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Construction Technologies for the Creation of Living and Industrial Modular Settlement of Lunar Base

Monograph

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1. EXPLORATION OF THE MOON

Before spaceflight [75]**.** The ancient Greek philosopher Anaxagoras (d. 428 BC) reasoned that the Sun and Moon were both giant spherical rocks, and that the latter reflected the light of the former [1]. In his book On the Face in the Moon's Orb, Plutarch suggested that the Moon had deep recesses in which the light of the Sun did not reach and that the spots are nothing but the shadows of rivers or deep chasms. Aristarchus went a step further and computed the distance from Earth, together with its size, obtaining a value of 20 times the Earth radius for the distance (the real value is 60; the Earth radius was roughly known since Eratosthenes).

Although the Chinese of the Han Dynasty (202 BC–202 AD) believed the Moon to be energy equated to qi, their 'radiating influence' theory recognized that the light of the Moon was merely a reflection of the Sun (mentioned by Anaxagoras above) [2].

By 499 AD, the Indian astronomer Aryabhata mentioned in his Aryabhatiya that reflected sunlight is what causes the Moon to shine [3].

Habash al-Hasib al-Marwazi, a Persian astronomer, conducted various observations at the Al-Shammisiyyah observatory in Baghdad between 825 and 835 AD [4]. Using these observations, he estimated the Moon's diameter as 3 037 km and its distance from the Earth as 346 345 km [4]. In the 11th century, the Islamic physicist Alhazen investigated moonlight through a number of experiments and observations, concluding it was a combination of the moon's own light and the moon's ability to absorb and emit sunlight [5][6].

By the Middle Ages, before the invention of the telescope, an increasing number of people began to recognise the Moon as a sphere, though many believed that it was "perfectly smooth"[7]. In 1609, Galileo Galilei drew one of the first telescopic drawings of the Moon in his book Sidereus Nuncius and noted that it was not smooth but had mountains and craters. Later in the 17th century, Giovanni Battista Riccioli and Francesco Maria Grimaldi drew a map of the Moon and gave many craters the names they still have today. On maps, the dark parts of the Moon's surface were called maria (singular mare) or seas, and the light parts were called terrae or continents.

Galileo's sketches of the Moon from the groundbreaking Sidereus Nuncius Thomas Harriot, as well as Galilei, drew the first telescopic representation of the Moon and observed it for several years. His drawings, however, remained unpublished [8]. The first map of the Moon was made by the Belgian cosmographer and astronomer Michael Florent van Langren in 1645 [8]. Two years later a much more influential effort was published by Johannes Hevelius. In 1647 Hevelius published Selenographia, the first treatise entirely devoted to the Moon. Hevelius's nomenclature, although used in Protestant countries until the eighteenth century, was replaced by the system published in 1651 by the Jesuit astronomer Giovanni Battista Riccioli, who gave the large naked-eye spots the names of seas and the telescopic spots (now called craters) the name of philosophers and astronomers [8].

In 1753 the Croatian Jesuit and astronomer Roger Joseph Boscovich discovered the absence of atmosphere on the Moon. In 1824 Franz von Gruithuisen explained the formation of craters as a result of meteorite strikes [9].

In 1834–1836, Wilhelm Beer and Johann Heinrich Mädler published their four-volume Mappa Selenographica and the book Der Mond in 1837, which firmly established the conclusion that the Moon has no bodies of water nor any appreciable atmosphere.

Space race. The Cold War inspired "space race" and "Moon race" between the Soviet Union and the United States of America accelerated with a focus on the Moon. This included many scientifically important firsts, such as the first photographs of the then-unseen far side of the Moon in 1959 by the Soviet Union, and culminated with the landing of the first humans on the Moon in 1969, widely seen around the world as one of the pivotal events of the 20th century, and indeed of human history in general.

The first artificial object to flyby the Moon was uncrewed Soviet probe Luna 1 (Fig. 1.1) on January 4, 1959 and went on to be the first probe to reach a heliocentric orbit around the Sun [10].

The first probe to impact the surface of the Moon was the Soviet probe Luna 2, which made a hard landing on September 14, 1959. The far side of the Moon was first photographed on October 7, 1959, by the Soviet probe Luna 3. The photos showed that the far side of the Moon almost completely lacked maria.

Luna 9 was an uncrewed space mission of the Soviet Union's Luna programme. In 1966 the USSR accomplished the first soft landings and took the first pictures from the lunar surface during the Luna 9 and Luna 13 missions [11][12]. Luna 16 first lunar sample return for the USSR in Sep 1970.

The first robot lunar rover to land on the Moon was the Soviet vessel Lunokhod 1 on November 17, 1970, as part of the Lunokhod programme.

Moon rock samples were brought back to Earth by three Luna missions (Luna 16, 20, and 24). Luna 24 in 1976 was the last Lunar mission by the Soviet Union.

The first American probe to flyby the Moon was Pioneer 4 on March 4, 1959 which occurred shortly after Luna 1. But it was the only success of 8 American probes that first attempted to launch for the Moon [13]

Ranger 1 launched in Aug 1961. It would be 3 more years and six failed Ranger missions until Ranger 7 returned close up photos of the Lunar surface before impacting it in July 1964. U.S. success rates improved greatly from Ranger 7 onward.

The U.S. followed Ranger with the Surveyor program [14] sending seven robotic spacecraft to the surface of the Moon. Five of the seven spacecraft successfully soft-landed, investigating if the regolith (dust) was shallow enough for astronauts to stand on the Moon.

a) b) c)

Fig. 1.1. Satellite: a) Luna 1 and Luna 2; b) Luna 3; c) Luna 9

On December 24, 1968, the crew of Apollo 8, Frank Borman, James Lovell and William Anders, became the first human beings to enter lunar orbit and see the far side of the Moon in person. Humans first landed on the Moon on July 20, 1969. The first human to walk on the lunar surface was Neil Armstrong, commander of the U.S. mission Apollo 11 (Fig 1.2). To date, the last human to stand on the Moon was Eugene Cernan, who as part of the Apollo 17 mission, walked on the Moon in December 1972.

Moon rock samples were brought back to Earth the Apollo missions 11 through 17 (except Apollo 13, which aborted its planned lunar landing). Clementine was the last Lunar mission by the U.S. in 1994.

Before the Moon race the U.S. had pre-projects for scientific and military moonbases: the Lunex Project and Project Horizon. Besides crewed landings, the abandoned Soviet crewed lunar programs included the building of a multipurpose moonbase "Zvezda", the first detailed project, complete with developed mockups of expedition vehicles [15] and surface modules [16].

The Lunex Project was a US Air Force 1958 plan for a crewed lunar landing prior to the Apollo Program [17] (Fig. 1.3). The final lunar expedition plan in 1961 was for a 21-person underground Air Force base on the Moon by 1968 [18]. The primary distinction between the later Apollo missions and Lunex was the orbital rendezvous maneuver. The Lunex vehicle, composed of a landing module and a lifting body return/re-entry module, would land the entire vehicle and all astronauts on the surface, whereas the final Apollo mission involved a separate ascent module leaving the command module and service module connected in lunar orbit with a single astronaut.

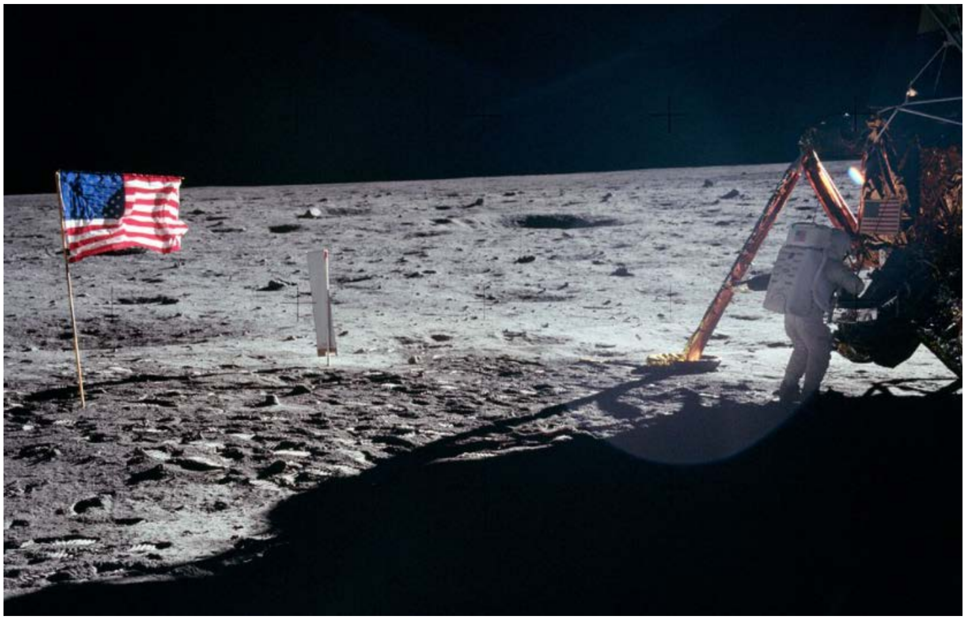
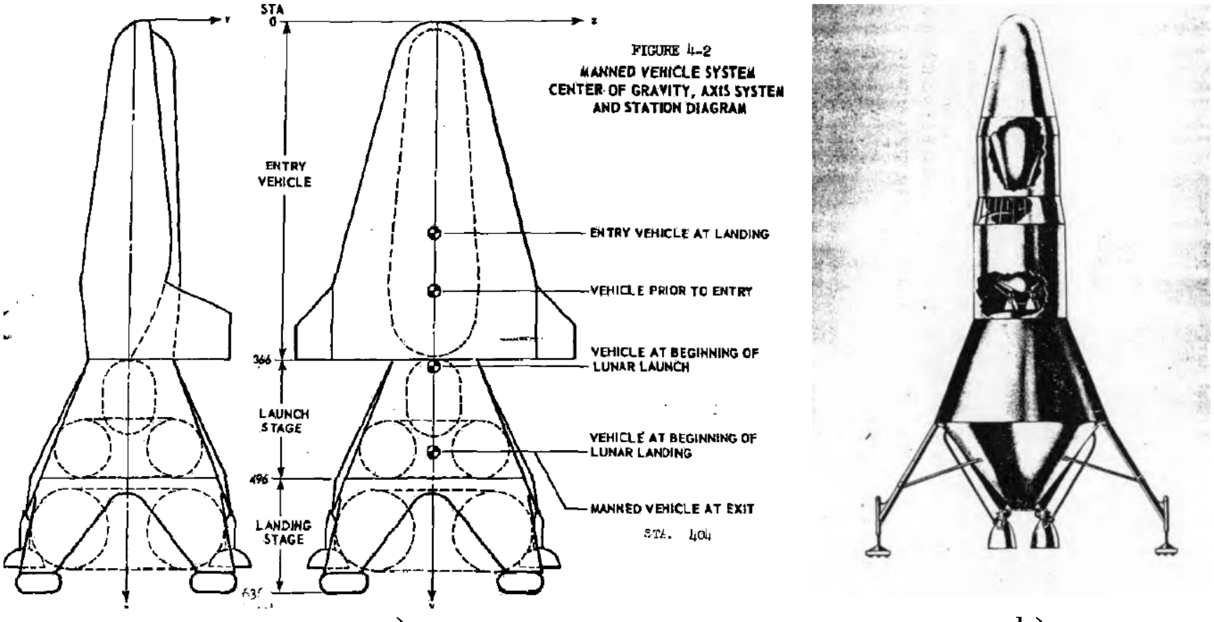


Fig 1.2. Neil Armstrong working at the Lunar Module Eagle during Apollo 11 (1969)

Project Horizon [19] was a 1959 study to determine the feasibility of constructing a scientific / military base on the Moon (Fig. 1.3). The project proposal states the requirements as:

The lunar outpost is required to develop and protect potential United States interests on the moon; to develop techniques in moon-based surveillance of the earth and space, in communications relay, and in operations on the surface of the moon; to serve as a base for exploration of the moon, for further exploration into space and for military operations on the moon if required; and to support scientific investigations on the moon [20]. The projected operational date with twelve soldiers was December 1966.

Horizon never progressed past the feasibility stage, being rejected by President Dwight Eisenhower when primary responsibility for America's space program was transferred to the civilian agency NASA [21].



a) b)

Fig. 1.3. Project: a) Lunex spacecraft concept; b) Horizon Lunar Landing-and-Return Vehicle

Zvezda moonbase was a Soviet plan and project from 1962 to 1974 [22] [23] to construct a crewed moonbase as successor to the N1-L3 human lunar expedition program (Fig. 1.4, Fig. 1.5). Zvezda moonbase was canceled with the rest of the Soviet human lunar programs.

The Artemis program [40] is a United States-led international human spaceflight program. Its primary goal is to return humans to the Moon, specifically the lunar south pole, by 2025 [24]…[26] If successful, it will include the first crewed lunar landing mission since Apollo 17 in 1972, the last lunar flight of the Apollo program.

The Artemis program began in December 2017 as the reorganization and continuation of successive efforts to revitalize the U.S. space program since 2009.

Its stated short-term goal is landing the first woman on the Moon; mid-term objectives include establishing an international expedition team and a sustainable human presence on the Moon. Long-term objectives are laying the foundations for the extraction of lunar resources, and eventually, make crewed missions to Mars and beyond feasible [27].

The Artemis program [40] is carried out predominantly by NASA and U.S. commercial spaceflight contractors, in partnership with the European Space Agency and the space agencies of several other nations. Other countries have been invited to join the program through signing the governing Artemis Accords, which remain open for signature since October 2020.

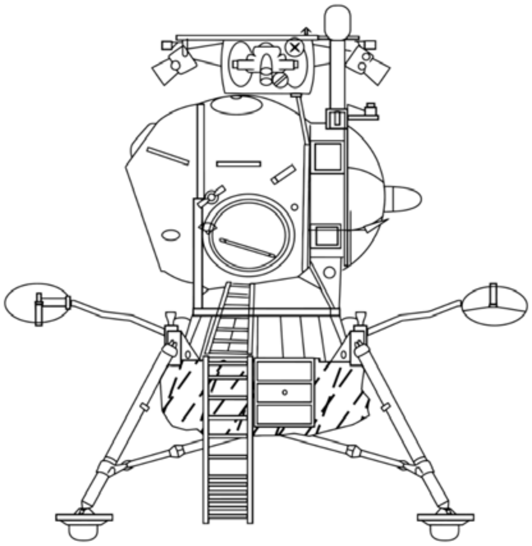
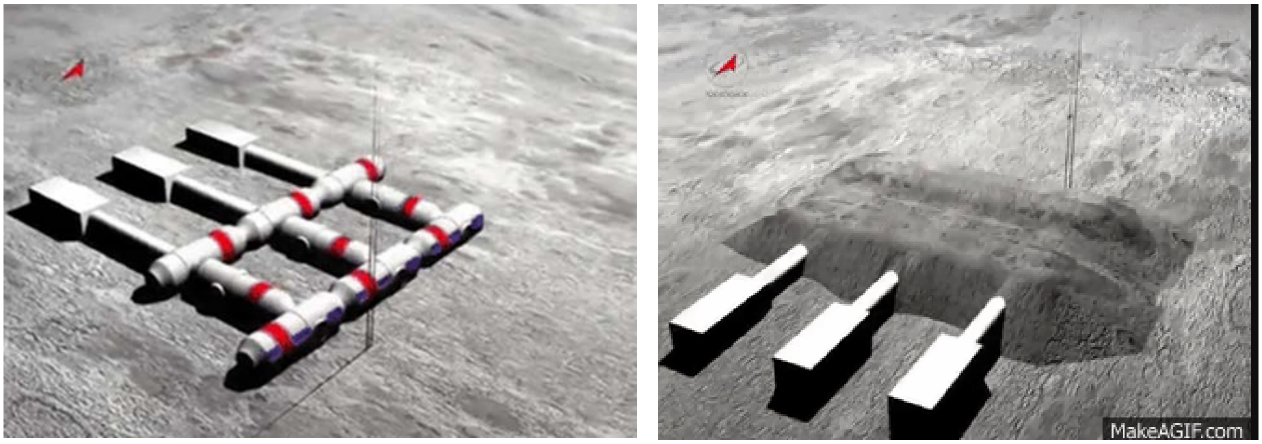


Fig 1.4. Soviet lunar lander



a) b)

Fig. 1.5. Project Zvezda: a) before- b) after grounding

On 5 May 2020, the US administration was drafting a new international agreement outlining the laws for mining on the Moon [28]. NASA Administrator officially announced the Artemis Accords on 15 May 2020 will be a series of a bilateral agreements between the governments of participating nations in the Artemis program "grounded in the Outer Space Treaty of 1967" [29][30]. The Accords were signed by the United States, Australia, Canada, Japan, Luxembourg, Italy, the United Kingdom, and the United Arab Emirates on 13 October 2020 [31] and later signed by Ukraine [32][33]. In May 2021, South Korea joined as 10th signatory state of the Artemis Accord [34], with New Zealand following later the same month. Brazil became the 12th signatory country in June 2021. Mexico became the 13th signatory country in December 2021.

The Artemis program is organized around a series of Space Launch System (SLS) missions. These space missions will increase in complexity and are scheduled to occur more than a year apart from each other. NASA and its partners have planned Artemis I through Artemis IV missions; later Artemis missions have also been proposed. Each SLS mission centers on the launch of an SLS booster carrying an Orion spacecraft. Missions after Artemis II will depend on support missions launched by other organizations and spacecraft for support functions.

Artemis I (2022) will be an uncrewed test of the SLS and Orion and is the first test flight for both craft. The mission will place Orion into a lunar orbit and then return it to Earth. The SLS will use the ICPS second stage, which will perform the trans-lunar injection burn to send Orion to lunar space. Orion will brake into a retrograde distant lunar orbit and remain for about six days before boosting back toward Earth. The Orion capsule will separate from its service module, re-enter the atmosphere for aerobraking, and splash down under parachutes [35].

Artemis II (2024) will be the first crewed test flight of SLS and the Orion spacecraft. The four crew members will perform extensive testing in Earth orbit and Orion will then be boosted into a free-return trajectory around the moon, which will return Orion back to Earth for re-entry and splashdown [36].

Artemis III (2025) will be a crewed lunar landing. The mission depends on a support mission to place a Human Landing System (HLS) in place in a NRHO lunar orbit prior to the launch of SLS/Orion. After HLS reaches NRHO, SLS/Orion will send the Orion spacecraft with a crew of four to rendezvous and dock with HLS. Two astronauts will transfer to HLS, which will descend to the Lunar surface and spend about 6.5 days on the surface. The astronauts will perform at least two EVAs on the surface before the HLS ascends to return them to a rendezvous with Orion. Orion will return the four astronauts to Earth [37].

Artemis IV (2026) is a crewed mission to the Lunar Gateway station in NRHO, using an SLS block 1B. A prior support mission will deliver the first two gateway modules to NRHO. The extra power of the Block 1B will allow SLS/Orion to deliver the I-HAB gateway module for connection to the Gateway [38].

Artemis V through Artemis VIII and beyond are proposed to land astronauts on the lunar surface, where they will take advantage of increasing amounts of infrastructure that are to be landed by support missions. These will include habitats, rovers, scientific instruments, and resource extraction equipment [39].

Artemis Base Camp. Artemis Base Camp (Fig. 1.6) is the prospective lunar base that was proposed to be established at the end of the 2020s. It would consist of three main modules: the Foundational Surface Habitat, the Habitable Mobility Platform, and the Lunar Terrain Vehicle. It would support missions of up to two months and be used to study technologies to use on Mars. The idea would be to build upon this initial base site for decades through both Government and commercial programs. Currently Shackleton Crater is the prime target for this outpost due to its wide variety of lunar geography and water ice. It would fall under the guidelines of the Outer Space Treaty [41][42].

Fig.1.6. A render of the Artemis Base Camp

Foundational Surface Habitat. Little is known about the surface outpost with most information coming from studies and launch manifests that include its launch. It would be commercially built and possibly commercially launched in 2028 along with the Mobile Habitat [43] (Fig. 1.7). The first habitat is referred to as the Artemis Foundation Habitat formerly the Artemis Surface Asset. Current launch plans show that landing it on the surface would be similar to the HLS. The pressurized habitat would be sent to the Gateway where it would then be attached to a descent stage separately launched from a commercial launcher, it would utilize the same transfer stage used for the HLS. Other designs from 2019 see it being launched from an SLS Block 1B as a single unit and landing directly on the surface. It would then be hooked up to a surface power system launched by a CLPS mission and tested by the Artemis 6 crew. The location of the base would be in the south pole region and most likely be a site visited by prior crewed and robotic missions [25] [41].

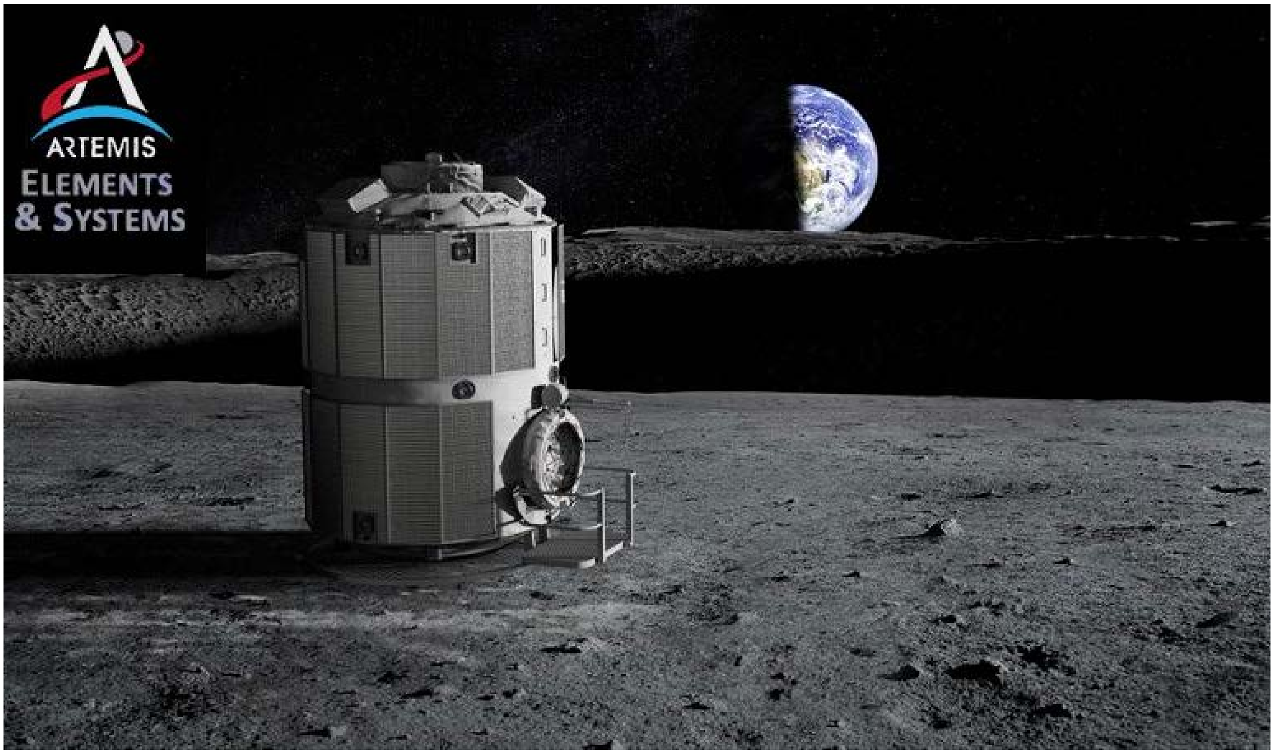


Fig.1.7. A render of the Foundational Surface Habitat

Space Exploration Vehicle. The Habitable Mobility Platform would be a large pressurized rover used to transport crews across large distances (Fig.1.8).

NASA has developed multiple pressurized rovers including the Space Exploration Vehicle built for the Constellation program which was fabricated and tested. In the 2020 flight manifest it was referred to as the Mobile Habitat suggesting it could fill a similar role to the ILREC Lunar Bus. It would be ready for the crew to use on the surface but could also be autonomously controlled from the Gateway or other locations [44][45][46][47].

Fig. 1.8. NASA Habitable Mobility Platform based on the post Constellation Space Exploration Vehicle.

NASA's baseline Lunar Terrain Vehicle. In February 2020, NASA released two requests for information regarding both a crewed and uncrewed unpressurized surface rover (Fig.1.9). The LTV would be propositioned by a CLPS vehicle before the Artemis 3 mission. It would be used to transport crews around the exploration site. It would serve a similar function as the Apollo Lunar Rover. In July 2020, NASA will move to formally establish a program office for the rover at the Johnson Space Center in Houston.

NASA's VIPER rover. The VIPER (Volatiles Investigating Polar Exploration Rover) is a lunar rover by NASA planned to be delivered to the surface of the Moon in November 2023. The rover will be tasked with prospecting for lunar resources in permanently shadowed areas in the lunar south pole region, especially by mapping the distribution and concentration of water ice. The mission builds on a previous NASA rover concept called Resource Prospector, which was cancelled in 2018 [48].

Fig.1.9. NASA's baseline Lunar Terrain Vehicle

The VIPER rover is part of the Lunar Discovery and Exploration Program managed by the Science Mission Directorate at NASA Headquarters, and it is meant to support the crewed Artemis program [49]. NASA's Ames Research Center is managing the rover project. The hardware for the rover is being designed by the Johnson Space Center, while the instruments are provided by Ames Research Center, Kennedy Space Center, and Honeybee Robotics [49]. As of March 2021, the estimated cost of the mission is US$433.5 million [50].

The VIPER rover will operate at a south pole region yet to be determined. VIPER is planned to travel several kilometers, collecting data on different kinds of soil environments affected by light and temperature — those in complete darkness, occasional light, and in constant sunlight. Once it enters a permanently shadowed location, it will operate on battery power alone and will not be able to recharge them until it drives to a sunlit area. Its total operation time will be approximately 100 Earth days.

Both the launcher and the lander to be used will be competitively provided through the Commercial Lunar Payload Services (CLPS) contractors, with Astrobotic delivering the Griffin lander and SpaceX providing the Falcon Heavy launch vehicle [51]. NASA is aiming at landing the rover in November 2023 [52].

Space suits. The Artemis program will make use of two types of space suit revealed in October 2019: the Exploration Extravehicular Mobility Unit (xEMU) [53] and the Orion Crew Survival System (OCSS) [54] (Fig 1.10).

On 10 August 2021, an Office of Inspector General audit reported a conclusion that the spacesuits would not be ready until April 2025 at the earliest, likely delaying the mission from the planned late 2024 [55]. In response to the IG report, SpaceX indicated that they could provide the suits [56].

NASA published a draft RFP to procure Commercially-produced spacesuits in order to meet the 2024 schedule [57].

a) b)

Fig. 1.10. Suit: a) xEMU suit for lunar surface extravehicular activity (EVA); b) OCSS suit for launch and reentry

Colonization of the Moon. Colonization of the Moon is a process [58] [59] or concept employed by some proposals, for claiming robotic [60][61] or human exploitation and settlement on the Moon (Fig. 1.11).

While a range of proposals for missions of lunar colonization, exploitation or permanent exploration have been raised, current projects for establishing permanent crewed presence on the Moon are not for colonizing the Moon, but rather focus on building moonbases for exploration and to a lesser extent for exploitation of lunar resources.

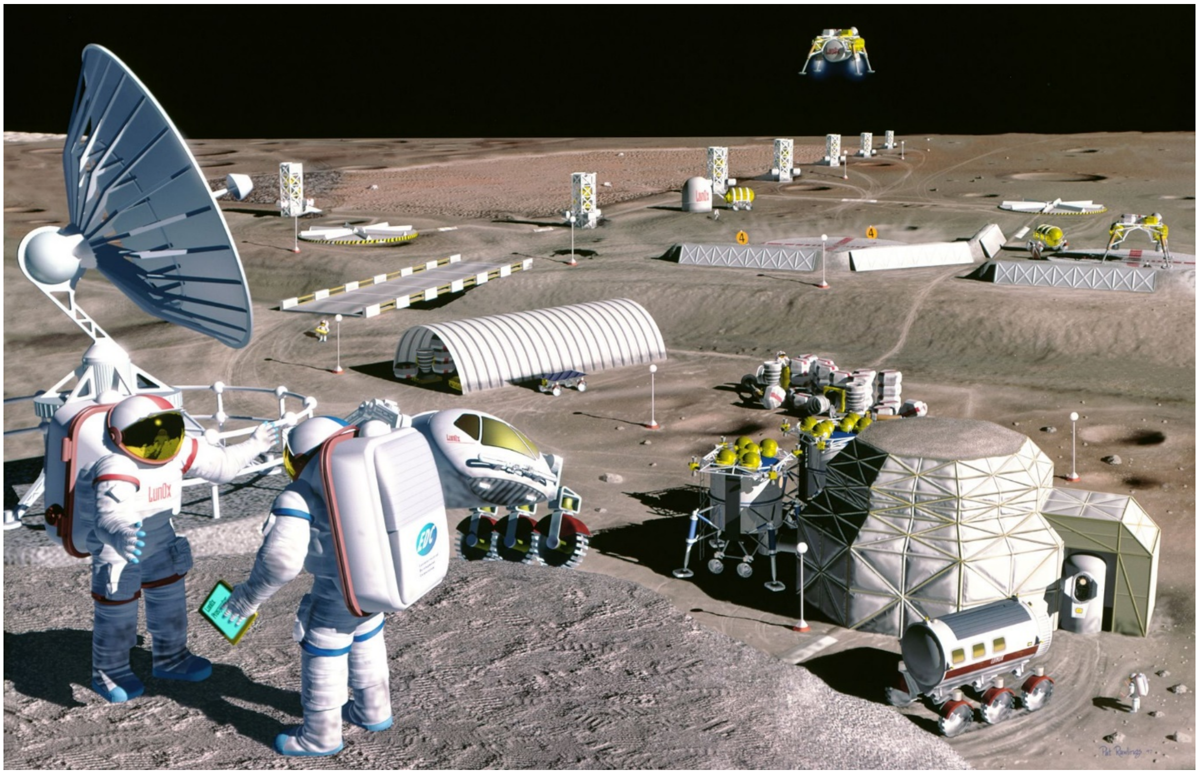


Fig. 1.11. NASA concept art of an envisioned lunar mining facility.

Economic prospecting and development. For long-term sustainability, a space colony should be close to self-sufficient. Mining and refining the Moon's materials on-site – for use both on the Moon and elsewhere in the Solar System – could provide an advantage over deliveries from Earth, as they can be launched into space at a much lower energy cost than from Earth. It is possible that large amounts of cargo would need to be launched into space for interplanetary exploration in the 21st century, and the lower cost of providing goods from the Moon might be attractive [62].

Space-based materials processing. In the long term, the Moon will likely play an important role in supplying space-based construction facilities with raw materials [63]. Microgravity in space allows for the processing of materials in ways impossible or difficult on Earth, such as "foaming" metals, where a gas is injected into a molten metal, and then the metal is annealed slowly. On Earth, the gas bubbles rise and burst, but in a zero gravity environment, that does not happen. The annealing process requires large amounts of energy, as a material is kept very hot for an extended period of time (allowing the molecular structure to realign), and this too may be more efficient in space, as the vacuum drastically reduces all heat transfer except through radiative heat loss.

Exporting material to Earth. Exporting material to Earth in trade from the Moon is problematic due to the cost of transportation, which would vary greatly if the Moon is industrially developed (see "Launch costs" above). One suggested trade commodity is helium-3 (3He) which is carried by the solar wind and accumulated on the Moon's surface over billions of years, but occurs only rarely on Earth.[40] Helium-3 might be present in the lunar regolith in quantities of 0.01 ppm to 0.05 ppm (depending on soil). In 2006 it had a market price of about $1500 per gram ($1.5M per kilogram), more than 120 times the value per unit weight of gold and over eight times the value of rhodium.

In the future 3He harvested from the Moon may have a role as a fuel in thermonuclear fusion reactors [64][65]. It should require about 100 metric tons of helium-3 to produce the electricity that Earth uses in a year and there should be enough on the Moon to provide that much for 10 000 years [66].

Exporting propellant obtained from lunar water. To reduce the cost of transport, the Moon could store propellants produced from lunar water at one or several depots between the Earth and the Moon, to resupply rockets or satellites in Earth orbit [67]. The Shackleton Energy Company estimate investment in this infrastructure could cost around $25 billion [68].

Lunar water ice. Lunar scientists had discussed the possibility of water repositories for decades. They are now increasingly "confident that the decades-long debate is over" a report says. "The Moon, in fact, has water in all sorts of places; not just locked up in minerals, but scattered throughout the broken-up surface, and, potentially, in blocks or sheets of ice at depth." The results from the Chandrayaan mission are also "offering a wide array of watery signals" [69][70].

It is estimated there is at least 600 million tons of ice at the north pole in sheets of relatively pure ice at least a couple of meters thick [71].

Solar power satellites. Gerard K. O'Neill, noting the problem of high launch costs in the early 1970s, came up with the idea of building Solar Power Satellites in orbit with materials from the Moon [72]. Launch costs from the Moon would vary greatly if the Moon is industrially developed (see "Launch costs" above). This proposal was based on the contemporary estimates of future launch costs of the Space Shuttle.

On 30 April 1979 the Final Report "Lunar Resources Utilization for Space Construction" by General Dynamics Convair Division under NASA contract NAS9-15560 concluded that use of lunar resources would be cheaper than terrestrial materials for a system comprising as few as thirty Solar Power Satellites of 10 GW capacity each [73].

In 1980, when it became obvious NASA's launch cost estimates for the Space Shuttle were grossly optimistic, O'Neill et al. published another route to manufacturing using lunar materials with much lower startup costs [74]. This 1980s SPS concept relied less on human presence in space and more on partially self-replicating systems on the lunar surface under telepresence control of workers stationed on Earth.

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2. TECHNICAL FEASIBILITY OF LUNAR SETTLEMENT SITES

The international space communities have significant interest in lunar exploration, and Ukraine is one of them. The long-term goal of the leading space powers (the USA, Russia, Japan, China) in their programs of lunar exploration is to build inhabited lunar bases, finding their location on the lunar surface. Ukraine also participates in some programs.

A large number of publications on the problems of lunar exploration show the unfailing interest in these issues not only in scientific community but also among ordinary citizens. The analysis of the information materials in open access has shown that the question of location of future lunar settlements is not paid enough attention. The information found is non-systemic, narrowly specialized and related to other problems.

The purpose of the research is to systematize the open access information in order to suggest potentially promising locations for the lunar settlements for a particular type of the life activity.

2.1. An overview of the Moon’s characteristics for the potential lunar settlment location

The purpose of the settlement, its location, and location conditions are closely related when exploring the potential location for lunar settlements. It is reasonable to characterize the conditions existing on the Moon, specific both to the Moon as a whole and its separate regions (shown in the following tables 2.1…2.4).

It is necessary to consider the development stages of separate regions of the Moon. The Moon is our only satellite, thus it is the only possible option for the most rapid human expansion in space. The Earth - Moon flight takes from 3 to 5 days which allows working shifts on the Moon to adapt to lunar conditions and to develop its resources gradually, which facilitates financing of projects. The acceleration at the equator is 1.62 m/sec2, which is about 6 times less than on the Earth. This makes it 6 times easier to transport cargo compared to terrestrial conditions. No one has ever stayed on the Moon for a long time in conditions of reduced gravity. Thus, there is not any evidence of the absence of its negative impact on the health of settlers. If a negative effect of reduced gravity is detected, it will be necessary to limit the period of stay on the Moon like on the ISS in full weightlessness. This issue is important because the cost of changing the shift crews is quite significant. Moreover, adapting to the lunar conditions the settlers will not be able to exist on the Earth because of the great difference in gravitational forces. The escape velocity on the Moon is 2.38 km/sec, which is 4.7 times less than on the Earth. This will significantly reduce the launch weight of the rocket vehicle when launching it from the Moon, or increase its live load. If the fuel is extracted on the Moon, this factor will significantly reduce the cost of interplanetary flights, including expedition to Mars, exploration of solar system objects and deep space.

Table 2.1. Astronomical characteristics

Item number	Description	Properties, parameters	Notes
1	Average distance Earth - Moon	384467 km	[1]
2	Time of Earth-Moon flight (launching, flight and landing)	3 to 5 days	NASA the Apollo program
3	Acceleration at the equator	1.62 m/sec.	[1]
4	Escape velocity (second space velocity)	2.38 km/sec.	[1]
5	Circulationperiod	27,332 days (around the Earth)	[1]
6	Rotationperiod	27,332 days	[1]
7	Averageorbitalvelocity	1.023 km/sec.	[1]
8	Radius at the equator	1,738 km	[1]
9	Inclination of the equator to the ecliptic	$1^{0}\ 32^{I}$	[1]
10	Tilt of the orbital plane to the ecliptic	$5^{0}8^{I}43^{II}$	[1]

The rotation period of the Moon around the Earth is equal to the period of its rotation around its own axis, i.e. it is a synchronous satellite, and is constantly turned to the Earth by one hemisphere. This allows constant communication of the Earth with the settlements located on the visible side of the moon, but for communication with the reverse side of the moon responders should be used. At the boundary between the visible and invisible hemisphere - the eastern and western limb, there are areas free from radio interference from the Earth, where the optical telescope will work in ideal conditions, X-ray and long-wave telescopes will not be blocked by the atmosphere. The equator area there allows observing the entire celestial sphere due to the slow rotation of the Moon around its axis. It is preferable to place the observatory in the equatorial zone of the Smith Sea in the satellite craters, for example, the Schubert crater or the Dark Valley. The location of the observatory in the equatorial zone of the western limb is debatable due to a system of lunar crust cracks in the area of the Riccoli crater, which indicates a possible tectonic activity. Tilt of the Moon's equator to the ecliptic is 1^{0} 32^{l}, which creates unique conditions in the circumpolar regions - the polar day on the Moon is much longer than the polar night and in the zone of the so-called eternal light it reaches 94 % of the duration of the Earth year (South Pole). At a low sunlight angle deep craters in these areas create conditions of eternal darkness, where sunlight does not penetrate, where there is a zone with absolute zero temperature, which contributes to preservation of volatile substances in frozen form. Settlements in the area of the South Pole can be perspective due to almost constant energy supply from the solar panels placed on the outer slopes of craters and the possible water ice in the areas of eternal darkness. For the permanent communication of the Earth with the reverse side of the Moon, it is necessary to place permanent responders at the poles.

Table 2.2. Lunar environment

Item number	Description	Properties, parameters	Notes
1	Average surface temperature	- 153 - night +107 - day	[1]
2	Temperature fluctuations	from – 233 to +123	[1]
5	Atmosphere	~104 mol/cm3 day ~2-105 mol/cm3 night Composition: plasma dust system - surface dust, dust at high altitudes (up to 150 km), solar wind, dust clouds	[1−2] [3−4]
4	Magnetic field	The Moon has no magnetic field. There are areas of residual magnetism	[5]

Table 2.3. Lunar relief

Item number	Descriptions	Properties, parameters	Notes
1	Lunar Seas	They cover 30% of the visible hemisphere and 17 % of the surface of the entire Moon. The surface of the seas is relatively flat with level differences of not more than 150 m at the base of 600 km. The level differences between the seas and the mainland are 2-3 km.	[6]
2	Lunar Continents	The surface of the continents is uneven - the average drop is 600 m at the base of 40 km, the number of craters is much greater than on the lunar seas.	[6]
3	Lunar craters	Depending on the diameter the morphological properties they are divided into the following types: BIO - the diameter is up to 5 km, SOS – the diameter is 5-30 km, TRI – the diameter 15-50 km, TYC – the diameter is 30-175 km. Basins - over 200 km in diameter. Thallisoids - large crater formations which are close in size to the round lunar seas. Several hundreds of craters in the polar regions of the Moon are craters of eternal darkness. A typical small crater of 5 km in diameter has a sharp outer rampart up to 1000 m high and a bowl bottom 100 m below the surrounding terrain. Large craters of about 100km in diameter have an outer rampart of 1000-5000 m elevation (the ratio of diameter to rampart elevation varies between 1/80÷1/1000).	[7]
4	Mountains, peaks	The data from the Clementine probe indicate that the level difference between the lowest and the highest places on the Moon is 18100 m. The highest place is located on the back side of the Moon, on the outer side of the Engelhard Crater.	[6]
	The peaks that have been named	The highest peaks of the Moon Mountains are Bradley Peak - 4.2 km, Gloigens Peak - 4.7 km, Headley Peak.	[6]

		1737400 meters from the center of the Moon is taken as a fiducial mark.	
	Mountains that have been named	There are 18 mountain formations on the Moon. The largest are Cordilleras – 956 km, Apennines – 600 km, Rooks – 651 km, Caucasus – 444 km, Jura – 421 km	[6]
5	Other features of the relief which have names	Fissures - cracks or narrow channels (Rima). Number – 53. Length - 2 to 311 km. Systems of fissures or narrow channels (Rimac). Number 58. Length - from 25 to 450 km Ridge-folds (Dorsum); often found in the lunar seas. Number - 21, Length - 7 to 380 km. Number – 18. Cline - 70÷228 km Folded terrain systems (Dorsa)	[6]
6	Gaps in the lunar surface	They are assumed failures of the overlapping lava tubes (voids). More than 200 were found of 40÷100 m in size, diameter and depth in marine basalt and 16m in diameter, 7m-deep in melted craters.	[8−11]

The location of the launch site. Locating the launch site on the Earth's equator and choosing the necessary moment of launch, it is possible to change velocity of the launched vehicle up to ± 4.6 km/sec, in addition to 30 km/sec of the average velocity of the Earth's orbit. Trajectories of motion of the Moon's surface points in the Solar system are conditioned by the Earth-Moon system's orbit around the Sun, the Moon's orbit around the common Earth-Moon system's center of mass, the Moon's rotation around its own axis and represent spirals with a diameter depending on the Selenological coordinates, coiled on the forming spiral - the trajectory of the Moon's center of mass.

Taking into account the dimensions and parameters of the Moon's movement (shown in the tables above), it is possible to determine that the Moon's rotation introduces a variable component into the movement of the Moon's center of masses of about ± 1,0 km/sec. The Moon's rotation introduces an additional variable into the movement of points of the Moon's surface up to ± 0,004 km/sec, depending on the selenological coordinates. It means that the selenological latitude, compared to the other parameters of the Moon's motion, insignificantly affects the choice of the site for the cosmodrome. Such local conditions as topography, availability of resources for extraction of rocket fuel and oxidizer may influence more significantly. The uncertainty of the launch moment, caused by the complexity of the trajectory of the starting point, taking into account the precession plane of the lunar orbit and the lunar rotation axis, can be compensated by orbital correction of the spacecraft after the launch.

Table 2.4. Other characteristics

Item number	Description	Properties, parameters	Notes
1	Water	Circumpolar areas are possible in the frozen soil.	[12−15]
2	Lunar earthquakes (Lunar earthquakes)	The recorded maximum strength of lunar shocks is 5 on the Richter scale. They can occur every day due to sudden temperature fluctuations during sunrise and sunset, the fall of meteorites, but twice a month under the influence of the gravitational forces of the Sun and the Earth.	[16−18]
3	Regolith (a layer of material covering the surface of the Moon, Earth, and other space objects)	Loose clastic-dusty material. The thickness of the layer is several tens of meters, the upper dust layer is about 1 to 3 cm. The regolith of continents consists mainly of anorthosite and its varieties, of lunar seas, it is formed from ancient volcanic rocks, basalts. Chemical composition: Oxygen (40-45 %), silicon, aluminum, calcium, iron, magnesium, titanium, manganese, potassium, sodium, fluorine. It contains metallic iron particles.	[19−22]
4	Mascon	Mascon is a region of excess gravitational attraction on the surface of the Moon. The Moon’s largest mascons coincide with the circular, topographically low impact basins. The examples are the Imbrium, Serenitatis, Crisium, and Nectaris basins (maria).	[23]

The average temperature on the Moon is -153 ^{0}C at night, +107 ^{0}C during the daytime, with fluctuations from - 233 to + 123. Temperature fluctuations are inherent almost all over the Moon. It is necessary to develop the ways to protect against them and take advantage of them, for example: to use the high temperature of the lunar day to accumulate heat energy in heat accumulators using it at night; to use the low temperature of the lunar night in technological processes that require such temperatures. The atmosphere of the Moon is a plasma-dust system which is blown by solar wind and penetrated by galactic cosmic rays of high energy [1−4]. Therefore, any location of the lunar settlement must be arranged in the enclosed spaces with artificial atmosphere. If there is no atmosphere, there will be no air transport, which limits the possibility of long-distance communication between settlements, so this factor must be taken into account when arranging not one but several settlements, in the global settlement of the Moon.

Magnetic field. The Moon currently does not have any global magnetic field, but it has areas of structures with increased magnetization, magnetic anomalies. They often coincide with the so-called "lunar vortices" - areas of the Moon's surface, which are characterized by increased albedo, and have a sinuous shape. Magnetic structures are located relatively close to the surface, where metallic iron is presumably located. It is the main reason of creating settlements [5] in these areas, for example, in the area of the Reiner crater and Marius.

Relief. The main structures of the lunar relief are lunar seas and lunar continents; the most characteristic are lunar craters, mountains, peaks and other details, furrows - cracks, crack systems, ridges - folds, fold systems. The relief can be characterized as complex on a global scale. On a local scale, within the moraines and large craters, for example, the terrain is relatively flat, which is a benefit for arranging the lunar settlements in these places. For transport development on a global scale, the Moon's terrain is difficult, with large altitude differences, which should be taken into account when placing settlements and production bases. Moreover, only ground transport is possible on the Moon, especially industrial transport. Exotic flying saucers are not taken into account yet, especially because of ubiquitous lunar dust. Gaps in the lunar surface are presumably entrances to lava tubes formed by falling meteorites or during lunar shocks [8−11].

The location of lunar settlements in lava tubes has great advantages as people can be protected from the solar wind, cosmic radiation, and temperature variations. Some of the most promising areas for the lunar settlement in the proposed lava tubes are the hole in the Sea of Tranquility and the hole in the Marius Hills area [8−9]. In the Sea of Tranquility NASA has carried out two landings of astronauts - Apollo 11 and Apollo 17 and plans to explore the lava tubes in 2025 through the hole which has already been discovered here. For this purpose, a special robot is being developed, descending through the hole to the bottom, with the help of a rope and subsequently moving independently to the lava tube [10]. The European Space Agency (ESA) is also involved in robotic speleological research on the Moon under the Artemis program [11]. The Sea of Tranquility, one of the oldest surface structures of the Moon, which has undergone significant erosion, must have large reserves of regolith. Being blown around for billions of years by the solar wind, it has accumulated larger reserves of volatiles, including helium-3, than other regions.

The location of the lunar settlement near the hole near the Marius Hills is promising due to the location of nearby lunar vortices associated with a magnetic anomaly suggesting metallic iron reserves and the possibility of a magnetic field protecting against solar wind particles. The location of the lunar settlement depends primarily on potential water sources, which are necessary for all human life support operations on the Moon - for general needs, drinking and growing food, getting oxygen for breathing and hydrogen for rocket fuel. By comparison, to provide four people with water and oxygen, several tens of tons of water per year would be required. For a long time, the Moon was thought to be completely waterless. In 2018 the evidence emerged that there are significant reserves of water ice at the bottom of subpolar craters. Experts estimate that up to ten billion tons of water are trapped near the South Pole. In addition to the large shaded areas, many small cold traps have been identified, most of them in the circumpolar regions [12−15]. More recently, the NASA Stratospheric Observatory's SOFIA Infrared Telescope detected signs of molecular water in sunlit areas. According to scientists, its recorded spectral signature indicates the presence of ice filling the voids of mineral grains in the Moon's soil. If the discovery is confirmed, the list of settlement sites will expand considerably [12−13].

Earthquakes (Lunar Shocks). The typical differences of Lunar shocks from earthquakes are as follows: they are both spontaneous and periodic, the maximum strength of tremors registered on the Moon is 5-5,7 points whereas 9,5 points on the Richter scale - on the Earth; the duration of tremors (seismic waves) on the Earth is several minutes, on the Moon seismic waves can last an hour or more, which can cause serious damage to structures depending on resonance frequencies [16−17]. The lunar shocks occur, as a rule, near fractures of the lunar crust with characteristic relief features: furrows - cracks or other narrow channels (Rima), systems of cracks or narrow channels (Rimac). Thus, settlements in these areas should be avoided, or appropriate measures should be taken to protect structures from destruction [17−18].

Regolith is a loose debris-dusty material covering almost the entire surface of the Moon. The thickness of the layer, determined by seismic wave’s velocity, reaches somewhere approximately 10 meters [17], the upper dust layer can reach from one to 3 cm, which is a serious obstacle to the settlement on the Moon. The dust is raised as a result of impact force, forming dust clouds that move under the effect of the solar wind. Dust grains lack an oxide film, so it is electrified, penetrates the smallest crevices, it is abrasive and toxic (can cause cancer if ingested). Dust is one of the main problems of lunar exploration.

The particular location of lunar settlement for mining valuable minerals from regolith depends on its chemical composition [19–22]. Regolith consists of 40-45 % of oxygen and its extraction is possible all over the Moon. Engineering design and economic estimation should be performed to mine other minerals and, therefore, find appropriate settlement location. Pre-project engineering and geological studies with drilling of regolith to the underlying layer, the analysis of the chemical composition at different depths, the determination of mineral reserves should be conducted. Nowadays, the samples of lunar regolith from the depth of approximately two meters were delivered to the Earth from the wells drilled only in the places of "Apollo" (USA), "Luna" (Russia), "Chane-5" (China) landing.

Mascons. The arrangement of lunar settlements in the areas of mascons influence should be avoided wherever possible. As the orbital trajectories of the lunar landers are designed to serve these settlements, they will need to be constantly adjusted by increasing the distance to the lunar surface.

CONCLUSION

Such factors as water, air, food are the main ones for human existence on the Moon. Water is available in the circumpolar regions; air (oxygen mixed with helium) can be extracted from the regolith. If water is available, it is also possible to grow necessary plants for food in greenhouses. Therefore, circumpolar regions can be considered as the primary locations for lunar settlements. If sufficient volumes of water for rocket fuel (hydrogen) production are confirmed, the Moon will become a reliable outpost for space exploration and exploration of the Solar System planets, primarily Mars. The small rotational velocity of the Moon around its own axis has little effect on the change of velocity of the launching pad for rockets, which simplifies the choice of their location and, with proper justification, allows their placement in the circumpolar areas of the Moon - near deposits of water ice - the source of rocket fuel. The arrangement of lunar settlements without any deposits of ice should be considered only under the conditions of settlements in the circumpolar regions and the development of transport infrastructure.

When selecting a particular site for the construction of a settlement, it is necessary to send expeditions for additional engineering and geological studies, especially of subpolar areas and lunar caves.

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3. DEVELOPING A MOON BASE CAMP FOR ACCOMMODATING THE EXPEDITION OF THE FIRST OPERATING CREWS ON THE LUNAR SURFACE

Interorbital system MILKY WAY (CHUMATSKYI SHLIAKH) provides delivery of a set of lunar base and members of the expedition from the Earth's orbit to the Moon's orbit (Fig. 3.1).

It consists of three main parts:

1. Acceleration- deceleration module
2. Reusable landing module
3. Multifunctional stage

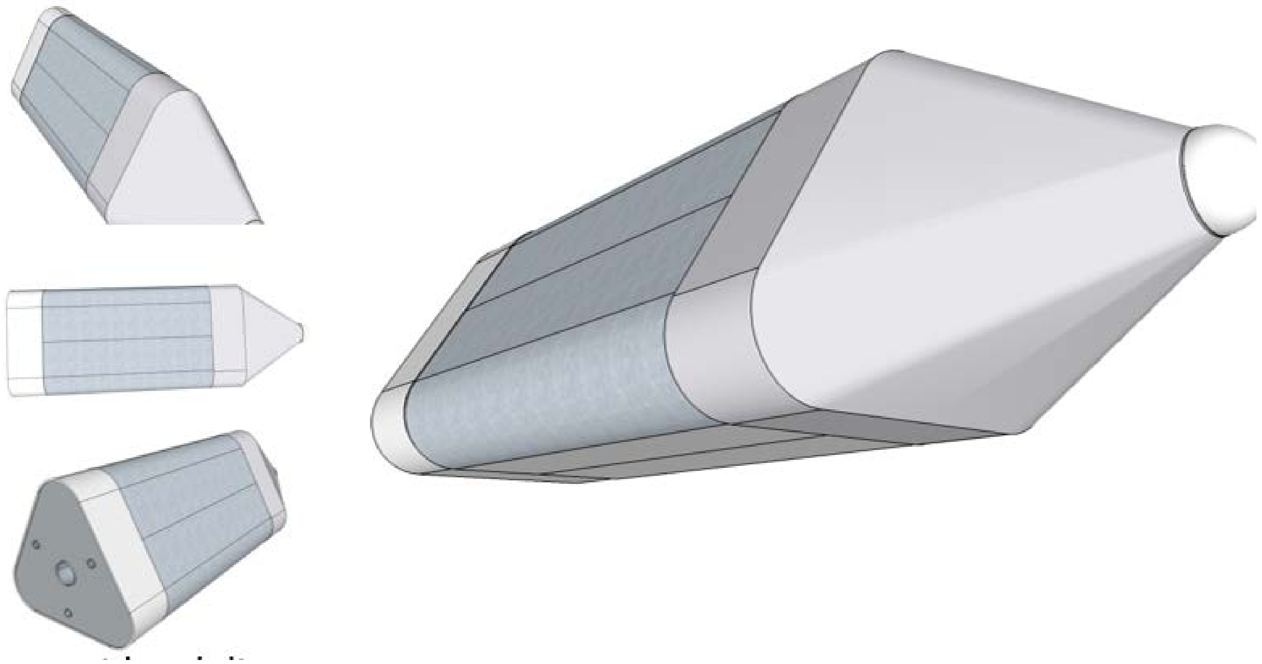


Fig. 3.1. Interorbital system MILKY WAY (CHUMATSKYI SHLIAKH)

Acceleration-deceleration module provides delivery of a reusable landing module, multifunctional stage, and other cargoes between the orbits of the Earth and the Moon. It is reusable.

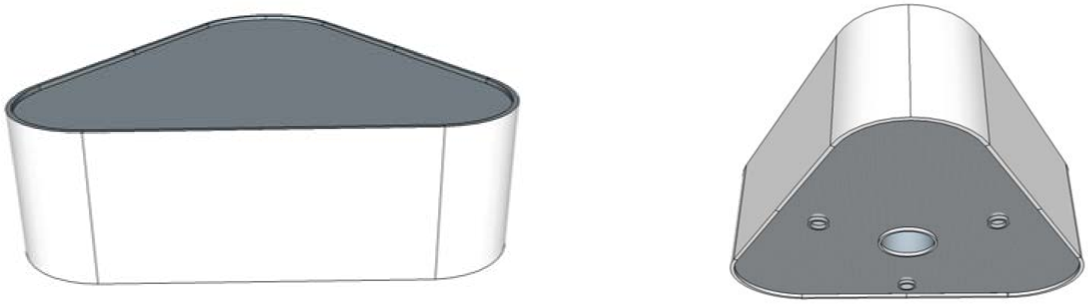


Fig. 3.2. Acceleration-deceleration module

Reusable landing module provides (Fig. 3.3):

1. Delivery of the expedition members to the surface of the Moon and their rotation;
2. Temporary stay of the expedition crews.

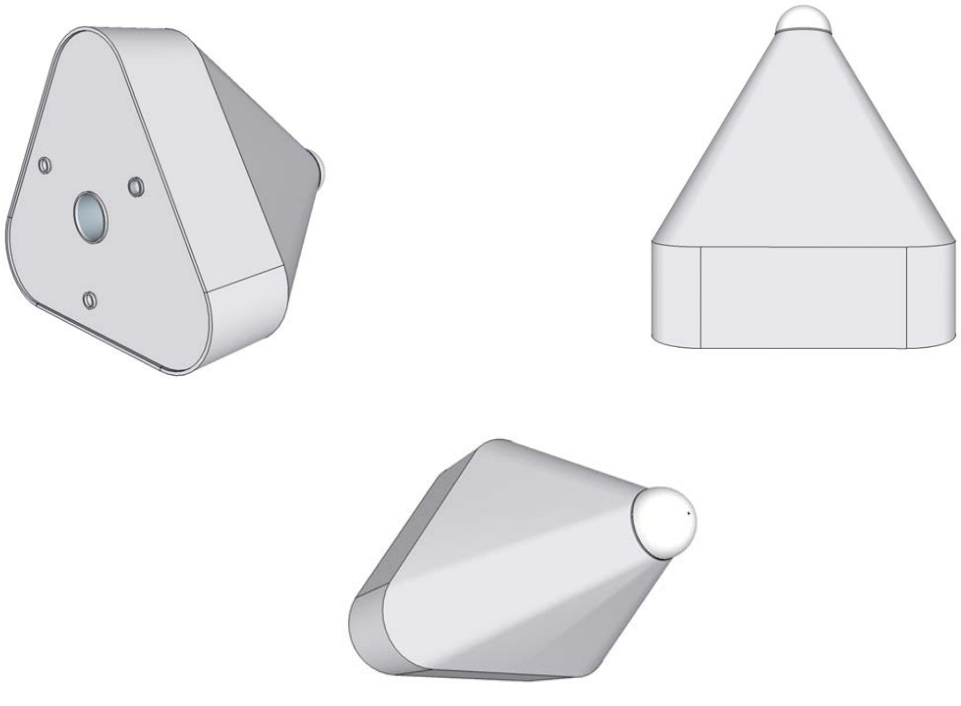


Fig. 3.3. Reusable landing module

Multifunctional stage consists of three main components (Fig. 3.4):

1. The transport compartment with a lunar base set, necessary equipment, and resources;
2. Life support compartment;
3. Airlock module.

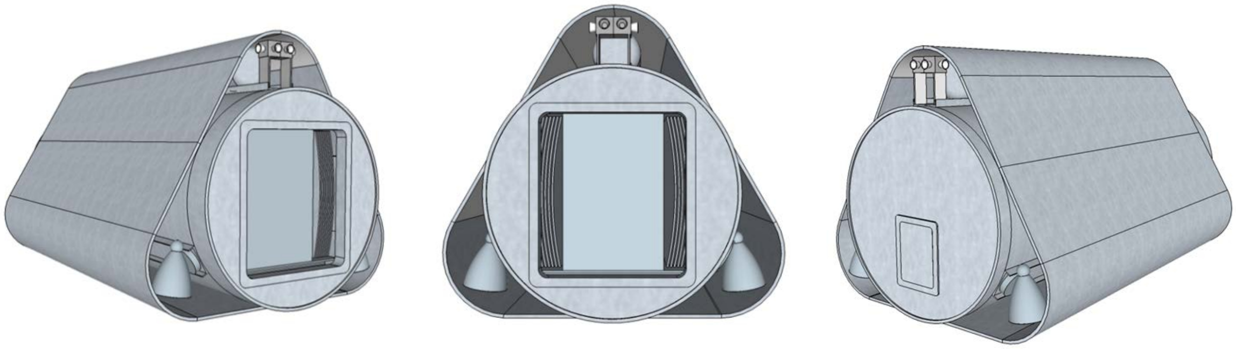


Fig. 3.4. Multifunctional stage

Lunar landing is carried out vertically in a horizontal position (Fig. 4.5). Retractable legs are equipped with motorized wheels to adjust the position after landing.

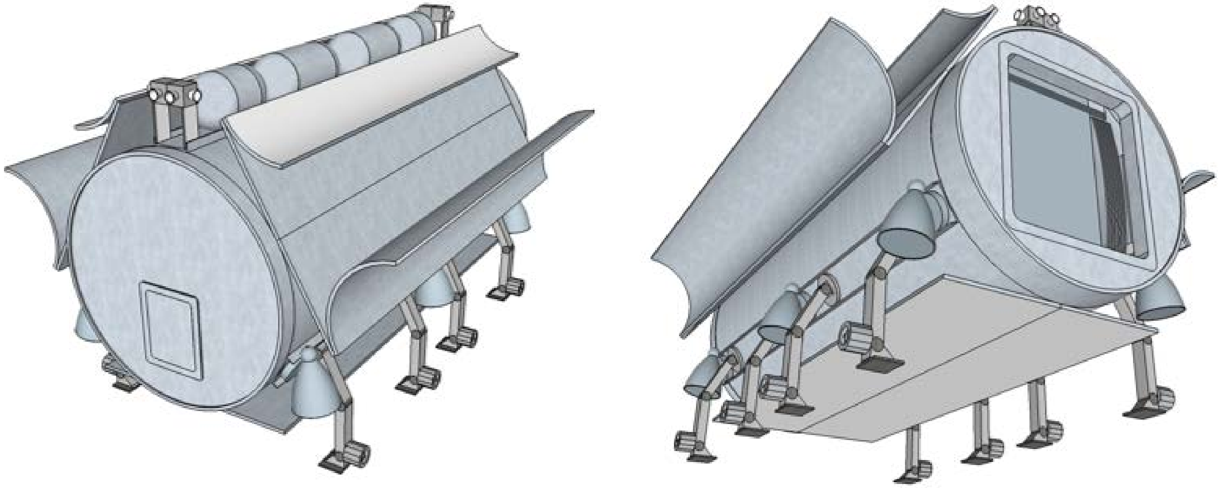


Fig. 3.5. Lunar landing of the   multifunctional stage

Multifunctional module (Fig. 3.6) provides living and working conditions for the expedition crews while constructing the base.

The module is equipped with a multifunctional stage and has two levels.

After releasing the cargo compartment, the cargo door is sealed.

Exterior panels, jet engines, fuel tanks, and motor wheels are dismounted for further use.

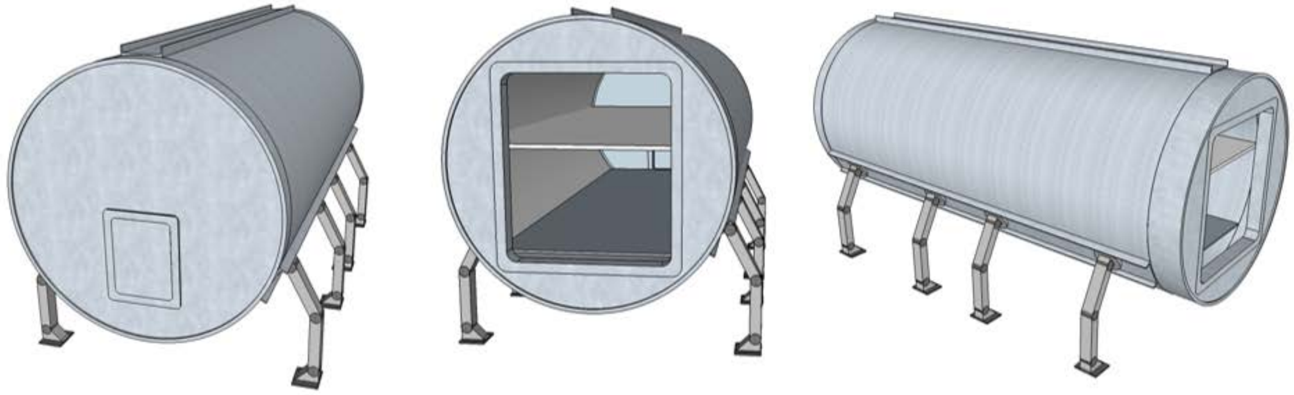


Fig. 3.6. Multifunctional module

A temporary solar power plant is installed on a horizontal lunar surface with 64 Helioprofile modules (Fig. 3.7).

Each module has 12 Helioprofile panels.

A helioprofile panel is a "3 in 1“ technical device that includes a structural element, a solar battery, and a heat collecting radiator with a circuit for a heat carrier.

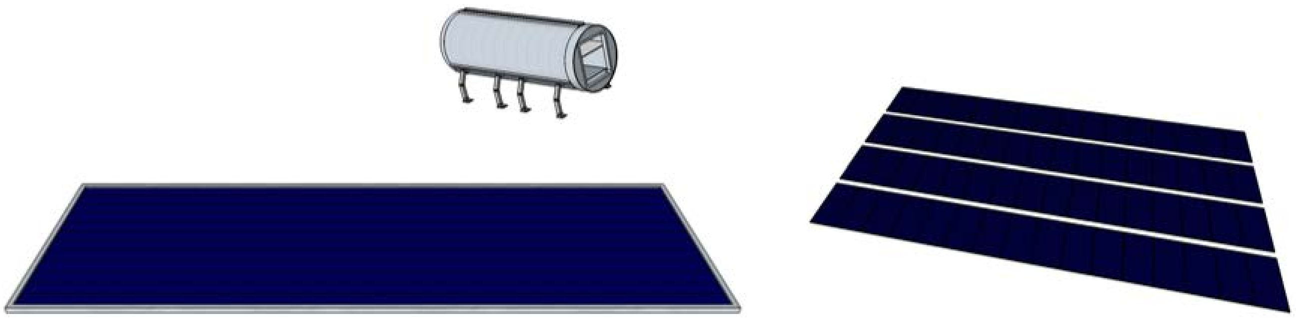


Fig. 3.7. A temporary solar power plant

The sealed module is designed for work and rest of the expedition crews for a long period of time (Fig. 3.8).

It has three levels.

It contains the elements of a biologically closed system.

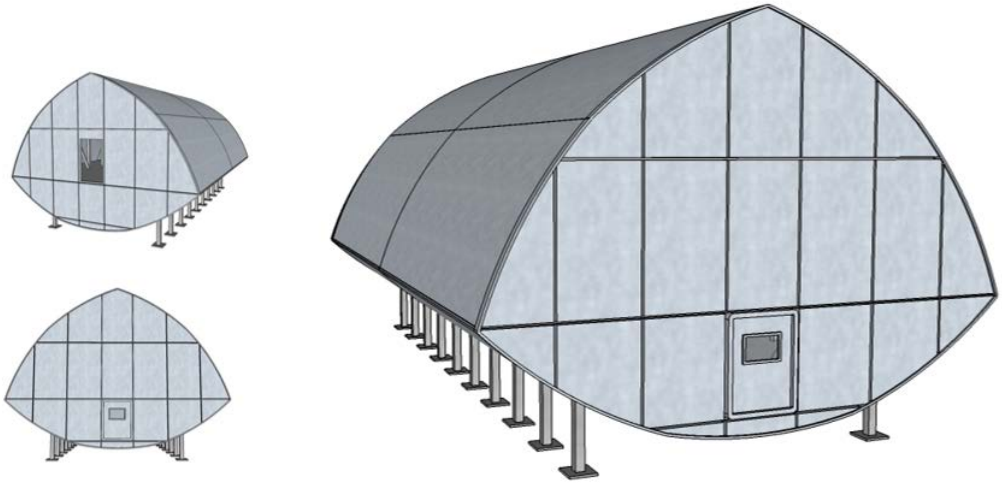


Fig. 3.8. Installation of a sealed module

Installation is carried out from a set of elements of the lunar base with the use of mechanical assembly and electric welding (Fig. 3.9).

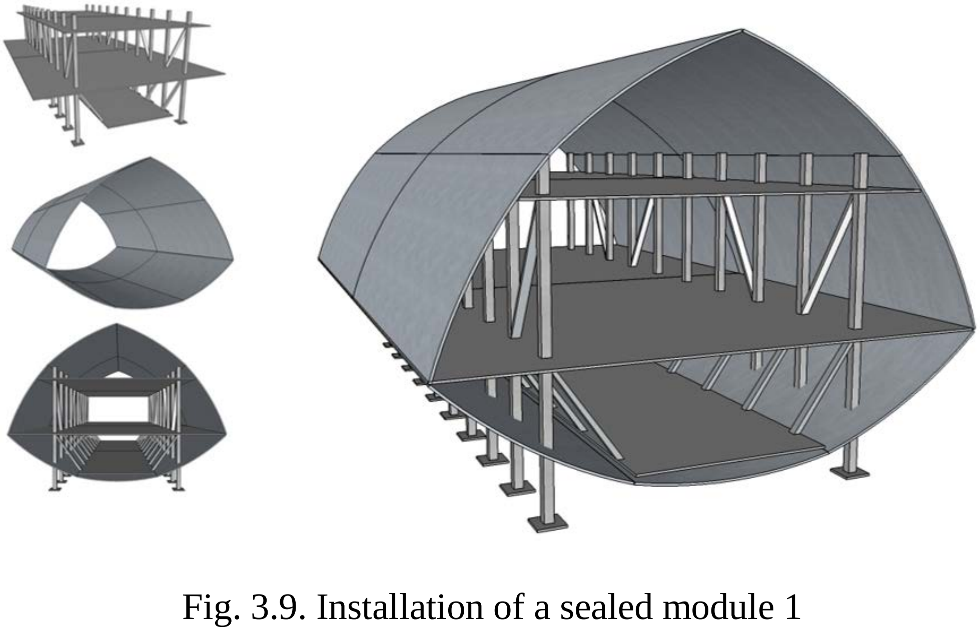
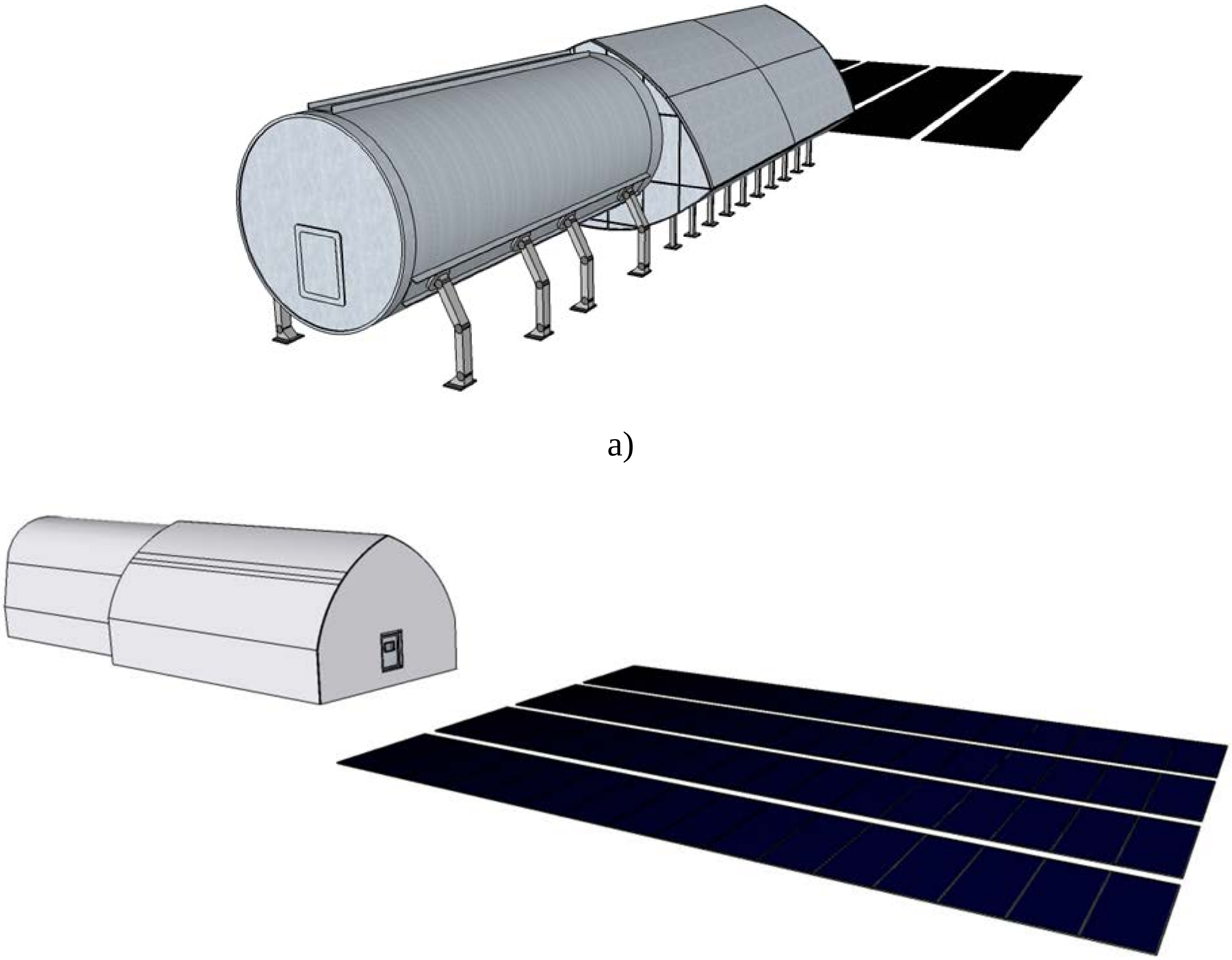


Fig. 3.9. Installation of a sealed module 1

Fig. 3.10 show evolution of the Moon Base Camp.


a)

b)

Fig. 3.10. Evolution of the Moon Base Camp:
a) the multifunctional module and the sealed module are connected;
b) The multifunctional module and the sealed module are connected and covered with screen-vacuum thermal insulation

Energy-active protection (Fig. 3.11) provides:
1. Mechanical protection of multifunctional and sealed modules;
2. Solar electricity production;
3. Thermal stabilization of multifunctional and sealed modules.

Helioprofile modules of a temporary solar power plant are used for manufacturing.

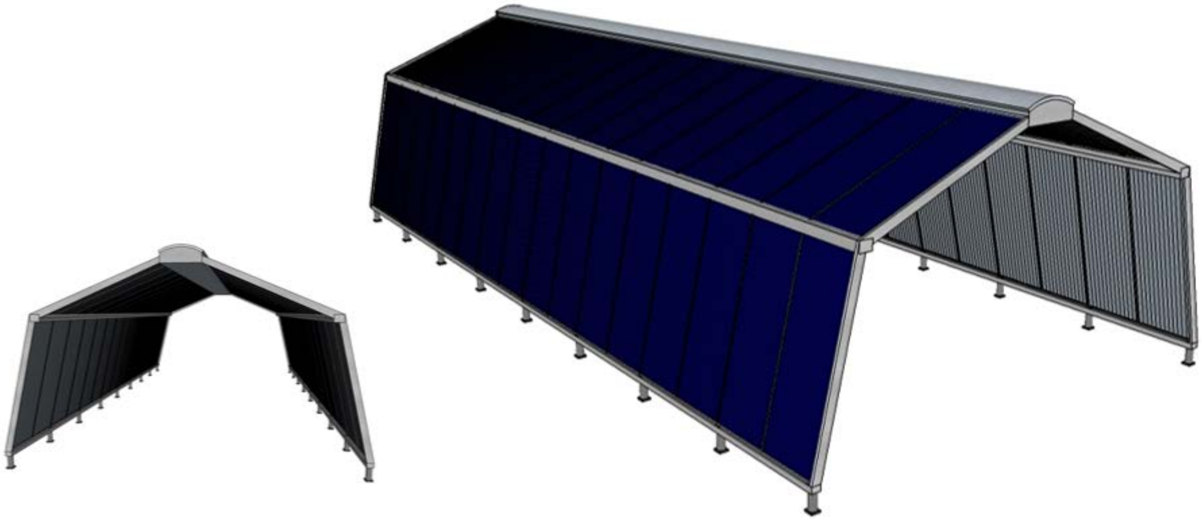


Fig. 3.11. Energy-active protection

Moon Base Camp is an operational and residential complex for the first operating crews of LUNAR SETTLEMENTS (Fig. 4.12).

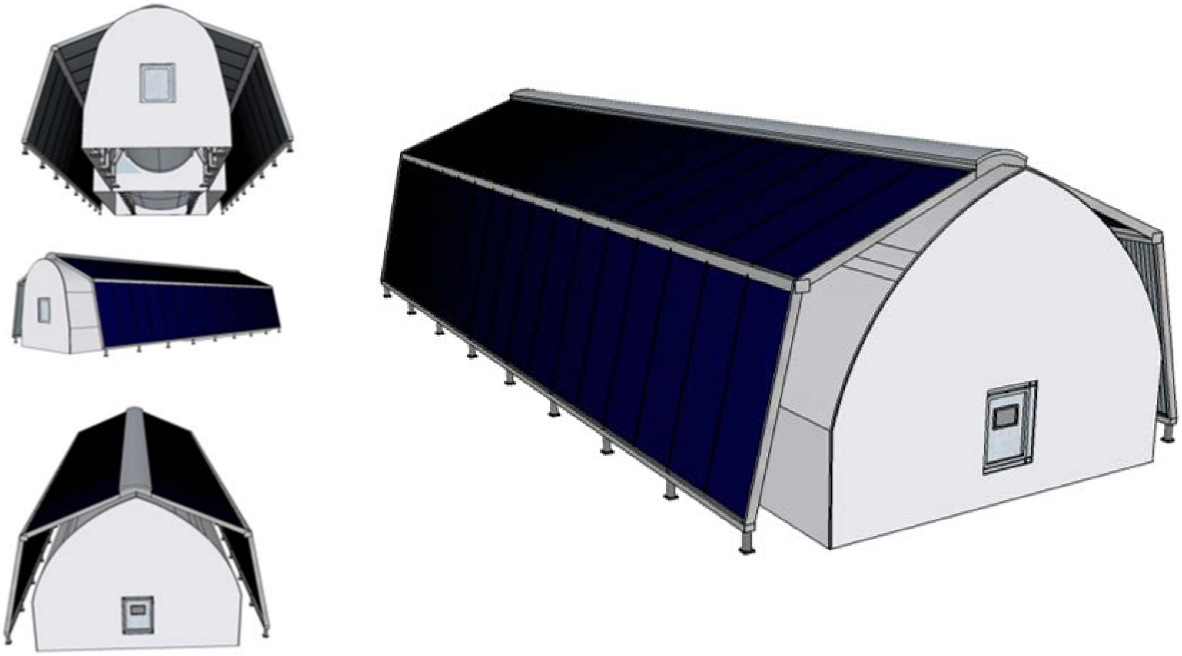


Fig. 3. 12. Moon Base Camp (MISIACHNA SICH)

The landing and steering control engines, fuel tanks, motor wheels of the multifunctional stage, a set of the necessary equipment, assemblies, and parts are multi usable.

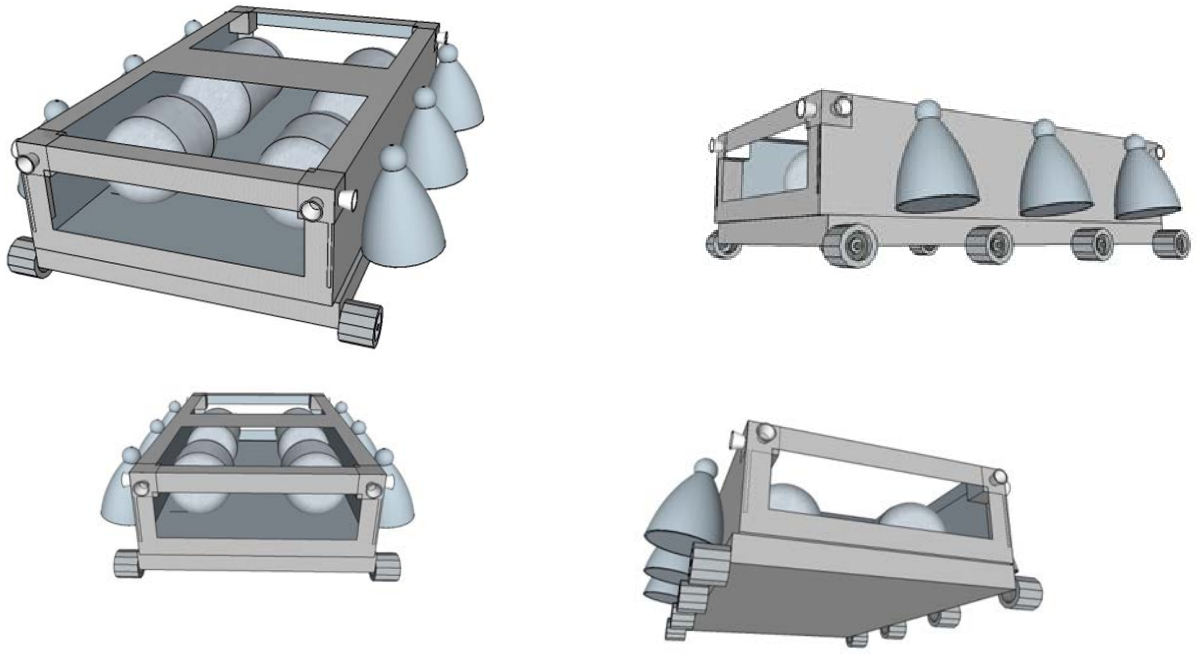


Fig. 3. 13. Multipurpose transport wheel - jet platform (schematic diagram)

4. ANALYSIS OF A MONOLITHIC DOME SHELL FOR A LUNAR LIVING MODULE

Introduction

Today, many countries around the world are developing projects for the exploration of outer space and colonization of other planets and space bodies, including the Earth's satellite - the Moon. To ensure the process of large-scale research and development of the lunar surface, it is necessary to create high-performance structures that can protect humans from the adverse conditions of space and can be built from the local raw materials using cost and time effective construction technologies.

The world's leading researchers are working on the problems of the creation of objects on the surface of the Moon. Peculiarities of geographical, geological, gravitational, temperature and other parameters of the lunar environment and their influence on the features of structures and equipment for human settlement on the Moon are considered in [1]. Recommendations for the conceptual designs for lunar buildings and the development of building codes for the design of structures on the Moon are given in [2, 3]. In the paper [4], the authors outlined a structural design approach, reviewed possible materials and evaluated several structural concepts for lunar living modules construction on the Moon.

To minimize the cost of transporting necessary materials to the Moon, it is proposed to use the local raw materials (moon dust, regolith) for the production of structural materials (sintered regolith bricks and blocks, lunar glasses and fiberglass composites, lunar waterless concrete, etc.) [5-7]. The 3D printing as a construction technology is considered a promising strategy for construction on the Moon. In [8], the authors presented the conceptual architectural and structural solution of the living module on the basis of a pneumatic shell with a protective layer of reinforced regolith put using the 3D printing. The mechanical properties of the additively manufactured lunar regolith samples were investigated in [9].

Research in the field of construction on the Moon surface using lunar resources is not limited to the publications cited above. Nevertheless, the data on the analysis of geometric parameters depending on the number of crewmembers and the stress state of lunar modules under the action of loads typical for the lunar environment, are still limited and require further study. Therefore, the purpose of this work is to perform the structural analysis of a lunar living module with a load-bearing structure in the form of a monolithic dome shell.

4.1. Structural concept of lunar living modules

A monolithic dome-shaped shell located on the surface of the Moon was considered as a load-bearing structure for the lunar living module. The erection of a monolithic dome is provided using pneumatic formwork. Concreting is carried out using a 3D printer after lifting the formwork surface and reinforcement cage into a working position.

The dimensions of the living module were taken based on the number of crewmembers according to the data [4]. Options of the living modules for 8, 10 and 12 people were considered with the parameters shown in Table 1. The effective height of the module in all cases was taken to be equal to 4 m and the total height was taken to be equal to 7 m. The schemes and dimensions of the living modules are shown in Fig. 4.1.

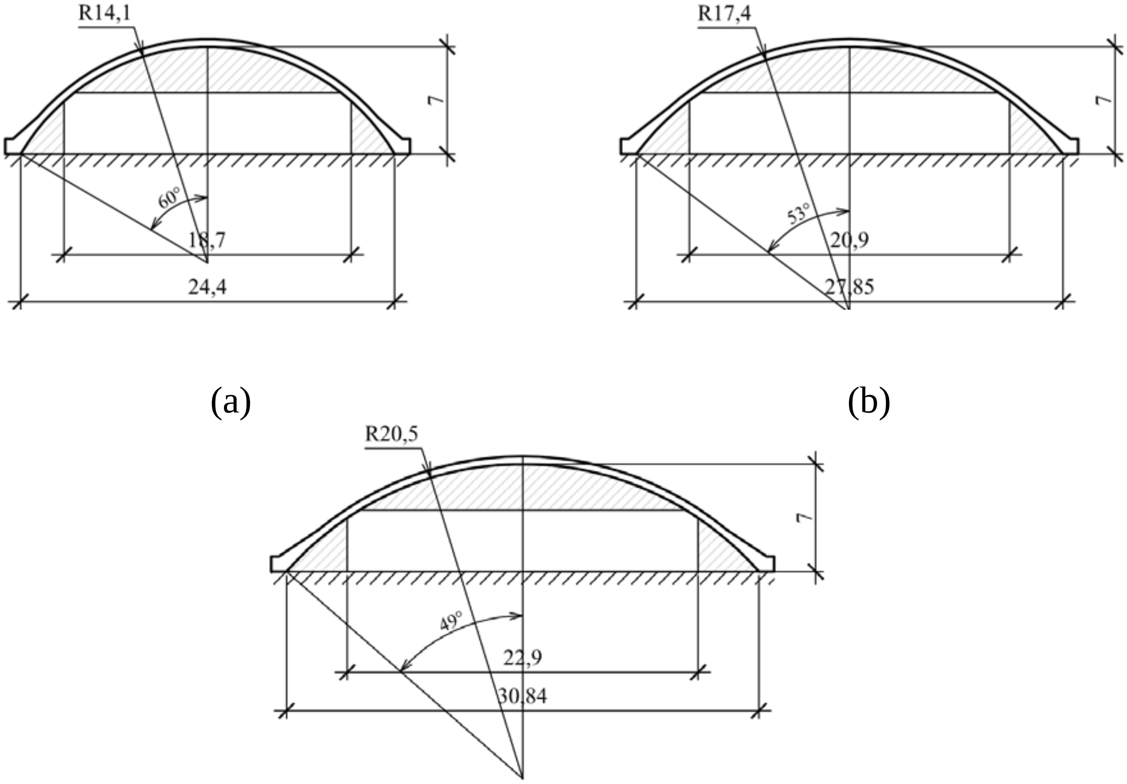
Table 4.1. Parameters of the lunar living modules.

Number of crewmembers	**Total area, m^2**	**Habitable area, m^2**	**Radius of curvature of a dome shell, m**	**Height, m**
8	467	275	14.1	7
10	609	343	17.4	
12	747	412	20.5	

4.2. Structural materials for lunar living modules

Lunarcrete is used as ‘concrete’ for a monolithic dome structure. Lunarcrete is an artificial material, which is produced directly on the Moon using regolith heated at 2000°C as a cementitious material, processed lunar rocks as aggregates and sulphur as a binding agent instead of water, since it is not present on the Moon surface. The physical and mechanical properties of lunarcrete were adopted using the available literature [6] and summarized in Table 4.2.

Fiberglass rods are used for reinforcement of the monolithic dome structure. Reinforcing bars for lunarcrete are supposed to be formed from glass derived from lunar regolith using the technology of melting and cooling it [7]. The physical and mechanical properties of fiberglass rods made by processing lunar regolith are shown in Table 4.3.



(a) (b)

(c)

Fig. 4.1. Schemes and dimensions of the living modules: a) 8; b) 10; c) 12 crewmembers.

Table 4.2. Properties of lunarcrete [6].

Strength in compression, MPa	**Strength in tension, MPa**	**Modulus of elasticity, MPa**	**Poisson's ratio**	**Density, kg/m^3**
24.0 – 33.8	2.0 – 3.7	21400	0.18	2200

Table 4.3. Properties of fiberglass rods [7].

Strength in tension, MPa	**Modulus of elasticity, MPa**
690	40800

4.3. Loads on the structure of a lunar living module

(a) (b)

Fig. 4.2. Loading schemes: a) weight of the regolith cover; b) internal pressure.

4.4. Preliminary design of a lunar living module

The preliminary design of the dome structure of a lunar living module was carried out as for a statically indeterminate spatial system according to the membrane theory of shells. The main design assumptions are: constant thickness and curvature of the shell, elastic behaviour of materials under load, and smooth change in load acting on the shell. The formulas for the internal forces determination are listed in Table 4.4. The maximum internal forces in the dome shells are presented Table 4.5.

Table 4.4. Formulas for the internal forces determination [10].

Loading scheme	**Internal forces**	
	N_1	N_2
Weight of the regolith cover	$-\frac{Gr_c}{1+\cos\varphi}$	$-Gr_c\cos\varphi - N_1$
Internal pressure	$0.5\,\mathrm{P}r_c$	$0.5\,\mathrm{P}r_c$

The designations in Table 4.4 are: G - weight of the regolith cover; P - internal pressure; N_1 – internal force in the meridional direction; N_2 – internal force in the hoop direction; r_c – curvature of the shell; φ – angle measured from the shell rotation axis.

Table 4.5. Maximum internal forces in the dome structures.

Type of a living module	**Meridional forces, kN/m**		**Hook forces, kN/m**	
	Regolith weight	**Int. pressure**	**Regolith weight**	**Int. pressure**
8 crewmembers	-66.74	486.4	-116.8	486.4
10 crewmembers	-77.12	600.3	-151.5	600.3
12 crewmembers	-87.9	707.2	-183.4	707.2

As it can be seen from the results obtained, the elements of the dome shell primarily resist the tension stresses. Thus, the design procedure is the same as for the reinforced concrete structure in axial tension [11].

The strength of the shell will be ensured, if the condition is met:

$$N_i \leq f_{fgr} A_{fgr} , \tag{4.1}$$

where N_i is the internal force in the dome shell; f_{fgr} is the strength of fiberglass reinforcement; A_{fgr} is the area of fiberglass reinforcement.

Since the dome shell must ensure the tightness of the module, the crack formation is not allowed in it. To meet this requirement, it is necessary to make a crack-resistance calculation, which is performed according to the formula:

$$N_i \leq N_{crc} = f_{lct} A_c + \sigma_{fgr} A_{fgr}, \tag{4.2}$$

where N_{crc} is the force that an element can sustain when cracking; f_{lct} is the tensile strength of lunarcrete; A_c is the area of cross-section; σ_{fgr} is the stresses in fiberglass reinforcement corresponding to cracking of concrete.

The stresses in fiberglass reinforcement corresponding to cracking of concrete can be obtained through the ultimate strain in lunarcrete in tension

$$\sigma_{fgr} = E_{fgr} \varepsilon_{lctu}, \tag{4.3}$$

where E_{fgr} is the modulus of elasticity of fiberglass reinforcement; ε_{lctu} is the ultimate strain in lunarcrete in tension that was taken as for ordinary concrete:

$$\varepsilon_{lctu} = 2 f_{lct} E_{lc}, \tag{4.4}$$

where E_{lc} is the modulus of elasticity of lunarcrete.

Using the formulas (3.1) – (3.4), the necessary area of fiberglass reinforcement and thickness of the dome shell can be calculated

$$A_{fgr} = \frac{N_i}{f_{fgr}}, \tag{4.5}$$

$$\delta_{shell} = \frac{N_i}{f_{lct}} - \frac{2 A_{fgr} E_{fgr}}{E_{lc}}. \tag{4.6}$$

Table 4.6. Necessary area of fiberglass reinforcement and thickness of the dome shell for living modules

Type of a living module	Area of fiberglass reinforcement, cm^2/m	Thickness of the dome shell, mm
8 crewmembers	7.1	160
10 crewmembers	8.7	197
12 crewmembers	10.2	232

4.5. Finite element modeling of a lunar living module

The parameters of the dome shells listed in Table 4.6 were rounded up to 10 mm, so the thickness of the dome shell for a 8-crewmembers module is 160 mm, for a 10-crewmembers one – 200 mm, and for a 12-crewmembers – 240 mm. These refined values were used in the finite element modeling of lunar living modules.

The stress-strain modeling of a lunar living module was performed for each option of a living module using the 3D finite element models of the dome shells. The modeling was performed using LIRA-SAPR commercial software. The universal triangle shell finite elements were used to create the 3D models. In order to simplify the model, lunarcrete was considered as an elastic isotropic material.

The deformative characteristics of finite elements (modulus of elasticity and Poisson's ratio) were assigned in accordance with Table 4.2. The shell thickness was assigned according to the preliminary calculation.

The hinged conditions were applied to the support nodes of the dome (movements along all three axes are disabled and rotations around them are allowed).

Loads due to the weight of the regolith cover layer and internal pressure were applied to the shell elements according to the schemes shown in Fig. 4.2.

A static analysis of the shell was performed. As a result, the data on the magnitude and intensity of internal stresses were obtained. As an illustration, the obtained 3D finite element model of the dome shell on the example of a dome for a 12-crewmembers module is shown on Fig. 4.3. The internal stresses isofields in the shell under the weight of the regolith cover and the internal pressure are shown on Fig. 4.4 and 4.5.

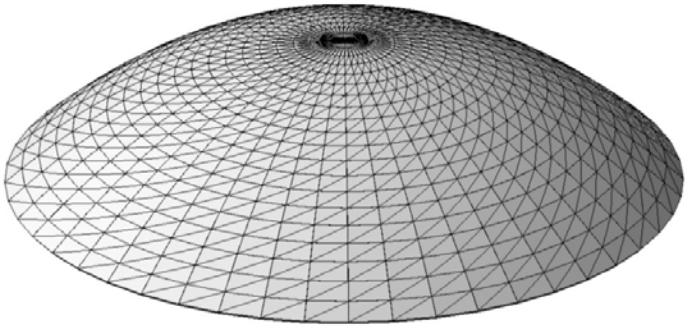
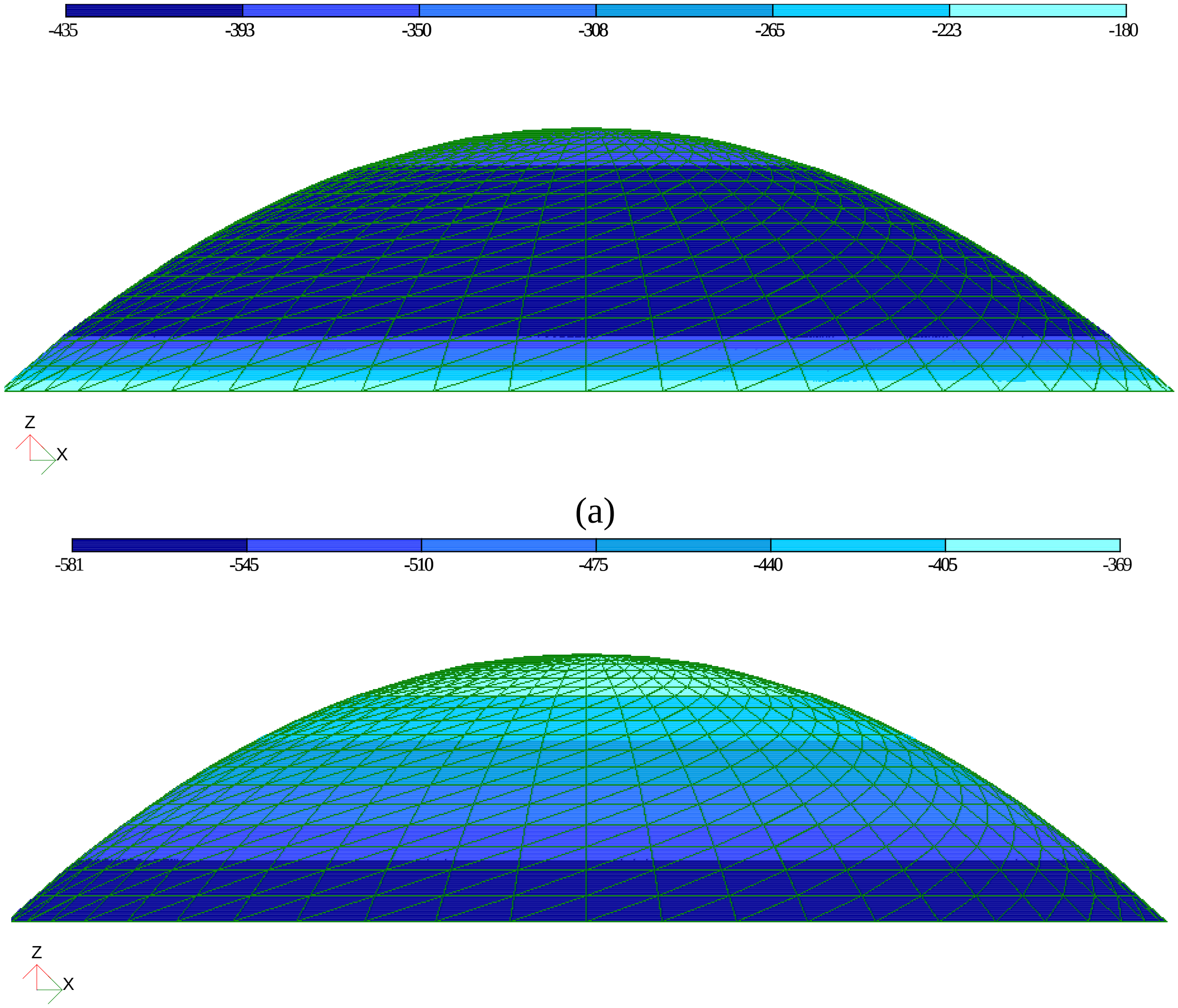


Fig. 4.3. 3D finite element model of the dome shell of a lunar living module.

The obtained data on the internal stresses were used to analyze the internal forces in the dome elements, as well as the required thickness and reinforcement of the dome shells of the living modules.

The comparative diagrams of the meridional and hook forces in the dome shells obtained as well as of the necessary area of fiberglass reinforcement and thickness of the dome shell according to the finite element modeling (FEM) and membrane theory are presented on Fig. 4.6-4.8.

As it can be seen from the results obtained, the internal forces according to the FEM differ from those according to the membrane theory. In this case, the values of the meridional internal forces from the weight of the regolith layer according to the membrane theory are 1.3-1.45 times higher than the FEM results (the exception is for a 12-people module, where the FEM values are 1.2 times higher), and those of the hook forces are 1.32-1.87 times higher. As for the internal pressure, the FEM results are 1.4-2 times higher than the data on the membrane theory for the meridional forces, and 1.2-1.8 times higher – for the hook forces.

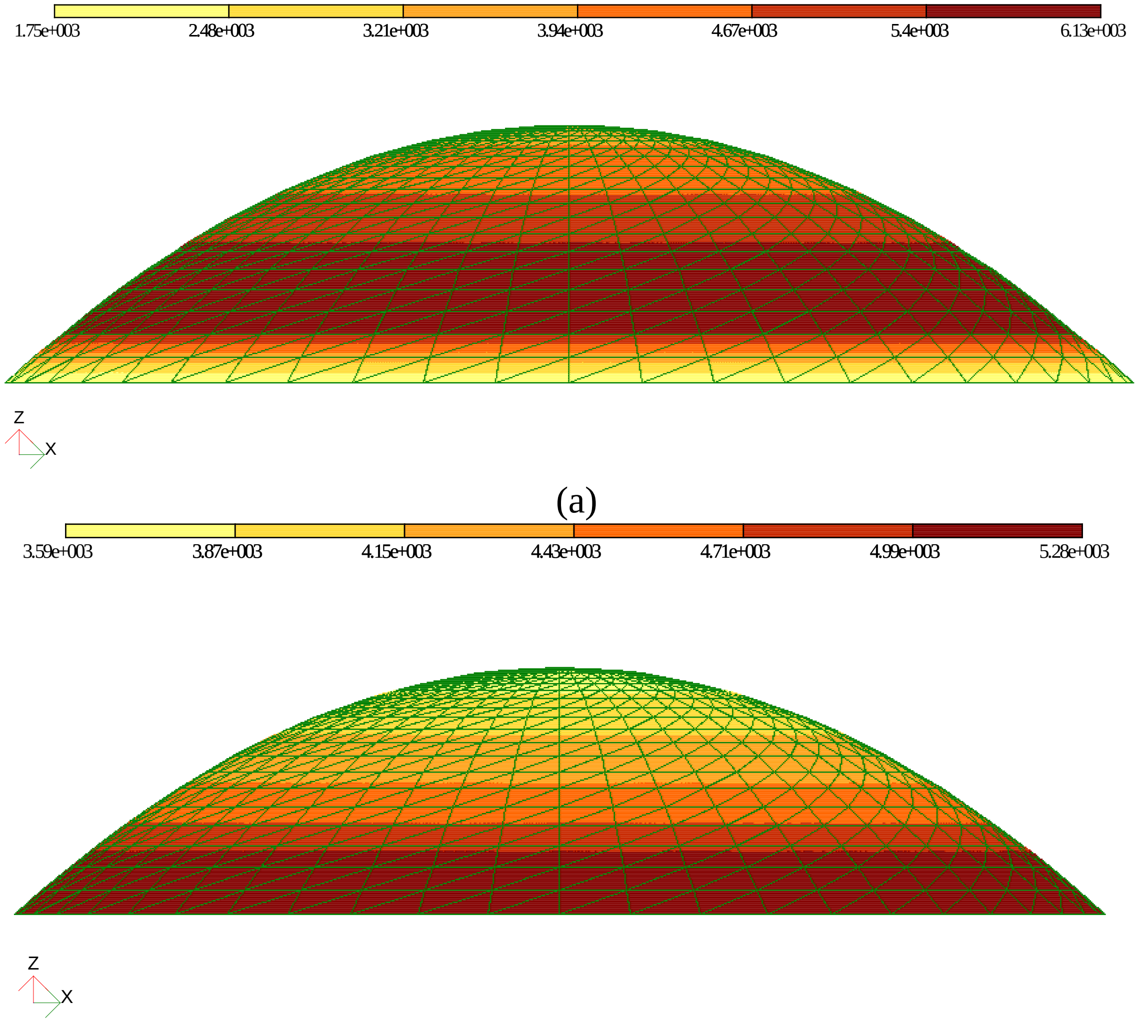


(a)

(b)

Fig. 4.4. Internal stresses isofields in the shell under the weight of the regolith cover: (a) Nx stresses, (b) Ny stresses (kN/m^2).

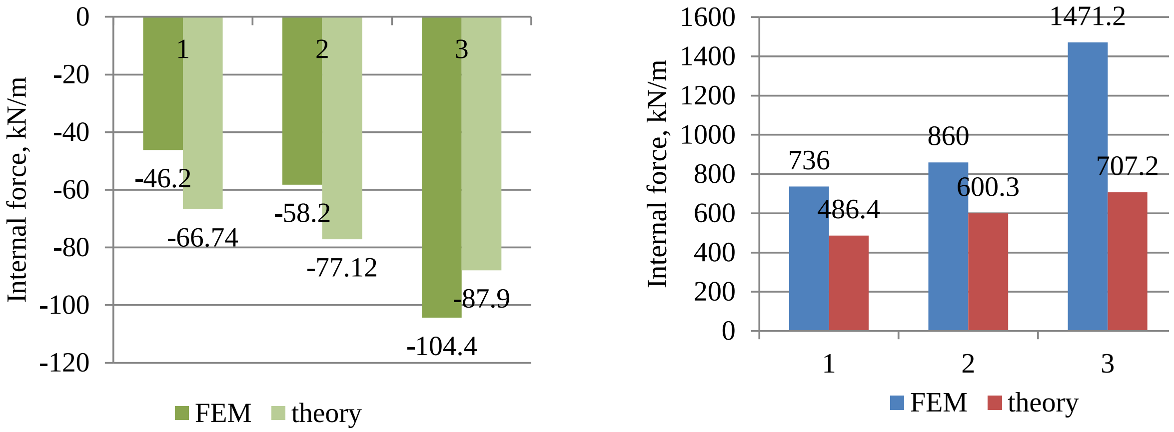
According to the results of the finite element modeling, the structural parameters of the domes are as follows: for the module for 8 crewmembers, the shell thickness is 240 mm with the reinforcement area of 10.1 cm2; for 10 crewmembers, the shell thickness is 280 mm with the reinforcement area of 12.5 cm2. As for the module for 12 crewmembers, the obtained shell thickness equal to 480 mm indicates that the adopted structural solution in the form of a solid section shell is irrational. It is necessary to consider options, for example, of a ribbed or T-shaped section, which may be the subject of further research.



(a)

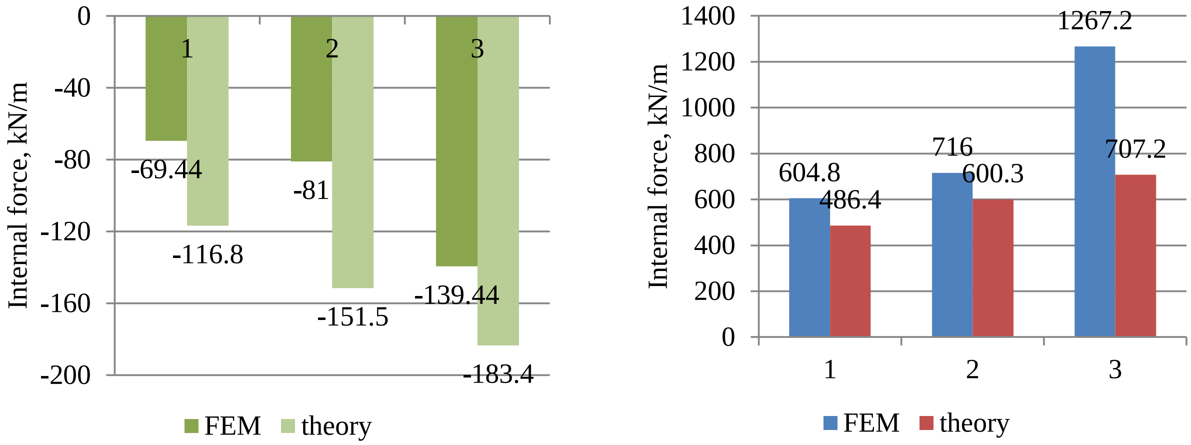
(b)

Fig. 4.5. Internal stresses isofields in the shell under the internal pressure: (a) Nx stresses, (b) Ny stresses (kN/m^2).



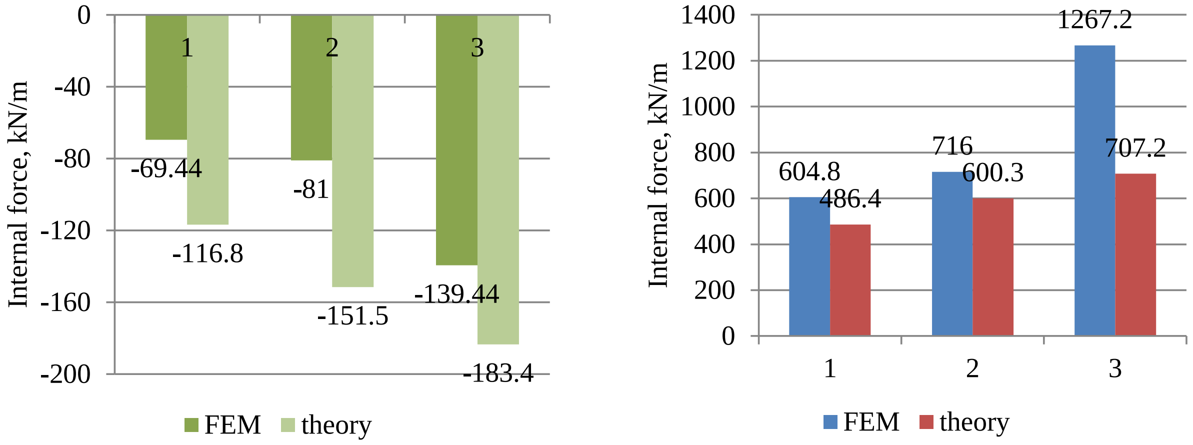
(a) (b)

Fig. 4.6. Comparative diagram of the meridional forces in the dome shells obtained according to the FEM and membrane theory: (a) regolith cover weight, (b) internal pressure; 1 - 8 crewmembers; 2 - 10 crewmembers; 3 - 20 crewmembers.



(a) (b)

Fig. 4.7. Comparative diagram of the hook forces in the dome shells obtained according to the FEM and membrane theory: (a) regolith cover weight, (b) internal pressure; 1 - 8 crewmembers; 2 - 10 crewmembers; 3 - 20 crewmembers.



(a) (b)

Fig. 4.8. Comparative diagrams of the necessary area of fiberglass reinforcement (a) and thickness of the dome shell (b) according to the FEM and membrane theory: 1 - 8 crewmembers; 2 - 10 crewmembers; 3 - 20 crewmembers.

CONCLUSION

The Article proposes the geometric parameters of monolithic dome shells for lunar living modules for 8, 10 and 12 crewmembers for the construction of shells using the 3D printing technology. The physical and mechanical characteristics of lunar concrete and fiberglass rods reinforcement on the basis of materials of local origin for the strength calculation and finite element modeling are systematized.

According to the well-known methods for the reinforced concrete structures design, a preliminary calculation of the dome shells on loads from the internal pressure and weight of the protective regolith layer has been performed. Based on the data obtained, the finite element modeling of shells was carried out using LIRA-SAPR software.

The internal forces obtained according to the finite element modeling (FEM) differ from those according to the membrane theory. The values of the meridional internal forces from the weight of the regolith layer according to the membrane theory are 1.3-1.45 times higher than the FEM results, and those of the hook forces are 1.32 - 1.87 times higher. As for the internal pressure, the FEM results are 1.4-2 times higher than the data on the membrane theory for meridional forces and 1.2-1.8 times higher - for the hook forces.

The structural parameters of the domes according to the FEM results are as follows: for the 8-crewmembers module, the shell thickness is 240 mm with the fiberglass reinforcement area of 10.1 cm^2; for the 10-crewmembers module, the shell thickness is 280 mm with the reinforcement area of 12.5 cm^2. For the 12-crewmembers module, it is necessary to consider a ribbed or T-shaped section to provide a rational structure.

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5. NUMERICAL SIMULATION OF THERMAL CONDITIONS AT THE MOON

Problem statement. For several decades, long-term inhabited structures for deep space explorations have been of a great interest for the largest space agencies and research communities (see, for example, a recent review by Benoraya [1]). The Moon is the closest celestial body to Earth. Thus, it is considered as the crucial point of the human space infrastructure and as the first place for the development of permanent settlements. Creation of the lunar outpost allows in the near future conducting medical and biological research, testing systems of extraterrestrial human life and performing unique physical experiments.

The lunar environment is characterized by very contrast thermal conditions. At the equatorial latitude, the surface temperature changes from about 100 K to 400 K during the lunar diurnal cycle [2], which lasts approximately 28 Earth days. Simonsen et al. [3] reported the specified range from 120 K to 374 K. Therefore, ensuring the efficient climate control of a lunar habitation module requires a precise simulation of the extreme temperature variations at the Moon.

Purpose of the study. This paper aims to simulate the heat balance at the lunar surface and to evaluate the depth temperature distribution in the lunar soil and its evolution in time.

Main results. The inclination of the lunar equator to the ecliptic plane is very small and equals 1.54°. Therefore, the annual variations of the intensity of solar radiation at the Moon can be neglected.

Almost the entire lunar surface is covered by the regolith layer, which thickness varies from 5 meters in mare areas up to 15 meters in old highland regions [2]. The properties of the regolith were reported by Langseth et al. [4], who revised the results of Apollo missions and estimated the average data valid for all landing sites.

We introduce the governing heat conduction equation that describes a non-stationary heat flow in the regolith layer. The boundary conditions are as follows:

1. The heat flux at the lunar surface equals to the difference between the solar heat gain and the heat loss through the infrared radiation. The solar heat gain is represented as a function of the lunar albedo (which equals approximately 0.09 [5]), the geographical latitude, and on Sun elevation angle. The power of the

infrared radiation is determined by the Stefan–Boltzmann law. The lunar surface emits as a nearly black body with the emissivity of about 0.9…0.95 [6].

2. In depth, far away from the surface, the temperature is constant and does not change in time.

The initial temperature of the entire regolith layer is assumed to be equal to the depth temperature. Then, performing numerical simulations during several diurnal cycles, one can observe that the alterations of the regolith temperature stabilize and become completely periodical. This approach allows us to determine the temperature variations at the lunar surface and in the regolith layer, as well as to predict the magnitude of the depth temperature.

The governing initial-boundary value problem is integrated numerically by the finite-difference method using Maple. Temperature at the lunar surface is presented in Figure 5.1. The obtained results agree with the data from literature [2; 3]. In order to verify the developed model, simulations of the Moon temperature were performed in FEM package ELCUT. Both solutions are in a good agreement.

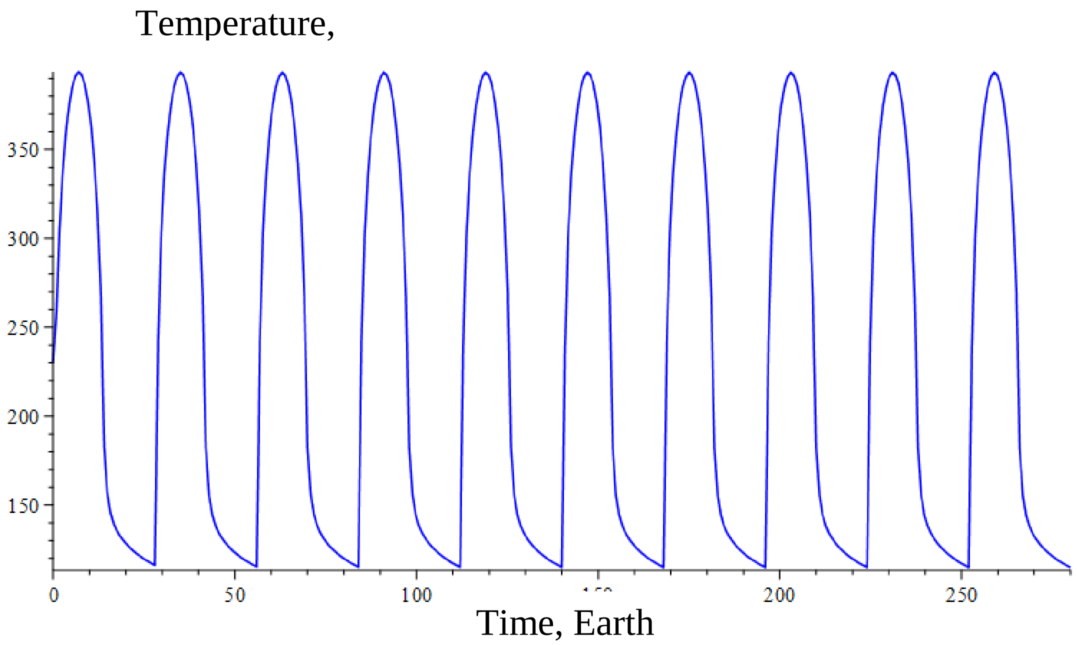

Fig. 5.1. Lunar surface temperature at the equatorial latitude

CONCLUSIONS.

A mathematical model describing the Moon thermal conditions is developed. The proposed non-stationary heat problem is solved numerically, which allows one to determine the heat flux at the lunar surface and the temperature distribution in the regolith layer. The results of the analysis are justified by the FEM modelling using ELCUT. The developed model can be further employed for the design of lunar habitation modules.

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6. FEATURES OF ENGINEERING AND TECHNICAL SOLUTIONS OF STRUCTURES OF GREENHOUSE MODULES FOR THE MOON BASE

Since the middle of the last century, mankind has been actively exploring outer space and celestial bodies. With the launch of the MIR orbital station in 1986 and the International Space Station (ISS) in 1998, the human presence in space is virtually constant. The next step in the development of outer space is the construction of a base on the moon and the colonization of Mars. The main task is to provide a safe environment for human life in extraterrestrial space**.**

According to NASA Advanced Life Support Baseline Values and Assumptions Document [1], a two-year lunar crew of six will require 57 tons of consumables, including 2.7 tons of sublimated food and 17 tons of drinking water. Given the high cost of delivering cargo to space (from $ 11,500 per 1 kg of cargo), the solution to reducing the cost of providing the base on the moon with food may be to grow food crops directly on site using a greenhouse module.

Table 6.1. Advanced Life Support Subsystem Descriptions and Interfaces

Air	The Air Subsystem stores and maintains the vehicle cabin atmospheric gases, including pressure control, overall composition, and trace constituents. The Air Subsystem is also responsible for fire detection and suppression and vacuum services.
Biomass	The Biomass Subsystem produces, stores, and provides raw agricultural products to the Food Subsystem while regenerating air and water. This subsystem is not present in a solely physicochemical life support system
Food	The Food Subsystem receives harvested agricultural products from the Biomass Subsystem, stabilizes them as necessary, storing raw and stabilized agricultural products, food ingredients, and prepackaged food and beverage items. The Food Subsystem transforms the raw agricultural products into a ready-to-eat form via food processing and meal preparation operations. In the absence of the Biomass Subsystem, this subsystem operates only on prepackaged, stored products.
Thermal	The Thermal Subsystem is responsible for maintaining

	cabin temperature and humidity within appropriate bounds and for rejecting the collected waste heat to the Cooling Interface. Note: Equipment to remove thermal loads from the cabin atmosphere normally provides sufficient air circulation.
Waste	The Waste Subsystem collects and conditions waste material from anywhere in the habitat, including: packaging, human wastes, inedible biomass, and brines from other subsystems such as the Water Subsystem. The Waste Subsystem may sterilize and store the waste or reclaim life support commodities, depending on the life support system closure and/or mission duration.
Water	The Water Subsystem collects wastewater from all possible sources, recovers and transports potable water, and stores and provides the water at the appropriate purity for crew consumption and hygiene as well as external users.
Crew	The Crew Interface interacts with most life support subsystems and external interfaces. Crewmembers have been, and should continue to be, the foremost consumers of life support commodities as well as the primary producers of waste products. Finally, life support technologies are specifically designed to provide for the health, safety, and maximum efficiency of crewmembers.
Cooling	The Cooling Interface rejects vehicle thermal loads, delivered by the Thermal Subsystem, to the external environment.
Extravehicular Activity Support	The Extravehicular Activity Support Interface provides life support consumables for extravehicular activities, including oxygen, water, and food. It also provides for the removal of carbon dioxide and waste.
Human Accommodations	The Human Accommodations Interface is responsible for the crew cabin layout, crew clothing (including laundering), and the crew’s interaction with the life support system.
In-Situ Resource Utilization	The In-Situ Resource Utilization Interface provides life support commodities, such as gases, water, and regolith from local planetary materials for use throughout the life support system.

Integrated Control	The Integrated Control Interface provides appropriate control for the life support system.
Power	The Power Interface provides the necessary energy to support all equipment and functions within the life support system.
Radiation Protection	The Radiation Protection Interface provides protection from environmental radiation.

Strict conditions on the Moon make certain demands on the construction of greenhouses. The design of the lunar greenhouse module should provide conditions for creating the necessary microclimate parameters for growing plants, as well as protect the interior from the effects of radiation, temperature changes, micrometeorite shocks and other external factors. It should also be integrated into the main infrastructure of the lunar base.

As part of the Alternative to the Microecological Life Support Program (MELiSSA), the German Aerospace Center (DLR) conducted research aimed at determining the basic requirements for the operation of lunar greenhouse modules. The study identified the main parameters of the microclimate required for growing plants, plant crops that should be grown in the monthly greenhouse module, the volume of the growth zone of the greenhouse module for these plants, as well as the monthly dry weight of the crop. The main crops proposed for cultivation in extraterrestrial conditions are potatoes, soybeans, durum wheat and bread varieties, lettuce, beets and rice, the monthly dry weight of which should be 171 kg [2]. Also during the study, three variants of greenhouse module designs were proposed: inflatable, combined (combination of rigid complex and inflatable structures) and rigid telescopic structure.

This paper describes the space architecture research and rapid concept design of a large greenhouse module (GHM) for the extreme environment on the Moon, considering all aspects of construction and utilization from an architectural perspective. This study is made in the frame of the project "Greenhouse Module for Space System", led by the EDEN (Evolution Design of Environmentally-closed Nutrition- Sources) group of DLR Bremen for the ESA MELiSSA (Micro-Ecological Life Support System Alternative) project. This greenhouse module is one of the producer compartments of the MELiSSA loop, a regenerative closed system based on micro-organisms and higher plants to recycle organic wastes of the crew, revitalize the atmosphere, recycle water, and produce food. The greenhouse concepts are based on the required plant growth volumes for sustaining a crew of six on the Moon for two years. Three different concepts for external configuration are presented together with examples of how they can be outfitted internally with growth accommodations and supporting functional areas as well as space for accommodating subsystems. The greenhouse structures are composed of rigid, rigid deployable and flexible deployable components in different configurations, optimizing volume and mass, in three concepts demonstrating the principal differences between the structural concepts. The greenhouse subsystems are estimated based on currently available off-the shelf systems and the greenhouse operations consider both human and robotic greenhouse maintenance and are reflected in the architectural solutions. The interior layouts demonstrate different plant arrangements and different degrees of automation for compact placement of the plant growth structures, while allowing for reasonable working conditions for the astronauts. The three concepts presented in this paper are innovative outcomes of diverse requirements given by the MELiSSA project and provide different holistic views on the greenhouse design for extreme environments. They include all aspects of the space flight logistics, deployment and operations on the lunar surface and serve as preliminary architectural options for further evaluation of the different concepts.

The greenhouse module is designed to support six people.

Inflatable (Fig. 6.1, 6.2). The main principle of this configuration is the utilization of an inflatable structure in the shape of a torus that deploys around the module’s vertical core, covered with regolith. The inflatable structure is divided into six parts, ("petals"), where the walls between the petals function as a structural, internal pressure loadbearing system, but also as separation walls, enabling operation of the petals independently in case of potential off-nominal scenarios happening in the other petals.

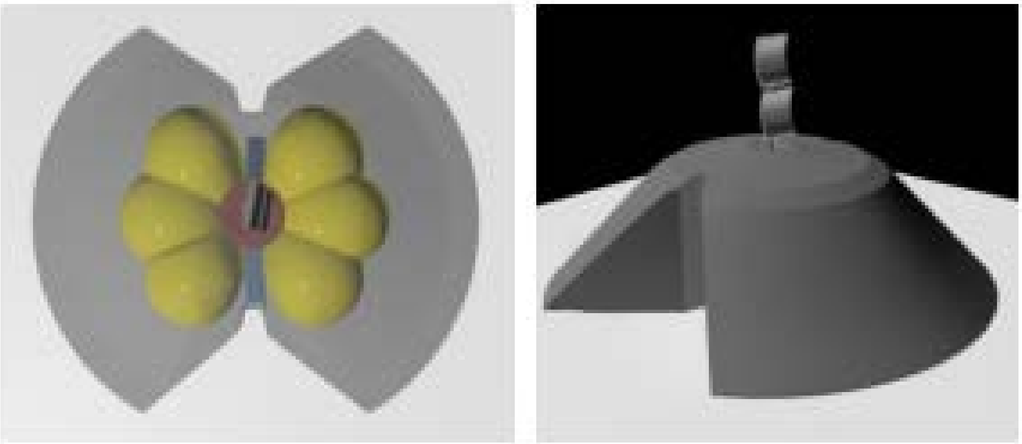

Figure 6.1. Inflatable concept - inflatable structures depicted in yellow, rigid core in red. Deployable greenhouse structure is covered by regolith.

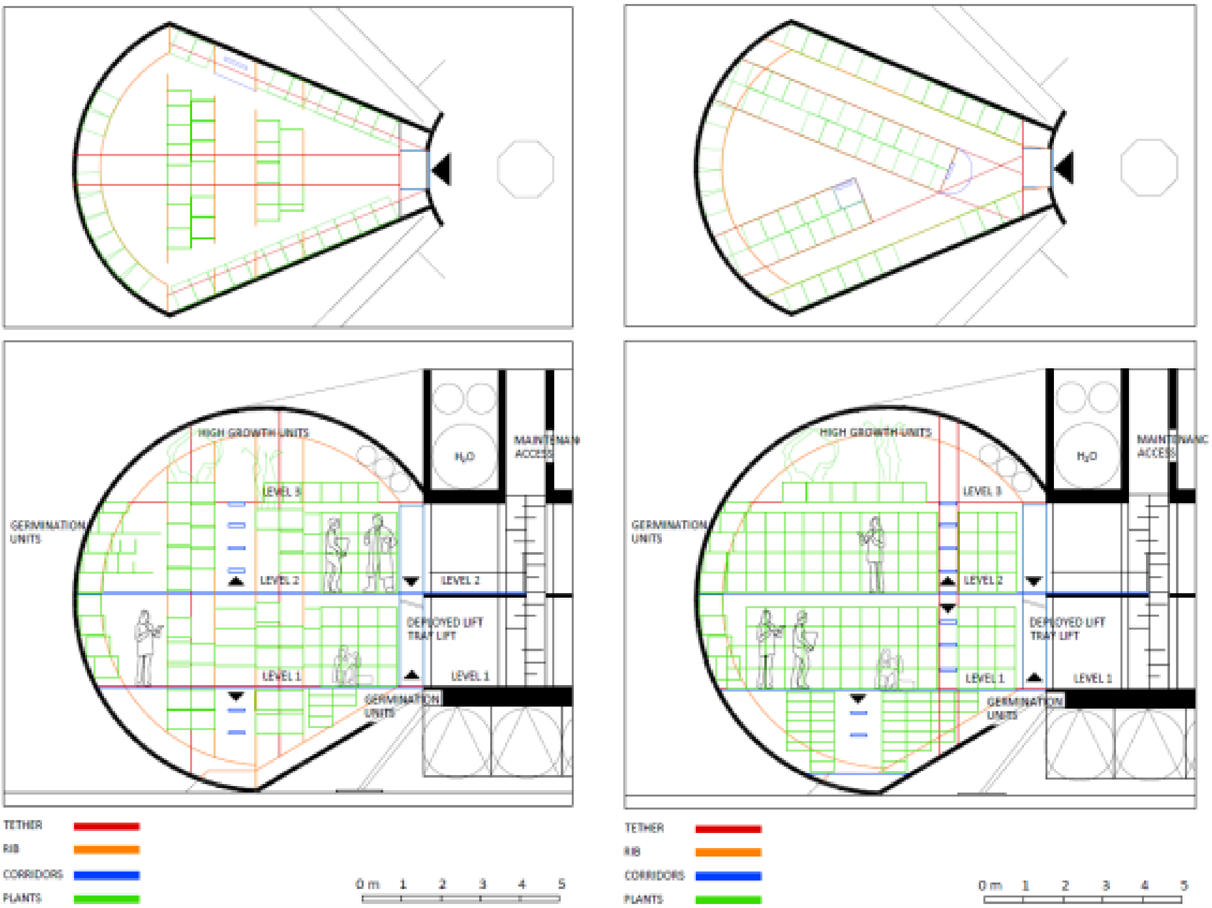

Figure 6.2. Two internal layout options for the Inflatable Concept including a possible structural configuration of the inflatable interior

Hybrid (Fig. 6.3, 6.4). The combination of deployment with a mechanical arm that can later on serve as a main system operator, deployable structures and inflatable structures is presented in the Hybrid concept. The system provides two independent tori with racks on two main levels and pre-integrated water, air, electricity infrastructure.

The system is deployed in sequence, one torus after the other. The structure is covered by lunar regolith in the final phase of construction. The structure is lower than the Inflatable option due to its volume distribution in two smaller diameter tori. Each torus has a small internal core with a deployable robotic arm for automated maintenance of the plants. The uninterrupted internal volume of the torus allows for variety of arrangement for an automated system that would spin around the central core if each torus (see Figure 6.3).

Two access ports are place on the core opposite of each other for access to the rest of the lunar base. The top center of the rigid core provides possibility for placement of a solar concentrator or photovoltaic system for light collection, or power generation independently of the lunar base infrastructure.

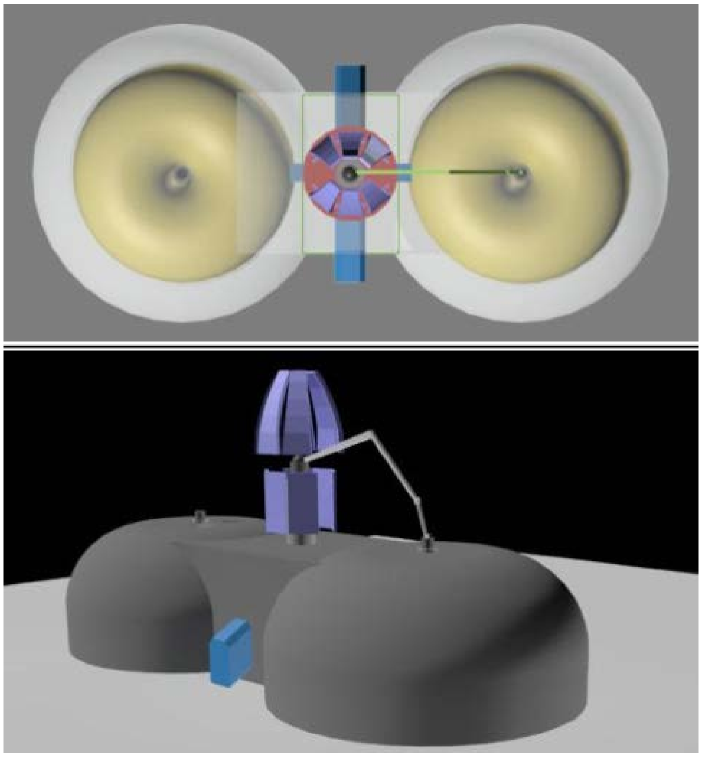

Figure 6.3. Hybrid concept composed of two inflatable tori. Inflatable structures are depicted in yellow on the top image. The bottom represents pre-fabricated deployable system covered by regolith shell.

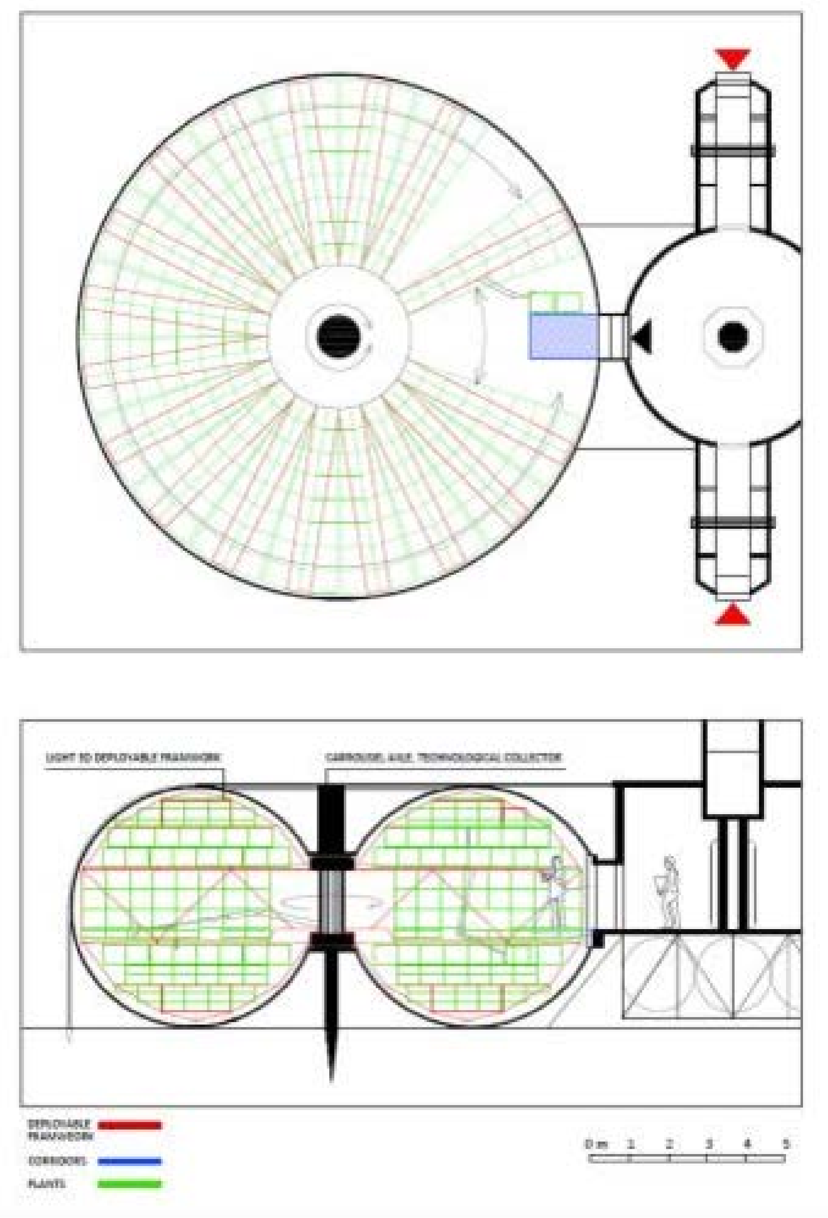

Figure 6.4. Hybrid Concept interior layout option showing the rotating shelves system.

Rigid (Fig. 6.5, 6.6). A fully rigid modular structure with telescopically deployable components is presented as the third option suitable for the lunar greenhouse module. The greenhouse depicted in Figure 6.3 is composed of 18 hexagonal telescopic components (HTC) covered by regolith shell. This configuration that volumetrically corresponds to options Inflatable and Hybrid would require at least 3 times more launches. In one launch six telescopic chamber components would be delivered to the

Although this concept requires multiple launches, its structures are very simple, utilizing a vertical sliding mechanism for its deployment and the universal lunar surface vehicle Athlete that is being developed by NASA. The hexagonal shape of the components allows for unlimited growth of the greenhouse system and also for pre-integration of all required technical infrastructure, subsystems or functional elements inside the un-deployed components. The Rigid concept as presented in Figure 9 allows for stowing of hexagonal solar concentrators or photovoltaic system allowing for light or power autonomy.

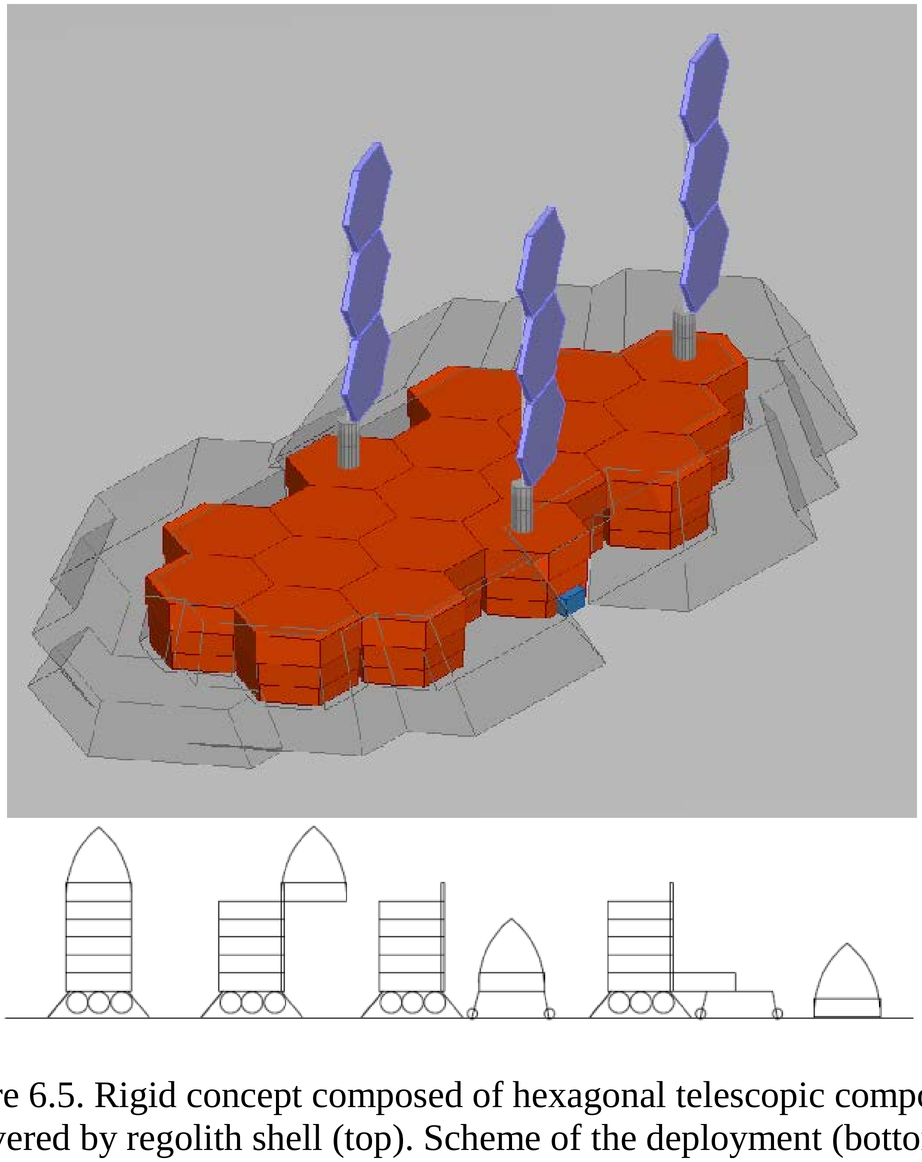

Figure 6.5. Rigid concept composed of hexagonal telescopic components and covered by regolith shell (top). Scheme of the deployment (bottom).

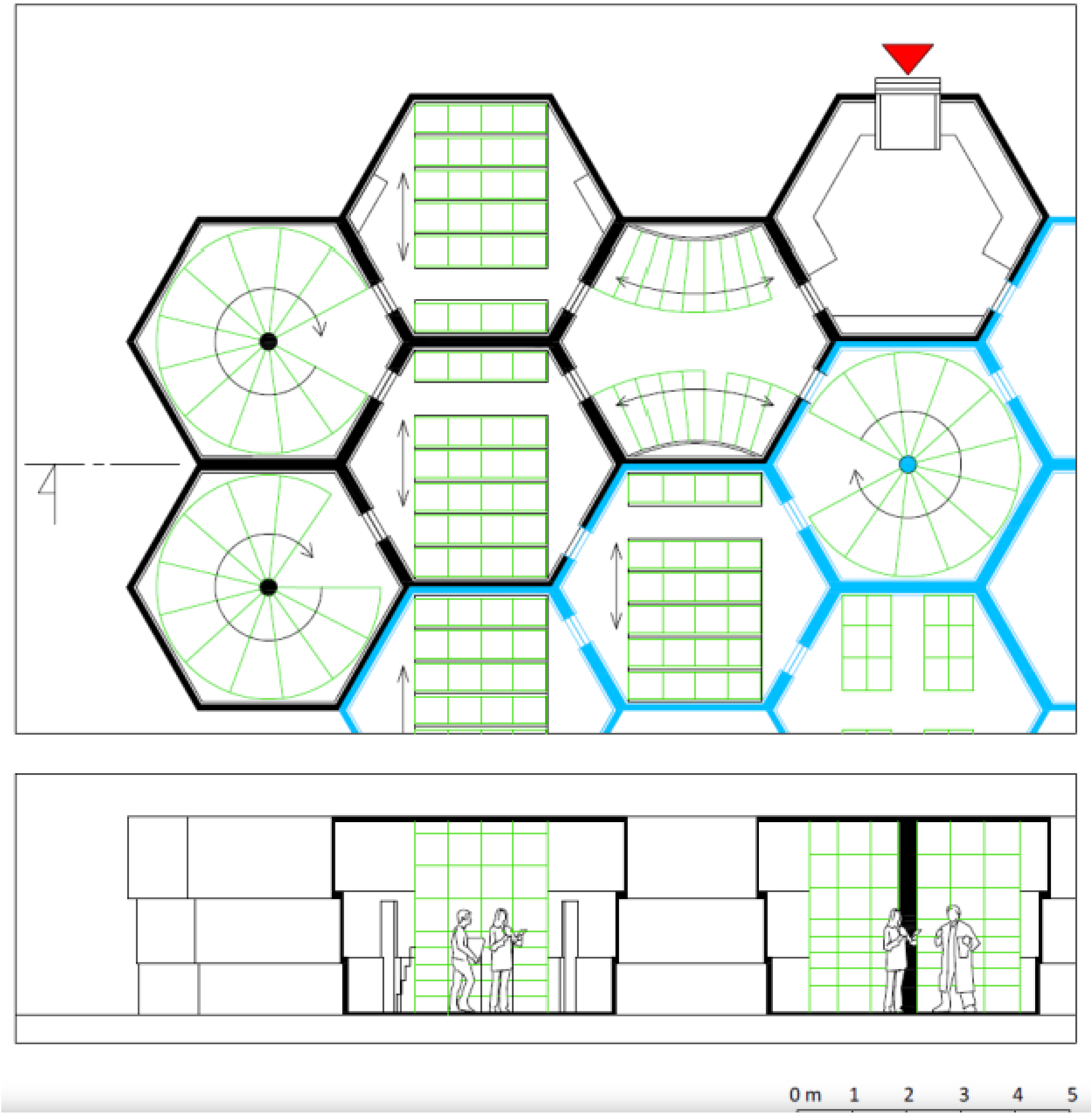

Figure 6.6. Rigid concept internal configuration provides a possibility of utilizing modular design and producing modular plant bed units. Both fixed and movable shelves systems are possible.

Future human-based exploration of the solar system will require architecting, constructing and deploying outposts on planetary bodies that last for years. Indeed Lunar outposts require oxygen generation and atmosphere revitalization which represent a critical component for sustainable long-term space missions. Whereas initial shorter duration Lunar missions (~60 day) may rely on meals supplied from Earth as well as rely on conventional physico-chemical support systems, Bio-regenerative Life Support Systems (BLSS) may be necessary for permanent outposts (e.g. > 6 months). BLSS uses plant-based biological processes to support the desired number of astronauts. As a complex, multi-component system, BLSS include 1) atmosphere revitalization, 2) water recycling, 3) food production, 4) organic waste recycling and 5) power generation. Consequently, designing future planetary outposts (e.g. Moon, Mars) must include a BLSS component. Over the past few years, the University of Arizona Controlled Environment Agriculture Center (UA-CEAC) and the Department of Systems and Industrial Engineering (UA-SIE) in collaboration with Sadler Machine Co. (SMC) has proposed and designed a lunar habitat architecture that can support the establishment of a lunar outpost (Fig. 6.7).

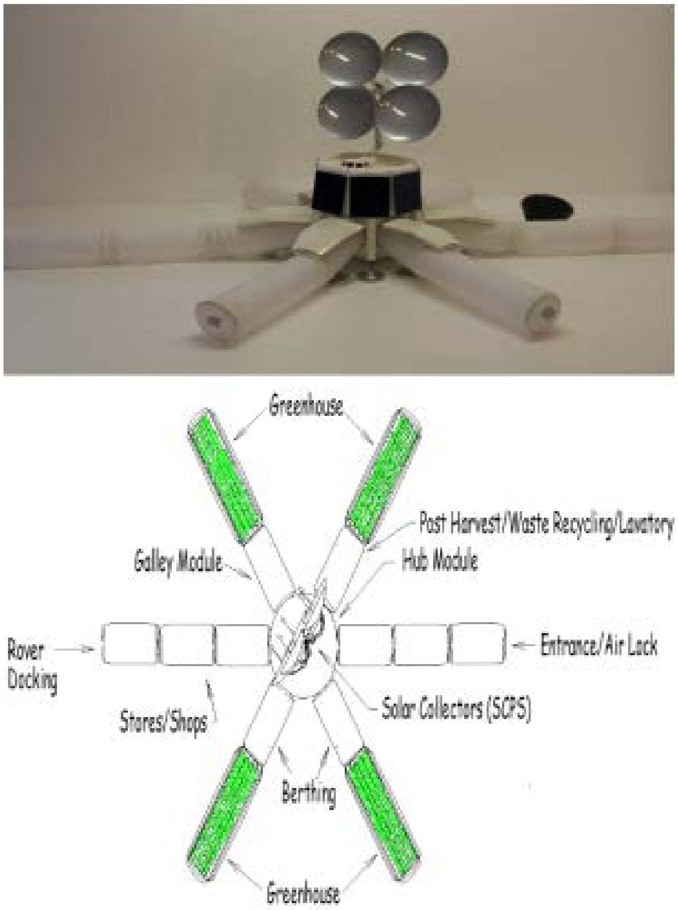

Figure 6.7. Prototype Inflatable Lunar Outpost.

The proposed lunar habitat is equipped with a BLSS capabilities which include a set of four inflatable greenhouse modules conceived to employ higher plants as a mean to produce a large portion of the daily calories necessary by four astronauts, while generating oxygen and recycling water. Based on such vision, the NASA Ralph Steckler Program funded the development of a high-fidelity testbed that can test and evaluate critical BLSS technologies for future long-duration missions.

The Mars-Lunar Greenhouse (MLGH) project consists of the development of set of lightweight inflatable membrane structures that provide a structure for a hydroponic polycultivation system for crop production and resource recycling that can be deployed on planetary surfaces (Fig. 6.8). Poly-culture or poly-cultivation is the agricultural practice of growing multiple types of plants or crops in the same area.

According to NASA estimates, 100% of air revitalization and water recycling can be achieved by means of crop production system capable of generating 50% of the crew caloric intake (based on a 2000 kcal/day assumption) on an estimated cultivated area varying between 28 and 40 m^2. Consequently, the primary purpose of the MLGH project is to achieve the NASA estimated target production goals in a semi-closed, full-scale prototype with a high-degree of mission fidelity, i.e. capable of sustaining the long-term presence of a crew comprising four astronauts on the Lunar/Mars surface. Additionally, the project aims at characterizing and evaluating the performance of the components necessary to sustain a BLSS prototype in an automatic fashion (Fig. 6.9). The latter include 1) a composting system, for crew waste and inedible biomass recycling (e.g. Composting-Wick-Evaporator, CWE), 2) a Fresnel-based Solar Concentrator Power System (SCPS) to tap into the solar energy and contribute to the outpost power balance and 3) an automatized decision support system that can support telepresence, intelligent crop system operations and monitoring as well as provide diagnostic capabilities.

The MLGH prototype consitsts of four inflatable hydroponic cylindrical units interconnected by a hallway (Fig. 6.8). Each unit exhibits a cylindrical shape of 2.06 m in diameter and 5.5 m in length. The overall canopy horizontal canopy area is 11 m^2 (measured at 1 m height) with a total internal volume of 21 m^3.

An ambitious set of goals and objectives have been established to evaluate the performance of the MLGH prototype within a BLSS framework, including: 1) evaluate food production capabilities, 2) evaluate water balance (from liquid irrigation water, biomass and water vapor), carbon balance (from gaseous carbon dioxide and biomass) and energy balance (from electrical, heat, light and food calories produced); 3) provide an analysis of the fertilizer consumption (kg per are per time) and of the required environmental control (spatial/temporal climate uniformity); 4) develop a model for crop production simulation and control; 5) develop a solar energy plant lighting-based power system; 6) develop a Remote Expert Network Decision Systems (RENDSys) and enhanced telepresence and 7) promote the STEM education access & outreach.

Figure 6.8. Unit #1 in the Martian Lunar Greenhouse Lab.

Cut off from the outside world, the DLR EDEN ISS greenhouse has been located in Antarctica, near the Neumayer III Antarctic station operated by the Alfred Wegener Institute (AWI), since 2018 (Fig. 6.10). On the seventh continent, vegetables, salads and herbs thrive during the polar night with the help of artificial light, effective nutrient solutions and completely without soil. With the EDEN ISS greenhouse in the inhospitable environment of the Antarctic, DLR wants to get as close as possible to the conditions of a long-term mission in space. The research laboratory is not only used to test vegetable cultivation for future manned space missions to the Moon and Mars. At the same time, the scientists are researching future food production in climatically unfavourable areas such as deserts and arctic regions.

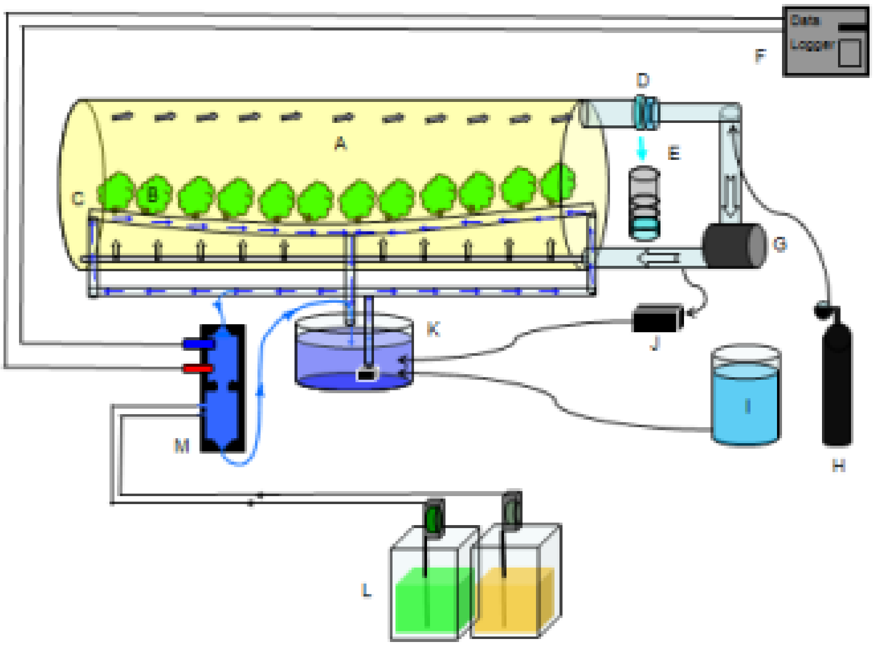

Figure 6.9. A schematic of the controlled environment for crop (B) production showing the water (C-envelopes, K-Resevouir, I-Water Supply Tank, M-Injectin Mixing Block, L-Nutrient and Acid Supply Tanks, E-Condensation Collection Tank) and air circulation (A-Chamber Air Exit, D-Condensor, G-Corculation Fan, H-CO2 Injection Tank) loops and the Data Logging and Control System (F).

Figure 6.10. DLR EDEN ISS greenhouse

For overwintering in 2021, plant scientist Jess Bunchek from NASA's Kennedy Space Center is spending a year at the Neumayer III Antarctic Station as a DLR guest researcher. During a joint research mission by DLR and NASA, she is investigating how astronauts will be able to grow large quantities of lettuce, cucumbers, tomatoes, peppers and herbs in the future, using as little time and energy as possible, and is putting greenhouse technology and robust plant varieties to the test. Bunchek is also recording how the green habitat and its produce affect the isolated overwintering crew on the eternal ice.

Figure 6.11. Inside view DLR EDEN ISS greenhouse.

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7. MOBILE TECHNOLOGICAL COMPLEXES OF 3D PRINTING FOR USE ON THE MOON

It is assumed that at the initial stage of deployment of the lunar base, all its elements will be delivered from Earth. After the creation of a lunar base of the minimum configuration, which will ensure the presence of man on the moon, the question of creating production and housing modules of the lunar base with the use of local resources will arise. This is also due to the high cost of delivery of payload to the surface of the Moon, the price of one kilogram of payload delivered to the surface of the Moon is at least 40 thousand US dollars.

As a result of scientific reconnaissance missions performed on the surface of the Moon, about three hundred kilograms of lunar soil and lunar rocks were delivered to Earth. It turned out that the surface of the Moon is covered with a layer of regolith, so its use as a structural external heat-shielding material becomes especially relevant, given the significant temperature differences on the surface of the Moon. Low thermal conductivity allows it to retain heat inside the modules [2]. By its chemical nature, regolith is an aluminosilicate, but in the marine rocks of the Moon (basalt) more iron and magnesium, and in the continental (anorthosites) - calcium and magnesium. Data on the structure of the lunar soil and comparative analysis with terrestrial counterparts are widely presented in scientific publications [3; 4]. The regolith layer can be from a few centimeters to tens of meters thick.

Given the similarity of lunar and terrestrial rocks, the development of the lunar construction industry can occur using technologies used on Earth [5]. Having analyzed the possibilities of erecting building structures on the Moon on the basis of marine regolith (analog of terrestrial basalt), we can identify the most promising:

use of a 3D printer to create blocks from lunar soil, such as surfacing lunar soil with solar energy on a growing surface;

stone casting, as a result of which we obtain high-temperature material based on regolith, which is highly resistant to cosmic radiation and micrometeorites.

3D printers are an integral part of these technologies [6; 7], which in the conditions of the Moon (Fig. 7.1) must meet a number of requirements:

- be mobile and have its own running gear, which allows the printer to move while printing structures, overcome obstacles in the terrain and place it in protective structures during storage;
- to provide printing of constructions as a whole and separate building constructions;
- be universal and adapt to changes in technological modes of printing;
- have a remote control and stand-alone power supply.

Before printing the construction site is prepared for the use of the printer: auxiliary equipment (loader, bulldozer) plan the surface (Fig. 7.1, a); install equipment for cooking and feeding regolith to the printer.

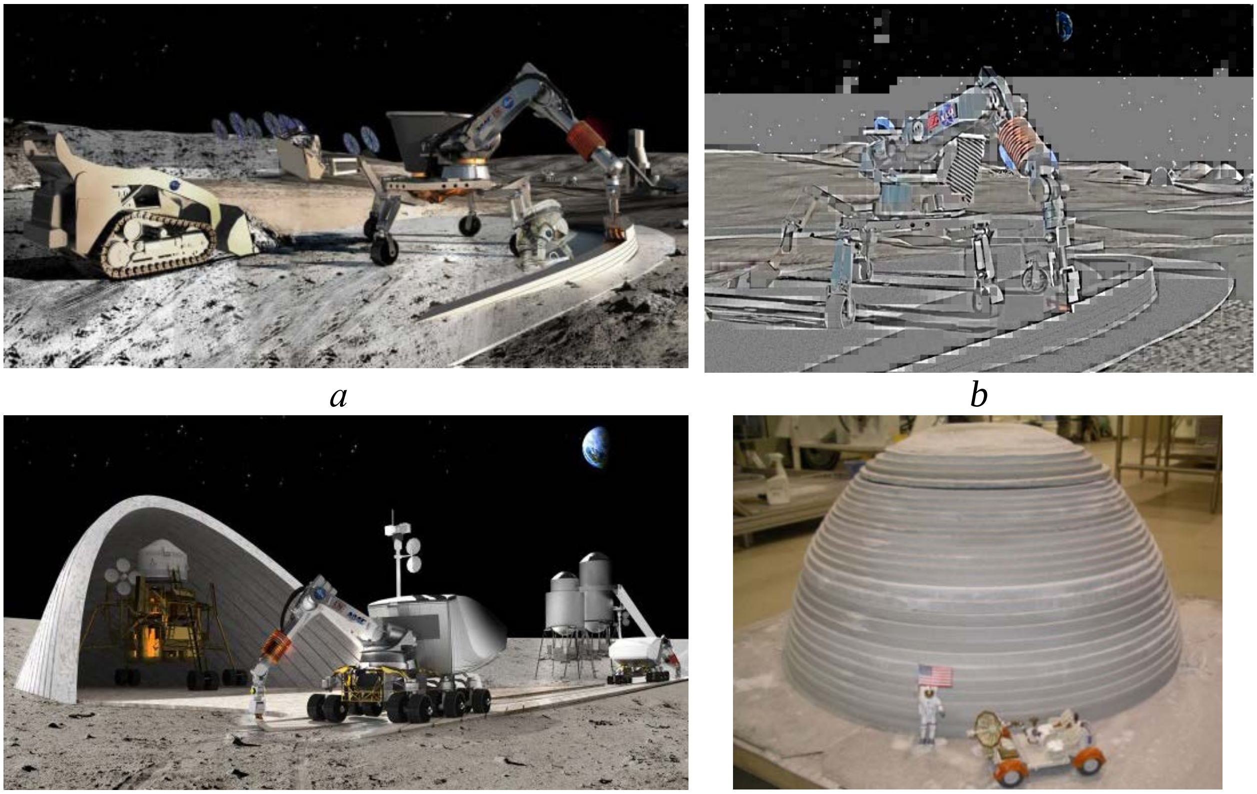
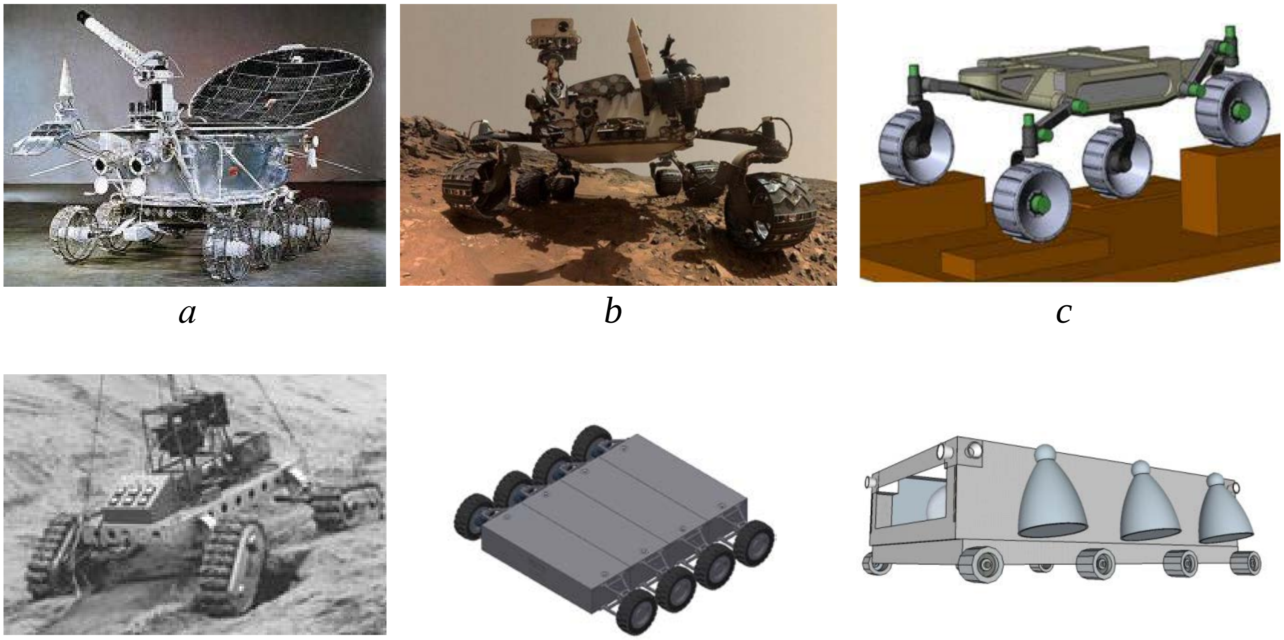

a b c d

Fig. 7.1. Use of 3D-printers for the conditions of the Moon: a - general location of the main and auxiliary equipment on the production site; b - printer on a special chassis; c - printers of various execution on a wheel course; d - layout of the printed structure

Depending on the type and volume of printing, set the required number of printers (Fig. 7.1 c) and erect objects. In the case of printing individual building structures (Fig. 7.1, b), the resulting products are used for installation. After using the printers, they are installed in protective structures to prevent external influences (meteorites).

Due to the need to move printers, in particular on the surface of the moon, their chassis must ensure the reliable operation of these systems in order to ensure the stable position of the equipment. Analysis of the proposals and use of spacecraft on the Moon and Mars showed that the most common chassis are wheeled (Fig. 7.2 a-c) and tracked propulsion (Fig. 7.2, d). The construction of spacecraft involves the implementation of the chassis in the form of wheels with their independent suspension relative to the platform (Fig. 7.2, c, d), which allows these vehicles to move over obstacles. In the construction of modular spacecraft of the State Enterprise "CB" South "(Fig. 7.2, e) provides for the installation of the required number of engines.



a *b* *c*

d *e* *f*

Fig. 7.2. Options for the implementation of spacecraft:
a, b, c, - wheel type; d - caterpillar; e - modular type;
f - wheeled type with additional rocket engines

At the suggestion of SHEE PDABA spacecraft should be equipped with combined propulsion - wheeled and rocket, to overcome obstacles and significant distances (Fig. 7.2, f). It is planned to install 3D printers on the platforms of the spacecraft.

CONCLUSIONS

1. Construction of an industrial research base on the Moon is appropriate for technology 3D printing using lunar soil - regolith.

2. As technological equipment, in particular 3D printers, rationally use mobile devices with their own chassis. The design of mobile 3D printers is offered.

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8. DEVELOPMENT OF THE TOPIC OF MOON SETTLEMENTS IN PSACEA

The Ministry of Education and Science of Ukraine provides estimates of world experts published in Forbes, BBC, Trade Schools Colleges, research group "Digitale Transformation" of the Research Institute of Future Labor Relations (Bonn) on the most popular specialties in the near future. According to these estimates, the most needed will be specialists who can design, implement new techniques and technologies of the future - "architect of territories, robotics specialist, design engineer of various profiles, 3D printing specialist, drone developer and dispatcher, cosmogeologist."

Given these trends, the State Higher Educational Institution "Prydniprovsk State Academy of Civil Engineering and Architecture" is developing fruitful scientific and technical cooperation with Ukraine's leading enterprise in the field of rocket and space technology - State Enterprise "Design Bureau" Southern"named after M.K. Yangel.

One of the promising areas of such cooperation may be a project to explore the moon. Scientists of the academy conduct research on materials and technologies that can be the basis for the construction of buildings and structures from lunar soil, including soil concrete. The specialists of the academy are pioneers in Ukraine in the development and implementation of 3D technology - printing of real construction projects.

At the Department of Architectural Design SHEE PSACEA prepared unique architectural diploma projects of settlements on other planets. In 2014 - on the Moon, in the Cassini Crater, on the edge of the Sea of Rains, on the visible side of our space neighbor (Fig. 8.1 - Fig. 8.2).

On September 10, 2020, a meeting of the management and leading scientists of the academy with the management and leading specialists of the enterprise took place in “Pivdenne”. Specialists of the academy were given the opportunity to get acquainted with the latest developments of the State Enterprise "Southern", research and production base, world-famous achievements in the development of outer space (Fig. 8.3 - Fig. 8.5).

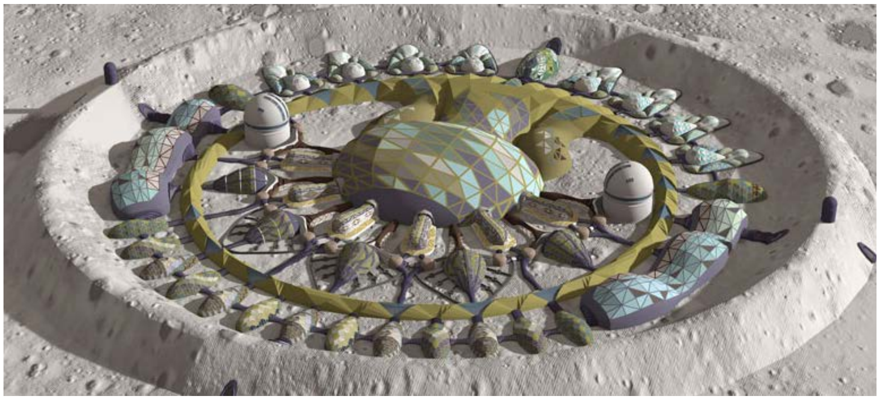


Fig. 8.1. A variant of the PSACEA Moon Base

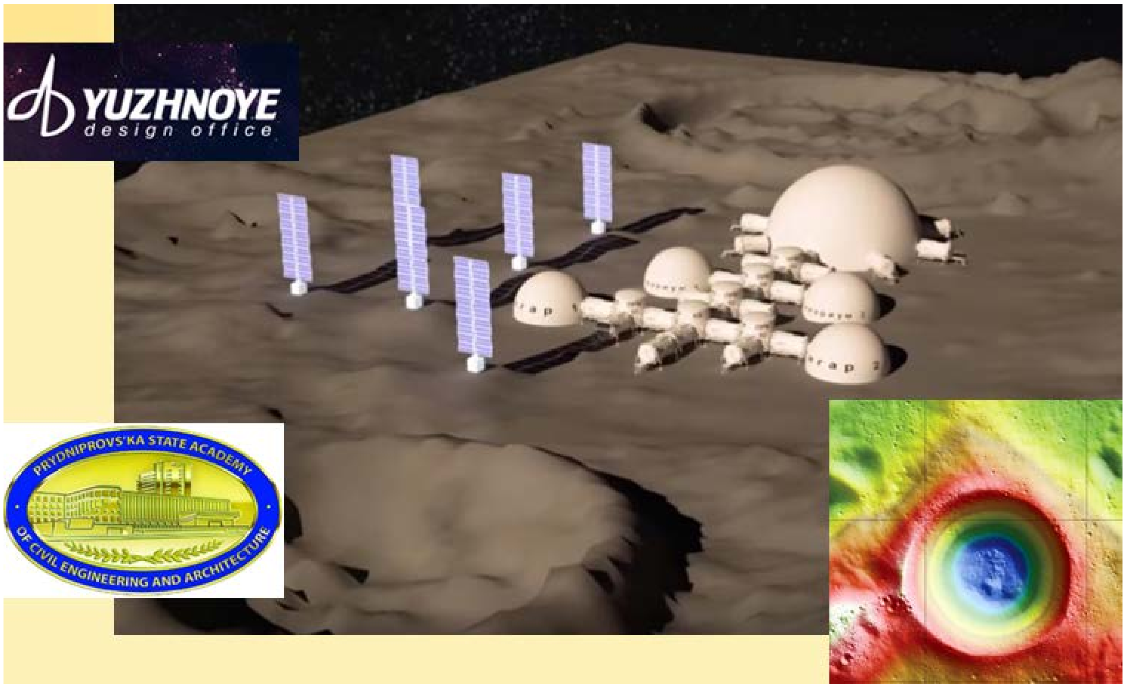


Fig. 8.2. Option of the Lunar Base of “Pivdenne” Design Bureau.

The program of the visit included awarding the diploma of Honorary Professor of PDABA to the Director General - General Designer of “Pivdenne” Alexander Degtyarev, discussion of the results of previous joint work, including the development of the Vertical Tower installation and operation of space rockets, scientific - educational cooperation, prospects for further cooperation.

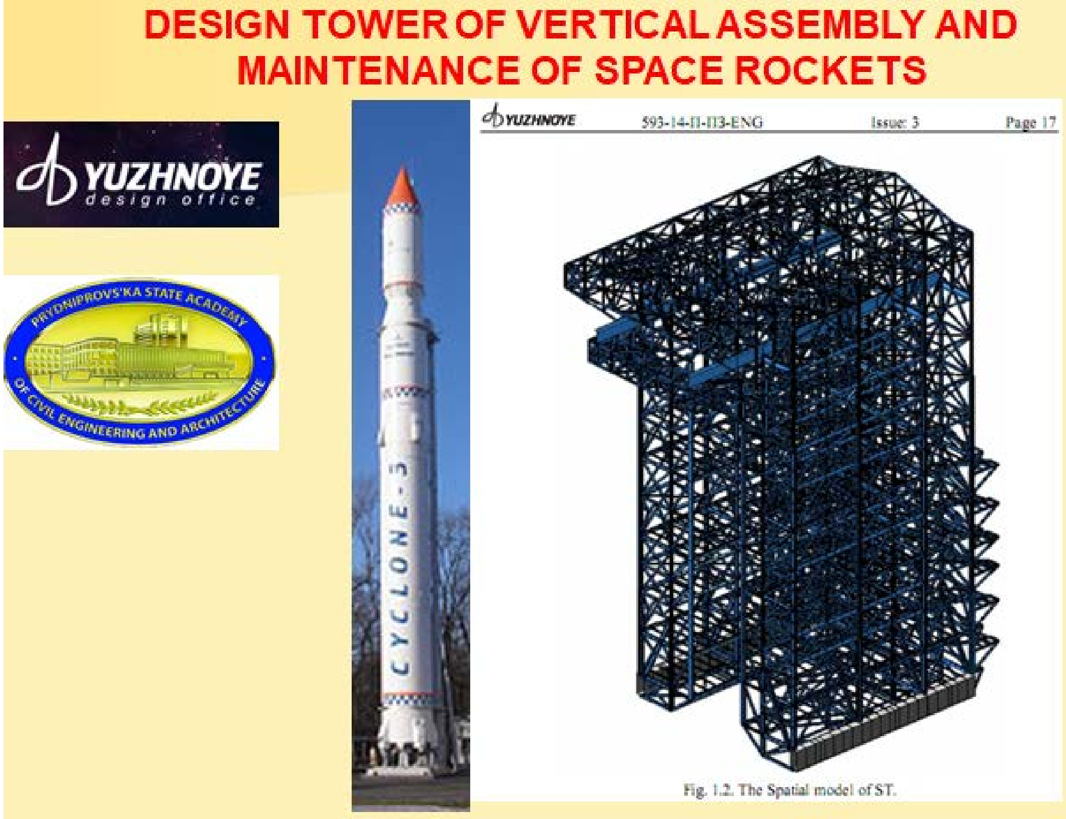
At the end of September 2020, a working meeting of specialists of the "Pivdenne" Design Bureau and teachers of the Academy on the implementation of the Agreement on Cooperation in the Development of Outer Space took place at the PSACEA. In particular, the topics of master's theses on the design of lunar settlements were discussed - spatial planning solutions, structural systems, materials and technologies for the construction of buildings and structures in the conditions of the Moon. In accordance with the agreement on cooperation between "Pivdenne" and the Academy, a model of one of the variants of the production and research base on the Moon was developed and made.

Fig. 8.3. Delegation of PSABA in Pivdenne CB and at Pivdenmash plant with main specialists.

Fig. 8.4. Degtyarev O. and Savytskiy M. after signing the commonwealth agreement.

Fig. 8.5. Degtyarev Oleksandr Viktorovych - General Director of the State Enterprise "Design Bureau" South " named M.K. Yangel”, Academician of the National Academy of Sciences of Ukraine, Honorary Professor of PSACEA.

The Academy already has a positive experience of cooperation with DB “Pivdenne”. PSACEA participated in the development of a project for the United Arab Emirates tower vertical installation and operation of space rockets commissioned by DB “Pivdenne” (Fig. 8.6).



DESIGN TOWER OF VERTICAL ASSEMBLY AND MAINTENANCE OF SPACE ROCKETS

Fig. 8.6. Tower of vertical installation and maintenance of space rockets according to the PDABA project commissioned by “Pivdenne” Design Bureau.

On September 29, 2020, in the framework of scientific, scientific-technical and scientific-educational cooperation between DB “Pivdenne” and SHEE PSACEA, scientists and employees of the Academy took part in the international online webinar "NON-SPACE BUSINESS GOES TO THE MOON". The webinar was organized by the European Space Agency Downstream Gateway and the Moon Village Association (MVA) to review the opportunities of non-space companies and organizations to contribute to the creation and development of the Moon Village project (Figure 8.7 - Figure 8.8).

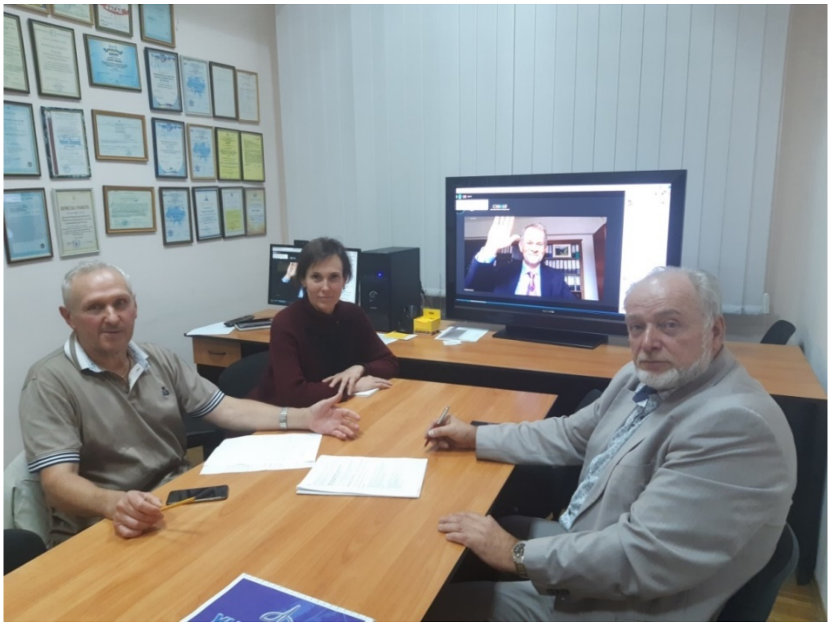


Fig. 8.7. Participants of the international online webinar "NON-SPACE BUSINESS GOES TO THE MOON" from PSACEA Konoplyanyk O., Degtyareva Yu., Shatov S.

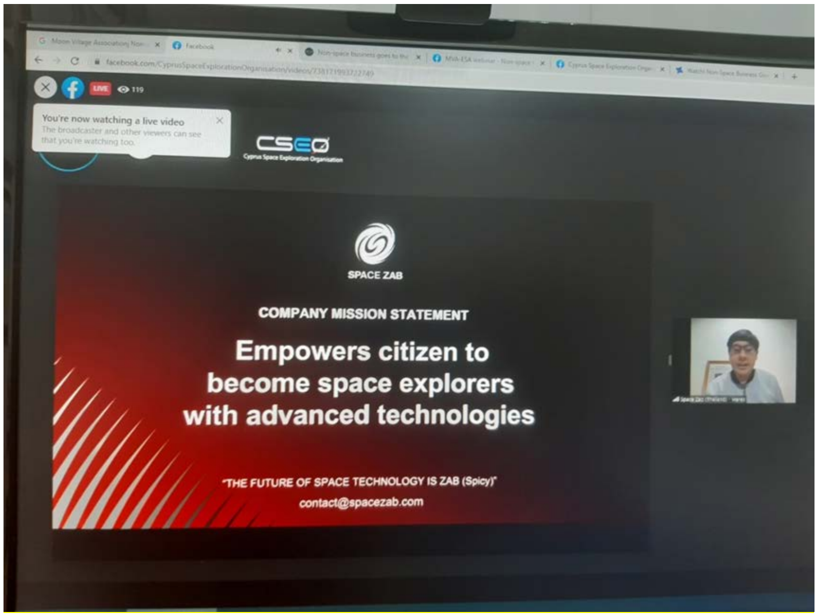


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Fig. 8.8. Participants of the international online webinar "NON-SPACE BUSINESS GOES TO THE MOON".

On October 2, 2020, the 12th successful launch of the Antares medium-range launch vehicle, created with the participation of Ukrainian space companies, was launched from the Space Flight Center in Wallops Island, Virginia, USA. The launch vehicle launched into orbit the automatic cargo transport ship Signus, which is to deliver to the International Space Station payload commissioned by NASA - National Aeronautics and Space Administration. Antares consists of two stages and the Signes spacecraft (third stage). The main design of the first stage was developed by DB “Pivdenne” and manufactured by VO PMZ in cooperation with Ukrainian enterprises Hartron-ARKOS, Kyivprilad, Hartron-YUKOM, CHEZARA, RAPID and others. The main developer of the launch vehicle is the American company Northrop Grumman Corporation. Preparation of "Antares", its testing and start-up took place with the participation of specialists from DB “Pivdenne”, "VO PMZ" and NGO "Hartron-ARKOS". Technical support of start-up, reception and processing of telemetry information was provided from the territory of DB “Pivdenne”.

On September 3, 2020, the European Vega RN was launched for the fifteenth time from the Kuro cosmodrome, the 4th stage propulsion engine unit of which was developed by the “Pivdenne” Design Bureau (Fig. 8.9).

Fig. 8.9. Successful start.

Ukraine is the ninth signatory to NASA's Artemis program for peaceful exploration of the Moon, Mars, comets and asteroids. This was reported by the press service of the State Space Agency of Ukraine on November 13, 2020.

"This is important for Ukraine, because we will be able to implement our own projects in partnership with the world's leading space agencies. This is a logical step to continue the fact that we have already joined the Moon Village Association. For the first time, Ukrainian projects have become part of the global scenario of the Moon's exploration from ISECG, and it is logical that we want to continue to realize our potential under the Artemis program”, the agency is convinced.

The State Agency added that Ukraine has all the scientific and technical capabilities and experience that allow it to be a partner of NASA. Earlier, Australia, Canada, Italy, Japan, Luxembourg, the United Arab Emirates and the United Kingdom joined the agreement.

The goal of the Artemis program is to land two astronauts at the moon's south pole in 2024 and ensure a permanent human presence on the satellite by the end of the decade. NASA expects to achieve this with the help of international partners, as well as with the assistance of private companies.

On November 13-14, 2020, the NOOSPHER Association held a competition of startups dedicated to the development of the Moon. Our project "Warm wall-energy-active module of the Lunar settlement with helioprofile" won the national competition (Fig. 8.10 - Fig. 8.11). Helioprofile is the best invention of Ukraine in 2005 in the field of energy.

These preconditions allow us to optimistically assess the prospects of scientific, scientific-technical and scientific-educational cooperation of the PSACEA with the leading enterprise of Ukraine in the field of rocket and space technology - State Enterprise Design Bureau "South" named after M.K. Yangel ».

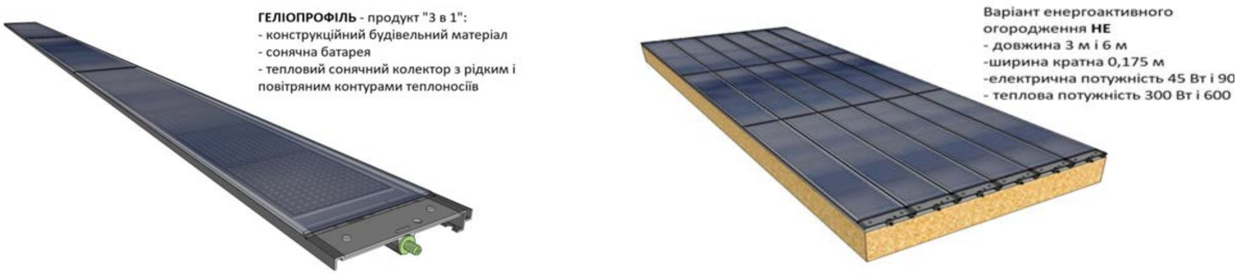

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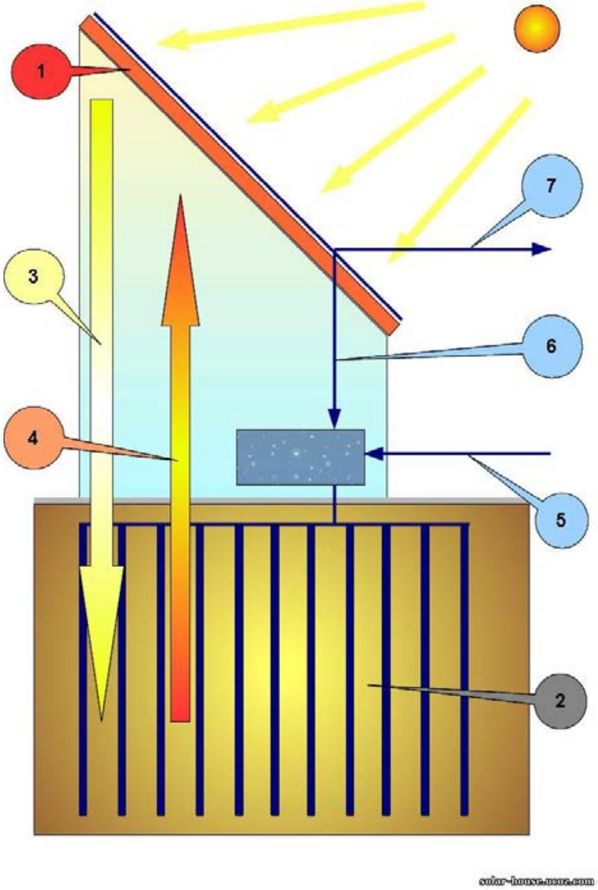
Fig. 8.10. Helioprofile and energy-efficient fencing.



Solar energy coming to the surface of buildings from helioprofile is transferred to the soil and is used in doses for heat supply.

1. Energy-active roof made of electric helioprofile
2. Seasonal ground heat accumulator
3. Accumulation of solar heat
4. Heating of the building
5. Consumption of external electricity
6. Supply of electricity for the needs of the building
7. Supply of electricity to the external network

Fig. 8.11. Scheme of an energy-efficient building with solar heating and solar power generation.

On November 28, 2021, a meeting of specialists of DB "Pivdenne," PSACEA, National Aerospace Education Center of Youth named after O.M. Makarov was held to discuss areas of cooperation (Fig. 8.12).

Fig. 8.12. A meeting of specialists of DB "Pivdenne," PSACEA, National Aerospace Education Center of Youth named after O.M. Makarov

Scientific publication

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