Determination of the thermophysical characteristics of the Moon soil with depthed thermoprobes

K K Dudkin¹, O M Alifanov² and A V Babaitsev²

¹ Lavochkin Association, Russia, 141402 Moscow region, Khimki, Leningradskaya 24
² Moscow Aviation Institute (National Research University), Russia, 125993 Moscow, Volokolamskoye-shosse 4

Abstract. Determination of thermophysical characteristics of the lunar soil is an important scientific task. This article examined three options for penetrating thermal probe design for measuring the thermal properties of soil. A numerical simulation was carried out, and revealed distortion of temperature distribution, which can be caused by design of the thermal probe and affect the measurements, was studied. The first scheme is a rod thermal probe, which is similar to the thermal probe used in Apollo missions. The second scheme is an improved rod thermal probe, with a detachable heater with an autonomous power source at the lower end of the rod. The third scheme is a more complicated design made by a series of autonomous heaters and temperature sensors that are fixed in a pre-drilled well and have no thermal connection. According to the calculation results, the rod thermal probe used in the Apollo missions and the thermal probe with a detachable heater showed the same level of temperature distribution distortion. The influence of the design of the split thermal probe was by 30% lower. The last type of the probe may allow to improve the accuracy of measurements of the TPC of the lunar soil.

1. Introduction

One of the most important problems in the study of the Moon is an evolution of thermal processes, i.e. understanding how the processes of heat transfer and the distribution of temperature zones inside the Moon over a certain geological time have changed. Studying the thermal processes within the planet is largely a key to understanding its evolution as a whole. The thermal regime inside the Moon determines the depth and duration of the main processes of differentiation of lunar substance, as well as global tectonic processes, such as compression, expansion, and volcanic activity.

Determination of the thermophysical characteristics (TPC) of the lunar soil is an important scientific problem. For example, to determine the density of the heat flux from inside the Moon, knowledge of the thermal characteristics of the lunar soil is necessary for most cases. The depth distribution of these characteristics is important in particular.

Understanding the distribution of these characteristics, in addition to scientific interest, is valuable for solving practical problems such as building a lunar base or mining on the lunar surface.

To determine the thermal characteristics, an approach based on the application of algorithms for solving inverse heat conduction problems (OST) is supposed to be used [1].
Thermophysical characteristics of the lunar soil (TPC) were determined in experiments carried on both in laboratories and directly on the surface of the Moon. In vivo measurements were been carried out only in the missions Apollo 15 and Apollo 17.

To measure the temperature and thermal conductivity of the soil, two thermal probes were been put into pre-drilled wells: at Apollo-15 station - to depths of 1.0 and 1.4 m, at Apollo-17 - to depths of 2.3 m (Figure 1). In these probes, 8 platinum resistance thermometers and 4 thermocouples were been installed for measurements at 11 depth levels below the surface. Four heaters controlled from the ground were been installed into the same units with four thermometers.

Temperature data from all thermometers were been transmitted to the Earth every 432 seconds.

![HEAT FLOW EXPERIMENT](image)

**Fig. 1.** The scheme of thermoprobe experiments in «Apollo 15» и «Apollo 17» missions [2]

Thermal conductivity was determined in three different experiments. The first method is based on cooling the probes from an initial temperature, which was higher than the surrounding soil; this made it possible to determine the thermal conductivity with initial thermal energy contained in the probe and transferred to the well. In the second method measurements were been made immediately in the wells using heaters. Thermal conductivity was calculated from the change of soil temperature after 20 hours of observation. The thermal probe described above allowed to measure the TPC at all sensors, i.e., at 8 different depths. In the third experiment, the temperature fluctuations of the daily period studied; they penetrate to a depth of approximately 80 cm, with annual variations influenced by surface temperature are felt at all studied depths. A significant decrease in the amplitude of these oscillations with increasing depth depends on the thermal conductivity of the surrounding soil. However, this method does not give an unambiguous result [3].

In Figure 2, one can see the results of determining the thermal conductivity of the lunar soil depending on depth, obtained in the missions "Apollo 15" and "Apollon-17" [3].
This article provides an analysis of the accuracy of measurements using a rod thermal probe, like one used in the Apollo 15 and Apollo 17 missions, as well as two other promising schemes: a thermal probe with a detachable heater and a section-detachable thermal probe.

2. Analysis of accuracy of measurements with depthed thermal probes

2.1. Penetrating thermal rod probe for measuring the TPC of the lunar soil

The layout of the thermal probe under consideration is similar to that used in the Apollo 15 and Apollo 17 missions. The key element of the design is a rod, in which heaters and thermometers are installed at certain distances (Figure 3).
The rod is placed in a pre-drilled well and after a certain time, sufficient for the rod-soil system to come into temperature equilibrium, heaters of a given power are turned on for a given period of time. By the change in the temperature of the thermometer located at a certain distance from the source, and by solving the inverse problem of thermal conductivity, the thermal characteristics of the soil are found. If two characteristics — thermal conductivity and heat capacity — are to be determined simultaneously, then the uniqueness of the solution can be ensured by measuring not only soil temperatures, but also non-zero heat flux, at least at one point on the well wall.

As one can see, several heaters located along the entire rod of the thermal probe allow determining the thermal characteristics at different levels and simulating layer-by-layer soil models.

The main disadvantage of such a probe when determining thermal properties in natural conditions is the combination of heating and measuring elements in one node. As a result, transferring of a significant amount of thermal energy through the probe elements, instead of through the soil, occurs. This, in turn, can lead to incorrect interpretation of measurement results [4].

A number of mathematical simulations of the direct problem, to obtain the temperature distribution during the experiment, had been done. The calculations were been carried out in the ANSYS Workbench software environment using the finite element method (FEM). The size of the finite elements was chosen to ensure the error of the calculated temperature not exceeding several thousandths of a degree.

Thermal calculations were been done for a section of the rod with one heater located between two parts of the main rod. The model consisted of fiberglass rods and a copper heater. The soil is a single-

Fig. 3. Penetrating thermal rod probe.
layer, with averaged TPC for depths from 0.5 m to 1 m, according to the Apollo missions. Fiberglass for the rod material was chosen as it has a sufficiently low thermal conductivity with acceptable strength characteristics. In their Apollo missions, NASA also used fiberglass as the rod material.

The properties of the materials used in calculations are shown in table 1.

**Table 1.** Properties of used materials for simulating penetrating rod probes

| Name | Material       | Diameter | Height/Length | Thermal conductivity, W/(m* \(C^\circ\)) | Heat capacity, J/(kg* \(C^\circ\)) |
|------|----------------|----------|---------------|----------------------------------------|--------------------------------------|
| Rod  | Fiberglass     | 10 mm    | 90 mm         | 0,4                                    | 1000                                 |
| Heater | Copper alloy | 10 mm    | 10 mm         | 401                                    | 385                                  |
| Soil | -              | -        | -             | 0,017                                  | 600                                  |

It was accepted for calculations:
heater power: 0.1 W;
heating time: 30 minutes;
The initial temperature of the system: minus 23 ° C.

Figure 4 shows the model used in simulating the heat problem.

![Fig. 4. Rod thermoprobe model used in simulating thermal problem](image-url)

Calculations showed that the most of the heat goes into the probe elements, while the soil heats up much weaker.
Then another calculation was carried out, where all the elements of the thermal probe except the heater were excluded from the model, with all other initial data remained the same. Figure 5 shows the temperature distribution after simulation of the two described models.

![Temperature distribution](image)

**Fig. 5.** Temperature distribution in lunar soil and rod thermal probe. Left – calculated with entire rod probe design; right – calculated with heater only.

Based on the calculation results, in both models the temperature on the well wall at a distance of 10 mm from the heater, where the thermometer installed, was found.

In the model with entire probe design, the temperature at the contact point of the temperature sensor and soil was minus 15.59 °C; whereas in the model with only the heater the temperature at the same point was minus 18.67 °C. Deviations of the temperature readings due to the influence of the thermal probe design amounted to 3.1° C. When solving the inverse heat transfer problem, this deviation value can cause significant errors in the determined thermophysical characteristics.

### 2.2. Thermal probe with detachable heater

The idea of a heat probe with a detachable heater is to use all the advantages of a penetrating heat probe and remove the main disadvantage: heat "flowing" along the rod. To do this, it is necessary to divide the probe and heater into two parts that are not thermally interconnected.

This type of thermal probe consists of two parts: a rod with thermometers and a detachable heater (Figure 6). The procedure of operation with such a probe is as follows.

At the first stage, the rod with thermometers and a heater at the end is lowered into the well. Then, the heater is separated from the rod and remains at the bottom of the well. Next, the rod is pushed up a predetermined distance. The heater turns on and measurements begin.
The heater consists of: a housing, batteries, an ohmic heater, and a remote on and off device. After separation, the heater is turned on by command from the Earth and generates a certain amount of heat. The value of the heat flux can be measured using an ammeter according to the following formula:

\[
\frac{dQ}{dt} = I^2R_e
\]

where \(Q\) is an amount of heat, \(t\) is time, \(I\) is an electrical current in the circuit, \(R\) is a resistance of the circuit.

The potential advantage of this scheme is the lack of connection between the heater and the rest of the thermal probe, which supposed to be resulted in less distortion of the temperature distribution. So, one may presume more accurate measurement of the TPC of the soil.

The main disadvantage of this scheme is an ability to determine the TPC only at one depth.

The data of the Apollo 15 and Apollo 17 missions show that the thermal conductivity of the soil changes most strongly in the surface soil layer within a depth of only a few centimeters (Figure 2) [3].

In account of this, the main points for measuring the thermophysical properties of the lunar soil are to be on the surface, and at a certain depth. The described thermal probe is well equipped for such a measurements.

The simulation of the direct non-stationary heat conduction problem is carried out using the FEM using the ANSYS software environment for analyzing the temperature distribution in the soil-thermal probe system. We take the thermophysical properties of the soil are to be typical for a depth of 1-1.5 m, according to the Apollo missions.

The properties of the materials used are presented in table 2.

| Name  | Material          | Diameter | Height/Length | Thermal conductivity, W/(m*\(^{°C}\)) | Heat capacity, J/(kg*\(^{°C}\)) |
|-------|-------------------|----------|---------------|--------------------------------------|----------------------------------|
| Rod   | Fiberglass        | 30 mm    | 460 mm        | 0.4                                  | 1000                             |
| Heater| Copper alloy      | 30 mm    | 30 mm         | 401                                  | 385                              |
| Soil  | Soil              | -        | -             | 0.02                                 | 600                              |
It was accepted for calculations:
- distance from heater to shaft: 10 mm.
- heater power: 0.1 W;
- heating time: 10 hours;
- the initial temperature of the system: minus 23 °C.

Calculations showed that the design also distorts the natural temperature distribution.

In this study, like in previous one, the calculations were been carried out in two ways: with entire probe design taken into calculations, and without all the elements of the thermal probe but the heater; boundary conditions stay the same.

Figure 7 shows the temperature distribution according simulation of the two described models.

![Figure 7. Temperature distribution in soil and the thermal probe with detachable heater. Left – calculations with all elements of the design; right – calculations with heater only.](image)

In each of the models, the temperature on the borehole wall at a distance of 10 mm from the heater, where the thermometer was installed, is determined.

In the model with all elements of the design, the temperature at the contact of the temperature sensor and soil was minus 21.2 °C; whereas in the model with the heater only, the temperature at the same point was minus 18.1 °C. Deviation of temperature readings due to the influence of the design of the thermal probe also amounted to 3.1 °C.

The distortion of the natural temperature distribution by such a thermal probe can be explained by the higher thermal conductivity of the rod (located above the heater) compared to the soil, as well as the large contact area of the rod and soil [4].

2.3. Section-detachable Thermal Probe

The idea of such a thermal probe is to create several separate fully autonomous devices operating in the same system. There will be two types of autonomous devices: a heater and a meter. Here, the word "meter" will mean a device for measuring soil temperature.

The entire system will consist of several meters and heaters placed in a drilled well and fixed at certain distances relative to each other (Figure 8).
The heater consists of: a battery; electronic control unit, which is responsible for turning the device on and off, collecting data on temperature and other various indicators; thermometers that measure the temperature of the device; ohmic heater; transmitter, for remote issuing commands to the electronic unit, as well as receiving various measurement information from it. At the command given remotely, the ohmic heater will turn on and the soil will be heated.

The meter consists of: a battery; electronic control unit, which is responsible for turning the device on and off, collecting data on temperature and other various indicators; temperature sensors measuring soil temperature; transmitter to remotely send commands to the electronic unit, as well as receive various measurement information from it. At a command given remotely, the meter will turn on and transmit data about the temperature of the soil at a predetermined frequency. Thus, it will be possible to track the distribution of temperature versus time.

A section-divided thermal probe has some installation features, namely: the elements of its system must somehow be fixed in the well, which should affect its design. One of possible options is presented below.

Figure 8 shows the design of one of the meters of such a thermal probe. Batteries and the rest of the electronics is planned to install inside the case. Thermal sensors are installed on so-called wings, most likely on its lower and upper parts.
The heater is of a similar design, with the only difference being that ohmic heaters are installed on the entire surface of the wings.

In a transport (non-working) status, all elements of the system (namely, meters and heaters) are fixed on three rods (Figure 10).
Elements are situated at certain distances from each other.

The fixing rods have a mechanism for locking the sliding wings. The wings are able to move apart under the action of a spring located in the upper and lower parts of the unit (Figure 9). Unclenching in different directions, the wings are to fix the unit in the well.

The probe installation procedure is as follows. The entire system in a transport status is lowered into a pre-drilled well. Then the wings on all the elements are unclenched and each of the unit is fixed in the well. Then the rods are removed up. Heaters and meters remain fixed in the well with the help of wings resting on its walls.

Thus, each element of the system does not have thermal contacts with others.

Also, a control module installed in close proximity to the surface is required to operate such a probe (Figure 8). It transfers control signals to heaters and meters in the well, receives information from them and exchanges information, for example, with an orbital vehicle.

A thermal calculation of the direct heat transfer problem was carried out to find out the temperature distribution and evaluate how the probe design affects it.

The properties of the materials used are given in table 3.

| Name                      | Material        | Diameter | Height/Length | Thermal conductivity, W/(m°C) | Heat capacity, J/(kg°C) |
|---------------------------|-----------------|----------|---------------|-------------------------------|------------------------|
| Meter (both sides from the heater) | Stainless steel | 60 mm    | 70 mm         | 15.1                          | 434                    |
| Heater                    | Copper alloy    | 60 mm    | 30 mm         | 401                           | 385                    |
| Soil                      | Soil            | -        | -             | 0.02                          | 600                    |

It was accepted in calculations:
- heater power: 0.1 W;
- heating time: 10 hours;
- the initial temperature of the system: -23 °C.

It should be noted that in the calculations we used simplified models of a heater and a meter in a shape of cylinders. The properties of the soil were taken typical for a depth of 1 meter. The size of the finite elements was chosen for the error in the solution not exceeding several hundredths of a degree.

Calculations showed that the design also distorts the natural temperature distribution.

After the first calculation, as in previous cases, another calculation was carried out with excluding from the model all the elements of the probe design except the heater; all other initial data stay the same.

Figure 11 shows the temperature distribution according to the simulation for the two described models.
As one can see, the heat propagates from the heater at first freely, but then, meeting with the meters, goes into them through the lower edge. As a result, some distortion appears regarding the natural distribution pattern. The distortion can be explained by the greater thermal conductivity of the meters.

Again, in both models the temperature was calculated on the well wall at the installation site of the thermometer, which was located at a distance of 10 mm from the heater.

In the model with entire design, the temperature at the contact point of the temperature sensor and soil was minus 22.75 °C; whereas in the model where only the heater is left under the same conditions, the temperature at the same point was minus 20.43 °C. Deviations of temperature readings due to the influence of the design of the thermal probe amounted to 2.32°C.

3. Conclusion
This article examined three options for penetrating thermal probe circuits for measuring the thermal properties of soil. A mathematical simulation carried out was aimed to study distortions caused by the influence of the design of the thermal probe on the measurements.

According to the calculation results, the rod thermal probe used in the Apollo missions and the thermal probe with a detachable heater showed the same level of temperature distribution distortion. The section-detachable thermal probe design distort temperature distribution by 30% lower. The last type of the thermal probe potentially improves the accuracy of measurements of the thermophysical properties of the lunar soil.

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