming back" costs an additional approximately 3.7–3.9 km/s—and this does not yet include the structural mass of the lander itself (such as the lander structure, thermal control, navigation, landing legs, and redundant systems). According to the rocket equation (Eq. 1), taking a specific impulse I_{sp} = 300 s (g_0 = 9.81 m/s²), a one-way landing ($\Delta V \approx$ 1.9 km/s) requires propellant of approximately 47.6% of the initial mass, and a landing–ascent round trip ($\Delta V \approx$ 3.7 km/s) requires as much as 71.6%. The total mass of the Apollo lunar module was 14,696 kg, of which propellant was 10,523 kg, exactly 71.6% [45]. The historical data agree in magnitude with the theoretical calculation (the actual I_{sp} and ΔV allocation of the lunar module are not exactly the same as the values taken here, so the agreement should be regarded as an order-of-magnitude verification). This means that for every 1 t of payload soft-landed on the lunar surface, a lander of approximately 2.9 t (payload 1.0 t + structure 0.5 t + propellant 1.36 t) must first be assembled in low lunar orbit (LLO) (Fig. 1). If crew round trips are considered, the energy cost of the lunar-surface paradigm is magnified manyfold.

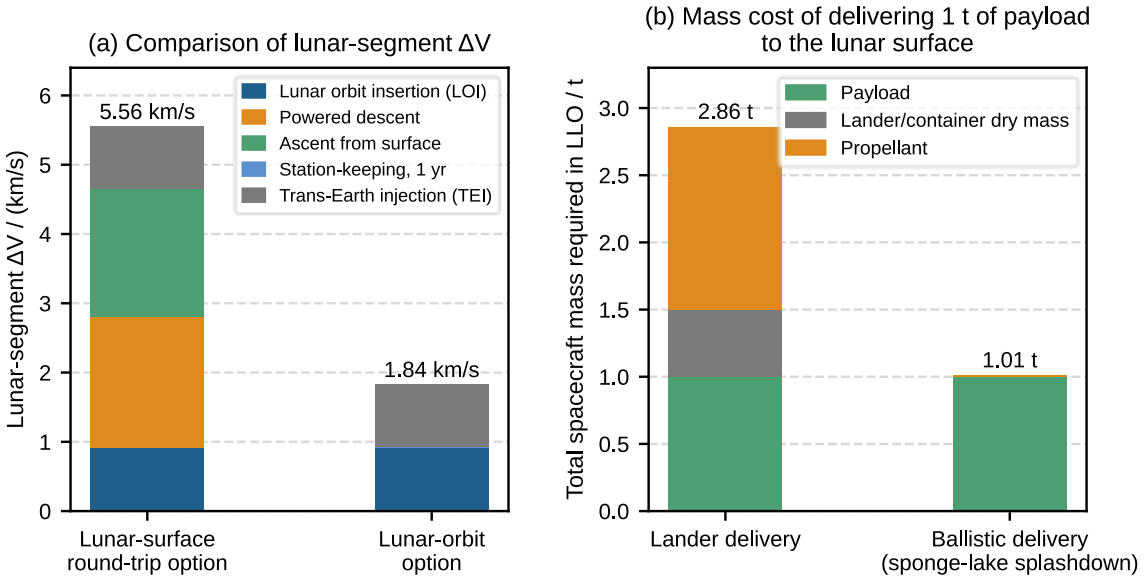


Fig. 1. Comparison of (a) the lunar-segment velocity increments of lunar-surface residence and circumlunar-orbit residence and (b) the mass cost of delivering 1 t of payload to the lunar surface.

According to the Tsiolkovsky equation:

$$\Delta V = I_{sp} \cdot g_0 \cdot \ln(m_0/m_1) \tag{1}$$

Assuming descent from low lunar orbit (h = 100 km, orbital speed v of approximately 1.63 km/s) to the lunar surface with a full landing, the theoretical minimum ΔV required is approximately 1.68 km/s; allowing for gravity losses, attitude control, and deceleration margins, the actual engineering consumption is approximately 2.1–2.4 km/s. To lift off from the surface and return to low lunar orbit, a further ΔV of approximately 1.8–1.9 km/s is needed. (The above 1.68 km/s is an ideal lower bound that excludes gravity losses; the Apollo measured descent phase, including hover and maneuvering, was about 1.7–2.0 km/s. Throughout the paper, the one-way landing range is uniformly expressed as 1.7–2.4 km/s, and the calculation examples take 1.9 km/s.)

By comparison, maintaining a circular or frozen orbit at an altitude of 100 km (e.g., at inclinations i = 27°, 50°, 76°, and 86°) is mainly a matter of countering the perturbation from the non-spherical gravitational-potential bias caused by lunar mass concentrations (mascons)

(higher-order harmonics such as J_2, C_{22}, and C_{20}). The energy required for a spacecraft to remain stably in lunar orbit is therefore very small (see 3.1): mascon perturbation and third-body effects are the main perturbation sources in low lunar orbit[1–4], whereas the Moon has no atmosphere, so there is no atmospheric-drag term and no fluctuation with the solar cycle.

Note: Station-keeping consumption for different propellants: (The following values are taken for frozen orbits with an annual station-keeping ΔV of 10–50 m/s and converted by the rocket equation; very low orbits and polar orbits require more—see 3.1.)

On an uncorrected low lunar orbit, mascons cause drift of the orbital eccentricity, so that the perilune gradually descends until the spacecraft strikes the lunar surface. With active control by electric propulsion (Hall-effect thruster, I_{sp} of approximately 1,500–3,000 s) or a small amount of cold-gas thrust, however, the calculation gives:

- **Cold-gas propulsion system** (I_{sp} = 70 s): annual mean propellant consumption of approximately 14–69 kg/t;
- **Chemical propulsion system** (I_{sp} = 300 s): annual mean propellant consumption of approximately 3.3–16.3 kg/t;
- **Hall electric propulsion system** (I_{sp} = 1, 600 s): annual mean propellant consumption of only approximately 0.6–3.2 kg/t;
- Conceivably, if an inter-platform cargo kinetic-energy exchange system is implemented, dependence on propellant can be partly eliminated when two-way logistics are balanced (explored quantitatively; see 3.3).

More specific orbit-maintenance costs are given in Section 3.1. In short, the cost of "making a trip down there" and that of "staying parked up there" differ by about two orders of magnitude; this is the energetic basis of the entire argument of this paper, and it gives important significance to the related "long-term, large-scale, continuous ballistic delivery of materials" (see 3.7).

Technical risk in the landing phase: historical statistics

Table 1 summarizes global lunar soft-landing attempts from 1966 to 2025. The Soviet Luna series suffered 11 consecutive soft-landing failures from 1963, until Luna 9 succeeded on the twelfth attempt; of the seven U.S. Surveyor landings, five succeeded; all six crewed Apollo landings succeeded, but Apollo 13 was abandoned before landing because of a service-module failure. In the 21st century, Chandrayaan-2 "Vikram" (2019), Beresheet (2019), Hakuto-R M1 (2023), Luna 25 (2023), Peregrine (2024, did not reach the lunar surface), IM-2 "Athena" (2025), and Hakuto-R M2 (2025) all failed, the failures being concentrated in the engine, ranging, and guidance links of the powered-descent phase [11, 12, 14, 15]; IM-1 "Odysseus" and SLIM, although they soft-landed successfully, tilted by about 30° and arrived on the Moon in an inverted, nose-down attitude, respectively, leaving spacecraft that could not move, and only a small fraction of mission objectives was achieved [13, 15]. In total there were 48 attempts, 24 fully successful, 3 partially successful, and 21 failures, a fully-successful rate of approximately 50% (Fig. 2).

Table 1. Statistics of lunar soft-landing missions (1966–2025)

Period	Principal missions	Attempts	Fully successful	Partially successful	Failures (main cause/phase)
1960s	Luna 9/13, etc. (13 attempts); U.S. Surveyor (7 attempts)	20	7	0	13 (mainly powered descent/lunar impact)
1970s	Luna 15–24 (8 attempts); Apollo 11–17 (6 attempts)	14	11	1	2 (Luna 15/18 crashed; Luna 23 tipped over)
2010s	Chang'e-3/4, Vikram, Beresheet	4	2	0	2 (loss of control during descent)
2020–2025	Chang'e-5/6, Chandrayaan-3, SLIM, Hakuto-R ×2, Luna 25, IM-1/2, Blue Ghost 1	10	4	2	4 (ranging/engine/guidance)
Total	—	48	24	3	21

Note: Because Peregrine did not reach the lunar surface, it is not counted as a "landing attempt"; partial success means that a soft landing was achieved but attitude or working capability was impaired. Data sources[10–15].

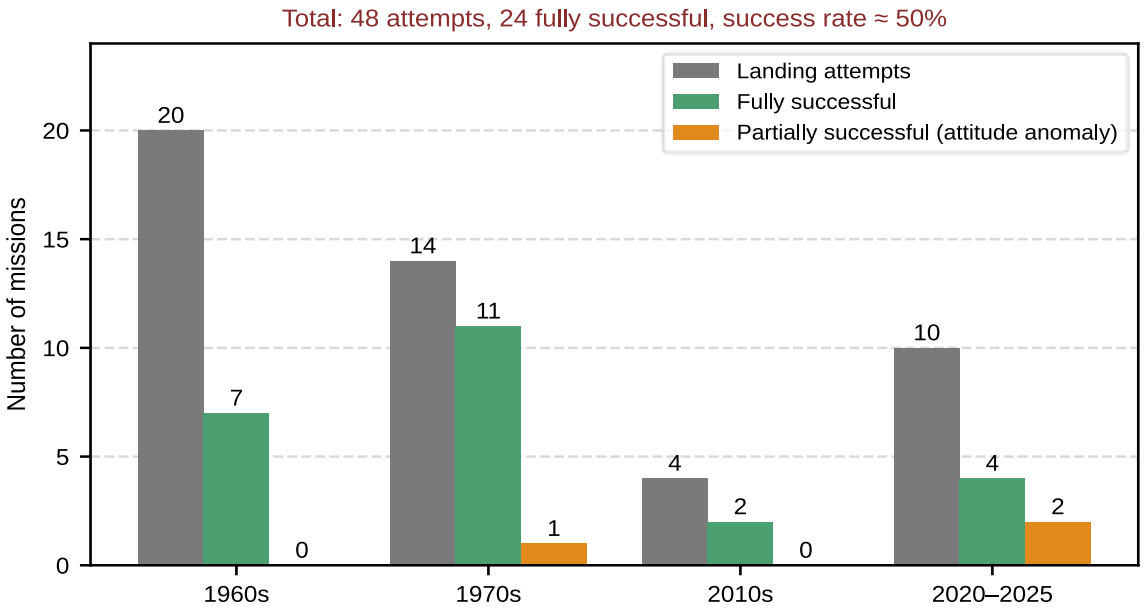


Fig. 2. Statistics of the success rate of lunar soft-landing missions (1966–2025). Data sources[10–15].

The above statistics reveal a fact obscured by the "moon-landing success narrative": soft landing is not a mature technique but a long, struggling curve of failures and successes, and it is not yet a mature process that can be replicated in large numbers at low cost; its reliability has improved with the accumulation of experience among operators but remains uneven. The difficulty lies in the fact that the lunar surface has no atmosphere and aerodynamic deceleration is impossible; the entire velocity increment must be expended by retro-engines in the last ten-odd minutes, depending throughout on precise closed-loop powered deceleration (powered descent initiation, PDI); a failure in any one link—terrain sensing, lidar hazard avoidance, ranging, hovering, or landing-leg cushioning—can be fatal, which places extremely high demands on real-time feedback and control. If lunar-surface development were carried out on a large scale, requiring daily landing frequencies on the order of hundreds, failure would, at current success rates, be the norm rather than the exception. The classic failure modes reveal a structural predicament: every link in a lunar landing—communications, sensing, guidance, propulsion—must coordinate precisely under "one-shot, irreversible" conditions, and an anomaly in any single link can cause the loss of the whole mission.

A common rebuttal is that, as technology advances, the reliability of lunar-surface landing will eventually improve, and the current failure rate does not represent future levels. In the long run this argument certainly holds—technology does advance—but time does not wait; during the long period of waiting for the technology to mature, a better scheme already exists that bypasses the above complex process altogether and turns fragmented landings into a permanent delivery-and-reception infrastructure, so why not implement it as early as possible? Moreover, lunar-orbit platforms, being close to the Moon, undoubtedly offer the convenience of conducting technical verification at any time, which will help shorten the maturation cycle of the above technologies drastically and thereby achieve safer crew-rated lunar landings. Even if the landing success rate rose to 100%, the energy penalty from low lunar orbit to the surface would remain: every kilogram of cargo would still have to pay a "landing tax" of approximately 1.7 km/s, and operation and maintenance of the spacecraft, wear and depreciation, logistics scheduling, and many other related provisions would still have to be established. In contrast, ballistic delivery from lunar orbit reduces the velocity increment of "delivering to the lunar surface" to approximately 23 m/s, and the transferred energy is even largely converted into changes in spacecraft momentum and energy storage in lunar craters (4.2.2); the evident advantage is that it fundamentally **bypasses** the energy penalty rather than optimizing the penalty internally. Ballistic delivery reduces the platform-side velocity increment to approximately 23 m/s and requires no landing propellant to be carried with the cargo; but it must be made clear that the cargo still carries approximately 1.45 GJ/t (approximately 401 kWh/t) of kinetic energy when it reaches the Moon. This energy has not disappeared but is taken up by fixed energy-dissipating/absorbing facilities on the lunar surface. The essence of ballistic delivery is therefore to exchange propellant mass that is "carried with the cargo and consumed on every trip" for permanent lunar-surface infrastructure that is "built once and used repeatedly"; its merit depends on the total delivered quantity (the break-even analysis in

Section 3.7) and on the mass and reliability of the absorption facilities (4.2.2).

Hazards of the lunar-surface environment

Even after a successful landing, the environmental risks facing a lunar-surface presence remain multidimensional and cannot be fully mitigated. In fact, humanity actually knows little about the Moon, and lunar-orbit platforms can help humans explore it more deeply. For living organisms, whether stationed on the lunar surface or in lunar space, robots and remote/autonomous operations should be given priority in the early development stage to reduce human exposure; crewed presence should be built on adequate radiation shielding, life support, and emergency-return capability (in any case, a small human presence is indispensable, so safety protection must be strengthened in the local areas where human activity takes place).

Moonquakes

Records from the Apollo seismic network (1969–1977) show that the Moon is not a "dead" body in the seismological sense[16–18]: only 28 shallow moonquakes were recorded in 8 years, but 7 of them had body-wave magnitudes above 5, and the energy of the largest event exceeded 6×10^{10} J, with focal depths of about 50–200 km; deep moonquakes number from several hundred to over a thousand per year, concentrated mostly at depths of 700–1,200 km, with body-wave magnitudes below 2–3; in addition, there are thousands of thermal moonquakes (caused by thermal expansion and contraction of the lunar surface). The lunar crust attenuates seismic waves very weakly, so a single moonquake can shake for tens of minutes to several hours, far longer than the tens of seconds of a terrestrial earthquake. For lunar-surface buildings and equipment, continuous excessive swaying under low gravity readily becomes a nearly saturated fatigue load. The local intensity of shallow moonquakes is sufficient to severely damage precision equipment and structures, which imposes requirements on structural design and materials research far more demanding than terrestrial standards; spacecraft in circumlunar

orbit, being fully decoupled from the lunar crust, are completely unaffected by moonquakes. Analysis: the 28 shallow moonquakes were distributed over the whole Moon and spanned 8 years, an average of approximately 3.5 per year; for a specific site, the probability of a strong quake is far lower than in the seismically active regions of Earth. The hazard of moonquakes to lunar-surface bases will manifest mainly as seismic design loads and long-term fatigue rather than as a high-frequency disaster, and should be managed through site selection, foundation isolation, and seismic monitoring; although moonquakes are not regarded as an insurmountable obstacle, in terms of the seismic standards of facilities they are a cost that every construction project must bear.

Meteoroid impacts

The Moon has no atmosphere, so meteoroids can strike the lunar surface without attenuation. It is estimated that the Moon receives about 1.4 t of meteoroid material per day[20]; a lunar-surface base would encounter approximately 1.5×10^4–2.3×10^4 micrometeoroid impacts per year of mass 10^{-6}–10 g[19, 21], and meteoroids larger than a ping-pong ball occur approximately 3.3×10^4 times per year; LRO observations show that a new impact crater about 50 m in diameter forms on the Moon each year [21]. The cumulative effects of tiny impacts not recorded by instruments are still difficult to estimate quantitatively and should be treated as a design margin. On April 7, 2026, during Artemis II's circumlunar mission, when the Orion spacecraft was about 46,000 miles from the Moon, the crew reported seeing five faint "pinpoint" flashes within a short time, all caused by rock fragments striking the lunar surface (Fig. 3).



Fig. 3. Hand-drawn sketch by the astronauts of the "flash" locations on the lunar surface; lunar meteoroid impacts are regarded as a high-frequency event. (Blue: annotations by Reid Wiseman; green: Victor Glover; red: Jeremy Hansen.)

For critical facilities on long-term duty (such as nuclear power stations), cumulative exposure is unavoidable. Permanent lunar-surface facilities must therefore adopt high-strength structures and protective-layer cover, which greatly increases construction cost; orbital platforms, by contrast, can rely on ground and space monitoring networks for early warning and, when necessary, evade by maneuvering with a small amount of propellant, turning meteoroid risk from something "endured" into something "managed." Going further, valuable facilities could even be protected (by performing self-sacrificial active intervention on certain meteoroids that must be intercepted), serving as a protective barrier for both the Moon and the Earth (for potential celestial threats, the earlier the intervention the more significant the effect).

Radiation

The Lunar Lander Neutron and Dosimetry (LND) instrument on the Chang'e-4 lander measured on the lunar surface an absorbed dose rate of about 13.2 μGy/h (in silicon), of which neutral particles (neutrons and gamma rays) account for about 23%, and a dose-equivalent rate of about 60 μSv/h, i.e., about 1.4 mSv/d, approximately twice the contemporaneous level on the International Space Station (about 0.7 mSv/d)[22]. The galactic cosmic ray (GCR) background fluctuates with the solar cycle between about 0.5 and 1.4 mSv/d; more dangerous are solar particle events (SPEs). For the extreme SPE of August 1972, between Apollo 16 and 17, had astronauts in spacesuits been exposed on the lunar surface at that time, the estimated dose could have reached the order of 3–4 Sv (higher at the body surface) [23]. Evidently, occupants of the lunar surface face an exceptionally harsh radiation environment, and long-term exposure markedly increases cancer risk. A spacecraft with about 20 g/cm² of equivalent aluminum shielding, in contrast, can reduce the dose of such an event by about 94% (from about 4,000 mSv to about 230 mSv) [50]; a circumlunar platform should use metal bulkheads supplemented by water/polyethylene liners for radiation shielding, exploiting the naturally present shielding of half a sphere and the refuge areas available during SPEs. The shielded fraction varies with orbital altitude; for example, taking the Moon's mean radius of 1,737.4 km, the geometric blockage of the 4π solid angle by the Moon is about 34% in a 100 km orbit, about 41% at 30 km, and about 28% at 200 km (Fig. 4). The arrival direction of SPE particles varies with time and the platform moves continuously around the Moon, so blockage by the lunar body can provide partial shielding over some orbital arcs. With personnel active inside storm shelters with complete protective measures, the overall protective effect can approach that of lunar lava tubes, which, although widely regarded as promising habitats, have not yet been clearly defined in actual number and volume.

Table 2. Comparison of dose rates in radiation environments

Scenario	Dose-equivalent rate/(mSv/d)	Remarks
Earth's surface (background)	≈0.0066	Natural background (including radon)
International Space Station (LEO ≈ 400 km)	≈0.7	Measured in low Earth orbit[22]
Deep-space transit (cruise)	≈1.8	Measured by MSL RAD during cruise[49]
Lunar surface (Chang'e-4 LND)	≈1.4	Absorbed dose 13.2 μGy/h; dose equivalent ≈ 60 μSv/h[22]
Inside lunar-orbit cabin (20 g/cm² equivalent shielding)	1.1–1.3 (estimated)	Estimated from MSL RAD measurements after deducting 28%–41% lunar-body blockage (Appendix B)
1972-type SPE (single event)	Unshielded 3–4 Sv; ≈0.23 Sv after 20 g/cm² shielding	[23]NASA 1988 estimate and shielding modeling

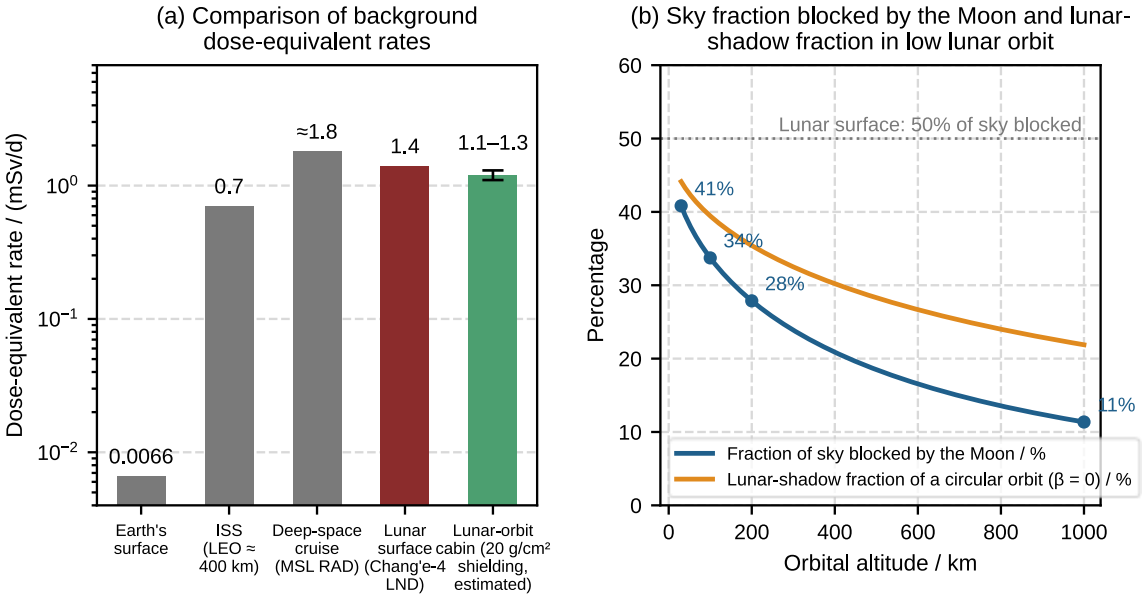


Fig. 4. (a) Comparison of background dose-equivalent rates; (b) fraction of the sky blocked by the Moon and lunar-shadow fraction in low lunar orbit (calculated in this paper; formulas in Appendix B).

Lunar dust

The threat of lunar dust is far more than the word "inconvenience" can convey. Research cited in NASA's lunar dust technical brief shows that when lunar dust coverage is only 3 mg/cm², the output power of photovoltaic cells drops by 50%. Lunar dust is angular and sharp and readily penetrates seals, connectors, bearings, optical lenses, and spacesuit joints, causing performance degradation and a sharp increase in maintenance needs. The failures of several commercial missions show that lunar dust kicked up by landing-engine plumes obscures laser

rangefinders and optical sensors and also interferes with radio communications. Post-event investigations confirmed a direct correlation among sensor contamination, dust-covered solar panels, damaged communication antennas, and lander toppling.

More serious are the health risks: NASA's human-system risk analysis points out that lunar dust exposure is associated with eye injury, lung injury, and skin irritation, and the potential consequences of long-term exposure include pneumoconiosis, hypersensitivity, and even cancer. The charged nature and submicron particle size of lunar dust make it difficult to remove completely by conventional filtration, while frequent filter replacement itself increases material consumption and crew time.

Lunar regolith and dust are the most "irremovable" threat of lunar-surface residence [24–26]: fine particles (<10 μm, respirable) account for a considerable proportion, and when charged they levitate electrostatically and adhere to all surfaces; inside the Apollo astronauts' return cabins, "lunar hay fever," eye and nose irritation, and respiratory symptoms appeared, and filters could not remove the fine dust, with allergic reactions worsening after repeated exposure[24, 25]. Lunar dust continuously attacks seals, bearings, optical devices, and the human respiratory tract. A circumlunar-orbit platform is entirely in a dust-free environment; the lunar dust problem disappears at the source and needs to be managed only in docking and extravehicular steps through airlocks and blow-off procedures.

Table 3. Lunar-surface environmental hazards versus circumlunar-orbit residence

Hazard dimension	Lunar-surface residence	Circumlunar-orbit residence
Moonquakes	Shallow moonquakes up to about magnitude 5, with shaking lasting tens of minutes to several hours, impose fatigue loads on structures[16–18]	Decoupled from the lunar crust; unaffected
Micrometeoroids/meteoroids	1.5×10^4–2.3×10^4 impacts per year; heavy protection required[20, 21]	Can be evaded after early warning; protection based mainly on granular-material skirt panels
Radiation	Background ≈ 1.4 mSv/d; SPE can reach the Sv level with no place to hide [22, 23]	Metal bulkheads plus water/polyethylene shielding; the Moon blocks only about 28%–41% of the sky; combined with storm shelters[23], a background of the same order as on the lunar surface is achieved
Regolith/lunar dust	Ubiquitous and irremovable; harmful to respiration and equipment[24–26]	Dust-free environment; only docking/extravehicular management required
Temperature cycling	Extreme day–night thermal cycling at the 300 K level; frequent thermal moonquakes	Steady illumination in orbit; simplified thermal-control design
Observing field of view	Lunar horizon limited; dust settling contaminates optical surfaces	All-sky survey, no dust, no thermal cycling; radio silence possible on far-side arcs[40, 41]
Logistics	Landing and departure require 3.7–3.9 km/s; high failure rate	Ballistic/electromagnetic delivery interface; platform-side propellant consumption markedly reduced; total cost depends on delivered quantity (3.7)

Psychological and physiological factors

The monotony of the lunar-surface environment, the isolation of enclosed space, ever-present lunar dust, the threat of meteoroids, and even the survival pressure of "being unable to leave at any time" all pose long-term challenges to the psychological and physiological health of crews. A lunar-orbit platform, by contrast, faces space and can see the home planet more often; distributed platforms circling the Moon provide facilities that can be visited and inhabited at any time, whose varied styles can relieve body and mind, and artificial gravity simulates the Earth experience. For crews in orbit, at least the possibility of rapid evacuation back to Earth by maneuvering is retained.

Resource and logistics bottlenecks of lunar-surface construction

Although in situ resource utilization (ISRU) on the lunar surface is highly anticipated, factories for oxygen production, smelting, and building materials themselves need complete sets of equipment shipped from Earth and long-term high-energy operation, so self-bootstrapping is difficult in the short term[26]. Although water ice has been confirmed to exist in the lunar polar

regions[28, 29], it is concentrated in permanently shadowed regions (PSRs), where low temperature, low illumination, and complex terrain make mining and residence extremely difficult; the so-called "regions of eternal light" are small in area, and competition for stations in limited space readily leads to disputes. Construction of a lunar-surface base takes a long time, movement of personnel is inconvenient, residents are trapped on the surface, and living facilities are rudimentary. All of these constitute the systemic bottlenecks of the lunar-surface paradigm.

By contrast, a circumlunar orbit spends long periods in space with abundant sunlight, and the night-side transit is brief (the lunar-shadow time of a near-circular orbit accounts for 22%–44%, corresponding to orbital altitudes of 1,000–30 km; a 100 km orbit is about 39%, about 46 min per revolution, with about 4,500 energy-storage battery cycles per year, and the orbit is not in lunar shadow throughout; choosing an orbit near the terminator with a high solar β angle can significantly shorten or even eliminate the lunar shadow). Compared with a lunar surface whose day and night are equally divided over 28 days, the orbital period around the Moon ensures a steady energy supply. As for the drawback of microgravity on orbital platforms, rotating artificial-gravity sections can be set up in some zones to house a small number of personnel, with water, air, and heat-circulation systems, and cultivation can be carried out, approaching the Earth environment as closely as possible. (Note: the 1/6 *g* of the lunar surface is likewise far below 1 *g*; a lunar-orbit platform can provide artificial gravity through rotating modules, with a clear upgrade path, whereas adding artificial-gravity facilities on the lunar surface is almost infeasible.)

Engineering advantages of circumlunar orbit

Orbit-maintenance cost: mascons, frozen orbits and propellant accounting

A circumlunar orbit is not entirely "free": the lunar mascons discovered in 1968 cause

significant perturbations in low orbit and can make a 100 km-class circular orbit decay and strike the lunar surface within several months if uncontrolled [1, 2]; the GRAIL mission advanced the spherical-harmonic model of the lunar gravity field to degree and order 900 (GRGM900C), so the perturbation sources can now be modeled and predicted accurately [3]. NASA's analysis of LRO showed that a 50 km circular polar orbit is not naturally stable and, if uncontrolled, could lead to lunar impact in about 41 days because of the Moon's non-spherical gravity; LRO was accordingly given a station-keeping Δv budget of 150 m/s per year. It should be explained that 150 m/s per year corresponds to the marginally stable 50 km circular polar orbit; the 10–50 m/s per year in Table 4 applies only to freezable inclinations (near approximately 27°, 50°, 76°, and 86°) and altitudes of 100–200 km. For polar orbits chosen to reach the polar regions, the maintenance cost lies between the two and must be calculated orbit by orbit. Synthesizing existing studies, extremely low orbits of the 30 km class, frozen orbits of 100–200 km, and high orbits of about 1,000 km may be taken as candidate ranges at different cost levels of maintenance. For example, among established countermeasures, a frozen orbit can suppress the long-term perturbation terms Synthesizing existing studies, extremely low orbits of the 30 km class, frozen orbits of 100–200 km, and high orbits of about 1,000 km may be taken as candidate ranges at different cost levels of maintenance. For example, among established countermeasures, a frozen orbit can suppress the long-term perturbation terms [4]: after insertion in 2009, LRO moved from December 2011 into a quasi-frozen elliptical near-polar orbit (approximately 30 km × 180 km), whose perilune is controlled and stable, and predictions show that it can be maintained beyond 2030 without large maneuvers [5];: after insertion in 2009, LRO moved from December 2011 into a quasi-frozen elliptical near-polar orbit (approximately 30 km × 180 km), whose perilune is controlled and stable, and predictions show that it can be maintained beyond 2030 without large maneuvers[5]; a Korean study of very-low-altitude maintenance gave an annual maintenance ΔV of approximately 35–65 m/s for orbits of the 15–

30 km class with ±5 km/±10 km deadbands[6]; and recent work further proposes zero-propellant maintenance of extremely low lunar orbits using solar sails[7]. In sum, the typical magnitudes of annual orbit-maintenance ΔV are: 35–65 m/s for 30 km-class extremely low orbits, 10–50 m/s for 100–200 km frozen orbits, and 1–10 m/s for approximately 1,000 km high orbits[6–8]. China's lunar relay communication satellite also adopts a frozen-orbit design to markedly reduce maintenance cost[37]. All of this shows that using specific dynamical orbit families to reduce maintenance cost is feasible.

Table 4. Circumlunar orbit parameters and annual maintenance cost (per unit mass; parameters in Appendix B)

Orbit	Period/h	Circular speed/(km/s)	Annual maintenance ΔV/(m/s, estimated)	Chemical propellant/(kg/(t·yr))	Electric-propulsion propellant/(kg/(t·yr))
LLO 30 km	1.85	1.666	35–65	12–22	2.2–4.2
LLO 100 km (frozen)	1.97	1.633	10–50 (typical 25)	3.4–16.8 (typical 8.5)	0.6–3.2 (typical 1.6)
LLO 200 km (frozen)	2.13	1.591	5–30 (typical 15)	1.7–10.2 (typical 5.1)	0.3–1.9 (typical 1.0)
Lunar high orbit ≈ 1,000 km	3.57	1.338	1–10 (typical 3)	0.3–3.4 (typical 1.0)	0.06–0.6 (typical 0.2)
Reference: ISS (LEO ≈ 400 km)	1.55	7.67	≈57	≈17.9	—
Reference: GEO	23.93	3.07	40–50	≈13.6–16.9	—

Note: Propellant is converted to first order from the ΔV ranges in the table by the rocket equation with I_{sp} = 300 s (chemical) and I_{sp} = 1,600 s (electric propulsion); the ISS annual reboost ΔV ≈ 57 m/s and propellant of about 7.5 t/yr (total mass about 420 t) are given only as an order-of-magnitude reference and are not used to prove that the costs of the two kinds of space infrastructure are equivalent [8].

Table 4 and Fig. 5 show that for medium and low circumlunar orbits operated as frozen orbits, the annual maintenance cost is comparable to or lower than the ISS reboost level; with electric propulsion (Hall or ion), propellant consumption can be reduced to the order of about 1 kg per tonne per year (1‰). An unloaded electric-propulsion platform could maintain its orbit almost "permanently" with solar-powered replenishment; if cargo ejection (see Section 4.3) is used as the propellant source, orbit maintenance and material delivery merge into one, and the cost is spread still further. In theory, the momentum change produced by part of the cargo ejection could be incorporated into platform orbit

control, reducing additional propellant needs; but the ejection mechanism, cargo losses, and energy cost must be counted in the system budget. By comparison, low-Earth-orbit satellites must continuously consume propellant to counter atmospheric drag (decay at 400 km altitude can reach the order of 2 km per month [8]), whereas circumlunar orbits carry no such burden: mascon and third-body perturbations can be actively managed through orbit design (frozen orbits, choice of altitude and inclination, etc.), whereas atmospheric drag leaves no room for avoidance and fluctuates with the solar cycle.

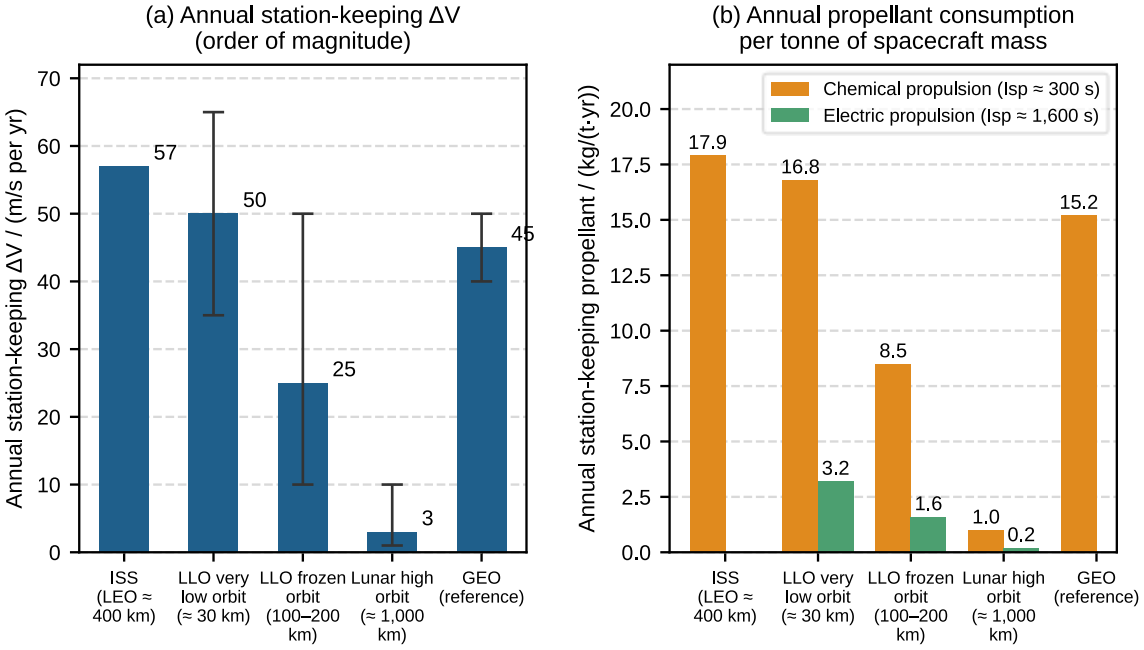


Fig. 5. Comparison of orbit-maintenance costs: (a) order of magnitude of the annual maintenance velocity increment; (b) annual propellant consumption per tonne of mass (calculated in this paper).

The feasibility of a near-lunar-orbit platform depends first on the energy cost of orbit maintenance. A common misconception is that maintaining a marginally stable low lunar orbit (LLO) is expensive because of perturbation by the Moon's non-spherical gravity field (mascons). For example, the Chang'e-2 mission did increase its orbit-maintenance propellant consumption because its orbit altitude was lowered from 200 km to 100 km. Quantitative analysis, however, shows that even the "expensive" LLO maintenance cost remains low in absolute terms.

An orbit-maintenance analysis for an LLO mission showed that, over a mission period of 365 days, 12 orbit-maintenance maneuvers were executed, consuming a total of about 6.658 kg of propellant (the working fluid was water). The propellant consumption of each maneuver was between 0.33 kg and 0.73 kg. For a typical orbiter platform, this means that annual maintenance propellant consumption is only of the order of a few kilograms. If an electric propulsion system were used, the specific impulse would be markedly higher and propellant consumption could be reduced further. This makes a meaningful comparison with the maintenance cost of low-Earth-orbit satellites. LEO satellites, under atmospheric drag, must continuously raise their orbits, and their annual propellant consumption is often on the order of tens of kilograms. In terms of propellant consumption per unit mass, maintenance of a near-lunar orbit is no more expensive than that of an Earth orbit—contrary to the intuitive impression that "lunar orbit maintenance is costly." (This comparison depends on the mass and altitude of the specific spacecraft; the annual propellant per tonne in Table 4 should be taken as the reference.)

Ejection kinematics and orbit departure

When the platform cruises to the designated delivery window, items wrapped in cushioning airbags, of mass M_{p}, are ejected backward (retrograde) or forward (prograde) at relative velocity V_{rel}. (Convention in this paper: "backward/retrograde" refers to ejection opposite to the platform's direction of flight; that is, to lower the cargo's orbit toward the lunar surface, it must be ejected backward.)

After ejection, the velocity vector of the item becomes:

$$V_{\mathrm{cargo}} = V_{\mathrm{platform}} + V_{\mathrm{rel}} \tag{2}$$

With retrograde ejection (V_{rel} opposite in direction to V_{platform}), the perilune R_{p} of the item's orbit falls below the lunar surface:

$$R_{\mathrm{p}} = a(1 - e) \leq R_{\mathrm{m}} \tag{3}$$

The item falls freely along an elliptical transfer orbit. Because the Moon has no atmosphere, the descent trajectory is determined entirely by the unperturbed Kepler orbit and the mascon gravity field, with no unpredictable crosswind disturbance, so the landing-point accuracy of delivery can be controlled to within the order of 100 m. After correction following repeated blind drops in orbit over a long period, a meter-level accurate model may be established. It should be noted that in the ideal two-body model the trajectory and altitude are predictable, but the actual landing-point dispersion is still affected by initial state errors, platform attitude/ejection errors, the Moon's higher-order gravity field, the target terrain, and the geometry of the lunar-surface reception area. Accuracy requirements must also be discussed by direction (estimated for a 100 km circular orbit with a half-revolution flight after ejection). Along-track, an ejection speed error of 1 m/s causes a deviation of about 11 km; cross-track, the first-order deviation at perilune caused by an out-of-plane velocity error at the ejection point is zero, and the deviation arises mainly from errors in determining the orbital plane and the Moon's rotation; and what decides success is the vertical direction: the sensitivity of perilune altitude to ejection speed is about 4.2 km/(m/s) (Appendix B, item 8), i.e., a 1% control accuracy of ejection speed (0.23 m/s) gives a perilune altitude deviation of about 1 km, far larger than the vertical tolerance of the cable-net reception zone, which is on the order of a few meters; to hold the deviation to about 10 m, the speed error must be reduced to about 2.4 mm/s. The engineering goal of "blind drop + post-hoc calibration" therefore may not fully meet the model requirements, and under existing technology the airbag cargo may still be provided with relative-navigation-based midcourse correction and terminal guidance during the half-revolution flight (about 1 h) after ejection (correction magnitude $\Delta V \approx 1$–5 m/s, about 0.3–1.7 kg/t of chemical propellant, $I_{sp} = 300$ s). This requirement shifts part of the lander's navigation complexity onto the airbag cargo, but large-thrust engines and landing legs are not needed.

From the standpoint of energy economics, lunar-surface landing and re-launch constitute the most costly link in the entire transport chain. Soft landing on the lunar surface from low lunar orbit requires eliminating an orbital speed of about 1.7 km/s and overcoming gravity losses during landing; lifting off from the surface to return to orbit requires regaining a velocity increment of about 1.7 km/s. This does not include the propellant reserve needed for precise control in the final landing stage. A concrete calculation example illustrates the magnitude of this penalty. Early NASA mission-analysis documents show that the braking segment from the Earth–Moon transfer orbit to lunar-surface landing needs a velocity increment of about 2,480 m/s and a propellant mass of about 52% of the initial mass. For a landing stage with an initial mass of 913 kg, this means that 479 kg of propellant is used only for the one-way landing.

If this cost is multiplied by the total quantity of material needed for lunar development, the conclusion is clear: with the lunar surface as the materials-delivery base, every kilogram of a spacecraft body must bear the "energy tax" of landing and relaunch; with near-lunar orbit as the delivery harbor, the spacecraft's receiving and transshipment of materials involves only orbital maneuvers, and the energy cost falls by orders of magnitude (for platform-side propellant only; the construction cost of the lunar-surface absorption facilities is counted separately, see 3.7). And if cargo adopts the "deceleration and delivery mechanism" of "circumlunar platform – capsule projectile – cable-net/pit/sponge-lake splashdown," one-way continuous delivery will greatly reduce energy expenditure (platform side); the cargo itself, serving at the same time as a momentum-exchange payload, can even become "propellant," and through careful calculation and regulation can step by step push a prograde- or retrograde-orbiting lunar-orbit platform to change its orbit gradually.

Platform momentum compensation and energy-level conversion

This section explores an inter-platform cargo kinetic-energy exchange system which, in the sense of ideal momentum exchange, markedly reduces propellant when two-way logistics are

balanced. Let cargo of ejected mass M_p produce a momentum recoil on a platform port of mass M_{plat}. The velocity increment ΔV_{plat} obtained by the platform is:

$$\Delta V_{plat} = -M_p \cdot V_{rel} / (M_{plat} - M_p) \quad (4)$$

- **Retrograde ejection of cargo:** the platform obtains a prograde ΔV_{plat} and its orbit is raised (orbit raising);
- **Prograde ejection of cargo:** the platform obtains a retrograde ΔV_{plat} and its orbit is lowered (orbit lowering).

The platform port can use the momentum difference between periodically receiving cargo ships from Earth (which bring impulse) and ejecting cargo to the lunar surface (which transfers part of the impulse) to regulate its orbit cyclically within a specific range of orbital altitudes, just like "electron energy-level transitions." It needs to be clarified that current cargo ships, after their own LOI braking, dock with the platform in the same orbit, so that the net impulse delivered to the platform is approximately zero and no "impulse is brought." In the modular configuration, since the platform mass will be far greater than the cargo-ship mass, under certain inertial conditions it can withstand a brief differential-speed berthing. What can truly offset the recoil of ejection toward the lunar surface is, additionally, cargo ascending from the lunar surface: cargo launched electromagnetically from the surface with a perilune speed of about 1.70 km/s rises along a transfer ellipse and has a speed of about 1.610 km/s at the 100 km apolune, 23 m/s slower than the platform; the platform's capture of this cargo at that point is equivalent to applying an impulse of equal magnitude and opposite direction to the recoil of ejection toward the lunar surface. Therefore: (1) when the descending and ascending masses are equal, the platform's net orbital change is zero, forming a momentum closed loop with the electromagnetic ejection of Section 4.7; (2) when early logistics are dominated by descent, the net recoil is $\Delta V_{plat} \approx 23$ m/s $\times M_p/(M_{plat} - M_p)$: taking $M_{plat} = 200$ t and $M_p = 1$ t, each tonne of descending cargo raises the platform's speed by about 0.12 m/s, and an annual delivery of

1,000 t accumulates to about 115 m/s, far more than the annual maintenance level of about 25 m/s, so it must be compensated by electric propulsion or equivalent means, with a required propellant of about $M_p \cdot 23/(I_{sp} \cdot g_0)$, approximately 1.2 kg/t at I_{sp} = 2,000 s, independent of platform mass. Therefore, in the early stage, ejection that neglects inclination does not "require almost no propellant" but requires "about 1–2 kg of electric-propulsion propellant per tonne of cargo," which tends to zero as the proportion of upward logistics rises. But we know that early lunar construction will necessarily be "extensive": materials entering the Moon will far exceed the "lunar-made" products sent out after refining and processing, and "imports" exceeding "exports" will necessarily persist for a considerable period. This paper deals precisely with the early to middle stage of lunar construction, for which, in terms of net gain, this propellant compensation is still "worth spending."

Methods for compensating the orbit raise: (1) using an inclined solar-sail face so that radiation pressure produces a retrograde component along the flight direction, thereby lowering the orbit, although the acceleration is small (estimated for a 1 t platform, a 1,000 m² sail, and ideal efficiency at about 10^{-5} m/s², at most 0.9 m/s per day); (2) continuously capturing slower cargo approaching the platform from electromagnetic launch on the lunar surface, thereby steadily lowering the orbit, although this requires high scheduling capability and is feasible only locally in the early stage; (3) converting this increment into receiving low-momentum items from Earth at the high-lunar end of the orbit by technical means, or delivering high-momentum items needed by Earth (unloading, cargo transfer), to achieve orbit lowering.

Environmental safety and mobility

The safety of orbital residence stems from the word "mobile": there is no moonquake coupling; meteoroids can be warned of and evaded; during SPEs the lunar-body blockage window and storm shelters can be used (during SPEs the storm shelter should be primary and lunar-body

blockage secondary), and the platform can also change orbit as a whole to adjust the residence time within the shielded zone. Lunar-surface facilities are fixed targets, whereas orbital facilities are maneuvering subjects. This corresponds one-to-one with the mitigation of the lunar-surface hazard inventory in Section 2.3.

Astronomical observation and sky-survey advantages

Lunar-surface telescopes are limited by lunar-horizon obstruction (half of the celestial sphere, and an even narrower field of view inside craters), lunar dust deposition, day–night temperature swings at the 300 K level, and structural thermal deformation; circumlunar orbital observatories can survey the entire celestial sphere, free of dust and extreme thermal cycling (the day–night alternation being short), and the Moon itself can serve as a natural shield against terrestrial radio-frequency interference (RFI)—the circumlunar orbit/far-side sky is widely regarded as one of the best windows for low-frequency radio astronomy [40, 41]. A distinction must be drawn: far-side ground stations receive lunar-body shielding at all times, whereas an array in circumlunar orbit is shielded only on the arcs that run behind the far side (depending on the orbital-plane orientation; at 100 km altitude the upper bound is about 39% of the orbital time), but lunar-surface stations can provide a stable large foundation and fixed long-baseline geometry. Far-side stations (such as LCRT [41]) and orbital arrays can be complementary, and building a clustered lunar-orbit interferometric array that relays data back after observing on the far side can realize a near-all-time low-frequency radio sky survey [40]. For some specific scientific objectives, the stable attitude and wide-field scanning capability of a high-lunar-orbit platform for optical surveys are also markedly better than those of fixed lunar-surface stations (lunar glass and starshade schemes have also been studied [46]).

Transfer hub and logistics efficiency

Circumlunar orbit is the geometric hub of Earth–Moon logistics (in contrast to space-elevator

alternatives[30–32]): a cargo ship departing from Earth need only complete the Earth–Moon transfer (TLI ≈ 3.1 km/s) and lunar orbit insertion (LOI ≈ 0.9 km/s) to reach the platform port, without paying 3.7–3.9 km/s for "going down and coming up again"; personnel and materials can be "smoothly transferred between modules" at the platform port (for one-time cargo, the platform avoids the need to provide a complete lunar-surface return stage for that batch; for reusable systems that must return from the lunar surface to orbit, the corresponding ascent ΔV must still be paid). As needed, the platform port can also be deployed in more distant "pseudo-synchronous regions" and frozen orbits, using berthing at the eccentric end to reduce ignition consumption (Appendix B). Thus the circumlunar-orbit transfer design gives lunar development a low-cost, high-throughput, low-risk logistics backbone, opening a continuous channel for two-way exchange of materials between Earth and Moon.

Comparison with the NRHO scheme: the NRHO (perilune altitude of about several thousand kilometers) has a lower insertion velocity increment and continuous Earth communication, and is suitable as a relay and communication node for Earth–Moon traffic[48]; but it is too far from the lunar surface to support the low-orbit ballistic delivery and electromagnetic upward transport of this paper (both require platform altitudes of tens to hundreds of kilometers). The NRHO and low-lunar-orbit platform ports are therefore not competitors: the former is oriented to transfer, the latter to logistics coupling with the lunar surface, and they should be planned together at the system level.

Table 5. Comprehensive comparison of the lunar-surface paradigm and the circumlunar-orbit paradigm

Dimension (preliminary system comparison)	Lunar-surface paradigm	Circumlunar-orbit paradigm (Lunar Stairway)
Energy cost	Landing 1.9 + departure 1.85 km/s (71.6% propellant for the round trip)	LOI 0.91 km/s + annual maintenance 1–50 m/s
Technical risk	Soft-landing success rate ≈ 50%, with failures concentrated in powered descent	Rendezvous and docking technology mature; no landing phase
Safety	Four hazards: moonquakes, meteoroids, radiation, lunar dust	Moonquakes and meteoroids can be evaded or mitigated; radiation of the same order as on the lunar surface, requiring own shielding; no lunar dust in lunar orbit
Observation	Half of the celestial sphere, dust contamination, thermal cycling	Full celestial sphere, dust-free, stable attitude; radio silence only on far-side arcs, but complementary to ground stations
Logistics	First-order lander mass estimate for 1 t of payload about 2.86 t; structure, thermal control, and redundancy must be added in practice	Ballistic delivery requires only 1.01 t per tonne ($\Delta V \approx$ 23 m/s) (some limitations and solutions in 3.7)
Expandability	Facilities fixed to the lunar surface; expansion constrained by transport and terrain	Modular cluster platforms; maneuverable, formation-capable, recoverable, distributed
Habitability	Requires dust isolation, radiation shielding, and thermal control; surface gravity about 1/6 *g*	Radiation-shielded floating islands, garden communities, optional artificial gravity, free from lunar dust, expandable into urban clusters

Table 5 gives a direct comparison of the two paradigms along the same set of dimensions. It must be emphasized that the two are not mutually exclusive: the orbital platform is the "front-end infrastructure" that ultimately enables lunar-surface operations, and lunar-surface outposts take the platform as their support. The former, as the main body, extends the range of human space activity around the Moon, and its cluster scale and frequency can be configured on demand.

Mass accounting and break-even analysis

This section performs a break-even analysis with "LLO-equivalent mass" as the unified metric (illustrative parameters, not engineering conclusions):

(1) Direct delivery by lander: each tonne of payload requires c_L = 2.86 t to be assembled in LLO (see 2.1).

(2) Ballistic delivery: each tonne of cargo requires 1.0 t of cargo plus container/cushioning packaging in LLO, with the packaging mass taken as 0.2 t (author's assumption), i.e., c_B = 1.2 t.

(3) Fixed investment: the platform-port mass M_{plat} is taken as 100/200/400 t (author's assumption, referring to the order of magnitude of the ISS, about 420 t); the lunar-surface deceleration-facility mass M_{inf} is taken as 50/100/200 t, which must be delivered by landers, each tonne being equivalent to c_L times its mass in LLO.

(4) Break-even cumulative delivered quantity $N^* = (M_{plat} + c_L \cdot M_{inf})/(c_L - c_B)$; that is, a positive gain is obtainable for long-term, large-scale, continuous ballistic delivery of materials.

Table 6. Break-even cumulative delivered quantity N^*/t of ballistic delivery relative to direct lander delivery (c_L = 2.86, c_B = 1.2)

M_{plat}/t	M_{inf} = 50 t	M_{inf} = 100 t	M_{inf} = 200 t
100	146	233	405
200	207	293	465
400	327	413	586

With representative values (M_{plat} = 200 t, M_{inf} = 100 t), $N^* \approx 293$ t (Fig. 6); if the lander is reusable so that c_L falls to 2.0 t, $N^* \approx 500$ t. This means that at the annual throughput of about 1,000 t envisaged in Section 6, about 4 months of delivery would recover the mass cost of the fixed investment; but for small-scale missions of only tens of tonnes, ballistic delivery is not cost-effective. The limitations of the above analysis are that it does not include operating costs, replacement of absorption consumables, failure probability, or platform lifetime, nor the conversion from the Earth LEO starting point (TLI + LOI ≈ 4.0 km/s; with I_{sp} = 450 s, about 2.5 t in LEO is required per tonne placed in LLO, and with I_{sp} = 360 s about 3.1 t).

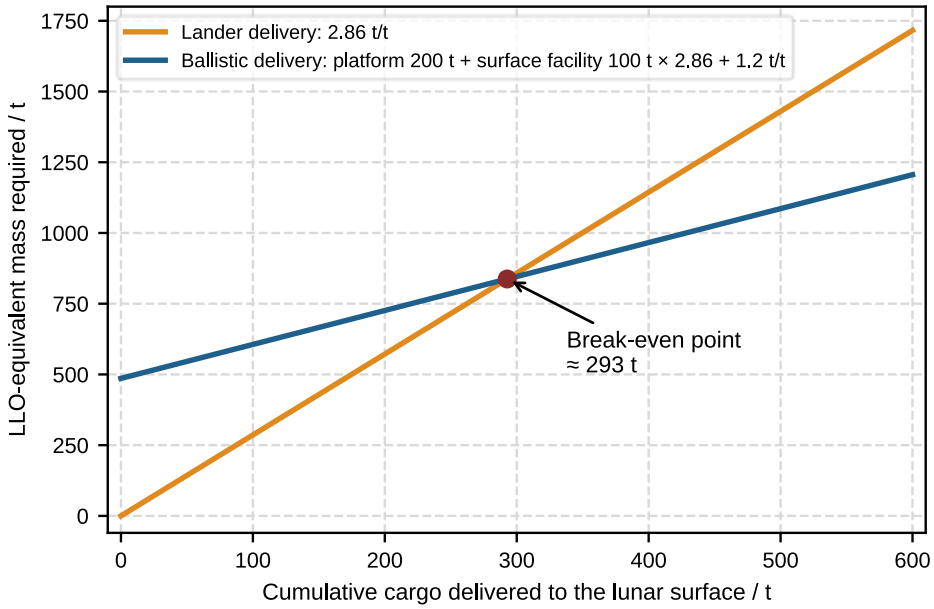


Fig. 6. Break-even of ballistic delivery relative to direct lander delivery (illustrative parameters: M_{plat} = 200 t, M_{inf} = 100 t, c_L = 2.86, c_B = 1.2).

Conclusion: if the supporting lunar-surface infrastructure costs of a reusable lander are not counted, and the construction of a lunar-orbit platform is treated as long-term, deterministically operated infrastructure, the cost of sinking materials to the Moon can be greatly reduced; for small-batch, low-frequency one-way delivery of materials to the Moon, on the other hand, when the landing risk is assumed to be zero, the traditional landing approach is still recommended.

System design of the “Lunar Stairway”

Overall architecture: platform ports, tender vessels and designated delivery sites

The “Lunar Stairway” is composed of three types of nodes: ① **Platform ports**—large resident platforms operating in 30–200 km frozen orbits, serving concurrently as delivery, relay, energy, and crew-habitation units; ② **Tender vessels**—shuttle spacecraft that travel between platforms and between Earth and the Moon, berthing frictionlessly in the same direction as a platform port and maintaining consistent inertia. They can temporarily dock modules for

cooperative transfer and then detach, help switch between high and low lunar orbits, and may even be transferred onto Earth–Moon transfer orbits; ③ **Designated delivery sites**—fixed craters selected on the lunar surface, with deceleration mechanisms and "sponge lake" buffer bodies arranged at the bottom and within the crater, pit air-membrane bladders installed along the ridge around the crater rim, and a large receiving-type cable net designed for high tensile resistance is installed above, achieving multi-level reduction of momentum and used to receive ballistically delivered cargo. The three together constitute the closed loop of "circumlunar platform – capsule projectile – cable-net/pit/sponge-lake splashdown" (Fig. 7A/B).

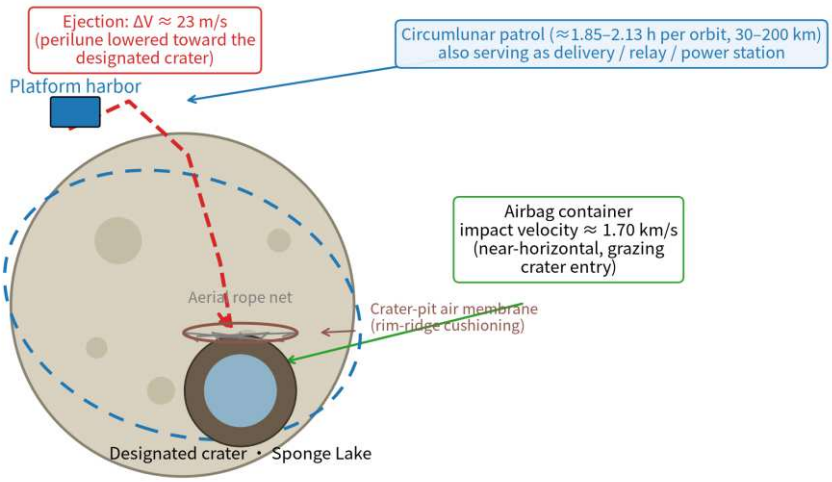


Fig. 7A. Conceptual schematic of the "circumlunar platform – capsule projectile – cable-net/pit/sponge-lake splashdown" delivery system.

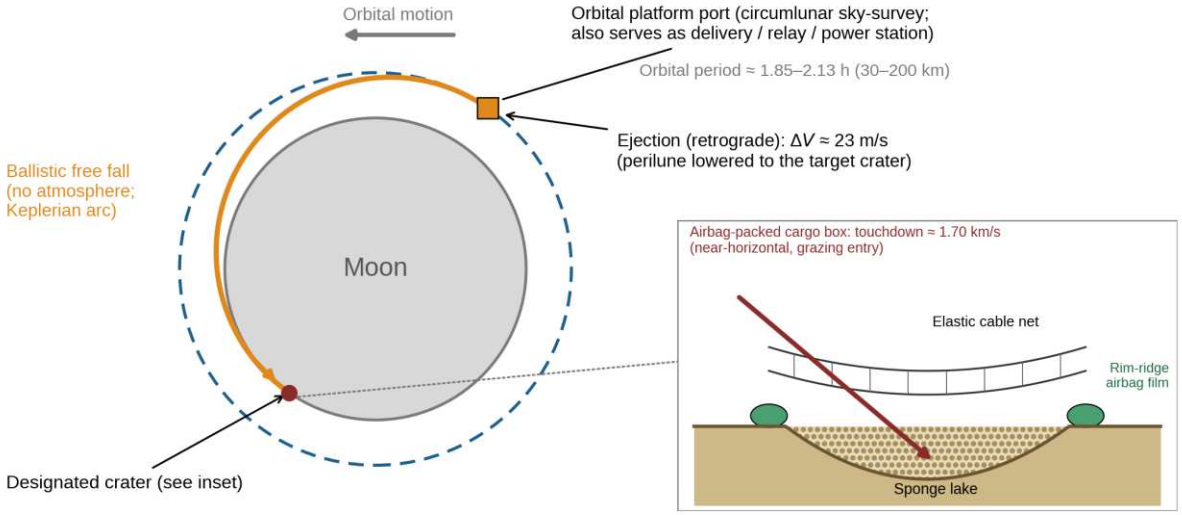


Fig. 7B. The grazing delivery trajectory enables the maximum buffering length along the inclined path of the lunar crater at the incidence angle into the sponge-lake.

Delivery scheme: "circumlunar platform – capsule projectile – cable-net/pit/sponge-lake splashdown"

Orbital effects of cargo ejection

The platform port uses cargo ejection as one of its orbit-maintenance means and thereby performs two functions: material delivery and momentum management. Taking the platform's instantaneous velocity direction as the reference, retrograde ejection gives the platform a prograde recoil, tending to raise the orbital energy; prograde ejection gives the platform a retrograde recoil, tending to lower the orbital energy. The actual change in the orbital semi-major axis also depends on the ejection point, the ejection angle, and the Moon's non-spherical gravity field. When the directions are opposite, the orbit evolves differently; see Section 4.3. By alternating prograde and retrograde ejection, the platform port can, in the ideal case, achieve partial orbit regulation without consuming additional dedicated propellant, but practical factors such as the energy consumption of the ejection mechanism, cargo mass loss, and platform structural loads must be counted. The platform's orbital balance can rely on two means:

capturing cargo ascending from the lunar surface (see 3.3 and 4.7) and electric-propulsion compensation; the direction of orbital evolution is given in 4.3. Ejection time and angle parameters can compensate only time/phase deviations; vertical deviations must be eliminated by midcourse correction and terminal guidance (see 4.2.2). This paper discusses only flight attitudes that neglect inclination, and actual operations should also start from low-mass objects and advance step by step to the tonne level. An intelligent scheduling system can be established to analyze the kinetic-energy status of each spacecraft and allocate them carefully, ensuring that the process of "item descent – platform orbit change" proceeds smoothly and in order.

Ballistic model and deceleration design

With 30–100 km at the extreme near-lunar end as the suitable delivery distance, the model sets the platform on a 100 km circular orbit (speed 1.633 km/s) and ejects a 1 t item at a retrograde velocity increment of about 23 m/s, lowering its perilune to the target crater; thereafter the item falls freely under lunar gravity alone (the lunar surface is an ultra-high vacuum with no aerodynamic drag). From the vis-viva equation, the touchdown speed is about 1.70 km/s [9], and this velocity is dominated by its horizontal component (grazing entry into the crater, with vertical component ≈ 0). The total impact kinetic energy of the 1 t item is about 1.45 GJ, equivalent to about 346 kg of TNT (Fig. 8); its kinetic energy is attenuated by a multi-stage layered absorption system, with an independent multi-stage energy-absorption system completing the final deceleration to achieve soft landing of the splashed-down cargo; before physical test data are obtained, this paper refers to it as "controlled ballistic delivery" rather than a verified soft landing. The lunar surface is an ultra-high vacuum, so there is no aerodynamic interference as the projectile falls and the parameters are extremely simple; the establishment of the splashdown model depends mainly on local variations of the lunar gravity field. Although its dynamic environment has none of the major uncertainties of terrestrial atmospheric winds and aerodynamic drag, the Moon's higher-order gravity field, the terrain,

and initial errors still produce landing-point dispersion; Monte Carlo error propagation and measured calibration are therefore needed, and an accurate "splashdown model [3]" can be established from a gravity-field model (such as GRGM900C [3]) and a small number of calibration shots. To exclude the time variation of the mascons (tides) and pointing errors, multiple rounds of blind-drop calibration are still required to improve operational accuracy.

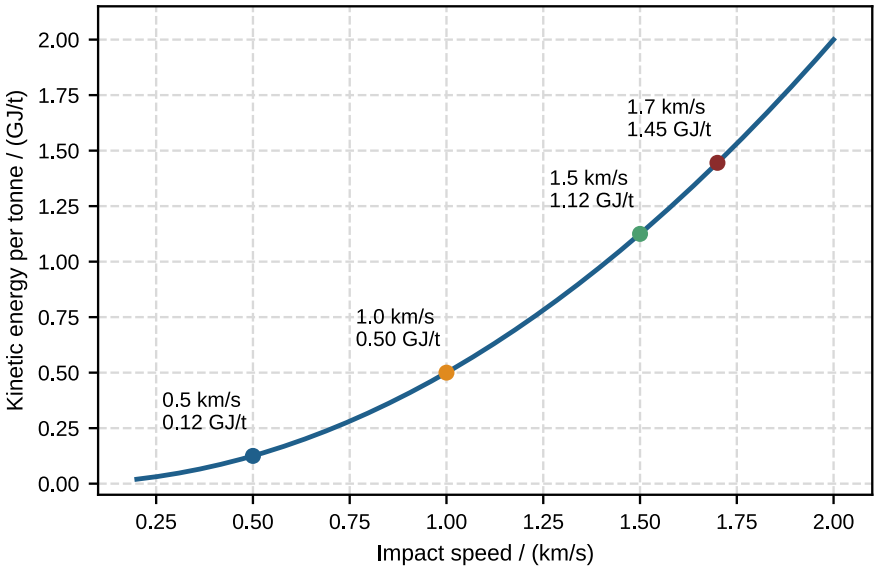


Fig. 8. Impact energy of an object in the near-vacuum environment of the lunar surface.

On the premise of accurate delivery, Table 7 gives the mean deceleration overload for different energy-absorption scales. It is assumed that the item is a solid sphere (to reduce flight-attitude disturbance) within the tolerable range of a reinforced container (airbag and foam shock-absorbing liner); the vertical component of the kinetic energy is cushioned by the aerial cable net, the pit airbags, and the sponge layer filling the crater (Fig. 9).

Table 7. Energy-absorption scale versus mean deceleration overload (touchdown speed 1.70 km/s, vacuum grazing entry, approximately constant deceleration)

Length scale L/km	0.2	0.5	1	2	5
Mean deceleration overload/g (ideal constant-deceleration model)	≈739	≈295	≈148	≈74	≈30
Impact kinetic energy of a 1 t item/(kg TNT equivalent)	346	346	346	346	346

Note: The overload is calculated as $a = v^2/(2L)/g_0$; in actual design the overload peak is governed by the airbag crush characteristics, and this paper uses a mean-value approximation.

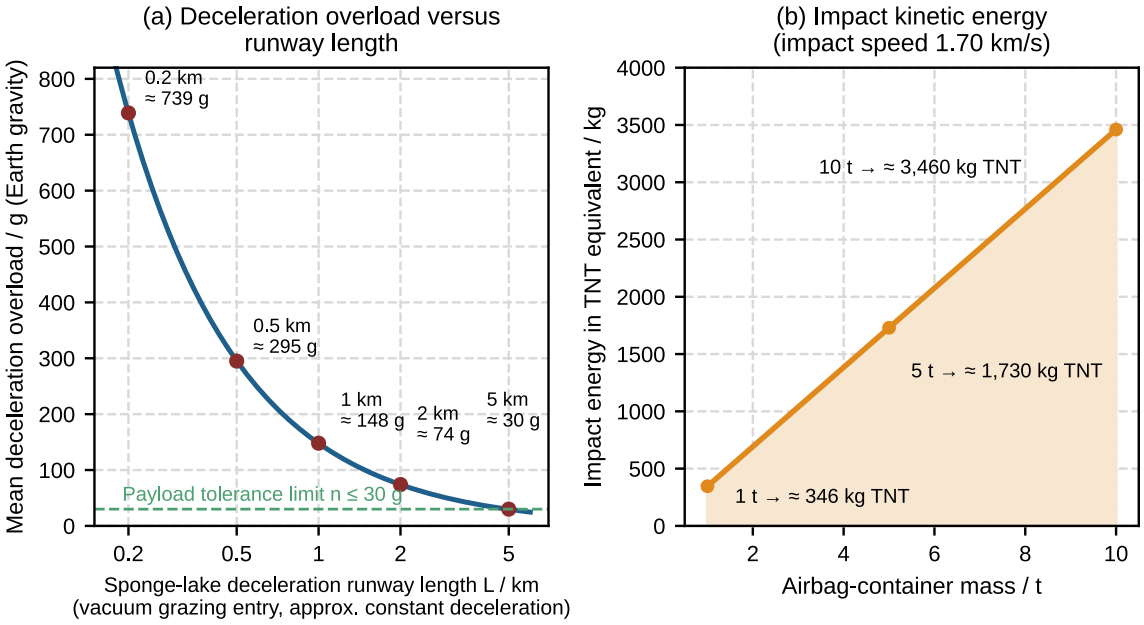


Fig. 9. Splashdown deceleration model: (a) deceleration overload versus energy-absorption scale; (b) impact kinetic energy of items of different mass.

The above model data show that, neglecting the projected area of the object, a 1 t cargo in free fall from an altitude of 100 km, even if it is allowed to endure a mean deceleration of only about 30 *g* at minimum, requires an energy-absorption scale of the kilometer class, which indicates that direct reception at the 1.70 km/s level is extremely difficult in engineering terms and cannot be solved with a single layer of sponge or airbags; subsequent design must therefore turn to graded, dynamic, replaceable energy-absorbing structures, verified step by step through ground high-speed impact tests and suborbital tests at the Moon.

To avoid the interference of multiple factors—overall center of gravity, shape, delivery angle, and initial velocity—to which ballistic delivery of large-mass objects from orbit is subject, a mild model is established: the projection distance in lunar orbit is shortened to 50 km; change from horizontal grazing incidence to vertical loading; the energy-absorption levels of the cable net, pit airbags, and crater sponge are simplified into sponges of different materials; the item remains a solid sphere, with its mass reduced to 1 kg, but with different packaging projections.

The engineering formula for free fall into a small crater [51] is used for the calculation:

$$L = E / (\sigma_p \cdot A \cdot \varepsilon_D) \quad (5)$$

- Two parameters of the crater sponge: the crush stress σ_p of the sponge and the contact area A between the object and the sponge; E is the kinetic energy of the object, and ε_D is the compaction strain of the sponge (the compressible fraction).
- This 1 kg object falls freely from 50 km of lunar space: touchdown speed $v \approx 397$ m/s (energy method with lunar curvature correction, $v = \sqrt{[2\mu(1/R - 1/(R + h))]}$; the approximation neglecting curvature is 403 m/s, a difference of 1.5%).
- Kinetic energy $E = \frac{1}{2}mv^2 \approx 79$ kJ, equivalent to about 19 g of TNT—only 5.5% of the single-item mass of the original "100 km orbit ballistic delivery" 1 t scheme (touchdown at 1.70 km/s, about 346 kg of TNT).

Table 8. Comparison of a 1 kg solid sphere launched from 50 km lunar-orbit altitude with different projected areas and different sponge materials (required pit depth *L*)

Sponge grade (crush stress σ_p/compaction strain ε_D)	A = 0.01 m² (small sphere, ≈11 cm dia.)	A = 0.1 m² (≈35 cm square)	A = 1 m² (parasol/pallet shape)
Ordinary packaging sponge (30 kPa/0.9)	≈292 m	≈29 m	≈2.9 m
Dense memory sponge (150 kPa/0.75)	≈70 m	≈7 m	≈0.70 m
High-density EPP (600 kPa/0.7)	≈19 m	≈1.9 m	≈0.19 m
Metal foams such as aluminum foam (3 MPa/0.5)	≈5.3 m	≈0.53 m	≈0.05 m

Key points of the results:

What determines the pit depth is the "cylindrical part formed by the object compacting the sponge"; that is, only the object's projected area A takes part in energy absorption. In the one-dimensional crushing model adopted in this paper, the result is governed mainly by the energy, the effective contact area A, the crush stress σ_p, and the available compaction strain ε_D; but the energy absorption of a real structure also depends on the dynamic strain rate, material failure, structural instability, rebound, and interlayer coupling, so this relation is

used only for first-order scale estimation. For example, with the same “dense memory sponge” (0.15 MPa), a small-sphere item requires a depth of 70 m, whereas an item made into a 1 m² parasol needs only 0.7 m, a difference of 100 times (Fig. 10).

Working backward, to bring the pit depth within the 10 m range: using the 0.15 MPa memory sponge requires an effective contact area of the object ≈ 0.07 m² (equivalent diameter ≈ 42 cm), that is, giving the cargo an “airbag wrap/deceleration pallet,” which in the ideal static crushing model can reduce the equivalent crush depth to within 10 m; this result does not represent the structural dimensions under real impact conditions, which still require dynamic material data and impact-test verification.

To ensure the object remains intact (that is, to limit the overload to $n \leq 30\ g$), the deceleration distance must be at least $v^2/(2ng_0) \approx 268$ m—a stricter constraint than merely “stopping,” corresponding exactly to the graded energy-dissipation approach in practice, in which the “sponge lake” must be provided with long depth/multi-stage cushioning (airbag crush + sponge + pit air-membrane bladders); engineering design should avoid relying on uncontrollable, highly resilient “bouncing”; a more reasonable route is to use multi-stage, dissipative, predictable energy-release units, with peak overload, peak force, structural deformation, and cargo integrity all taken as constraints.

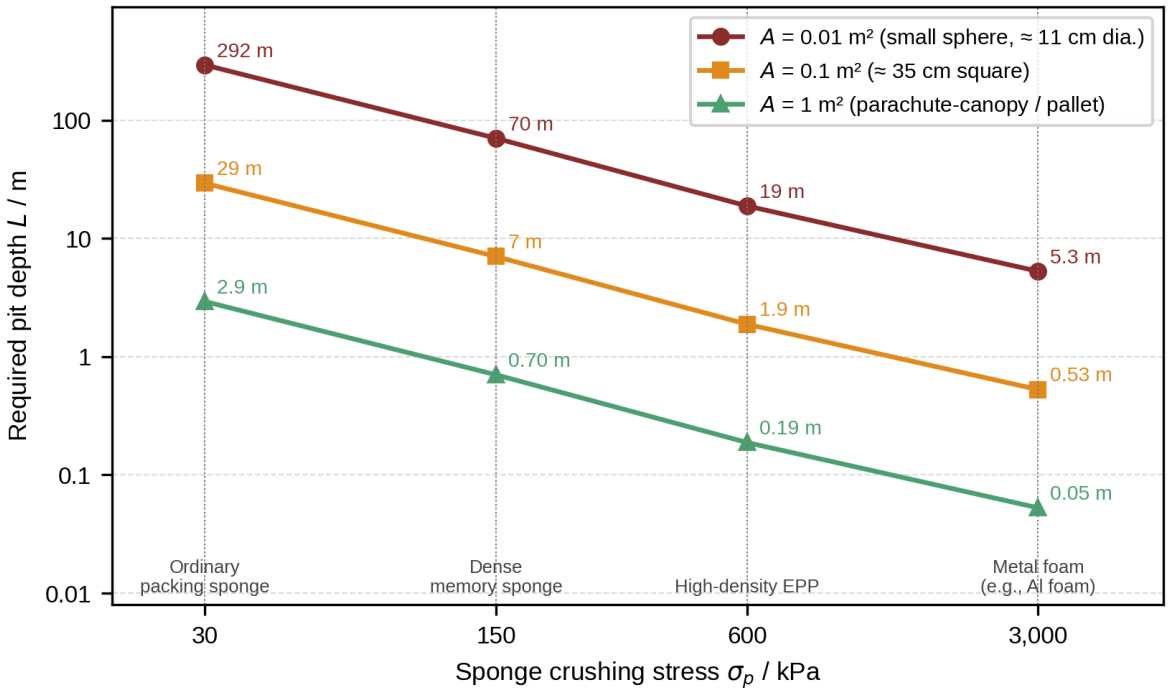


Fig. 10. Variation of pit depth with sponge stiffness and contact area (logarithmic coordinates); the idealized pit depth can be looked up according to the projected area of the actual item.

Conclusion: with conventional dense sponge (0.15 MPa class) receiving a 1 kg small item, a pit about 70 m deep is required. Merely packaging the item as an airbag "pallet" with a large contact area of 0.1–1 m² can reduce the pit depth to the meter scale (0.7–7 m). Under the idealized crushing model of this paper, increasing the effective loaded area can indeed markedly reduce the equivalent crush depth; but 0.7–7 m is only a static energy-balance result. Engineering design should further adopt a graded system of "airbag/flexible-structure pre-deceleration + high-efficiency energy-dissipating material + structural limit + final capture," with peak overload and cargo integrity as acceptance criteria.

To dissipate the E = 79 kJ of kinetic energy, craters of a certain depth are the necessary foundation, supplemented by measures such as shortening the lunar-orbit altitude, enlarging the lunar-surface contact area of the enveloping airbag, using large-area cable nets, and using high-density sponge bodies. Various additional aids may also be applied, for example: terminal retro-thrust devices carried by the item; electromagnetic/hydraulic

dampers installed on the crater wall, which can also generate and store electricity; collapsible, energy-absorbing blocks of water ice, with lattice-pattern holes, taken from permanently shadowed regions of lunar craters; airbag-type projectiles that can be aimed precisely at the item to strike it repeatedly; a “buffer zone” formed by compressed gas; and precise guidance of the “down-falling” item into the long electromagnetic track used for “upward delivery,” cleverly making use of existing facilities by operating the launch track in reverse as a buffer. Multiple means working together are thus used to dissipate the kinetic energy carried by tonne-class cargo ejected from a high lunar orbit.

Discussion: for the 1.70 km/s, 1 t-class target, results cannot be extrapolated directly from sponge-body tests. A high-speed impact numerical model must truly be established, and its parameters verified layer by layer with graded scaled tests. All the results can serve only as a lower bound on the geometric scale, and a real system must also consider peak overload and interlayer dynamic response. Therefore, before test data are obtained, this paper defines the “sponge lake” as a conceptual receiving system, not a landing facility already proven for tonne-class cargo.

It is not hard to imagine that, with the help of guided retro-propulsion, a living body wrapped in multi-stage airbags could someday descend from lunar space to the lunar surface in the manner of an Earth parachute, splashing down efficiently and directly into the sponge lake, thereby becoming a unique personnel-entry mode on the Moon (an unpowered/low-powered soft-landing system for personnel).

Sponge lake and buffer facilities

The sponge lake consists of a lunar crater filled with loose, sponge-like material, and requires long life, high utilization, and reusability. The materials of a high-specific-energy mechanical energy-absorption system should be manufactured in situ on the Moon as far as possible: the

buffer body formed by sintering lunar regolith with concentrated solar energy may be replaced by in situ foamed glass/aerogel. Early pilots can begin with small craters: compressed, densified sponge blocks are ejected into the crater, automatically release and expand, and accumulate repeatedly into a small sponge lake, after which the pit airbags and cable net are built. Small items (tested from gram-class to kilogram-class payloads upward) are released from lunar space to verify the splashdown survival rate, keeping the technical climb curve gentle and the risk controllable. The core scientific problem of this scheme is not static energy conservation but the dynamic material response and peak-load control under high-speed impact. For the 1 kg test article with a touchdown speed of about 397 m/s (4.2.2), material dynamic-crush tests, single-layer energy-absorption module tests, multilayer coupling tests, and complete-container tests should be carried out in turn; test indicators should include at least peak deceleration, peak force, energy-absorption efficiency, rebound velocity, permanent structural deformation, landing-point dispersion, and cargo damage rate.

Delivery windows and throughput

The platform port orbits the Moon with a period of about 1.85–2.13 h; within each window it can deliver multiple cargoes in turn in concentrated fashion, and multiple reception points (sponge lakes) can be set in the lunar-surface projection area of its ground track. For the platform port, ejecting cargo backward is equivalent to expelling propellant and produces a positive orbit-maneuver effect (orbit raising), while ejecting forward lowers the orbit (cargo ejected forward does not fall toward the lunar surface; it is designated for inter-platform momentum exchange and is used only to adjust the platform orbit or to move to other orbits)—delivery is orbit change, and logistics and orbit are maintained in a unified way (see 4.3). After accumulation over multiple windows, the platform port restores its nominal orbit through the capture of ascending cargo and the electric-propulsion compensation described in 3.3 (Fig. 11). For high-throughput scenarios, multiple platform ports can be placed on the same circumlunar

line to form a formation for throughput (Fig. 12).

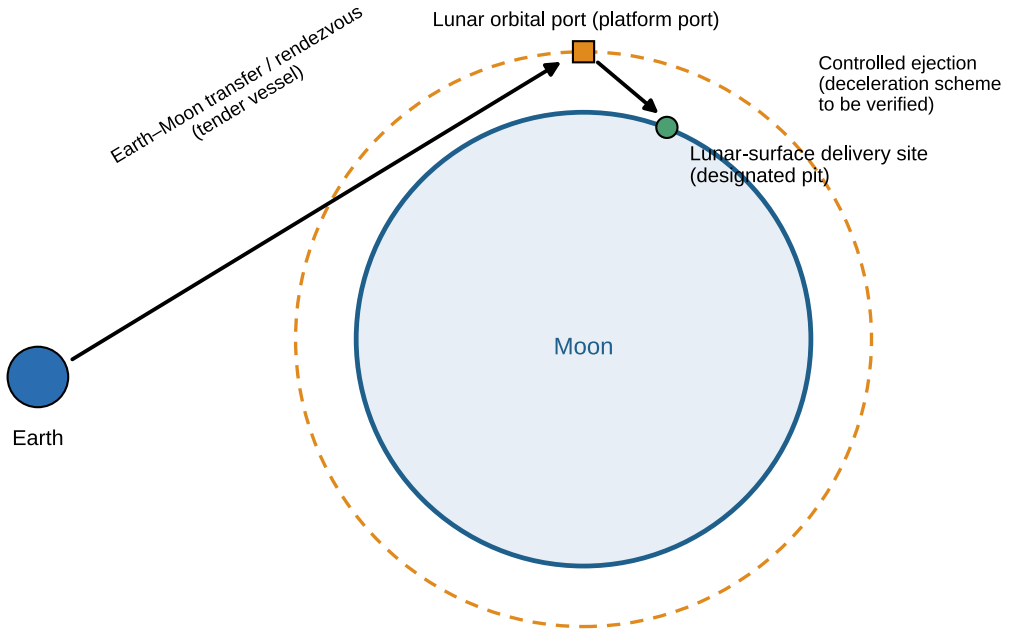


Fig. 11. Architecture of the "Lunar Stairway": orbital port – tender vessel – lunar-surface designated site.

Eccentric orbit and optimization of solar energy collection

The circumlunar platform port is set in a non-circular orbit (perilune H_p = 30 km, apolune H_a = 300 km), and the apolune is placed over the lunar-day hemisphere (the Sun–Moon geometry and orbital precession necessarily change, and the apolune is continuously optimized to remain fixed in the lunar-day hemisphere). According to Kepler's second law, the platform moves slowly and dwells for a long time at apolune, so photovoltaic generation and energy storage by solar panels can be maximized there (the actual net generation benefit must consider simultaneously the solar incidence angle, lunar shadow, orbital precession, attitude constraints, and heat dissipation), and cargo handover is also conducted in this zone; while passing quickly through the lunar-night zone (perilune), dependence on battery storage is reduced; at the same time, the 30 km perilune shortens the delivery distance and the concentrated energy supply to the area below, and also allows real-time regulatory compensation of spacecraft instability in good time, preventing lunar-impact events. It should be explained that keeping the apolune

always in the lunar-day zone requires the line of apsides to precess about 360° per year following the Sun's azimuth (about 1°/day), which must be maintained by orbit design (using the Moon's J_2 and third-body perturbations) or additional ΔV; the maintenance cost of a 30 km perilune under mascon perturbation is high (Table 4: 30 km orbit, 35–65 m/s per year), and an elliptical orbit must be calculated orbit by orbit. The net benefit of this configuration awaits numerical verification.

Orbital energy management: ejection-induced orbit change, prograde/retrograde evolution and formation scheduling

Suppose the platform ejects cargo prograde (in the same direction as the rotation of the lunar surface): the platform obtains a reverse impulse, its kinetic energy decreases, and its orbit is lowered. Prograde and retrograde ejection cause orbital evolution in opposite directions, and mascon perturbation affects prograde and retrograde orbits differently (Appendix B), which can be exploited for flexible scheduling. Going further, cargo ships of different mass/velocity can be arranged to enter the port in an "elastic coupling" manner, so that the kinetic-energy difference between the two is gradually converted into stored electrical energy through electromagnetic coupling during the adjustment (the principle is similar to momentum-exchange tethers/electromagnetic damping [47]), thereby achieving smooth regulation of the platform port's orbit at the energy level; this momentum–energy exchange mechanism is still at the concept stage and must be verified through orbital-dynamics propagation, ejection-mechanism tests, and cargo-flow optimization. The "orbit-raising–orbit-lowering" back-and-forth of prograde/retrograde ejection is just like the changes in the waterline (draft line) caused by rising and falling tides, and may give rise to a corresponding space-engineering theory. Consistent with 3.3 and 4.2.1, delivery to the lunar surface can be done only by backward ejection, and the stability and energy budget of this back-and-forth regulation must be verified through orbital-dynamics simulation.

At the formation level, multiple platform ports interweave along frozen orbits of different inclinations and non-co-directional, forming an ellipsoidal circumlunar orbit network (Fig. 12), serving as backups and relays for one another; unloaded platforms can carry high-specific-impulse electric propulsion or solar sails[7]to maintain orbit, while loaded platforms maintain orbit by exchanging ejected propellant (cargo), the aim being to reduce dependence on propellant resupply from Earth; in real missions, independent propellant budgets for fault recovery, attitude control, and long-term orbit maintenance must still be reserved. Distributed platforms in different lunar orbits, like multi-level steps in lunar space, perform different functions between Earth and Moon.

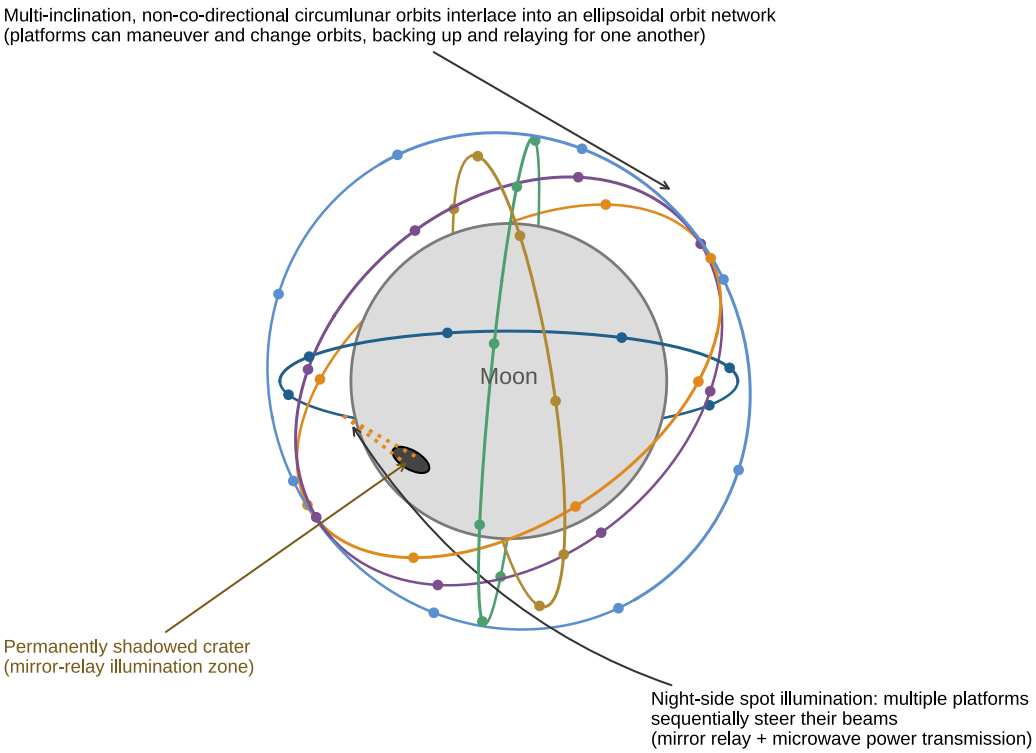


Fig. 12. Multi-platform circumlunar orbit network, with energy supply and illumination (schematic).

Energy, illumination and microwave power transmission

The lunar night lasts 14.6 Earth days, which is the greatest weakness of the energy structure of the lunar-surface paradigm; although orbital platforms experience periodic lunar shadow, it is

markedly different from the lunar-surface cycle, and long-term energy constraints can be reduced through orbit selection, power-system redundancy, and energy-storage management: a low-orbit platform spends most of its time in sunlight, and a high-orbit platform (for example, one with eccentricity flattened over the lunar-day zone) can further extend the sunlit window. The platform can perform three functions: ① reflect sunlight from the high-orbit zone by mirror relay onto the lunar night zone and permanently cold craters—sustained illumination of the PSR valley floors can evaporate water ice and promote a "constant-temperature town with a transparent dome" on the crater floor [28, 29]; ② multiple platform ports can carry concentrating mirror groups to form a series constellation. When a platform enters the lunar-night zone, an intelligent, seamless beam-pointing system directs a spotlight or microwave energy beam onto specific work areas on the lunar surface, such as lunar-surface mining sites or the reception base for projected cargo (to prevent sponge-like bodies from losing temperature and changing properties). Intelligent steering, fixed-point illumination, and sequential flight achieve stable illumination of fixed night-zone areas and provide a relay network with wide coverage of the lunar region. Physical limits of mirror relay: the angular diameter of the solar disk is about 9.3 mrad, and the spot diameter of a plane-mirror reflection is no less than 9.3 mrad × distance, i.e., about 0.93 km at 100 km (about 2.8 km at 300 km and about 9.3 km at 1,000 km); if the mirror diameter is smaller than the spot, the lunar-surface irradiance decays as (mirror diameter/spot diameter)^2; for example, a 100 m aggregate mirror at 100 km can supply about 1% of the solar constant (about 16 W/m^2), and to meet illumination needs the mirror diameter must approach 300 m. In addition, a 100 km-orbit platform is visible from a given site (elevation > 30°) for only about 3 min per revolution, so continuous illumination would require about 36 platforms in relay. Mirror-relay illumination is therefore suitable only for small-area, low-power-density, or intermittent needs, and this "stable illumination" remains a concept; ③ energy-supply devices provide "canopy-beamed power" for lunar-surface work from above,

transmitting power to the lunar surface by wireless power transfer (WPT), where electromagnetic energy-conversion devices convert it into electricity—since Glaser [33] proposed the space solar power station, in 2023 Caltech's MAPLE completed the first in-orbit demonstration of space microwave power transmission [34], giving the first flight data for its engineering (but the transmitted power and distance of that demonstration differ by several orders of magnitude from the hundred-kilowatt to megawatt level and hundred-kilometer range needed here; estimated for 5.8 GHz, a 100 m transmitting aperture, and a 100 km distance, the main-lobe spot diameter is about 126 m ($2.44\lambda R/D$), and is likewise limited by the roughly 3 min visibility per revolution, requiring relay among multiple platforms). The canopy-beaming method makes lunar energy supply flexible; its orbital inclination and altitude can be dynamically scheduled, so that coverage is not limited to particular regions. If throughput and power demand rise further, small nuclear power plants can also be considered—the United States, China, and Russia have all proposed building small nuclear facilities on the lunar surface by 2036 at the latest, but moonquakes and meteoroids will inevitably increase the risk of nuclear leakage, and protective measures will also add cost. If high-power small modular reactor (SMR) devices were placed on a Stairway platform as a mobile "nuclear-powered port," the risk of ground leakage caused by moonquakes and meteoroids could be avoided (the United Nations Principles Relevant to the Use of Nuclear Power Sources in Outer Space[52]would also have to be followed), and surplus energy could likewise be beamed directionally to the lunar surface or relayed to other platforms.

In-orbit manufacturing and zero-gravity factories

The platform port can host small zero-gravity factories: free of moonquake disturbance and dust, and able to maneuver to avoid meteoroids, they are especially suitable for precision smelting and manufacturing (such as alloys, optical fibers, and semiconductor crystals). In microgravity, the assembly of large structures (such as trusses, antennas, and solar sails)

requires no heavy ground-based lifting equipment; the factory's products can either remain in orbit for use or be shipped by cargo ships to the lunar surface or to Earth. The zero-gravity environment also offers unique experimental value for pharmacology and materials science. As for manufacturing bases placed in lunar-surface factories, apart from a few sites (such as regions of eternal light and lava tubes), the Moon is an extreme thermal environment, and temperature control, lunar dust interference, moonquakes, meteoroids, and radiation are all weaknesses; in terms of protection and operating costs, early lunar-surface conditions are not the optimal choice.

Computing-power heat dissipation and "thermal-mass delivery"

Heat dissipation for space computing platforms (data centers, "token factories," deep reasoning) is currently a hot topic. In vacuum, radiation is the main heat-dissipation mode: by the Stefan–Boltzmann law, a 300 K blackbody surface radiates about 459 W/m², and a 100 kW-class platform needs a radiator of the order of 220 m², which is mature engineering. This paper further proposes "thermal-mass delivery" as an auxiliary heat-dissipation concept: a dedicated platform module uses its cabin walls to dissipate heat and carries liquid-phase/phase-change "thermal items" of high specific heat (latent heat of phase change of about 200–400 kJ/kg), using the "ejection–splashdown" channel to deliver heat with the items to the lunar night zone; the items re-solidify at night on the lunar surface and are then re-launched to the platform, circulating to cool the computing units. Calculation shows, however, that if a continuous 100 kW thermal load were borne entirely by phase-change materials, about 1,440 kg/h (at 250 kJ/kg) would be needed—a very large quantity—so this method is suitable only as a peak-shaving means for peak thermal loads, with radiators remaining the main path; the idea of "using the Moon as a heat sink" still has exploratory value. For example, because lunar-surface temperature differences are extreme, existing research directions pour phase-change materials into sintered lunar-regolith bricks to make intelligent building blocks that can bear loads and

also store and release heat; the demand for phase-change materials as building materials on the Moon is therefore predicted to be very large, a hard demand. Phase-change cargo shipped from Earth can thus be sent first to the computing module for heat storage, then ejected to the Moon to make regolith bricks, meeting the heat-dissipation needs of space computing in a continuous cargo-turnover mode.

Upward delivery from the lunar surface: electromagnetic launcher

Upward transport of materials from the lunar surface to lunar orbit can use electromagnetic launch (mass drivers) [35, 36]: accelerating the payload to about 1.7 km/s allows entry into LLO, with a kinetic energy of about 406 kWh/t and an electromagnetic drive efficiency above 90% [35], far exceeding the energy performance of chemical propulsion; the Moon's low gravity and vacuum make it an ideal electromagnetic launch site. Recent research shows that lunar gravity anomalies can also be used to fine-tune ejection trajectories [36]. On the lunar-orbit side, the platform port or a dedicated catcher performs rendezvous capture, completing the "lunar surface – lunar orbit" closed loop. Thus raw materials mined on the lunar surface and manufactured products can be sent up to orbit at low cost for processing, further weakening the necessity of "having to be stationed on the lunar surface." Note: for cargo launched horizontally from the lunar surface at about 1.70 km/s, the perilune is the launch point (ground surface), and it must be captured by the platform at the 100 km apolune (where the speed is about 1.610 km/s, 23 m/s slower than the platform), or the cargo must circularize at apolune with its own small thruster; otherwise it will strike the lunar surface again. The electromagnetic acceleration section requires about 1.5 km at 100 *g* and about 14.7 km at 10 *g*. This upward logistics and the downward logistics of 4.2 constitute a momentum closed loop in Section 3.3.

On in situ resource utilization

In situ resource utilization (ISRU) on the Moon is often put forward as the core argument for

lunar-surface bases: using regolith to produce oxygen, extracting water ice, and 3D-printing building materials. But the maturation of ISRU requires a great deal of preliminary verification and equipment deployment, and itself depends on reliable lunar-surface landing and long-term residence capability. Before ISRU technology matures, the lunar-orbit platform offers an agile scheme that can operate without ISRU: materials are shipped from Earth and transferred in orbit, in situ resources are launched to the lunar port, and finished products are stored at low cost or delivered back to the Moon.

ISRU and the lunar-orbit scheme are not in opposition. With the support of a lunar-orbit platform, ISRU verification can be more unhurried: small test equipment is delivered by descent through the orbital platform, and data are relayed back to Earth through the lunar-orbit platform; the cost of failure is far lower than for a crewed lunar-surface mission, and the lunar-orbit platform can also provide more habitats for the staff.

Earth–Moon material cycling and "hull orbitalization"

The lunar crust lacks siderophile elements; metals that are abundant on Earth are instead very scarce on the Moon. Lunar basalts typically contain less than 100 ppm nickel, and siderophile elements in lunar rocks (Ni, Ir, Au, Re, Os, etc.) are depleted overall by about 20–50 times relative to the Earth's mantle[26]; elemental metallic iron is less than 1 wt% in lunar rocks and mostly occurs as submicroscopic grains dispersed in the regolith (about 0.5–1.5 wt%), derived mainly from meteoritic input [26] (Fig. 13). Reducing metal from silicates/oxides requires complete sets of smelting facilities and large amounts of energy, which is almost infeasible in the early stage. By contrast, finished steel is extremely plentiful on Earth: global crude steel output in 2024 was about 1.88 billion tonnes [42], annual nickel production is also measured in millions of tonnes, and steel is one of the cheapest engineering metals on Earth. For lunar development, smelted steel is precisely a rare asset that is "valued for being scarce."

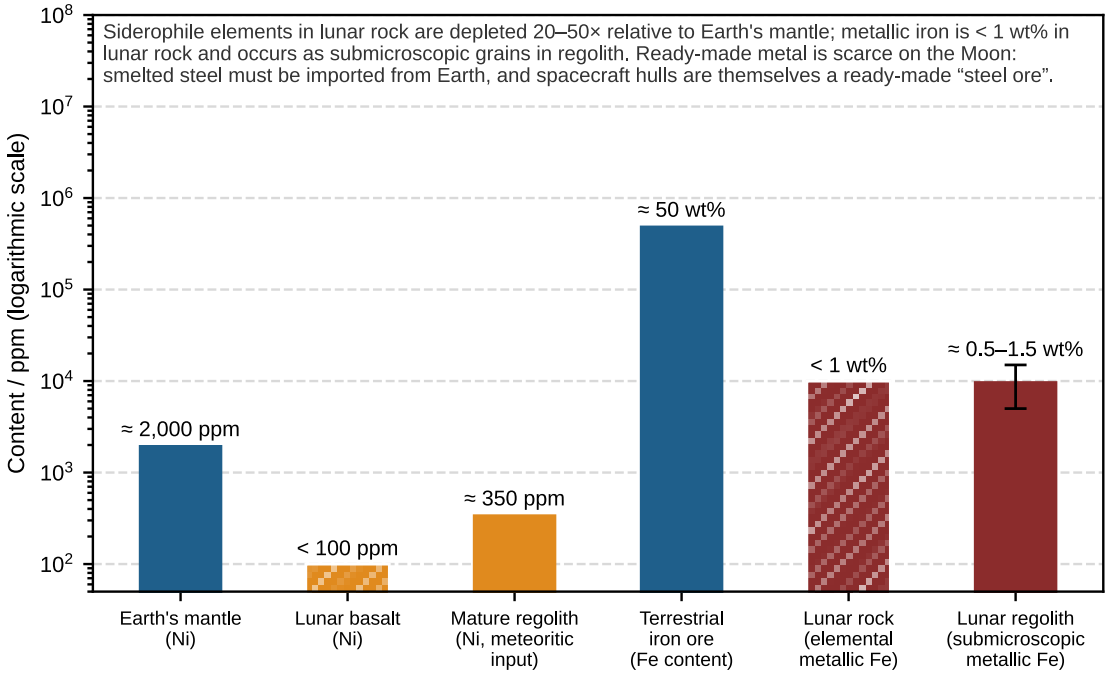


Fig. 13. Comparison of iron and nickel resources on the Moon and on Earth (schematic; order of magnitude of content from the literature[26]).

Accordingly, this paper advocates "thinking one step further": the hulls of today's mainstream transport spacecraft are mostly made of stainless steel—heavy, cheap, and durable, precisely the cheapest "steel ingots" that humanity can ship to the Moon. After a lunar mission, rather than returning the hull to Earth for reuse, it is better to leave it in lunar orbit as a "lunar-space floating module" and metal reserve (a logical extension of Fig. 13). Such hulls can serve as extension modules of the platform port, as temporary docking modules, and even as carriers of small nuclear power units, and they are also a raw-material depot for smelting in future lunar construction. Therefore, some cargo spacecraft may be designed as one-way vehicles, with their remnants left in lunar orbit as platforms. When the scale of lunar logistics expands, dedicated "steel-ingot ships," together with spacecraft remnants, will convert Earth's surplus production capacity into fixed assets on the Moon.

The economic logic of this strategy is intuitive: the cost of returning a hull (propellant, landing system, refurbishment) is far higher than the cost of maintaining and using the hull in lunar

orbit, and the long-term value of the hull material in lunar orbit (as construction raw material or shielding) is far higher than its value as scrap metal on the ground, with no re-entry pollution[27].

Orbital habitability and prospects for long-term residence

Large platform ports, as "flying floating islands," may in future take on multiple functions—long-term residence, scientific research, manufacturing, and observation—creating gardens, art centers, unmanned factories, cinemas, and viewing domes within air cities; a metal shell covered with polyethylene/water/regolith blocks can block cosmic radiation. People could gaze at the lunar surface at close range from the lunar sky port, make short protected landings on the lunar surface for "leisure tours," and even develop future lunar-sky city clusters. Long-term life at a future lunar port calls to mind the Tanka people ("Dan people") of China's South China Sea, who have lived on boats for generations. If lunar-space habitability always exceeds that of the Moon, we can likewise imagine a population that lives and evolves steadily on "ship-islands" circling a planet generation after generation—using the planet's gravity for low-power maintenance, traveling from time to time between neighboring planets, and occasionally setting out for farther places. Orbital life is not "settling for second best" but a form of civilization chosen deliberately; the space springboard that humans imagine is built not on the Moon but in lunar space, and it is also the starting point of Earth's "generation voyage" in space (the greatest advantage of a lunar-space launch port is that it spares rockets the most energy-consuming initial acceleration stage, equivalent to saving an entire rocket-stage structure; on Earth, the first stage accounts for about 45% of a rocket's hardware cost while consuming more than 80% of the whole rocket's propellant). If space agencies could adopt this proposal and adjust their space strategies, the enormous costs of changing course could be reduced.

This paper poses a systematic challenge to the lunar-development paradigm centered on lunar-

surface stationing and demonstrates the multidimensional advantages of a near-lunar-orbit platform architecture in the early development stage. A further conclusion: orbital stationing is not limited to the Moon; human exploration of planets should proceed from peripheral observation until familiarity is gained, entering only once there is real certainty, and this holds for any unfamiliar celestial body.

Projected technology timeline

Table 9. Phased timeline of the "Lunar Stairway"

Phase	Time window	Main content	Key milestones	Main risks and countermeasures
1. Pilot verification	T0–T0+5 years (T0 is the project-initiation year)	Small verification ejection capsules; trial drops of sponge blocks into small craters; blind-shot calibration and splashdown model, midcourse-correction and terminal-guidance verification; small-mass ballistic delivery; scaled test of electromagnetic deceleration track; principle prototype of electric-propulsion platform port	First successful sponge-lake splashdown and recovery; perilune-altitude control accuracy at the ±100 m level (terminal guidance required); scaled deceleration track completing dissipation verification	Guidance accuracy and mass of deceleration-track consumables—verify small masses first and account for consumables; sponge-lake material life and landing-point deviation—control by redundant trial drops and gravity-field-model iteration
2. Platform Port I	T0+5–T0+10 years	30–100 km near-lunar-orbit platform port; routine ballistic delivery; verification of lunar-surface electromagnetic ejection; cargo-ship docking transfer	Platform port in orbit and operating continuously for more than 2 years; annual throughput at the 1,000 t level; must pass the break-even review of Section 3.7 (cumulative-delivery threshold approximately 300–1,000 t)	Impact-load constraints on payloads—formulate cargo-box load specifications; orbit maintenance relies on electric propulsion
3. Formation and energy network	T0+10–T0+18 years	Multi-platform formation and orbit network; mirror-relay illumination; microwave power transmission; zero-gravity factory; assessment of nuclear-powered port	Fixed-point illumination of the night zone and PSR water-ice mining demonstration; in-orbit factory commissioned	Power-transfer efficiency, nuclear-power approval—non-nuclear scheme first
4. Lunar-surface outposts and closed loop	After T0+18 years	A small number of crewed lunar-surface outposts; large-scale lunar-orbit storage of hull remnants; closed Earth–Moon material cycle	Lunar-surface outposts achieve energy/water self-sufficiency; metal stored in lunar orbit reaches the 10,000-tonne level	Lunar-orbit debris management, long-term residence medicine—establish registration and traffic rules[53]

Notes: (1) The time windows are illustrative planning, adjusted according to actual investment and technical verification, and revised on a rolling basis according to test data and mission conditions;

(2) Deploying living and production clusters in lunar orbit greatly expands the range of human space activity; under this collaborative human system, the significance of symbolic lunar-surface sovereignty activities [54] represented by "planting flags" is relatively reduced;

(3) Decision gates are set for each phase: without passing the previous phase's reviews of guidance accuracy, deceleration-

track consumable mass, and break-even, the next phase is not entered; time windows are expressed in relative years and constitute no schedule commitment.

Near-term verifiable work

(1) In-orbit verification of the capsule's relative navigation and midcourse correction (perilune set above the ground, not touching the Moon, with flight continuing after passage); (2) ground-based scaled electromagnetic/eddy-current deceleration-track tests to obtain data on peak power and regeneration efficiency; (3) tests of energy absorbers at impact speeds of 0.1–1 km/s to establish the relationship between specific energy absorption and speed; (4) accumulation of in-orbit data on the long-term maintenance of frozen orbits.

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Appendix A Notation

Table A.1. Principal symbols

Symbol	Meaning	Value/unit
R_m	Mean lunar radius	1,737.4 km
μ_m	Lunar gravitational parameter	4,902.8 km³/s²
g_0	Standard gravitational acceleration of Earth	9.81 m/s²
g_m	Lunar-surface gravitational acceleration	1.624 m/s²
ΔV	Velocity increment	km/s or m/s
I_{sp}	Specific impulse	s
m_0/m_1	Initial/final mass	t
a	Orbital semi-major axis	km
T	Orbital period	h
v_{circ}	Circular-orbit speed	km/s
r_{Hill}	Hill-sphere radius of the Moon	≈6.15×10⁴ km
L	Deceleration runway length of the sponge lake	km
n	Mean deceleration overload (in units of g_0)	g
E	Impact kinetic energy	GJ
TNT equivalent	Energy conversion	kg

Appendix B Calculation Parameters and Assumptions

(1) Orbit calculations: the circular-orbit speed is $v_{circ} = (\mu_m/r)^{1/2}$ and the period is $T = 2\pi(a^3/\mu_m)^{1/2}$, using R_m = 1,737.4 km and μ_m = 4,902.8 km³/s² as the uniform parameters of the two-body approximation in this paper. Ballistic delivery model: the platform is on a 100 km circular orbit (v = 1.633 km/s); after ejection it enters a transfer ellipse with perilune r_p = 1,737.4 km and apolune r_a = 1,838.4 km, with ejection increment $\Delta V_{ej} = v_{circ} - v(r_a) = 1.633 - 1.610 \approx 0.023$ km/s; the touchdown speed is evaluated by the vis-viva equation at perilune, $v_p \approx 1.70$ km/s, with direction predominantly horizontal.

(2) Rocket equation: $m_{prop}/m_0 = 1 - \exp(-\Delta V/(I_{sp} \cdot g_0))$. The chemical-propulsion I_{sp} is taken as 300 s (in the Table 4 comparison, the ISS is taken at 300 s and the Earth–Moon transfer at 320 s); the electric-propulsion I_{sp} is taken as 1,600 s (typical value for Hall thrusters); the cold-gas I_{sp} is taken

as 70 s. The "chemical propellant/electric-propulsion propellant" columns in Table 4 are converted at the midpoint of the corresponding ΔV ranges.

(3) Deceleration model: mean overload $n = v^2/(2L \cdot g_0)$, taking v = 1,700 m/s and neglecting the vertical component (grazing entry into the crater) and the peak effect of airbag crushing; this formula is used only for first-order scale estimation of the mean deceleration and does not represent the real impact peak; the real peak must be determined by high-speed impact tests or an explicit dynamics model.

(4) Radiation dose: the lunar-surface background cites the Chang'e-4 LND measurements [22]; the SPE cites the NASA 1988 estimate and the latest shielding-modeling results [23]; the "about 1.1–1.3 mSv/d inside a lunar-orbit cabin after 20 g/cm² shielding" is estimated in this paper by multiplying the MSL RAD cruise-phase measured dose-equivalent rate (about 1.8 mSv/d) [49] by (1 − lunar-body blockage fraction), where the blockage fraction is $(1 - \cos \rho)/2$ and $\rho = \arcsin[R_m/(R_m + h)]$ (about 41%, 34%, and 28% at 30, 100, and 200 km, respectively), to be corrected by in-flight measurements.

(5) Orbit maintenance: the ΔV ranges are synthesized from the literature [6–8] and the LRO measurements [5]; the ISS reboost $\Delta V \approx 57$ m/s and propellant of about 7.5 t/yr (total mass about 420 t) are taken from public flight data [8].

(6) Energy and mass accounting: the electromagnetic-ejection kinetic energy is calculated as $0.5mv^2$ (v = 1.71 km/s, corresponding to the LLO transfer entry), about 406 kWh/t; conceptual items such as sponge-lake buffering and thermal-mass delivery are all explicitly labeled "concept/estimate" and constitute no engineering commitment.

(7) Lunar-shadow fraction: for a circular orbit ($\beta = 0$), the fraction of the orbital period spent in lunar shadow is ρ/π, with ρ as above (about 44%, 39%, 35%, and 22% at 30, 100, 200, and 1,000 km, respectively).

(8) Perilune sensitivity: from conservation of angular momentum and the vis-viva equation, $h = r_a v_a$, $p = h^2/\mu$, $e = 1 - p/r_a$, $r_p = p/(1 + e)$; taking r_a = 1,837.4 km and $v_a = v_c - \Delta V_{ej}$, at the nominal ΔV_{ej} = 23 m/s, $r_p \approx R_m$, and in its vicinity $dr_p/dv_a \approx 4.2$ km/(m/s). The along-track deviation (after a

half revolution of flight following ejection) is about 11 km/(m/s). The incidence angle is obtained from $\cos \gamma = h/(R_m \cdot v)$; at $\Delta V_{ej} = 24$ m/s the perilune is about 4.2 km below the ground surface, $\gamma \approx 0.65°$.

(9) Deceleration and energy absorption: stroke $L = v^2/(2n \cdot g_0)$; dissipated energy $E = \frac{1}{2}mv^2$ (v = 1.70 km/s; 1.445 GJ ≈ 401 kWh for 1 t); consumable absorber mass $m_{abs} = E/\mathrm{SEA}$, with the specific energy absorption SEA taken as 10–30 kJ/kg (assumption); for an illustrative case in which an electromagnetic deceleration section reduces the speed to 150 m/s, and the residual kinetic energy of the final stage is ½ × 1,000 × 150² ≈ 11.25 MJ/t; mean power $P = E/(2L/v)$.

(10) Recoil and propellant: $\Delta V_{plat} = M_p \cdot V_{rel}/(M_{plat} - M_p)$, $V_{rel} = 23$ m/s; the electric-propulsion propellant needed for compensation is $m_{prop} \approx M_p \cdot V_{rel}/(I_{sp} \cdot g_0)$, approximately 1.2 kg/t at I_{sp} = 2,000 s.

(11) Break-even: $N^* = (M_{plat} + c_L \cdot M_{inf})/(c_L - c_B)$, with $c_L = 2.86$ and $c_B = 1.2$, and M_{plat} and M_{inf} taking the illustrative values of Table 6; the LEO-to-LLO mass conversion is $m_{LEO}/m_{LLO} = \exp[\Delta V/(I_{sp} \cdot g_0)]$ with $\Delta V = 4.0$ km/s, and $I_{sp} = 450$ s and 360 s give about 2.5 and 3.1, respectively.

(12) Optics and microwave: the mirror-reflected spot diameter is ≥ 9.3 mrad × distance; the microwave main-lobe spot diameter is $\approx 2.44\lambda R/D$ (f = 5.8 GHz, $\lambda \approx 5.2$ cm, D = 100 m, R = 100 km, about 126 m); the visibility time is obtained from the central angle $\lambda = \arccos[R_m \cdot \cos(\mathrm{el})/(R_m + h)] - \mathrm{el}$ (el = 30°), about 3 min per revolution.