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THE "TOR-I" APPARATUS FOR INVESTIGATING LUNAR GROUND

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In order to solve engineering research problems involved in the movement of vehicles and man over the lunar surface, working lunar ground, constructing stations, landing sites, etc., it is necessary to know such parameters of the lunar ground as the density, cohesion, carrying capacity, static and dynamic friction coefficients, abrasivity (resistance to wear), resistivity, heat conductivity, and others. Under terrestrial conditions there are standard instruments and methods which can be used with several hundreds of grams of matter for rapid and reliable determination of the properties mentioned above. But what about the lunar matter which must be delivered to the earth by the "Luna-16" automatic station? At first glance it is all very simple: take terrestrial instruments and methods, subject them to lunar climatic conditions (that is, a deep vacuum, temperature range of ±150°C, exposure to radiation) and determine the pertinent parameters.

However, it is found that as soon as a terrestrial instrument is subjected to a deep vacuum it ceases to function. The problem is that instruments and mechanisms usually consist of gears, roller and ball bearings, and all kinds of guides and cams which operate reliably with liquid or consistent lubrication which cannot be used in a vacuum due to rapid evaporation and a marked increase in viscosity beginning at a temperature of -70°C. If extreme measures are taken (let the instrument be ruined), that is, exclude lubricants and operate the instrument dry, under terrestrial conditions it can function for but a few hours. In this process the role of a temporary lubricant will be played by oxide films which form as a result of the interaction between oxygen and the surfaces of the working parts. This process is impossible in

a vacuum because the initial terrestrial oxide film is worn off in a few minutes, quickly forming perfectly clean surfaces with active centers of molecular forces at the contact points, which immediately leads to jamming (cold welding of materials) and instrument malfunctioning.

At the same time it was necessary to solve a methodological difficulty attributable to the fact that for the investigations, as a result of the uniqueness of the lunar ground, only two grams of matter were obtained instead of several hundred, and nevertheless the results obtained with small samples must be reliable and trustworthy because this is the governing factor in designing and constructing the instrument.

Long before the "Luna-16" automatic station was launched to the moon scientists and engineers proceeded to the creation of a "nonterrestrial" instrument whose design after preliminary theoretical design work was unexpectedly taken from an ordinary child's toy: "geese around a feeding trough," alternately feeding from it while someone tugged at the cord by which they were tied.

The instrument for investigating the lunar ground was named the "TOR-I." A trough containing the material to be investigated, mounted on a rotating vertical axis, is mounted at the center of a baseplate. Around this trough there are eight actuating manipulators ("geese") with individual drives (cord) and sensors which interact in a definite sequence with the investigated rock and carry information on density, cohesion, etc. (Fig. 1).

The lunar temperature regime in the samples is maintained using a heater and liquid nitrogen which has a temperature of -196°C and flows through spiral tubes mounted in the trough. The moving couplings and friction units of these mechanisms employ special solid lubricants which will not evaporate in a vacuum and which retain their lubricating properties in the temperature range from -200° to +1,000°C. The "TOR-I" instrument is placed in a high-vacuum chamber with a volume of 900 liters (Fig. 2) where the operator wearing rubber gloves through a hatch opens a container with lunar ground in a medium with an inert gas and places it in the central trough. Then the hatch is closed and the chamber is evacuated by means of powerful pumps to a high vacuum, close to that prevailing on the moon. Windows and internal and external illumination are provided for visual observation.

First the "TOR-I" instrument and the method were tested using two postulated analogues (pulverized basalt, ground in a ball mill, and andesite-basalt sand), strewn through a spec-

ial calibrating screen with openings close to the characteristic dimensions of the particles of lunar ground. The results of experiments with the "TOR-I" instrument were compared with the results obtained using standard instruments and samples and future correlation coefficients were computed for determining the scaling factor.

The lunar ground constituted a fine-grained dark gray powder with a mean grain size of about 0.01-0.1 mm and a density of 1.3 g/m^3 which was readily shaped and fused into individual tiny loose lumps. It formed a natural slope of about 45° and was easily strewn through a sieve. The ground deformation which arises due to the simultaneous action of the vertical force (force exerted by weight) and the shearing force in the horizontal direction (thrust imparted through the treads or wheels) was studied by a method similar to some degree to the method for operation of the penetrometer carried aboard the "Lunokhod-1."

The ground to be investigated was poured into the central trough with a ribbed bottom. It was compressed from above by a ribbed disk with a fixed compressive force. With rotation of the trough the upper disk tended, due to the cohesivity of the ground, to turn about the vertical axis. A tensometer, constituting a flat spring with glued-on wire resistance sensors, connected to an amplifier and recorder, was inserted for preventing its rotation. For the lunar ground the shear strength was 0.034-0.302 kg/cm^2, depending on the compressive force; for terrestrial analogues it was: andesite-basalt sand -- 0.043-0.282 kg/cm^2 and for pulverized basalt -- 0.023-0.304 kg/cm^2.

Many contradictory opinions have been expressed concerning the adhesion of lunar ground: some scientists have stated that as soon as cosmonauts or lunar vehicles come into contact with the lunar surface they will stick to it due to the molecular forces which operate actively in a vacuum and further movement will be difficult. Others, having some experience with terrestrial tests of rocks in a vacuum, were not so sceptical.

The American astronauts and the Soviet "Lunokhod-1" dissipated all doubts: movement is possible and there is no sticking of the ground to the wheels and to the foot as happens in rainy weather on a clayey road. For this reason it was interesting to register the numerical values of friction of different materials on the lunar ground, which for the most part is determined by the molecular forces acting at the points of actual contact. But the researchers were faced with

a difficulty: is the lunar ground possibly unconsolidated? A solution was found: lunar ground and its analogues were strewn in a medium of inert gas on a metallic backing to which a layer of epoxy resin had first been applied, that is, something similar to sandpaper was prepared, just like that which is used everyday for such purposes as removing rust. The samples were dried in the chamber and placed in the "TOR-I" instrument.

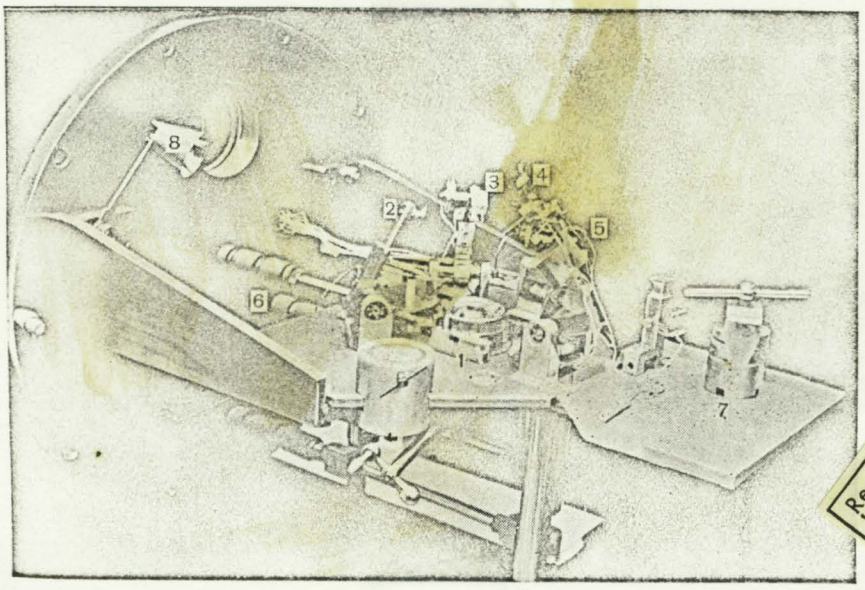

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Fig. 1. General appearance of the "TOR-I" instrument: 1) central trough; 2, 3, 4, 5, 6) manipulators for determining the electric properties, density, carrying capacity, abrasivity and friction coefficients and shearing strength; 7) container with lunar ground; 8) light source.

Measurements of the friction coefficients were made using a system which can be represented graphically in the form of gramophone records and needles, that is, a sample of the investigated material is pressed against a disk with the lunar rock with a stipulated force and during rotation of the disk the developing friction is registered. Fourteen materials were investigated: they ranged from rubbers and leathers through the solid alloys used in space engineering. In all cases the coefficients of friction over the lunar ground differed little from the coefficients of friction for andesitic-basaltic sand or pulverized basalt (see Table 1). The result (the approximate equality of the friction coefficients for the lunar ground and analogues) is a very important and practical finding since now the testing of mechanisms which in the future will move along the lunar surface or work lunar ground

can be successfully and reliably carried out in vacuum chambers using terrestrial analogues.

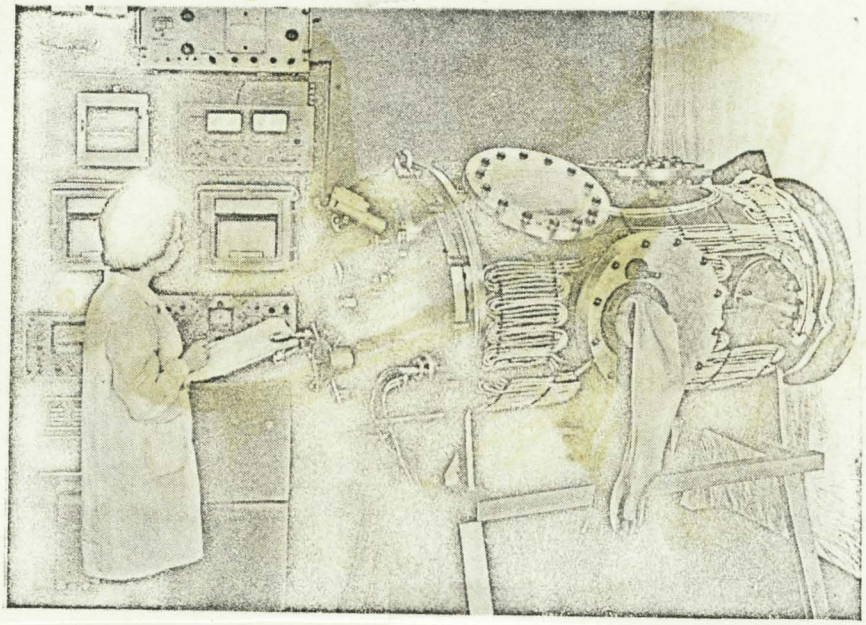

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Fig. 2. High-vacuum receiving chamber of "TOR-I" instrument.

Friction is always accompanied by wear and therefore the particles of lunar ground will remove microshavings from the surfaces with which they come into contact. Accordingly, it was necessary to ascertain the quantity of matter which can be carried away in a unit time, comparing lunar ground against terrestrial analogues. In engineering such tests are called abrasivity determinations.

Abrasivity was determined by two independent methods: in the first case from the weight loss of a metallic standard (duralumin) sample worn from the rotating butt surface of a cylinder which as described above, was covered by a layer of rock; in the second case abrasivity was evaluated from the degree of darkening of the surface of a plastic plate, also wearing on the end of a cylinder with a layer of lunar ground and its analogues. The degree of darkening was determined using a light source (neon-helium laser), a system of lenses creating a parallel beam of light which fell perpendicularly first on a polished plastic plate and then onto a plate which was subjected to abrasive processing. The scattered light on the arising rough surface of the plate was discriminated in a solid angle by means of a system of lenses and diaphragms and

registered with a photomultiplier and microammeter. The degree of attenuation of the light flux also served in this case as a measure of abrasivity.

Table 1

Инженерно-физические свойства лунного реголита и земных аналогов (1)

Измеренные параметры (2)	(3) Лунный реголит	Земные аналоги (4)	
		(5) базальт размельченный	(6) андезито-базальтовая смесь
(7) **Сопротивление сдвигу**			
(8) при разных сжимающих напряжениях, кг/см²			
0,052	0,034	0,023	0,043
0,238	0,169	0,147	0,154
0,550	0,302	0,304	0,282
(9) **Коэффициенты трения**			
(10) титановый сплав	0,35	0,3	0,3
(11) магниевый сплав	0,3	0,25	0,28
(12) кожа натуральная	0,4	0,5	0,45
(13) селиконовая резина	0,45	0,5	0,6
(14) **Абразивность**			
(15) вес, мг	3,7	4,0	4,1
(16) помутнение К, %	4,5	4,4	4,8
(17) **Микротвердость, кг/мм²**	800	791	719
(18) **Электрические параметры**			
(19) диэлектрическая проницаемость	3,39	3,97	3,37
(20) тангенсы угла диэлектрических потерь	$1,6 \cdot 10^{-2}$	$1,1 \cdot 10^{-2}$	$1,08 \cdot 10^{-2}$
(21) удельное электрическое сопротивление, ом·м	$3,42 \cdot 10^{6}$	$4,15 \cdot 10$	$4,9 \cdot 10^{6}$

1) Engineering-Physical Properties of Lunar Regolith and Terrestrial Analogues; 2) Measured parameters; 3) Lunar regolith; 4) Terrestrial analogues; 5) pulverized basalt; 6) andesite-basalt mixture; 7) Shearing strength; 8) for different compressive stresses, kg/cm²; 9) Friction coefficients; 10) titanium alloy; 11) magnesium alloy; 12) natural leather; 13) silicone rubber; 14) Abrasivity; 15) weight, mg; 16) darkening K, %; 17) Microhardness, kg/mm²; 18) Electric parameters; 19) dielectric constant; 20) tangent of dielectric losses; 21) resistivity, ohms·m

The use of the methods described above for the first time made it possible to determine the abrasive properties of the lunar ground. It was found that in the investigated type of lunar regolith abrasivity is relatively small and is approximately at the same level as for the selected analogues, but in this case it is substantially less, for example, than

for quartz sand.

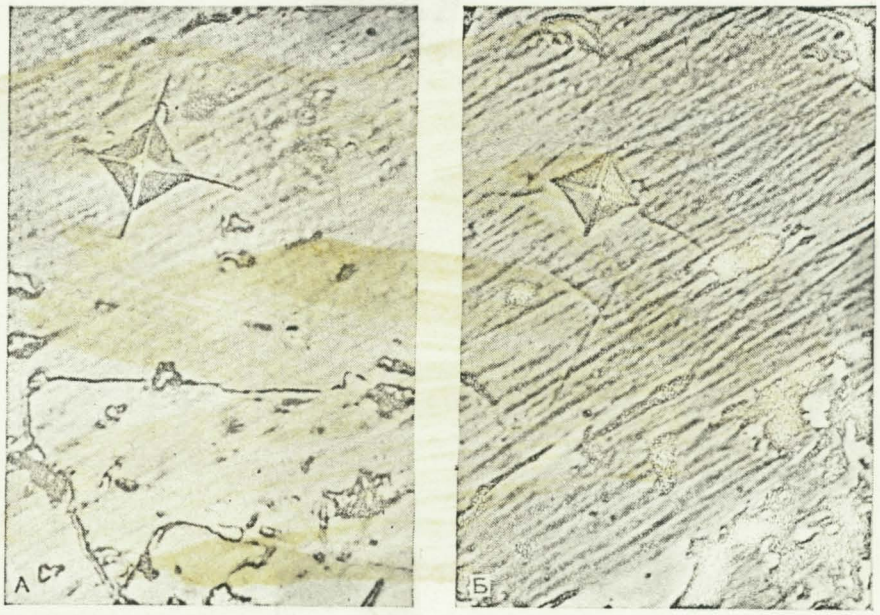

Fig. 3. Imprints of tetrahedral pyramid with a magnification of 800 times: A) in basalt, B) in lunar ground.

It is known that abrasivity is dependent to a significant degree on the hardness of particles. Accordingly, studies were made of the microhardness of individual grains of lunar regolith and its analogues.

Microhardness was determined by the punching method: a tetrahedral diamond pyramid was driven into individual grains of rock held in epoxy resin, leaving in the material the mark of a square with diagonals (Fig. 3) which were examined and measured with an 800 magnification; the harder the material, the shorter was the length of the diagonals of the imprints (see Table 1).

The correctness of the instrument readings was checked prior to each series of measurements by determining the microhardness of a sodium chloride crystal.

Until now the study of the electric properties of the upper cover of the moon has been done from the earth's surface by studying its characteristic radio emission and also on the basis of direct radar measurements. After returning the lunar ground to the earth it became possible to make a direct study of its electric properties. For this purpose there was a mini-

aturized plane capacitor on the "TOR-I" instrument; it consisted of two metal polished circular plates (capacitor plates). On the lower plate there is a ring of a high-frequency dielectric onto which the lunar ground was poured, whereas the upper plate was attached to the lever of a manipulator and could be pressed against the ring with a stipulated force. The mobility of the upper electrode facilitated the evacuation of helium from the rock. A Q-meter was used in measuring the capacitance and quality of this sample and they were used in computing resistivity, the relative dielectric constant, etc.

The results of the experiments cited in Table 1 once again confirmed that the lunar ground is not an exotic substance and in its electric properties differs little from the selected analogues. It should be noted that investigation of the electric properties is of considerable importance for determining some characteristics of the lunar surface by the radar method in which a study is made of the process of reflection of radio pulses of different frequency by the lunar surface. We will not dwell in detail on investigations of the thermophysical properties; we will only note that the results obtained using the "TOR-I" instrument by the instantaneous source method and by the periodic heat input method coincide well with the results described in Priroda[1] and once again confirm that the moon is surrounded by a reliable "warm coat."

Investigations of lunar matter and its analogues on the "TOR-I" instrument made it possible to draw the following fundamental conclusions. First, the studied type of lunar ground in its engineering and physical characteristics was close to some terrestrial rocks selected as proposed analogues, specifically to pulverized basalt and andesitic-basaltic sand. This means that the indicated substances can be successfully used in the terrestrial testing of machines and mechanisms designed for mechanical interaction with the lunar ground. Second, the good agreement between the "TOR-I" results and data obtained by standard methods using considerably greater quantities of rock confirmed the correctness of the new methods and thereby the possibility of using but a small quantity of ground for its speedy analysis. Third, the high reliability of the "TOR-I" instrument and its universality, noted in carrying out the entire complex of investigations of lunar ground and its analogues, confirmed the possibility of using our instrument for the complex investigation of different types of ground under a wide range of conditions.

[1] See A. P. Vinogradov, "Preliminary Data on the Lunar Ground Returned by the 'Luna-16' Automatic Station," Priroda (Nature), No. 3, 1971.