UDC [553.041+620.1]:536.7(15) DOI: https://doi.org/10.15407/geotm2022.163.140

REVIEW OF POTENTIAL SOURCES FOR OBTAINING ENERGY CARRIERS AND MINERAL RAW MATERIALS IN OUTER SPACE

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Abstract. The problem of resource provision on Earth includes three main aspects – depletion due to the lengthy development of large volumes of non-renewable resources, shortage of certain types of resources due to their rarity and insignificant concentrations, high cost of extraction and beneficiation due to a number of factors, including the conditions of occurrence and imperfection of technologies. Resources in general are all types of resources – energy, mineral, water, and, separately, oxygen. Space objects are one of the possible directions of searching for alternative non-traditional sources of energy and mineral raw materials. Space exploration will help to solve a number of global problems for humanity, including demographic, food, energy, raw materials, and the environmental.

The purpose of the paper is to justify the need of searching for potential alternative ways of obtaining energy carriers and mineral raw materials of a non-traditional type and to determine their possible sources in outer space.

On the basis of the analytical review of potential alternative ways and sources of obtaining energy carriers and mineral raw materials of a non-traditional, it is justified that the research of space objects (planets, satellites, comets, asteroids) aimed at searching non-traditional type is relevant. The relevance of this direction is confirmed not only by the development of appropriate technologies for the exploration of space objects but also by the development and improvement of the legal framework governing space exploration. The main and most important directions of research are life support during the development of space objects, energy supply, mining and processing of minerals, chemical and biological production. Issues of life support involve providing, first of all, oxygen and water. For energy supply, it is advisable to consider helium-3 (He-3), water, oxygen, hydrogen, and ethane as potential sources. The most promising mineral resources in space are rare and rare-earth elements, platinum and metals of the platinum group, nickel, and cobalt. It is proven that the most promising space objects for the extraction of mineral raw materials are asteroids due to their relative availability, structural features, and higher concentration of minerals.

Keywords: space, planets, satellites, asteroids, energy carriers, mineral raw materials.

1. Introduction

The growth of the Earth's population, as well as the depletion of natural resources, forces humanity to look for alternative sources that would allow the continuation of human activity and development. Despite the implementation of resource-saving policies by many countries, the demand for mineral raw materials in the world is growing rapidly, both quantitatively (by approximately 5 % per year) and in terms of "assortment". The problem of depletion of the earth's interior is exacerbated by the extremely uneven distribution of deposits, which does not contribute to the stability of global economic relations. In fact, no country on the planet has reserves of all the necessary types of mineral raw materials and cannot do without their import. Thus, the USA fully provides its needs for only 22 types of mineral raw materials (excluding building and stone materials), while for many types of strategic raw materials (uranium, cobalt, strontium, tantalum, cadmium, tungsten, chromium, manganese, etc.) are chronically dependent on import. In general, the USA imports 15–20% (in terms of value) of the mineral raw materials they need, Western Europe – 70–80%, and Japan – 90–95%. Even China, which is second to none by the assortment of its mineral resources, imports chromites in large volumes [1].

Mineral resources are the primary source, the initial basis of human civilization in almost all phases of its development. The resources of mineral raw materials are limited, most of them are actually non-renewable and, if their consumption continues to grow exponentially, they will be exhausted in the foreseeable future. At the same time, it is important to consider the following circumstance: humanity is not in fact threatened by the imminent exhaustion of mineral resources that are physically present in the Earth's interior – the part of many important types of minerals that is technically available and economically effective (according to the conditions of occurrence and quality) is very limited. Its rapid depletion and direction of fewer effective deposits will mean a serious challenge for the economies of many states. That is why the questions about whether mineral resource reserves are large or small and how well they provide for humanity as a whole are completely correct. Only that part of the natural substance which can be used technically and economically is of real interest. Despite the fact that in the center of the Earth, there is a metallic earth's core consisting mainly of iron and nickel, and many other valuable elements, there are good reasons to assert that the earth's core will never become a source of replenishment of balance reserves of these elements for the world economy.

Thus, the problem of resource provision on Earth includes three main aspects:

1) depletion due to the lengthy development of large volumes of non-renewable resources;

2) shortage of certain types of resources, due to their rarity and small concentrations;

3) high expensiveness of extraction and beneficiation due to a number of factors, including deposit conditions and technological imperfections.

Speaking about resources in general, we are talking about all types of resources – energy, mineral, water and, separately, oxygen.

Over time, the depletion of the Earth's resources will be able to justify the cost of their extraction in airless space, and the creation of processing factories directly on space bodies and their orbits will significantly reduce the cost of the process. In the era of globalization, the exploration of outer space becomes an important component of the overall strategy for the development of humanity. The scientific and technical progress of the XXI century, which has a powerful impact on a person, society and nature, is unthinkable without the active use of space technologies and materials [2].

State and commercial structures of a number of countries (the USA, Great Britain, Luxembourg, China, Taiwan, India, and Japan) are taking concrete steps to develop space technologies aimed at the exploration of space resources, primarily asteroids. The development of technologies for researching space objects and methods of transportation to them, as well as technologies for exploration and extraction of minerals, is being intensified. The relevance of this direction is confirmed not only by the development of appropriate technologies for the exploration of space objects but also by the development and improvement of the legal framework governing space exploration. The juridically legal aspect of the problem of space exploration confirms the relevance, necessity and timeliness of research aimed at searching alternative ways and sources of obtaining energy carriers and mineral raw materials in outer space.

Studies of space objects (planets, satellites, comets, asteroids) aimed at searching potential alternative sources of energy carriers and non-traditional mineral raw materials are relevant. Space exploration will help to solve a number of global problems of humanity, including demographic, food, energy, raw materials, and environmental.

The **purpose** is to justify the need of searching for potential alternative ways of obtaining energy carriers and mineral raw materials of a non-traditional type and to determine their possible sources in outer space.

Potential space objects for obtaining energy carriers and mineral raw materials. Potential space objects are planets, satellites, comets, asteroids. In this regard, it should be noted that the resource potential of most space objects is still unexplored due to a number of legal and, to a large extent, technical and technological problems. At present, technical capabilities allow extracting only samples of lunar, Martian, or other soil for scientific purposes, but science and technology do not stand still. Researchers note that one of the main directions in the development of cosmonautics is the activity of research and development of the bodies in the Solar System. Of course, the development of technologies in the field of space in the nearest future will make it possible to carry out commercial activities related to its exploration, including the extraction of minerals. A number of non-governmental organizations already today have capabilities to launch spaceships.

If we consider planets as potential objects for the exploration of resources, it is advisable, first of all, to pay attention to the planets adjacent to the Earth, that is, the planets of our Solar System. These are Mercury, Venus, Mars. In addition to the planets in the Solar System, there are still many potentially very resource-rich satellites, such as the Moon, Io, Europa, Ganymede, and Callisto.

Below is a brief overview of the planets in our Solar System based on the materials of paper [3].

Mercury. A small planet that is closest to the Sun. Despite this, the temperature on Mercury can drop to -200 degrees Celsius. The most valuable resource on the planet is soil, due to the fact that there is a lot of Helium-3 in the soil of Mercury, which can be used to obtain clean energy without radioactive waste. There are also reasons to believe that there is a lot of magnesium, sulfur and deposits of various ores in the depths.

Venus. A planet on which, during rain, sulfuric acid falls from the sky instead of the water usual for earthlings. According to available data, the second planet from the Sun is rich in lead and bismuth. Since the planet is located very close to the star, the temperature can sometimes reach +500 degrees Celsius. Extracting resources there can be problematic.

Mars. Mars is believed to be very similar to Earth in the past, so there is reason to suggest that there may be a large supply of water under the surface. The presence of iron, copper and gold, which may be suitable for mining in the future, is also assumed.

Almost nothing is known about minerals on other planets [3].

Asteroids are the most promising for priority exploration as sources of mineral raw materials, owing to the peculiarities of their structure. The essence of the difference between the structure of asteroids and the structure of planets and their satellites is as follows.

The planets, including the Earth, have a zonal structure from the center – the core - to the periphery, that is, to the surface (core, mantle, earth's crust). This determines the differentiation by specific gravity and, accordingly, the distribution of light and heavy elements and a decrease in the concentration of the latter from the core to the Earth's surface. And, as a result, their rarity within the shallow depths available for development and production. In contrast to planets with a zonal structure, asteroids are fragments, debris of once integral cosmic bodies and are devoid of zonality, originally determined by the differentiation of substance by its specific gravity. That is, the concentrations of individual elements on different asteroids can significantly exceed Clark ones for planets and satellites. Unlike Earth, where heavy metals are located closer to the core, metals in asteroids can be distributed throughout the object. Thus, extracting them is much easier. Asteroid resources have a number of unique features that make them even more attractive. They can contain water, gases – oxygen O_2, hydrogen H_2, methane CH_4, ammonia NH_3, carbon dioxide CO_2, carbon monoxide CO (Fig. 1). The content of many valuable components, taking into consideration the peculiarities of the structure and composition of asteroids, as mentioned above, at times exceeds the concentration of the corresponding elements on Earth (Table 1). Platinum and elements of the platinum group are particularly valuable components.

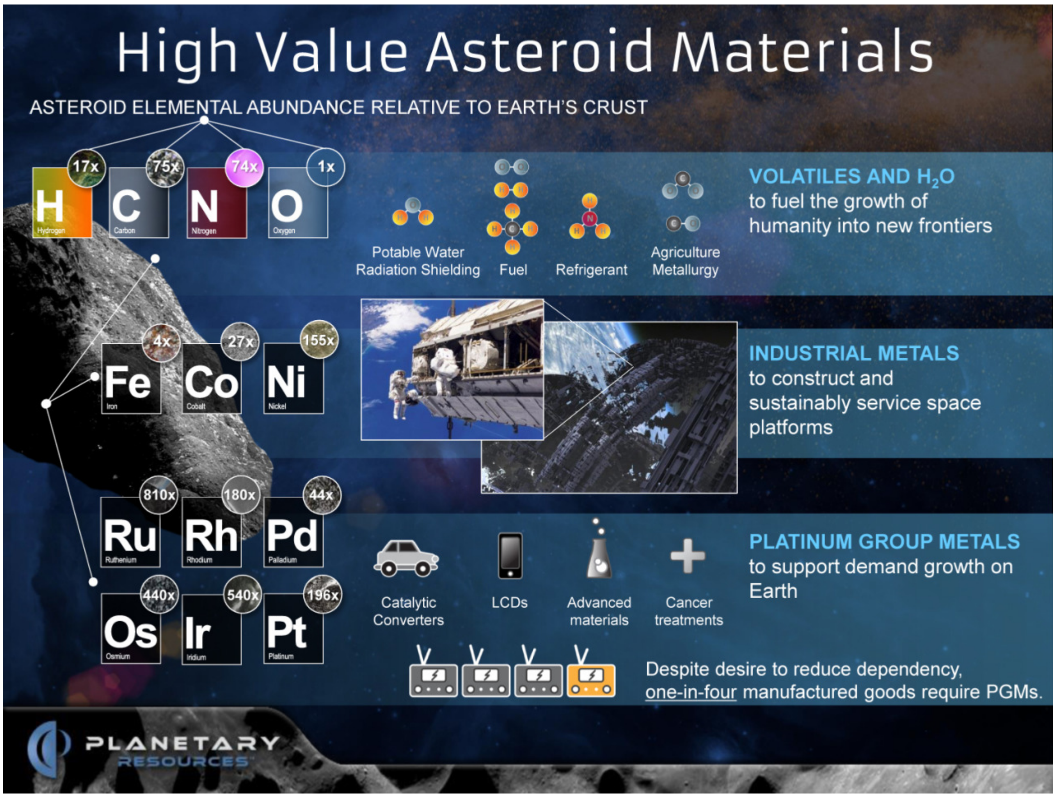

Figure 1 − Potential resources of space asteroids [4]

Water from asteroids is a key resource in space. Water can be turned into rocket fuel or supplied for human needs. In addition, it can radically change the way to study space. One water-rich asteroid with a width of 500 m contains 80 times more water than can fit in the largest tanker, and if it is turned into fuel for spacecraft, it will be 200 times more than would be needed to launch all the rockets in human history [4].

Table 1 – The multiplicity of the exceeding content of certain elements on asteroids compared to Clarks on Earth (according to [4])

Chemical element	The multiplicity of the exceeding content on asteroids compared to Earth
Hydrogen H	17
Carbon C	75
Nitrogen N	74
Iron Fe	4
Cobalt Co	27
Nickel Ni	155
Ruthenium Ru	810
Rhodium Rh	180
Palladium Pd	44
Osmium Os	440
Iridium Ir	540
Platinum Pt	196

Having gained access, and having learned how to extract, remove and use the water resources of asteroids, the extraction of metals on them will become much more real. Some near-Earth objects contain platinum group metals in such high concentrations that only the richest earth mines can boast. One platinum-rich asteroid with a width of 500 m contains almost 174 times more of this metal than is mined on Earth in a year and 1.5 times more than all known world reserves of platinum group metals.

The advantages of asteroid development also include such factors as:

– proximity to the Earth – some asteroids are close enough that sending a manned or automatic mission to these objects is not an impossible task for a person;

– experts are already identifying thousands and thousands of promising objects, over time their number will only increase as we study.

Currently, hundreds of thousands of asteroids have been discovered in the Solar System, and the catalog already contains about 700 thousand of them. The orbits of most of them (almost half a million) have been determined with satisfactory accuracy, and the asteroids themselves have received an official catalog number. About 20 thousand celestial bodies have officially approved names. Experts say there are likely 1.1 to 1.9 million objects larger than 1 km in size in the Solar System. The largest number of asteroids is in the asteroid belt, which is located between the orbits of Jupiter and Mars. This area is also often referred to as the main asteroid belt or simply the main belt, thus emphasizing its distinction from other similar regions of the minor planet cluster, such as the Kuiper belt orbiting Neptune, as well as the cluster of the scattered disk and the Oort cloud. Reachable for humans are those from asteroids whose orbits are in space between Mars and the Moon. If a spacecraft can be sent there (with minimal costs), then, most likely, such an asteroid can be developed. So far, about 12 thousand asteroids accessible to humans have been counted – and this is already a significant number [5].

Promising asteroids for development are considered to be those that can be brought closer to the Earth with minimal energy expenditure. Such asteroids are proposed to be transferred to one of the orbits near the so-called Lagrange points L_1 and L_2, where they can be left in relative immobility. Both orbits are about a million kilometers away from Earth.

Asteroids vary widely in composition. Each of them contains water, metals and carbon materials in different amounts. The qualitative composition of asteroids determines their spectrum during astronomical study, and their classification is based on this. Clark Chapman, David Morrison and Ben Zellner proposed the current classification in 1975 [6]. It contained three types: C – dark carbon objects, S – stony (silicon) objects and U – for asteroids that do not fall within C and S categories. Later, this classification was expanded and clarified.

Currently, there are a number of classifications, and although they keep some mutual uniformity, some asteroids in different schemes belong to different classes – due to the use of different criteria in the approach. Two classifications are most commonly used: David Tolen [7] and SMASS (Small Main-belt Asteroid Spectroscopic Survey) [8, 9]. Nowadays, spectral classifications are standard. Presently, three main classes of asteroids have been identified, depending on their chemical composition:

1) class C – with a high carbon content (75 % of known asteroids);
2) class S – silicate or stony (17 % of known asteroids);
3) class M – predominantly metal (most others).

Review of potential energy resources of space. Water H_2O, hydrogen H_2, oxygen O_2, helium-3 (He-3) should be considered as the most promising potential energy resources of space.

Helium-3 (helion). According to many experts, helium-3 is the only one of minerals whose delivery from the Moon to Earth can be economically justified. Helium-3 is an isotope of helium, the nucleus of which consists of two protons and one neutron, unlike helium-4, which has two protons and two neutrons. Helium-3 is very rare in nature on Earth. Its total amount in the Earth's atmosphere is estimated at 35 thousand tons. Most of the helium-3 on Earth has been preserved since its creation. It is dissolved in the mantle and gradually enters the atmosphere. However, its entry from the mantle into the atmosphere (through volcanoes and fractures in the crust) is estimated to be only a few kilograms per year.

Helium-3 is the main fuel component for thermonuclear reactors, and although it is a future prospect, it is still in high demand today. It is not in demand for energy, but for nuclear physics, cryogenic industry and medicine. This is:

− neutron counters (gas counters filled with helium-3 are used to detect neutrons, this is the most common technique of measuring the neutron flux);

− obtaining ultra-low temperatures (by dissolving liquid helium-3 in helium-4, millikelvin temperatures are reached);

– medicine (polarized helium-3 (it can be stored for a long time) has recently begun to be used in magnetic resonance tomography to obtain images of the lungs using nuclear magnetic resonance).

But despite the usefulness of this isotope for the above-mentioned areas, it is advisable to consider it, first of all, as nuclear fuel. Helium-3 is, firstly, a very efficient thermonuclear fuel, and secondly, what is even more valuable, it is environmentally friendly. When it is used, radiation does not occur, so the problem of nuclear waste disposal, which is so acutely facing the world, disappears by itself [10]. Currently, helium-3 is not extracted from natural sources but is created by the decay of artificially obtained tritium.

Despite the fact that the helium- 3 abundance on Earth is negligible, hydrogen and helium are the most abundant elements in the Universe. A group of astronomers from the University of Manchester (Great Britain), together with colleagues from Spain and Mexico, discovered helium-3 at a distance of 4.000 light-years from Earth. This discovery became possible thanks to the use of the largest antenna (70 meters in diameter) of the NASA surveillance complex [11]. Unexpectedly high concentrations of this gas were detected, more than 500 times higher than the concentrations of helium-3 known on Earth, and several times higher than the most "optimistic" forecasts obtained by calculation. According to the authors of the paper, the observed increased concentrations of helium-3 can be explained by the atypical nature of the star under research, otherwise, the total content of helium-3 in the Universe should be even higher. The research was published in the journal Monthly Notices of the Royal Astronomical Society, Letters.

There is much more primary helium-3 in the Sun and in the atmospheres of the giant planets than in the Earth's atmosphere. Helium-3 is a by-product of reactions occurring in the Sun and is contained in a certain amount in the solar wind and the interplanetary medium. In the Solar System, the largest supply of helium-3 is in the depths of gas giants such as Jupiter or Saturn. However, unlike stars that constantly produce this isotope, giant planets close to us received it at the stage of their formation, and now only store helium-3 reserves in their layers [12].

The moon, which has no atmosphere, retains a significant amount of helium-3 in the surface layer. Helium-3 is gradually accumulated in the lunar regolith over billions of years of exposure. Regolith is a residual soil that is a product of space weathering of rock at the place of its distribution. Nowadays, this term is most often used to refer to the surface layer of loose lunar soil. The term can also be applied to the materials that cover the surfaces of other small atmosphere-less planets and moons (for example, Mercury, Deimos), as well as asteroids. Regolith occurs as a result of the crushing, mixing and sintering of rocks during the fall of meteorites and micrometeorites in conditions of vacuum and in no way attenuated space radiation. By radioisotopes, it was established that some fragments on the surface of the regolith were in the same place for tens and hundreds of millions of years. By its structure, it is a non-layered, loose, of different grain size, detrital-dust layer, reaching a thickness of several tens of meters. It consists of fragments of erupted rocks, minerals, glass, meteorites and breccias of shock-explosive origin, cemented with glass. According to the granulometric composition, it belongs to silty sands (the main mass of particles has a size of 0.03 – 1.00 mm). The color is dark gray to black with inclusions of large particles that have a mirror shine. The mineral composition of lunar regolith is a mixture containing ilmenite $FeTiO_3$, olivine $(MgFe)_2[SiO_4]$, anorthite $Ca[Al_2Si_2O_8]$, pyroxene $R_2[Si_2O_8]$ (where R is Na, Ca) [13]. The regolith contains helium-3 in the sorbed state.

Research on the determination of the helion content in samples brought from the Moon showed that it is approximately 7.43×10^{-5} m^3/t [14–15], which in terms of physical chemistry is called the sorption capacity of the regolith in relation to the helion. Thanks to the solar wind, helium is not only adsorbed on the surface of the regolith but also penetrates through diffusion into its crystal lattice. At the same time, such processes take place during the entire existence of the Moon. The pressure of the helium on the surface of the Moon is estimated using a formula that has the form [16]:

$$P = 1.6726\times10^{-6}\times n\times V^2,$$

where P – pressure (nPa); n – particle density (sm^{-3}); V – the speed of particles (km/s).

Given that $n = 15\times10^{-5}$ cm^{-3}, V = 1000 km/s, we have P = 0.025 nPa = $= 2.5\times10^{-11}$ Pa. At such low pressures, not exceeding 0.1 MPa, the adsorption process (a) of gases is well described by Henry's isotherm [16]:

$$a = k\times P,$$

where k is Henry's constant, which is 3×10^6 $m^3/t/Pa$ for this particular process of helium adsorption on the lunar regolith. This value is of practical importance, as it allows for evaluating more accurately the total amount of helium on the Moon, as well as for designing regolith processing facilities for its extraction.

According to estimates [17,18], the available reserves of helium-3 on the Moon will be enough for thousands of years ahead – a ton of lunar soil (in the thinnest surface layer) contains about 0.01 g of helium-3 and 28 g of helium-4. This isotopic ratio is much higher than in the Earth's atmosphere. According to experts, the minimum amount of helium-3 on the Moon is about 500 thousand tons, according to more optimistic estimates, it is at least 10 million tons. During the thermonuclear fusion reaction, when 0.67 tons of deuterium and 1 ton of helium-3 react, energy is released, which, as already mentioned above, is equivalent to the energy of burning 15 million tons of oil. At the same time, it is worth noting the fact that at present it is still necessary to further study the technical possibility of carrying out such reactions.

The main problem at this point in time remains the reality of helium extraction from the lunar regolith. Although helium-3 is contained in the surface layer, its concentration in it is very low. The content of helium-3 necessary for energy production is approximately 1 gram per 100 tons of lunar soil. It is important that helium-3 will have to be separated from unnecessary helium-4, the concentration of which in the regolith is 3 thousand times higher. According to [10], in order to obtain 1 ton of helium-3 on the Moon, it will be necessary, as already noted, to process 100 million tons of lunar soil. We are talking about an area of the Moon with a total area of about 20 square kilometers, which will have to be processed to a depth of 3 meters.

At the same time, the very procedure of delivering 1 ton of this fuel to Earth will cost at least 100 million dollars. But in fact, even this very large amount is only 1 % of the cost of energy that can be extracted at a thermonuclear power plant from this raw material.

According to estimates [19, 20], the cost of extracting 1 ton of helium-3, taking into account the creation of all the necessary infrastructure for its extraction and delivery to Earth, can amount to 1 billion dollars. It is important that transporting 25 tons of helium-3 to Earth will cost 25 billion dollars, which is not such a large amount, if you consider that such a scale of fuel is enough to provide Earthlings with energy for a whole year. The benefit of such an energy carrier becomes obvious if you calculate that only the USA spends about 40 billion dollars a year on energy carriers. According to Harrison Schmitt's calculations [17, 18], the use of helium-3 in terrestrial energy, considering all the costs of delivery and extraction, will begin to pay off and will be commercially profitable when the production of thermonuclear energy using this raw material will exceed the capacity of 5 GW. In fact, this suggests that even one power plant running on lunar fuel would be enough to make delivery to Earth cost-effective. According to H. Schmitt's estimates, the number of preliminary expenses still at the stage of research will amount to about 1 billion dollars.

Erik Mikhailovich Galimov [10] proposed one of the possible options for the production of helium-3. In order to organize the extraction of the isotope from the lunar surface, he suggests heating the regolith to 700 degrees Celsius. After that, it can be liquefied and extracted to the surface. From the viewpoint of contemporary technologies, these procedures are quite simple and well-known. The scientist proposes to heat the raw materials in special "solar ovens", which will focus sunlight on the regolith with the help of large concave mirrors. At the same time, it will be possible to extract oxygen, hydrogen and nitrogen contained in the lunar soil. And this means that the lunar industry could produce not only raw materials for the Earth's energy complex but also fuel for the rockets that carry it, as well as air and water. Currently, similar projects are also being worked on in the USA.

The paper [16] presents the scientific justification of the technologies for extracting helium from the lunar regolith using thermodynamic heating, resonant electromagnetic radiation, and active oxidation by microorganisms as promising and effective methods that may have practical use in the future.

The regolith also contains a large amount of titanium, which in the distant future may help establish the production of elements of rocket bodies and industrial structures directly on the Earth's natural satellite. In this case, only high-tech elements of rockets, computers and devices will have to be delivered to the Moon.

The economic potential of helium-3 attracted the attention of American scientists. Projects on processing regolith and extracting helium-3 were carried out at one time by experts from NASA. Gerald Kulczynski and John Santarius of the University of Wisconsin assert that helium-3 is the future of American energy. It contains all the energy that the United States may need [21].

China is currently working on a helium-3 mining program on the Moon. Chinese scientists are considering the possibility of fully providing the national economy with its own energy due to the extraction of the helium-3 isotope on the Moon and its use on Earth as fuel for a new generation of thermonuclear reactors. A leading scientist working on China's lunar program said recently that the helium-3 found on the Moon is enough to meet energy needs for at least the next 10 thousand years. According to his calculations, 0.02 g of helium-3 is equal to one barrel of oil in terms of the energy contained in it [22]. Chinese scientists plan to extract helium-3 by heating the lunar dust to 600 degrees. Then the received element will be sent to Earth for its targeted use [23].

An employee of the Indian Space Research Organization (ISRO), Professor Sivathanu Pillai stated that the development of a lunar surface rich in helium-3 is a priority area of work of the ISRO and his country intends to obtain energy resources from the Moon by 2030. The necessary energy will be obtained from helium-3, which will be mined on the surface of the Earth's satellite. Pillai said that his organization intends to deploy large-scale processing of lunar dust. He added that other countries are also interested in lunar energy, and the reserves of lunar soil are enough to meet the energy needs of the entire Earth [24, 25].

So, at present, China, India, the USA, Russia, and Japan – all these countries are striving to explore the Moon, and later these countries will become more and more.

Water H_2O, oxygen O_2, hydrogen H_2. As an energy carrier, water is also important because its chemical composition allows it to be split into hydrogen and oxygen. Water during space exploration can be required not only directly for work on space stations but also when it is split into hydrogen and oxygen – as fuel for reactors. Hydrogen is something that can be used to recharge fuel cells. By recombining hydrogen with oxygen, you can get a fairly energy-intensive fuel.

Water from asteroids can either be converted into rocket fuel or delivered to special storage facilities located at strategic areas in orbit for refueling spacecraft. Such type of fuel, which is supplied and sold, can give a huge impetus to the development of space flights.

Water from asteroids can significantly reduce the cost of space missions, since they all depend primarily on fuel. For example, it is much more profitable to transport a liter of water from one of the asteroids to the Earth's orbit than to deliver the same liter from the surface of the planet. In orbit, water can be used to refuel satellites, increase the payload capacity of rockets, maintain orbital stations, provide radiation protection, etc.

Review of potential mineral resources of space. In general, the main resources that are necessary and possible to extract in space are water, gases and metals.

As mentioned above, the content of many valuable components on some space objects is many times higher than their concentration in the earth's crust. The most promising mineral resources of space are, first of all, rare and rare-earth elements, platinum and platinum group metals (PGM): ruthenium, rhodium, palladium, osmium, iridium, as well as nickel and cobalt. The PGM are very rare on Earth. They (like metals similar to them) have specific chemical properties that make them extremely valuable for industry and the economy. In addition, their overabundance and excess can give rise to their new, not studied yet usage. Platinum group metals are the prospect of quick payback for investments in the space mining industry. It is one of the rare space-mined products that can be cost-effectively delivered to Earth. Platinum group metals are indispensable in automotive catalysts, and in the production of silicone and glass. They are present in computer hard drives, in the automotive industry. In medicine, these metals are indispensable due to their compatibility with biological tissues.

In addition to being delivered to Earth, metals mined on asteroids can be used directly in space. Such elements as, for example, iron and aluminum, can be used in the construction of space objects, protection of apparatus and so on.

Before talking about the prospects of space development, it is advisable to find out what can still be mined in space. As mentioned earlier, M-class asteroids are the most promising object – the third most abundant element in the Solar System. Most (though not all) asteroids of this class consist of an alloy of nickel and iron. Quite often these are huge pieces of alloy, and almost without impurities. They are believed to be formed as a result of the destruction of the iron cores of large asteroids and protoplanets that had emerged at the initial stages of the development of the Solar System. The largest asteroid of this type is 16 Psyche. Its diameter is about 100 kilometers and it consists almost entirely of metal (according to researchers, the mass of the asteroid is one percent of the mass of the entire main asteroid belt, where it is located). The main merit and advantage of M-class asteroids is the high nickel content in the alloy compared to terrestrial ones.

Another class of asteroids that could potentially be useful for mining is the S type. They make up about 17 percent of the entire population of asteroids in the asteroid belt and are composed mostly of magnesium and iron silicates. Scientists believe that such asteroids may contain deposits, although mainly in the form of veins – iron, nickel, magnesium, and other metals. In addition, experts argue that asteroids may well have deposits of gold and many other metals.

A typical M-class asteroid with a diameter of about a kilometer contains (in compliance with estimates by planetary scientist John Lewis) 30 million tons of nickel, 1.5 million tons of cobalt, and 7.5 thousand tons of platinum [5]. The cost of only the latter is about 150 billion dollars. It is believed that the Solar System may have up to a million of such asteroids – for example, 3554 Amon, its value was estimated at 20 trillion dollars.

The considerable volume of space resources (including those on the Moon) also provides information on deposits of titanium, barium, aluminum, and zirconium.

Review of necessary resources for life support. The main resources for life support are oxygen and water. In addition to its critical hydration role, water provides other important benefits for space. It can protect against solar radiation, be used as fuel, give oxygen, etc. Today, all water and related resources needed for spaceflight are transported from the Earth's surface at prohibitively high prices. Of all the restrictions on human expansion into space, this is the most important. It would be much cheaper to find water in space than to deliver it from Earth. After all, launching each kilogram into space will cost tens of thousands of dollars. The price of such water can be lower than the cost of its delivery from Earth.

Asteroids made of carbonaceous chondrite can be considered the best sources of water. On such an asteroid, drilling is not required – to remove water, it will be enough to simply scrape its surface, given its loose, fragile structure.

The possession of water is not a distinguishing characteristic of our planet alone. Meteorites that fall to Earth contain up to 0.5 % of it. Scientists have established with sufficient conviction: water in one form or another is present on comets, asteroids, small and large planets of the Solar System.

NASA scientists announced the discovery of liquid water on Mars. To date, the most thorough evidence concerning the presence of salt water flows on the surface of the planet was discovered by the automatic interplanetary station Mars Reconnaissance Orbiter (MRO). It is worth noting that dark streaks on the Martian surface, the length of which can reach hundreds of meters in warm periods, were first discovered in 2010 and even then indirectly confirmed the fact of the presence of liquid moisture. However, it was not possible to prove their origin at that time. But, with the help of the CRISM spectrometer, which is on board the MRO, scientists managed to analyze the reflected sunlight and determine the composition of the substances of these bands, as well as detect molecular water in the structure of the minerals that make them up. As for the possible source of this water, a clear explanation has not yet been found. It can be formed from underground ice that melts upon contact with salts or salty aquifers, or it can condense from the atmosphere of Mars [26, 27].

NASA's interplanetary probe Cassini discovered an ocean with salt water in the bowels of one of Saturn's satellites, Enceladus [28]. In 2005, Cassini discovered on Enceladus jets of water ice particles and steam, which are emitted into space from parallel cracks near the south pole – the so-called tiger stripes. The question of the source of this steam and ice was being considered.

In 2009, with the help of Cassini, scientists studied one of Saturn's rings, the E ring, formed by ice particles ejected by Enceladus. Now, scientists have analyzed relatively fresh ice particles captured by Cassini during its three approaches to Enceladus in 2008 and 2009. As it turned out, the vicinity of Enceladus is dominated by relatively large particles of ice, while almost 90 % of the particles are similar in composition to ocean water and contain large amounts of salts, as well as potassium and sodium. The new data indicate the existence of a reservoir of salt water with a large evaporating surface, which serves as the source of almost all the substance in the emissions, meaning that there is an ocean of salt water below the surface of Enceladus.

Evidence suggests that the ocean on Enceladus resides between the moon's stone core and its icy surface, possibly as deep as 80 kilometers below the surface. This water washes salts from the stone core and rises closer to the surface, where it accumulates. When cracks appear in Enceladus' ice shell, the pressure in the subsurface reservoirs drops sharply, and the water begins to evaporate rapidly and is emitted into space, where it subsequently freezes [28].

In compliance with the data of some researchers, there are significant deposits of water on the Moon, which is there in the form of icy inclusions placed in deep layers of regolith. Previously, scientists believed that water is located mainly in the polar latitudes of the Moon, near the poles of the planet [29]. However, recent studies by NASA have shown that water on the moon is spread over the entire surface, and not limited to the polar regions, as previously thought. Scientists from the Institute of Space Research in Boulder came to such conclusions after analyzing the data of two orbital probes [30, 31].

However, the findings suggest that water is not the same as on Earth and may also be unavailable. Lunar water probably exists mainly as the more reactive hydroxyl, or OH, groups. Since it is more reactive, water on the moon quickly converts chemical compounds. It also attaches to other molecules. This means that water must be extracted from minerals on the Moon before they can be used.

Detailed research will help to understand whether it is possible to use water on the moon as a resource. If it is readily available, it can be taken as a drink water and also converted into oxygen, which can be used for breathing, or hydrogen, which can be used for rocket fuel.

In line with some reports, the conditions on Mars are almost ideal for obtaining oxygen directly from the planet's atmosphere, which is almost 96 % carbon dioxide. It is possible to decompose carbon dioxide into oxygen and carbon monoxide with the help of a low-temperature plasma-ionized gas, the charged particles of which can tear individual ions out of the carbon dioxide molecule, and indirectly contribute to their separation, transferring additional energy to individual atoms in the molecule and increasing the amplitude of molecular vibrations.

Due to the fact that the temperature on Earth is usually relatively high, in terrestrial laboratories, carbon monoxide oxidizes back to carbon dioxide rather quickly. Therefore, this method of obtaining oxygen on Earth is not very effective. On Mars, however, where the average temperature is about minus 60 degrees Celsius, and the pressure is 160 times lower than on Earth, the re-oxidation reaction will take place very slowly, which will give time to separate the oxygen and carbon monoxide and have time to place them in different containers.

Companies that will develop an efficient way of extracting water in space will be able to use it not only for various life support systems and the creation of rocket fuel, but also use it for radiation protection, and will also be able to sell it to others. If the extraction of water and oxygen is successful, the development of other elements and metals on space objects will become much more realistic.

2. Conclusions

The performed analysis of potential alternative ways and sources of obtaining energy carriers and mineral raw materials in outer space was aimed at searching for the most promising space objects and types of resources (energy, mineral, water) for their possible exploration. Asteroids should be recognized as promising space objects for the extraction of mineral raw materials due to their relative availability, peculiarities of their structure, and higher concentrations of minerals. Exactly metal asteroids are the most valuable among them, and rare and rare-earth elements, platinum and metals of the platinum group, nickel, cobalt are the most promising raw materials.

The Moon is a potentially attractive and possible object, on which the processing of the lunar soil – regolith, and the extraction of helium-3 from it can be the most expedient and useful. It should be noted separately that the extraction of helium-3 from the regolith on the Moon is the most realistic for the primary exploration of space resources in view of proximity, potential technological capabilities and the value of the final product.

The main and most important directions of extraction and use of resources in space are 1) life support during the exploration of space objects, 2) energy supply, 3) extraction and beneficiation of minerals, 4) chemical and biological production.

Issues of life support involve providing, first of all, oxygen and water. For energy supply purposes, it is advisable to consider helium-3 (helion), water, oxygen, hydrogen, and methane as potential sources.

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ОГЛЯД ПОТЕНЦІЙНИХ ДЖЕРЕЛ ОТРИМАННЯ ЕНЕРГОНОСІЇВ І МІНЕРАЛЬНОЇ СИРОВИНИ У КОСМІЧНОМУ ПРОСТОРІ

Безручко К.А.

Анотація. Проблема ресурсного забезпечення на Землі включає в себе три основних аспекти – виснаження внаслідок тривалої розробки у великих обсягах невідновлюваних ресурсів, дефіцит окремих видів ресурсів, завдяки їх рідкісності та незначним концентраціям, висока дорожнеча вилучення і збагачення за низкою чинників, у тому числі умов залягання та недосконалості технологій. Ресурси в цілому це усі види ресурсів − енергетичні, мінеральні, водні та окремо кисень. Одним з можливих напрямків пошуків альтернативних нетрадиційних джерел енергії та мінеральної сировини є космічні об'єкти. Освоєння космосу допоможе вирішити цілий ряд глобальних проблем людства, в числі яких: демографічна, продовольча, енергетична, сировинна та екологічна.

Мета роботи – обґрунтування необхідності пошуку потенційних альтернативних шляхів отримання енергоносіїв і мінеральної сировини нетрадиційного типу та визначення їх можливих джерел у космічному просторі.

На засадах аналітичного огляду потенційних альтернативних шляхів та джерел отримання енергоносіїв і мінеральної сировини нетрадиційного типу обгрунтовано, що дослідження космічних об'єктів (планет, супутників, комет, астероїдів), спрямовані на пошук потенційних альтернативних джерел отримання енергоносіїв і мінеральної сировини нетрадиційного типу є актуальними. Підтвердженням актуальності даного напрямку є не тільки розробка відповідних технологій освоєння космічних об'єктів, але і розвиток та вдосконалення юридично-правової бази, яка регламентує освоєння космосу. Основними найважливішими напрямками досліджень є життєзабезпечення при освоєнні космічних об'єктів, енергозабезпечення, видобуток і збагачення корисних копалин, хімічне та біологічне виробництво. Питання життєзабезпечення передбачають забезпечення, в першу чергу, киснем та водою. Для енергозабезпечення як потенційні джерела доцільно розглядати гелій-3 (Не-3), воду, кисень, водень, метан. Найбільш перспективними мінеральними ресурсами у космосі є рідкісні та рідкісноземельні елементи, платина та метали платинової групи, нікель, кобальт. Доведено, що найбільш перспективними космічними об'єктами для видобутку мінеральної сировини є астероїди через відносну доступність, особливості своєї будови та більш високі концентрації корисних копалин.

Ключові слова: космос, планети, супутники, астероїди, енергоносії, мінеральна сировина.