

Review Article

Karst Cave as Terrestrial Simulation Platform to Test and Design Human Base in Lunar Lava Tube

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Developing efficient approaches to building a suitable environment for humans on the moon play a key role in future long-term sustainable lunar exploration activities, which has motivated many countries to propose diverse plans to build a lunar base. The lava tubes discovered by the Kaguya mission offer huge potential sites to host such bases. Through computation and analysis, we show that lunar lava tubes offer stable structures, suitable temperatures, low radiation doses, and low meteorite impact rates. We summarize previous research results and put forward the conditions to find and use a suitable lunar lava tube for human habitation on the moon. The establishment of extraterrestrial bases still faces many technical bottlenecks; many countries have begun to use the earth's environment for extraterrestrial exploration and simulation missions. In this regard, we proposed the idea of using the Earth's karst caves to simulate extraterrestrial lava tubes, selected caves in Chongqing as the simulation site, and demonstrated the feasibility from both structural and environmental aspects. Finally, we proposed a karst cave simulation platform with three main research directions: cave sealing technology, efficient daylight system, and internal circulation research of artificial ecosystems containing natural soil and rock. We hope to promote the development of related research on extraterrestrial bases through simulation experiments.

1. Introduction

Extraterrestrial exploration offers humankind new perspectives to expand human presence in space beyond Earth, develop science and technology, and access to precious resources in space. However, the environment of extraterrestrial planets is usually extremely hostile, with extreme temperature, high vacuum, low gravity, large cosmic radiation, harmful dust, and a high frequency of small meteorite impacts. If human beings want to survive on the other planets for a long time, they must first find or set up a safe, stable, and long-term shelter.

Caves can provide people with natural protection against harsh environments, as they represent the cradle of human culture and society and are still in use today. In northern China, about 40 million people live in caves (called cave dwellings), and the largest cave-dwelling community in Europe can be found in Granada, Spain. These caves usually have a relatively stable temperature, so people normally live in them. Caves on the earth can provide a suitable living envi-

ronment for human beings. Similarly, recent studies have shown that caves on other planets could also provide necessary protection for crews to establish initial settlements.

Lunar lava tubes are geological structures of the moon discovered in recent years. They take the shape of hollow pipe-shaped caves formed on the surface of the planet by volcanic activity as natural results of the ejection and further cooling of high-temperature low-viscosity basaltic magma flowing on the lunar surface. While the flow continuously cools, a shell of a certain thickness is consolidated on the surface of the lava flow, forming an insulating protective layer. At the beginning of its formation, the lava tube is a nearly circular pipe. Then, as the lava is continuously replenished and consolidated, the bottom is continuously filled, gradually forming a tubular structure with a round-semicircular top and a flat bottom [1–3]. Because a lunar lava tube has a hard basalt roof, its internal environmental factors such as temperature changes, radiation doses, and the probability of being hit by meteorites are relatively limited. As such, it offers in theory an ideal human lunar habitat

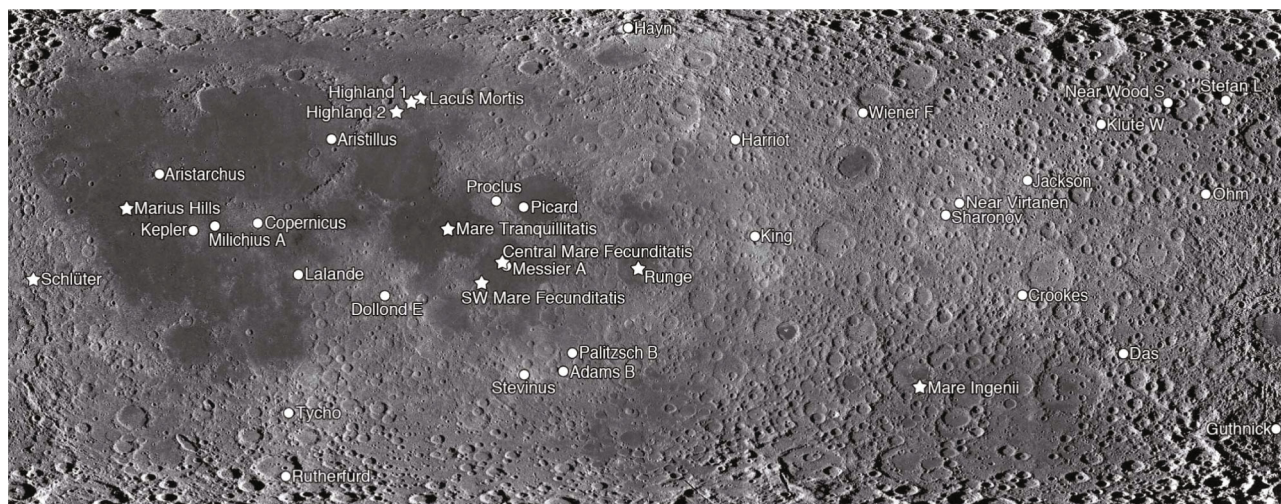


FIGURE 1: Map of the locations of the eight known mare pits and two known highland pits (stars), and the 29 known craters with impact melt pits (dots). The map extends from 70°N to 70°S, 90°W, to 270°E [7].

[3, 4]. The underground volcanic structures have previously been proposed as ideal sites for human settlements. Scientists have now assessed how stable these features might be and found that tubes of 1 km in size and bigger would be structurally sound. They could protect against the challenges posed by the lunar environment.

The first examples of lunar lava tubes were discovered by a Japanese research team, which analyzes the lunar holes (i.e., skylights) that appeared in the JAXA Kaguya exploration mission data based on their location within a sinuous rill [4]. Since then, evidence of new lava tubes has been discovered continuously [5–7]. Until now, more than 300 potential cave entrances have been identified on the moon [8]. The “skylight” is a kind of pit caused by the active lava tube collapsing. Also, most lunar lava tubes are discovered on the mare of the moon. The distribution of lunar lava tube “skylights” on the moon is shown in Figure 1.

Due to the low gravity and high eruption rate, the volume of the lunar lava tube hole is one to three times more than that on earth [9]. According to the gravity data of the GRAIL probe, the width of the lunar lava pipeline is expected to reach 1–2 km [10], and the length can reach tens to hundreds of kilometers [11].

Demonstrating in practice that such caves are indeed suitable for human habitation requires tremendous simulation experiments on Earth. This, indeed, implies to identify a reasonable Earth analog to lunar lava tubes. Attempts to simulate long-term human occupation of extraterrestrial bases have been carried out since the 1950s [12], among which, the most famous experiments are the “BIOS-3” ground simulation system launched by the former Soviet Union in 1972, the BPC (Biomass production chamber) laboratory of the Kennedy Space Center in the United States, Biosphere 2, Chang’e-4 lunar surface micro-ecosystem developed by Center of Space Exploration (China), the experimental cabin in Chinese Astronaut Training Center (Shenzhen), and Moon-Mars analogue bases by HI-SEAS in Hawaii [8, 13–17]. At present, the small-scale ground simulation level is sufficiently to test and validate the closed-

circuit circulation of water and oxygen, but the circulation of food cannot yet be guaranteed. With large-scale ground simulation experiments such as Biosphere 2, the current technical level cannot even guarantee the stability of the internal ecosystem for a long occupation period. It is thus difficult to achieve and maintain a closed loop of material.

For simulating whether the lunar lava tubes can be transformed into a base, we need to find a similar cave system on the earth. The widely distributed karst caves on the earth become one of the best choices. Karst caves are developed due to the excavation of soluble limestone by groundwater which is usually characterized by rocky floors, sinkholes, and underground rivers.

Biosphere 2 artificial ecological system is the most famous attempt. Biosphere 2 is a steel frame type with double-glazed window panels. It prohibits material transformation with the outside atmosphere and underground soil through engineering means but allows sunlight to pass through the glass structure for the photosynthesis of plants. However, it ultimately failed; the common view on this failure is that the oxygen content of Biosphere 2 decreased with time, which led to the inability of organisms to survive stably for a long time.

The soil and rocks in nature play a very key role in the ecosystem. Sealing the caves that exist in nature and preserving the role of soil and rocks in the ecosystem enable people to better understand the circulation of substances in nature and also can enhance the stability of the artificial ecosystem.

The objective of this paper is to introduce a research project that will establish on solid grounds the suitability of using lunar lava tubes for human habitation, using parallel studies of the lunar habitat itself and realistic simulation studies on Earth using karst caves as an Earth analog of lunar lava tubes. In Section 2, we will address the rationality of the choice of lunar lava tubes for hosting a future lunar base, focusing on mainly two aspects: (1) energy budget of the base required to maintain both the needs of human nutrition and respiration and a stable environment and (2) the safety conditions offered by lava tubes. In Section 3, we

TABLE 1: Light condition of the experiment and the edible dry matter yield and oxygen productivity of soybean (calculated with a planting area of 20m², 12.8~19.2 plants per m²) [19].

	Light intensity $\mu\text{mol}/\text{m}^2\cdot\text{s}$	Frequency * hz	Yield of edible dry matter g/d	Oxygen production rate g/d
Soybean	815	5.087×10^{14}	95.3	363.3

Note: *The frequency of the light is calculated by a wavelength of 589.3 nm.

analyzed the feasibility of the transformation from both the structure and the environment and proposed a transformation plan. In Section 4, we will analyze the significance of using the karst cave as a simulated platform.

2. The Rationality of Using a Lunar Lava Tube to Establish a Lunar Base

2.1. The Energy Estimation of Lunar Base. The lunar base needs to provide adequate food and protection with low power consumption. Water and food supply within artificial systems have been studied before [13, 16], and here we focus on energy consumption and protective effects that can be provided by lunar lava tubes.

The external energy required by the closed system involved in the operation of a human Lunar base mainly consists of three parts: human respiration, plant photosynthesis, and internal temperature control. Our estimates consider the basic survival needs of eight astronauts. Their living space is assumed to be a semicircular tunnel cave with an area of about 8,000 square meters and a height of 50 meters. These data can be used to help us predict the ground simulation system. More accurate data can be obtained from the simulation system and finally applied to the lunar base.

2.1.1. Energy Required to Maintain Basic Human Life. Oxygen, food, and suitable temperature need to be provided on bases for members to live. Studies have shown that the oxygen requirement of a normal adult is about 3.51 ml/min/kg [18]. Consider 8 astronauts with an average weight of 70 kg in a day and night on the moon (about 27 days, precise value is 2360591.47 seconds). The volume of oxygen required is 77333 L, and the weight is 101.155 kg according to the ideal gas equation (at 25 °C, 1 atmospheric pressure).

Regarding the calorie needs of adults, related studies have shown that human's recommended daily calorie intake is about 2900 kcal, while women's is about 2200 kcal [13]. Then, for 8 astronauts, the heat required in a day and night on the moon is about 557361.91 kcal (233034.337 kJ). According to the biomass of soybeans in NASA's Biomass Production Chamber (BPC) project, dry matter and oxygen production of soybean in closed ecosystems are shown in Table 1 [19]. Based on Wheeler's study about the nutrient composition of soybean, 20.253 kJ of energy per gram of soybeans in a closed system can be estimated [20].

According to the above data, two constraints can be established: oxygen constraint and energy constraint. Specifically, oxygen constraint means that the oxygen produced by the system in a day and night on the moon must be larger than or equal to the oxygen demand of 8 astronauts and plants themselves, and the energy constraint is the same.

Oxygen constraints in the system:

$$(363.3/24/3600) * 2360591.47 * x \geq 101155. \quad (1)$$

Energy constraints in the system:

$$(95.3/24/3600) * 20.253 * 2360591.47 * x \geq 2333034.37, \quad (2)$$

where x indicates the required area is several times larger than the BPC (BPC size is 20m²). Combining these two equations, it is clear that the wheat's units must be larger than 45 (900 m²). It means that 900 m² of soybeans can meet the food and oxygen needs of eight adults in one month (27 days). With the planted area, we can calculate the minimal energy that the system needs to obtain from the sun. From the light quantum energy equation, the energy provided to the crop during the production cycle of a day and night on the moon is

$$W = h \cdot \nu \cdot PPF \cdot S \cdot t \cdot x, \quad (3)$$

where W is totally required energy, J; h is Planck's constant, approximately 6.63×10^{-34} J · s; ν is the frequency of the light source irradiated on the crop canopy; according to the wavelength of the high-pressure sodium lamps, the value is 5.087×10^{14} hz; PPF is the intensity of light irradiated on the crop canopy ($\mu\text{mol}/\text{m}^2\cdot\text{s}$); S is the total area of the crop canopy in the device, m²; and t is the production time of the crop (27 days). Therefore, the total energy required to support eight astronauts living is 1.76×10^{11} J (48889 kW·h).

2.1.2. Energy Required to Maintain a Stable Internal Environment. There have been some previous studies about the temperature in lunar lava tubes [4, 21]. The average temperatures found at depths of 1.3 m and 2.3 m below the lunar surface of the Apollo 15 and 17 landing sites are -17 °C and -16 °C [6], and temperature also increases with depth [22]. Haruyama and others analyzed the thermal environment of Marius Hills Hole (303.3°E, 14.2°N), which has a diameter and depth of 50 m (Figure 2). The temperature change is relatively mild in areas not exposed to direct sunlight. Assuming that the internal temperature of the lunar lava tube base is 20 °C and the humidity is 85% [19], the specific heat capacity of the air in the system can be calculated [23]. The equation of specific heat capacity of humid air is as follows:

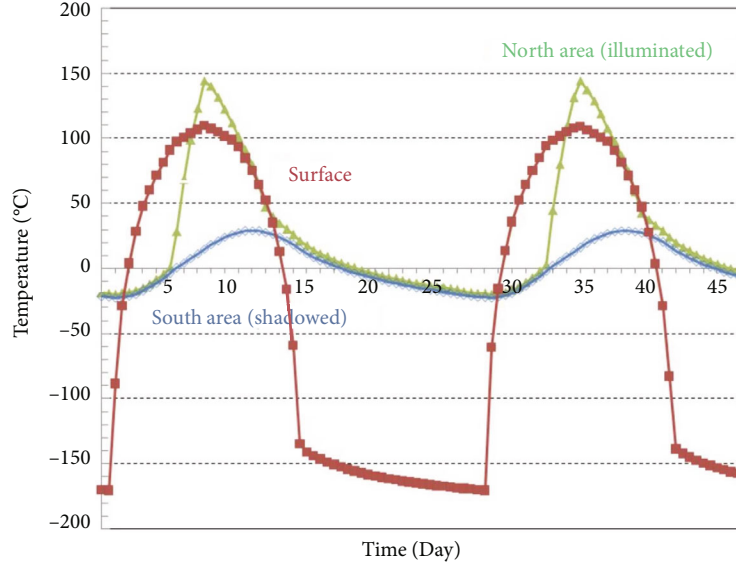


FIGURE 2: Lunar surface and lava tube illumination and shadow temperature simulation results; the red line represents the temperature change of the lunar surface, the blue line represents the temperature change of the southern shadow area of the Marius Cave, and the green line represents the temperature change of the northern light area of the Marius Cave (assume that the bottom and surface of the cave are covered with a weathered layer of about 2 cm, and its albedo is equal to 0.1) [6].

$$C_{p,ma} = \frac{C_{p,da}}{1+d} \left(1 + d \frac{C_{p,v}}{C_{p,da}} \right), \quad (4)$$

$$d = 0.622 \frac{\phi P_v}{P_{ma} - \phi P_v},$$

where $C_{p,ma}$ is the specific heat capacity of humid air at constant pressure, J/(kg·K); $C_{p,da}$ is the specific heat capacity of dry air at constant pressure, J/(kg·K); $C_{p,v}$ is the specific heat capacity of water vapor at constant pressure, J/(kg·K); d is air moisture content, kg/kg; P_{ma} is wet air pressure, pa; and P_v is the partial pressure of water vapor, pa. The equations of water vapor pressure and relative humidity [22] are as follows:

$$E = 6.112 \exp \left(\frac{17.67t}{t + 243.5} \right), \quad (5)$$

$$\phi = \frac{e}{E},$$

where E means saturated vapor pressure of air at a certain temperature, pa; e is the water vapor pressure of air at a certain temperature, pa; t is air temperature, K; and ϕ is relative humidity, %. Then, the specific heat capacity of the air inside the system is 510.89 J/(kg·K). Fitting the blue curve in Figure 2, one can estimate the time integral value of the total cooling/heating temperature required by the system on a day and night on the moon.

According to the previous assumptions, the volume of the system is $3.14 \times 10^7 \text{ m}^3$, and the contained air quality (normal pressure at 20 °C) shows the following equation [23]:

$$\rho_{ma} = \frac{P_{ma}}{R_{da}T} \left[1 - 0.378 \frac{\phi P_s(t)}{P_{ma}} \right], \quad (6)$$

where ρ_{ma} is the density of humid air, in kg/m³; R_{da} is constant, 287.06 J/(kg·K); and P_s is water vapor saturation pressure corresponding to temperature, pa. Based on this formula, the mass of air that can be contained in the system is $6.8 \times 10^7 \text{ kg}$, and the energy required to maintain 20 °C over a daily cycle on the moon is $2.05 \times 10^{13} \text{ J}$ ($5.7 \times 10^6 \text{ kW} \cdot \text{h}$). Therefore, the energy value required to maintain the basic survival requirements of 8 astronauts in 27 days on the moon should be at least $2.07 \times 10^{13} \text{ J}$ ($5.75 \times 10^6 \text{ kW} \cdot \text{h}$).

Fitting the red curve in Figure 2 (temperature of the lunar surface), the energy required to maintain the temperature in the system at 20 °C is $1.04 \times 10^{14} \text{ J}$ ($2.89 \times 10^7 \text{ kW} \cdot \text{h}$). Results show that it takes much less energy to maintain a human base in a lunar lava tube than on the lunar surface (Table 2).

2.2. Safety Assessment of Lunar Base in Lava Tubes. Compared with the lunar surface, lunar lava tubes have the advantages of small radiation and less extreme conditions, more suitable for a human lunar base. We now quantitatively analyze these advantages concerning the lunar surface.

2.2.1. Radiation Simulation. A numerical simulation study performed in 2002 proved that lava tubes buried more than 6 m below the lunar surface can be protected from cosmic rays and solar wind [24]. More specifically, Figure 3 shows the variation in depth of radiation intensity of different particles in the lunar soil.

One can see that this intensity at 6 m below the lunar surface is almost zero [25]. Even at a depth of less than 1 m, solar flares and solar particle events (SPE) do not affect the interior of the lava tube.

TABLE 2: The summarize table for the energy estimates [6].

Location	Ecosystem repair (kW·h)	Stable environment (kW·h)	Total (kW·h)	Power (kW)
Lunar surface ^{*1}	48889	2.89×10^7	2.89×10^7	4.41×10^4
Marius hill south ^{*2}	48889	5.7×10^6	5.74×10^6	8.8×10^3

Note: ^{*1}Use the data of the temperature change of the lunar surface in Haruyama's simulation [2]. ^{*2}The shadow area of the Marius hole.

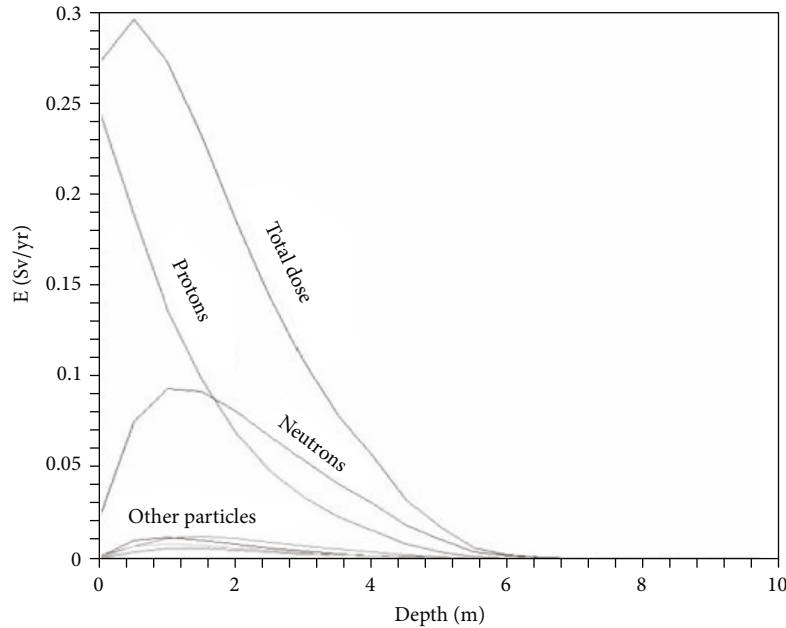


FIGURE 3: Intensity changes of various particles with depth. The figure shows the total particle mass, protons, neutrons, and other particles including electrons, positrons, protons, mesons, muons, k-mesons, and deuterons [26].

2.2.2. Meteorite Impact. Because lunar lava tubes are deeper below the surface of the Moon, they also have the advantage of avoiding the impact of the meteorite. This advantage can protect the humans and their base. For a suitable tube, it should not be broken down by meteorites. This means that the possible influence radius of the meteorite must be smaller than the tube's burial depth. According to experimental and simulation studies, the most safety condition the scientist calculated now is the ratio of target thickness-to-crater diameter. That is, if it is smaller than 0.87 then a "skylight" (crater) will appear [27].

For example, the Mare Tranquillitatis hole (MTh) might be produced by a 7.2 m impactor with a 45° angle and a speed of 18 km/h in a 47 m thick target [28]. The projectile's material is basalt and its density is 2.86 kg/m^3 . The target is overlaid by 3 m of regolith. The crater diameter D_c is $75.67 \pm 3.0 \text{ m}$, and the depth is $30.07 \pm 3.6 \text{ m}$. Then, the ratio target thickness-to-crater diameter is 0.85 which is around and smaller than 0.87 [27].

Also, to build a habitat in a lunar lava tube, it is important to build the habitat accordingly deployed at some distance to the skylight itself, to avoid possible subsequent collapse related to the same mechanism that formed the hole's structure.

2.2.3. Moon Dust. There is very little moon dust inside lunar lava tubes. Moon dust is the charged dust formed by small

debris on the lunar surface under the action of the solar wind. Particles of less than $20 \mu\text{m}$ in size of the debris on the lunar surface (the regolith) account for 20% of the total mass of moon dust. Being charged, they can be adsorbed on any equipment. In addition, moon dust is abrasive, and very harmful to people and machines, particularly below a size of 24 microns [4]. But the interior of lava tubes is a permanent shadow zone, generally inaccessible to the solar wind, where charged moon dust is hardly produced. It is also well protected from the impact of micrometeorites [27].

2.2.4. Moon Quake. Decades of analysis of the seismic data collected by the lunar seismic network revealed that vibrations on the moon mostly fall into four types, each with a distinct cause rooted in the moon's structure and its position in our solar system:

- (i) Deep moonquakes, quakes originating deep (over 700 kilometers deep) within the moon, caused by the stretching and relaxing of the gravitational pull between the Earth and the moon, the same force that drives our ocean tides
- (ii) Shallow moonquakes, quakes at the surface of the moon (20-30 kilometers deep), are likely caused when the moon's crust slips and cracks due to the gradual shrinking or "raising" of the moon as it cools

TABLE 3: Earthquake events on the moon observed by the Apollo probe.

Seismic event categories observed by the Apollo passive seismic experiment from 1969 to 1977	Number of events
Shallow moonquakes	28
Deep moonquakes	~7,200
Meteor impacts	~1,700
Thermal quakes	~1,160
Artificial (human) impacts	9

- (iii) Meteor impacts, vibrations caused when meteors crash into the surface of the moon
- (iv) Thermal quakes, quakes caused by the short-term thermal expansion and contraction of materials on the surface of the moon as it is warmed by, and shaded from the rays of the sun
- (v) Bonus! Mission “quakes” were caused by the force of the later Apollo mission landings on the moon’s surface, which helped guarantee the accurate measurements of the first seismic stations

The moon quakes observed by the lunar seismic network between 1969 and 1977 varied in where how often and how severely they shook the moon, as shown in Table 3. The fact that the lunar lava tube has survived on the moon for so many years suggests that its structure is stable enough to withstand the effects of moon quakes. This is a natural advantage over bases built on the moon’s surface.

2.3. Conclusions on the Use of Lava Tubes for Lunar Bases. Building a lunar base into lunar lava has many advantages, some of which we reviewed in this section. Lunar lava tubes can give us a natural, ready-made infrastructure that eliminates the need for additional construction. It only needs to be closed, reinforced, and transformed into functional areas, and there is no need to launch the building materials and equipment from Earth to the surface of the moon. Second, as we just showed, a lunar lava tube offers a relatively stable environment. The changes in various environmental parameters are relatively regular, easy to control, and facilitate the adaptation of host organisms. The buried depth of lunar lava tubes protects them from the risk of moon dust, moon quake, cosmic radiation, and meteorite impact. Finally, thanks to suitable temperatures and small temperature variations, the energy required to maintain a temperature suitable for humans and organisms is very low.

In summary, compared to the lunar surface, lunar lava tubes may offer a more stable, more suitable, safer, and less energy-consuming environment. Due to these benefits, lava tubes seem to be more suitable for a lunar base than on the lunar surface. While the Moon’s surface has been well documented by orbital spacecraft, it hides an underground world that remains a mystery [29]. The shelter that lunar caves provide, as well as the access to water and other

resources, could be vital for our future human or robotic exploration of the Moon.

3. Using a Karst Cave to Simulate Lunar Lava Tubes

3.1. Formation and Structure of Kester Caves on the Earth. Karst caves refer to the underground space formed by the dissolution, invasion, and collapse of soluble limestone under certain conditions. It is the combination of CO_3^{2-} ions produced by the ionization of CaCO_3 and H^+ produced by the interaction of CO_2 and H_2O to produce HCO_3^- , which destroys the ionization balance of CaCO_3 so that CaCO_3 continues to be ionized and continuously dissolved.

The formation of karst caves is mainly divided into three stages: (1) In the initial stage, the water seeps along the cracks existing in the limestone, and the slow chemical dissolution is mainly carried out. (2) In the piping stage, through chemical dissolution, the channel continuously expands and forms a crevice pipeline under the action of water flow. (3) Highly tube passage stage: crevice tubes are further developed. When the diameter of the tube expands to several meters or even tens of meters, the flow of water will increase. The tube expands through physical effects and even forms canyon-like passages up to tens of meters or even hundred meters. Sometimes, it also extends to the surface to form geological phenomena such as skylights.

Due to the special formation process, the internal structure of the karst cave is very complicated; there are usually accumulations in the caves, resulting in not smooth. Its length can reach hundreds of kilometers, the width is between several meters to tens of meters, and some caves also have a layered structure. Temperatures deep in the caves are similar to the local average annual temperatures [30]. The air in the cave is relatively clean, and some areas also use the cave as a treatment place.

Karst areas are widely distributed in Chongqing, such as Wulong, Youyang, Nanchuan and Wansheng, including karst caves, skylights, earth cracks, canyons, and other landforms. We have explored some caves in these areas; the height of the hall in caves can reach 18 m (Figure 4(a)), and some caves exist rivers (Figure 4(c)). The volume of the hall reaches tens of thousands of cubic meters, which is enough to accommodate man-made buildings of various sizes.

3.2. The Feasibility of Chongqing Karst Caves Reconstruction. Taking karst caves in Chongqing as an example, we show now that Earth karst caves can be considered as good analogs of lunar lava tubes under three aspects: structure, environment, and insulation.

3.2.1. Structural Aspects: Karst Caves and Lava Tubes Have Different Formation Mechanisms and Environments, but They Are Comparable in Size. They are both curved semicircular caves, though their formation mechanisms are different. Lunar lava tubes can collapse due to meteorite impacts, moonquakes, and tectonic activities [31], just like karst caves can collapse on Earth. The figure below illustrates the similarities between the two structures.

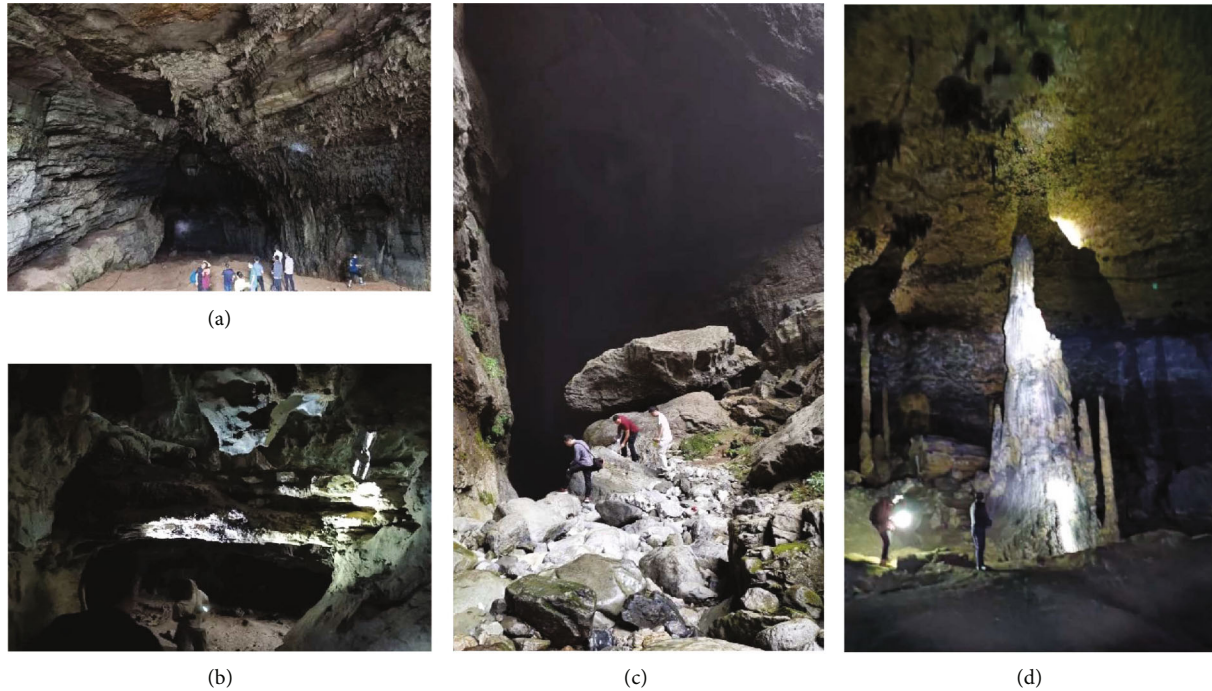


FIGURE 4: Karst caves in Wulong (a, c) and Youyang (b, d).

Although the caves on the moon are expected to be much larger than those on the earth due to special environments such as low gravity, karst caves on the earth still provide us with the best choice, and the space it provides can meet the research needs at this stage. Moreover, the largest known karst cave in the area can reach 77020 meters in length [32, 33]; this range of sizes is sufficient to simulate various types of lunar lava tubes.

3.2.2. Environmental Aspects: Karst Caves and Lava Tubes Have Relatively Mild Environments. In terms of temperature, the temperature range in the cave is between 18 and 25 °C; even for caves with good ventilation, the internal temperature and external temperature are less than 5 °C. Other literature points out that karst cave in Wulong has a small temperature difference throughout the year, ranging from 14 to 21 °C [34]. For the shadow area at the bottom of the collapsed lava tube in Marius hill, the internal temperature range is between -20 and 30 °C, and the temperature difference is small [6]. The mild temperature inside the lava tube can reduce energy consumption in terms of heat control.

In terms of acidity and alkalinity, the lunar lava tube is mainly composed of lunar basalt. The rock composition is mainly composed of iron and titanium compounds. The hydrolysis product is weakly alkaline. The karst cave is mainly composed of carbonate rock, and most of the hydrolysis product is hydrogen carbonate, also weakly alkaline.

In terms of air quality, one advantage of the lunar lava tube is that there is almost no moon dust. For karst caves, they are enough ventilated, and oxygen and carbon dioxide contents are within the normal range (oxygen 20.4-20.7 VOL%, carbon dioxide 400-800 ppm), and no toxic and harmful gases are detected.

In addition, as both types of cavities are buried deep underground, their lighting conditions are very similar (the atmospheric difference between the earth and the moon has very little effect on the experiment because the atmosphere needs artificial construction both on the lunar base and ground karst cave).

3.2.3. Insulation Aspects: Karst Caves and the Lava Tubes Can Provide an Environment Relatively Isolated from the Outside World. The lunar lava pipeline is protected by the weathered layer, and the internal and external environments are isolated. Due to the lack of conductive media, the internal environment is very independent. As for karst caves, since they have almost no communication with the external environment during their formation process, they are rarely affected by the external environment. Their internal humidity is relatively high, and the density of aerosol particles is very low.

Due to the presence of the air, the connectivity between the caves on the earth and the external environment is greater than that of the extraterrestrial lava pipeline, which is very unfavorable for the study of closed artificial ecosystems, so it must be reformed. At present, there are few of research on cave sealing, and research on lunar soil building materials rarely pays attention to the sealing performance of materials. The current lunar sintering and extrusion technologies tend to focus only on the mechanical properties of the material (compressive strength, brittleness, etc.). In our opinion, the substrate for the lunar base should have good sealing properties while meeting the strength requirements to reduce the extra work. Some of our preliminary work so far indicates that extruded lunar soil appears to have better sealing properties. We hope to use this example to explore

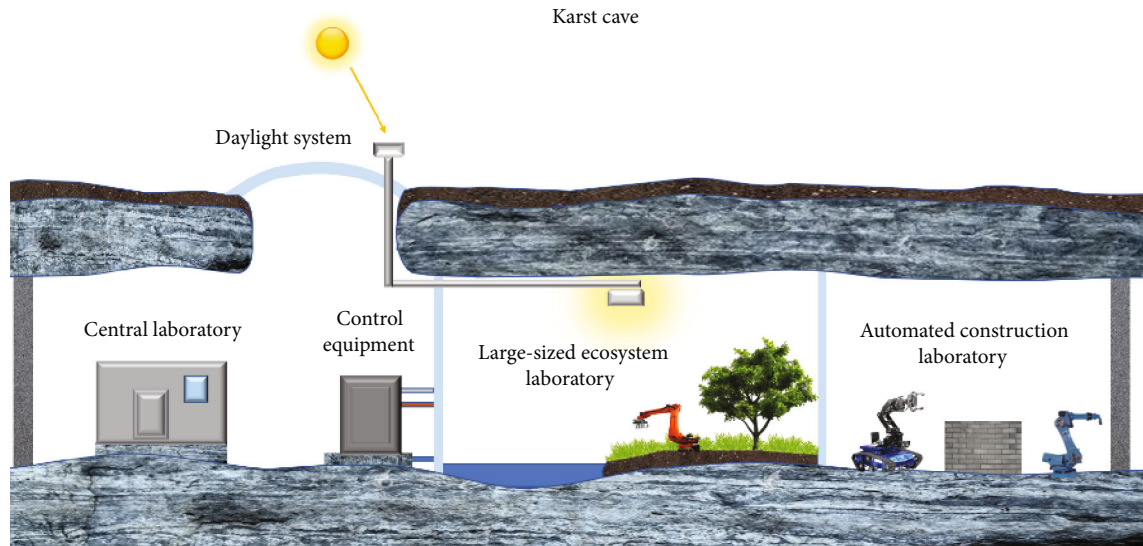


FIGURE 5: Karst cave simulation platform.

the technology of sealing extraterrestrial caves economically using in situ resources by sealing caves on the earth.

This analysis shows that the Chongqing karst cave can provide a relatively closed ecosystem containing soil, rocks, and organisms. We can use this special environment to simulate the situation that human beings may face in the lunar lava tubes in the future. Experience gained through this project could provide valuable lessons for humans to build ecosystems in moon caves.

3.3. Using Karst Cave as a Simulation Location. We intend to use karst caves to simulate the internal environment of extraterrestrial caves and isolate them from the external environment by sealing the caves. The cave experiment is divided into two parts. The first part is the automatic construction technology in the cave and the in situ utilization technology. At present, people have conducted a lot of research on automatic construction and in situ resource utilization in the cave. The adaptability of these technologies has not been studied yet. In addition, the experiences gained from Biosphere 2 allow us to conduct a separate study on sealability [25].

The other part is the artificial ecosystem experiment. Many ideas have been proposed for building bases using extraterrestrial caves. However, due to insufficient research on the internal circulation theory of ecosystems, it is impossible to effectively control large-scale ecosystems. Therefore, the second part of the experiment will select a section of the cave to seal it, and through the study of the interaction of animals, plants, microorganisms, and limestone in the system, team members will enter after the laboratory has developed to the stable functioning stage.

Regarding energy supply and light, we tried to use light pipes to introduce sunlight into the ecological laboratory and provide it for crop growth. Develop a set of automatic control energy control systems, use solar energy for charging during the day, use the stored energy supply system at night, and artificially provide the plants with light to ensure their

growth when the light is insufficient. The conceived laboratory structure is shown in Figure 5.

4. The Significance of Using Karst Cave to Simulate Extraterrestrial Lava Tubes

The United States has launched the Artemis plan to return to the moon. Its goal is to send astronauts to the moon and return safely before 2024 and establish a normalized residency mechanism to pave the way for future manned landing missions to Mars. China and Russia also promulgated the Route Map of International Lunar Research Station in 2021. We account the best steps to build a lunar base should be as follows: Establish a lunar orbiting space station; use satellites for site selection and enter the tubes for on-site evaluation; remotely control robots to build an unmanned base and establish a micro-ecosystem; expand a small manned base; and expand the base and build an ecosystem and large extraterrestrial base (Figure 6).

Human beings have had the habit of living in caves since ancient times, to resist external influences. Similarly, lava tubes can also provide initial shelters for humans on extraterrestrial planets. Karst caves and the lunar lava tubes have certain similarities; they can be used as a research platform to study the problems encountered in the development of the lunar lava tubes in the future (Figure 7).

There have been attempts to use the earth's environment to simulate other planets. Researchers have already used commanding rovers to drive in lava tubes in Lanzarote, in Spain's Canary Islands, to prepare for future lunar exploration. Mars Desert Research Station (MDRS) is a Mars-simulation campus set in a Martian planetary analog in southern Utah [35]. It is used to simulate the surface environment of Mars to train people to solve the psychological and technical problems that may be faced by landing on Mars in the future.

The use of extraterrestrial lava tubes to build human bases mainly faces the following challenges:

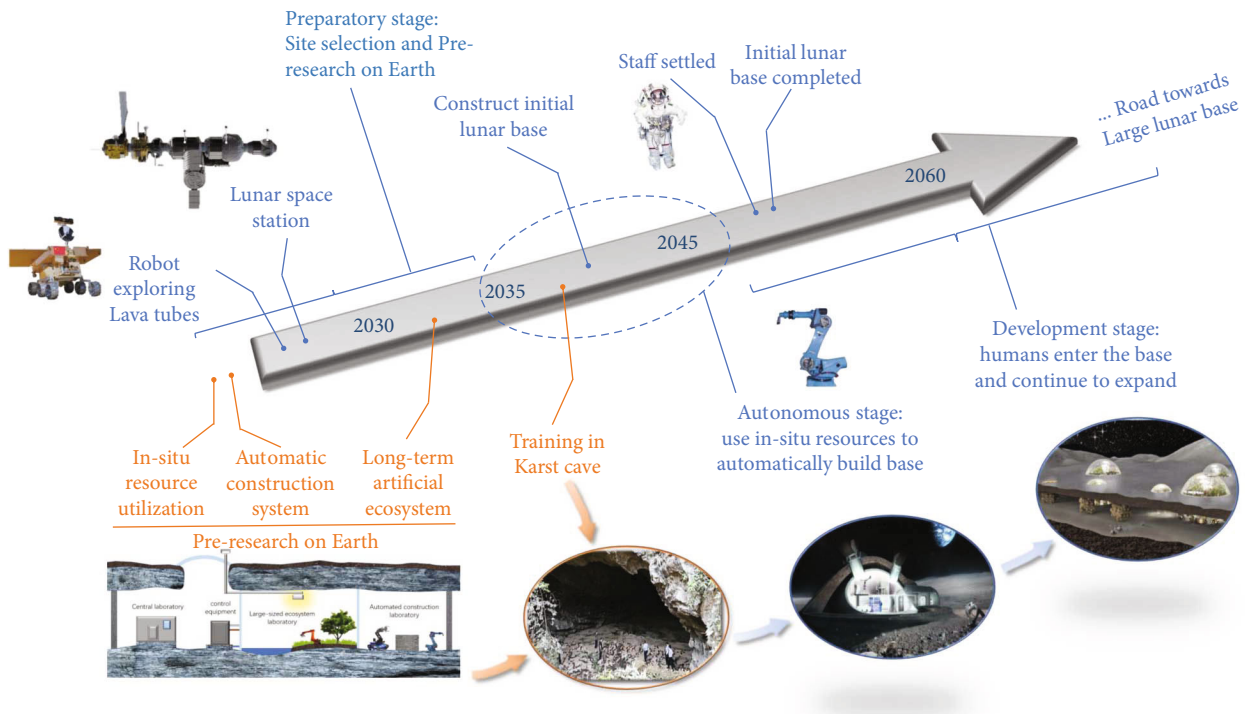


FIGURE 6: Roadmap of the construction of extraterrestrial bases.



FIGURE 7: Using caves in Spain's Canary Islands as Mars and lunar caves analogs for staff training.

- (i) Lack of internal measurement data of the lava pipeline, unable to accurately assess
- (ii) Large artificial closed ecosystems have not yet been a successful case
- (iii) Low-cost sealing and maintenance solutions for lava tubes
- (iv) In situ resource utilization of the moon is still in the laboratory stage
- (v) Many technologies and equipment on the earth need to be improved due to low gravity
- (vi) The psychological impact of long-term appearance survival needs to be alleviated

Simulation through caverns can simulate the internal environment of the lunar lava tubes, and the construction conditions inside the tubes. For example, the techniques of using in situ resources within lunar lava tubes to seal them.

In addition, emerging technologies such as 3D printing and robotics will also be applied to the construction of the system. Concepts such as lunar soil sintering, 3D printing, and cave robots have been proposed to build lunar bases [36–38], but there are few examples of applications in the natural environment. These technologies are indispensable for mankind to build a lunar base in the future. But at this stage, they are all used in other industries that cannot be directly applied to the construction of lava tube bases, and the karst caves provide an example with analogous environment. Using this platform, many interesting extraterrestrial base ideas can be realized on the earth, preparing for their future realization on the moon.

5. Conclusion

Lunar lava tubes have large overlying depths and wide internal widths. Their internal temperature change, radiation exposure, and meteorite impact are relatively small, so their

internal environment is relatively stable. This makes them good candidates to host a lunar base where humans could live and work. We showed that the minimum energy consumption for maintaining a lunar base hosting 8 astronauts deep inside a lava tube cave is about 145.5 kW in a semicircular tunnel cave with an area of about 8,000 square meters and a height of 50 meters. At this stage, a lava tube is the best choice for establishing a lunar base.

Compared with artificial construction, Karst cave provides a natural ecosystem that includes soil and rocks. The feature of convenient sealing allows us to build a well-structured ecosystem at a low cost. The feasibility of using karst caves to transform extraterrestrial caves is analyzed from two aspects: structure and internal environment. The results show that the structure and size of the karst cave can meet the research needs at this stage. The internal environment of the cave is comparable to that of the extraterrestrial lava tubes, but due to the existence of air convection, karst caves need to be sealed first.

Karst cave as a platform to study how to use lunar lava tubes to build a lunar base is promising. We conceived a cave simulation platform that is relatively isolated from the outside world and tried to carry out automatic construction and in-situ resource utilization. The use of in situ resources to seal caves, light supply system, and material circulation relationship of soil and rock in the artificial ecosystem is very important for the construction of extraterrestrial bases. We have carried out relevant pre-experiments in this area and will continue to advance them.

We shall call for increasing attention to the extraterrestrial lava tubes, using satellite remote sensing technology, and autonomous robots to detect the tubes and measure their internal size and structure. Building settlements in an earth cave system is worth it to simulate and evaluate extraterrestrial bases while promoting the development of earth cave systems.

Data Availability

The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest

The authors declare no competing interests.

Authors' Contributions

These authors contributed equally to this work. D.J. contributed to the data analysis, writing draft, modification, and search reference. X.G. contributed to the idea, draft's structure, modification, and funding. L.L. and W.X. contributed to the suggestion. X.X. and Y.H. contributed to the modification and suggestion.

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