Review Article

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Underground terraforming as a strategy for human settlement in the solar system: a review of opportunities, technologies, and challenges

Abstract

Human expansion beyond Earth will require the development of habitats capable of protecting settlers from radiation, vacuum exposure, extreme temperatures, micrometeoroid impacts, and the absence of breathable atmospheres. While planetary terraforming has long been proposed as a pathway toward large-scale settlement, the modification of entire planetary environments remains technologically uncertain and may require timescales extending over centuries or millennia. An alternative approach involves the creation of localized habitable environments within subsurface regions of planets, moons, asteroids, and other solid Solar System bodies.

This article examines the concept of underground terraforming, defined as the transformation of natural or engineered subsurface environments into habitable spaces through the integration of environmental control systems, life-support technologies, resource utilization, and habitat engineering. The article emphasizes current literature concerning candidate subsurface environments, including lunar and Martian lava tubes, asteroid interiors, icy moon crusts, and dwarf planets. It evaluates key engineering requirements such as excavation technologies, radiation protection, structural stability, energy systems, in-situ resource utilization (ISRU), and closed ecological life-support systems (CELSS).

Particular attention is given to the distinction between technologies that are currently demonstrated, technologies that appear plausible based on ongoing research, and concepts that remain speculative. The review also examines human factors, economic considerations, governance challenges, and major research gaps that must be addressed before large-scale underground settlement becomes feasible.

Current evidence suggests that subsurface habitats offer several advantages over planetary-scale terraforming, including reduced environmental modification requirements, natural radiation shielding, and applicability across a wide range of Solar System environments. However, substantial uncertainties remain regarding excavation scalability, long-term ecological closure, economic sustainability, and human adaptation to long-duration subsurface habitation. Consequently, underground terraforming should presently be regarded as a promising research framework rather than a demonstrated pathway toward widespread Solar System colonization.

Keywords: underground habitats, space settlement, subsurface habitation, lava tubes, in-situ resource utilization, closed ecological life-support systems, extraterrestrial colonization, planetary engineering

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Introduction

The long-term expansion of human civilization beyond Earth remains one of the central objectives of contemporary space exploration. Over the past several decades, advances in rocketry, robotics, planetary science, and habitat engineering have transformed space settlement from a purely speculative concept into an active area of scientific and engineering research. Permanent human presence beyond Earth is now widely discussed in the context of lunar bases, Martian settlements, asteroid resource utilization, and long-duration habitation in deep space.

Despite these advances, extraterrestrial environments remain fundamentally hostile to unprotected human life. Most planetary bodies in the Solar System lack breathable atmospheres and expose their surfaces to elevated radiation levels, extreme temperature variations, vacuum conditions, and micrometeoroid impacts. These hazards create substantial challenges for long-term habitation and require the development of protective infrastructure capable of maintaining stable environmental conditions.

One proposed solution is planetary terraforming, which involves modifying atmospheric, climatic, and ecological conditions to create environments more closely resembling those found on Earth. Although terraforming has received considerable attention in both scientific and popular literature, many proposed scenarios involve technological requirements and timescales extending far beyond current capabilities. Furthermore, only a limited number of Solar System bodies possess environmental characteristics that make planetary-scale terraforming theoretically plausible.

An alternative approach focuses on the development of localized habitable environments beneath planetary surfaces. Subsurface habitats utilize natural geological shielding provided by rock, regolith, or ice while maintaining habitable conditions within enclosed volumes. This strategy significantly reduces the scale of environmental modification required for settlement and may be applicable to a broader range of planetary environments.

Subsurface habitat concepts have been proposed for lunar lava tubes, Martian cave systems, asteroid interiors, and the ice-rich crusts of outer Solar System moons. These environments offer potential advantages including radiation protection, thermal stability, reduced exposure to surface hazards, and access to local resources. At the same time, they introduce important challenges involving excavation, construction, life-support systems, energy generation, and long-term human habitation in confined environments.

The concept explored in this review is referred to as *underground terraforming*. The term is used here not to imply the modification of entire planetary environments but rather the creation of controlled habitable ecosystems within subsurface regions. The objective is to assess whether underground habitation may provide a viable complement or alternative to conventional terraforming strategies.

This article synthesizes current literature from planetary geology, habitat engineering, ecological life-support research, robotics, resource utilization, human factors, and space policy. Particular emphasis is placed on distinguishing between demonstrated capabilities, plausible technological developments, and highly speculative concepts. By evaluating both opportunities and limitations, the review seeks to identify the current state of knowledge and the major uncertainties that will shape future research on subsurface settlement throughout the Solar System.

Methodology

This article was conducted as a narrative interdisciplinary review of literature relevant to subsurface human settlement in extraterrestrial environments.

Literature was identified through searches of major scientific databases, including Scopus, Web of Science, Google Scholar, NASA Technical Reports Server (NTRS), and ESA publication repositories. Searches were conducted using combinations of the following terms:

a) "space habitats"
b) "subsurface habitats"
c) "lava tubes"
d) "planetary caves"
e) "underground settlements"
f) "closed ecological life support systems"
g) "CELSS"
h) "MELiSSA"
i) "in-situ resource utilization"
j) "ISRU"
k) "extraterrestrial mining"
l) "space architecture"
m) "planetary colonization"
n) "radiation shielding"
o) "space governance"
p) "space settlement economics"

Priority was given to peer-reviewed journal articles, conference proceedings, agency reports, and technical studies published between 2000 and 2025. Earlier publications were included when considered foundational to the development of settlement concepts or life-support research.

Sources were evaluated according to their relevance to five major themes:

A. Candidate subsurface environments.
B. Habitat engineering requirements.
C. Life-support and ecological systems.
D. Energy and resource utilization.
E. Human, economic, and governance considerations.

The review does not attempt a quantitative meta-analysis because the available literature spans multiple disciplines with highly heterogeneous methodologies and objectives. Instead, evidence is synthesized qualitatively to identify areas of agreement, major uncertainties, technological readiness levels, and priorities for future investigation.

Particular attention is given to distinguishing between concepts supported by experimental evidence, concepts under active technological development, and proposals that remain largely speculative. This distinction is intended to provide a balanced assessment of the current feasibility and limitations of underground terraforming as a strategy for long-term human settlement beyond Earth.

Candidate subsurface environments for human settlement

One of the principal advantages of subsurface settlement strategies is their potential applicability across a wide range of Solar System environments. Unlike planetary terraforming, which requires favorable planetary-scale conditions such as sufficient gravity, volatile inventories, and atmospheric retention capacity, subsurface habitats rely primarily on local geological conditions and engineered environmental control systems.

Numerous Solar System bodies possess geological structures that may provide natural shielding against radiation, micrometeoroid impacts, and temperature extremes. These structures include lava tubes, impact-generated cavities, fractured rock systems, ice-rich crusts, and excavated subsurface volumes. However, the suitability of these environments varies considerably depending on geological characteristics, resource availability, energy requirements, and accessibility.

This section reviews the principal categories of candidate subsurface environments that have been proposed for future human settlement.

Lunar lava tubes

The Moon has long been considered one of the most attractive locations for early extraterrestrial settlement because of its proximity to Earth and its strategic importance for future exploration activities. Among proposed habitat locations, lunar lava tubes have received particular attention.

Lava tubes are naturally occurring subsurface conduits formed by volcanic activity. Orbital observations from missions including

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Kaguya, Lunar Reconnaissance Orbiter (LRO), and SELENE have identified skylights and collapse features interpreted as entrances to extensive lava tube networks. Modeling studies suggest that some lunar lava tubes may reach diameters substantially larger than those found on Earth due to reduced lunar gravity.

Several characteristics make lunar lava tubes attractive for settlement:

a. Significant radiation protection provided by rock overburden.
b. Shielding from micrometeoroid impacts.
c. Reduced temperature fluctuations compared with the lunar surface.
d. Large internal volumes that may reduce excavation requirements.

However, important uncertainties remain. Most proposed lava tubes have not been directly explored, and their structural integrity, accessibility, internal morphology, and long-term stability remain poorly constrained. Future robotic exploration will be required before these formations can be evaluated for habitation purposes.

Martian lava tubes and subsurface cavities

Mars is frequently regarded as the leading candidate for long-term human settlement because of its relatively accessible resources, moderate gravity compared with other planetary bodies, and evidence for past and present water.

Like the Moon, Mars contains extensive volcanic provinces that likely host lava tube systems. Observations of collapse pits and cave-like features suggest that large subsurface voids may exist beneath volcanic regions such as Tharsis and Elysium.

Martian subsurface habitats may offer several advantages:

a) Protection from galactic cosmic radiation and solar particle events.
b) Reduced exposure to global dust storms.
c) Access to nearby water-ice deposits.
d) Greater availability of local resources for ISRU.

Nevertheless, Mars presents challenges that differ from those of the Moon. The mechanical properties of Martian subsurface materials remain incompletely understood, and many candidate cave systems have not been directly investigated. In addition, dust infiltration, habitat pressurization, and long-term environmental control remain significant engineering concerns.

Current evidence suggests that Martian lava tubes represent one of the most promising targets for future subsurface habitat research, although substantial geological characterization remains necessary.

Asteroids and small bodies

Asteroids represent a fundamentally different category of settlement environment. Unlike planets and moons, most asteroids possess extremely low gravity and highly variable geological structures.

Several settlement concepts propose excavating or hollowing asteroid interiors to create pressurized habitats. Other concepts envision rotating asteroid structures capable of generating artificial gravity.

Potential advantages include:

a) Access to mineral resources.
b) Availability of water-rich asteroids.
c) Low launch and landing energy requirements.
d) Potential integration of mining and habitation activities.

However, asteroid settlement faces major challenges:

A. Uncertain internal structures.
B. Low-gravity operational difficulties.
C. Pressure containment requirements.
D. Rotational stress management.
E. Limited understanding of long-term structural stability.

Many asteroid settlement concepts remain conceptual and have not progressed beyond theoretical or engineering feasibility studies.

Icy moons and ice-rich bodies

The outer Solar System contains numerous bodies characterized by substantial water-ice inventories. These include Europa, Ganymede, Callisto, Enceladus, and Titan. From a settlement perspective, ice-rich environments offer several potentially valuable characteristics.

First, water is a critical resource for life support, agriculture, radiation shielding, and fuel production. Second, ice can provide significant protection against radiation. Third, volatile-rich environments may support future industrial activities.

Several habitat concepts have proposed excavation within ice crusts or the construction of subsurface chambers protected by thick ice layers.

Despite these advantages, ice-rich environments present unique engineering challenges:

a) Long-term creep deformation of ice structures.
b) Thermal management requirements.
c) Potential instability associated with melting and refreezing.
d) Extremely low surface temperatures.
e) Large transportation distances from Earth.

In addition, several icy moons exist within intense radiation environments generated by their parent planets, creating further operational constraints.

Consequently, while ice-rich bodies offer significant resource advantages, their practical suitability for settlement remains uncertain.

Dwarf planets and trans-Neptunian objects

Dwarf planets and trans-Neptunian objects (TNOs) have received comparatively little attention in settlement studies because of their extreme distance from Earth and the limited amount of available observational data.

Examples include - Ceres, Pluto, Eris, Sedna, Makemake, Haumea.

These bodies may contain substantial quantities of water ice, volatile compounds, and other resources that could support localized habitation.

The principal argument for considering such objects as settlement targets is that underground habitats are largely independent of external environmental conditions. If sufficient energy and resources are available, habitable conditions can theoretically be maintained regardless of surface temperature.

However, enormous uncertainties remain regarding:

I. Resource accessibility.
II. Economic viability.
III. Transportation logistics.
IV. Infrastructure development costs.

At present, settlement scenarios involving dwarf planets and trans-Neptunian objects should be regarded as highly speculative.

Comparative assessment of candidate environments

Although many Solar System bodies possess subsurface environments potentially suitable for habitation, their relative attractiveness depends on multiple factors including accessibility, resource availability, geological stability, and engineering complexity.

Table 1 summarizes a qualitative comparison of major candidate environments.

Table 1 Comparative assessment of candidate subsurface settlement environments

Environment	Natural shielding	Water availability	Accessibility	Engineering complexity	Current settlement potential
Lunar Lava Tubes	High	Moderate	High	Moderate	High
Martian Lava Tubes	High	High	Moderate	Moderate	High
Asteroid Interiors	Moderate	Variable	Moderate	High	Moderate
Icy Moons	High	Very High	Low	High	Moderate
Dwarf Planets	High	Variable	Very Low	Very High	Low
Trans-Neptunian Objects	High	Variable	Very Low	Very High	Very Low

The comparison suggests that lunar and Martian subsurface environments currently represent the most realistic targets for early settlement efforts due to their relative accessibility and the growing body of geological data available from orbital and surface missions.

By contrast, asteroid habitats, icy moons, and distant dwarf planets may become increasingly relevant only if future advances in transportation systems, energy production, and autonomous infrastructure significantly reduce the costs and risks associated with deep-space settlement.

Overall, existing evidence supports the conclusion that subsurface environments substantially expand the range of potential settlement locations beyond those typically considered suitable for conventional planetary terraforming. However, the practical feasibility of settlement remains highly dependent on local geological conditions, resource availability, and technological capabilities.

Engineering requirements for underground habitats

The feasibility of underground habitation depends not only on the availability of suitable subsurface environments but also on the ability to engineer and maintain safe, long-duration living spaces. Although underground habitats may benefit from natural shielding and environmental stability, they require the integration of numerous technological systems that collectively support human survival and economic activity.

This section reviews the principal engineering requirements associated with underground settlement and evaluates current technological capabilities and remaining challenges.

Site selection and geological assessment

The success of any underground settlement begins with the identification of an appropriate geological site. Geological conditions influence construction costs, habitat safety, resource accessibility, and long-term expansion potential.

Several criteria are particularly important.

Structural stability

The host rock or ice must remain stable under both natural and anthropogenic stresses. Potential hazards include:

a) Faulting and fracturing.
b) Seismic activity.
c) Roof collapse.
d) Thermal stress cracking.
e) Long-term deformation.

Geotechnical investigations similar to those conducted in terrestrial mining and tunneling projects would therefore be essential before permanent habitation is established.

Resource availability

Sustainable settlements require access to local resources. Favorable sites should ideally contain:

A. Water ice.
B. Construction materials.
C. Industrial minerals.
D. Metal-bearing deposits.
E. Volatile compounds.

Resource proximity reduces transportation requirements and improves long-term economic viability.

Accessibility

The ease with which habitats, equipment, and personnel can access a site strongly influences settlement feasibility. Some geologically attractive locations may prove impractical if entry, construction, or expansion are excessively difficult.

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Expansion potential

Most settlement architectures envision gradual growth over time. Consequently, site selection should consider future development rather than only initial habitat requirements.

Radiation protection

Radiation exposure is one of the most significant challenges facing long-duration human habitation beyond Earth.

Major sources include:

A. Galactic cosmic rays (GCRs).
B. Solar energetic particles (SEPs).
C. Secondary radiation generated within shielding materials.

Unlike Earth, most Solar System bodies lack both dense atmospheres and global magnetic fields capable of providing substantial radiation protection.

Advantages of subsurface habitats

One of the strongest arguments for underground settlement is the shielding provided by geological materials.

Studies suggest that:

a) Several meters of regolith can substantially reduce radiation exposure.
b) Greater depths provide increasingly effective protection.
c) Lava tubes may naturally provide shielding comparable to or exceeding many engineered surface solutions.

Because radiation mitigation is largely passive, underground habitats may require less imported shielding material than equivalent surface installations.

Remaining uncertainties

Although shielding effectiveness is generally well understood, uncertainties remain regarding:

a) Optimal habitat depth.
b) Secondary radiation production.
c) Long-term health impacts of low-dose exposure.
d) Radiation effects on biological systems and agriculture.

Additional research is required to establish acceptable exposure limits for multi-generational settlements.

Habitat pressurization and atmospheric integrity

Human survival requires atmospheric conditions within a relatively narrow range of pressures and gas compositions.

Consequently, underground habitats must function as large pressure vessels embedded within geological structures.

Atmospheric Requirements

Habitats must maintain:

a) Adequate oxygen levels.
b) Carbon dioxide control.
c) Appropriate atmospheric pressure.
d) Humidity regulation.
e) Air circulation.

These functions are routinely performed aboard spacecraft and space stations but have never been demonstrated at city scale.

Structural challenges

Pressurized habitats exert continuous outward forces on surrounding geological materials.

Potential engineering concerns include:

a) Gas leakage through fractures.
b) Seal degradation.
c) Structural fatigue.
d) Failure of pressure boundaries.

Habitat design must therefore integrate geological and structural engineering considerations.

Research needs

Future investigations should address:

A. Long-duration pressure retention.
B. Large-volume habitat construction.
C. Geological sealing techniques.
D. Emergency compartmentalization strategies.

Thermal control and environmental regulation

Extraterrestrial environments frequently experience temperature extremes outside the range compatible with human habitation.

Although subsurface locations generally experience more stable temperatures than exposed surfaces, active thermal management remains essential.

Heat sources

Potential heat sources include:

a. Human metabolism.
b. Industrial activities.
c. Nuclear reactors.
d. Electrical systems.
e. Solar energy systems.

Heat rejection

Underground habitats must also remove excess heat.

This challenge may become particularly important in large settlements where industrial operations and population density generate significant thermal loads.

Engineering considerations

Thermal management systems must balance:

i. Energy efficiency.
ii. Reliability.
iii. Redundancy.

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iv. Environmental stability.

Because habitat failure could threaten human life, thermal control systems require exceptionally high reliability.

Structural stability and habitat reinforcement

Natural underground cavities may reduce excavation requirements, but they do not eliminate the need for engineering reinforcement.

Geological variability

Subsurface environments exhibit substantial variability in:

a) Rock strength.
b) Fracture density.
c) Ice composition.
d) Mechanical behavior.

Consequently, each habitat location requires site-specific analysis.

Reinforcement strategies

Potential approaches include:

A. Rock bolting.
B. Structural liners.
C. Composite reinforcement systems.
D. Regolith-based construction materials.
E. Additively manufactured support structures.

Long-term performance

A key challenge is ensuring stability over decades or centuries.

Factors affecting long-term performance include:

a) Thermal cycling.
b) Material fatigue.
c) Creep deformation.
d) Seismic activity.
e) Human-induced stresses.

These issues remain insufficiently studied for extraterrestrial environments.

Excavation technologies

Habitat construction requires the creation of sufficient internal volume to support habitation, agriculture, industry, and transportation.

Conventional excavation

Near-term settlement concepts generally rely on adaptations of terrestrial technologies such as:

a) Tunnel boring machines.
b) Mechanical drills.
c) Blasting systems.
d) Robotic excavation equipment.

These technologies benefit from extensive operational experience on Earth.

Advanced excavation concepts

Proposed alternatives include:

i. Laser excavation.
ii. Plasma drilling.
iii. Microwave-assisted excavation.
iv. Thermal excavation of ice.

Although promising, these approaches remain largely experimental and have not been validated at operational scale.

Key constraint: energy

Excavation is fundamentally an energy-intensive activity.

The rate at which settlements can expand may ultimately be constrained more by available energy than by excavation technology itself.

This issue has received comparatively little attention in settlement literature and deserves greater investigation.

Construction and manufacturing systems

Excavation alone does not create habitable environments. Underground spaces must be converted into functional infrastructure.

Construction requirements

Habitats require:

A. Pressure vessels.
B. Internal partitions.
C. Utilities.
D. Transportation systems.
E. Environmental control systems.

Local manufacturing

To reduce dependence on Earth, future settlements are expected to rely heavily on local production.

Potential technologies include:

a) Additive manufacturing.
b) Regolith-derived construction materials.
c) Automated assembly systems.
d) In-situ fabrication facilities.

Current status

Laboratory demonstrations have shown encouraging results, particularly for regolith-based construction. However, large-scale extraterrestrial implementation remains unproven.

Transportation and internal infrastructure

As settlements expand, transportation systems become increasingly important.

Internal transportation

Potential systems include:

a) Electric vehicles.

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b) Automated rail systems.

c) Conveyor networks.

d) Autonomous logistics systems.

Utility infrastructure

Habitats must also support:

A. Power distribution.

B. Water circulation.

C. Waste management.

D. Communications networks.

E. Emergency systems.

The complexity of these systems increases substantially with settlement size.

Scalability challenges

While infrastructure requirements for small research stations are relatively well understood, little research has examined the engineering requirements of underground settlements supporting tens of thousands or millions of inhabitants.

Technology readiness and major constraints

The engineering requirements reviewed in this section vary considerably in technological maturity (Table 2).

Table 2 Engineering technologies relevant to underground habitats

Technology	Current status	Approximate readiness	Major challenges
Radiation Shielding	Well understood	High	Long-term biological effects
Pressurized Habitats	Demonstrated in space	Medium-High	Scaling to large volumes
Thermal Control	Demonstrated	High	Large-scale reliability
Mechanical Excavation	Mature on Earth	Medium	Extraterrestrial adaptation
Autonomous Construction	Emerging	Medium-Low	Reliability and maintenance
ISRU Construction Materials	Experimental	Medium-Low	Industrial-scale production
Laser/Plasma Excavation	Experimental	Low	Power requirements
Large Underground Cities	Conceptual	Low	Multiple unresolved challenges

Overall, current evidence suggests that many individual technologies required for underground habitation already exist in some form. However, the integration of these systems into large, self-sustaining extraterrestrial settlements has not yet been demonstrated. Consequently, engineering feasibility should presently be considered plausible but unproven, with substantial uncertainties remaining regarding scalability, reliability, and long-term operational sustainability.

Life-support systems and human habitability

The long-term viability of underground settlements depends not only on engineering infrastructure but also on the ability to sustain human life in isolated and resource-constrained environments. Life-support systems must provide air, water, food, waste management, environmental stability, and psychological well-being while minimizing dependence on resupply from Earth.

Unlike short-duration missions, permanent settlements require systems capable of functioning continuously over years, decades, or potentially generations. Consequently, life-support and habitability considerations represent some of the most important and least resolved challenges in extraterrestrial settlement research.

Closed ecological life-support systems (CELSS)

One of the central objectives of long-term settlement planning is reducing dependence on imported supplies. Closed Ecological Life-Support Systems (CELSS) seek to accomplish this objective by recycling air, water, nutrients, and waste through integrated biological and technological processes.

In principle, CELSS function by establishing controlled ecological cycles in which:

a) Humans consume oxygen and food.

b) Plants and photosynthetic organisms produce oxygen.

c) Water is continuously recycled.

d) Organic waste is processed and reused.

e) Nutrients circulate through biological and technological pathways.

Experimental research

Several major research programs have explored aspects of ecological closure:

i. Biosphere 2 (United States).

ii. MELiSSA (European Space Agency).

iii. NASA bioregenerative life-support programs.

iv. Controlled ecological test facilities in Russia, China, and Japan.

These programs have demonstrated that substantial recycling efficiencies are achievable. However, they have also revealed the complexity of maintaining stable ecological systems over extended periods.

Major challenges

Persistent challenges include:

a) Nutrient imbalances.

b) Microbial population shifts.

c) Crop failures.

d) Pest management.

e) System resilience to disturbances.

f) Ecological unpredictability.

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Even relatively small biological systems may exhibit complex behaviors that are difficult to predict or control.

Current assessment

Although significant progress has been achieved, no fully closed ecological system capable of indefinitely supporting a large human population has yet been demonstrated. Consequently, CELSS remain a promising but still developing technology area.

Water recovery and recycling

Water is one of the most essential resources for human survival and settlement operations.

In addition to drinking water, settlements require water for:

a) Agriculture.
b) Hygiene.
c) Industrial processes.
d) Thermal regulation.
e) Oxygen production.

Because transportation of water from Earth is costly, efficient recycling is considered essential.

Existing technologies

Modern spacecraft already employ advanced water recovery systems.

Examples include:

a) Condensate recovery.
b) Urine recycling.
c) Filtration technologies.
d) Chemical purification systems.

The International Space Station has demonstrated water recovery efficiencies exceeding those achieved in most terrestrial systems.

Long-term considerations

Permanent settlements will require:

A. Higher recycling rates.
B. Greater system reliability.
C. Reduced maintenance demands.
D. Integration with agricultural systems.

Although high levels of water recycling appear achievable, fully closed water systems have not yet been demonstrated at settlement scale.

Food production systems

Food production represents one of the largest ongoing resource requirements for long-duration settlements.

Importing food indefinitely from Earth would impose substantial logistical and economic burdens. Consequently, most settlement concepts assume increasing levels of local agricultural production.

Controlled environment agriculture

Several agricultural approaches have received attention:

A. Hydroponics.
B. Aeroponics.
C. Vertical farming.
D. Controlled-environment greenhouses.

These methods offer several advantages:

a) Reduced water consumption.
b) Improved productivity per unit area.
c) Controlled environmental conditions.
d) Reduced exposure to pests and contaminants.

Crop selection

Suitable crops must balance:

a. Nutritional value.
b. Growth rate.
c. Resource efficiency.
d. Reliability.

Research on space agriculture has focused on species including:

a) Wheat.
b) Potatoes.
c) Soybeans.
d) Lettuce.
e) Tomatoes.
f) Various legumes.

However, no consensus exists regarding optimal crop portfolios for long-duration settlements.

Remaining uncertainties

Major research gaps include:

A. Agricultural performance under reduced gravity.
B. Multi-generational crop cultivation.
C. Ecosystem resilience.
D. Resource requirements at urban scales.

Algae, aquaculture, and integrated biological systems

Many researchers have proposed supplementing conventional agriculture with highly productive biological systems.

Algal cultivation

Algae offer several potential advantages:

a) High productivity.
b) Oxygen generation.
c) Carbon dioxide utilization.
d) Waste processing.
e) Nutritional value.

Because of their efficiency, algae are frequently included in CELSS concepts.

Aquaculture

Fish and other aquatic organisms may provide important protein sources.

Integrated aquaponic systems combine:

a) Fish production.

b) Plant cultivation.

c) Nutrient recycling.

Such systems can improve overall resource efficiency but also increase ecological complexity.

System complexity

As biological diversity increases, so does the difficulty of ecosystem management.

Future settlements must balance ecological resilience against operational simplicity.

Atmospheric management and environmental quality

Maintaining a breathable atmosphere is a fundamental requirement of any habitat.

Atmospheric management systems must regulate:

a) Oxygen concentration.

b) Carbon dioxide levels.

c) Humidity.

d) Air circulation.

e) Trace contaminants.

f) Particulate matter.

Lessons from spaceflight

Experience aboard spacecraft and space stations has demonstrated that air quality management remains a continuous operational requirement.

Potential concerns include:

a) Accumulation of contaminants.

b) Microbial growth.

c) Equipment failures.

d) Fire hazards.

Long-term underground settlements will likely require more sophisticated environmental monitoring than current spacecraft.

Monitoring and automation

Advanced sensor networks and automated control systems may play an important role in maintaining environmental stability and responding to anomalies.

Human health in reduced-gravity environments

One of the most significant unknowns in settlement planning concerns the long-term effects of reduced gravity.

Research conducted aboard the International Space Station has identified several physiological effects associated with microgravity exposure:

a. Bone density loss.

b. Muscle atrophy.

c. Cardiovascular changes.

d. Visual impairment.

e. Altered immune responses.

Although partial gravity environments such as the Moon and Mars may mitigate some of these effects, insufficient data currently exist to determine whether long-term habitation is safe.

Medical infrastructure

Permanent settlements will require:

a) Diagnostic capabilities.

b) Preventive healthcare systems.

c) Emergency medical facilities.

d) Telemedicine support.

e) Long-term health monitoring.

Healthcare requirements become increasingly important as populations grow and diversify.

Research priorities

Further investigation is needed to determine:

A. Human adaptation to lunar gravity.

B. Human adaptation to Martian gravity.

C. Reproductive health in reduced gravity.

D. Multi-generational health outcomes.

These questions remain largely unresolved.

Psychological and social habitability

Engineering systems alone cannot ensure settlement success. Human beings possess psychological, emotional, and social needs that strongly influence long-term well-being.

Studies of Antarctic stations, submarines, isolation experiments, and space missions indicate that confined environments can produce challenges including:

a) Social conflict.

b) Stress.

c) Anxiety.

d) Depression.

e) Reduced group cohesion.

Habitat design strategies

Several approaches have been proposed to improve psychological well-being:

A. Access to vegetation.

B. Naturalistic lighting.

C. Open communal spaces.

D. Recreational facilities.

E. Private living areas.

F. Cultural and educational activities.

These strategies are often grouped under the concept of biophilic design.

Long-term unknowns

Little empirical evidence exists regarding multi-decade or multi-generational habitation within enclosed underground environments.

Consequently, psychological adaptation remains one of the least understood aspects of future settlement planning.

Artificial gravity as a habitability strategy

Artificial gravity is frequently proposed as a potential solution to health problems associated with reduced gravity.

Most concepts rely on rotational systems that generate centripetal acceleration.

Potential applications include:

A. Residential habitats.

B. Medical facilities.

C. Agricultural systems.

D. Research laboratories.

Current status

Although the underlying physics is well understood, no large-scale rotating habitat has yet been constructed or tested.

Important uncertainties remain regarding:

I. Human adaptation.

II. Engineering complexity.

III. Construction costs.

IV. Integration with underground settlements.

Consequently, artificial gravity should presently be regarded as a promising but unproven mitigation strategy.

Major challenges and research priorities

Life-support systems represent one of the most significant barriers to long-term extraterrestrial settlement.

Table 3 summarizes the current status of major habitability technologies.

Table 3 Life-support and habitability systems

System	Current status	Demonstrated scale	Major uncertainties
Water Recycling	Operational in space	Small crews	Long-term scaling
Atmospheric Control	Operational in space	Small crews	Urban-scale implementation
Controlled Agriculture	Experimental	Pilot scale	Reduced gravity performance
CELSS	Experimental	Limited	Long-term ecological closure
Aquaponics	Experimental	Pilot scale	Ecosystem stability
Artificial Gravity	Conceptual	None	Human adaptation and cost
Multi-Generational Habitation	Not demonstrated	None	Health and social outcomes

Current evidence suggests that many individual life-support technologies are technically feasible. However, the integration of these systems into large, self-sustaining settlements remains unproven. As a result, long-term habitability should be regarded as one of the most important research frontiers for underground settlement studies.

Energy and resource systems

The viability of underground settlements depends fundamentally on the availability of reliable energy supplies and accessible material resources. Energy is required to support virtually every settlement function, including life support, environmental control, excavation, construction, manufacturing, transportation, communications, and scientific operations. Similarly, access to local resources is essential for reducing dependence on costly imports from Earth and enabling long-term settlement growth.

Because energy production and resource utilization are closely interconnected, they are considered together in this section.

Energy requirements for subsurface settlements

Energy demand is likely to increase substantially as settlements grow in scale and complexity.

Small scientific outposts may require energy primarily for:

a) Life-support systems.

b) Communications.

c) Scientific equipment.

d) Thermal control.

By contrast, larger settlements may require additional energy for:

a. Excavation and tunneling.

b. Industrial manufacturing.

c. Resource processing.

d. Transportation infrastructure.

e. Agricultural production.

f. Water extraction and purification.

Consequently, energy availability may become one of the principal constraints on settlement expansion.

The excavation-energy relationship

One frequently overlooked issue in settlement literature is the strong relationship between excavation and energy consumption.

Creating habitable underground volumes requires:

a) Material removal.

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b) Transportation of excavated material.

c) Structural reinforcement.

d) Environmental conditioning.

All of these processes consume significant amounts of energy. As settlement size increases, total excavation requirements may become comparable to those of major terrestrial mining or civil-engineering projects. Therefore, future settlement growth may depend as much on energy production capacity as on excavation technology itself.

Solar energy

Solar power is among the most mature and widely studied energy technologies for space applications.

Current spacecraft, satellites, and many proposed planetary habitats rely extensively on photovoltaic systems.

Advantages

Solar energy offers several important benefits:

A. High technological maturity.

B. Operational experience in space.

C. Modular scalability.

D. Minimal fuel requirements.

E. Low operational complexity.

Limitations

Solar power performance varies substantially across the Solar System.

Important limitations include:

A. Reduced solar intensity with increasing distance from the Sun.

B. Lunar night cycles.

C. Martian dust accumulation.

D. Seasonal variations.

E. Energy storage requirements.

For example, solar flux at Jupiter is approximately 4% of that received at Earth, making solar-dependent settlement increasingly challenging in the outer Solar System.

Assessment

Solar energy appears well suited for early settlements on the Moon and Mars. However, reliance on solar power alone may prove insufficient for large-scale industrial development or operations in distant regions of the Solar System.

Nuclear fission power

Nuclear fission is widely regarded as one of the most promising energy sources for long-duration extraterrestrial settlements. Unlike solar power, fission systems can provide continuous power independent of environmental conditions.

Potential advantages

Key benefits include: High energy density, Continuous operation, Independence from sunlight, Compatibility with remote and underground locations.

Several national space agencies have actively investigated compact fission reactors for lunar and Martian applications.

Engineering challenges

Potential concerns include Reactor deployment logistics, Heat rejection, Radiation shielding, Operational safety, Waste management.

Although terrestrial experience with nuclear power is extensive, space-specific operational requirements introduce additional complexities.

Current Assessment

Among currently available technologies, fission power represents one of the most credible options for supporting permanent extraterrestrial settlements.

Fusion energy: potential and uncertainty

Fusion energy is frequently cited as a transformative technology for future space settlement.

If successfully commercialized, fusion could provide:

a) Extremely high energy output.

b) Reduced fuel transportation requirements.

c) Support for large-scale industrial activities.

d) Enhanced deep-space transportation capabilities.

Current status

Despite decades of research, commercial fusion power has not yet been demonstrated.

Numerous technical challenges remain, including sustained net energy production, reactor durability, operational economics, and maintenance requirements.

Implications for settlement planning

Many settlement scenarios assume future availability of fusion power. However, such assumptions should be treated cautiously.

At present, fusion should be regarded as a potentially important future technology rather than a capability that can be incorporated into near-term settlement architectures.

Geothermal and local energy sources

Certain planetary bodies may possess exploitable geothermal resources.

Potential candidates include Mars, Europa, Enceladus, Io.

In principle, geothermal energy could provide:

a) Continuous power generation.

b) Thermal energy for habitats.

c) Support for industrial activities.

Current Limitations

The availability and accessibility of extraterrestrial geothermal resources remain poorly understood.

Major uncertainties include:

a) Resource distribution.

b) Drilling feasibility.
c) Infrastructure requirements.
d) Long-term sustainability.

Consequently, geothermal energy remains an interesting possibility but cannot currently be considered a primary settlement power source.

Energy storage systems

Reliable energy production alone is insufficient; settlements must also maintain energy reserves capable of supporting operations during interruptions or peak demand periods.

Potential storage technologies include:

A. Electrochemical batteries.
B. Hydrogen storage systems.
C. Thermal storage.
D. Flywheel systems.
E. Regenerative fuel cells.

Importance for settlement resilience

Energy storage contributes to operational reliability, emergency preparedness, load balancing, renewable energy integration.

Future settlements will likely employ combinations of storage technologies rather than relying on a single solution.

In-situ resource utilization (ISRU)

In-Situ Resource Utilization (ISRU) refers to the extraction and processing of local materials to support settlement operations. ISRU is widely viewed as a critical enabling technology because transportation from Earth remains expensive and logistically constrained.

Potential product

Proposed ISRU products include water, oxygen, hydrogen, construction materials, metals, industrial chemicals.

Current development status

Numerous ISRU concepts have been investigated through laboratory studies and technology demonstrations.

Examples include:

a) Oxygen extraction from lunar regolith.
b) Water recovery from Martian ice deposits.
c) Production of construction materials from regolith simulants.

These studies provide encouraging evidence of technical feasibility but remain limited in scale.

Key challenges

Important barriers include industrial scaling, equipment durability, energy requirements, process reliability, and maintenance logistics.

As a result, ISRU should currently be viewed as a developing capability rather than a mature industrial system.

Resource extraction and mining

Many settlement concepts incorporate mining as both a logistical necessity and a potential economic activity.

Resources of interest include, water ice, metal-bearing ores, rare elements, industrial minerals, volatile compounds.

Benefits of local resource extraction

Local resource production may:

a) Reduce import requirements.
b) Enable infrastructure growth.
c) Support manufacturing activities.
d) Increase settlement autonomy.

Constraints

Mining in extraterrestrial environments introduces unique challenges:

a) Reduced gravity.
b) Dust generation.
c) Equipment wear.
d) Transportation difficulties.
e) Limited maintenance capability.

In addition, economic viability depends on market demand, transportation costs, and competition from terrestrial sources.

Current assessment

While resource extraction appears technically plausible, the scale and profitability of future extraterrestrial mining operations remain uncertain.

Resource economics and sustainability

Technological feasibility does not necessarily imply economic viability.

Many settlement studies emphasize engineering solutions while devoting comparatively little attention to economic sustainability.

Factors influencing viability

Key considerations include: infrastructure costs, energy availability, resource quality, transportation expenses, population size, trade opportunities.

Early settlement economics

Historical experience suggests that early settlements may depend heavily on external support.

Potential initial motivations may include scientific research, Strategic objectives, Exploration, Technology development. Commercial profitability may emerge only after substantial infrastructure has been established.

Long-term sustainability

Whether large underground settlements can ultimately become economically self-sustaining remains an open question.

At present, no widely accepted economic model demonstrates the profitability of large-scale extraterrestrial settlement.

Comparative assessment and research priorities

The literature suggests that energy and resource systems represent both major opportunities and major constraints for underground settlement (Table 4).

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Table 4 Energy and resource technologies relevant to underground settlement

Technology/system	Current status	Approximate readiness	Principal uncertainties
Solar Power	Operational in space	High	Storage and outer Solar System performance
Nuclear Fission	Mature technology	Medium-High	Space deployment and safety
Fusion Power	Experimental	Low	Commercial feasibility
Geothermal Energy	Conceptual for space use	Low	Resource accessibility
Water Extraction	Demonstrated in principle	Medium	Industrial-scale deployment
Oxygen Production from Regolith	Experimental	Medium	Scaling and reliability
Additive Manufacturing with Local Materials	Experimental	Medium-Low	Structural performance
Large-Scale Extraterrestrial Mining	Conceptual/Early development	Low	Economics and scalability

Overall, current evidence indicates that many of the individual technologies required for resource production and energy generation are technically plausible. However, substantial uncertainties remain regarding their integration, scaling, economic viability, and long-term reliability. Consequently, energy and resource systems should be regarded as one of the most important determinants of future settlement feasibility and a major priority for continued research.

Governance, economics, and long-term development

While engineering and life-support technologies are essential prerequisites for extraterrestrial settlement, long-term success ultimately depends upon the development of sustainable social, economic, and governance systems. Historical experience demonstrates that infrastructure alone does not guarantee the viability of permanent settlements. Human communities require institutions capable of managing shared resources, resolving conflicts, coordinating economic activity, and adapting to changing environmental and social conditions.

Compared with habitat engineering, governance and settlement economics remain relatively underdeveloped areas of research. Consequently, many aspects of long-term extraterrestrial societal development remain uncertain.

Economic sustainability of underground settlements

One of the central questions in settlement research concerns whether permanent extraterrestrial communities can become economically self-sustaining.

Although technological feasibility receives considerable attention in the literature, economic viability is often addressed only qualitatively. Yet long-term settlement requires the continuous production of goods and services sufficient to justify infrastructure costs and support resident populations.

Potential economic functions

Several economic activities have been proposed as potential foundations for extraterrestrial settlements:

a) Scientific research.

b) Resource extraction.

c) Manufacturing.

d) Transportation support services.

e) Energy production.

f) Data processing and communications.

g) Tourism and exploration.

The relative importance of these activities will likely vary according to location, available resources, technological capabilities, and market demand.

Frontier settlement analogs

Historical frontier settlements on Earth often depended on substantial external investment during early stages of development.

Similarly, initial extraterrestrial settlements may require prolonged support from governments, international partnerships, or private organizations before achieving significant economic autonomy.

Major uncertainties

Key unresolved questions include:

A. The cost of settlement infrastructure.

B. The value of extraterrestrial resources.

C. Future transportation costs.

D. Population growth rates.

E. Market demand for exported products.

At present, no broadly accepted economic model demonstrates the profitability of large underground settlements beyond Earth.

Resource governance and common infrastructure

Underground settlements are likely to depend heavily on shared infrastructure systems.

Examples include:

a) Life-support systems.

b) Energy networks.

c) Transportation systems.

d) Water recycling facilities.

e) Communications infrastructure.

These systems differ from many terrestrial resources because failure may pose immediate risks to human survival.

Common-pool resource challenges

Research on common-pool resources suggests that shared systems require effective governance mechanisms to prevent overuse,

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inequitable allocation, infrastructure degradation, coordination failures.

Because life-support systems are essential for habitation, governance structures must ensure both efficiency and reliability.

Infrastructure dependence

The high degree of interdependence expected within underground settlements may necessitate forms of coordination that differ significantly from those observed in many contemporary terrestrial communities. However, empirical evidence remains limited because no permanent extraterrestrial settlement currently exists.

Legal and regulatory frameworks

Human activities in space currently operate within a framework of international agreements, national regulations, and institutional practices.

The most significant legal foundation remains the Outer Space Treaty of 1967, which established key principles governing exploration and use of outer space.

Existing legal principles

Current international agreements address issues including:

a) Peaceful use of outer space.

b) National responsibility for space activities.

c) Liability for damages.

d) Scientific cooperation.

e) Protection of celestial bodies.

Emerging questions

Large permanent settlements raise additional questions that remain unresolved:

A. Property rights.

B. Resource ownership.

C. Jurisdiction.

D. Taxation.

E. Labor regulations.

F. Environmental protection.

As settlement activities expand, legal frameworks may require substantial adaptation to accommodate permanent human communities beyond Earth.

Research needs

Space law scholars increasingly emphasize the need for proactive examination of settlement governance before large-scale habitation becomes technologically feasible.

Governance models for future settlements

A wide range of governance models has been proposed in settlement literature.

These include:

a) Nationally administered settlements.

b) International research communities.

c) Corporate-operated settlements.

d) Cooperative communities.

e) Hybrid public-private systems.

Each model presents distinct advantages and challenges.

Government-led approaches

Government-administered settlements may benefit from:

a) Stable funding.

b) Regulatory oversight.

c) Long-term planning capacity.

However, they may also face bureaucratic constraints and political fluctuations.

Corporate models

Commercial organizations may provide:

a) Operational efficiency.

b) Investment capital.

c) Innovation incentives.

Potential concerns include:

a) Accountability.

b) Labor relations.

c) Monopoly power.

d) Concentration of critical infrastructure.

Cooperative and community models

Cooperative structures may encourage:

a) Shared decision-making.

b) Community participation.

c) Social cohesion.

However, questions remain regarding scalability and operational efficiency in highly technical environments.

Current assessment

Because no permanent extraterrestrial settlement yet exists, there is insufficient evidence to determine which governance model would be most effective. Comparative analysis therefore remains largely theoretical.

Human communities and social development

Long-term settlements will eventually evolve beyond their initial engineering and scientific functions.

As populations increase, communities may develop:

a) Educational institutions.

b) Cultural traditions.

c) Economic specialization.

d) Political structures.

e) Social identities.

Population growth

Most settlement concepts assume gradual population expansion.

However, the demographic dynamics of extraterrestrial communities remain highly uncertain and may depend on:

a) Immigration rates.

b) Birth rates.

c) Economic opportunities.

d) Environmental conditions.

Cultural evolution

Isolation, environmental constraints, and unique settlement experiences may contribute to the emergence of distinctive local cultures.

Such developments are common throughout human history but remain difficult to predict in extraterrestrial contexts.

Knowledge gaps

Research concerning the social evolution of long-duration space communities remains limited and represents an important interdisciplinary research opportunity.

Development pathways for underground settlements

Many settlement studies propose phased development models rather than immediate large-scale colonization.

Although specific frameworks vary, most envision progressive expansion through several stages.

Stage 1: Exploration and characterization

Robotic missions identify suitable sites and evaluate local resources.

Stage 2: Technology Demonstration

Pilot systems test excavation, ISRU, habitat construction, and life-support technologies.

Stage 3: Initial human presence

Small crews establish continuously occupied facilities with substantial support from Earth.

Stage 4: Infrastructure expansion

Growing reliance on local resources reduces logistical dependence on Earth.

Stage 5: Mature settlement

Larger populations support diversified economic and social activities.

Limitations of development models

These stages should be interpreted as conceptual frameworks rather than predictive timelines.

Actual development trajectories will depend on technological progress, economic incentives, political priorities, and societal choices.

Underground habitats and planetary terraforming

Underground habitation is often discussed as an alternative to planetary terraforming. However, the relationship between these approaches may be more complementary than competitive.

Advantages of underground habitation

Subsurface habitats offer several near-term advantages:

a) Reduced environmental modification requirements.

b) Natural radiation shielding.

c) Applicability across diverse planetary environments.

d) Lower initial infrastructure demands.

Potential benefits of terraforming

If technically achievable, terraforming could eventually provide:

a) Expanded habitable surface areas.

b) Reduced dependence on enclosed habitats.

c) More Earth-like environmental conditions.

Comparative perspective

Current scientific understanding suggests that underground habitats are likely to be achievable on significantly shorter timescales than planetary-scale environmental modification.

Nevertheless, future settlement strategies may incorporate combinations of underground habitats, surface settlements, and partially modified environments.

Consequently, underground habitation should not necessarily be viewed as a replacement for terraforming but rather as one component of a broader settlement continuum.

Long-term settlement scenarios and uncertainties

Discussions of future Solar System civilizations frequently appear in both scientific and popular literature. However, such scenarios involve substantial uncertainties extending far beyond current empirical knowledge.

Critical unknowns include:

a) Long-term economic sustainability.

b) Population growth trajectories.

c) Transportation infrastructure development.

d) Governance evolution.

e) Technological breakthroughs.

f) Human adaptation to extraterrestrial environments.

Scenario-based thinking

Rather than making deterministic predictions, it is more appropriate to view future settlement outcomes as a range of possible scenarios.

Potential futures include:

a) Isolated scientific outposts.

b) Regional settlement networks.

c) Industrial resource hubs.

d) Large permanent communities.

Current evidence does not support confident forecasts regarding which pathway, if any, will ultimately emerge.

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Research priorities and future directions

The literature reviewed throughout this article highlights several major research priorities that must be addressed before underground settlements can be evaluated as a practical strategy for long-term human expansion beyond Earth.

Geological priorities

A. Characterization of lava tubes and subsurface cavities.

B. Ice mechanics and long-term stability.

C. Resource distribution mapping.

Engineering priorities

a) Autonomous excavation systems.

b) Large-scale habitat construction.

c) Long-duration structural integrity.

d) Dust mitigation technologies.

Life-support priorities

i. Ecological closure.

ii. Reduced-gravity agriculture.

iii. Multi-generational habitability.

iv. Integrated biological systems.

Human and social priorities

a) Psychological adaptation.

b) Community development.

c) Governance systems.

d) Legal frameworks.

Economic priorities

a. Infrastructure cost assessment.

b. Resource economics.

c. Transportation models.

d. Long-term sustainability analyses.

Addressing these research gaps will require collaboration across planetary science, engineering, ecology, economics, social science, and policy disciplines.[1–30]

Conclusion

This review examined underground terraforming as a framework for human settlement within subsurface environments across a broad range of Solar System bodies.

Current evidence indicates that subsurface habitats offer several important advantages, including natural radiation shielding, thermal stability, and protection from surface hazards, and potential access to local resources. These characteristics make underground habitation one of the most frequently proposed strategies for long-duration human presence beyond Earth.

At the same time, substantial challenges remain unresolved. Major uncertainties include excavation scalability, habitat construction, ecological life-support closure, long-term human adaptation, economic sustainability, governance structures, and the deployment of autonomous systems at settlement scale.

Importantly, many technologies frequently associated with large underground settlements—including fully autonomous construction systems, mature closed ecological biospheres, commercial fusion power, and extensive extraterrestrial industrial networks—have not yet been demonstrated. Their future availability should therefore be regarded as uncertain rather than assumed.

Based on the current literature, underground terraforming should not be viewed as a demonstrated pathway to Solar System colonization. Rather, it represents a promising interdisciplinary research framework that integrates planetary geology, habitat engineering, life-support systems, resource utilization, human factors, economics, and governance.

Future progress will depend upon advances across these fields as well as the acquisition of new empirical data from lunar, Martian, asteroid, and outer Solar System exploration. If these challenges can be successfully addressed, subsurface habitats may become an important component of long-term human expansion beyond Earth. The scale and ultimate significance of that contribution, however, remain open scientific and engineering questions.

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