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MINING ON THE MOON

Modern research into technologies for extracting mineral resources on the Moon has revealed some harsh limitations related to dependence on Earth's resources and high technological requirements. While the chemical and carbothermal reduction of lunar regolith is theoretically possible, it requires a constant supply of reducing agents such as hydrogen or carbon from Earth. This significantly increases mission costs and complicates logistics, making such methods unsuitable for large-scale applications. Pyrolysis, which involves heating regolith to extremely high temperatures, is also not an optimal solution due to the need for complex and energy-intensive equipment that exceeds the capabilities of current space technologies.

Electrolysis using molten fluoride salts or calcium chloride ($CaCl_2$) has been proposed as an alternative, but its efficiency is limited by the need to deliver fluxes from Earth. This reduces the autonomy of the process and makes it less economically viable in the long term. In light of these limitations, the most promising technology appears to be the direct electrolysis of molten regolith, which stands out for its simplicity and independence from terrestrial materials. This method involves melting local raw materials, followed by electrolytic separation into useable components such as oxygen, metal alloys, and other materials.

However, the key challenge to implementing this technology is the development of refractory conductive materials for anodes that can withstand the extreme conditions of high temperatures and aggressive oxygen environments. Existing materials degrade rapidly under these factors, leading to reduced efficiency and increased maintenance costs. Additionally, reliable protective coatings for equipment must be developed to prevent corrosion and mechanical wear.

Overcoming these technical challenges would enable the creation of an autonomous lunar resource extraction system, which is critical for future lunar bases and further space exploration. Such a system could provide astronauts with oxygen, water, and construction materials without constant supplies from Earth, significantly reducing the cost of space missions.

Thus, despite existing technological challenges, direct electrolysis remains the most viable option for the industrial use of local lunar resources. Further research should focus on optimizing materials and application methods, as well as on developing energy-efficient solutions to ensure the stability and economic feasibility of lunar mining. This will open new possibilities for a sustained human presence on the Moon and will be a significant step in deep space exploration.

Keywords: electrochemical reduction of melts, inert anodes, electrolysis, pyrolysis.

Сучасні дослідження технологій видобутку корисних копалин на Місяці виявили ряд серйозних обмежень, пов'язаних із залежністю від земних ресурсів і високими технологічними вимогами. Хімічне та карботермічне відновлення місячного реголіту, хоча й теоретично можливе, потребує постійного постачання відновлювачів, таких як водень або вуглець, із Землі. Це істотно збільшує вартість місій та ускладнює логістику, роблячи такі методи малопридатними для масштабного застосування. Піроліз, який передбачає нагрівання реголіту до вкрай високих температур, також не є оптимальним рішенням через необхідність використання складного та енергозатратного обладнання, що перевищує можливості сучасних космічних технологій.

Електроліз з використанням розплавлених фтористих солей або хлориду кальцію ($CaCl_2$) пропонують як альтернативу, проте його ефективність обмежено необхідністю доставляння флюсів із Землі. Це знижує автономність процесу та робить його менш економічно вигідним у довгостроковій перспективі. У світлі цих обмежень найбільш перспективною технологією виявився прямий електроліз розплаву реголіту, який відрізняється простотою та незалежністю від земних матеріалів. Цей метод передбачає розплавлення місцевої сировини з подальшим електролітичним розділенням на корисні компоненти, такі як кисень, металеві сплави та інші матеріали.

Проте ключовою проблемою, яку необхідно подолати для впровадження цієї технології, є розроблення жаростійких струмопровідних матеріалів для анодів, здатних витримувати екстремальні умови високих температур й агресивного кисневого середовища. Існуючі матеріали швидко руйнуються під впливом цих факторів, що призводить до зниження ефективності та збільшення витрат на обслуговування. Крім того, необхідно створити надійні захисні покриття для обладнання, які запобігатимуть його корозії та механічному зносу.

Вирішення цих технічних завдань дасть змогу розробити автономну систему видобутку ресурсів на Місяці, що є критично важливим для майбутніх місячних баз і подальшого освоєння космосу.

Така система могла б забезпечити астронавтів киснем, водою та будівельними матеріалами без необхідності постійних поставок із Землі, що суттєво знизить вартість космічних місій.

Отже, незважаючи на існуючі технологічні виклики, прямий електроліз залишається найбільш реальним варіантом для промислового використання місцевих ресурсів Місяця. Подальші дослідження мають бути спрямовані на оптимізацію матеріалів, методів їх застосування та розроблення енергоефективних рішень, щоб забезпечити стабільність та економічну доцільність місячної гірничої промисловості. Це відкриє нові можливості для постійної присутності людини на Місяці та стане важливим кроком у дослідженні далекого космосу.

Ключові слова: електрохімічне відновлення розплавів, інертні аноди, електроліз, піроліз.

Introduction

Today, humans traveling into space rely exclusively on equipment and supplies delivered from the Earth. However, creating human settlements on the Moon and beyond the Earth requires the extraction of minerals from local resources. Oxygen, water, solar energy, and construction materials are essential for establishing permanent bases on other planets. Oxygen is the primary element of human life and a critical component of rocket fuel. Samples obtained from six Apollo missions and three Luna missions did not contain free oxygen. However, lunar rock and soil contain approximately 40–45 wt % of oxygen that produces oxides of metals or nonmetals. On the Moon, these minerals exist in several forms, including solid rocks and regolith, the Moon's soil.

Mining technologies on the Moon

Regolith is the primary raw material resource on the Moon. The hardened rock of the Moon's crust and mantle consists of silicon, magnesium, calcium, and aluminum oxides, which occur in lunar minerals in the same proportions as on the Earth, with more iron and titanium oxides (Fig. 1). In lunar sea basalts, the content of iron oxides exceeds 25 %, which is twice as high as in terrestrial basalts. The share of titanium oxides sometimes reaches 13 % (Fig. 2). On the Earth, rocks contain about 1 % titanium [1].

Two lunar materials appear promising for producing metals and oxygen, particularly ilmenite $FeTiO_3$ and silicates $CaAl{\cdot}2Si_2O_8$. Technologies for extracting metals and oxygen from these raw materials on the Moon include

– chemical reduction (using hydrogen, carbothermic reactions, and plasma);

– high-temperature pyrolysis;

– electrolysis of molten silicates.

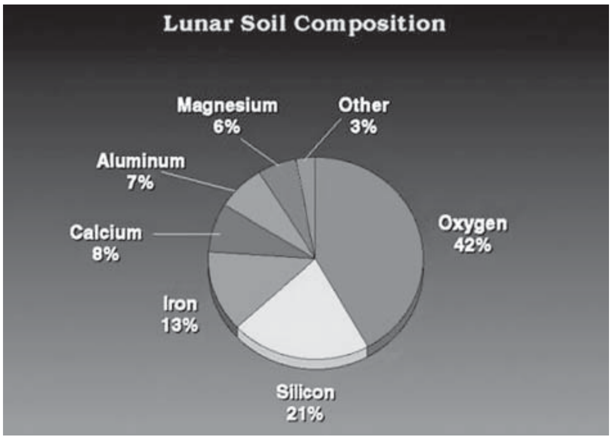

Fig. 1. Composition of regolith

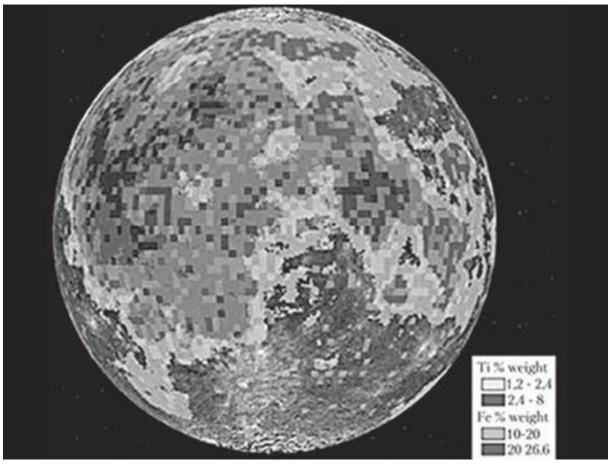

Fig. 2. Distribution of titanium and iron in the surface rocks of the Moon

Chemical reduction

Producing oxygen from lunar regolith by reduction with hydrogen, followed by water electrolysis, is the most widely studied method. The basic process involves separating ilmenite from lunar soil, grinding it to a fine powder to maximize surface area, and heating it in a closed reaction vessel with gaseous hydrogen. The vapor produced by the reaction is condensed and split to extract oxygen and recover hydrogen.

Recovery: $FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$.

Splitting of water: $2H_2O \rightarrow 2H_2 + O_2$.

Total reaction: $2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2$.

The reaction must be carried out at temperatures above ~700 °C but below 1,050 °C to avoid the sintering of ilmenite. The oxygen is removed from the system for further use, and the hydrogen returns to the process. The feasibility of reducing ilmenite with hydrogen was tested and demonstrated in a laboratory, achieving oxygen recovery of 1.5 %. The recovery process was tried on samples collected in Apollo missions using a lunar soil simulator. The iron produced in the process can be separated by carbonyl extraction or by re-grinding the reaction products and using a magnet. Titanium dioxide can also be reduced to produce titanium metal and additional oxygen.

The reduction of ilmenite is an equilibrium reaction and requires removing water from the reaction site to continue the process. One way to shift the equilibrium of the reaction in the forward direction involves reducing the partial pressure of water by removing heat and consensing water in the cold trap. Diffusion calculations show that the vapor pressure cannot be reduced sufficiently in a large-sized system [2]. This approach was implemented in a miniature analytical laboratory ProSPA with a limited weight of up to 10 kg (Fig. 3). The results show that the maximum yield that can be obtained practically at a temperature of 1,000 °C is 3.40± 0.17 wt % O_2 [3].

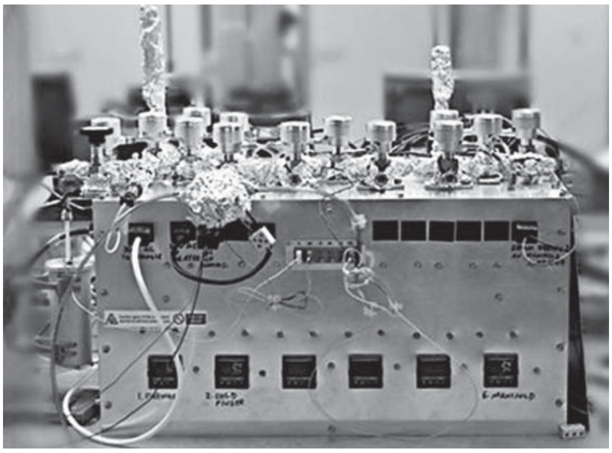

Fig. 3. ProSPA laboratory (ESA)

It is possible to increase the oxygen yield from ilmenite by reducing iron oxide with hydrogen at elevated temperatures in a fluidized bed reactor. Such a reactor was developed and tested by Carbotek (USA) at the Mauna Kea volcano in Hawaii (Fig. 4) [4].

Fig. 4. Regolith hydrogen reduction reactor (NASA)

Ilmenite reduction with hydrogen by conventional methods at temperatures of 1,200 °C and below yields only about 30 % of the available oxygen. The effectiveness of hydrogen in ilmenite reduction can be significantly enhanced by a non-equilibrium hydrogen plasma. Solid ilmenite reacts in hydrogen plasma at temperatures between 600 and 970 °C. At a sample temperature of 850 °C, the proportion of reacted hydrogen was 24 % compared to the 7 % theoretical limit calculated from thermodynamic theory for the same temperature. These experiments showed that the utilization of hydrogen could be significantly improved [5, 6].

Supplies of hydrogen from the Earth for replenishment will be necessary at the initial stage, which complicates this technology on the Moon.

Oxygen can be produced from ilmenite ($FeTiO_3$) and rutile (TiO_2) by carbothermic reduction with carbon, methane, or carbon monoxide CO.

Carbothermal methane reduction is a three-step process. It starts with heating regolith to approximately 1,625 °C. The molten regolith is exposed to methane gas, which produces carbon monoxide and hydrogen. In the second stage, the temperature is lowered, and the gases combine to form methane and water. The third stage involves the electrolysis of water to produce oxygen. The process requires the next stage of methane conversion.

In the carbothermal reduction process, coal and ilmenite or rutile powders are mixed evenly and then heated to 1,500 °C. The end products of this reaction are oxygen and a high-strength metal-ceramic composite of iron (Fe) and titanium carbide (TiC) featuring high chemical stability:

Ilmenite: $FeTiO_3 + 4C \rightarrow Fe + TiC + 3CO$,

Ilmenite and rutile: $FeTiO_3 + nTiO_2 + (4 + 3n)\,C \rightarrow Fe + (1 + n)TiC + (3 + 2n)CO$.

The reduction of ilmenite using CO is based on a fluidized bed method, which is similar to hydrogen reduction:

$FeTiO_3 + CO \rightarrow Fe + TiO_2 + CO_2$.

Endothermic cracking: $2CO_2 \rightarrow 2CO + O_2$.

The reaction in its pure form is $2FeTiO_3 + 2CO \rightarrow 2Fe + 2TiO_2 + 2CO + O_2$.

The product of CO reduction in ilmenite is carbon dioxide (CO_2), which is reduced to CO and oxygen [7].

The process requires the delivery of consumables from the Earth, which complicates implementing this technology on the Moon.

Oxygen production by vacuum pyrolysis of regolith

Pyrolysis is the decomposition of a material when heated in an environment without oxygen oxygen, i.e., in a vacuum. When a material is heated above its vaporization temperature, the molecules dissociate to form monoxides, metals, and oxygen.

The reaction does not require consumables or catalysts, and any lunar regolith can be used without enrichment as a feedstock.

Experiments on the vacuum pyrolysis method were conducted at the Goddard Space Flight Center in Greenbelt, Maryland. The experimental installation uses solar energy focused through a Fresnel lens into a vacuum chamber with a crucible containing a regolith equivalent (Fig. 5) [8].

When regolith is heated to a gaseous state, additional heating causes regolith oxides to dissociate into monoxides and free oxygen. The highest effective operating temperatures for maximum oxygen production are 1,800–2,100 °C in a rough vacuum and between 1,300 and 1,400 °C in a high vacuum.

Pyrolysis is the most energy-intensive process of all possible oxygen production techniques. For engineering purposes, minimizing energy transmission losses in the system is crucial. The current technology readiness level of vacuum pyrolysis where experiments have proved the concept is TRL3.

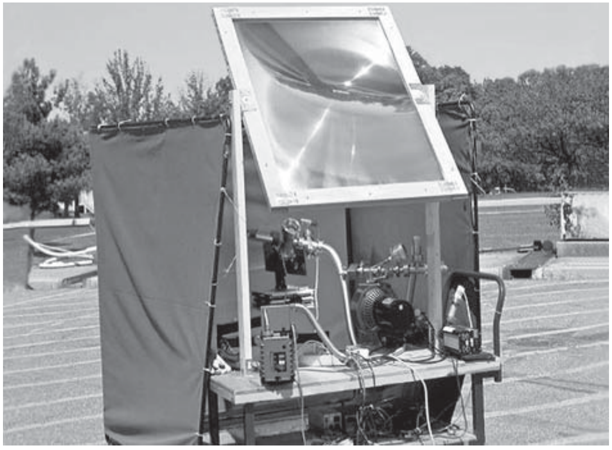

Fig. 5. Experimental pyrolysis installation with a Fresnel lens

The process has the advantage of using only local resources, namely, regolith, a high vacuum, and solar energy. However, pyrolysis has very high energy requirements to maintain the required temperature in the reactor. It complicates the process due to the dependence on solar energy as the primary energy source on the Moon. This process requires a higher technology readiness level than it is now, which makes it very unlikely that the demonstration of the process will occur in the selected time frame [8].

Electrolysis of regolith

It is possible to extract oxygen from lunar soil by electrolysis, which might also yield many essential metals. The electrochemical reduction of solid metal oxides in molten $CaCl_2$ salt at temperatures around 900 °C is called the FFC-Cambridge process.

In a previous NASA-funded study (2004), the FFC-Cambridge process was successfully tried in a laboratory for lunar ilmenite electrolysis. Later, it was demonstrated that oxygen could be produced by the FFC-Cambridge electrolysis of ilmenite pellets at 900 °C using an inert anode of doped tin oxide or a mixture of titanate and calcium ruthenate.

Over the past decade, Metalysis (UK) has successfully developed the laboratory FFC-Cambridge technology into an end-to-end commercial process. The Metalysis-FFC electrolyzer uses an aluminum oxide crucible with a stainless steel retort inside and a water-cooled hermetic lid. The lid has passages for three electrode rods, and it is equipped with thermocouples, a viewing window, an argon line inlet to create an inert atmosphere and remove process gases, and an outlet to a massive stainless steel grid attached to two cathode rods. A SnO_2 anode is mounted on the end of the anode rod and is centered relative to the cathode basket (Fig. 6).

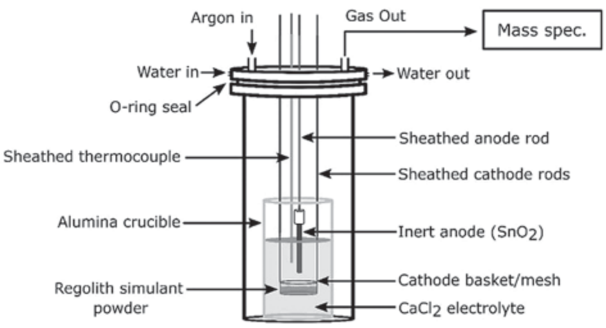

Fig. 6. Experimental electrolysis cell for powdered regolith recovery

After ~49 hours of operation, the total oxygen registered was approximately 34 % of the oxygen present in the feed material.

Metalysis-FFC is well suited to extract oxygen from all primary components of lunar regolith while creating useful alloys and metals as by-products. The application of the Metalysis-FFC process, with developments during the last decade, offers an alternative to other technologies for producing oxygen on the lunar surface [9].

Supplies of $CaCl_2$ salt from the Earth for replenishment will be necessary at the initial stage.

Molten fluoride salts are also used as a flux to dissolve lunar regolith oxide equivalents and related silicate rocks. These salts allow electrolysis at 960 to 1,250 °C. American researchers conducted an electrochemical reduction to extract elemental oxygen from silicate melts using an iridium anode and LiF / BaF_2 fluxing agents in a molten electrolyte, a silicate bath, at a temperature ranging between 1,050 and 1,250 °C. Molecular oxygen was produced directly at the anode, but gas separation led to volatile LiF escaping from the electrolyte cell.

Recovering fluoride fluxes from the electrolyte bath was extremely difficult. Considering the observation during the experiment that SiO_2, the primary oxide component of the melt, underwent slight electrical recovery, it was concluded that significant amounts of flux must be supplied from the Earth, or suitable substitutes found on the Moon are needed [6].

Direct electrolysis of regolith

The electrolysis technology can be developed without flux materials and with a non-destructive anode for oxygen production. Preliminary experiments show that molten rock or soil is conductive enough to support electrolysis [6].

The direct electrolysis of molten regolith requires extreme temperatures over 1,600 °C. Therefore, significant improvements in electrode materials and protective materials are needed. The Israeli company Helios has proposed oxygen extraction from lunar soil using the direct electrolysis of oxide melts. The system has been tested in terrestrial conditions using a regolith simulator with a composition identical to that delivered to the Earth in the Apollo program [10].

Lunar Resources is developing a technology for extracting iron, aluminum, magnesium, and silicon from the Moon's regolith by the direct electrolysis of its melt at a temperature of 1,600 °C. A prototype of the reactor under development is planned for sending to the Moon for demonstration tests (Fig. 7).

Fig. 7. Electrolyzer under development by Lunar Resources

The reactor will be approximately 1 meter in diameter and height and will process up to 100 kilograms of lunar regolith delivered by a small lunar rover within 24 hours. The reactor is planned for a flight to the Moon in the

Commercial Lunar Payload Services Agency's commercial missions [11].

The disadvantage of the process is the need for inert anodes capable of operating for a long time at temperatures of 1,600 °C in an active oxygen environment. When developing the Lunar Resources electrolyzer, NASA researchers chose platinum for the anode. In the direct electrolysis of regolith with a high content of iron oxides, an iridium anode was used [12]. It is a promising candidate for the anodes due to its high melting point, good oxidation resistance, extreme strength at high temperatures, and ductility. However, iridium is an expensive and rare metal.

The direct electrolysis of regolith does not require the delivery of materials from the Earth. It can be a fully autonomous process on the Moon. The disadvantage of this method is the lack of heat-resistant anode materials that can operate for a long time at temperatures of 1,600 °C in an active oxygen environment and have a reasonable cost.

Thus, the analysis of the existing technologies for extracting metal materials and oxygen from regolith demonstrated that every method has advantages and disadvantages. The chemical reduction of regolith and electrolysis in LiF / BaF_2 and $CaCl_2$ salts require the delivery of consumables from Earth. The vacuum pyrolysis of regolith and the direct electrolysis of molten regolith can be fully autonomous processes on the Moon. Pyrolysis requires a lot of energy, and it is not feasible for use on the Moon at the current technology readiness level. The direct electrolysis of regolith is the most attractive process, provided that inert anodes with the required complex of properties are available. Therefore, it is necessary to develop anodes that will enable this process on the Moon for long periods.

The authors first proposed using the heat-resistant protective conductive coating they invented from ultra-high-temperature ceramics based on zirconium borides with $MoSi_2$ additives for inert anodes made of traditional materials. This ceramic has the highest resistance to high-temperature oxidation among materials of this type. At temperatures up to 2,000 °C in an oxidizing environment, a protective layer is formed on the surface of the ZrB_2-$MoSi_2$ material, and the composition of this layer varies with temperature.

The fundamental possibility of applying coatings from ZrB_2-$MoSi_2$ by vacuum ion-plasma sputtering has been demonstrated. The coatings were applied to samples in a special-purpose vacuum installation based on the vacuum chamber designed by Yuzhnoye State Design Office. The ZrB_2-$MoSi_2$ coatings were deposited at Yuzhnoye SDO by the vacuum arc method on substrates made of 40Kh steel, 12Kh18N10T steel, and carbon.

Conclusions

Regolith is the primary raw material resource on the Moon.

The technologies for extracting metals and oxygen from this raw material on the Moon include chemical reduction (using hydrogen, carbothermic reactions, and plasma), high-temperature pyrolysis, and the electrolysis of molten silicates.

All methods have their advantages and disadvantages. The chemical reduction of regolith and electrolysis in LiF / BaF_2 and $CaCl_2$ salts require the delivery of consumables from the Earth. The vacuum pyrolysis of regolith and the direct electrolysis of molten regolith can be fully autonomous processes on the Moon. Pyrolysis requires a lot of energy, and it is not feasible for use on the Moon at the current technology readiness level. The direct electrolysis of regolith is the most attractive process, provided that inert anodes with the required complex of properties are available.

We propose the heat-resistant protective conductive coating we developed from ultrahigh-temperature ceramics based on zirconium borides with $MoSi_2$ additives for inert anodes made of traditional materials.

The fundamental possibility of applying coatings from ZrB_2-$MoSi_2$ UHTC by vacuum ion-plasma sputtering has been demonstrated.

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