STUDY OF THERMAL PROPERTIES OF THE LUNAR REGOLITH BASED ON IN SITU TEMPERATURE MEASUREMENTS AND EXPERIMENTS ON SOIL SIMULANTS

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FINAL TECHNICAL REPORT

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Period Covered by the Report: 2/1/72 - 8/1/73

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NASA Grant NGR 33-008-174

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Sept. 24, 1975

Mr. F. D. Nolin, Contracting Officer
National Aeronautics and Space Administration
Manned Space Center
Houston, Texas 77058

Re: NASA Grant NGR-33-008-174
Feb. 1, 1972 to August 1, 1973

Dear Mr. Nolin:

Access to classified information on the basis of this grant had not been authorized. At no time was classified information received, transmitted or generated in relation to performance on subject grant.

Please do not hesitate to contact us if we may be of further assistance.

Sincerely yours,

Vincent F. Phelan

Vincent F. Phelan
Security Officer
Lamont-Doherty Geological Obs.

VFP:vc

The purpose of the study undertaken as part of this grant is to conduct research for a better understanding of the mechanism of heat transfer in the lunar regolith. We worked on a method to make measurements of the thermal conductivity of lunar core samples in the laboratory. In the period covered by this proposal, we concentrated our effort on the experimental design and the development of a theory that is necessary to interpret the experimental data.

After examining several possible methods of measurement, we concluded that one of the best methods that can be applied to the measurement of thermal conductivity of lunar core samples is to make the measurements while the lunar material is still in the core tube. This approach would reduce the possibility of physical and chemical disturbances to the sample. The approach we chose is to heat the sample externally by radiation at a known rate, measure the variation of temperature at the surface of the core sample, and determine thermal conductivity by comparing the observed temperature with the theoretically expected one.

We chose to heat the sample by radiation because a direct contact of the heating element to the sample can be avoided. The thermal conductivity of lunar regolith material is very sensitive to the interstitial gaseous pressure. To simulate the lunar surface condition, the measurement must be made at a pressure below 10^{-3} torr. At gaseous pressures below 10^{-3} torr, the heat transfer due to convective motion of the gas is negligible, so that the rate of thermal energy transmitted from the heating unit to the sample can be estimated accurately by the theory of thermal radiation.

One of the most important tasks of this project was to obtain a mathematical expression for a surface temperature of core sample changes with time when it is heated externally at a known rate. The sample of lunar regolith material is contained in a metallic circular cylinder. Therefore, the core sample constitutes concentric composite cylinders of two materials. The variation of temperature in this system, subject to the inflow of heat through the outer surface of the cylinders, should be given. The solution will be a function of the physical properties of the materials consisting of the outer and the inner cylinders. Since the physical properties of the metallic core tube are known, those of the lunar regolith material will be obtained by comparing the solution with experimentally observed temperature.

As far as we know, the mathematical solution to this problem cannot be found in the literature. We spent a considerable amount of time to formalize the problem, obtain a solution, and put it in a form readily applicable to the analysis of data. The details are given in Appendix 1. Computer programs were constructed so that the least-square fit to the data is done by trial and error to yield a best estimate of the thermal conductivity of the lunar regolith sample.

Two types of lunar core samples are available for our experiment. One is the Apollo 15 type drive-tube core sample. The other is the Apollo 15 type drill-core sample. To provide radiation to the outer wall of the core sample, two sets of a heating unit were constructed to fit each type of core sample. The heating units are coaxial cylinders. Heat transfer from the heating unit to the core sample is two-dimensional thermal radiation. The heat flux Q, per unit time, per unit axial length of the core tube is

$$Q = A_c \frac{T_h^4 - T_c^4}{\frac{1}{\sigma_c} + \beta\left(\frac{1}{\sigma_h} + \frac{1}{\sigma_b}\right)} \tag{1}$$

where T_c and T_h are the surface temperatures of the core tube and the heater, $\epsilon_c = (\sigma_c/\sigma_b)$ and $\epsilon_h = (\sigma_h/\sigma_b)$ are the thermal emissivities of the core tube and the heater surfaces, A_c is the area of the core tube surface per unit length of the core tube, β is the ratio of the surface areas of the core tube and the heater per unit axial length of the cylindrical system. If the radius of the core tube is r_c and the inner radius of the heater r_h, then

$$A_c = 2\pi r_c$$

and

$$\beta = 2\pi r_c / 2\pi r_h = r_c / r_h \quad .$$

When the temperature difference between the heater and the core tube is small, (1) is approximated by

$$Q = \frac{4A_c T_c^{\,3}}{\frac{1}{\sigma_c} + \beta\left(\frac{1}{\sigma_h} - \frac{1}{\sigma_b}\right)} \Delta T \tag{2}$$

where
$$\Delta T = T_h - T_c.$$

Since σ_h and σ_c are constants that depend on the surface finish of the materials in a complicated way, the coefficient in (2)

$$f = \frac{4A_c T_c^{\,3}}{\frac{1}{\sigma_c} + \beta\left(\frac{1}{\sigma_h} - \frac{1}{\sigma_b}\right)} \tag{3}$$

can be determined experimentally. A core tube, not filled with sample material, is used for this experiment. Let the specific heat, the density the outer and the inner radii of the core tube be c_2, ρ_2, r_2 ($= r_c$) and r_1. Then, the heat capacity of the core tube per unit length of the core tube is

$\pi(r_2^{\ 2} - r_1^{\ 2})c_2\rho_2$. Since the core tube is made of thermally conductive metal and the rate of temperature variation is comparatively small, it can be assumed that the temperature of the core tube is uniform and equal to its surface temperature. Therefore, the rate of heat inflow into the core tube is given by

$$Q = \pi(r_2^{\ 2} - r_1^{\ 2})c_2\rho_2 \frac{dT_c}{dt} \tag{4}$$

which is to be equated to the rate of heat transfer from the heater to the core tube. Equation (4) combined with (2) allows us to calculate f. The experimental result showed that a better fit to the data is obtained if an additional term, proportional to the core tube temperature, is included in (2), i.e.,

$$Q = f\Delta T + g\,T_c \tag{5}$$

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

$$\pi(r_2^{\ 2} - r_1^{\ 2})c_2\rho_2 T_c(t) = f\int_0^t \Delta T\ (t)\ dt + g\int_0^t T_c(t)\ dt \tag{6}$$

Values of f and g are determined from the measured T_c and T_h by the least square criteria.

Comparison of the experimentally determined f with the theoretical expression (3) yields an estimate of ϵ_c. The surface of the heater is painted a non-glossy black. Therefore, $\epsilon_h = 1$. The estimated ϵ_c is 0.47 for the Apollo 15 type drive-tube and is 0.64 for the Apollo 15 type drill-core tube. The material of the Apollo 15 type drive-tube is an aluminum alloy 6016-T6 with a surface finish of sulfuric anodize type II, class 1 per mil - A - 8625 manufactured by J. T. Ryerson & Co. The surface layer is less than 0.001" thick and consists mainly of aluminum oxide. The

The Apollo 15 type drill core-tube is made of a titanium alloy Ti-6Al-4V. The estimated emissivities are in reasonable agreement with published emissivities for these materials.

The experimentally determined g has a negative sign. This implies that the second term on the right-hand side of (5) represents a loss of heat from the core tube, probably by conduction along the axial direction of the core tube.

Experimental Setup

Figure 1 illustrates the heater-sample holder assembly for the experiment. The heater for the measurement of the Apollo 15-type drive-tube core sample is 8.0" long, 2.135" in inner diameter and 2.677" in outer diameter. The heater for the measurement of the Apollo 15-type drill-core sample is 8.0" long, 1.40" in inner diameter and 1.937" in outer diameter. The sample holders are fabricated in accordance with the sizes of the core tube, 14.75" long and 4.39 cm in outer diameter for the Apollo 15-type drive-tube and 16.75" long and 2.33 cm in outer diameter for the Apollo 15-type drill-core. Since the heater and the sample holder will be in contact with the lunar samples, materials permissible by NASA standards are used for the fabrication of the assembly. For temperature measurements on the surface of the core tube, thermocouples sheathed in a copper disk, 5 mm in diameter and having the same curvature as the outer surface of the core tube, were tied on the core tube by a polyimide strap and springs. For the temperature measurement at the surface of the heater, stainless steel thermocouples, sheathed in a copper strip, were bolted to the inner surface of the heater.

The heater-sample holder assembly is encased in a vacuum chamber 36.0" long and 5.90" in inner diameter. There are two reasons for making the experiment in a vacuum. First, since the thermal conductivity of the lunar regolith material strongly depends on the interstitial gaseous pressure, gas pressure in the sample must be kept below 10**(-3) torr during the measurement to simulate the lunar surface condition. Second, to simplify the theoretical interpretation of heat transfer from the heater to the core tube, heat transfer due to convective motion of the gas filling the space between the heater and the core tube must be eliminated by keeping the gas pressure as low as possible.

Our vacuum system is schematically shown in Figure 2. It is necessary to control the time rate of evacuation so that a reduction in pressure does not cause any mechanical disturbance in the sample. A fine metering valve, illustrated in Figure 2, is used to establish and control the very slow rate of evacuation. An optimum pumping rate was sought experimentally. A glass tube of the same dimension as the core tube was filled with material simulating lunar soil and artificial stratifications were constructed by intercalating layers of clay of a different color than the simulated lunar material. The adoption of a rate of 760 torr/12 hours resulted in no disruption in the strata and no leakage of soil particles through the small hole in the plug inserted in the top end of the core tube.

Test Measurement

A series of test experiments was performed on simulated samples of lunar regolith material. The result of an experiment with glass beads and powdered Knippa basalt, in an Apollo 15-type drive tube, is summarized in Horai et al. (1974).* An experiment with Apollo 12 simulant lunar regolith material, contained in an Apollo 15-type drill-core tube, also yielded a satisfactory result. We think that the feasibility of the method developed under this proposal has been demonstrated.

As a continuation of this study, we plan to make measurements on lunar core samples. We would like to note that the Lunar Sample Analysis Planning Team has already approved the usage of one Apollo 15-type drive-tube core sample and one or two Apollo 15-type drill-core samples returned by Apollo 16 and 17 missions. The performance of the measure-

ments and the interpretation of the results will be undertaken under the companion contract (NGR33-008-169).

The work performed under this grant is being continued under a renewal of grant NGR33-008-177.

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* **Horai, M. Langseth, Jr., A. Wechsler, J. Winkler, D. Colvin and S. Keihm; (1974) A new technique of thermal conductivity measurement of lunar core samples; The Moon, v. 9, p. 243.**

Figure 1

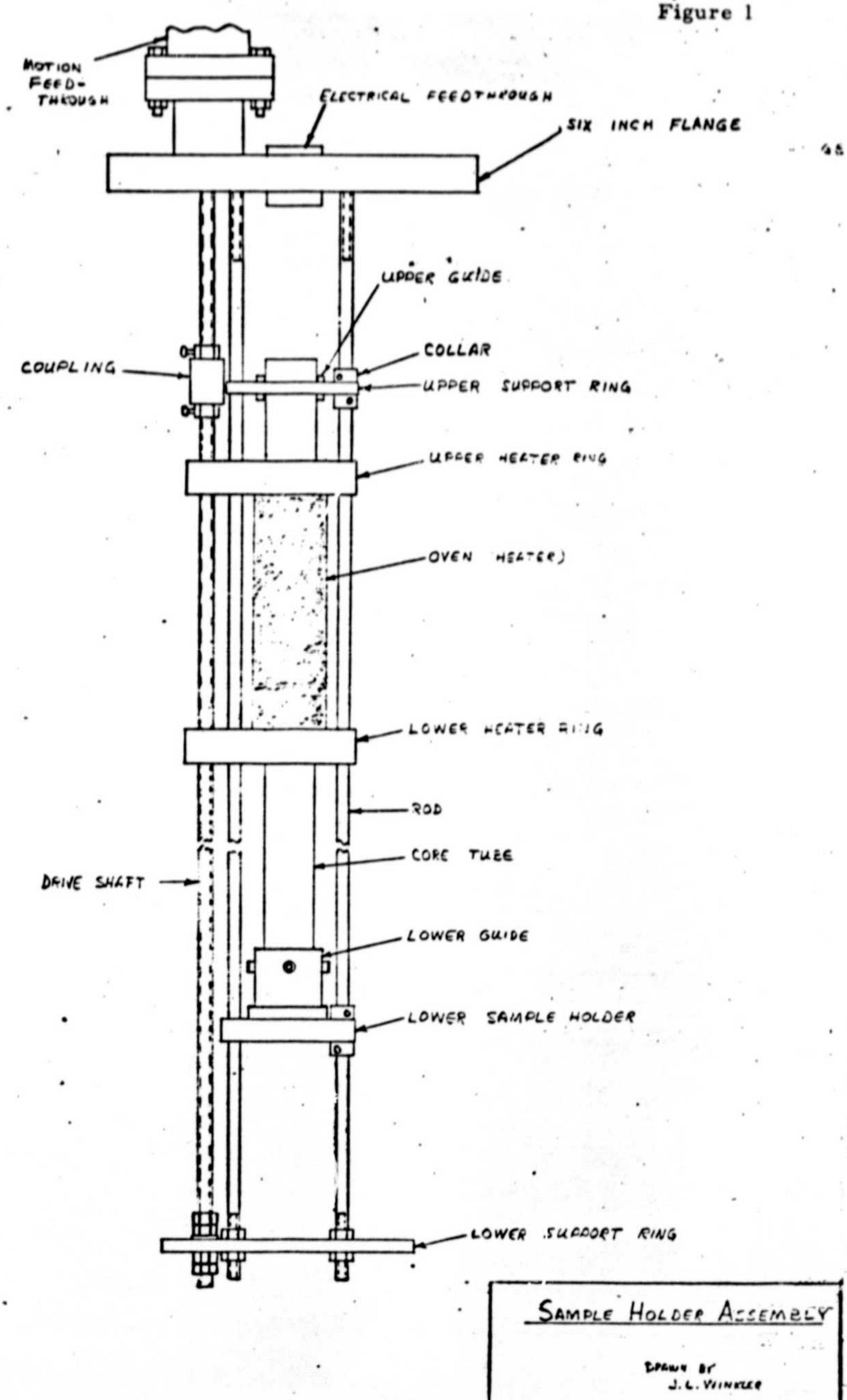
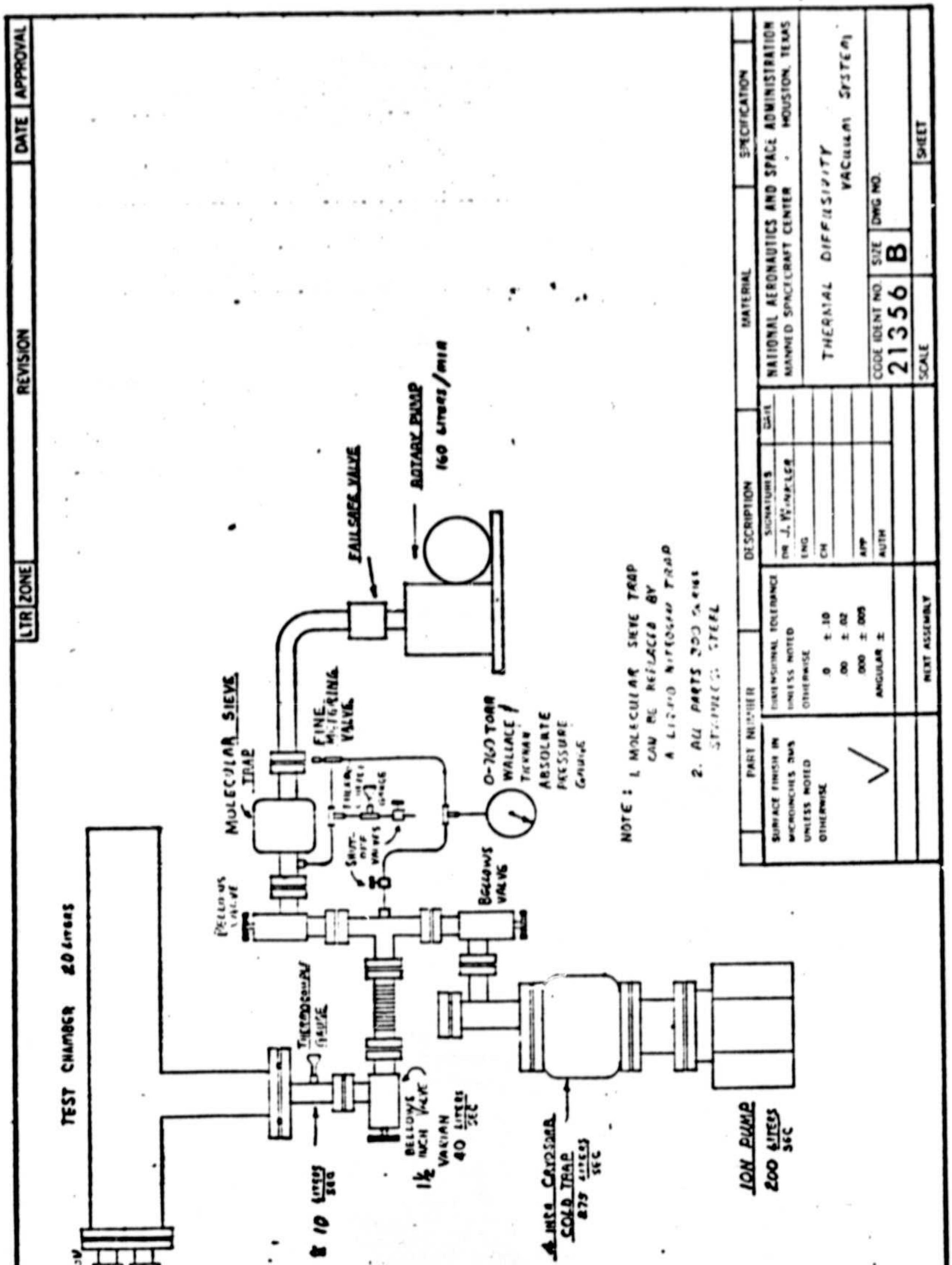

MOTION FEED-THROUGH
ELECTRICAL FEEDTHROUGH
SIX INCH FLANGE
UPPER GUIDE
COLLAR
COUPLING
UPPER SUPPORT RING
UPPER HEATER RING
OVEN HEATER)
LOWER HEATER RING
ROD
CORE TUBE
DRIVE SHAFT
LOWER GUIDE
LOWER SAMPLE HOLDER
LOWER SUPPORT RING
SAMPLE HOLDER ASSEMBLY
DRAWN BY
J. L. WINKLER

Figure 2


LTR
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TEST CHAMBER 20 LITERS
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BELLOWS 1½ INCH VALVE
VARIAN 40 LITERS/SEC
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BELLOWS VALVE
SHUT-OFF VALVES
MOLECULAR SIEVE TRAP
FINE METERING VALVE
FAILSAFE VALVE
ROTARY PUMP
160 LITERS/MIN
0-760 TORR WALLACE / TIERNAN ABSOLUTE PRESSURE GAUGE
CRYOSORB COLD TRAP
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200 LITERS/SEC
NOTE: 1. MOLECULAR SIEVE TRAP CAN BE REPLACED BY A LIQUID NITROGEN TRAP
2. ALL PARTS 300 SERIES STAINLESS STEEL
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SURFACE FINISH IN MICROINCHES RMS UNLESS NOTED OTHERWISE
DIMENSIONAL TOLERANCE UNLESS NOTED OTHERWISE
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We want to discuss a conduction of heat in composite coaxial circular cylinders. In cylindrical coordinate system, the inner cylinder ($0 \leq r \leq r_1$) is of one substance with thermal conductivity k_1, specific heat c_1, density ρ_1 and thermal diffusivity κ_1 ($= \frac{k_1}{c_1 \rho_1}$), the outer cylinder ($r_1 \leq r \leq r_2$) is of another substance with thermal conductivity k_2, specific heat c_2, density ρ_2 and thermal diffusivity κ_2 ($= \frac{k_2}{c_2 \rho_2}$). The cylinders extend to infinity in both positive and negative z-directions. Initially, the cylinders are at constant temperature zero and for time $t > 0$ heated externally at a constant rate F_0 per unit time and per unit length of the cylinders.

In the case we are going to discuss, the outer cylinder (metal) is 10^4 times more conductive than the inner cylinder (lunar regolith material under high vacuum). Besides, we are going to adopt a comparatively small rate of heating F_0. We will assume that the outer cylinder is a perfect thermal conductor ($k_2 = \infty$) and no temperature difference exists between the outer and the inner surfaces of the outer cylinder.

Therefore, the equation to be solved for the temperature $v_1(r,t)$ that is defined in the ranges of parameters $0 \leq r \leq r_1$ and $t > 0$ is

$$\frac{\partial^2 v_1}{\partial r^2} + \frac{1}{r}\frac{\partial v_1}{\partial r} - \frac{1}{\kappa_1}\frac{\partial v_1}{\partial t} = 0 \tag{1}$$

with the initial and the boundary conditions

$$v_1(r,0) = 0 \tag{2}$$

and

$$\pi (r_2^2 - r_1^2) c_2 \rho_2 \left.\frac{\partial v_1}{\partial t}\right|_{r=r_1} + 2\pi r_1 k_1 \left.\frac{\partial v_1}{\partial r}\right|_{r=r_1} = F_0 \tag{3}$$

The temperature in the outer cylinder $v_2(r,t)$, defined in the ranges of parameters $r_1 \leq r \leq r_2$ and $t > 0$, is constant as a function of r and is equal to $v_1(r_1,t)$.

A solution of (1) with the conditions (2) and (3) will be obtained by the Laplace transformation method (see, for example, Carslaw and Jaeger (1959, chapter 12)). If we denote the Laplace transformation of $v_1(r,t)$ by

$$\overline{v}_1(r,p) = \int_0^{\infty} \exp(-pt)\ v_1(r,t)\ dt$$

, the subsidiary equation that is obtained by the Laplace transformation of (1) becomes

$$\frac{d^2\overline{v}_1}{dr^2} + \frac{1}{r}\frac{d\overline{v}_1}{dr} - q_1^{\,2}\overline{v}_1 = 0 \tag{4}$$

where

$$q_1^{\,2} = p/\kappa_1$$

with the boundary condition

$$\pi(r_2^2 - r_1^2)\, c_2 \rho_2\, p\, \overline{v}_1\Big|_{r=r_1} + 2\pi r_1 k_1 \frac{d\overline{v}_1}{dr}\Big|_{r=r_1} = F_0/p \tag{5}$$

The solution of (4) that satisfies the condition (5) is

$$\overline{v}_1(r,p) = \frac{F_0}{p}\ \frac{I_0(q_1 r)}{\pi(r_2^2 - r_1^2)\rho_2 c_2\, p\, I_0(q_1 r_1) + 2\pi r_1 k_1 q_1 I_1(q_1 r_1)} \tag{6}$$

where $I_0(z)$ and $I_1(z)$ are the zero order and the first order modified Bessel functions.

The solution of (1) with the conditions (2) and (3) is obtained by the inversion theorem for the Laplace transformation

$$v_1(r,t) = \frac{1}{2\pi i}\int_{\gamma - i\infty}^{\gamma + i\infty} e^{\lambda t}\ \overline{v}_1(r,\lambda)\ d\lambda \tag{7}$$

where $v_1(r,\lambda)$ is the function obtained from $v_1(r,p)$ by replacing real variable p by complex variable λ.

Since the integrand of (7) has no branch point at $\lambda = 0$, the integral can be evaluated by calculating the residues at the poles of the integrand. Inspection of (6) reveals that the poles exist at $\lambda = 0$ and $\lambda = -\kappa_1 \gamma_n^2$ where γ_n is the n'th positive root of

$$\frac{1}{2} \frac{(r_2^2 - r_1^2)\, \rho_2 c_2}{r_1^2 \rho_1 c_1} (r_1 \gamma_n)\, J_0(r_1 \gamma_n) + J_1(r_1 \gamma_n) = 0 \tag{8}$$

Here, $J_0(x)$ and $J_1(x)$ are the zero order and the first order Bessel functions.

If we put $D_1 = \pi r_1^2 \rho_1 c_1$ and $D_2 = \pi (r_2^2 - r_1^2)\, \rho_2 c_2$, the residual at $\lambda = 0$ is

$$F_0 \left\{ -\frac{t}{D_1 + D_2} + \frac{1}{4 k_1} \frac{r^2 \rho_1 c_1}{D_1 + D_2} - \frac{1}{8\pi k_1} \frac{D_1 (D_1 + 2D_2)}{(D_1 + D_2)^2} \right\} \tag{9}$$

and that at $\lambda = -\kappa_1 \gamma_n^2$

$$- F_0 \left[\frac{J_0(r \gamma_n)}{J_0(r_1 \gamma_n)} e^{-\kappa_1 \gamma_n^2 t} \Big/ \left\{ \pi k_1 (r_1 \gamma_n)^2 \left[\frac{D_2}{D_1} \left\{ \frac{D_2}{D_1} \left(\frac{r_1 \gamma_n}{2} \right)^2 + 1 \right\} + 1 \right] \right\} \right] \tag{10}$$

From (9) and (10) we have

$$v_1(r,t) = F_0 \left[\frac{t}{D_1 + D_2} + \frac{1}{4\pi k_1} \left\{ \frac{\pi r^2 \rho_1 c_1}{D_1 + D_2} - \frac{1}{2} \frac{D_1 (D_1 + 2D_2)}{(D_1 + D_2)^2} \right\} \right.$$
$$\left. - \frac{1}{\pi k_1} \sum_{n=1}^{\infty} \frac{\dfrac{J_0(r \gamma_n)}{J_0(r_1 \gamma_n)} e^{-\kappa_1 \gamma_n^2 t}}{(r_1 \gamma_n)^2 \left[\dfrac{D_2}{D_1} \left\{ \dfrac{D_2}{D_1} \left(\dfrac{r_1 \gamma_n}{2} \right)^2 + 1 \right\} + 1 \right]} \right] \tag{11}$$

The temperature at $r = r_2$ is

$$v_2(r_2,t) = v_1(r_1,t)$$
$$= F_0 \left[\frac{t}{D_1 + D_2} + \frac{1}{8\pi k_1} \frac{D_1^2}{(D_1 + D_2)^2} \right.$$
$$\left. - \frac{1}{\pi k_1} \sum_{n=1}^{\infty} \frac{e^{-\kappa \gamma_n^2 t}}{(r_1 \gamma_n)^2 \left[\dfrac{D_2}{D_1} \left\{ \dfrac{D_2}{D_1} \left(\dfrac{r_1 \gamma_n}{2} \right)^2 + 1 \right\} + 1 \right]} \right] \tag{12}$$

For numerical calculation of (11) and (12), the series in the formulas must be computed for sufficiently large n so that the residuals become negligibly small. From (11) by putting $t = 0$ we obtain a relationship

$$\frac{1}{4(D_1+D_2)}\left\{\pi r_1^2\rho_1 c_1 - \frac{1}{2}\frac{D_1(D_1+2D_2)}{D_1+D_2}\right\}$$

$$= \sum_{n=1}^{\infty} \frac{J_0(r\gamma_n)/J_0(r_1\gamma_n)}{(r_1\gamma_n)^2\left[\frac{D_2}{D_1}\left\{\frac{D_2}{D_1}\left(\frac{r_1\gamma_n}{2}\right)^2+1\right\}+1\right]} \tag{13}$$

Since the lefthand side of (13) is a constant, this relationship can be used to test the convergence of the series. To evaluate the individual terms of the righthand side of (13), γ_n must be calculated from (8). Since the coefficient in the equation (8) is positive, the roots γ_n exist in the intervals where J_0 and J_1 have opposite signs. According to the elementary theory of Bessel function, the signs of J_0 and J_1 are opposite in the interval between α_n and β_n where α_n and β_n are, respectively, the n'th positive roots of J_0 and J_1. Therefore, we have a relationship

$$\alpha_n < \gamma_n r_1 < \beta_n \tag{14}$$

Since the values of α_n and β_n are known and available in the literature, the relationship (14) provides an effective way of calculating γ_n by computer. The numerical evaluation of (13) showed that, for the ranges of values of the physical constants that are encountered in our problem, a summation of first 20 terms leaves the residual less than 0.1 % for any value of r that is in the range $0 \leq r \leq r_1$. For the analysis of data, γ_n's are calculated up to $n = 100$ and the summation of first 100 terms is used to fit the formula to the data.

The formulas (11) and (12) were obtained for a constant heat flux F_0. We want to extend the formulas to the case when the heat flux changes stepwise as a function of time. Let the heat flux be a constant F_i in the time interval between t_{i-1} and t_i. Then, the variation of temperature at time t ($> t_i$) due to the heating is given by

$$v_1(r,t)_{t_{i-1},t_i} = F_i\left\{f(r,t-t_{i-1}) - f(r,t-t_i)\right\} \tag{15}$$

where

$$f(r,t) = v_1(r,t)/F_0$$

is a function derived from (11).

The variation of temperature due to the stepwise varying heat flux will be obtained by superposing (15) for all time intervals.

$$\begin{aligned}
V_1(r,t) &= \sum_{i=1}^{i_{max}} v_1(r,t)_{t_{i-1},t_i} \\
&= \sum_{i=1}^{i_{max}} F_i \cdot \left\{ f(r,t-t_{i-1}) - f(r,t-t_i) \right\} \\
&= \sum_{i=1}^{i_{max}} F_i \left[\frac{t_i - t_{i-1}}{D_1 + D_2} \right. \\
&\qquad \left. - \frac{1}{\pi k_1} \sum_{n=1}^{\infty} e^{-\kappa_1 r_n^2 t_{i_{max}}} \frac{J_0(r r_n)}{J_0(r_1 r_n)} \frac{e^{\kappa_1 r_n^2 t_{i-1}} - e^{\kappa_1 r_n^2 t_i}}{(r_1 r_n)^2\left[\frac{D_2}{D_1}\left\{\frac{D_2}{D_1}\left(\frac{r_1 r_n}{2}\right)^2 + 1\right\} + 1\right]} \right]
\end{aligned} \tag{16}$$

where $t_{i_{max}} = t$.

The temperature at $r = r_2$ is

$$\begin{aligned}
V_2(r_2,t) &= V_1(r_1,t) \\
&= \sum_{i=1}^{i_{max}} F_i \left[\frac{t_i - t_{i-1}}{D_1 + D_2} \right. \\
&\qquad \left. - \frac{1}{\pi k_1} \sum_{n=1}^{\infty} e^{-\kappa_1 r_n^2 t_{i_{max}}} \frac{e^{\kappa_1 r_n^2 t_{i-1}} - e^{\kappa_1 r_n^2 t_i}}{(r_1 r_n)^2\left[\frac{D_2}{D_1}\left\{\frac{D_2}{D_1}\left(\frac{r_1 r_n}{2}\right)^2 + 1\right\} + 1\right]} \right]
\end{aligned} \tag{17}$$

In the case when heat flux $F(t)$ is a continuous function of time, the effect of heating in the time interval between t_{i-1} and t_i can be approximated by that of constant heating rate by putting

$$\int_{t_{i-1}}^{t_i} F(t)\, dt = F_i \cdot (t_i - t_{i-1})$$

Therefore, with an appropreate selection of time intervals, (16) and (17) will be applied to the case when the heat flux varies continuously as a function of time.

K. Horai, M. Langseth, Jr., A. Wechsler, J. Winkler, D. Colvin, and S. Keihm: A New Technique of Thermal Conductivity Measurement of Lunar Core Samples.

A new technique has been developed to measure thermal conductivity of lunar core samples returned by Apollo missions. Since these samples are to be used for various scientific studies, the measurement must be performed without deteriorating any physical and chemical properties of the samples. The new technique does not require the extraction of sample material from the core tube. The lunar material in the core tube is mounted in a vertical position inside a vacuum chamber and heat flux is supplied radially from outside of the core tube. The thermal conductivity is determined by analyzing the time variation of temperature at the surface of the core tube. An experimental setup has been constructed to fit the Apollo 15 type drive tube core samples. Heat is transmitted to the sample by radiation from a coaxial cylindrical heater. The heat transmission coefficient was determined experimentally for a given temperature difference between the heater and an empty core tube. The comparison of the experimentally determined coefficient with the theory of radiative heat transfer yielded an estimate of therma emissivity $\varepsilon = 0.47$ which is reasonable for an anodized aluminum surface of the core tube. The solution of the time-dependent heat conduction equation for a concentric composite cylinder (outer cylinder, the core tube; inner cylinder, the sample of lunar regolity) was obtained under the conditions that the initial temperature is zero and the influx of heat through the outer surface of the core tube is a continuous function of time. Since the physical properties of the core tube are known, a single unknown parameter, either thermal conductivity or diffusivity of lunar regolith, can be determined by comparing the theory with the experimental data.

Test experiments have been performed on powdered Knippa basalt (grain sizes ranging from 74 to 149 μ; bulk density, 1.39 g cm^{-3}) and glass beads (grain size, 90 μ; bulk density, 1.48 g cm^{-3}). Gaseous pressure in the sample was below 0.78×10^{-6} torr for powdered Knippa basalt and below 1.0×10^{-4} torr for glass beads. For both of these samples, the initial temperature was about 300 K, which increased about 7 K during the measurement. The values of thermal conductivity obtained by the present method were 1.10×10^{-5} cal cm^{-1} s^{-1} K for powdered Knippa basalt and 0.41×10^{-5} cal cm^{-1} s^{-1} K for glass beads. These values are consistent with the values obtained by other standard techniques on these materials. It is considered that the new technique is particularly suitable for the measurement of thermal conductivity of lunar core samples for the following reasons: (1) The measurement is made without disturbing the sample mechanically. It is not necessary to dissect the core tube and extract the lunar material for the experiment. (2) The sample is heated in an indirect manner. Heat is transmitted to the core tube by radiation to avoid a direct contact to the heat source. The sample temperature need not be raised more than 10 K to obtain reliable data. (3) The attachment of a temperature sensor to the outer surface of the core tube is the only mechanical contact required for the measurement. This will greatly reduce possible chances of chemical contamination to the sample during the measurement.

This work was supported by NASA grant NGR 33-008-169.