A Penetrometer Mounted Radiometer for Rapid In-Situ Measurement
of Magma Temperature

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ABSTRACT

A Penetrometer-mounted radiometer has been constructed to make in-situ measurements of magma temperature. The radiometer sensor is a small photodiode-operational amplifier package which produces a voltage output proportional to incident radiant power. Although capable of making precise, high speed measurements, the emittance of the magma must be known to convert the readings to accurate temperature measurements.

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Introduction

A recent proposal^{1,2} to investigate magma as an energy source has stimulated interest in the measurement of in-situ magma properties. Obviously, temperature is one of the most important intensive properties needed. This report describes the design and construction of a radiometer to be mounted in an earth penetrometer³ for rapid in-situ measurement of magma temperatures.

Previous field measurements of magma temperature have been taken by thermocouples, pyrometers, or passive techniques and have been made on erupting magma pools or lava flows.⁴ Due to high temperatures (up to 1500 K), corrosive environments and resulting difficulties in approaching the measurement site, thermocouples have been used to depths of less than a meter. Optical pyrometer measurements have been limited to surface readings, which are usually lower than actual temperatures due to smoke and haze in the optical path and also difficulties in making emittance corrections. However, Seeger Cones (passive temperature indicators) have been used to derive temperatures to a depth of 13 meters.⁵

The penetrometer mounted radiometer described in this report is designed to measure subsurface magma temperature. The radiometer technique has the advantage of a very short response time which allows many readings to be taken before the instrument is destroyed. As will be seen later in this report, it does have the disadvantage that the emittances must be known for accurate temperature measurements.

Design and Construction

Factors influencing the design of the radiometer were:

- (1) The instrument must have a fast response, as the entire period for measurement will be at most one second;
- (2) It must be capable of making measurements over a temperature range of 1100-1500 K;
- (3) The radiometer must be able to withstand the shock of penetrometer entry;
- (4) As space within the penetrometer is limited, the radiometer must be kept small;
- (5) The electrical characteristics of the radiometer must be compatible with penetrometer power supplies and telemetry.

The sensor which best fit these requirements was a photodiode packaged with a differential input operational amplifier (EG&G, Electro-Optics Div., Salem, Mass; Model HAD-1000). Among its important characteristics are:

1. Small size - 1 cm dia. x 0.5 cm long
2. Active photodiode diameter - 0.25 cm.
3. Broad spectral response - 450-1100 nm
4. Rise time $\sim$ 400 nsec
5. Output (volts) is directly proportional to the light intensity striking the photodiode.

The electrical configuration of the op-amp/photodiode is shown in Figure 1.

The housing and viewing orifice for the radiometer was kept as simple as possible. It consisted solely of a mild steel tube with a recess at one end for the photodiode/op-amp, trim, and feedback resistors (Figure 2). The sighting orifice was sized to overfill the active photodiode area and threaded to reduce internal reflections. The dimensions of the sighting orifice defined a field of view of about 10° . After machining, the casing was given a flat black ebanol finish to further reduce reflections.

Op-amp feedback resistors were chosen for electrical compatibility with the penetrometer telemetry package, which required a signal with a threshold of about 100 mv and a maximum of 5 V. When coupled with the magma temperatures of interest and the response of the photodiode/op-amp, this limited the span of the radiometers to about 400 K. Since it was thought that temperatures encountered by the penetrometers might range from 1100 to 1550 K, it was decided to field two radiometers per penetrometer, with ranges of 1100 to 1500 K and 1150 to 1550 K. Feedback resistance needed to achieve these temperature ranges were determined for each radiometer while it was sighted on a hot nickel strip at the required temperatures. Trim resistors were chosen while light to the photodiodes was cut off. Values ranged from 150 to 222 K Ω for feedback resistors, and from 3 to 7 K Ω for the trim resistors. After the resistors were soldered to the photodiode/op-amp leads, the assembly was potted with Epon 828 resin into the recess at the back of the radiometer casing.

Calibration

Each radiometer was calibrated against a commercial radiometer of known calibration. A precisely controlled windowless blackbody furnace was used as the temperature source. The output of each radiometer was measured with a precision digital voltmeter at six points which spanned the temperature range while the temperature of the blackbody was monitored by the calibrated commercial radiometer.

An example of a plot of the calibration curves is given in Figure 3. The most obvious characteristic of the curve is that the radiometer output varies exponentially with temperature. This is because the response of the photodiode/op-amp for this temperature range is proportional to the radiance (M_λ , w/cm²) striking the detector, which according to Plank's law is an exponential function of temperature:

$$M_\lambda = C_1 \lambda^{-5} [e^{C_2/\lambda T} - 1]^{-1}.$$

C_1 and C_2 are the radiation constants and λ is the effective wavelength.

It can be seen from the equation and Figure 3 that the sensitivity of the radiometers, $\Delta E/\Delta T$, increases with increasing temperature. For this reason, the portion of the output curves with greater sensitivity was kept centered about the expected magma temperature, ~ 1400 K.

Testing

A finished model of the radiometer was tested for several effects which might affect its performance: variation in op-amp and photodiode power supply voltage, variation of target distance, and emittance effects.

To test the effect of variations in power supply voltage, the radiometer was sighted on a nickel strip at 1450 K and the output monitored while the power supply voltages were varied from 6 to 10 V (nominal = 8.2 V). No significant change in radiometer output was noted for these variations.

The effect of distance from the radiometer to the target was tested by monitoring the output as the distance from a 5 x 15 cm nickel strip at a temperature of 1450 K was varied from 2 to 20 cm. The dimensions of the nickel strip were large enough to completely illuminate the radiometer sighting aperture at a distance of 20 cm. Again, no significant variation in radiometer output was noted for this test.

Target emittance, however, has a sizable effect on radiometer performance. From the definition of emittance, ϵ , the ratio of radiated power, P_s , from an object to that of a blackbody, P_b , at the same temperature ($\epsilon = P_s/P_b$), it can be seen that radiometer response is proportional to sample emittance. To check for emittance effects similar to those which might be encountered during an actual magma measurement, the temperature of a freely cooling crucible of molten Hawaiian basalt* (major chemical components⁶: 45% SiO_2 , 16% Al_2O_3 , 10% FeO , 9% CaO , 6% MgO) was monitored with the radiometer and a chromel-alumel thermocouple. The radiometer was mounted about 10 cm above the molten basalt surface while the thermocouple junction was placed about 0.1 cm into the melt.

As can be seen from a summary of the results in Table 1, there was an 80 degree difference between the thermocouple temperature and those calculated from the radiometer output using the blackbody calibration curve (Figure 1). Since the output is proportional to the radiated power of the sample, the emittance correction of the molten basalt can be calculated as the radiometer output divided by the output predicted by Figure 1 for the thermocouple temperature. These values of about 0.53 are thought to be realistic for the molten basalt although no data could be found for comparison. Conversely, if the emittance of the target material is known, the radiometer output voltages can be converted to true temperatures by dividing the output by the emittance and obtaining the corresponding temperature from the blackbody calibration curve. It is calculated that an emittance of 0.5 in error by $\pm 20\%$ could cause an error of ± 25 K at 1450 K. Thus, emittance corrections need to be fairly accurately known in order to make accurate temperature measurements with this radiometer.

* The basalt sample was appreciatively obtained from Professor Klaus Keil of the University of New Mexico.

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Table 1

Results of Monitoring the Temperature
of Molten Basalt

<u>Thermocouple Temperature (K)</u>	<u>Radiometer Output (V)</u>	<u>Radiometer "Brightness" Temperature (K)</u>	<u>Calculated Emittance Correction</u>
1458	1.376	1375	0.53
1389	0.835	1311	0.54
1353	0.601	1270	0.52
1302	0.423	1230	0.55

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Figure 1. The Radiometer Circuit

Figure 2. Sketch of Radiometer

Figure 3. Radiometer "Blackbody" Calibration Curve

Figure 1. The Radiometer Circuit - Numbers represent photodiode/op-amp package pin numbers. Dashed lines represent external connections. R_f - feedback resistor. R_t - trim resistor. V_D - diode voltage supply. V_S - op-amp supply.

Figure 2. Sketch of the Radiometer.

Figure 3. Radiometer "Blackbody" Calibration Curve. $V = -21.91 + 1.652 \times 10^{-1} T + 5.227 \times 10^{-4} T^2 - 7.222 \times 10^{-7} T^3 + 2.504 \times 10^{-10} T^4$

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