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On the influence of the trace element composition of regoliths on the labor safety of astronauts on the Moon

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Introduction. The problem of using near-Earth space to meet various human needs, including the development of minerals, especially on the Moon, is becoming relevant, which increases the importance of research on occupational safety in these conditions.

The study aims to research the trace element composition of regoliths in comparison with terrestrial rocks and its significance for the safety of astronauts on the lunar surface.

Materials and methods. The researchers evaluated the trace element composition of the regolith by calculating the concentration coefficients and the quality drop coefficient. When identifying homogeneous classes of regoliths by concentrations of 38 chemical elements, we used computer technology to classify multidimensional observations under conditions of self-organization.

Results. We know that the concentrations of many trace elements in regoliths significantly exceed their concentrations in terrestrial soils. Calculated for the Luna-16 and Luna-24 marine regoliths, as well as for Apollo-11 and Apollo-12, the quality reduction coefficient varies from 27 to 100, which corresponds to the "crisis" category. This indicates that the content of trace elements in the regolith ranges from weekly critical (27 for the Luna-16 regolith) to highly critical (100 for the Apollo-12 regolith). The researchers identified trace elements whose concentrations in lunar regoliths significantly exceed their concentrations in terrestrial soils: Cr, Be, Co, Sc, Ho, Se, Ni, Au, Ag, Er, Tm, Y, Sm, Gd, Tb, Dy Yb, Lu, Cd, Zr, Sr, Ce, Pr, Nd, Eu. Trace trace elements are included in the group of substances with allergenic, fibrogenic and carcinogenic effects and can have a negative impact on the health of future lunar colonists.

Limitations. The authors have conducted the study for the composition of regolith on the surface of the Moon and did not cover aspects of human protection from lunar dust by space stations, structures, spacesuits and special equipment.

Conclusion. *When assessing the impact of environmental factors on the safety of astronauts during the colonization of the Moon, attention should be paid to the toxicological aspects of working conditions, in particular the trace element composition of regoliths and lunar dust.*

Keywords: *lunar dust; regolith; trace element composition; lunar colonists; occupational safety; health status*

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Introduction. Occupational health covers all new areas of human activity. Currently, the problem of using near-Earth space to meet various human needs, including the development of minerals and, above all, on the Moon, is becoming urgent. There are many works that outline projects for the exploration of the Moon, Mars and other planets, for the construction of industrial, residential and storage facilities there from local materials. Researchers consider the extraction of various minerals on the moon as a priority [1–7]. Many space agencies of countries such as Russia, China, USA, Japan, India, and the EU are planning to explore the Moon.

The stay of astronauts on the Moon is associated with a high risk to health due to a number of adverse factors: the absence of a gaseous atmosphere and oxygen, sudden temperature changes (from –170 to +130°C), hypogravity, high levels of galactic radiation and solar radiation, etc. [6, 8, 9]. The microelement composition of the lunar soil — regolith — will have a significant negative impact on the health of astronauts [10].

The aim of the study is to research the trace element composition of regoliths in comparison with terrestrial rocks and its significance for the safety of astronauts on the surface of the Moon.

Materials and methods. Scientists used Clark concentrations of trace elements in the Earth's soil [11, 12] and in regolith delivered by the Luna and Apollo space expeditions [1–4, 13–16], also: "Luna-16" (L-16) — the northeastern part of the Sea of Plenty (Mare Foecunditatis), "Luna-24" (L-24) — the southeastern part of the Sea of Crises (Mare Crisium), "Apollo-11" (A-11) — The Sea of Tranquility (Mare Tranquillitatis); "Apollo-12" (A-12) — the Ocean of Storms (Oceanus Procellarum).

The authors have evaluated the quality of the chemical composition of regoliths and the possible effect of trace elements in high concentrations on the health of astronauts using the method known in geochemistry and geoecology for calculating the concentration coefficient (K_i) and the quality reduction coefficient (PC) [17, 18]. At the same time, we have five levels (categories) of chemical hazards: norm, risk, crisis, disaster and catastrophe.

The concentration coefficient of the i-th component is calculated by the following formula:

$$K_i = C_i/C_K \quad (1),$$

where C_i is the concentration of the component in the regolith;

C_K is the Clark concentration of the component in the earth's soil.

The quality of regoliths for n components is estimated by the quality reduction coefficient (P_C):

$$P_C = \Sigma_i K_i - (n-1) \quad (2).$$

The developed quality reduction coefficient (P_C) [17, 18] makes it possible to evaluate any types of natural and artificial objects (soils, air, water, rocks, products, plants, etc.) by their chemical composition. The gradations of this coefficient correspond to the levels of danger of the content of trace elements of the lunar soil when colonists work in direct contact with lunar dust ***(Table 1)***.

Table 1

Categories (levels) of danger of colonists' labor

Quality reduction coefficient (P_C)	Danger levels
<2	Norm
≥2–16	Risk
≥16–128	Crisis
≥128–1024	Disaster
≥1024	The Great disaster

When studying new information, each researcher understands that it is necessary to classify observations that have many features. In relation to the chemical composition of lunar regoliths, scientists used an original innovative computer technology — the G-method [19] of classification of multidimensional observations (isolation of homogeneous aggregates).This method allows the construction of classification in the absence of a priori information about the taxonomic structure of observations (the task of self-organization without a teacher); unlimited ratio between the number of features (M) and the number of observations (N); use of dependent features; allocation of taxonomic structures of various levels (types, classes, etc.).

Results and discussion. ***Characteristics of classes of trace elements.*** According to the value of the concentration coefficient K_i using the G-method computer technology, homogeneous classes of trace elements in regoliths delivered by the Luna-16, Luna-24, Apollo-11 and Apollo-12 space expeditions were identified. The coefficient shows how many times the concentration of a trace element in a lunar sample is greater than its concentration in the earth's soil [11, 12, 22]. ***Table 2*** shows the results of the classification of trace elements with the allocation of homogeneous classes by concentration coefficient.

In total, we have identified 10 classes of chemical elements, depending on the level of their concentration in regoliths. In the first four classes, the concentrations of trace elements in regoliths (14 trace elements) do not exceed their concentrations in the earth's soil. In the next six classes, 25 trace elements have a high concentration, as a result of which the composition of such lunar dust can have a negative impact on the health of future lunar colonists. The element chromium has a very high Ki value and is therefore allocated to a class with an abnormally high concentration.

According to the classification results, the researchers assessed the quality of the lunar regolith based on the concentration of 25 "critical" trace elements of grades 5–10: Cr, Be, Co, Sc, Ho, Se, Ni, Au, Ag, Er, Tm, Y Sm, Gd, Tb, Dy, Yb, Lu, Cd, Zr, Sr, Ce, Pr, Nd, Eu.

Assessment of the quality of lunar regoliths. On the Moon, astronauts plan to build residential, industrial and storage facilities from regoliths, move along their surface, mining is mainly planned from regoliths.

All this makes it necessary to assess the quality of regoliths by calculating the hazard levels of chemicals based on the total indicator of PC quality reduction. ***Table 3*** shows the calculation of this indicator by the value of the concentration coefficient for 25 "critical" trace elements. For example, for chromium, this coefficient reaches a value of 33.4, for beryllium — 8.3. for nickel — 14, etc. ***(Table 3)***.

According to the results of calculations of the quality drop coefficient (Pic) for individual trace elements ***(Tables 1 and 3)*** concentrations of six trace elements (Cr, Be, Co, Sc, Ho, Ni) are classified as "crisis", concentrations of fourteen elements (Au, Ag, Er, Tm, Y Sm, Gd, Tb, Se, Dy Yb, Nd, Pr) are classified as "risk"), to the category "norm" — five elements (Cd, Zr, Sr, Ce, Eu).

Calculated for the Luna-16 and 24, Apollo-11 and twelve expeditions, the coefficient of decline in the quality of P_C regoliths corresponds to the "crisis" category and varies from

Table 2

Homogeneous classes of trace elements by size K_i

Class	L-16	L-24	A-11	A-12	Trace elements	Concentration level
1	0.03	0.02	0.03	0.15	*Cs, Rb, As*	Very low
2	0.3	0.12	0.31	0.15	*Zn, Ga, Pb*	Low
3	0.7	0.1	0.3	0.5	*Cu, Sn, Sb, W, La*	Moderately low
4	0.45	0.58	0.53	0.78	*Ba, V, W*	Moderately low
5	1.1	0.3	1.0	1.4	*Cd, Zr, Sr, Ce, Pr, Nd, Eu*	Moderately high
6	2.4	0.7	3.6	4.2	*Y, Sm, Gd, Tb, Dy Yb, Lu*	High
7	3.4	0.9	2.9	4.8	*Ag, Er, Tm*	High
8	5.85	3.9	6.7	6.2	*Be, Co, Sc, Ho*	Very high
9	3.8	9.2	5.5	4.2	*Se, Ni, Au*	Very high
10	29.6	31.4	26.1	32.5	*Cr*	Abnormally high

Table 3

Evaluation of regolith quality

Element	Coefficients of K_i concentration in regoliths					Pic
	L-16	L-24	A-11	A-12	Total	
Cr	28.6	33.4	26.1	32.5	121	118
Be	8.30	3.30	7.00	5.67	24	21
Co	5.13	6.25	3.40	5.19	20	17
Sc	5 30	4.70	8.70	5.30	24	21
Ho	4.67	1.50	7.57	8.67	22	19
Se	0.90	12.0	0.24	0.77	14	11
Ni	8.50	8.00	14.0	10.0	41	38
Au	2.00	7.50	2.10	1.80	13	10
Ag	5.60	0.800	2.00	3.40	12	9
Er	2.90	1.25	4.75	7.90	17	14
Tm	1.61	0.500	2.00	3.00	7	4
Y	1.45	0.620	3.25	3.40	9	6
Sm	3.00	0.500	2.40	2.90	9	6
Gd	2.90	1.00	5.10	4.50	14	11
Tb	1.84	0.760	4.15	6.15	13	10
Dy	3.10	0.880	4.25	5.05	13	10
Yb	1.97	0.670	2.77	3.53	9	6
Lu	2.75	0.80	3.25	3.75	11	8
Cd	1.50	0.430	0.86	0.47	3	0
Zr	0.89	0.33	1.50	1.60	4	1
Sr	0.73	0.33	0.59	0.47	2	0
Ce	0.68	0.20	0.78	1.43	3	0
Pr	1.23	0.20	0.71	2.42	5	2
Nd	1.08	0.30	1.42	2.18	5	2
Eu	1.47	0.40	1.26	1.20	4	1
P_C	27	58	87	100	—	—

Note: Pic is the coefficient of the drop in the quality of individual trace elements; P_C is the coefficient of the drop in the quality of the trace element composition of regoliths.

27 to 100. This indicates that, according to the trace element composition of lunar dust, the content of trace elements ***(Tables 1 and 3)*** range from weakly critical (twenty seven for the Luna 16 regolith) to highly critical (100 for the Apollo twelve regolith) levels.

Regolith, lunar dust and astronauts' vital activity. The data obtained indicate the possibility of a negative impact on the health and safety of astronauts on the Moon of trace elements whose concentrations in regoliths significantly exceed their concentrations in terrestrial soils. So, it is known that the lack, excess or imbalance of trace elements in the environment has a significant impact on human health. The new scientific disciplines "Medical Geology" and "Medical Geochemistry" are designed to study possible diseases associated with high concentrations of trace elements in rocks on the surface of both the earth and other cosmic bodies [20–22]. As you can see, this is quite relevant for regoliths and lunar dust. For example, all six trace elements classified as "crisis" are toxic, genotoxic and carcinogenic. With chronic exposure in elevated concentrations, they can lead to the development of specific diseases — berylliosis, dermatitis, stomach ulcer, sarcoma, asthma and others. All lanthanides found in regoliths also belong to toxic elements.

The review papers [8, 23] comprehensively characterize the properties of lunar dust and consider various aspects of its potential danger. More than 95% of the regolith mass consists of particles less than one mm. Particles less than 100 microns belong to the lunar dust. The average size of lunar dust is from 40 to 100 microns, and these particles make up about half the mass of the regolith. The shape of dust particles is diverse with pronounced pointed edges, which causes their very high penetrating power. It turned out that the rotation speed of levitating micron and submicron particles on the Moon can be millions of revolutions per second. This feature determines the high aggressiveness of the impact on the surface of the instruments, the ability to penetrate through hermetic seals and the potential danger to astronauts during their work on the Moon. Thus, dust vortices combined with the abrasive properties of dust led to the fact that the dials of many devices were so scratched in a short time that it was impossible to read the readings.

The influence of lunar dust on human health remains an insufficiently studied factor of labor on the surface of the Moon. All astronauts noted a sharp specific smell of dust, reminiscent of gunpowder, complained of watery eyes, sore throat, cough and unanimously claimed that the dust problem is the number one problem during their stay on the Moon.

In an analytical article [10], scientists examined in detail the toxicology of lunar dust in the aspect of possible occupational pathology in the study of the Moon.

The authors summarized extensive literature data on the toxicity of lunar dust, including general toxicity, pulmonotoxicity, cardiotoxicity, local irritant effect, some specific types of toxicity, as well as bioavailability and kinetics of dust particles in the body: "The systematization of these data suggests that allergic reactions, irritation of the eyes, mucous membranes of the nasopharynx and respiratory tract can be considered as possible direct consequences of exposure to lunar dust. As delayed effects, disturbances of external respiration, mental and physical performance are possible. As long-term consequences, the development of oncological and neurodegenerative diseases is possible. When inhaling moon dust, the lungs are a target organ of the first level, the brain as a target organ of the second level, the heart as a target organ of the third level" [10].

It is important to note that most experimental studies of the toxicity of lunar dust were conducted by scientists on crushed basalts — terrestrial analogues of lunar soil, which are called imitators or imitators of lunar dust. The average particle diameter of the simulators was 86 microns. However, the greatest danger for astronauts on the Moon is represented by particles of five-ten microns in size, which settle in the middle sections of the lungs, and smaller ones (0.5–5 microns) penetrate into the alveoli. In this regard, the researchers raised the question of the need to create a Russian lunar dust simulator [24], including for biomedical research [25].

Conclusion. *Currently, many countries pay great attention to the problem of using space natural resources and, above all, minerals on the Moon, researchers have proposed numerous projects for the development of the lunar surface. At the same time, astronauts are expected to come into contact with a number of negative factors on the Moon during work, including lunar dust. The study of the physico-mechanical and toxicological properties of lunar regoliths, the trace element composition of lunar dust is extremely relevant for assessing the safety of astronauts during the colonization of the Moon. Scientists have found that the concentration of many trace elements in regoliths significantly exceeds their concentrations in terrestrial soils, and this can negatively affect the well-being and health of colonists.*

As a result of the conducted research, scientists assessed the quality of the chemical composition of lunar regoliths, classified trace elements according to their concentration in the marine regoliths of the Luna and Apollo space expeditions using innovative computer technologies, identified potentially dangerous trace elements, their possible influence on the occurrence of pathological abnormalities. The authors also analyzed the state of health and diseases during the work of astronauts on the Moon. We consider allergic reactions, irritation of the eyes, mucous membranes of the nasopharynx, respiratory tract, impaired respiratory functions, mental and physical performance as possible multi-system consequences of exposure to lunar dust on astronauts. This determines the need to develop and implement measures to protect astronauts from lunar dust as a negative production factor.

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