TAKASHI TSURUMAKI

第11回月惑星に社会を作るための勉強会

2021年5月26日

第10回(4月23日)「月面居住施設建設と3Dプリント技術」発表に関するフィードバックに基づく追加情報

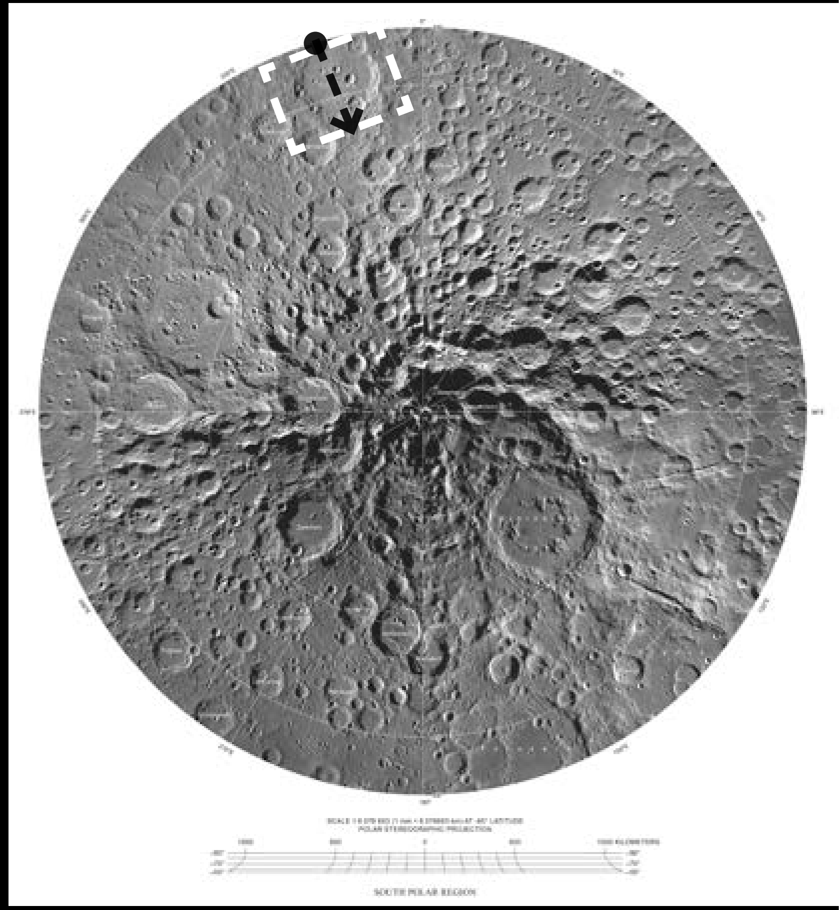
鶴巻　崇

1. 南極付近の地形と日照率
2. 光ファイバーによる彩光
3. 内圧
4. 放射線

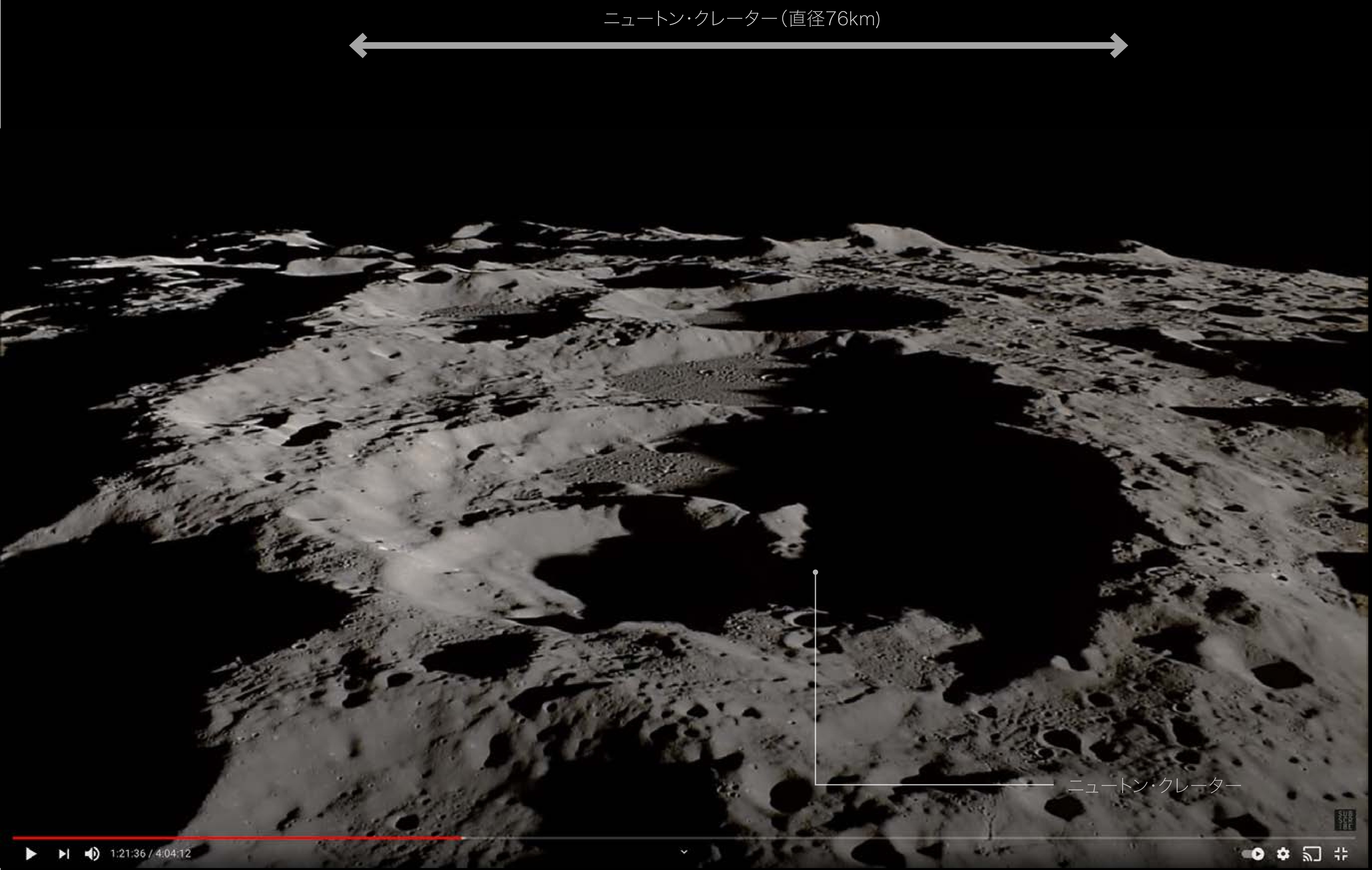
1. 南極付近の地形と日照率

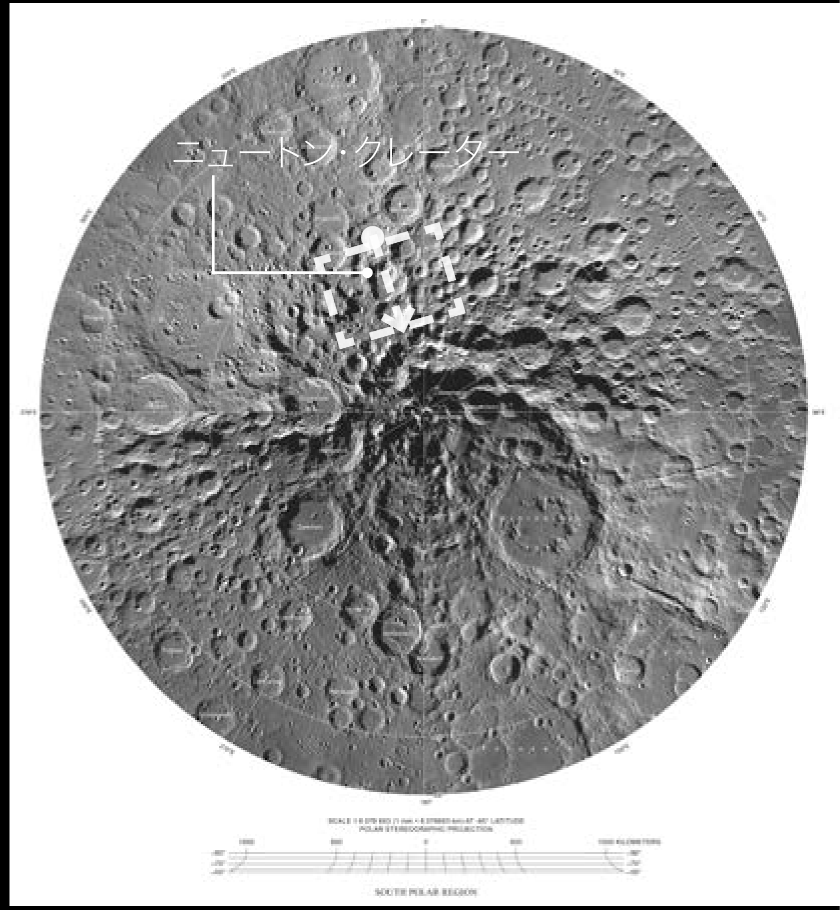
月の海の地形　—　南極の地形はこれとは対比的に起伏が激しい

クラビウス・クレーター（直径225km）



南極から2000kmほど北にあるクラビウスクレーターの北側の縁から南極へ向かってみたところ



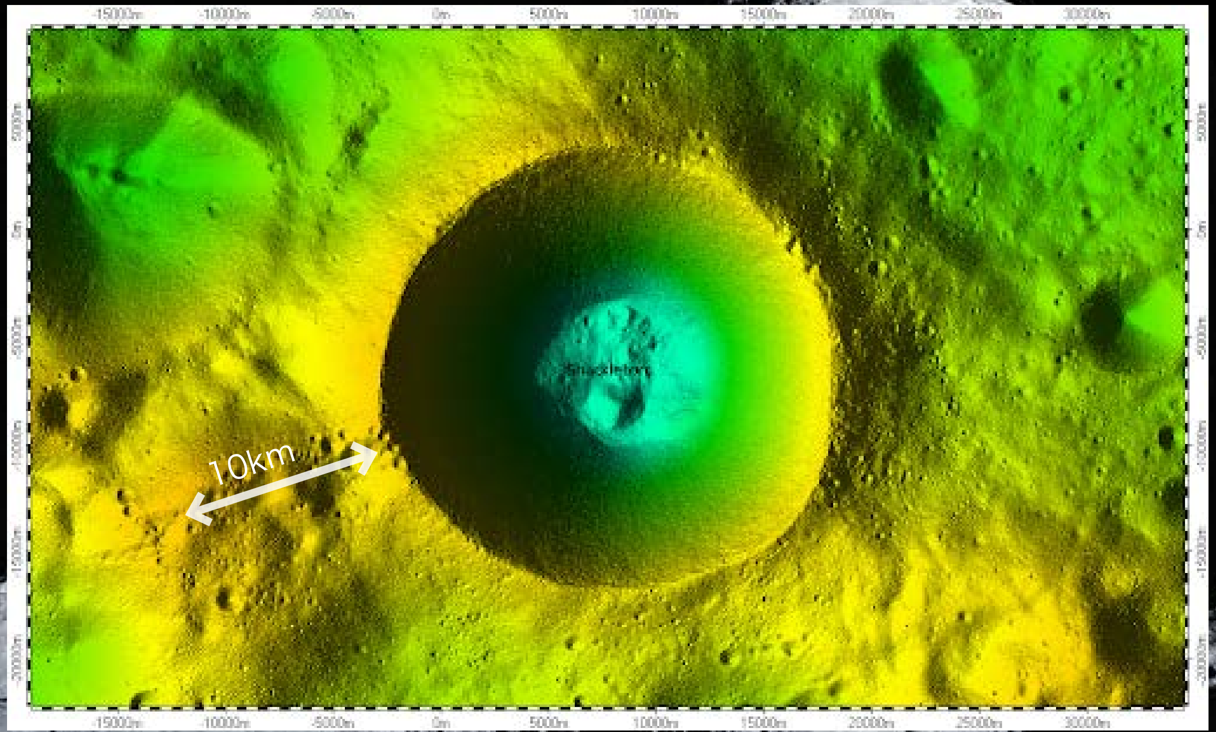


南極から750kmほど北にあるニュートンクレーターの様子：起伏の大きい地形を考慮した施工計画が重要である。

出典：ESA(Jorge Mañes Rubio)

極地方の日照率に関して考慮すべき点

- シャックルトンクレータの縁と、そこから約10km離れた尾根の上の場所を互いに行き来出来るという前提がでトータルで94%の日照率は考えられる。（つまり一方が影の時、もう一方の方に移れていれば、年にトータルで94%日照率が達成される）
- 二点間は10km、さらに尾根とはいえ起伏があり、簡単に行き来はできない。
- 極の日照率が良い場所というのは、よくて85%程度と考えておいた方が良い。
- 長期日照域の日照率について、パネルを10m程度立ち上げるという前提条件が考慮されていない傾向が見受けられる。今後の計画で注意が必要。



2. 光ファイバーによる彩光

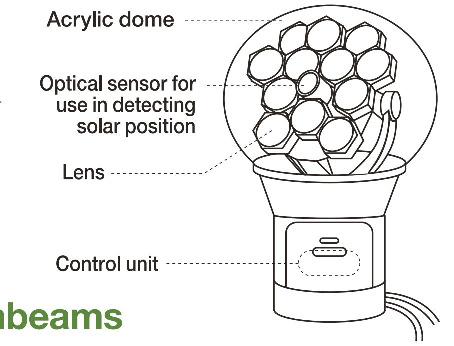
The Himawari solar lighting system comfortably brightens your daily life.

太陽追尾システム
建築･船舶へ応用可能

The technologies that enable the Himawari system to develop the possible uses of sunlight in your life

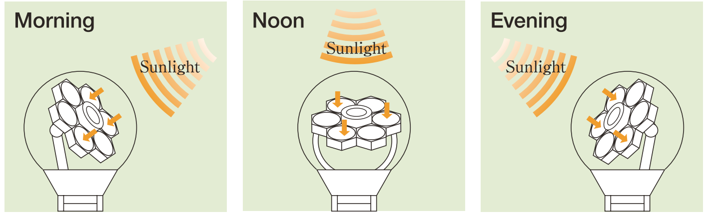
■ Sunlight collection at maximum efficiency with a system—lens focusing + optical fiber transmission

The Himawari system consists of a lens focusing unit and optical fiber devices. Its outdoor collector can collect sunlight always at maximum efficiency and transmit it through optical fibers to anywhere you want. Unlike conventional solar lighting systems which use skylights and mirrors, stable daylighting is possible all day long without suffering constraints imposed by room location, window orientation, and solar altitude.



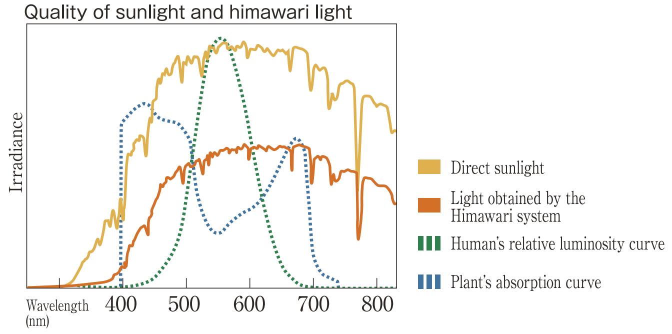
■ Automatic tracking system to accurately detect sunbeams

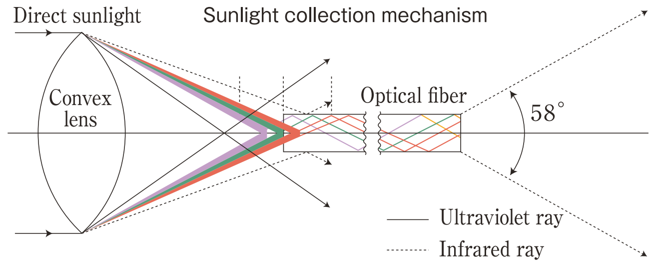
In order to accurately track the sun as it continuously changes its position from sunrise to sunset, Himawari is equipped with an automatic tracking system. A solar sensor and clock mechanism control the movement of the light-focusing lens so that it is always accurately aimed at the sun. Even when clouds block out the sun, the system can track the movement of the sun by calculating the trajectory and respond speedily to changes in the weather.



■ It's ultraviolet-free light, so it's gentle on the eyes and the skin

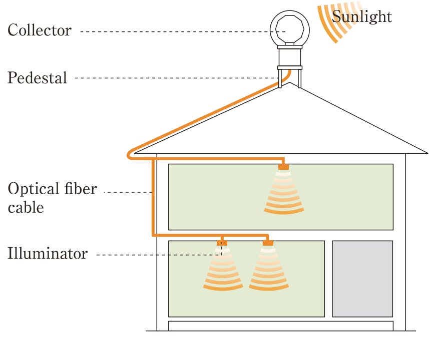
- High-quality sunlight is what the Himawari system provides. The tone of the light is natural and gentle on the eyes, qualities that cannot be reproduced by any artificial illumination.
- By using the acrylic dome covering the lenses and chromatic aberration through single lens focusing,the sun's UV can be eliminated. Therefore, the light consists predominantly of visible rays, a kind of light that is best suited for promoting photosynthesis in plants.
- Since the Himawari system screens out ultraviolet rays, it protects furniture and carpets from color fading.





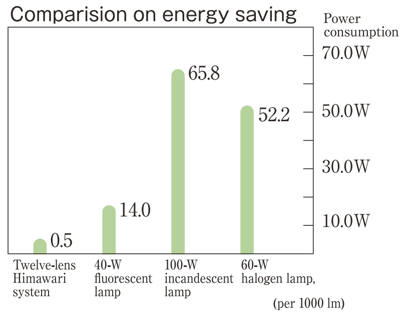
■ High-purity optical fiber, enabling free transmission of sunlight

Collected sunlight passes through quartz-glass optical fibers which transmit visible ray-dominated sunlight. Optical fibers are so thin and flexible that they can freely transmit light to rooms in any building, whether old or new.



■ Energy saving, and what's more,maintenance-free

- The running cost of the Himawari system is approximately 1 yen a day when equipped with a twelve-lens collector.
- Once the Himawari system is installed, it operates automatically without any need for manual operation. Since the precision collector is covered with an acrylic dome, the daylighting is stable over a long duration, and free from the effects of rain and dust.



From houses to condominiums, offices, and public spaces, the Himawari system is used in a wide variety of places.



光ファイバーの敷設距離によって光量の減衰が大きいので注意

HOME

From now on, all your rooms have a southern exposure. Living rooms become sunny.

Sunlight issues raised in the center of a city will be immediately resolved with the Himawari system. You can lead a sunlit life by lighting up living rooms, north-facing rooms, and basements, which sunlight cannot reach, as well as the kitchen and the lavatory which often tend to be in dark areas.





1. Living room
2. Kitchen
3. Bedroom
4. Basement
5. Lavatory



OFFICE

Sunlight brings comfort. Gentle light improves office environment.

How would you like to improve your working environment by exposing your office to sunlight? This is a system best suited not only for offices, but also for elevator halls, lobbies, aquaria, and planted areas. Optical fibers make the Himawari system effective in any type of buildings.





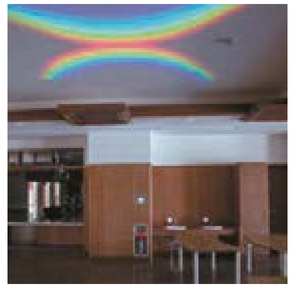
1. Office room (underground)
2. Elevator hall
3. Aquarium in a lobby
4. Wall surface of a passage
5. Patio (court)



PUBLIC

Friendly to the global environment, sunlight is best for lighting public spaces.

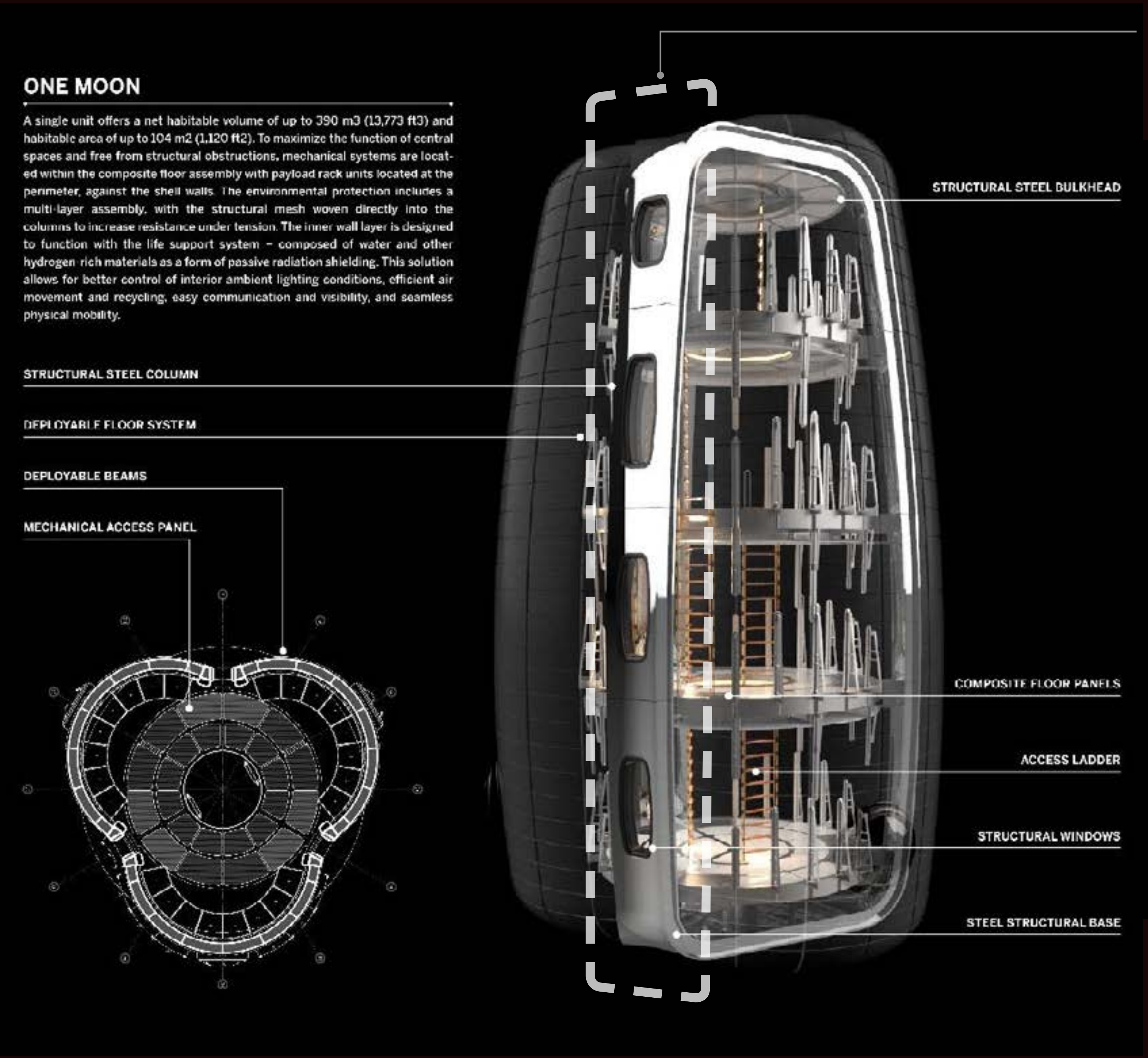
The Himawari system is used for public space such as underground passages, sculptures built in underground open spaces, and parking areas. This is a maintenance-free system that enables you to feel safe in the knowledge that you are saving both energy and costs.



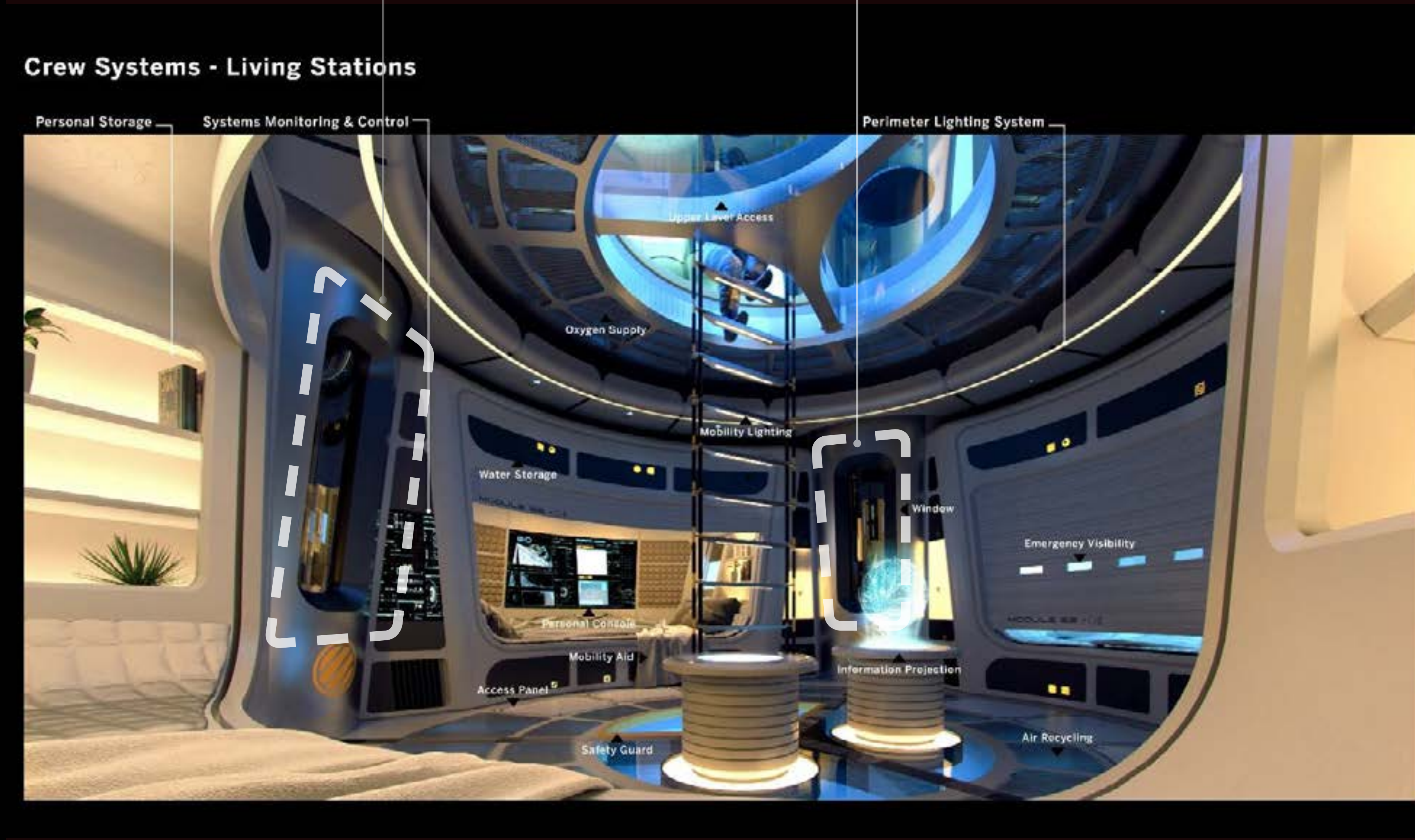


1. Arch of rainbow
2. Underwater illumination
3. Sculpture
4. Underground public space
5. Planted object

ESA,SOM,MIT - Lunar Habitat 2020



Windows



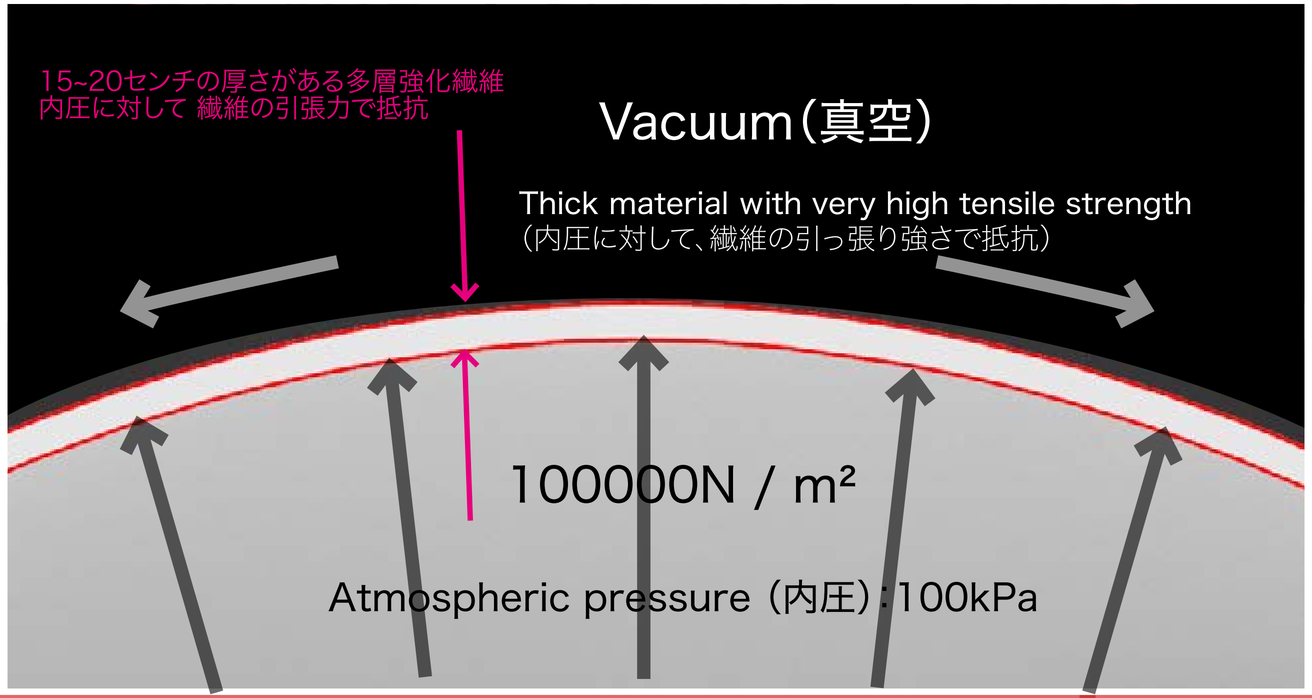
光ファイバーによる太陽光の彩光は可能であるが、外部を視認できることの重要性も強調されるべきであろう。
300から500日の長期滞在を目標とするとき精神的にも外部が確認できることの意義は大きいはずである。
また、外部で活動するクルーが内部と視覚コミュニケーションを取る上でも有用であると考えられる。

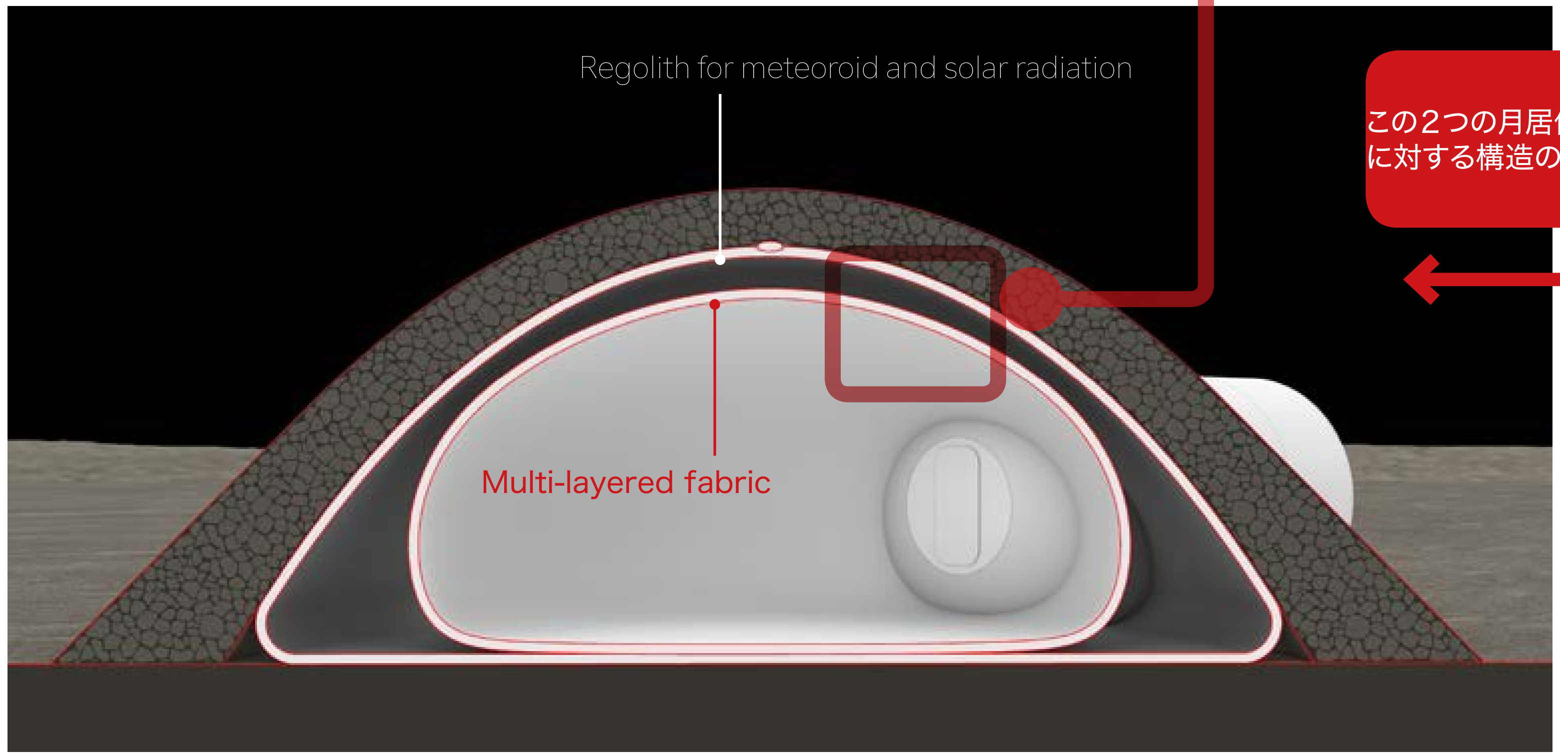
3. 内圧

真空中に建造物を作り、内部を約1気圧(101hPa)の空気で満たすと1平方メートルあたり100000Nの荷重がインテリアの壁において外側に向かって働くことになる。
これに抗する構造は、月面に考案されている居住施設の個々により、大きく異なる。
構造システムをなるべく軽減するため、酸素分圧を上げて内圧を約70kPaとする考え方を採用する施設設計もあるので数値設定の裏付けは重要である。

ESAによる3Dプリント月面居住施設

ESAの3Dプリント月面居住施設では金属とナイロンを原料とする15-20センチの厚さがある多層強化繊維の使用が膜構造として採用される。100kPaの内圧により1平方メートルあたり100000Nとなる荷重に対しては繊維の引張力で抵抗する。
3Dプリントされるレゴリスと強化繊維の間には30cmの緩衝帯が設けられており、この内圧はレゴリスの外壁に到達しないように設計されている。
つまり、レゴリスの外壁はメテオロイドと放射線の遮蔽に専念する。
また、多層強化繊維は分厚く強度の高い材料なので比較的小さな4人収容の施設に必要な膜でも地球で打ち上げの際の重量は数トンの重さになる。





この2つの月居住施設の参照例において内圧に対する構造の考えはまったく異なる。

太陽光集光リフレクターを装備したレゴリスより作られるパンテノン居住施設

40人を収容する大型建物である本計画では、強化繊維膜を地球から運搬する手間を省き、代わりにレゴリスの重量をおもしにして1平方メートルあたり70000Nの内圧に抵抗させるという構造コンセプトを採用している。
レゴリスの重しだけで1平方メートルあたり70000Nの内圧に抵抗するので20mの厚さの壁が必要になってくる。
気密性を確保するために採用されているのは0.1mmという極薄のプラスチックシートで、この薄い材料は引張力による抵抗力がほとんない。

From "Pantheon habitat made from regolith with a focusing solar reflector"
by Nick Wolf and Roger Angel (Steward Observatory, University of Arizona, USA)
https://ui.adsabs.harvard.edu/abs/2021RSPTA.37900142W/abstract

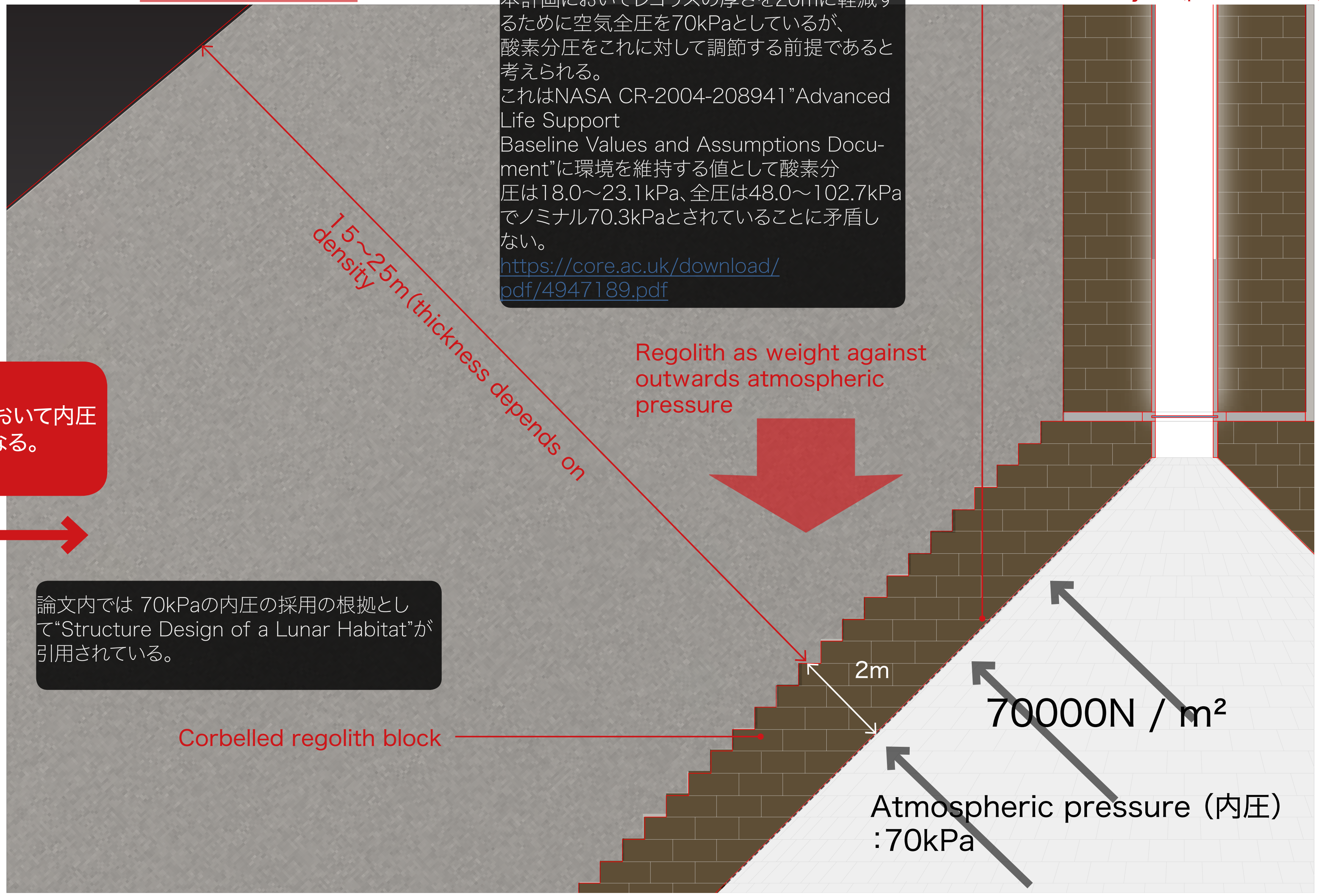
The density of regolith is approximately 1.7 and of cast blocks 3.0. Supposing an atmospheric pressure of 70 kPa (following Ruess) and allowing for the reduced gravity on the Moon, 1/6 that of Earth, a minimum thickness of 25 m of regolith or 15 m of the denser cast blocks is needed.

From "Structure Design of a Lunar Habitat"
by F. Ruess, J. Schaenzlin, and H. Benaroya
https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.503.9275&rep=rep1&type=pdf

The habitat module pressure and the pressure used in space suits for EVA influence one another. EVA productivity increases with the use of lower pressures because the gloves become more flexible (Elrod 1995). At the same time, low pressures increase the fire hazard, and lower voice and cough mechanism effectiveness for astronauts. It is assumed that the actual habitat pressure will be around 69 kPa (10 psi; 42,600 kg/m^2).

論文内では 70kPaの内圧の採用の根拠として"Structure Design of a Lunar Habitat"が引用されている。
参照として航空機の客室の空気全圧は80kPaに対し、酸素分圧は16kPaである。
本計画においてレゴリスの厚さを20mに軽減するために空気全圧を70kPaとしているが、酸素分圧をこれに対して調節する前提であると考えられる。
これはNASA CR-2004-208941"Advanced Life Support Baseline Values and Assumptions Document"に環境を維持する値として酸素分圧は18.0〜23.1kPa、全圧は48.0〜102.7kPaでノミナル70.3kPaとされていることに矛盾しない。
https://core.ac.uk/download/pdf/4947189.pdf

Airtight seal:
0.1mm thick mylar (plastic sheet)



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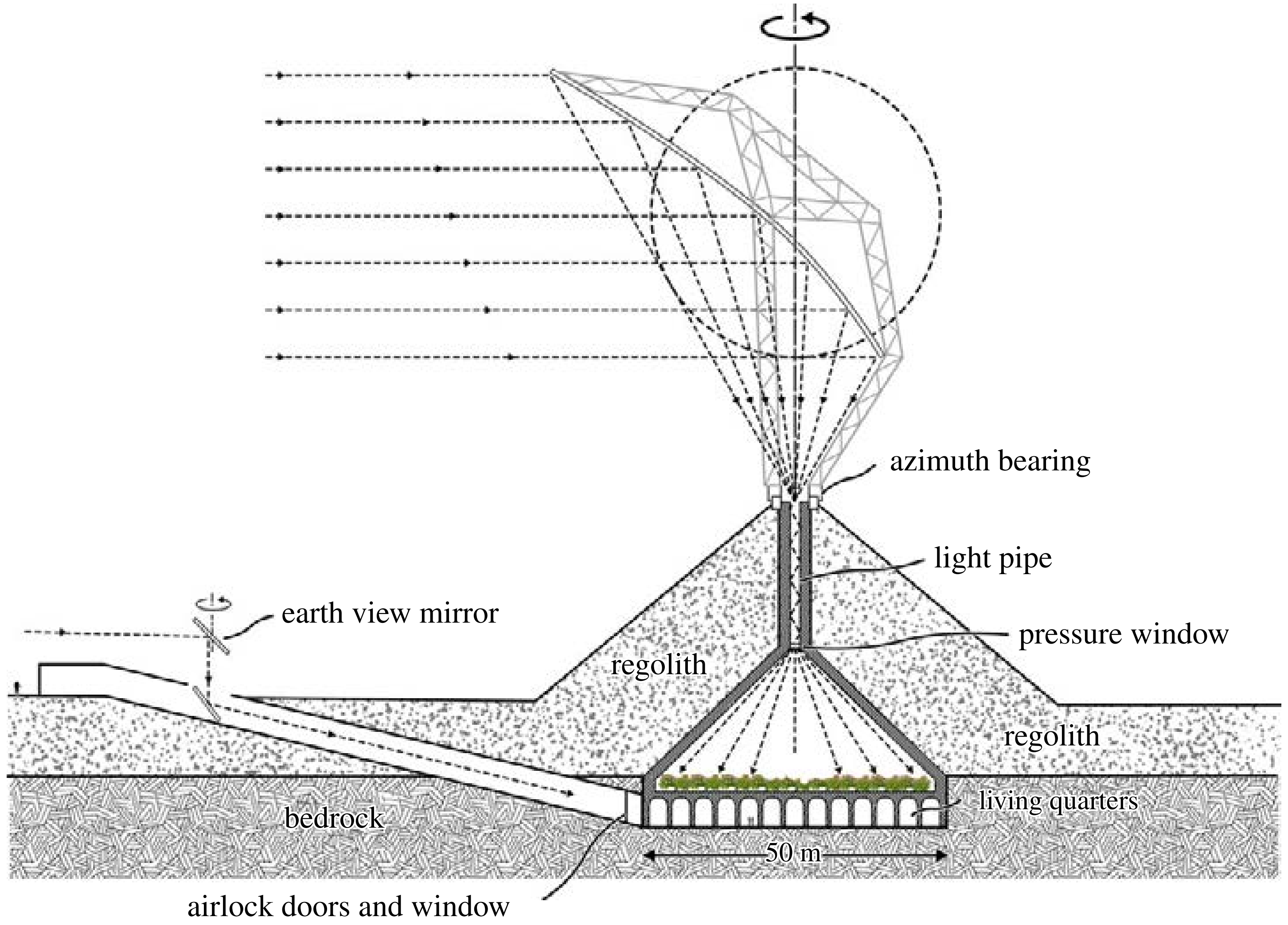
Analysis of

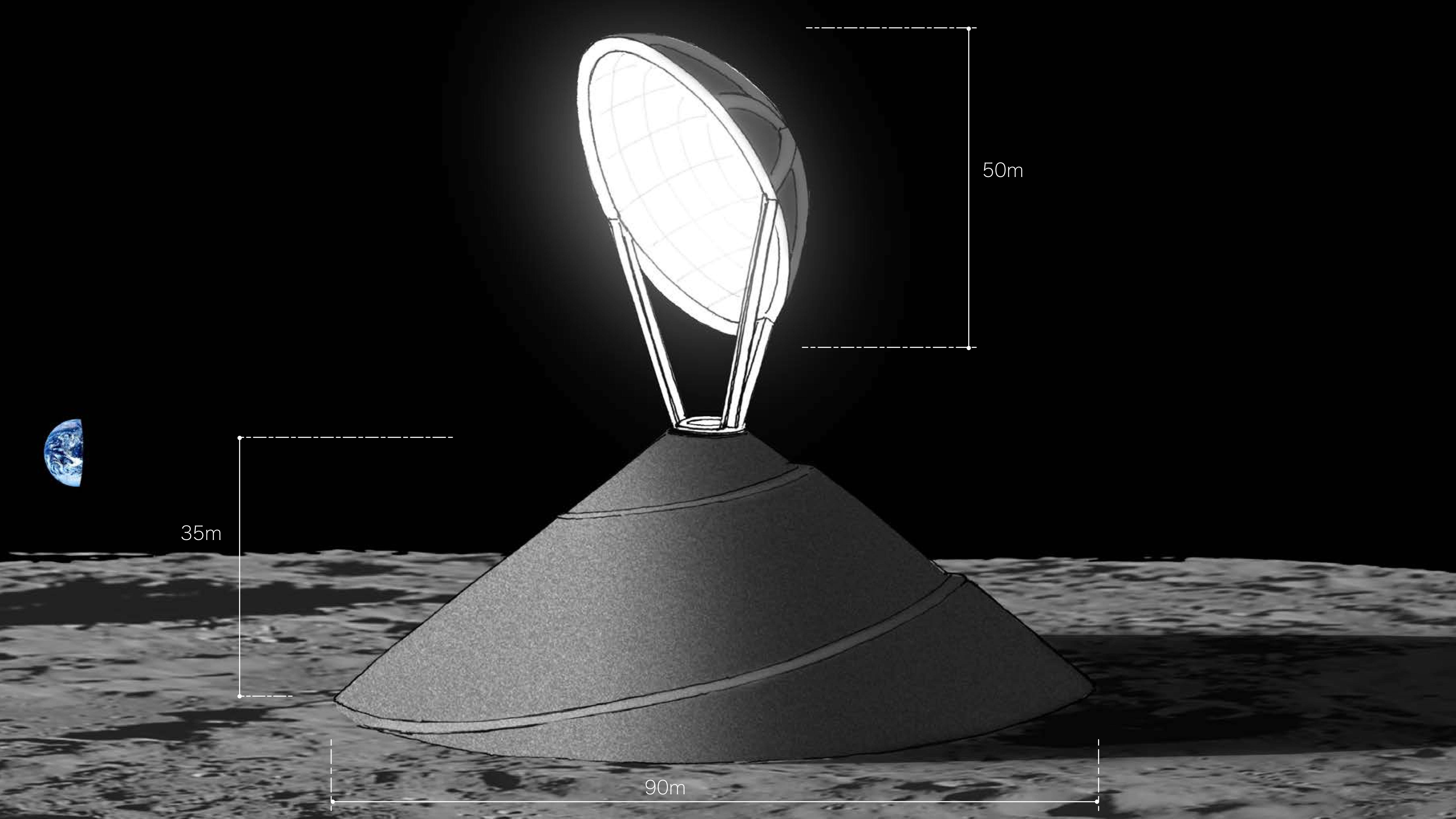
Pantheon habitat made from regolith, with a focusing solar reflector

Nick Wolf and Roger Angel

Steward Observatory, University of Arizona, USA



Pantheon, Rome (126 AD)


50m
35m
90m

Existing problems

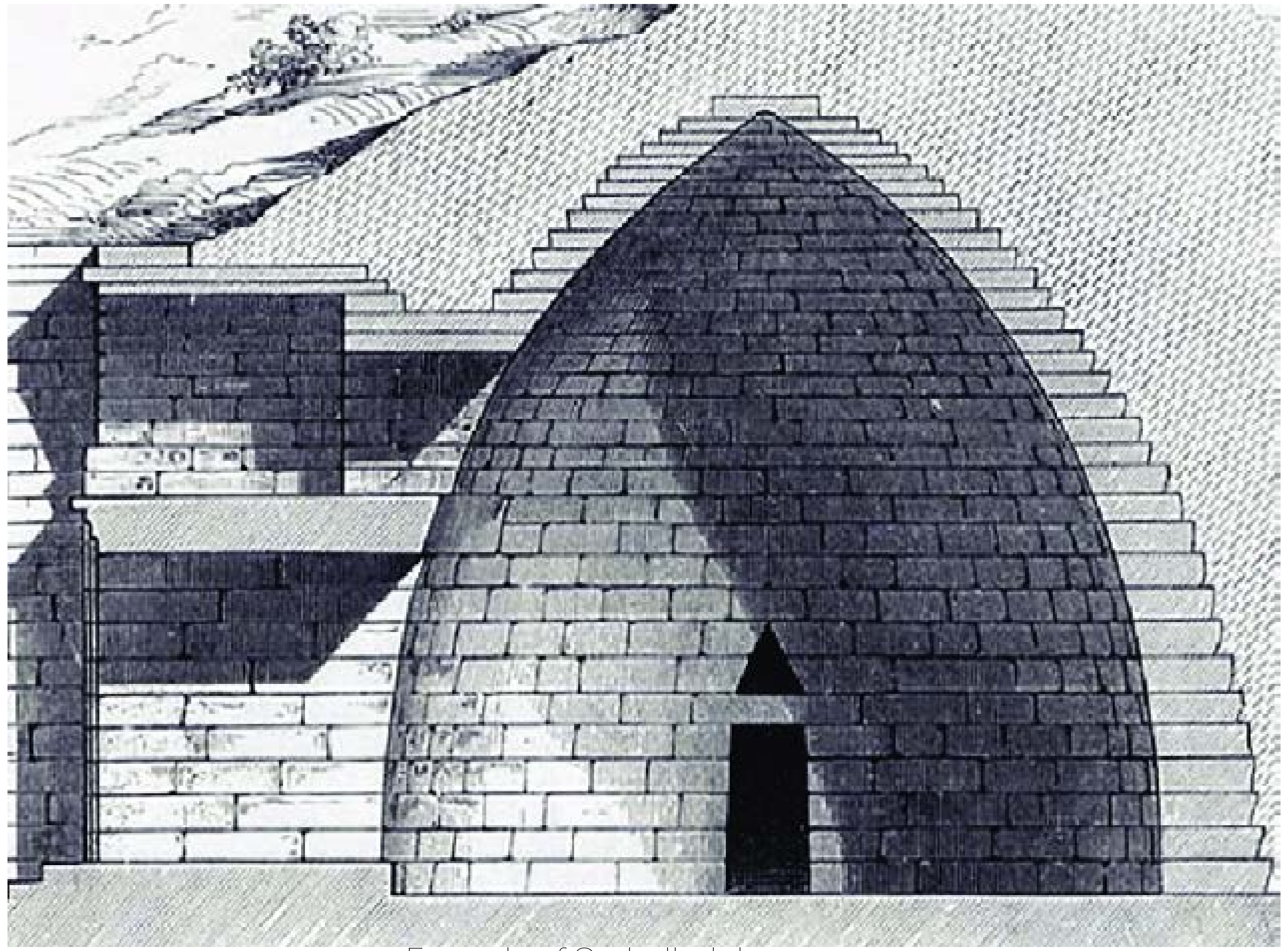
- High cost of transport (to bring resources from Earth to Moon)
- Requirement of advanced material processing

Proposal of this project

- Using In-situ resources
- Minimal manufacturing process (primitive constitution method)
- Building food supply facility

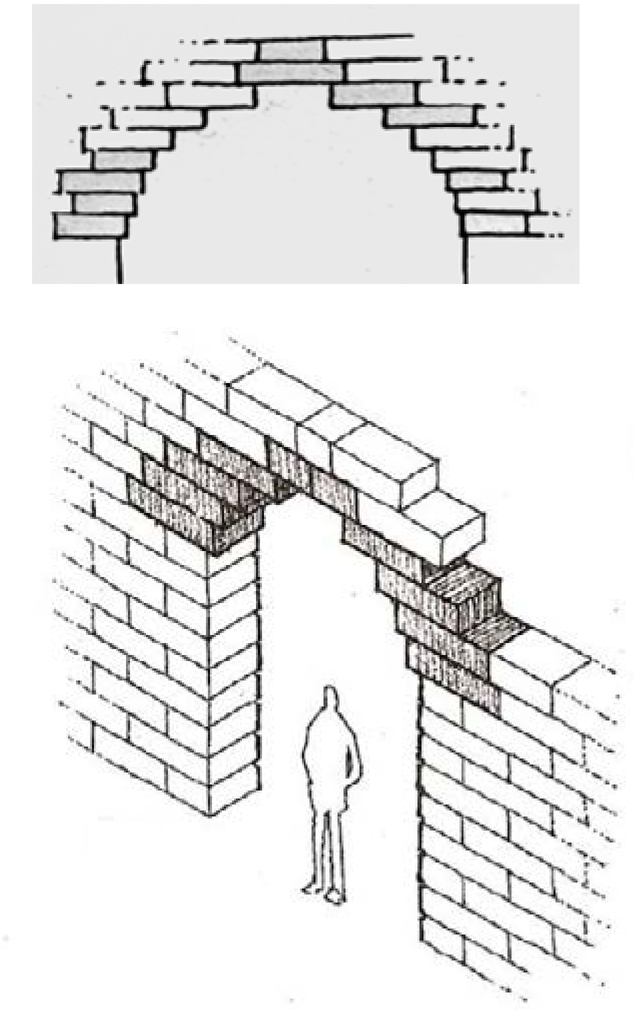
Key Structure Concept

This project adopts one of the most primitive structure systems older than voussoir arch

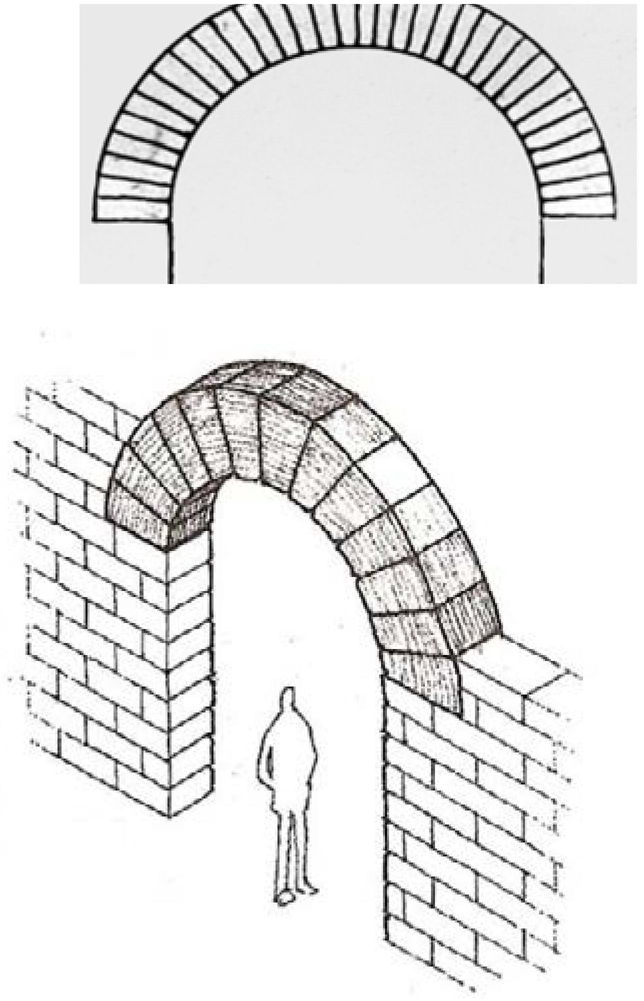


Example of Corbelled dome

Treasury of Atreus (1250 BC)

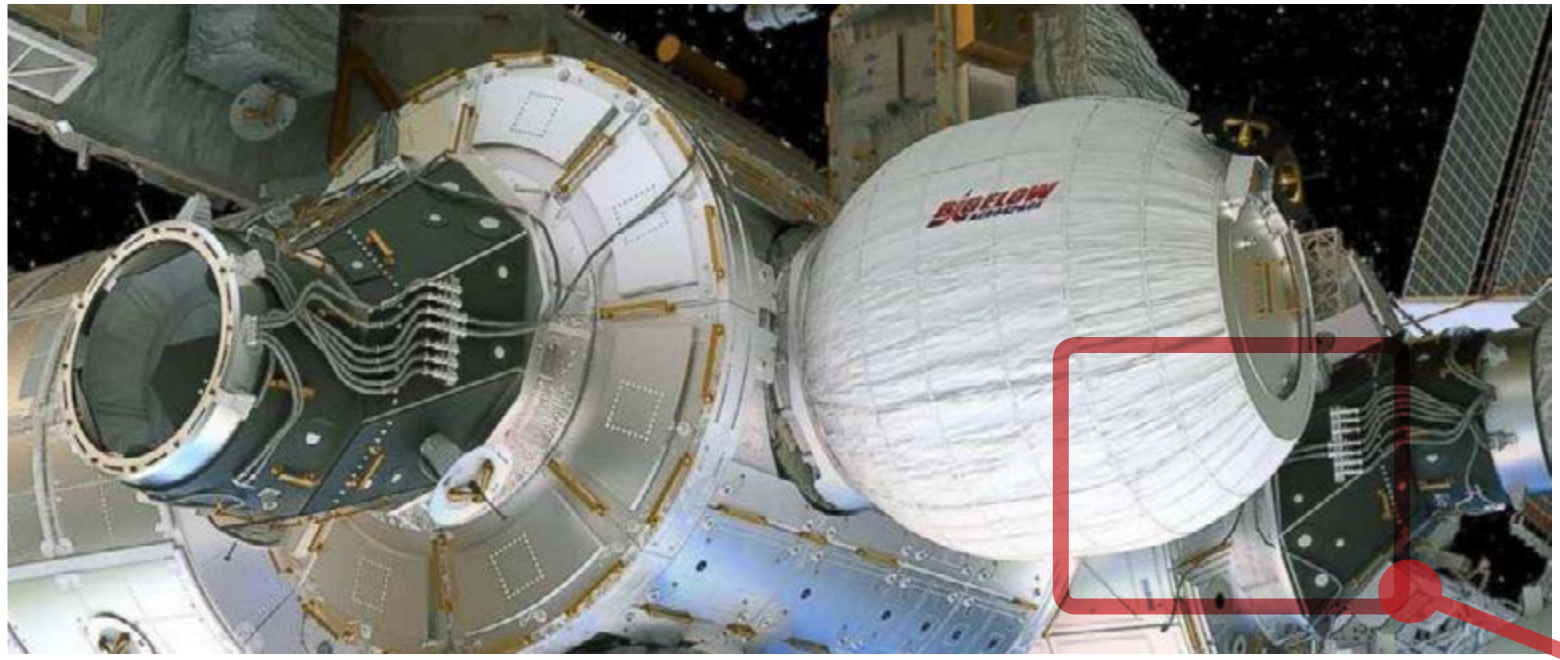


Corbelled Arch
3000 B.C.

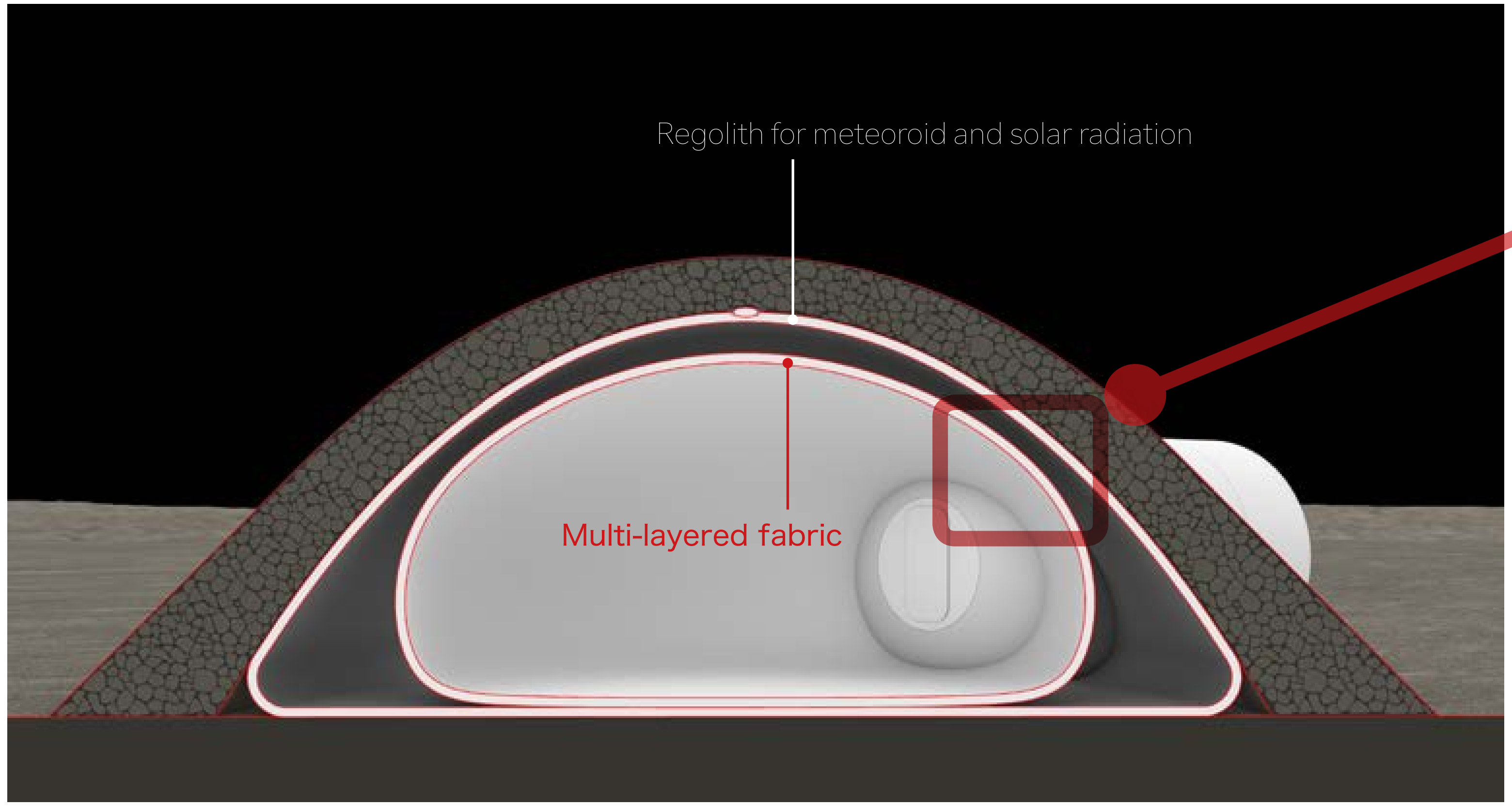


Key Structure Concept

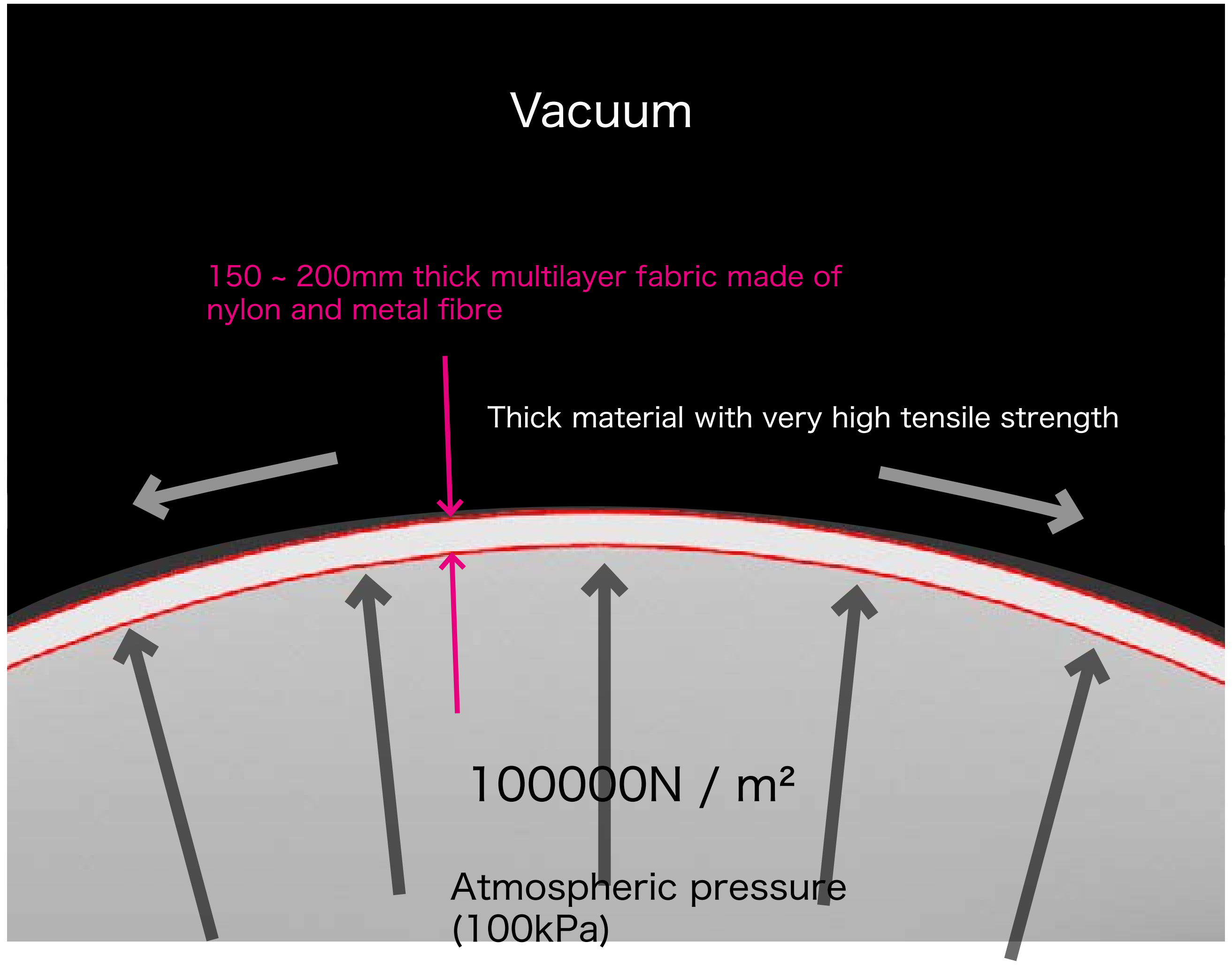
Not relying on advanced fabric technology



ISS BEAM



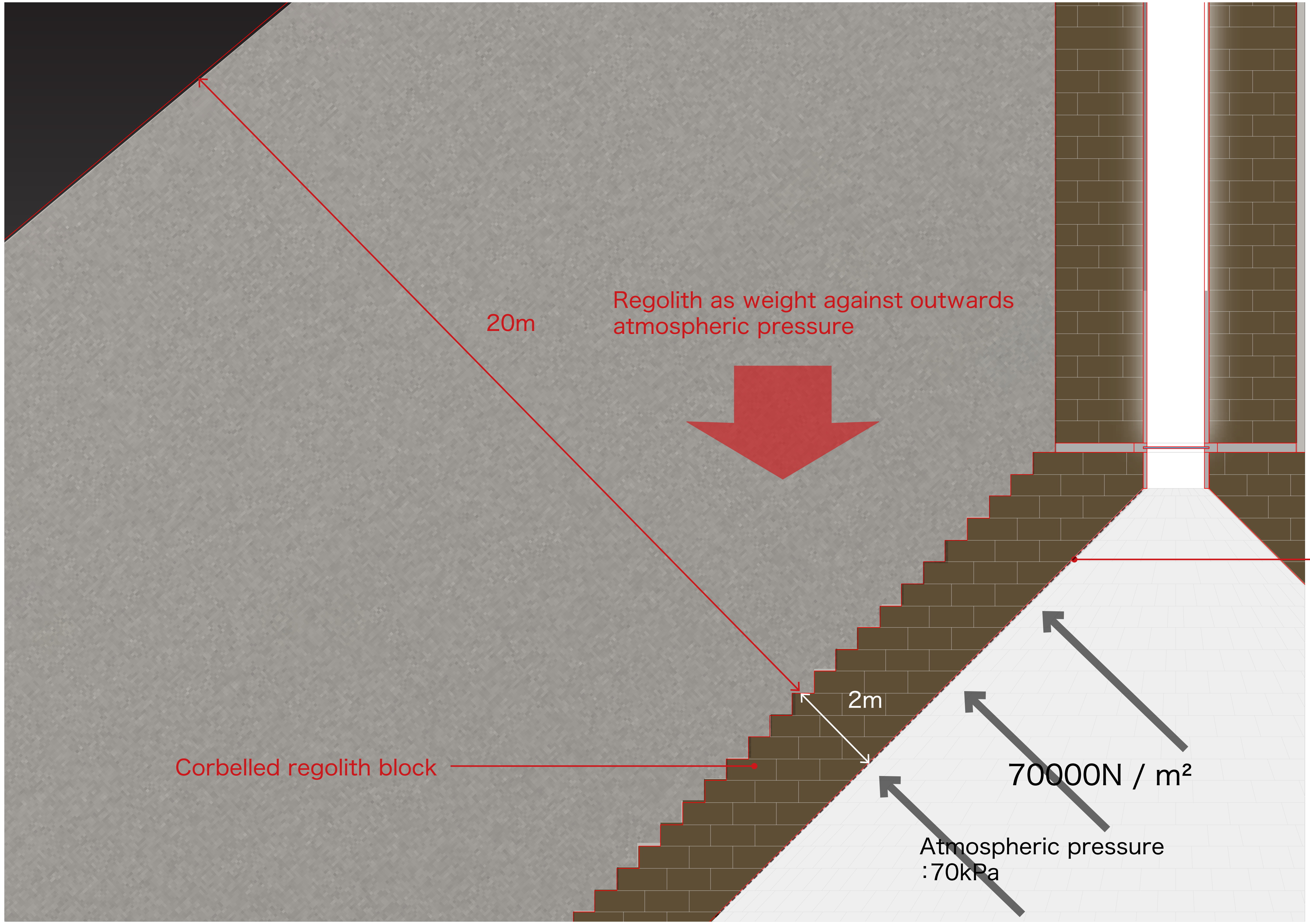
Various lunar habitat project based on inflatable membrane technology

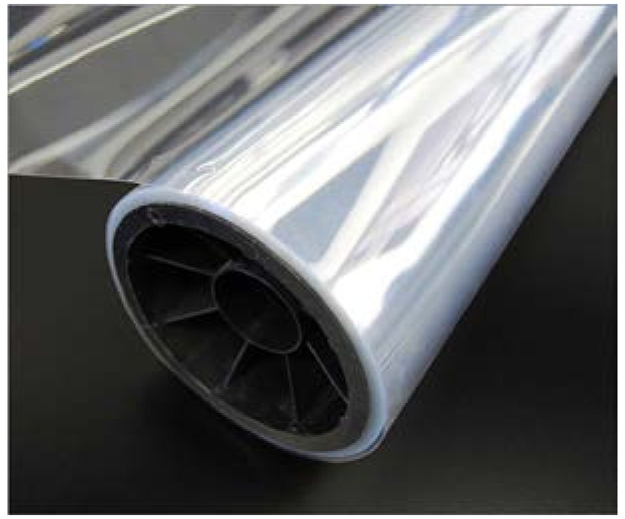


But this project to be away from advanced fabric technology due to limitation of rocket payload

Key Structure Concept

Not relying on advanced fabric technology

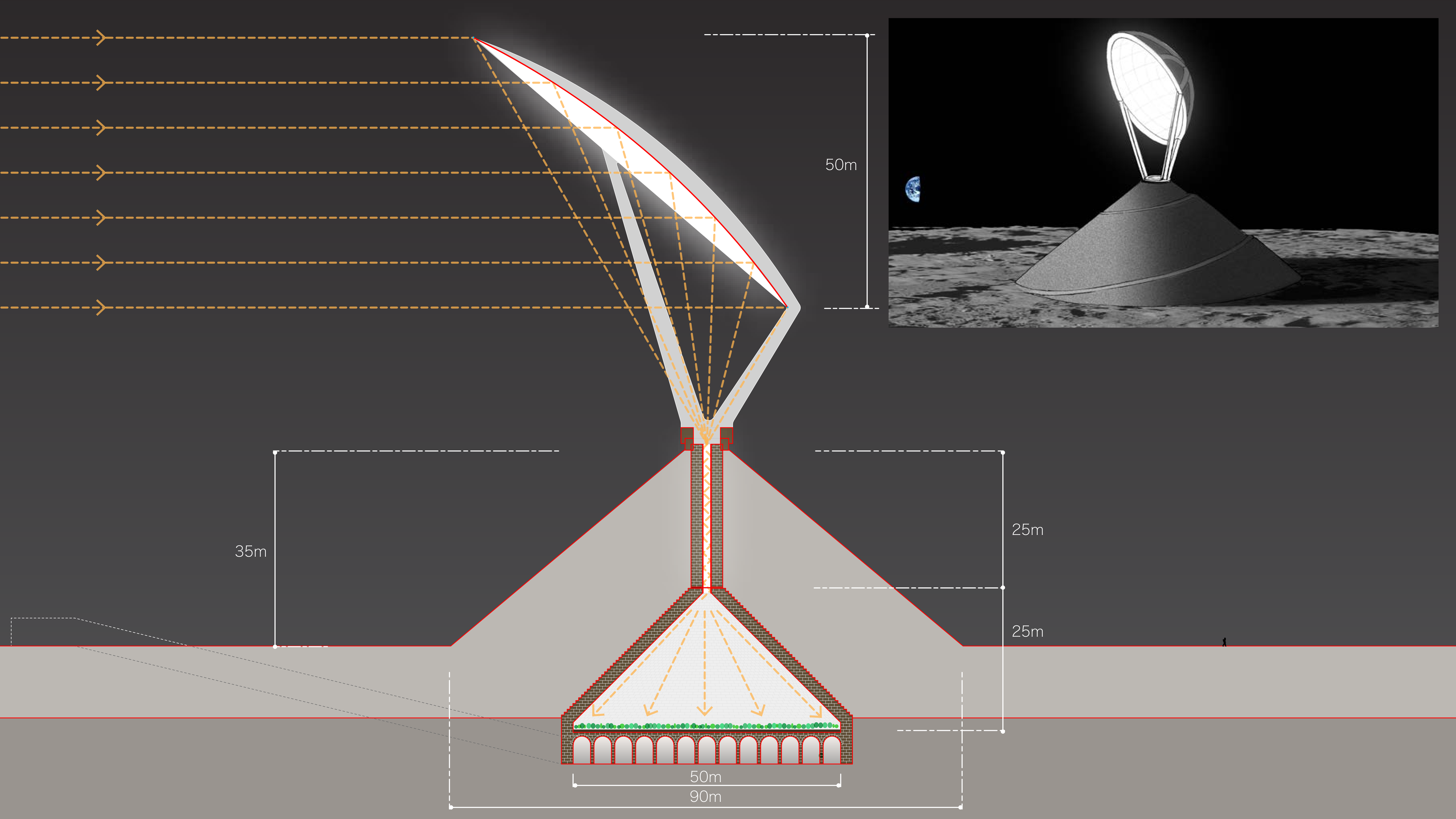




Airtight seal:
0.1mm thick mylar (plastic sheet)

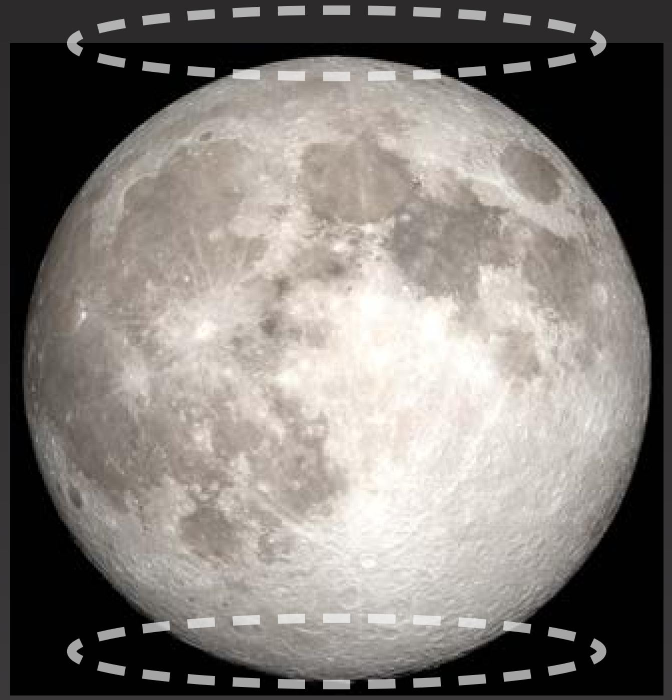
Atmospheric pressure (69kPa)

Reason:
Productivity of extravehicular activity increases with the use of lower pressure because the gloves become more flexible.


50m
35m
25m
25m
50m
90m

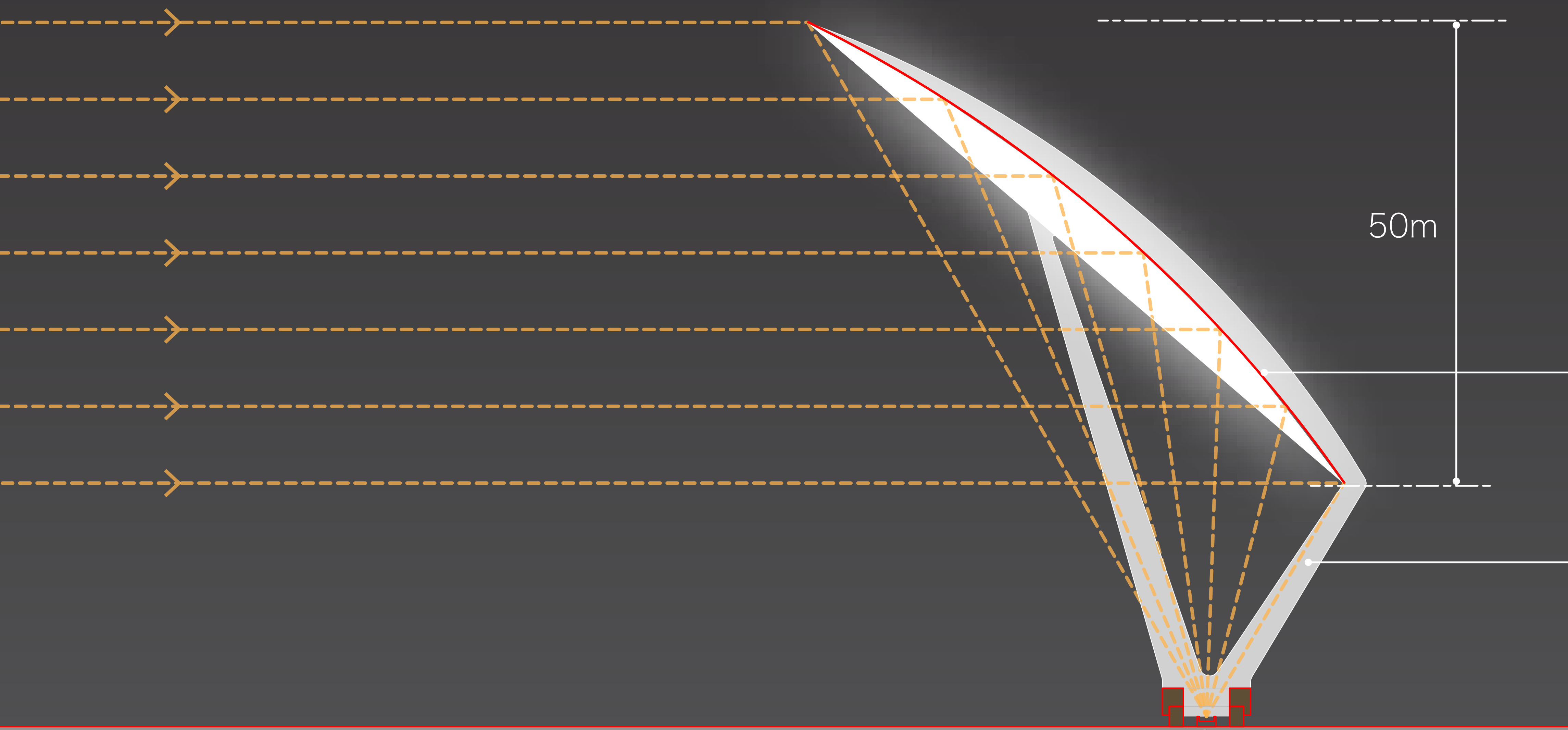
Construction Sequence 1

- Transport a solar concentrator with 50m diameter
- Produce regolith block by solar sintering (melting method)
- Production process will take 3 years



Location: Lunar pole

Deposit of water & volatiles
Permanganate solar illuminations



Regolith block produced in ceramic fibre mould at 1600 °C

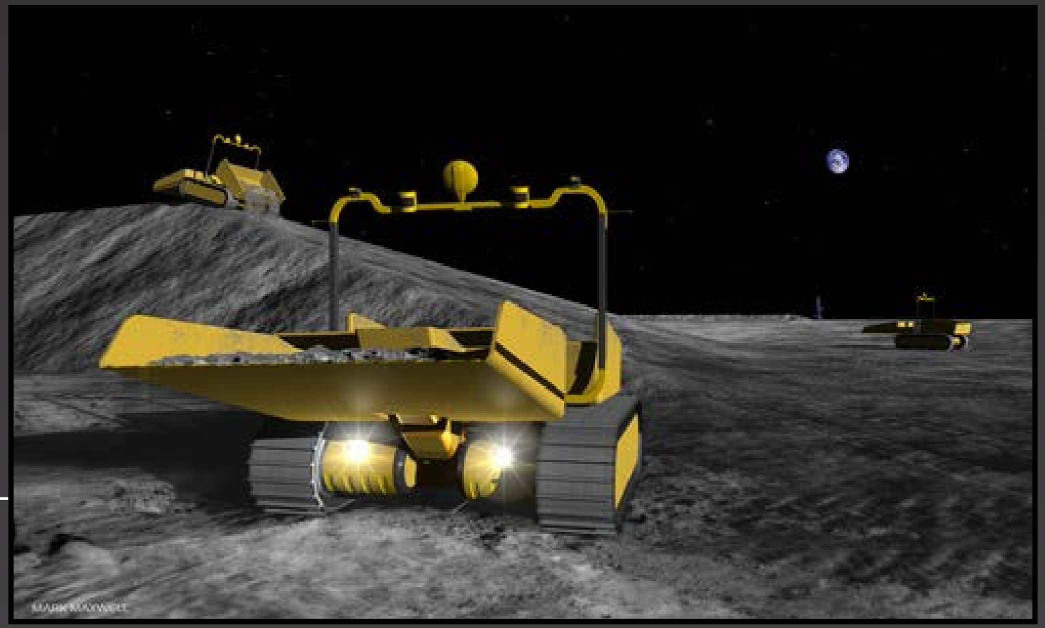
Light weight mirror system brought from Earth

Honeycomb backed mirror panel

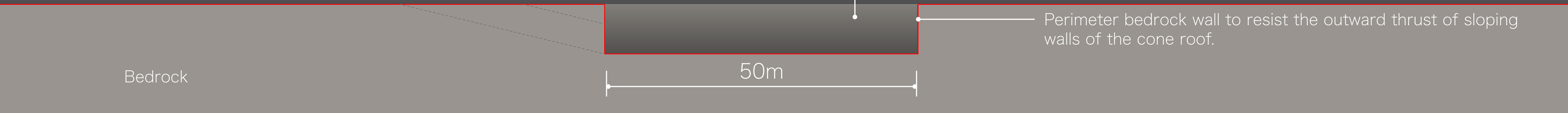
Carbon fibre structure frame

Construction Sequence 2

- Find bedrock
- Excavate bedrock and make surface good to start piling up regolith block
- The pit to be sealed against air leakage

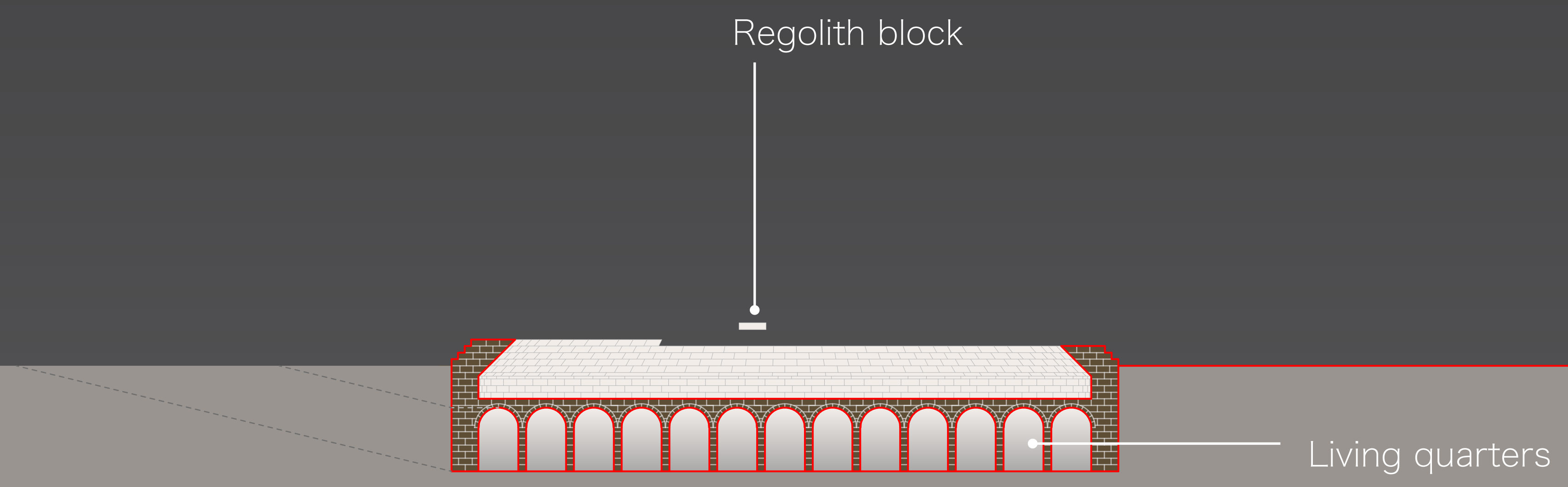


Lunar digger



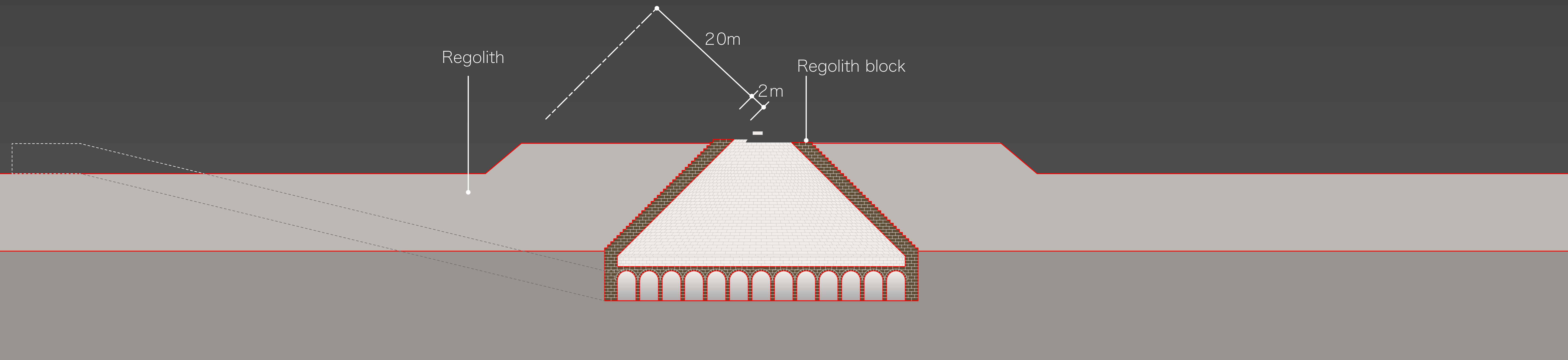
Construction Sequence 3

- Living quarters built with vaulted ceiling



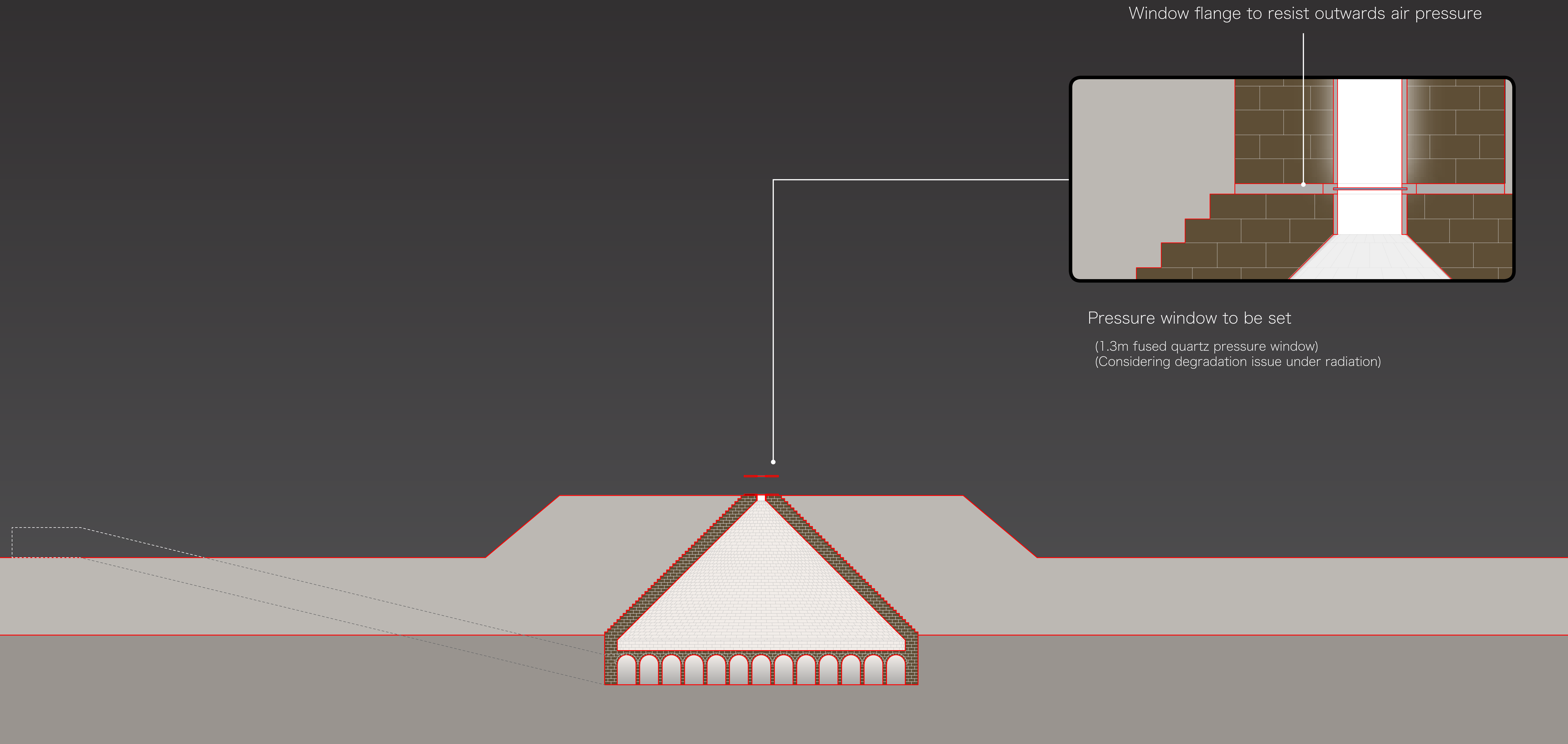
Construction Sequence 4

- Entrance tunnel and airlock built



Construction Sequence 5

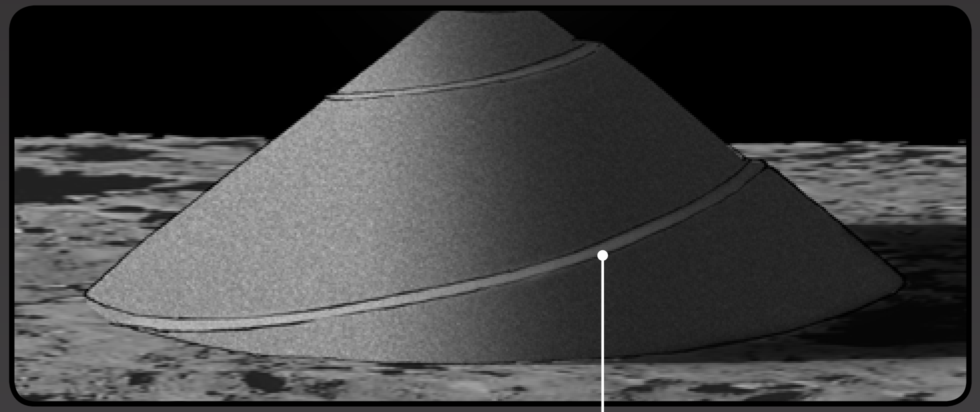
- Pressure window installed on the top of the cone roof



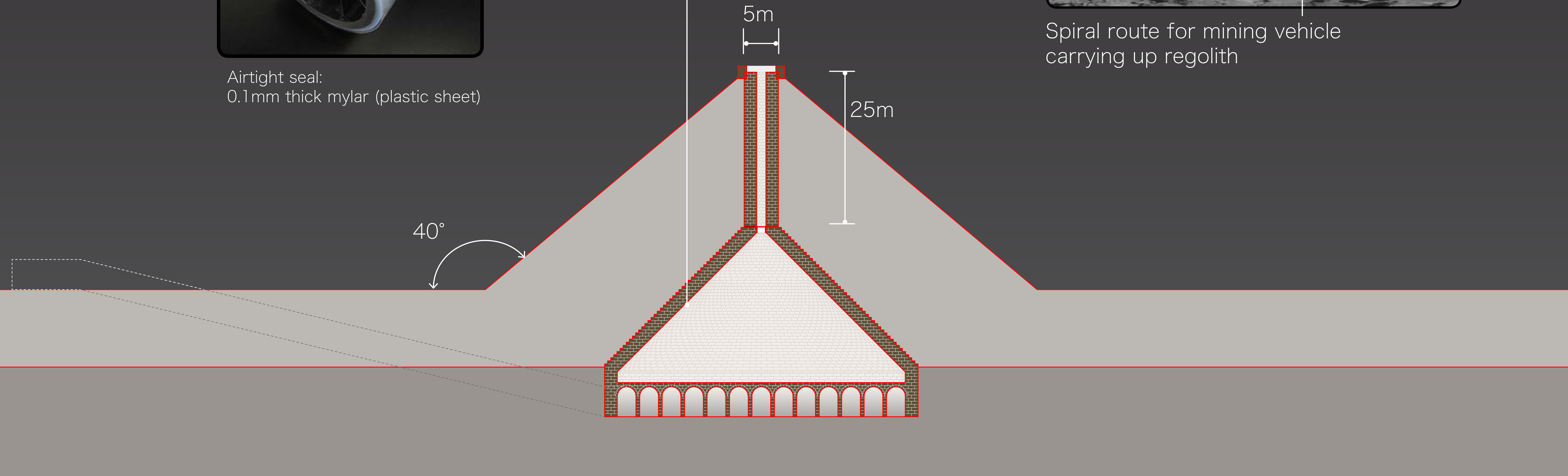
Construction Sequence 6

- 25m tall light path built

Airtight seal:
0.1mm thick mylar (plastic sheet)



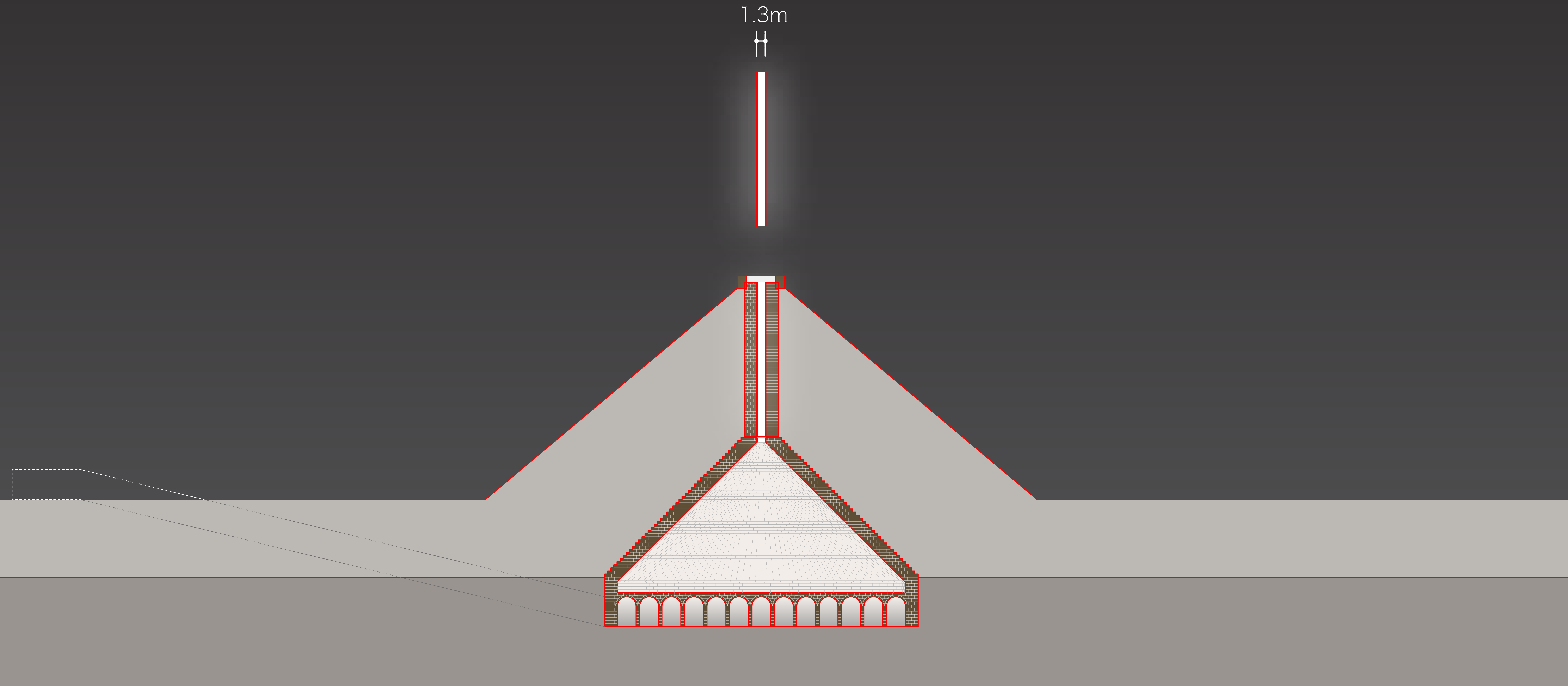
Spiral route for mining vehicle
carrying up regolith



Construction Sequence 7

- Light pipe installed (1.3m diameter)

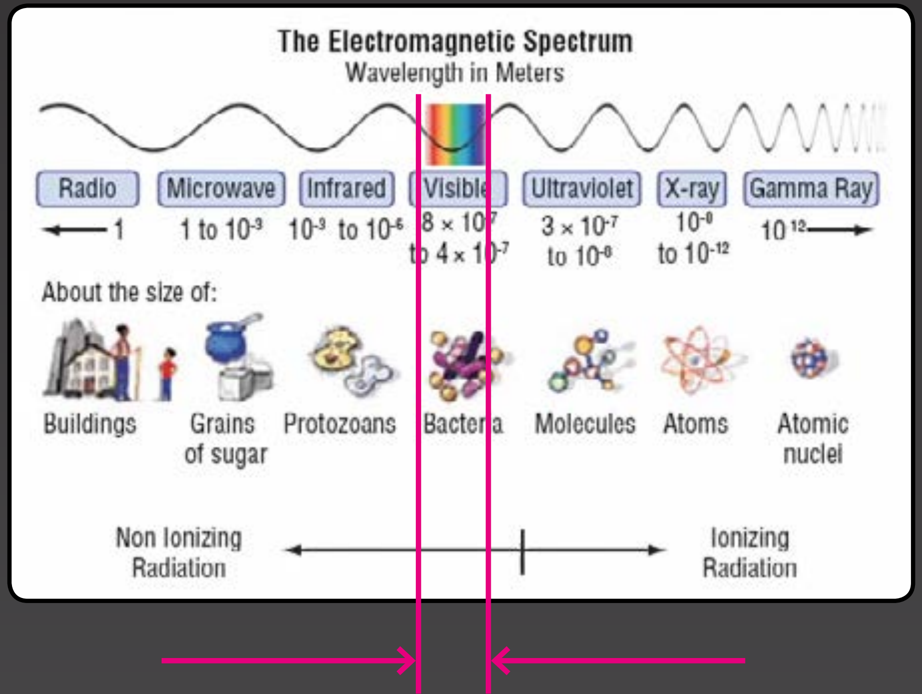
- Light pipe with dielectric coated mirror
(fused silica fibre will be too heavy (73 tons))



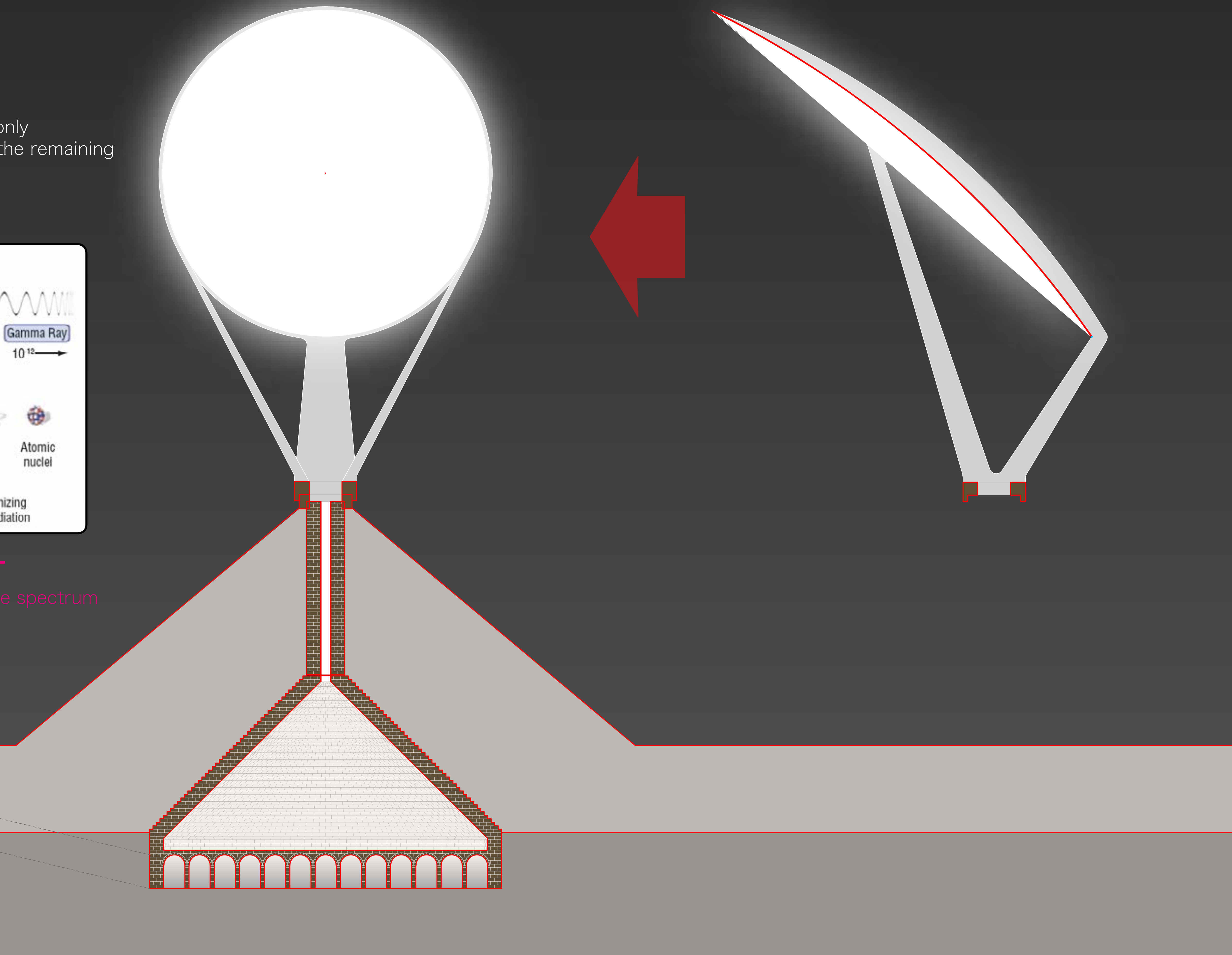
Construction Sequence 8

- Solar concentrator 50m diameter installed

- Mirror with multilayer dielectric coating will reflect only the wavelength range 450nm - 600 nm and reject the remaining spectrum (eliminate solar radiation)

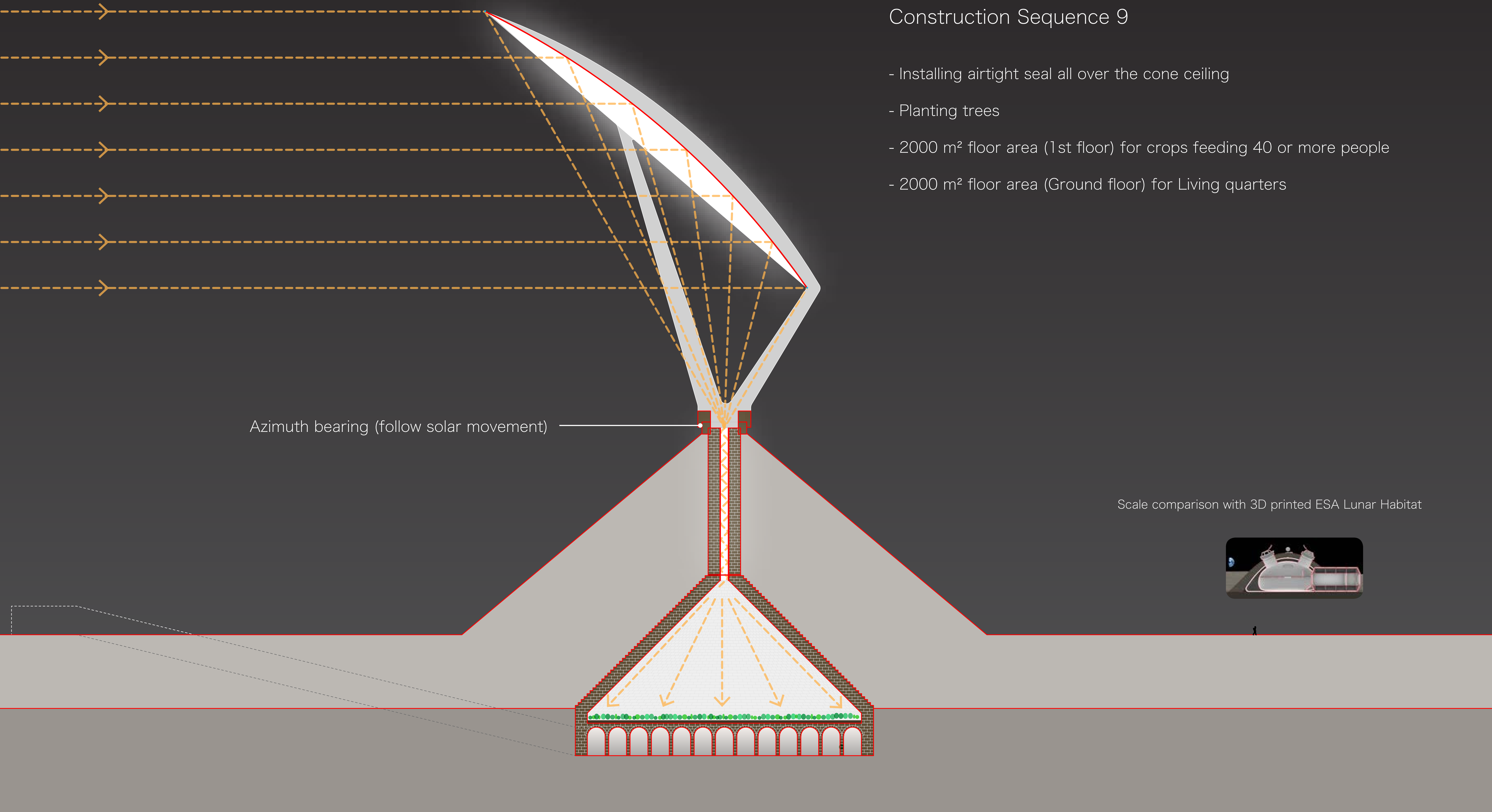


Multilayer dielectric coat only reflect visible spectrum (the wavelength range 450nm - 600 nm)



Construction Sequence 9

- Installing airtight seal all over the cone ceiling
- Planting trees
- 2000 m² floor area (1st floor) for crops feeding 40 or more people
- 2000 m² floor area (Ground floor) for Living quarters

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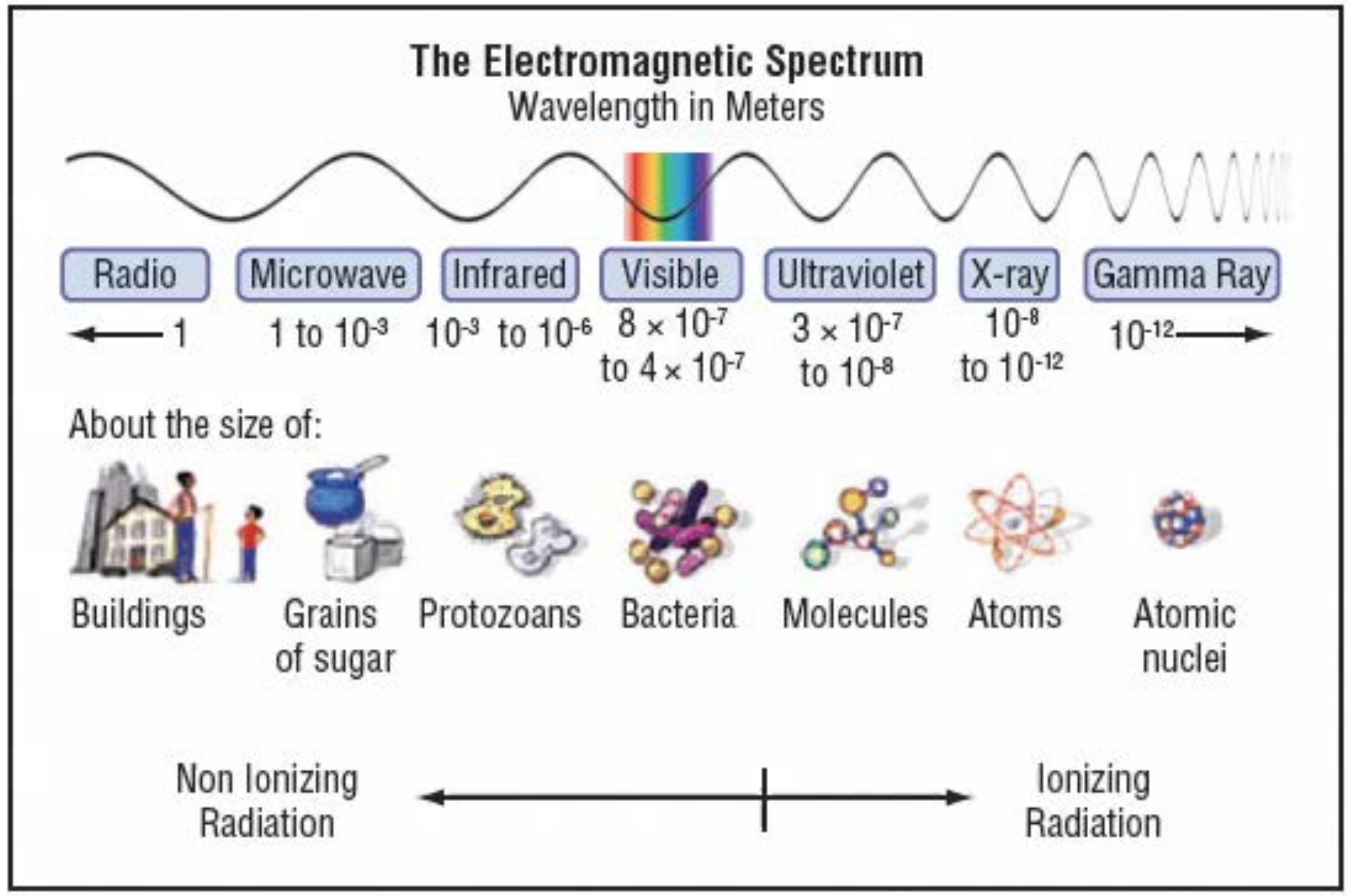
4. 放射線


The Electromagnetic Spectrum
Wavelength in Meters
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
1
1 to 10⁻³
10⁻³ to 10⁻⁶
8 × 10⁻⁷ to 4 × 10⁻⁷
3 × 10⁻⁷ to 10⁻⁸
10⁻⁸ to 10⁻¹²
10⁻¹²
About the size of:
Buildings
Grains of sugar
Protozoans
Bacteria
Molecules
Atoms
Atomic nuclei
Non Ionizing Radiation
Ionizing Radiation

Necessary thickness of regolith wall as radiation shield

Radiation:

A shield to protect against radiation exposure in a lunar habitat must reduce crew exposure levels from lunar radiation sources (GCR & Solar) to acceptable levels. A layer/shield of regolith accomplishes this reduction by increasing the mass/material a radiation source must traverse to reach the crew. The more material a radiation source passes through the more its radiation energies are reduced or stopped by its particles interacting with the material. Specifically, solar wind particles have such low energies (keV) that they are stopped in less than a micrometer of regolith while solar event particles will pass through ~50-100 centimeters of regolith before being significantly mitigated (See Figure 4). In addition, heavy nuclei GCR particles are stopped by ~10 centimeters of regolith while all other GCR (GeV) particles are stopped by 1000g/cm^3 of material which equates to 5 meters of lunar regolith (2g/cm^3) or the Earth's atmosphere [Heiken 1991]. However since NASA's current acceptable limit for radiation exposure is 25 rem/month not zero, less than 5 meters of regolith shielding (i.e., 10cm_{AL} - Standard Space Vehicle Shielding = 13$cm_{regolith}$) would be acceptable GCR protection. Therefore based on the maximum protection required, as described above, 1–2 meters of regolith appears to be adequate for effective shielding of a lunar habitat to avoid radiation sickness in the crew [Silberberg 1988].

Nancy J. Lindsey,
International Lunar Conference 2003

Reference:
[Silberberg 1985]Silberberg, R. et al, "Radiation Transport of Cosmic Ray Nuclei in Lunar
Material and Radiation Doses," Lunar Bases and Space Activities of the 21st Century, NASA
Symposium Publication (Houston, Texas: Lunar and Planetary Institute, 1985).

Note:
25 rem = 250mSv

1 - 2m thick regolith wall not to exceed 250 mSV a month

kind of lunar surface habitat will have to be protected from three different kinds of ionizing radiation in space: Solar wind, solar cosmic rays, and galactic cosmic radiation.

Meteoroids are naturally occurring small solid bodies traveling through space at very high speeds.

Most likely, a layer of compacted regolith will be placed atop the structure for protection against all of those hazards. It provides shielding against most micrometeoroid impacts because the relatively dense and heavy regolith absorbs the kinetic energy. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 5 rem, which is the allowable level for radiation workers. In addition, it greatly reduces the effects of the extreme temperature cycles. The mass of regolith is about 1.7 g/cm^3. With an assumed regolith cover of 3 m, the resulting dead load on the structure will be 5,100 kg/m^2.

Other shielding concepts include passive bulk shielding with material other than regolith, electromagnetic shielding, electrostatic shielding, and chemical radioprotection.

Vacuum

A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be stable if exposed under such conditions. Outgassing materials and structures, e.g., hydraulic systems, have to be avoided. A lunar structure will not be subjected to any kind of wind loads.

Dust

The lunar surface has a layer of fine particles that is easily disturbed and placed into suspension. These particles cling to all surfaces, are highly abrasive, and pose serious challenges in the utility of construction equipment and the operation and maintenance of airlocks (Benaroya and Ettouney 1992a,b).

Moonquakes

There is little or no seismic activity on the Moon. Therefore, lunar structural design will not include earthquakelike loads.

Temperature

Temperatures on the lunar surface rapidly change from approximately 100 to −150°C in the transition between day and night, which occurs in roughly two-week cycles.

Structural Requirements

Building a structure on the Moon results in many different and additional requirements that have to be fulfilled by the structure.

Structural Adequacy

The structure must sustain all dead and live loads with an acceptable degree of safety. A minimum of structural material is desired. The use of lightweight high stiffness to weight ratio materials is necessary.

Material Properties

Properties for lunar construction materials should include high strength, ductility, durability, stiffness, and tear and puncture resistance, together with low thermal expansion. The stability of these mechanical properties and low leakage are important.

Ruess F 2006
Structural design of a lunar habitat

Note:
5 rem = 50mSv
This is a 1/5 of the allowance defined by NASA and ESA

2.5m thick regolith wall not to exceed 50 mSV a year

Table 3: Radiation penetration and exposure limits.

Depth of Radiation Penetration and Exposure Limits for Astronauts and the General Public (in mSv)				
	Exposure Interval	Blood Forming Organs (5 cm depth)	Eyes (0.3 cm depth)	Skin (0.01 cm depth)
Astronauts	30 Days	250	1,000	1,500
	Annual	500	2,000	3,000
	Career	1,000-4,000	4,000	6,000
General Public	Annual	1	1,500	50

Table 4: Missions and radiation dose.

Mission Type	Radiation Dose
Space Shuttle Mission 41-C (8-day mission orbiting the Earth at 460 km)	5.59 mSv
Apollo 14 (9-day mission to the Moon)	11.4 mSv
Skylab 4 (87-day mission orbiting the Earth at 473 km)	178 mSv
ISS Mission (up to 6 months orbiting Earth at 353 km)	160 mSv
Estimated Mars mission (3 years)	1,200 mSv

Table 3 compares the specific exposure limits between the general public and astronauts. Astronauts who spend three months in the ISS will be subjected to over three times the maximum recommended dosage of radiation for one year.

Table 4 compares and contrasts various missions and their durations with the observed radiation dose.

Crews aboard the Space Station receive an average of 80 mSv for a six-month stay at solar maximum (the time period with the maximum number of sunspots and a maximum solar magnetic field to deflect the particles) and an average of 160 mSv for a six-month stay at solar minimum (the period with the minimum number of sunspots and a minimum solar magnetic field).

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NASA
Space Radiation ebook

Radiation exposure limit for astronauts

250 mSv (30 days)
500 mSv (a year)

the ground floor of the habitat. This approach will give a slight overestimation of the GCRs dose due to the fact that the crew do not spend the whole year in the top floor of the habitat. However, in this study EVAs, which would provide an increased dose rate, have not been considered.

BFO: Blood Forming Organ

To estimate the minimum amount of shielding material to be placed in the habitat, the dose limits provided by ESA and presented in Table 10-1 were used: **the BFO dose equivalent may not exceed 500 mSv/year and 250 mSv/30 days**. With these dose limits the career of the astronaut will be limited to two years and the average life-time loss can be expected to be more than 10 years, as reported in Table 10-2. A safer and recommended shielding configuration is therefore more in line with what is proposed in Configuration 3.

Configuration 1:

Simulations on Configuration 1 are performed on the habitat model without any additional shielding. Row 1 Table 10-5 shows that the BFO average dose, of 720 mSv, at the ground floor during this SPE far exceeds the yearly BFO dose limits stated by ESA, Table 10-1, even without taking the radiation dose due to the GCRs into account. The total annual BFO average dose equivalent of 994 mSv is close to the total career dose of 1000 mSv for ESA astronauts, see Table 10-1. Even when considering the BFO Average dose equivalent from the Oct 1989 SPE, of 241 mSv, the annual total dose still exceeds the 500 mSv/year limit. From these simulation results, it can be concluded that the habitat needs additional radiation shielding.

The difference between the estimated BFO average dose equivalent, in Table 10-5, due to GCRs at the ground floor, of 225 mSv/year, and the top floor, of 274 mSv/year, shows the additional shielding that is due to the material, such as storage, which is located in the ground floor and the additional shielding that the upper floors provides for the ground floor.

The simulation results from configuration 1 clearly show that additional radiation shielding is needed. Using additional habitat material, such as extra layers of inflatables, water, or lunar regolith, could solve the issue. The disadvantage of adding additional fabric layers is the additional launch mass, costs, and risks. It is therefore recommended to use the materials already present on the Moon, such as the lunar regolith or rocks, to shield the habitat. For this study, it has not been assumed that any larger amounts of water are available for extraction from the Moon and the water used for the radiation shielding has to been launched from Earth. The water that would be needed for the life support of the crew could be stored in a tank located in the roof of the habitat or the shelter and hence act as additional radiation shielding. The amount of water needed for the minimum shielding, around 8 tons for configuration 2, has been chosen in order to be in agreement with the amount needed for life support, see Chapter Life Support.

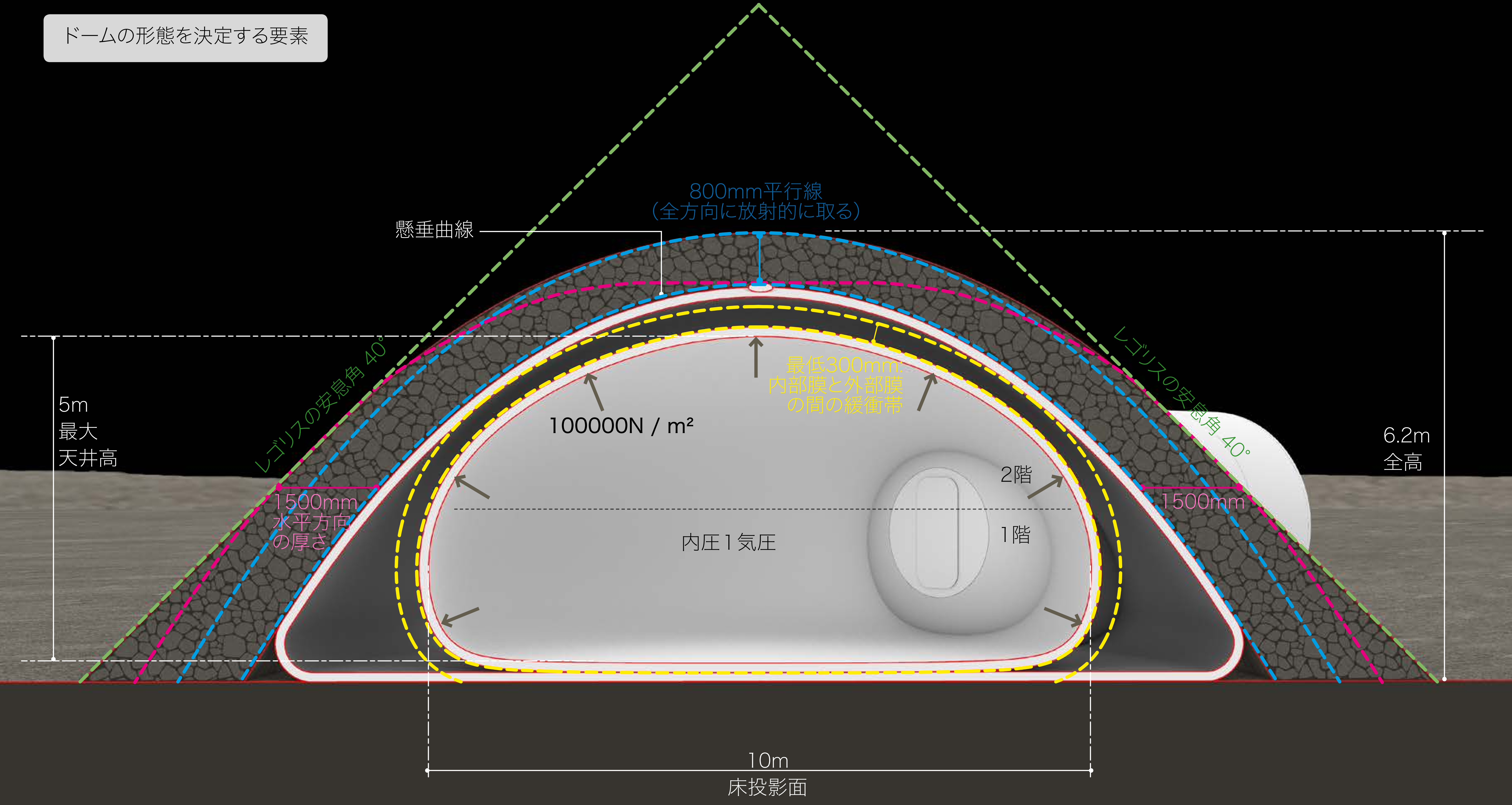
Configuration 2:

The minimum shielding required to stay below the BFO average dose equivalent limits of 500 mSv/year and 250 mSv/30 days are listed in Table 10-3. For the surfaces covered by the inflatables a minimum of 2 cm of sintered lunar regolith or 4 cm of loose regolith, is needed. With this amount of shielding the BFO average dose equivalent from GCRs in the top floor of the habitat will reach 248 mSv/year, see Table 10-3 column 3. The

ESA Concurrent Design Facility Report (September 2020)

NASAとESAによる宇宙飛行士の月間の被曝上限は250ミリシーベルトと定められている。これは一般の人に対する 被曝上限 1ミリシーベルト に比べるとかなり大きい値であることが分かる。NASAのシンポジウムで発表された論文に、年間250ミリシーベルトの被曝を超えないために１から２メートルの厚さのレゴリスが必要と概算している論文がある。ただし、遮蔽壁に使えわれるレゴリスの密度によってこの数字は変動する。被曝量の上限についての基準について宇宙飛行士と一般人に対して大きな開きがある点と合わせて考えると、施設に使われるレゴリスや施設を占有する人間のミッションにおける立場により、放射線遮蔽性能と必要な壁の厚さは大きく異なり、壁に求められる厚さの絶対値が出てくるイメージではないことが想像できる。
1．5メートルでは不足しているであるとか、5メートルあれば十分というような壁の厚さの数字のみを一人歩きさせる議論には注意が必要である。

ドームの形態を決定する要素



図版：鶴巻 崇