Remote Sensing Brief

STUART E. MARSH
JOHN P. SCHIELDGE
ANNE B. KAHLE
Jet Propulsion Laboratory
Pasadena, CA 91109

An Instrument for Measuring Thermal Inertia in the Field

The Thermal Inertia Meter (TIM) was used to discriminate different rock and soil types at a number of test sites in Nevada and California.

ABSTRACT: *Based on a previously developed laboratory method (Schultz, 1968) for the nondestructive determination of thermal inertia, an instrument [Thermal Inertia Meter (TIM)] has been developed and employed to measure the thermal inertia of geologic materials in situ. A target and two standards are radiantly heated with calibrated lamps. The temperature history of the target and the standards are monitored with an infrared radiometer, and comparison of the target heating history with that of the two reference standards yields the target thermal inertia. We have used the TIM to discriminate different rock and soil types at a number of test sites in Nevada and California.*

BACKGROUND

THE PAUCITY of laboratory measurements of the thermal inertia components (conductivity, density, and specific heat) for rocks and soils found in natural field conditions is apparent after review of the heat conduction literature. The vast majority of these measurements have been of engineering or insulating materials, not geologic materials. For example, the *Handbook of Physical Constants* (Clark, 1966) presents five rock type conductivity values, only a few density values, and no specific heat values. Even less information is available for geologic materials under natural field conditions. With the availability of HCMM satellite and other remotely sensed thermal data, there is now a need for measurements of thermal inertia of surface materials in situ.

A laboratory method has been developed by Schultz (1968) for nondestructively determining the thermal inertia of materials at ambient temperatures. The method involves the radiant heating of an unknown sample and a standard. The temperature history of the sample and standard are monitored with an infrared radiometer, and comparison of their temperature histories yields the local thermal inertia of the sample.

In this study, we have adapted Schultz's techniques to construct a field instrument to measure the thermal inertia in situ. The surface temperature rise of the materials is used to calculate the thermal inertia of the sample. This calculation is based upon the following assumptions: (1) the compositions of the standard and sample materials are homogeneous, (2) the heat flux density at the surface of each material is constant and equal for each material, and (3) the materials are thick enough to be approximated as semi-infinite bodies. This allows us to calculate the thermal inertia of the sample from an algebraic equation adapted by Schultz from Carslaw and Jaeger (1959), that is,

$$P_t = \frac{\Delta T_s}{\Delta T_t} \times P_s \times (\epsilon_t/\epsilon_s)^2 \qquad (1)$$

where P_t is the target's thermal inertia, P_s the standard's thermal inertia, ΔT_s the standard's change in temperature, ΔT_t the target's change in temperature, ϵ_t the target's emissivity, and ϵ_s the standard's emissivity.

INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

A photograph of the thermal inertia meter and its experimental design is shown in Figure 1. The power source for the lamps and PRT-5 in the laboratory is line current and, in the field, a portable

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 48, No. 4, April 1982, pp. 605-607.

0099-1112/82/4804-595$02.25/0

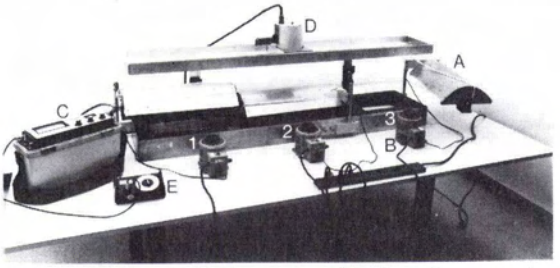

FIG. 1. Thermal Inertia Meter (TIM) with quartz infrared heat lamps (A), voltage regulators (B), PRT-5 (C) and detector head (D), and digital voltmeter (E).

5-kilowatt gas generator mounted in a van or truck. The radiant energy sources (A) are 3200-W quartz infrared heat lamps (GE #3200T3/1CL/Ht-384V). The lamps are mounted in parabolic, polished aluminum reflectors coated with lacquer to prevent discoloration. Each lamp is pivoted, which permits it to be quickly moved into position to heat the surface and removed to allow monitoring of the surface temperature. The lamps are connected to Variac voltage regulators (B) which permit the mutual balancing of the three infrared lamps. The surface temperature rise is monitored using a Barnes Engineering Company precision radiation thermometer (C), model PRT-5. The instrument is specified to be accurate to 0.5°C. The instrument's detector head (D) is mounted in such a way as to permit rapid movement from reference standard to target. The detector head is 38.7 cm above the target or standard, yielding a circular field of view 1.35 cm in diameter at the center of the area undergoing heating. A portable digital voltmeter (E) measures the voltage from the PRT-5. The PRT-5 and voltmeter are calibrated against a temperature-controlled blackbody.

The base of the thermal inertia meter consists of three compartments. They are open to the surface below; their interiors are painted with flat-black, and they are surrounded by 5 cm of styrofoam insulation. Compartments 1 and 3 hold the thermal inertia standards, which are placed within flat-black plywood boxes. Compartment 2 is left open to the surface and the TIM is placed over the surface to be measured.

The thermal inertia reference standards chosen were geologic materials with high and low thermal inertia values. A dolomite block (30 by 18 by 5 cm) and 20/30 mesh Ottawa sand (quartz) were acquired for use as standards. Both materials were sent to independent laboratories[1] for determination of their respective thermal conductively, specific heat, and density (see Table 1). The specific heat of both standards was determined by the method of mixtures, the density by a Beckman air pyncnometer, and the conductivity by the American Society of Testing Materials (ASTM) method.

[1] (Geosciences Ltd., Solana Beach, CA 92075; Dynatech, Cambridge, MA 02139)

TABLE 1. THERMAL INERTIA STANDARDS

	Dolomite	Ottawa Sand
Conductivity (K) cal cm^{-1} sec^{-1} $°C^{-1}$	0.01182	0.00081
Density (ρ) g cm^{-3}	2.97	1.74
Specific Heat (c) cal g^{-1} $°C^{-1}$	0.20	0.25
Thermal Inertia (T.I.) cal cm^{-2} $sec^{-1/2}$ $°C^{-1}$	0.0838	0.0188

The experimental procedure was as follows. After recording the initial temperature of the two standards and the target, the three lamps were allowed to warm up for 300 seconds. They were then successively swung into position over their respective targets at 5-second intervals. After four minutes of heating, lamp 1 was removed and the maximum temperature of target 1 was recorded. Five seconds later the maximum temperature of target 2 was recorded, followed in five seconds by the temperature of target 3. In the field, prior to the initiation of a measurement at a site, the target was shaded for approximately 20 to 30 minutes so that the initial temperature profile within the layer affected by the heating was nearly isothermal.

RESULTS

Measurements were obtained from field trips to selected test sites in and around Goldfield, Hawthorne, and Elko, Nevada, and Pisgah Crater, California. These sites were chosen because thermal modeling or thermal inertia mapping by remote sensors had either been performed or was planned over these sites. Approximately 50 usable measurements with the thermal inertia meter were recorded. As thermal inertia is very sensitive to soil moisture variations (Quiel, 1975), soil moisture samples of all alluvial materials were taken. All sites were located in arid areas and the soils were quite dry (less than 10 percent moisture content per unit volume near the surface).

The thermal inertia meter yields two independent measurements of thermal inertia for each target: one is based upon the dolomite and the other upon the Ottawa sand. Table 2 gives the value and the error of the calculated thermal inertia for several rock and soil types based upon both the Ottawa sand and dolomite. A previously published value for a similar material is also given when available. The error limits given only pertain to a 0.5°C inaccuracy in the PRT-5 measurement. However, note that the dolomite-based val-

TABLE 2. THERMAL INERTIA DERIVED FROM IN SITU THERMAL INERTIA METER MEASUREMENTS

Material	T.I. Relative to Ottawa Sand	T.I. Relative to Dolomite	Published Value
Olivine Basalt	0.032 ± 0.003	0.042 ± 0.005	0.054 (Janza)
Pahoehoe Basalt	0.027 ± 0.002	0.039 ± 0.004	
Aa Basalt	0.032 ± 0.002	0.042 ± 0.003	
Barite	0.038 ± 0.003	0.043 ± 0.005	
Chert	0.042 ± 0.005	0.053 ± 0.005	
Andesite	0.033 ± 0.003	0.044 ± 0.005	0.055 (Brennan)
Rhyolite Ash Flow Tuff	0.16 ± 0.001	0.022 ± 0.003	
Silicified Rhyodacite	0.040 ± 0.004	0.048 ± 0.005	
Aerolian Sand	0.012 ± 0.001	0.015 ± 0.002	
Clay-Silt Playa	0.018 ± 0.001	0.024 ± 0.002	
Sandy Alluvium	0.010 ± 0.001	0.014 ± 0.002	0.014 (Clark)

ues are consistently larger (about 21 percent on average) than the Ottawa sand-based values. Part of this discrepancy may be due to the fact that we used typical values of emissivity for both standards. Any deviation from the actual emissivities would cause a consistent difference between the P value based on the dolomite standard and that based on the Ottawa sand standard. For example, an error of 5 percent in either standard will introduce a consistent error of 10 percent between the two calculations. Also, dolomite can be quite heterogeneous in composition, and this can result in variations in thermal properties among samples, or even in the same sample.

The TIM field tests indicate that the instrument is useful in a relative sense. As long as very accurate measurements of thermal inertia are not required, it is adequate for discriminating among different materials. For example, our measurements of thermal inertia near Elko were made to test the premise that exploration for barite might be feasible because of barite's very high density and hence high thermal inertia. We used the TIM to measure the thermal inertia of some very high grade barite deposits and the surrounding rock materials. Somewhat surprisingly the chert, which is located in the same area as the barite, in all cases was found to have a higher thermal inertia than the barite. This was true both for outcrops and rubble. While barite has a higher density than chert, chert must have a higher thermal conductivity. Regardless of any error in the absolute value of thermal inertia of these two materials, the use of the TIM demonstrated that the chert consistently had a higher thermal inertia than the barite.

ACKNOWLEDGMENTS

The authors thank Warren Rachwitz of JPL who was responsible for the construction and much of the design of the Thermal Inertia Meter. We also thank Mike Abrams and Helen Paley of JPL who helped with the field work and made numerous suggestions during the research program, and Jim Conel and Frank Palluconi who contributed stimulating discussion.

The work was performed while Dr. Marsh was a National Research Council Research Associate at JPL. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Carslaw, H. S., and J. C. Jaeger, 1959. *Conduction of Heat in Solids*, Oxford Press, London, 75 p.

Clark, S. P., ed., 1966. *Handbook of Physical Constants*, Geological Society of American Memoir 97, New York, 459-483.

Quiel, F., 1975. Thermal/IR in Geology. Some Limitations in the Interpretation of Imagery, *Photogrammetric Engineering and Remote Sensing*, Vol. 41, No. 3, pp. 341-346.

Schultz, A. W., 1968. An Infrared Transient Method for Determining the Thermal Inertia, Conductivity, and Diffusivity of Solids, *Applied Optics*, Vol. 7, No. 9, 1845-1851.

(Received 14 April 1980; revised and accepted 1 November 1981)