https://doi.org/10.15407/knit2024.02.028
UDC 523.3

I. O. HUSAROVA[1]**,** Leading Researcher, Doctor of Engineering Sciences, Senior Researcher
G. G. OSINOVYY[2]**,** Head of Project Department, Doctor of Philosophy
L. P. POTAPOVYCH[3]**,** Scientific Secretary — Head of the Scientific and Educational Center, Candidate of Engineering Sciences

Yuzhnoye State Design Office named after M. K. Yangel
3, Kryvoriz'ka Str., Dnipro, 49008 Ukraine
E-mail: info@yuzhnoye.com

TECHNOLOGY FOR WATER MINING ON THE MOON WITHOUT ICE PHASE CHANGE

An analytical study into technologies developed for mining water on the Moon has been carried out, and its results demonstrate that methods without the ice phase change are energy efficient. Based on an analysis of temperature distribution over the regolith depth at the lunar poles, it was found that water in the form of ice can be present at depths less than 11 cm. According to their properties, ice regoliths are not loose rocks like dry regoliths but rather hard. With this in mind, a two-phase technology has been proposed to extract water from ice regolith without the ice phase change: the extracted raw material is first crushed and then separated by screening. The regolith hardness rapidly increases as water content increases. Since the equipment mass and power increase as the material hardness increases, in the first phase of the Moon exploration, it is advisable to mine and process ice regoliths with an ice content of ~1.6 %, which are relatively soft rocks with a hardness of 2. Small mobile excavators, already developed and tested, can be used for digging such materials, and impact crushers with low weight and power can be used for processing the raw materials.

The concept of an integrated system for separating ice from regolith without the ice phase change has been developed based on a selective impact crusher, which combines the operations of crushing the extracted raw materials and separating individual components in one device. Selective impact crushers are the most energy-efficient pieces of equipment for crushing and separating raw materials. The power consumption of the proposed integrated selective crushing system to separate ice from regolith for mining 100 kg of ice per hour is 118 W, which is comparable with the Aqua Factorem system (100 W) and significantly less than the power consumption required for the thermal method, i.e., 800 kW.

Keywords: *water mining, Moon, ice regoliths, without ice phase change.*

INTRODUCTION

In recent years, research and exploration of the Moon have again attracted the attention of space agencies around the world. There are currently scientific and potentially commercial reasons for humanity's return to the Moon. Today, the main competitors in the Moon race are the United States, the People's Republic of China, Europe, India, Japan, and the number of these countries is increasing.

The driving force that makes the major powers to strive for the Moon exploration is lunar resources, which can solve the approaching global energy crisis, as well as contribute to further technological progress and colonization of not only the Moon but also

Цитування: Husarova I. O., Osinovyy G. G., Potapovych L. P. Technology for water mining on the Moon without ice phase change. *Space Science and Technology.* 2024. **30**, № 2 (147). P. 28—37. https://doi.org/10.15407/knit2024.02.028

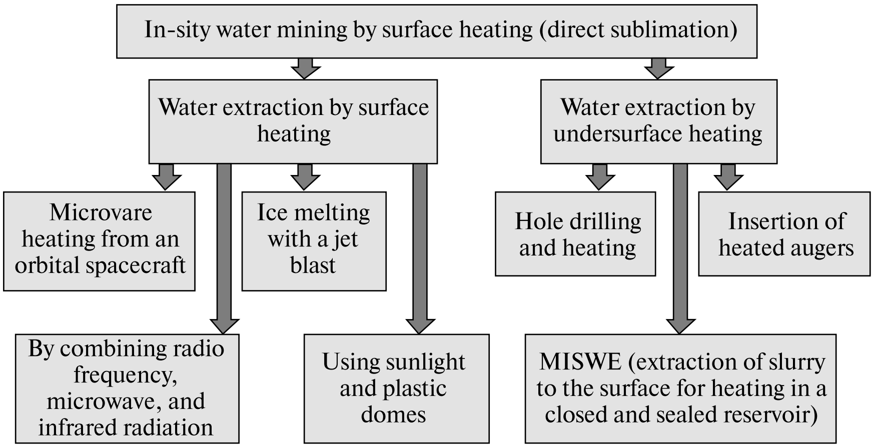

Figure 1. In-situ surface-heating thermal mining technologies

Mars. Using local natural resources will support the stable lunar base infrastructure on the lunar surface.

Potentially, the main resource of the lunar base is ice, which is necessary for life support systems (growing plants, manufacturing propellants, extracting oxygen for breathing, etc.). NASA's return to the Moon, the Artemis Program, is targeting future astronaut landings in 2024 near the lunar South Pole, where ice may be present. This ice will be a key resource for long-duration lunar missions and will also be able to support deep space exploration.

There are three methods formining water from raw materials: thermal, mechanical, and chemical, i.e., by hydrogen reduction of lunar soil oxides.

During the thermal process, the regolith, which contains free or bound water, is heated to remove vapor. In the case of regolith-ice mixtures, the addition of heat directly converts ice into a vapor phase that can be removed.

In the case of water bound within regolith particles, the addition of heat will first break any bonds between the water molecules and other compounds (e.g., hydrated water attached to another molecule), i.e.:

$$M(xH_2O) \rightarrow M + xH_2O.$$

The evaporation process in ice regolith occurs at a lower temperature than in the extraction of bound water, which usually requires a higher temperature to break the hydration bonds [4].

The technologies of thermal extraction of water from the original lunar raw material (regolith or ice) can be grouped into two classes:

• Extraction based on the removal of icy regolith from the subsoil with subsequent transportation to the processing site. Excavation of the surface using rovers equipped with shovels, bucket ladders, or bucket wheels is typical. Excavation methods require excavating, transporting, and processing large volumes of regolith.

• Thermal extraction based on the sublimation of ice directly from the surface using directed energy, such as sunlight, microwave, or radiant heaters (Figure 1). It is an effective method of ice mining, requiring equipment with less weight and fewer moving parts compared to the excavation methods, and it is a real alternative to excavation [2, 5].

Today, under NASA programs, a significant number of technologies and equipment are developed for extracting water from regolith by various phase-change-based thermal methods: injecting energy into the regolith to sublimate ice into vapor, then capture the vapor, refreeze it and transport the solid ice for storage or further processing. A system for thermal water production, which will be launched to the Moon on board the RESOLVE module, has been manufactured and tested. The equipment package includes an RVC regolith volatile chamber oven that uses a unique fluidization technique and microwaves to penetrate the regolith, which provides more uniform heating (Figure 2) [12].

Thermal water extraction technologies require a lot of power during the heating of the entire mass of the regolith for further ice sublimation. The methods

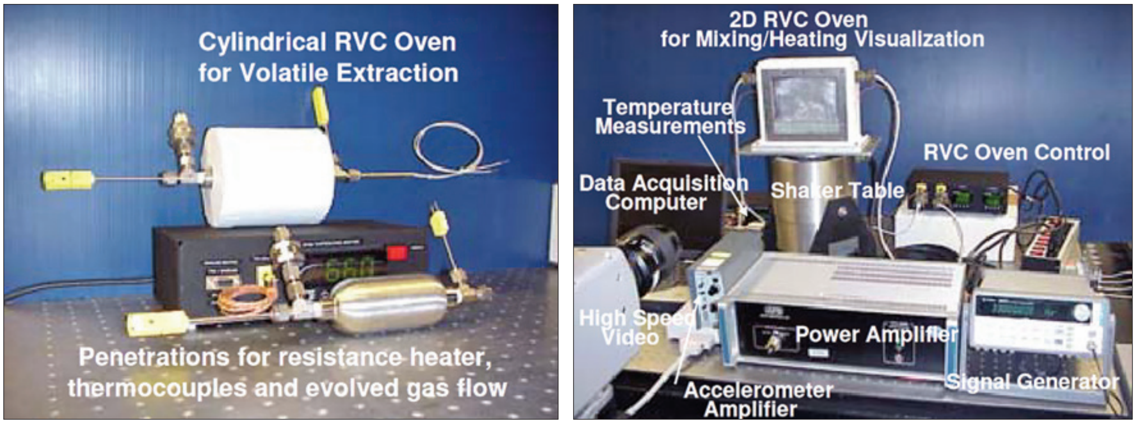

Figure 2. RVC oven layout [1]

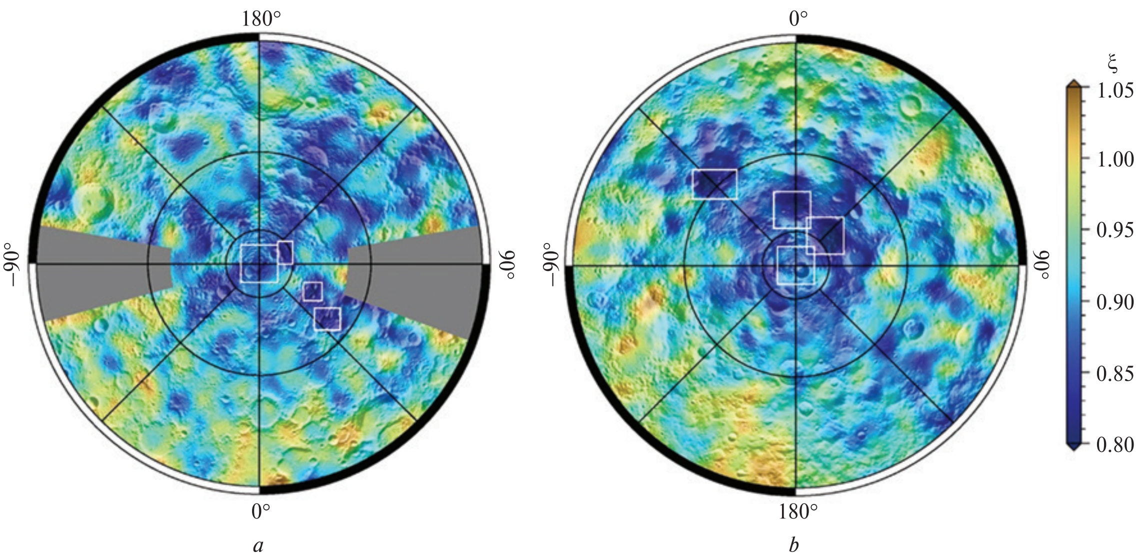

Figure 3. Map of hydrogen distribution at the North (*a*) and South (*b*) lunar poles [6]

Table 1. **The minimum, average, and maximum temperature as a function of depth for the eight polar regions [6]**

RoI	T, K (Min/Avg/Max)			
	Surface	2.25 cm	11 cm	185 cm
SP — central	23.35/184.18/339.07	23.59/187.39/261.20	23.91/187.82/203.66	27.91/191.66/191.77
SP — Haworth	23.35/182.85/320.82	23.59/193.80/253.88	23.91/194.81/206.88	27.91/198.62/198.65
SP — Cabeus	23.35/188.70/330.89	23.59/200.97/262.02	23.91/202.10/212.77	27.91/205.89/205.92
SP — Shoemaker	23.35/184.10/338.26	23.59/188.02/260.89	23.91/189.06/203.24	27.91/192.89/192.93
NP — central	23.35/189.35/330.46	23.59/192.38/255.71	23.91/192.86/204.20	27.91/196.70/196.88
NP — Peary	23.35/180.48/327.22	23.59/192.38/256.75	23.91/193.44/204.43	27.91/197.25/197.32
NP — Fibiger	23.35/183.54/333.72	23.59/195.18/260.61	23.91/196.30/206.47	27.91/200.08/200.13
NP — Whipple	23.35/189.34/330.94	23.59/192.38/256.63	23.91/192.86/204.20	27.91/196.69/196.88

of separating water ice from regolith without changing the water ice phase, i.e., mechanical separation of the mixture, are considered more energy efficient. Let's discuss them.

STATEMENT OF RESEARCH PROBLEM

The purpose of the research is to develop a technology and equipment concept for water extraction by mechanical method to meet NASA requirements regarding the water ice separation from regolith without the phase change [13].

Today, we know about the only concept of water mining by mechanical method, which was proposed by the scientists of the University of Central Florida: *Aqua Factorem*, ultra-low-energy lunar water mining [9]. This technology will use the effects of meteoroid bombardment of the lunar surface, which has broken up most of the solid material, including ice, into fine grains in the upper churn zone of the lunar regolith. Ice will be separated from a mixture of minerals without the phase change by a size sorting process with ultra-low power consumption. According to experts, using the new method can reduce the power of 800 kW to less than 100 W.

The *Aqua Factorem* technology can be used to extract ice from the surface layer of regolith, crushed naturally. Let's estimate the amount of ice that can be mined using this method.

The exploration of the Moon will start from the South Pole region, so it is at the poles where the presence of water has been investigated. The Lunar Exploration Neutron Detector (LEND) on board the Lunar Reconnaissance Orbiter (LRO) has mapped the lunar polar regions for their abundance of hydrogen, which possibly exists there in the form of water ice (Figure 3). The LEND has detected the presence of hydrogen in the upper ~1 meter of the regolith, which allowed identifying several areas at the North and South Poles where there is much more water ice than elsewhere (marked by squares on the map).

The extremes of the minimum, average, and maximum surface and subsurface temperatures were calculated for these locations (Table 1) [6].

As seen in Table 1, the distribution of the maximum temperatures as a function of depth was analyzed in eight Polar Regions (Figure 4), and it was established that the temperatures are very close in all the sites. The

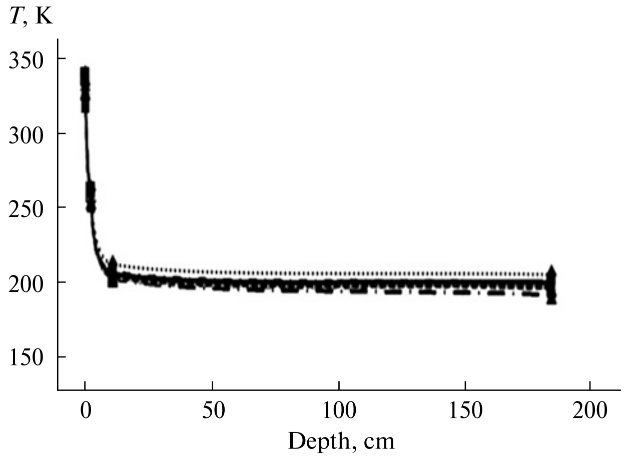

Figure 4. Maximal temperature vs. depth in eight lunar regions (see Table 3)

maximum temperatures reach 320—340 K on the surface and 253—262 K at 2.25 cm depth. According to the water pressure vs. temperature profile, sublimation of ice happens at these temperatures in the extremely rarefied lunar atmosphere (Figure 5). There is probably no ice in the regolith top layers. At 11 cm depth, the temperature is 203—207 K, so these top layers and soft soil layers can contain ice that can be mined.

Ice exists in many modifications (I...XVIII), which differ in their physical characteristics, namely, in terms of strength, density, etc. (Figure 5). The pressure on the Moon is approximately 10 nPa. In these conditions, at above 170 K, the ice is in the Ih modification. The Ih Ice is a regular hexagonal crystalline ice. Almost all the ice on Earth belongs to this modification, and its properties have been carefully studied.

The regolith density in the top layer is 800—1000 kg/m^3, but it increases rapidly with depth, and its greatest changes occur at 10—30 cm depth, where it reaches 1500—1700 kg/m^3 (Figure 6). The data refer to the density of dry regolith. Tests into the effect of water ice concentration in the 0—11 % mass range showed that the compacted and frozen simulant behaves more like a rock than a granular soil [1].

PROBLEM SOLUTION

Excavation of ice regolith deposits from a depth of more than 15—30 cm will be technologically more difficult than from the top layers, the raw material may be in the form of frozen lumps of regolith with

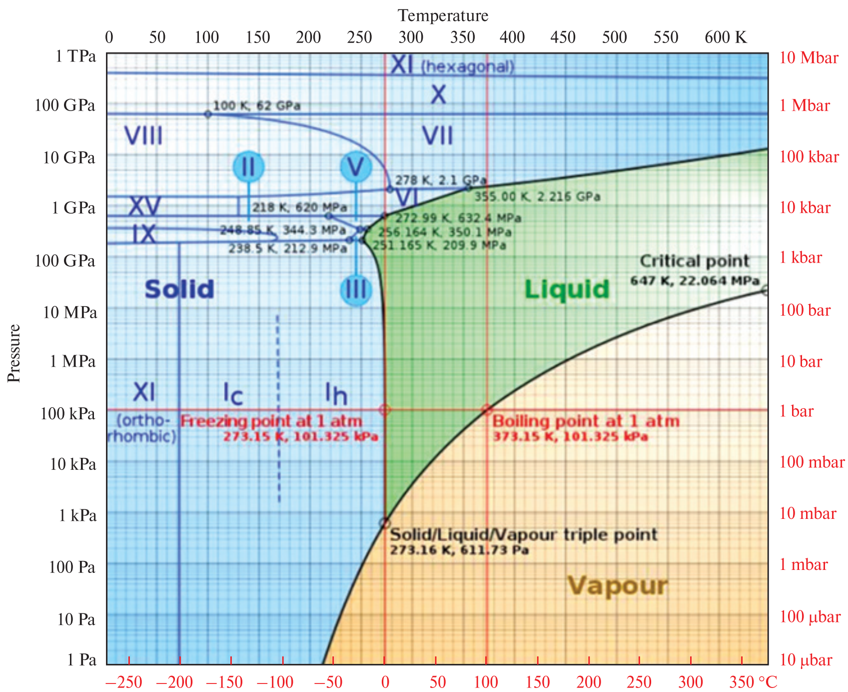

Figure 5. Phase diagram of water

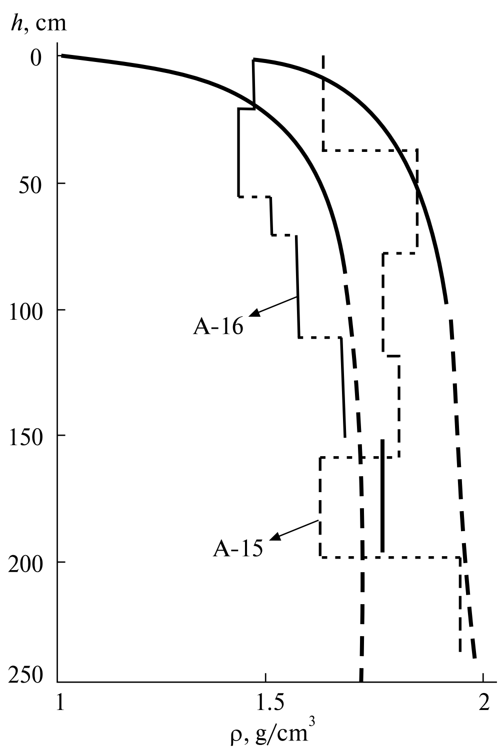

Figure 6. Regolith density ρ vs. depth *h* (according to A-15, 16 deep drilling data) [10]

ice. To solve the problem of effective water extraction by mechanical method, it is proposed to extract ice from a depth of more than 11 cm in two phases: first, the frozen lumps of ice regolith need to be crushed, and then the ice needs to be mechanically separated from the regolith.

The method of raw material crushing is selected depending on the physical and mechanical properties and the particle size of the initial material and the final product. The parameter used when selecting the crushing method is the rock hardness: a general conventional concept that characterizes a set of mechanical properties of rocks, which is manifested in various processes during mineral extraction and processing. The rock hardness ranges from 20 for the strongest rocks (quartzites, basalts) to 0.3 for floating rocks (swamps, marshy soil). Dry regolith is a loose rock with a hardness of 0.5. Frozen soils have a hardness of 2.0 and belong to fairly soft rocks [14].

Experimental studies with the simulant found that ice regolith behaves as follows with the indicated ice content:

— 0.6 to 1.5 %, like weak shale or mudstone (hardness of 2.0, fairly soft rocks)

— ~8.4 %, like moderate-strength lime stones, sandstones, and shales (hardness of 4.0, medium-strength rocks)

— ~10.6 %, strong limestone or sandstone (hardness of 8—10, hard rocks) [8].

Jaw crushers and cone crushers, designed for crushing high- and medium-strength abrasive materials, can be used for crushing regolith with ~10.6 % ice content; roll crushers can be used for ~8.4 % ice content, which corresponds to medium-strength materials, and impact crushers, used for low- and medium-strength materials with low abrasiveness, can be used for the ice content of 0.6—1.5 %. The advantages and disadvantages of each crusher type are shown in Table. 2.

The analysis established that impact crushers have a simple, compact, and reliable design and low power consumption. Their disadvantage is the rapid wear of the hammers, which can be solved by choosing modern materials.

Since the requirements for the Moon exploration equipment are very rigorous: low weight, low power consumption, resistance to the abrasive lunar dust, vacuum, low temperatures, and radiation, in the initial phase of the Moon exploration, it is advisable to use integrated selective-crushing systems based on an impact crusher for regolith with a small amount of ice. Small mobile excavators, which have already been developed and tested, can be used to excavate such regolith.

The technology of separating ice from a mixture of minerals without phase change by sorting with a combination of pneumatic, magnetic, and electrostatic separation was developed by scientists of the University of Central Florida: Ultra-Low-Energy Lunar Ice Mining "Aqua Factorem" [9].

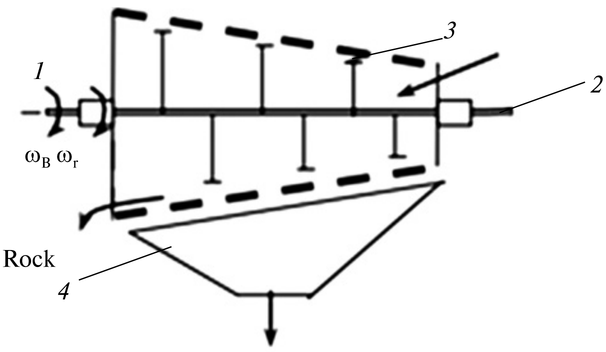

Figure 7. Integrated selective crushing system for separating ice from regolith (*1* — conical screen, *2* — shaft, *3* — hammers, *4* — concentrate collector)

The disadvantage of this technology is its complexity and the need to use a significant amount of equipment. An alternative can be sieving the product of selective crushing of the ice regolith through a sieve.

The advantage of impact crushers is the combination of crushing and screening (sorting) in one device, which is implemented in the terrestrial technology of selective crushing and selective grinding for crushing and separation of the components with different strengths.

The integrated selective crushing system based on an impact crusher for separating ice from regolith on the Moon is a conical sizing screen with a shaft with hammers installed in the center (Figure 7). The regolith, which is not crushed, goes into the over-screen

Table 2. **Crusher design and performance**

Crusher	Advantages	Disadvantages
Jaw crushers with a simple jaw movement	Simple design, low height	Hard rocks crushing into large and medium lumps
Jaw crushers with a complex jaw movement	Simple design	Material heating with friction during abrasion; water loss
Cone crushers	Designed for coarse, medium, and fine crushing	Heavy weight (heavier than jaw crushers), complex
Roll crushers	Simple compact design, reliability	Low output, high specific power consumption
Impact crushers (hammer and rotary)	Simple compact design, reliability. High output, low specific power consumption	Crusher hammers wear out quickly

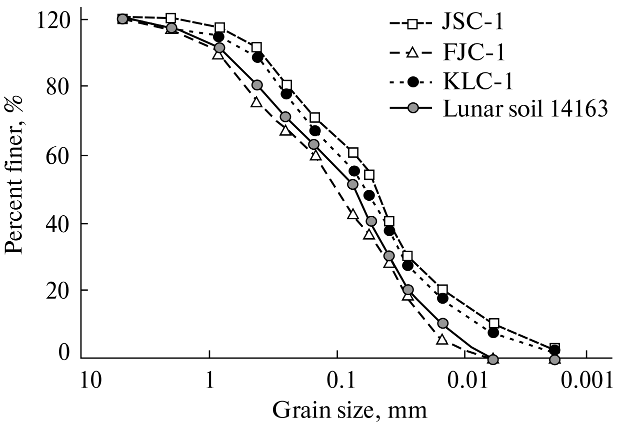

Figure 8. Particle size distribution of real lunar regolith and lunar simulants JSC 1, FJS-1

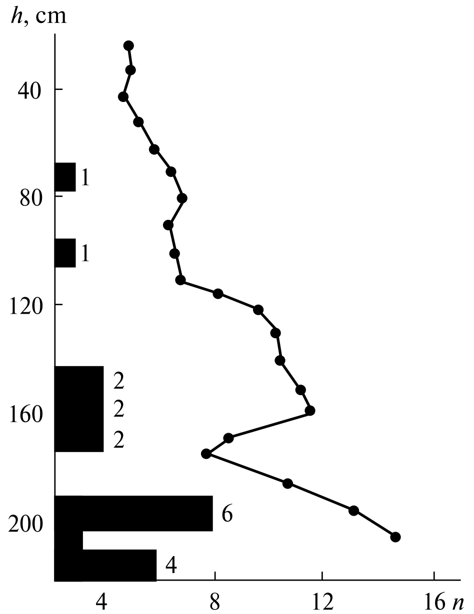

Figure 9. Average amount *n* of regolith particles with a diameter of more than 5 mm (dotted line) and more than 1 cm (black strips) along the vertical column *h* of soil of the A-15, drilling diameter 20 mm

Table 3. **Ice and regolith characteristics**

Parameter	Ice	Regolith
Density, kg/m³	760—950	1150—1800
Breaking strength, MPa	0.92—0.36	
Compressive strength, MPa	1.11	75—100
Shear strength, MPa	0.58	

product, and the crushed ice into the under-screen product.

The crusher is installed horizontally, and ice regolith moves because of the inclination of the conical surface of the sizing screen.

For sieving the product of selective crushing of the ice regolith through a sieve, preliminary estimates have been given using the properties of frozen soils on Earth because it is quite uncertain if there is water ice on the Moon and in which form water on the Moon exists.

Ice in frozen soils on Earth can be in the form of ice cement, ice inclusions, and massive deposits of ground ice. Ice cement is small crystals of various sizes embedded in the soil skeleton and cementing the minerals. The ice inclusions are various lenses, veins, and layers with a thickness from fractions of a millimeter to tens of centimeters [7]. After the ice is separated by crushing the ice regolith, its particles will have dimensions of the order of 0.25—0.2 mm.

Cone crushers for fine crushing have a degree of crushing of 10—15, so the size of raw material lumps must be of the order of 2—2.5 cm. Extraction of raw materials will be carried out by compact excavators with little effort, so probably the size of lumps of frozen regolith will be exactly this.

The structure of ice regolith can be considered as a composite material with chaotic reinforcement, where the soil is the reinforcing phase and the ice is the binder. The destruction occurs in the less strong phase, that is, in the layers of ice, which has a strength almost an order of magnitude less (see Table 3). Regolith is an unsorted sandy siltstone soil that varies in the upper soil layer from medium sand to fine silt: on average, 95 % of the soil is smaller than 1.37 mm by mass; and 5 % is smaller than 0.01 mm (Figure 8) [11].

The change in the granulometric composition of the regolith with depth has not been sufficiently studied. There are reasons to believe that the degree of shock-explosive processing of the regolith material decreases with depth. The results of drilling in the area of the A-15 landing (Figure 9) and geological and morphological observations on Luna-2 confirm this assumption [15].

In the regolith surface layer, the content of particles with $D \geq 1$ mm is about 10 %, $D \geq 5$ mm, 20 %, and at a depth of 1.5 m, their number increases approximately three times, and they account for the bulk of the regolith. Therefore, it is likely that when using a working sieving surface with a hole diameter of 0.2—0.25 mm, the ice crushed to the size of the smaller size of the holes of the sieving surface of the screen is released into the under-sieve product.

Since the ice particles are very small (0.2 mm), and the gravitational force on the Moon is six times lower than on Earth, it is necessary to impart the particles with a velocity sufficient for them to pass through the holes in the sieve. For this, the centrifugal force created by the rotation of the crusher body can be used. In the field of centrifugal forces, the ice particles will be thrown out through the sieve holes, and the regolith particles will settle on the drum walls, cut with a knife on the way and discharged from the installation.

The speed of particle deposition, at which the ice will pass through the sieve and the regolith will settle on its surface without disturbing the process of sieving the target product, is regulated by the rotation speed of the case.

To develop a perfect technology for sieving the product of selective crushing of the ice regolith, development testing is required using lunar regolith or its simulants. Such testing will be planned subject to the involvement of foreign partners.

The over-sieve product is unloaded at the exit from the conical screen.

The efficiency of existing single-rotor hammer crushers was analyzed to estimate the power consumption of separating 100 kg/h of ice from regolith (see Table 4) [15].

The crusher efficiency (E) is estimated by the amount of crushed (ground) product per 1 kWh of consumed power. The inverse of the efficiency is called the specific power consumption. It is very close to the analyzed systems and ranges from 1.14 to 1.21 W h/kg. The estimated specific power consumption of the selective crushing system for separating ice from regolith with an output of 100 kg/h, calculated from the average value for existing crushers, is 1.18 W h/kg, and the power consumption for the production of 100 kg of ice per hour is 118 W. The estimate is made for Earth's conditions. On the Moon, in a vacuum with no air resistance, the power consumption will be lower and will approach the power consumption of the Aqua Factorem method, i.e., 100 kW.

SCIENTIFIC NOVELTY

For the first time, based on the analysis of existing data on the distribution of maximum temperatures by depth in the eight lunar regions at the South and North poles, it was demonstrated that the maximum temperatures throughout the polar plane are similar and reach 320—340 K on the surface and 253—262 K at 2.25 cm depth. At these temperatures, ice sublimates in the lunar environment, so there is probably no ice in the top layers.

For the first time, the concept of extracting water by the mechanical method has been further developed in terms of the use of ice regolith from a depth of more than 11 cm, where the temperature is 203—207 K, and there is no ice sublimation. It is proposed to extract ice in two phases: crushing frozen lumps of ice regolith and then separating ice with mechanical equipment. For the first time, the dependence of the ice regolith hardness on the frozen water content was estimated, the strength increasing from 2 to 10 as water content increased from 1.5 to 10.6 %.

Table 4. **Single-rotor hammer crusher efficiency**

Parameter	Unidirectional crushers			Notes
	М6-4Б	М13-16В	М20-30Г	
1	2	3	4	5
Output, kg/h	14000	175000	1050000	Output 0.1 t/h for the Moon, according to NASA data [11]
Electric motor power, kW	17	200	1250	
Specific power consumption, W·h/kg	1.21	1.14	1.19	We take the average value of Columns 2—4, i.e. 1.18

CONCLUSIONS

Based on the analysis of lunar water extraction methods, it is shown that water vapor extraction from the lunar regolith by the thermal method requires high levels of thermal power. Therefore, methods of mechanical separation of water ice from regolith without the phase change are of interest.

Taking into account the temperature distribution by the regolith depth at the lunar poles, it was established that water in the form of ice is probably present at depths of less than 11 cm. It has been shown that the ice regoliths are quite hard, so it is necessary to first crush the extracted raw materials and then separate them by screening or other methods of beneficiation.

Since the equipment mass and power increase as the material hardness increases, in the first phase of the Moon exploration, it is advisable to use selective impact crushers, as they are the most energy-efficient pieces of equipment for crushing and separating raw materials. Such equipment can be used for icy regolith with a nice content of ~1.6 % and hardness of 2, with small mobile excavators, already developed and tested, used for regolith excavation.

The integrated selective crushing system is proposed to separate ice from regolith. The power consumption of the proposed system for mining 100 kg of ice per hour is 118 W, which is comparable with the *Aqua Factorem* system (100 W) and significantly less than the power consumption required for the thermal method, i.e., 800 kW.

REFERENCES

1. Carrier D., Olhoeft G., Mendell W. (1991). Physical properties of the lunar surface. *Lunar Sourcebook, A User's Guide to the Moon*, Cambridge: University Press, 475—594. ISBN 0521334446. URL: https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter09.pdf (Last accessed: 29.04.2023).
2. *Extracting Water from the Moon with Basic Home Appliances* (2008). URL: https://www.universetoday.com/19244/extracting-water-from-the-moon-with-basic-home-appliances (Last accessed: 29.04.2023).
3. Florenskyi K. P., Bazilevsky A. T., Nikolayeva O. V. (1975). *Lunar soil: properties and analogues. 1974 Model*. Vernadsky Institute of Geochemistry and Analytical Chemistry, 50 p.
4. Hegde U., Balasubramaniam R., Gokoglu S. (2012). Analysis of Water Extraction from Lunar Regolith. *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Nashville, Tennessee. URL: https://AIAA2012-634-2071WaterExtraction.pdf (Last accessed: 29.04.2023).
5. *How NASA Hopes to Mine Water on the Moon* (2009). URL: https://www.space.com /7350-nasa-hopes-water-moon.html (Last accessed: 29.04.2023).
6. Gläser P., Sanin A., Williams J.-P., Mitrofanov I., Oberst J. (2020). *Temperatures Near the Lunar Poles and Their Correlation With Hydrogen Predicted by LEND*. URL: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020JE006598 (Last accessed: 29.04.2023).
7. Kramarenko V. V. (2019). *Pedology. Manual*. Moscow: Yuright, 480 p.
8. Mantovani J. G., Swanger A., Townsend I. I., Sibille L., Galloway G. (2014). *Characterizing the physical and thermal properties of planetary regolith at low temperature*. URL: https://ntrs.nasa.gov/api/citations/20140017852/downloads/20140017852.pdf (Last accessed: 29.04.2023).
9. Metzger P. T., Sapkota D., Fox J., Bennett N. (2022). AQUA FACTOREM: Ultra low energy lunar water extraction. final report NASA Innovative Advanced Concepts (NIAC) Phase I Grant Number 80NSSC 20K1022. University of Central Florida, Florida Space Institute. March 15, 2021. URL: https://fsi.ucf.edu/wp-content/uploads/sites/4/2022/11/FInal-Report_Aqua-Factorem_v1.pdf (Last accessed: 29.04.2023).
10. Mitchell J. K., Carrier W. D., Houston W. N., Scott R. F., Brownwell L. G., Durgunoqlu H. T., Hovland H. J., Treadwell D. D., Costes N. C. (1972). Soil mechanics. *Apollo 16 Preliminary Science Report*. Washington, NASA.
11. *Particle size distribution of real lunar regolith and lunar simulants JSC1, FJS1*. URL: https://www. researchgate. net/figure/Particle-size-distribution-of-real-lunar-regolith-and-lunar-simulants-JSC-1-FJS-1-and_fig2_320618170/ download? (Last accessed: 29.04. 2023).
12. Sanders G. B., Moore L., McKay D. S., Simon T. M., Lueck D. E., Parrish C. F., Johnson K. R., Mungas G., Pelletier M., Sacksteder K., Duke M., Taylor J., Taylor L., Boucher D. (2005). Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) for Robotic Lunar Polar Lander Mission. Int. Lunar Conf., 1—16. URL: https://Regolith_and_Environment_Science_and_Oxy-1.pdf (Last accessed: 29.04.2023).

13. *Small Business Innovation Research (SBIR) & Small Business Technology Transfer (STTR) program. Extraction of Oxygen, metal, and water from lunar regolith*. (2022). URL: https://sbir.nasa.gov/content/extraction-oxygen-metal-and-water-lunar-regolith (Last accessed: 29.04.2023).
14. Smirnov V. O., Biletskyi V. S. (2012). *Preparatory processes for mineral enrichment. Study guide*. Donetsk: Eastern publishing house, 285 p. [In Ukrainian]
15. Sokur M. I., Biletskyi V. S., Yegurnov O. I., Vorobyov O. M., Smirnov V. O., Bozhik D. P. (2017). *Preparation of minerals for beneficiation: monograph*. Kremenchuk, 392 p. [In Ukrainian]

Стаття надійшла до редакції 26.06.2023 — *Received 26.06.2023*
Після доопрацювання 12.12.2023 — *Revised 12.12.2023*
Прийнято до друку 20.12.2023 — *Accepted 20.12.2023*

І. О. Гусарова, пров. наук. співроб., д-р техн. наук, член-кор. Академії технологічних наук України, лауреат Нац. премії України імені Бориса Патона
E-mail: info@yuzhnoye.com
Г. Г. Осіновий, нач. проєктного відділу, д-р філософії
Л. П. Потапович, учений секретар — нач. науково-освітнього центру, канд. техн. наук

Державне підприємство «Конструкторське бюро «Південне» ім. М. К. Янгеля»
вул. Криворізька 3, Дніпро, Україна, 49008

ТЕХНОЛОГІЯ ВИДОБУТКУ ВОДИ НА МІСЯЦІ БЕЗ ЗМІНИ ФАЗИ ЛЬОДУ

Проведено аналітичне дослідження відомих технологій видобутку води на Місяці та доведено, що енергоефективними є методи, що не потребують зміни фази льоду. На основі аналізу розподілу температури по глибині реголіту на місячних полюсах встановлено, що вода у формі льоду може бути наявна на глибинах менш ніж 11 см. Крижані реголіти за своїми властивостями не є сипучими породами, як сухий реголіт, а досить тривкі. Тому для видобутку води з крижаного реголіту без зміни фази льоду запропоновано двостадійну технологію: спочатку подрібнення видобутої сировини, а потім розділення її грохоченням. Ступінь тривкості реголіту стрімко зростає при збільшенні вмісту води. Оскільки маса та потужність обладнання збільшується при збільшенні ступеня тривкості матеріалу, на першому етапі освоєння Місяця доцільно видобувати та обробляти крижані реголіти з вмістом льоду 1.6 %, що належать до досить м’яких порід і мають ступінь тривкості 2. Для викопування таких матеріалів можна використовувати невеликі мобільні екскаватори, що вже розроблені і протестовані, а для обробки сировини застосовувати дробарки ударної дії, що мають малу масу та потужність.

Опрацьовано концепцію комплексної системи відокремлення льоду від реголіту без зміни фази льоду на основі дробарки ударної дії вибіркового дроблення, що поєднує операції подрібнення видобутої сировини і розділення окремих компонентів в одному пристрої. Дробарки ударної дії вибіркового дроблення є найбільш енергоефективним обладнанням для подрібнення та розділення сировини. Витрати потужності запропонованої комплексної системи вибіркового дроблення для відокремлення льоду від реголіту на видобуток 100 кг льоду на годину становлять 118 Вт, що близько до витрат системи «Aqua Factorem» (100 Вт) і значно менше від витрат термічного методу (800 кВт).

***Ключові слова*:** видобуток води, Місяць, крижані реголіти, фази льоду.