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LUNAR PHYSICAL PARAMETERS STUDY

PARTIAL REPORT No. 2

MEASUREMENT OF LUNAR THERMAL PROPERTIES

A FEASIBILITY STUDY

August 31, 1960

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THERMAL MEASUREMENTS

HISTORICAL BACKGROUND

Lunar radiations have been used to estimate surface and subsurface temperatures as functions of time (1, 2,3,4). Such data have been used to estimate the thermal conductivity and the character of the lunar surface material (4,5). The temperature extremes were calculated to be about 390° K at maximum and about 120° K at minimum for the surface (1). These values were determined by use of a vacuum thermocouple at the focus of a telescope. Temperatures at an average depth of about 40 cm were calculated using the microwave thermal radiation from the moon at a wave length of about 1.25 cm (4). The amplitude of the temperature variation was seen to be considerably smaller than at the surface, a maximum of 300° K and a minimum of 197° K. From the microwave data an estimate of 234° K was formed for the temperature of the deep interior of the moon. Extreme temperature fluctuations noted during total eclipse (3) are possible only if the superficial layer of the moon's surface consists of extremely poor heat conductors. Wesselink (5), Piddington and Minnett (4) proposed the theory that the moon's surface is covered by a layer of dust, which, at very low pressures of atmospheric gases, becomes an excellent insulator. Piddington and Minnett (4) computed the thickness of this layer to be on the order of 1 millimeter, based on the assumption that the material of the moon's crust is solid, with a conductivity similar to that of terrestrial rocks or lava. If these suppositions are correct it is interesting to speculate on the disturbance of the surface of the moon and the changes in surface

properties as a rocket landing is attempted with, presumably, decelerating and steering blasts directed at the surface. Aside from removal of surface dust layers there is also the probability that chemical transformations would be brought about in surface layers in the atmosphere of high temperature exhaust gases from the rocket.

MEASUREMENTS

Surface Temperatures

The nature of the surface is unknown, is probably variable from place to place on the moon's surface, and will possibly be altered by the landing itself. The intent is to determine values in the immediate region of instrument package for surface temperatures, temperatures as a function of depth, and thermal diffusivity. Placing thermocouple junctions or thermistors in intimate contact with a surface presumed to be that of a material of low thermal conductivity is difficult, and it would be virtually impossible to place junctions exactly at the outer surface of a thin dust layer. Severe thermal gradients are presumed to exist in a very thin surface layer of the moon's crust, making a true surface measurement desirable. Thermocouple or thermistor elements to be used in the instrument package would have to be placed in contact with a surface which could be a dust layer, a fairly soft rock, or a hard glassy rock. Designing a system of placement to meet all conditions would probably result in an uncertainty of depth of the measuring points below surface, giving rise to corresponding uncertainties in temperature measurement. Further, placement of thermocouple junctions or

thermistor beads with the wires necessary for measurement involves transfer of heat between measuring unit and environment which produces another uncertainty in temperature measurement, particularly when the environment is a material of low heat capacity and low thermal conductivity.

Methods of estimating errors in surface thermometry are given by Jakob (8, section 33-4, page 153). Assume an infinitely extended body of thermal conductivity K_1 and uniform temperature θ bounded by a plane surface, which is perfectly insulated against heat losses except at one small circle of diamter $2r_o$, from which a wire of thermal conductivity K_w of length l and radius r_o perfectly insulated except at the ends extends to a body of constant temperature θ_b. Allow the contact between wire and surfaces at each end to be without resistance to heat flow. The temperature θ_o of the interface between infinite body and wire is to be determined. For the amount of heat per unit time transferred between wire and infinite body Jakob gives the equation

$$(1)\quad q_o = 4\, r_o\, K_1\, (\theta - \theta_o).$$

For the amount of heat transferred per unit time along the wire

$$(2)\quad q_o = \frac{K_w}{l}\, \pi r^2_o\, (\theta_o - \theta_b).$$

The quantity $\theta_o - \theta_b$ is the measured difference between reference point and thermocouple junction, while the quantity $\theta - \theta_o$ can be considered the error in measurement

$$(3)\quad \theta - \theta_o = \frac{K_w}{K_1}\, \frac{\pi}{4}\, \frac{r_o}{l}\, (\theta_o - \theta_b)$$

Taking the following values for the conductivites,

$$K_1 \approx 10^{-4} \text{ cals/cm } ^oC \text{ sec.}$$

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$K_w \approx 10^{-1}$ (approx. value for iron, constantan. Copper is on the order of 1).

and assuming a value for r_o of .01 cm and for l, 100 cm., then

$$(4)\ \theta - \theta_o = 10^3 \frac{\pi}{4} 10^{-4} (\theta_o - \theta_b)$$

$$(5)\ \text{Error} = .08 (\theta_o - \theta_b)$$

An ideal system has been assumed in which radiation transfer has been neglected and in which there is perfect thermal contact at the measuring point. The thermocouple wire has been represented by a 1 meter length of wire having a diameter of 0.2 mm. For this case, an error in measurement exists amounting to 8% of the observed temperature difference between reference point and measuring junction.

In the case of thermistor beads, a further complication exists in the need for a small power dissipation within the bead during measurement.

Development of a suitable radiation pyrometer offers some promise for surface temperature measurement. Regardless of the nature of the surface the radiation pyrometer need not physically disturb it, and can be placed at such a distance from the surface as to have no effect on its temperature. Indeed the radiation pyrometer can be housed within the instrument package and can possibly be arranged to "scan" the surrounding areas.

The reading given by such a device is dependent on other parameters in addition to the temperature of the surface, these being the "emissivity" of the surface, (a property determined by the nature of the surface and the material of which it is composed) and the nature and temperature of the environment of the detecting device (6,7). The environment of the detecting device can be held

constant, leaving the surface properties as variables. Mouzen and Dyer (7) and McAdams (9, Fig. 4-2, page 62), show that, as temperatures decrease, the emissivities of various paints and refractories approach 90 percent or more at 100°C. It is quite possible that within the temperature ranges considered the emissivity of moon's surface will be close to that of a black body.

Jakob (8, section 33-10, page 190) states that the response of a total radiation pyrometer is given by the expression

$$(6) \quad \phi = C \epsilon \theta^4$$

θ = absolute temperature of the radiating surface.

C = instrument constant.

ϵ = emissivity.

ϕ = response.

then,

$$(7) \quad \theta^4 = \frac{\phi}{C} \cdot \frac{1}{\epsilon}, \text{ or}$$

$$(8) \quad \theta = \sqrt[4]{\frac{\phi}{\epsilon C}}$$

The apparent black body temperature is

$$(9) \quad \theta_a = \sqrt[4]{\frac{\phi}{C}} \qquad \text{if } \epsilon = 0.9 \text{ then}$$

$$(10) \quad \theta = 1.03\, \theta_a$$

Giving a maximum error due to emissivity variation in determination on the order of 3 percent of the observed value, this error resulting from an unknown emissivity $1 > \epsilon \geq 0.9$.

Several means are available for creating a known emissivity, or correcting for an unknown emissivity. The "two color"

principle uses the ratio of two intensities in two fractions of the spectrum as a measure of temperature on the assumption that the mean emissivities are the same at both wave length ranges. A known emissivity can be created by spraying a fine film of known material on the surface (which may alter conductivity properties to some extent). If a hole is created within the surface, a measure of the emitted radiation will give the black body temperature, but this temperature will be some average over the depth of the hole. The most promising attack on a true surface temperature measurement is felt to be radiation pyrometer development.

Subsurface Temperature Measurement and Thermal Diffusivity Determination

Subsurface measurements have again the problems of contact and disturbance of environment commented upon in the discussion of surface temperature determination. It is difficult to imagine a radiation pyrometer sufficiently small to be lowered in a tool. If a good reflector could be found for portions of the spectrum considered usable for temperature measurements this, providing it could be made in a form and weight to give minimum disturbance of the hole, might be used to "log" a hole for temperature by reflecting wall emission into a pyrometer focused for a narrow beam.

Using thermistors or thermocouples subsurface would involve developing probe elements of low heat capacity and low thermal conductivity provided with means for establishing thermal contact at each point of measurement. The error involved in use of thermocouples for surface measurement on the assumption of good thermal contact and ignoring radiation loss was discussed previously. This

development illustrated the disturbance in temperature associated with placing fine wires in contact with materials of conductivity less than 10^{-4} cals/cm. sec. °C. Probe systems for subsurface measurement would of necessity be sturdily constructed involving therefore a fairly large mass and a high thermal conductivity. It is possible to design a system which compensates for heat transfer along the probe (13). This would require construction of a probe with radiation shielding to minimize heat transfer to the surface except at the point of measurement. A differential system of temperature sensing elements would then detect thermal gradients along the probe and a means of heating and cooling between the measuring point and reference junction would be used to bring axial heat flux from the measuring point to a desired negligible value. If radiation shielding and this low axial heat transfer were attained for the probe, the response of the system would be a function of the mass of the measuring point, the transfer of energy (by conduction and/or radiation) between surface and measuring point, and the thermal diffusivity of the environment. A slow attainment of equilibrium could be expected for each point.

Probe systems have been developed for estimation of thermal diffusivity by transient heat flow observations (11, 12). These probes contain a means of heating and temperature sensing elements. The device could take the form of a subsurface linear probe or sphere or a disc placed on surface. In the latter case the boundary transfers of energy by radiation would have to be estimated in data treatment. The thermal diffusivity could be estimated from any of the following observations.

1. Temperature vs. time curve of the probe instantaneously brought to a temperature differing from the environment.

2. Temperature vs. time for the probe, originally in equilibrium with the environment, at a constant power dissipation.

3. Power vs. time required to maintain a probe temperature differing from the original temperature of the environment.

Carslaw and Jaeger (10, Chapt. X, 104, page 222) treat the problem of a continuous spherical source with a constant rate of heat liberation. Their solution for temperature distribution is:

$$(10)\quad \theta = \frac{\frac{q}{\rho c}}{8\pi k r r'}\left\{2\left(\frac{kt}{\pi}\right)^{1/2}\left[e^{-\frac{(r-r')^2}{4kt}} - e^{-\frac{(r+r')^2}{4kt}}\right] - |r-r'|\,\mathrm{erfc}\,\frac{|r-r'|}{2(kt)^{1/2}} + (r+r')\,\mathrm{erfc}\,\frac{r+r'}{2(kt)^{1/2}}\right.$$

where

θ = temperature rise

k = thermal diffusivity

r = radial position

q = rate of heat dissipation

c = specific heat of medium

r' = radius of spherical source

t = time

ρ = density of medium

The equation at r = r' reduces to

$$(11)\quad \theta = \frac{\frac{q}{\rho c}}{4\ kr'^2}\left\{\left(\frac{kt}{\pi}\right)^{1/2}\left[1-e^{\frac{-r'^2}{kt}}\right] + r'\,\mathrm{erfc}\,\frac{r'}{(kt)^{1/2}}\right\}$$

This is assumed to be a close approximation, for a small value of r', to the temperature increases seen at the surface of a

spherical body of radius r' in an infinite medium generating heat at a constant rate q with perfect thermal contact at the surface. For estimating temperature increases in a spherical probe the following values of the parameters were selected.

$q = 1$ cal/min. $t = 100$ min.

$r' = 1$ cm $\rho = 1.6 \frac{gms}{cm^3}$ $c = 0.25 \frac{cals}{gm\ °C}$

Take the following values of K_1:

$K_1 = 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 2.7 \times 10^{-6}$ cals/cm. sec. °C

The solutions obtained are given in Table I.

TABLE I

K_1 (Cal/cm. sec. °C)	θ (°C)
10^{-3}	1
10^{-4}	8
10^{-5}	30
2.7×10^{-6}	52
10^{-6}	92

To estimate the effect of contact it is next assumed that no conduction path exists between sphere and medium, heat transfer taking place by radiation across a very thin non-absorbing layer. The temperature difference between surfaces of the sphere and the environment is estimated by use of the following equation (8, Jakob, Section 31-3, page 3), assuming emissivities of both surfaces are unity.

$$(12) \quad q^1 = \sigma (\theta_1^4 - \theta_2^4)$$

q^1 = energy interchange per unit time per unit area

σ = constant of the Stefan-Boltzman law = 4.88×10^{-8}K - cal/m^2 hr °K^4

θ_2, θ_1 = absolute temperatures of the surfaces

For a heat transfer of 1 cal/min. (equilibrium conditions) across the surface of a sphere radius = 1 cm, q^1 = 50 K-cal/m^2 hr. then

$$(13)\quad (\theta_1^4 - \theta_2^4) = 10^9$$

From (13, Table II was constructed where θ_2 is the temperature of the medium.

TABLE II

θ_1°K	θ_2°K	$\Delta\theta$°K
182	100	82
226	200	26
265	250	15
309	300	9

It is now possible to construct a table for the observed temperature rise of the sphere under the assumed conditions of power dissipation, considering that the additional resistance to heat flow generated by radiation adds as a simple increment of temperature to the previously calculated values of observed temperature rise under conditions of perfect thermal contact.

TABLE III

K_1 cals/cm sec °C	Temp. Rise Perfect Thermal Contact	Temp. Rise Radiation Med. at 200°K	Temp. Rise Radiation Med. at 250°K	Temp. Rise Radiation Med. at 300°K
10^{-3}	1	27	16	10
10^{-4}	8	34	23	17
10^{-5}	30	56	45	39
2.7×10^{-6}	52	78	67	61
10^{-6}	92	118	107	101

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Table III was used to construct Fig. 1 which will allow an estimate of the uncertainty in thermal conductivity determination for various values of thermal conductivity and at various temperature levels for the assumed probe parameters. The idea suggests itself that, instead of attempting to attain good thermal contact with a surface of unknown character, a more reasonable approach is to force a situation of no physical contact. In this case, with fair accuracy a correction for radiation transfer may be feasible, eliminating the need for estimating the physical contact areas between probe and surface.

Using the solution for an instantaneous spherical surface source, the temperature distribution in an infinite medium is given by (Jakob, Vol. I, Sec. 17-4, page 340)

$$\theta = \frac{H_1}{8\pi^{3/2}\, sr\rho c(kt)^{1/2}} \left[e^{-\frac{(r-s)^2}{4\,kt}} - e^{\frac{-(r+s)^2}{4\,kt}} \right]$$

This has been used to estimate the upper limit of cooling rate for a body in the following manner. An iron sphere of radius 1 cm, is originally 100°C above the environment temperature. The amount of heat to be transferred to the environment is $\rho_{iron}\, C_{iron}\, \frac{4}{3}\, \pi\, r^3 (\Delta\theta) =$ 370 calories. It is next assumed that this quantity of heat is released in an instantaneous spherical surface source, S = 1 cm, and the temperature followed with time at r = 1 cm.

then,

$$\theta = \frac{370}{8\pi^{3/2}\,(0.4)(kt)^{1/2}} \left[1 - e^{-\frac{1}{kt}} \right]$$

k = thermal diffusivity of the medium

K = thermal conductivity of medium

$k = \frac{K}{\rho c}$ where ρ and c are the medium density and specific heat respectively. Fig. 2 plots results of this calculation. Under the assumed conditions a very slow attainment of thermal equilibrium is experienced for thermal conductivities below $10^{-5} \frac{\text{cals}}{\text{cm. sec. °C}}$. For these low conductivities there is some concern about the effect of additional heat sources on thermal measurements. These additional thermal disturbances are, for example, heat generated in drilling and heat transferred between medium and large masses of material of relatively low conductivity. Slow attainment of equilibrium temperature can be expected after any such disturbance for a medium conductivity of less than 10^{-5} cals/cm. sec. °C.

CONCLUSIONS

1. The most likely device for surface temperature determination is some form of total radiation pyrometer.

2. The most likely device for subsurface temperature determination is a thermocouple probe provided with heating/cooling devices between reference junction and measuring point to obtain minimum axial heat flow. A slow response can be expected from such an instrument.

3. It seems feasible to arrange some form of probe system for a single point determination of thermal diffusivity by imposing a transient heat flow. It may be desirable in such an instrument to transfer heat between probe and medium by radiation only.

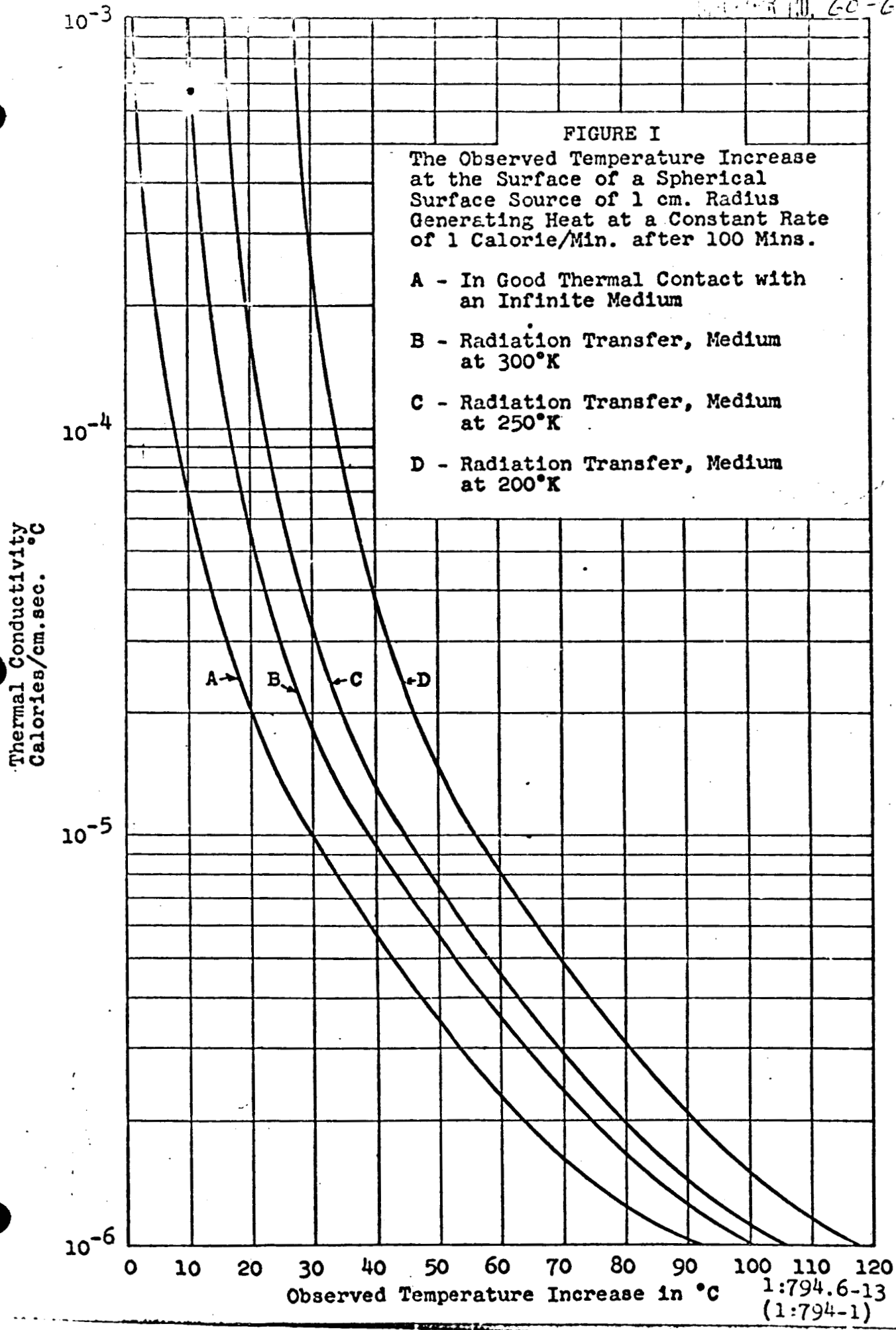
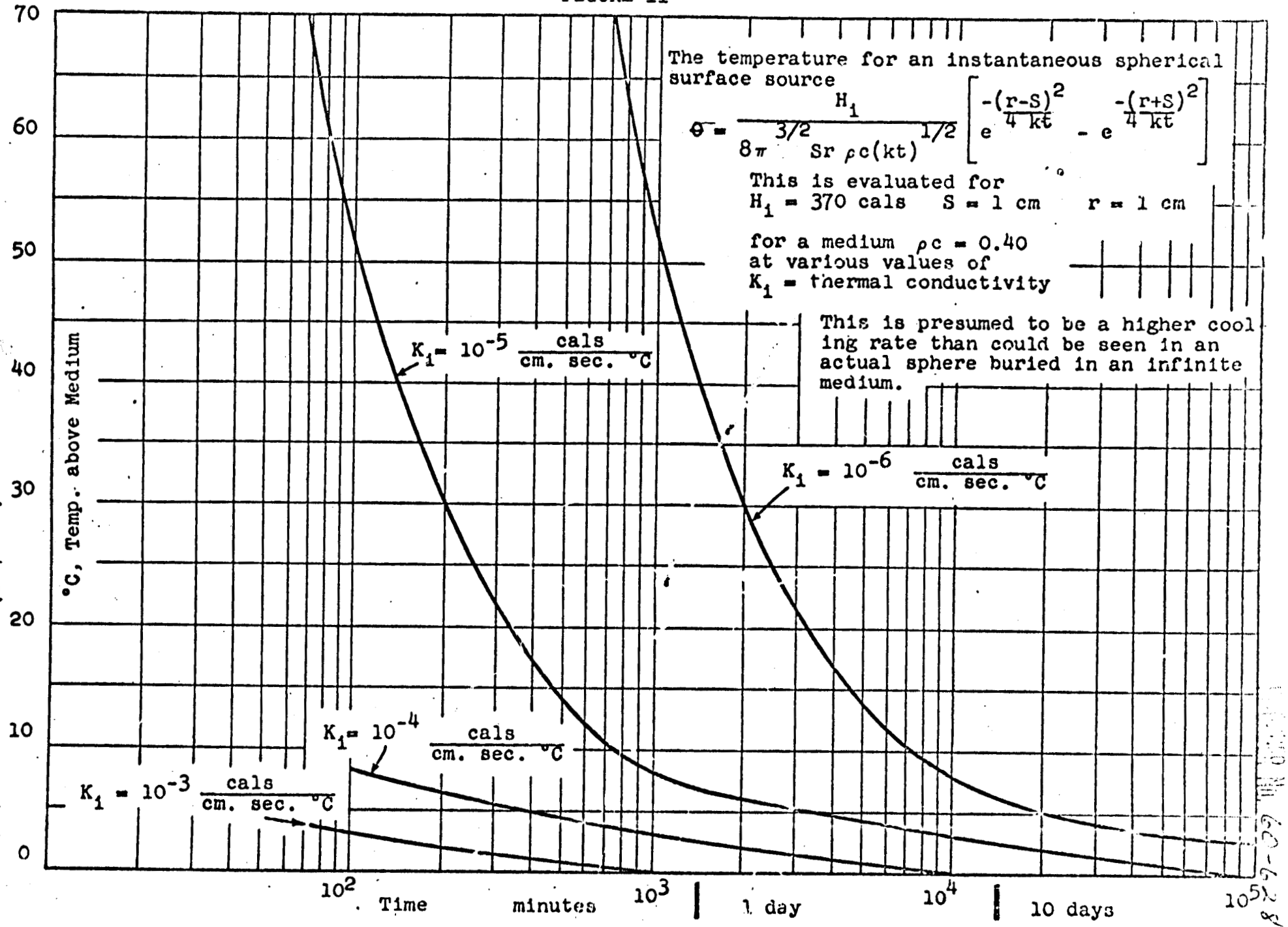


FIGURE I
The Observed Temperature Increase at the Surface of a Spherical Surface Source of 1 cm. Radius Generating Heat at a Constant Rate of 1 Calorie/Min. after 100 Mins.
A - In Good Thermal Contact with an Infinite Medium
B - Radiation Transfer, Medium at 300°K
C - Radiation Transfer, Medium at 250°K
D - Radiation Transfer, Medium at 200°K
A
B
C
D
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Thermal Conductivity Calories/cm.sec. °C
0
10
20
30
40
50
60
70
80
90
100
110
120
Observed Temperature Increase in °C

FIGURE II



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