A Guideline for a Sustainable Lunar Base Design for Constructed in Lunar Lava Tubes and Their Vertical Skylights

Masato Sakurai[1], Asuka Shima[2], Isao Kawano[3], Junichi Haruyama[4]
Japan Aerospace Exploration Agency (JAXA), Chofu-shi, Tokyo, 182-8522, Japan.

and

Hiroyuki Miyajima[5]
International University of Health and Welfare, Narita Campus 1, 4-3, Kōzunomori, Narita, Chiba, 286-8686 Japan

The lunar surface is a hostile environment subject to harmful radiation and meteorite impacts. A recently discovered lava tube avoids these risks and, as it undergoes only slight temperature changes, it is a promising location for constructing a lunar base. JAXA engages in research in regenerative ECLSS (Environmental Control Life Support Systems), particularly addressing water and air recycling and treating organic waste. Overcoming these challenges is essential for long-term lunar habitation. This paper presents a guideline for a sustainable lunar base design.

Nomenclature

ECLSS	=	Environmental Control Life Support System
HTV	=	H-II Transfer Vehicle
ISS	=	International Space Station
JAXA	=	Japan Aerospace Exploration Agency
JSASS	=	Japan Society for Aeronautical and Space Science
MHH	=	Marius Hills Hole
MIH	=	Mare Ingenii Hole
MTH	=	Mare Tranquillitatis Hole
SELENE	=	Selenological and Engineering Explorer
UZUME	=	Unprecedented Zipangu Underworld of the Moon Exploration (name of the research group for vertical holes)
SDGs	=	Sustainable Development Goals
SELENE	=	Selenological and Engineering Explorer

I. Introduction

Future space exploration will extend beyond low Earth orbit and dramatically expand in scope. In particular, industrial activities are planned for the Moon with the development of infrastructure that includes lunar bases. This paper summarizes our study of the construction of a crewed permanent settlement, which will be essential to support long-term habitation, resource utilization, and industrial activities on the Moon.

[1] Senior Researcher, Research Unit II, Research and Development Directorate, JAXA, 7-44-1 Jindaiji-higashi-machi, Chofu-shi, Tokyo, 182-8522, Japan.
[2] Researcher, Research Unit II, Research and Development Directorate, JAXA, 7-44-1 Jindaiji-higashi-machi, Chofu-shi, Tokyo, 182-8522, Japan.
[3] Senior Researcher, First Space Technology Directorate, JAXA, Tsukuba, Ibaraki, 305-8505, Japan.
[4] Assistant professor, Department of Solar System Science, ISAS, JAXA, 3-1-1, Yunodai, Chuoh-ku, Sagamihara.
[5] Professor, School of Health Sciences at Narita, 4-3, Kōzunomori, Narita, Chiba, 286-8686 Japan.

Crewed bases will not be built on the lunar surface, as long imagined by science-fiction writers. Instead, they will be constructed in a natural vertical hole in the Marius Hills, with interconnecting underground cavities. Unlike Earth, the Moon has no atmosphere, but it experiences high cosmic radiation and temperature extremes between sunlight and shade. We studied how a base could be constructed on the Moon that avoids such harsh conditions. A living module, the size of the Konotori (HTV) space station supply vehicle of Japan, was installed on the Moon as a thought experiment. Assuming that the top three-quarters of the module is covered by 60 cm of lunar regolith, the remaining quarter would be completely underground. Several tens of tons of regolith would be required to provide sufficient radiation shielding. The task of constructing a regolith dome several meters thick shielded from life-threatening radiation is challenging.

However, underground facilities require no radiation shielding. An inflatable structure could be used, reducing the weight and volume of structural materials, but it would be necessary to install elevators to move cargo vertically. Such cargo includes the habitation module, which would need to be moved from the lunar surface to the bottom of the vertical shaft, 50 m below the surface. The elevator equipment must be designed so that its mass is less than that of the regolith shielding construction equipment, thus enabling it to excavate considerable regolith to the surface[1]

In a vertical hole at Mare Tranquillitatis, temperatures are expected to be stable at approximately -20 °C, comparable to colder regions found on Earth. Establishing a crewed base while utilizing one of the Moon's underground cavities is an appropriate first step toward constructing a permanent lunar base for future human habitation. To this end, we examine the following prospective technical issues.

II. Discovery of lunar vertical holes and underground cavities

In 2009, JAXA's lunar explorer SELENE (the Kaguya) discovered the Moon's first large vertical hole, 60 m in diameter and 50 m deep, in the Marius Hills[2]. In addition, a global survey using SELENE data revealed two other, larger vertical shafts, several tens of meters in diameter and a hundred meters deep[3]. The Marius Hills Hole (MHH) is located at 303.3° E, 14.2° N. The Mare Tranquillitatis Hole (MTH) is at 33.2° E, 8.3° N. Moreover, the Mare Ingenii Hole (MIH) is located at 166.0° E, 35.6° S.

Figure 1 shows the locations of the three vertical holes discovered by SELENE. The data suggested that underground cavities larger than the diameter of the holes extend below these holes[4,5]. In addition, data analysis of the SELENE radar sounder revealed that the vertical hole in the Marius Hills connects to a long horizontal cavity, a lava tube that extends up to 50 km[6].

Analogous to the Earth's topography, these vertical holes and underground cavities are believed to have formed due to volcanic activity and crustal deformation, producing lava tubes and open skylights. The underground horizontal ceiling cavity that follows a lunar hole acts as a shield to the space environment's radiation and meteorites. Moreover, temperatures in the underground cavity are highly stable, substantially reducing the required resources for support during colder dark periods. In addition to its scientific significance, further investigation of vertical lunar holes and underground cavities is critical to future lunar and planetary exploration and the development of permanent lunar bases.

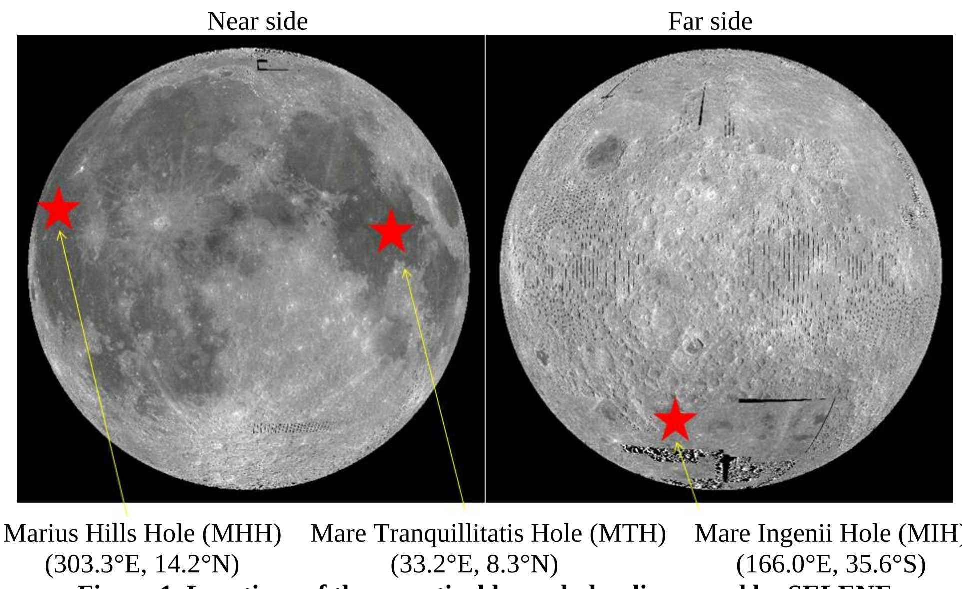

Figure 1. Locations of three vertical lunar holes discovered by SELENE

The radiation and temperature in an underground space are sufficiently moderate to raise the prospects for long-term human habitation. Yet, we do not know the vertical hole's depth precisely nor whether this depth is adequate to protect against radiation. Furthermore, the temperature extremes over a lunar day (i.e., one month) remain unknown. These considerations, including how far the lateral hole extends, must be known to design an underground lunar base. Accurate information cannot be unobtained without direct, in-situ measurements.

The research group UZUME, short for the Unprecedented Zipangu Underworld for Moon Exploration, focuses on the Moon's vertical holes. UZUME studies possible locations for bases in vertical holes and underground cavities. We considered using an airtight cover on a vertical hole to provide an environment for an underground base. For the near future, we consider making a habitation module from an inflatable structure delivered by a craft landing on the floor of a lunar hole.

A long-term lunar base can serve as a platform for addressing issues on Earth, which could be aided by observations through openings in the cave ceiling. Lunar habitation requires a supply of air, water, food, energy, and other resources. Obtaining these needs from Earth imposes unreasonable logistical and maintenance costs, so we must prioritize self-sufficiency and find better methods for recycling the air, water, and food. Additionally, improved energy, air, and water regeneration techniques will support the United Nations Sustainable Development Goals (SDGs). We are examining the use of lunar holes and cavities as a testbed for UN SDGs.

This paper describes the merits of exploring lunar holes and underground cavities as potential candidates for a lunar base and a lunar base design. The paper also reviews the required systems for recycling energy, air, water, other resources, the relevant research topics.

III. Lunar base construction in lunar holes and cavities

A. Advantages of using the Moon’s vertical holes and underground cavities for bases

The lunar holes[2,3] discovered by SELENE and the following underground cavities have several advantages for constructing lunar bases. Table 1 lists the pros and cons of building a base underground over one on the lunar surface. The regolith above the ceiling of an underground cavity would provide shielding against radiation exposure and the threat of meteorites.

A solar flare in 1989 released 4200 mSv of radiation (i.e., more than half the lethal amount), which would have required EVA astronauts to seek the safety of their spacecraft. Tunnel roofs are very stable seismically, whereas the situation at the edge of the hole is not well understood. However, moonquakes are weak, and tunnels have existed for billions of years, so there is little danger. The floors of lava tubes are believed to be flat. Dust may not be deep along a tube, but it is unknown how deep it is close to the opening.

The depth of a hole ranges from 50−100 m, meaning that the temperature at the bottom is notably more stable than on the lunar surface. Figure 2 shows the results of a temperature analysis across a lunar hole and the underground cavity compared to the lunar surface. As shown in the upper right part of Fig. 2, the analyzed points were taken during periods when the bottom of the north side of the hole was exposed to sunlight (green triangles) and when the bottom of the south side of the hole was not (blue triangles). Lunar surface temperatures fluctuated between -170 and 110 °C, a range of nearly 300 °C. On the north side of the sunlit hole, the temperature rose to 150 °C when in sunlight but only -20 °C on the cold south side. The drop of 170 °C was unexpected. The temperature range at the northern part of the bottom of the hole that never receives sunlight is about -20−30 °C. This temperature fluctuation is exceptionally stable, only about 50 °C. For this reason, only a fraction of the expected resources will be necessary during dark periods compared to what would be needed by a base on the lunar surface.

Furthermore, such locations may be airtight in the cavities and have flat floors, analogous to Earth's geological formations[6]. In particular, the two vertical holes in the Marius Hills and Mare Tranquillitatis face the Earth and would provide unobstructed line-of-sight communications. An analysis by the UZUME research group revealed that the bottom of the vertical hole in Mare Tranquillitatis has consistently clear Earth visibility.

Lunar holes and underground cavities are more secure than the lunar surface or lunar orbits. They demonstrate numerous advantageous characteristics for supporting long-duration lunar bases. Plans are underway to perform direct observation of the vertical holes and underground cavities to confirm the identified advantages and measure their size and internal structuring. Overall, we believe Japan can make significant scientific and engineering contributions to the International Space Exploration Program.

Table 1. Advantages of building a base in a vertical hole and underground cavity

Location	Radiation	Meteorites	Temperature	Construction materials	Other
Lunar surface or in orbit	Severe 4200 mSv maximum	Considerable danger	Large fluctuation -170–110 ℃	Thick shielding and pressure-resistant structure	Construction is time-consuming.
Vertical hole, underground cavity	Safe, almost 0	Safe from im-pacts	Stable -20~ 30℃	Only airtightness is required. An inflatable structure (lightweight, easy to transport) can be used.	Use natural holes with minimal modification. Also has a high sealing performance, a solid floor surface, and no dust.

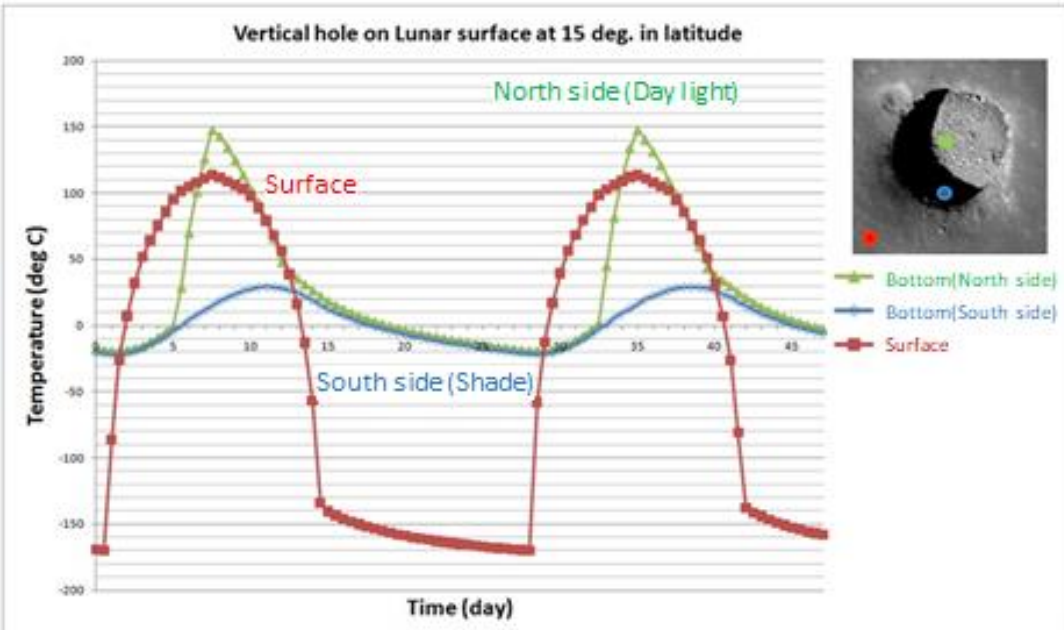

Figure 2. Temperature analysis of hole bottom vs. surface of the Moon [5]

B. Material recycling (water/air/waste treatment)

Technological development of environmental control and life support technology (ECLSS) is essential for constructing crewed bases. In the 2020s, we will apply ECLSS technology to the lunar orbiting platform using physicochemical methods based on demonstrations on board the ISS. Looking to the 2030s, we will improve regeneration rates for air and water and update the practices and systems for long-duration stays. Ultimately, we target a physicochemical regeneration rate of 100% for oxygen and 95% for water. Toward the 2040s, once a lunar base is established, priorities will shift to plant-based techniques, including smart food production, and establish a largely independent ecosystem that promotes the carbon cycle. However, for practical use on the lunar surface, the system must support functions under 1/6 Earth's gravity (that of the Moon).

C. Food production

In the 2020s, expeditions to the ISS, lunar orbit, and the lunar surface will not require food self-sufficiency. Hence, sustainable food production in space is not likely. Furthermore, finding the room needed for food production is challenging. During this period, we will continue to rely on resupply from the Earth. Meanwhile, research will continue developing plant varieties that can grow in a space environment and practical, closed-environment agricultural practices.

Table 2. Lunar self-sufficiency and life support system (per person)

No.	Food self-sufficiency	Energy intake, kcal	Water regeneration rate (for 10 kg)	Oxygen regeneration rate (for 0.835 kg)	Required power, kW	Crop group
1	4%	106	0.4	0.1	1	Crop group 1: cucumber, tomato, lettuce, strawberry
2	14%	370	1.4	0.2	3	Crop group 1 + Crop group 2: potato, sweet potato
3	38%	1,017	3.9	0.7	10	Crop group 1-2 + Crop group 3: soybean
4	92%	2,439	10.6	1.6	23	Crop group 1-3 + Crop group 4: rice
5	100%	2,650	—	—	25	Crop group 1-4 + animal protein

Table 3. No. 4 (92% lunar food self-sufficiency) 3-MW autonomous hydrogen energy supply system for 100 people

Power Generation System	Spec.	Unit
Electric-generating capacity	3	MW
Power generation efficiency	0.5	
Volume	435	m^3
Mass	174	t
Body	174	m^2
Installation	435	m^2
Pure hydrogen consumption	2,010	Nm^3/h
Hydrogen volume for 14 days overnight	675,360	Nm^3
Hydrogen mass for over 14 days	61	t
Hydrogen production equipment		
Hydrogen production unit cost	8	MWh
Hydrogen production	2,010	Nm^3/h
Power consumption	8	MW/h
Mass	603	t
Solar panels		
Electrical capacity	8	MW
Aare	51456	m^2
Mass	44	t
Area (3 MW daytime, 8 MW overnight）	70,656	m^2
Mass (3 MW daytime, 8 MW overnight)	60	t
Total system mass	837	t
Hydrogen mass consumption	61	t

Calculations based on the specifications of Toshiba's H_2Rex next generation 100-kW, hydrogen production equipment H_2 One (200-kW class SOEC), solar panel H_2 One.

From the 2030s, following the completion of a lunar base, long-duration stays, food production systems, and initial food production in space will be realized. The variety and amount of food produced will scale up in step with the number of inhabitants. Simultaneously, we will establish an efficient food production system, such as autonomous robotic farming. Crop cultivation shall begin in the 2040s, with food self-sufficiency rates reaching 90% or more.

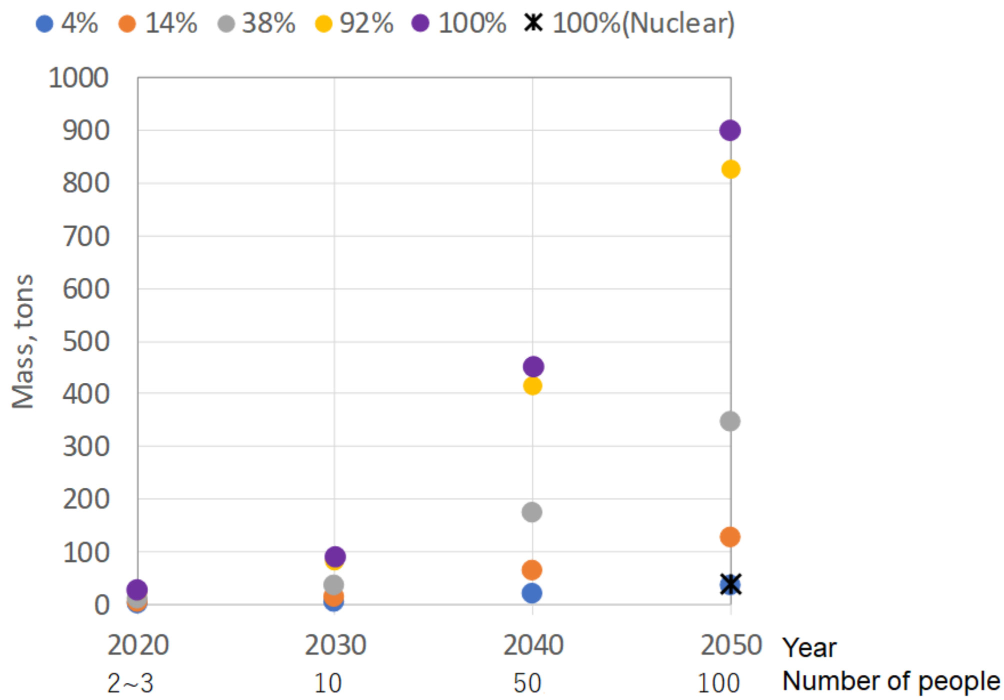

Figure 3. Relationship between lunar self-sufficiency and mass of power generation system
The horizontal axis denotes the age and number of inhabitants; the vertical axis denotes the mass of the power generation system; and the legend shows the monthly food self-sufficiency rate. The power generation system mass was calculated based on the independent hydrogen energy supply system, but only 100% (Nuclear) was calculated based on the small reactor SP-100.

D. Reference: Examination of life support systems including food production system using hydrogen energy

There will likely be two or three lunar explorers per mission in the 2020s, up to ten in the 2030s, fifty in the 2040s, and perhaps hundreds in the 2050s. As shown in Table 2, we compared the material regeneration rate and the required power for the five lunar food self-sufficiency rates. The JSASS (Japan Society for Aeronautical and Space Science) Lunar Base Working Group has been tasked with devising a construction plan for a manned lunar outpost[1]. We used data and models from the Lunar Farm WG to find a correlation between food production and life support systems[7,8].

The food self-sufficiency rate is calculated based on energy intake. Considering water and oxygen regeneration rates, the No.1 (4%) amount of water that plants can purify is 0.4 kg, and oxygen for crew consumption is 0.1 kg. In addition, food production requires a considerable amount of water. The electricity required for food production was assumed to be 25 kW per person. Combined with the electrical power needed for daily life, the total amounts to 30 kW per person. Water electrolysis would be done using solar energy to store energy by storing hydrogen and oxygen, consumed by operating a fuel cell during the dark period. It is assumed that the mass of the power generation system is proportional to the number of people.

If daily water consumption is 10 L per person, the rate of self-sufficiency on the lunar surface is 14% (No. 2), and the rate of water regeneration exceeds 100%. This means that the amount of water purified by the transpiration of plants is greater than the amount of water required for one human being.

However, because the regeneration rate of oxygen from food production is only 20% of the required amount, physicochemical regeneration remains necessary. To regenerate all the required oxygen via food production, a lunar food self-sufficiency rate of about 60% (between rates No. 3 and No. 4) is necessary if waste treatment consumes no oxygen.

Next, the specifications of an independent power supply system for life support systems, including a food production system, were determined based on Toshiba's specifications for an independent hydrogen energy supply system. The system consists of three subsystems: (1) a power generation system, (2) a hydrogen production facility, and (3) solar panels (including planned lighting). Table 3 lists the specifications for a 3-MW hydrogen energy supply system to produce food for 100 people at rate No. 4 (92% of monthly food self-sufficiency). Daytime power generation is 3 MW, but hydrogen production for an overnight period of two weeks requires 8 MW of power generation, and solar panels require equipment that can provide 11 MW. At this point, the solar panel area would be 70,000 square meters but could be reduced by about 30%, considering that the Moon has no atmosphere. The total system mass, accounting for the two-week darkness period, is 837 tons with 61 tons of hydrogen. Hydrogen would be supplied from Earth and reused, while lunar resources could support oxygen production. If a small reactor, SP-100 (power generation: 2 MW, mass: 25 tons), is used, overnight periods will not require power storage, and a supply of only 3 MW would be necessary. The mass of a small 3-MW reactor is calculated by proportional calculation to 37.5 tons. When comparing masses of power generating equipment, there is a difference of 22 times (≒ 837/37.5), making it difficult to produce food without nuclear power (Fig. 3). This will not significantly contribute to material regeneration. However, when the production of leaf-based vegetables begins, a hydrogen-based energy supply system remains possible.

IV. Conclusion

As we establish a permanent human presence in space, the population living in space will continue to grow. For habitation in lunar orbit, the Moon, and Mars to succeed, humans must be able to locally produce and consume water, energy, propellants, and other resources. This paper examined the elements required to achieve a lunar base for humans and formulated a roadmap for some technologies. Future studies will weigh the lunar surface and the lava tube in terms of mass (lighter inflatable structure) or power (required heating or cooling energy) for the enormous pressurized structures required to produce food. It is generally considered that an inflatable structure has a weight per unit volume of one tenth or less than that of a normal structure[9]. It will quantitatively show the benefits of using underground bases.

However, the prospects presented here remain limited, and there are many technical fields, such as transportation and base construction techniques requiring more in-depth coverage. Despite our best scientific and engineering practices, expanding humankind into the universe remains a challenge. There are significant gaps to cover in R&D. The scale of such expansion cannot be covered by conventional aerospace engineering and must comprehensively incorporate several sciences.

A crewed lunar base can serve as a platform for achieving UN SDGs and supporting areas of broad utility such as lunar-based Earth observation. We hope this research stimulates wide-ranging research and technological developments, including interdisciplinary exchanges and entry from new research fields, to achieve a “space vision.”

Acknowledgment

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