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COMPREHENSIVE STUDY OF THERMAL PROPERTIES OF LUNAR CORE SAMPLES

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FINAL TECHNICAL REPORT

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INTRODUCTION

In this research grant, we proposed to make thermal conductivity measurements of the lunar core samples returned by the Apollo missions. The objective of the measurement was to refine the interpretation of the lunar heat-flow data as well as to improve our understanding of the mechanism of heat transfer within the lunar regolith.

The lunar regolith thermal conductivity was measured during the Apollo 15 and 17 lunar heat-flow experiments. The measurement method is similar to the line heat-source technique employed in the laboratory to measure the thermal conductivity of powdered material. The heating element installed in the temperature probe which penetrated into the lunar regolith to measure the thermal gradient, was activated, and the time variation of temperature due to heating was measured. The thermal conductivity of the lunar regolith at a depth of 35 to 234 cm, determined from an analysis of the measured temperature, ranges from 1.4 to 3.0 x 10^{-4} w/cm°K.

Later, the thermal conductivity values obtained by this method were revised. The new method of measurement is the same in principle as the Ångstrom technique used in the laboratory to measure the thermal diffusivity of a solid material. The downward propagation of temperature waves caused by the annual variation of the lunar surface temperature is measured by a temperature probe at various depths in the lunar regolith. The thermal diffusivity of the lunar regolith is determined by analysis of the decay of amplitude and the phase delay of the temperature waves with depth. The thermal diffusivity is then converted to thermal conductivity using measurements of the specific heat and density of returned lunar samples. The new result gives thermal conductivities ranging from 0.9 to 1.3 x 10^{-4} w/cm°K. This value, being significantly lower than the old one, is still nearly an order of magnitude higher than the laboratory value for the thermal conductivity of lunar soil samples. The laboratory measurements are consistent with the thermal conductivity of the upper 1-2 cm of surface layer inferred from remote sensing observations of the lunar surface brightness temperature.

If the laboratory value of the thermal conductivity of the lunar soil samples is representative of the top few centimeters of the lunar surface layer, the measurements obtained by the heat-flow experiment imply a rapid increase with depth of the thermal conductivity of the lunar regolith. The remote sensing observation of the lunar surface brightness temperature also showed that in the upper tens of centimeters of the lunar surface layer the thermal conductivity increases significantly with depth. A clear explanation for the increasing thermal conductivity with depth has not yet been given. Since intergranular thermal contact has a strong effect on the thermal conductivity of lunar soil, it is likely that the micromechanical structure of the regolith changes with depth. Compression of the regolith, induced by meteoritic impact, is one of the possible mechanisms that could improve the intergranular thermal contact in the lunar soil. If the micromechanical structure of the regolith, especially the state of thermal contact between the soil grains, is the origin of increasing thermal conductivity, then it is highly desirable to make measurements on lunar core samples because they are the only lunar material brought to the earth that may have retained the in situ properties of the regolith.

Since the lunar core samples returned by Apollo missions will be used for various scientific studies, it is mandatory that, if thermal conductivity is to be measured on these samples, the measurement should be made in such a way as not to result in any chemical or physical alteration of the samples. In our preceding NASA Grant (NGR 33-008-174) we examined several possible techniques and reached the conclusion that one of the best methods would be to heat the sample from the outside by radiation at a known rate, measure the variation of the temperature at the surface of the core tube, and determine the thermal conductivity by comparing the observed temperature with the theoretically expected one. As a basis for this technique, we solved the thermal conduction equation for a composite cylinder to obtain a mathematical expression for the surface temperature of the core tube filled with lunar material.

Since this is a new technique for the measurement of thermal conductivity and will be applied to the lunar core samples, our task under this grant was twofold: one, to demonstrate the feasibility of this technique by a test experiment; and, two, to construct an experimental setup in conformity with the standards and technical requirements imposed by the Lunar Sample Analysis Planning Team (LSAPT) and the NASA-JSC Lunar Sample Curator.

The apparatus for the measurement of the thermal conductivity of lunar core samples consists of three parts: (1) the sample holder and the heater; (2) the nitrogen cabinet combined with the vacuum chamber; and, (3) the vacuum station. The sample holder is a frame consisting of two end pieces and four holding rings supported by three rods. The lunar core sample is held in a vertical position by the holder supporting the core tube at the upper and lower ends by the supporting rings. The heater is a hollow cylinder, concentric with the core tube, attached to the frame by the two holding rings. We chose radiation as a mode of heat transfer to avoid a direct contact of the heating element with the sample. The vacuum chamber is a cylinder, 31.7" long and 6" in outer diameter with a vacuum flange at the top. The sample holder and the electric feedthrough for heater and thermocouple wires are attached to the flange. Also attached to the flange is the mechanical feedthrough by which it is possible to adjust the position of the heater along the axial direction of the core tube.

In our prototype setup, the vacuum chamber had been attached to the vacuum station. Later, according to the suggestion of the Lunar Sample Curator, the vacuum chamber was removed from the vacuum station and combined with the nitrogen cabinet. The lunar core samples to be used for the thermal conductivity measurement are taken out of storage, transported to the nitrogen cabinet and mounted on the sample holder. The core samples mounted on the sample holder are then moved out of the cabinet and encased in the vacuum chamber. The combination of the nitrogen cabinet and the vacuum chamber eliminated the process of transferring the samples from the nitrogen cabinet to the vacuum chamber. In the present setup, the nitrogen cabinet is supported 36" above the floor of the laboratory and the vacuum chamber is fixed to the floor of the cabinet with the top of the chamber protruding 2" above the floor of the cabinet. The vacuum chamber is connected to the vacuum station. With a combination of absorption and ionization pumps, it is not difficult to produce a vacuum of 10^{-7} torr in the vacuum chamber.

TEST EXPERIMENTS

We first tested the effect of vacuum pumping on the stratification of core samples. The measurement of the thermal conductivity of lunar core samples must be made under vacuum conditions in order to simulate the lunar surface condition. Therefore, it is necessary to maintain vacuum conditions inside the core tube during the measurement. Maintaining the outside of the core tube in a vacuum is also necessary. If the gas pressure is high enough to produce a significant heat transfer due to convection, a clear cut relationship between the inflow of heat into the core tube and the temperature difference between the heater and the core tube (which must be known accurately for a successful measurement) cannot be obtained.

The lunar core samples are stored in a nitrogen atmosphere. Therefore, before the measurement of thermal conductivity is made, the nitrogen gas filling the interstices of the lunar material must be removed. We demonstrated experimentally that the nitrogen gas can be drawn out of the core tube without causing any disturbance to the fine stratification of the core sample.

There are two types of lunar core samples available for thermal conductivity measurements. One is the Apollo 15 type drive tube, 4.39 cm in diameter and 37.47 cm in length. The other is the Apollo 15 type drill core, 2.33 cm in diameter and 42.54 cm in length. We first constructed a sample holder and a heater to fit the drive tube core samples. Then, being informed of the greater accessibility of the drill core samples, we fabricated a second heater and sample holder designed for the drill core samples. Pumping tests were made for both of these core tube types.

We took an empty Apollo 15 type drive tube made of alluminum alloy, filled it with terrestrial soil and glass beads to form artificial stratifications, pumped the sample down to a vacuum, and returned it to atmospheric conditions. We took x-ray photographs before and after the sample's exposure to vacuum that showed that no visible change had occurred in the sample. Upon the request of the LSAPT, we then used a glass tube with the same inner diameter as the drive tube and repeated the same experiment. No appreciable migration of soil particles in the sample was detected. In both of the above experiments a plug of the same type as that used for flight models was used to confine the simulated lunar regolith material in the core tube. We detected no leakage of fine particles through the small holes in the plug. It is concluded, therefore, that the fine stratification of the core sample can be preserved if the rate of pumping is kept under a certain limit.

Tests were also made on Apollo 15 type drill cores. With the consent of the Lunar Sample Curator, it was decided that the plug in the upper end of the core tube(placed there immediately after the recovery of the sample from the lunar regolith) be replaced by a new plug before the thermal conductivity measurements. The new plug, made of Teflon, has a metal screen with a mesh size of 50 μ m. The test core tube was filled with an Apollo 12 simulant lunar soil sample and evacuated. Later, as requested by LSAPT, we put a small amount of fluorescent material (Ca WO_4) on top of the soil layer and repeated the test. We examined the possible leakage of the fluorescent material to the outside of the core tube, but the result was negative. During these experiments, we controlled the rate of pumping by a needle valve and found that, if more than twelve hours were taken to reduce the gas pressure from 1 atm to 1 torr, there is no leakage of material through the screen of the plug. Hence, there is no disturbance in the microstratification of the sample.

To demonstrate the feasibility of our technique, we filled a core tube with powdered terrestrial material, measured the thermal conductivity by our technique, and compared the result with the conductivity of the same material under the same conditions as measured by some other standard technique.

Prior to the thermal conductivity measurement we determined experimentally the heat transmission characteristics from the heater to the core tube. The time rate of heat transfer, $\dot{Q}$, by radiation between coaxial cylinders is given by:

$$\dot{Q} = \frac{A_1(T_2^4 - T_1^4)}{\frac{1}{\sigma_1} + \beta(\frac{1}{\sigma_2} + \frac{1}{\sigma})} \tag{1}$$

where σ is the Stefan-Boltzman constant, $\varepsilon_1 = \sigma_1/\sigma$ $\varepsilon_2 = \sigma_2/\sigma$ are the surface thermal emissibilities of the core tube and the heater, A_1 is the surface area of the core tube per unit length, and β is the ratio of the surface areas of the core tube and the heater per unit length*. If the temperature difference is small Equation (1) can be approximated by

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* and T_1 and T_2 are the temperatures of the core tube and heater respectively.

$$\dot{Q} = \frac{4 A_1 T_0^3}{\frac{1}{\sigma_1} + (\frac{1}{\sigma_2} + \frac{1}{\sigma})} \Delta T \tag{2}$$

where $\Delta T = T_2 - T_1$ and T_0 is the initial equilibrium temperature $T_0 = T_1 = T_2$ at time $t = 0$.

Equation (2) shows that the inflow of heat into the core tube is proportional to the difference in surface temperature between the heater and the core tube. The coefficient of proportionality

$$\alpha = \frac{4 A_1 T_0^3}{\frac{1}{\sigma_1} + \beta (\frac{1}{\sigma_2} + \frac{1}{\sigma})} \tag{3}$$

depends, however, on the surface thermal emissivities of the heater and the core tube. The emissivity is not a material constant, but varies greatly according to the surface finish. Also, the measurement of the thermal emissivity of a curved surface is usually very difficult to make. Therefore, we decided to determine the value of α from the experiment

We took an empty core tube, placed it in the position of the core sample, and heated it in the same manner as for conductivity measurements. Since the core tube is made of thermally conductive metal, the temperature difference across the wall of the core tube can be assumed to be negligible unless the rate of heating is exceedingly high. Since the heat capacity C of the core tube per unit length is known, the rate of heat inflow $\dot{Q}$ into the core tube is given by

$$\dot{Q} = C \frac{d T_1}{dt} \tag{4}$$

where T_1 is the temperature at the surface of the core tube. By equating (2) with (4), the coefficient α can be determined from the measurement of the heater and the core tube surface temperatures as a function to time. The analysis showed, however, that a better fit to the data is obtained if an additional term, proportional to the core tube surface temperature, is included:

$$Q = \alpha \Delta T + \gamma T_1 \tag{5}$$

Equating (4) and (5) and integrating with respect to time, we obtain

$$CT_1(t) = \alpha\int_0^t \{ T_2(t) - T_1(t)\}\, dt + \gamma\int_0^t T_1(t)\, dt \qquad (6)$$

Values of α and γ are determined by the least square criteria from the core tube surface temperature T_1 and the heater surface temperature T_2, measured as a function of time.

The second term in Equation (5) signifies a loss of heat, probably by conduction through the thermally conductive core tube, in the axial direction of the heater-core tube system. There is a possibility, though, that the loss of heat is by radiation through the hollow space inside the empty core tube. If this mode of heat transfer is more effective, the use of the empirical Equation (6) would become meaningless if the core tube were filled with opaque material.

To ascertain that conduction is the major mode of axial heat loss, we did a numerical simulation of the measurement. The heater-core tube system was modeled and the equation of heat transfer by both conduction and radiation was solved by finite difference technique. A comparison of the numerical result with the experimental data showed that heat loss in the axial direction of the core tube is almost entirely by conduction. We concluded that the values of α and γ determined experimentally using an empty core tube are valid when the core tube is filled with lunar material.

We made some preliminary measurements of thermal conductivity using an Apollo 15 type drive tube filled with regolith simulant. The heater used for this measurement was six inches long and 1.93 inches in inner diameter with its surface coated by black glossy paint. The coefficients of the heat transfer equation determined at the center of the heater were $\alpha = 0.764 \times 10^{-3}$ cal/sec cm K and $\gamma = -0.66885 \times 10^{-3}$ cal/sec cm K. The samples used for the test measurements were glass beads and powdered Knippa basalt. The measurements were made at about 300°K under air pressure of about 10^{-6} torr. The results of the measurements are summarized as follows:

Sample	Grain size (μm)	Bulk.dens. (g/cc)	Therm. conduct. (10^{-6}cal/cm sec K)
Glass beads	90	1.48	4.1
Knippa basalt	74-149	1.39	11.0

The thermal conductivity values to be compared with the above were obtained by J.A. Fountain of NASA/Marshall Space Flight Center using the line heat source technique. The results were:

Sample	Grain size (μm)	Bulk density (g/cc)	Thermal conductivity (10^{-6}cal/cm sec K)
Glass beads	90	1.56	6.12
Knippa basalt	74-149	1.39	2.68

The agreement is not satisfactory. Our results cited above were obtained in the earliest stage of our project. We will see that the measurement accuracy has been improved substantially in the subsequent experiment.

More extensive test measurements were made using Apollo 15 type drill cores. For these measurements, an Apollo 12 simulant lunar soil sample, prepared by D. Carrier of NASA/Johnson Space Center, was used for the sample. During the course of this experiment, a number of modifications were made in our sample holder-heater assembly and, after each of these modifications, the heat transfer characteristics between the heater and the core tube, i.e., the values of α and γ were redetermined. We summarize the result of our experiment in the following table. All of the measurements were made at about 300 K under an air pressure ranging from 10^{-6} to 10^{-7} torr.

Heater*	Core-tube**	Coefficients α (10^{-3}cal/cm sec K)	Coefficients γ (10^{-3}cal/cm sec K)	Bulk density (g/cc)	Thermal conductivity (10^{-6}ca;/cm sec K)
CA	No. 1	0.646	-0.248	1.47	4.89
CA	No. 2	0.559	-0.338	1.58	5.49
BN	No. 2	0.813	-0.419	1.67	5.12
BN	No. 1	1.009	-0.388	1.61	6.33
HA	No. 3	0.907	-0.245	1.49	5.06

* CA: Stainless steel, inner diameter = 3.05 cm; length = 15.24 cm; inside surface = chromic acid coating.

BN. Same as CA, except that the inner surface was changed to a black nickel coating.

HA. Aluminum, inner diameter = 3.56 cm; length = 20.32 cm; inside surface = hard, anodized, using a stainless steel electrode.

** No. 1 Titanium alloy, inner diameter = 2,04 cm; outer diameter = 2,33 cm; length = 38.74 cm; weight = 169.1 g.
No. 2 Similar to No. 1, except that the length = 42,54 cm and the weight = 193.4g.
No. 3 Similar to No. 2, except that the weight = 195,5g.

The thermal conductivity data to be compared with the above were again obtained by J.A. Fountain. The thermal conductivity of an Apollo 12 simulant lunar soil sample was measured as a function of the temperature and bulk density under an air pressure below 10^{-5} torr using the line heat source technique. At 300 K the values of thermal conductivity for various bulk densities are as follows:

Bulk density (g/cc)	Thermal conductivity (10^{-6} cal/cm sec K)
1.25	3.76
1.50	3.84
1.75	6.91
1.80	12.14

The agreement between the two independent techniques of measurement appears satisfactory. We concluded that the validity of our new method is quite well established. Modifications to the original measurement design are described in the next section.

CONSTRUCTION OF THE EXPERIMENTAL SETUP AND ITS MODIFICATION

The original experimental setup was constructed for the test measurement using Apollo 15 type drive tube cores. Subsequently, the setup was subjected to a number of modifications to facilitate the experimental operation, to improve the measurement accuracy, and also to fulfill the technical requirements necessary when handling the lunar samples. Eventually, we ended with a totally new setup that is ready for the measurement of Apollo 17 drill core samples. The modifications we have made to our prototype setup and the major features of our present setup are outlined below.

Our first sample holder was designed for Apollo 15 type drive tube core samples. A Teflon socket, fixed to an anodized aluminum plate, was used to support the lower end of the core tube. The upper end of the core tube was held by a supporting ring, made of Teflon, attached to an anodized aluminum ring. Both the upper and the lower supports were tightly fixed to the frame of the sample holder. The design of the sample holder for Apollo 15 type drill core samples was similar except that its size was changed in proportion to the smaller diameter of the drill cores. Later, we changed the design of the upper supporting ring, a loose Teflon ring holding the upper end of the core tube, to a Teflon cap fixed to the anodized aluminum plate to tightly hold the upper end of the core tube. The use of the Teflon cap prevents the sample from popping out of the core tube in case the pressure difference between the inside and outside of the core tube accidentally exceeds the threshold value.

We used thermocouples for measuring the temperature at the surfaces of the heater and the core tube. Since the use of adhesives is prohibited in our experiment, we attached thermocouples mechanically to the surface of the core tube. We fabricated a copper disk, 5 mm in diameter and 1 mm in thickness, and drilled a thin hole on its side surface, and inserted into it the tip of the thermocouple. The copper disk was then pressed tighly against the surface of the core tube by a band of mylar. The two ends of the mylar band were tied by a silk string. Repeating the experiments, we found that the measured core tube surface temperature was very sensitive to the thermal contact between the core tube and the disk containing the thermocouple. Therefore, we fabricated a special tool to compress the copper disk, after the thermocouple was inserted into the hole, in order to ensure maximum thermal contact between the thermocouple and the disk. Moreover, we designed the tool to bend the disk when compressing, so that one of the surface of the disk had the same curvature as that of the core tube, to improve the thermal contact between the disk and the core tube. We replaced the mylar band by a polymide band after learning that the former material was one of the materials not to be exposed to lunar samples. To tie the ends of the polymide band, we decided to use stainless steel springs instead of a silk string to give a constant compressing force on the copper disk. The use of the springs, with hook and ring on the ends, greatly facilitated the tying and untying of the thermocouples on the core tube when it is mounted on the sample holder installed in the nitrogen cabinet.

Heat transmission efficiency by radiation between the heater and the core tube depends on the surface thermal emissivity of the heater and the core tube. Since we are not allowed to modify the surface properties of the core tube, we tried to bring the thermal emissivity of the heater surface as closely as possible to unity. In our original experimental setup, designed for a preliminary test measurement of an Apollo 15 type drive tube cores, we painted the inner surface of the heater in glossy black. We found that the use of paint is not permissible on parts of the experimental setup in direct contact with the lunar samples. Therefore, we adopted a chromic acid coating for the heater designed for the Apollo 15 type drill core samples. Later it was changed to a black nickel coating. However, the use of material containing either chromium or nickel also turned out to be undesirable. Eventually, we have the inside surface of the heater made of a hard anodized aluminum using stainless steel electrodes. By this treatment, we obtained an emissivity measured by the Gier Dunkle DB-100 Infrared Reflectometer of 0.936.

In constructing the heater and the sample holder, we used materials that are permissible according to NASA standards. They are stainless steel, aluminum, Teflon, and a few other materials. Any part of the experimental setup with the possibility of being exposed to the lunar sample should be made of these materials. As mentioned already, the vacuum chamber and the vacuum flange are made of stainless steel. Since the use of a copper gasket is not permissible, a specially fabricated aluminum gasket was used to seal the vacuum chamber. The heater body consists of a hollow aluminum cylinder with a surface hard - anodized using a stainless steel electrode. The heating wire wound on the heater is a Teflon coated constantan thermocouple wire. Since the use of solder is not allowed, the heating wire connection to the lead wires is achieved by pressing the wire ends, entangled together and covered by Teflon tubing, by a screw tightened against the inner wall of the heater. The body of the heater was then encased in an aluminum cylindrical jacket to protect the heating wire.

Temperatures at the surfaces of the heater and the core tube are measured by copper-constantan thermocouples. The use of copper thermocouple wire was permitted on the condition that most of the copper wire be covered by Teflon tubing. As already mentioned, a small copper disk is used to attach the thermocouples' tip to the core tube surface. We also used a piece of copper, a small rectangular parallelepiped 1 x 3 x 5 mm, with a thin hole on its side surface to encase the thermocouple tip, to attach thermocouples on the heater surface. The center of the piece is compressed by a wedge to ensure thermal contact with the thermocouple. The thermocouple holding piece is then affixed to the heater by a stainless steel screw. The thermocouple holding pieces and wires are embedded in a thin groove on the inner heater surface. A stainless steel slab, 1x3x20 mm, fixed to the heater surface by a screw, is used to maintain the thermocouple wires in the groove. The use of copper was allowed on the grounds that a good thermal contact between the thermocouples and heater/core tube is essential for the precise measurement of temperature and that the excellent copper thermal properties cannot be emulated by any other metal. Also, the small amount of copper precludes the possibility of chemical contamination to the lunar sample.

We attached four thermocouples to the heater to check the uniformity of the temperature distribution over the heater surface, and six thermocouples to the core tube to determine the thermal conductivity at various positions along the length of the core tube. Polymide bands with stainless steel springs were used to tie the thermocouple wires to the heater. Care was taken not to let the thermocouple wires touch the heater surface so that the heat conduction through the thermocouple wires would not invalidate the assumption of purely radiative heat transfer from the heater to the core tube. To avoid the use of solder, a special electric feedthrough was used to connect the thermocouple wires from the inside of the vacuum chamber to the outside. The feedthrough consists of a vacuum sealed connector with copper and constantan pins. The thermocouple wire's end is clipped by either a copper or a constantan socket and the socket plugged into the pin.

The heater is supported by two Teflon rings attached to the sample holder frame. A drive screw runs through the Teflon ring to move the heater to a desired position along the length of the core tube. The drive screw, of stainless steel, is driven by a moving feedthrough attached to the flange of the vacuum chamber.

Our original vacuum station consisted of a rotary pump and a diffusing pump affixed to a wooden frame. With these pumps we were able to attain a vacuum of 10^{-5}torr, appropriate for a simulated lunar surface condition. However, to eliminate any possible oil backflow from the pumps to the vacuum chamber, the use of rotary and diffusion pumps was abandoned. In the present setup, we are using an adsorption and an ionization pump affixed to a stainless steel frame as a vacuum station. The viton and copper gaskets in our old vacuum station have been replaced by aluminum gaskets, and the brass tubings by stainless steel tubings. By a combination of adsorption and ionization pumps, it is possible to produce a vacuum of 10^{-7}torr in the vacuum chamber. The use of a needle valve is an essential feature of our vacuum station by which a very low pumping rate can be maintained to prevent a sudden change of pressure inside the core tube.

EXPERIMENTAL PROCEDURE

A thermal conductivity measurement of lunar core samples, as outlined above, will be performed in the Lunar Sample Curator's Laboratory, Room 270, Building 31, NASA Johnson Space Center. The experimental setup must be cleaned before laboratory installation. The vacuum station, chamber, sample holder, and heater are disassembled into a total of 547 parts, and each part is cleaned according to the directions of the preassigned level of cleaning procedure, ranging from CP1 to CP 7. The cleaning is undertaken by the staff of the Johnson Space Center Cleaning Facility. After cleaning, the vacuum station, sample holder and heater are assembled in the clean room of the Cleaning Facility. In particular, the sample holder and heater are assembled on a clean bench, sealed in Teflon bags and transported to the Curator's Laboratory. The nitrogen cabinet is also cleaned and combined with the vacuum chamber after transfer to the Curator's Laboratory.

Laboratory maintenance and experiment performance are according to the regulations of the Lunar Sample Curator for the Lunar Storage and Preparation Laboratories. Room admittance is limited to personnel engaged in the experiment. The room must always be kept clean. All cleaned materials and equipment must be approved by the Lunar Sample Curator before being brought into the room. Materials and tools to be used in the nitrogen cabinet must be certified for their cleanliness by the Cleaning Facility, and be sealed in double Teflon bags. The outer bags must be opened when the materials and tools are passed into the airlock of the nitrogen cabinet. The inner bags can be opened in the nitrogen cabinet as the materials and tools are ready to be used.

For the conductivity measurement, the lunar core sample is taken out of storage, transferred to the nitrogen cabinet, mounted on the sample holder, and encased in the vacuum chamber. After the measurement, the core sample is recovered from the vacuum chamber, removed from the sample holder, taken out of the nitrogen babinet, and returned to storage. During these processes, the lunar core sample is handled by the Lunar Sample Curator's staff. The operational procedure has already been documented, with detailed instructions, so that step-by-step execution may serve to curtail unnecessary delay in handling. The procedure has been revised in accordance with our operational experience. We believe that the present procedure is nearly complete.

CHRONOLOGICAL DEVELOPMENT

1972

February	Design and fabrication of vacuum chamber and a vacuum station for preliminary testing.
April	Sample holder and heater designed and fabricated for preliminary testing using an Apollo 15 type drive tube.
August	Elaboration of the thermal conduction theory in a composite circular cylinder.
October	Experimental testing to determine heat transfer characteristics between heater and core tube.
November	Testing thermal conductivity of glass beads.
December	Determination of the thermal conductivity of powdered Knippa basalt.

1973

January	An outline of the technique and the result of the preliminary test measurements were presented at the symposium "Geophysical and Geochemical Exploration of the Moon and Planets" held at the Lunar Science Institute, Houston, Texas.
February	Beginning of Grant Period.
May	LSAPT presented with project briefing.
July	The pumping effect on the stratification of a core sample was studied on an Apollo 15 type drive tube by x-ray photography.
September	The pumping effect on the core sample stratification was studied using a glass tube.
October	A sample holder and heater fitting the Apollo 15 type drill core samples were designed and built.
November	Heater transmission characteristics of the new heater and core tube were measured.
December	A test of thermal conductivity was made on an Apollo 12 lunar soil simulant.

1974

January	Request made to LSAPT to preserve five Apollo drill core samples for thermal conductivity measurement.
February	Heater calibrated for new test core tube.
March	Determination of thermal conductivity of an Apollo 12 lunar soil simulant using the new test core tube.
July	The experimental setup was modified: the rotary pump was replaced by an adsorption pump; the vacuum chamber flange equipped with a motion feedthrough; copper gaskets replaced by aluminum gaskets; and, the heater surface changed to a black nickel coating.
August	A simulation of the assembling of the clean parts of the heater and sample holder on the clean bench and the installation of the core sample on the sample holder in the nitrogen cabinet were made.
September	Thermal conductivity was measured on the test core sample prepared by the preceding simulated operation. Using the motion feedthrough, thermal conductivity was determined at four different locations along the length of the core tube.
October	The heater with the nickel black coating was calibrated.
November	Calibration of the heater and determination of the thermal conductivity were repeated. The core sample used for the test measurement in December 1973 was remeasured to test the reproducibility of results.
December	Thermocouples used for the heater and core tube surface temperature measurement were calibrated. The design of the nitrogen cabinet, combined with a vacuum chamber, was approved by LSAPT and sent to the NASA Technical Services Division for fabrication.

1975

January	The heater design was changed. A new heater was made of aluminum (8" long and 2.135" in inner diameter) with its surface hard anodized using a stainless steel electrode. The surface thermal emissivity of the heater was measured by a Gier Dunkle Double Black Body Infrared Reflectometer, model DB-100. Heat transmission characteristics were determined for the new heater.
May	A thermal conductivity test measurement was made using the new heater.

June	The Apollo 17 drill core samples inventory was reviewed and a new priority assigned for the thermal conductivity measurement.
August	NASA Technical Services Division finished the fabrication of the nitrogen cabinet combined with the vacuum chamber.
September	An experimental procedure simulation, mainly the handling of the core sample in the nitrogen cabinet, was performed in the presence of LSAPT members for their inspection.
November	Calibration of a new set of thermocouples.
December	The nitrogen cabinet and its accessories were modified according to the recommendations of LSAPT.
1976	
January	The vacuum station, sample holder and heater, and vacuum chamber were disassembled and turned into the Johnson Space Center Cleaning Facility.
February	The cleaned vacuum station, sample holder and heater, and vacuum chamber were assembled and installed in the Lunar Sample Curator's laboratory.
March	The nitrogen cabinet was cleaned and installed in the Lunar Sample Curator's laboratory.
April	Final simulation of the experimental procedure.

CONCLUSION

As outlined above, the period covered by Grant NGR 33-008-169, from February 1973 to January 1976, has been devoted to the preparation of the experiment. We have successfully demonstrated the feasibility of our new thermal conductivity measurement technique. We have completed the experimental setup to be used for the measurement and described the experimental procedure and data processing for the most efficient measurement and data reduction.

The research undertaken by this grant will be continued under the companion proposal "Study of thermal properties of lunar samples"; (NGR 33-008-177) a renewal of grant NGR 33-008-169, dated February 1976. As of May 3, 1976, LSAPT allocated Apollo 17 drill core sample 70002 for our measurement. The Lunar Sample Curator recommended that the sample measurement should not be started later than June 21, 1976. We explect to obtain the data before the fall of 1976.