# Radiometric surface temperature measurement

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**Publisher's version / Version de l'éditeur:**
https://doi.org/10.4224/20358932
*Technical Note (National Research Council of Canada. Division of Building Research); no. TN-259, 1958-07-01*

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# NATIONAL RESEARCH COUNCIL OF CANADA

## DIVISION OF BUILDING RESEARCH

No. 259

# TECHNICAL NOTE

NOT FOR PUBLICATION

FOR INTERNAL USE

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DATE July 1958

SUBJECT Radiometric Surface Temperature Measurement

Trial surface temperature measurements have been made with two kinds of radiometers, a Cambridge radiation thermopile and a thermistor radiometer manufactured by Williamson Development Co. after the design of Stoll (1).

## Thermopile Radiometer

The thermopile radiometer (which is now housed in the emissivity apparatus) consists of an 18-element thermopile mounted on a strip behind a system of diaphragms which define the receiving area, protect the surface from draughts and shield the instrument from stray radiation. The receiver is coated with zinc black, and the instrument was supplied with an adjustable slit aperature, a fluorite window and a reflecting cone. The sensitivity of the instrument with fluorite window, but without slit or cone, was stated to be 48.8 mv/watt/$cm^2$ with the radiator at 1000°C.

The radiometer was calibrated with the reflecting cone attached and without the fluorite window (maximum sensitivity). The thermopile output was measured by a Leeds and Northrup recorder pre-amplifier, with range -25, 0, +25 $\mu$V, and scale multipliers, 1, 2, 4, 10, 20 and 40. The calibrating black body was a 6 by 6 by 6-inch metal can with one outside surface covered with acetylene black. The can contained $CaCl_2$ solution and dry ice. The calibration was performed in the dry room to prevent frost deposition on the black surface at the lower temperatures. The temperature of the liquid in the can was measured with a thermometer with 0.5°F gradations. The radiometer was held so that the end of the reflecting cone was approximately 1/4 in. from the black body surface.

The calibration covered a temperature range from 20°F to 105°F, the thermopile output ranging from -130 $\mu$V to 120 $\mu$V. The calibration curve of black body temperature versus thermopile output (Fig. 1) is non-linear, but over small temperature ranges (about 30°F) it can be considered linear.

The output V of the radiometer is given by

$$V = Ce\ (T^4 - T_o^4) \qquad (1)$$

where C is a number determined by the Stefan-Boltzmann constant, the thermo-electric power of the radiometer thermopile, a geometrical shape factor and other constant factors determined by the design of the instrument, e is the emissivity (assumed constant), T the absolute temperature of the surface 'seen' by the thermopile receiver and $T_o$ is the absolute temperature of the receiver.

It will be noted that when V = 0, $T = T_o$. Thus if the radiometer were surrounded by a jacket through which liquid could be circulated, the liquid temperature could be varied until V = 0. The liquid temperature under this condition directly gives the surface temperature without the need for emissivity corrections or calibration of the radiometer. This technique was not attempted.

By differentiating equation (1) with respect to T, the following is obtained

$$\frac{dV}{dt} = 4CeT^3 \qquad (2)$$

This calibration was performed with the radiometer at a temperature of 70°F (the value of T in Fig. 1 when V = 0). It appears from equation (2), however, that the slope dV/dT, $\mu$V per °F) of this calibration curve may be used with good approximation for any radiometer temperature near 70°F. The reason that the slope cannot be used for all radiometer temperatures is that C is proportional to the thermoelectric power of the radiometer thermopile which varies slowly with radiometer temperature.

In the determination of the radiant temperature of a surface, either the radiometer temperature itself must be known or a reference black body at known temperature must be used. The use of a reference black body is illustrated in the trial measurements now described.

## Window Surface Temperature Measurements with Thermopile Radiometer

The thermopile radiometer was used to measure the inside surface temperature of the inner pane of a double window installed in an opening of a partition in the Building Services cold room. The warm and cold room temperatures were maintained at 72°F and 0°F respectively.

The thermopile radiometer was sighted on the black plastic tape fastening a thermocouple to the inside surface of the inner pane of the double window. Following this it was sighted on the same black body that was used in obtaining the calibration curve given in Fig. 1. The following gives the results of measurements made with the radiometer and the thermocouple beneath the tape.

### Trial No. 1

| | |
|---|---|
| Radiometer output for window surface | = 60.4 $\mu$V |
| Apparent radiant temperature of the window surface obtained from the calibration curve | = 47.8°F |
| Radiometer output for black body | = 12.1 $\mu$V |
| Apparent temperature of black body obtained from the calibration curve | = 66.3°F |
| Temperature difference between black body and the window surface | = 18.5°F |
| Temperature of black body as measured with a thermometer | = 64.4°F |
| ∴ Radiant temperature of the window surface | = 45.9°F |
| Temperature of window surface as obtained with the thermocouple | = 46.6°F |

Trial No. 2

| | |
|---|---|
| Radiometer output for window surface | = 62.8 $\mu$V |
| Apparent temperature of the window surface from the calibration curve | = 46.8°F |
| Radiometer out for black body | = 15.8 $\mu$V |
| Apparent temperature of black body from the calibration curve | = 65.0°F |
| Temperature difference between black body and the window surface | = 18.2°F |
| Temperature of black body as measured with a thermometer | = 64.4°F |
| ∴ Radiant temperature of the window surface | = 46.2°F |
| Window surface temperature as measured with a thermocouple | = 46.6°F |

The radiant temperature of the window surface is the temperature of a black body which would produce the same radiometer output as the actual surface. Equation (3) gives the relationship between actual surface temperature and radiant temperature.

$$T_w = \sqrt[4]{\left(\frac{e_w - e_b}{e_w}\right) T_r^4 + \left(\frac{e_b}{e_r}\right) T^4} \qquad (3)$$

where $T_w$ is the window surface temperature in °R

$T_r$ is the radiometer temperature in °R

$T$ is the radiant temperature of the window surface °R

$e_w$ is the emissivity of the window surface

$e_b$ is the emissivity of the black body which was used to obtain the calibration given in Fig. 1.

A glass surface temperature of 45°F was calculated by using the above relationship and a radiant temperature of 46°F and by assuming values of emissivities of 0.97 and 0.94 for acetylene black and the glass surface (2). In addition the radiometer was assumed to be at the warm room air temperature of 72°F.

## Thermistor Radiometer

The thermistor radiometer consists of a Wheatstone bridge formed by four flake thermistors, two of which are exposed to the incident radiation, and two which are hidden from it and act as thermal compensators. Only one-half the thermistor bridge was used. The circuit is shown (Fig. 2). V is a vacuum tube voltmeter, one lead of which is grounded. Readings were taken on the 10mV range. An applied bridge voltage of 50V gave ample sensitivity.

Trial surface temperature measurements were made on the Bell-Rock panel installed in the cold room. Measurements were made on the warm side surface only. Because the sensitivity of the instrument may be varied at will (by varying the voltage applied to the bridge) it was thought to be better not to rely on a predetermined calibration of the instrument. Two black bodies were used in conjunction with the measurements, so that the calibration of the radiometer was performed simultaneously with the surface temperature measurements. The black bodies were hollow metal cubes (Leslie cubes) each containing a conical cavity with black surfaces. This cone closely approximates a black body. The cubes were filled with water their temperature being measured by thermometers graduated to 0.1°C, and care was taken to keep the water well stirred while the temperature was being measured and when the radiometer was sighted on the black body cone.

The black body temperatures chosen were 10°C and 20°C since the surface temperatures to be measured were between these two limits. The radiometer was sighted on one black body and the variable arm of the helipot moved until a large deflection to the right of the vacuum tube voltmeter was obtained. The radiometer was then sighted on the second black body and adjustments were made to the helipot setting and/or the applied voltage to produce a large deflection to the left. Thus, readings were always on scale when the radiometer was sighted on the wall surface.

Assuming that the variation of output versus temperature is linear in the temperature range between the two black body temperatures, the radiant surface temperature T may be obtained by interpolation.

Thus,

$$T = T_{B2} - \frac{V - V_{B2}}{V_{B1} \; V_{B2}} (T_{B2} - T_{B1}) \qquad (4)$$

where $T_{B1}$ and $T_{B2}$ are the temperatures of the two black bodies, $V_{B2}$ and $V_{B1}$ are the corresponding deflections, and V is the deflection when the radiometer is sighted on the wall surface. The above radiant surface temperature T is the temperature of a black body which would produce the same output V as the actual surface.

For most building materials the emissivity e lies between 0.85 and 0.99. If the emissivity is known, the true surface temperature T' may be calculated from

$$T' = T_{B2} - \frac{V/e - V_{B2}}{V_{B1} - V_{B2}} (T_{B2} - T_{B1}) \qquad (5)$$

Also when the test surface has an emissivity $e < 1$, some radiation originating from lamps and other surfaces at different temperatures is reflected from the test surface into the radiometer, giving a 'high' measured surface temperature. The radiometer was therefore held about 1/2 in. from the test surface to reduce the reflected radiation as much as possible. Even under these conditions the apparent surface temperatures dropped by approximately two degrees almost instantly when the lights in the room were switched off.

The following gives the results of measurements of surface temperature with the thermistor radiometer and a thermocouple on the Bell-Rock panel.

| | |
|---|---|
| Temperature of black body No. 1 as measured with thermometer | $T_{B1} = 52.3°F$ |
| Radiometer output for black body No. 1 | $V_{B1} = -10.4 \mu V$ |
| Temperature of black body No. 2 as measured with a thermometer | $T_{B2} = 68.9°F$ |
| Radiometer output for black body No. 2 | $V_{B2} = +8.5 \mu V$ |

| | | |
|---|---|---|
| Radiometer output for panel with lights on | V | = +1.60 $\mu$V |
| Radiometer output for panel with lights off | V | = 0.5 $\mu$V |
| Assumed emissivity for panel | e | = 0.93 |
| Temperature of panel with lights on based on equation (5) | | = 63.0°F |
| Temperature of panel with lights off based on equation (5) | | = 61.0°F |
| Temperature panel measured with a thermocouple with lights on or off | | = 61.2°F |

## Conclusion

The glass surface temperature obtained with the thermopile radiometer was 1.6 degrees lower than the temperature obtained with the thermocouple fastened to it with black plastic tape. From the observations of the extent of condensation on the inner pane and known warm room dew points it was observed that the surface temperature obtained with the thermocouple exceeded the actual surface temperature by 1 1/2 degrees. Thus the temperature obtained with the radiometer is more accurate than that obtained with the surface thermocouple.

The surface temperature of the Bell-Rock panel as measured with the thermistor radiometer with the lights off corresponds very closely to the temperature obtained with an embedded thermocouple. Thus the surface temperatures obtained with embedded thermocouples will be as accurate as those obtained with either the thermistor or thermopile radiometer.

The measurements of radiant surface temperatures with radiometer should be taken with the lights off in the warm or cold rooms to reduce the error due to the reflection of light from the test surface. If the radiometer is at a higher temperature than the test surface the effect of reflection from the test surface would cause outputs to be on the low side. Thus the radiant temperatures obtained from these outputs would be higher than the actual radiant temperature.

The performance of the radiometer calibration in situ, by the use of two reference black bodies at known temperatures as was done with the thermistor radiometer measurements, is preferable to the technique used with the thermopile radiometer.

References

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2. McAdams, W.H., Heat transmission. Third edition, New York, McGraw-Hill, 1954. 532 p.

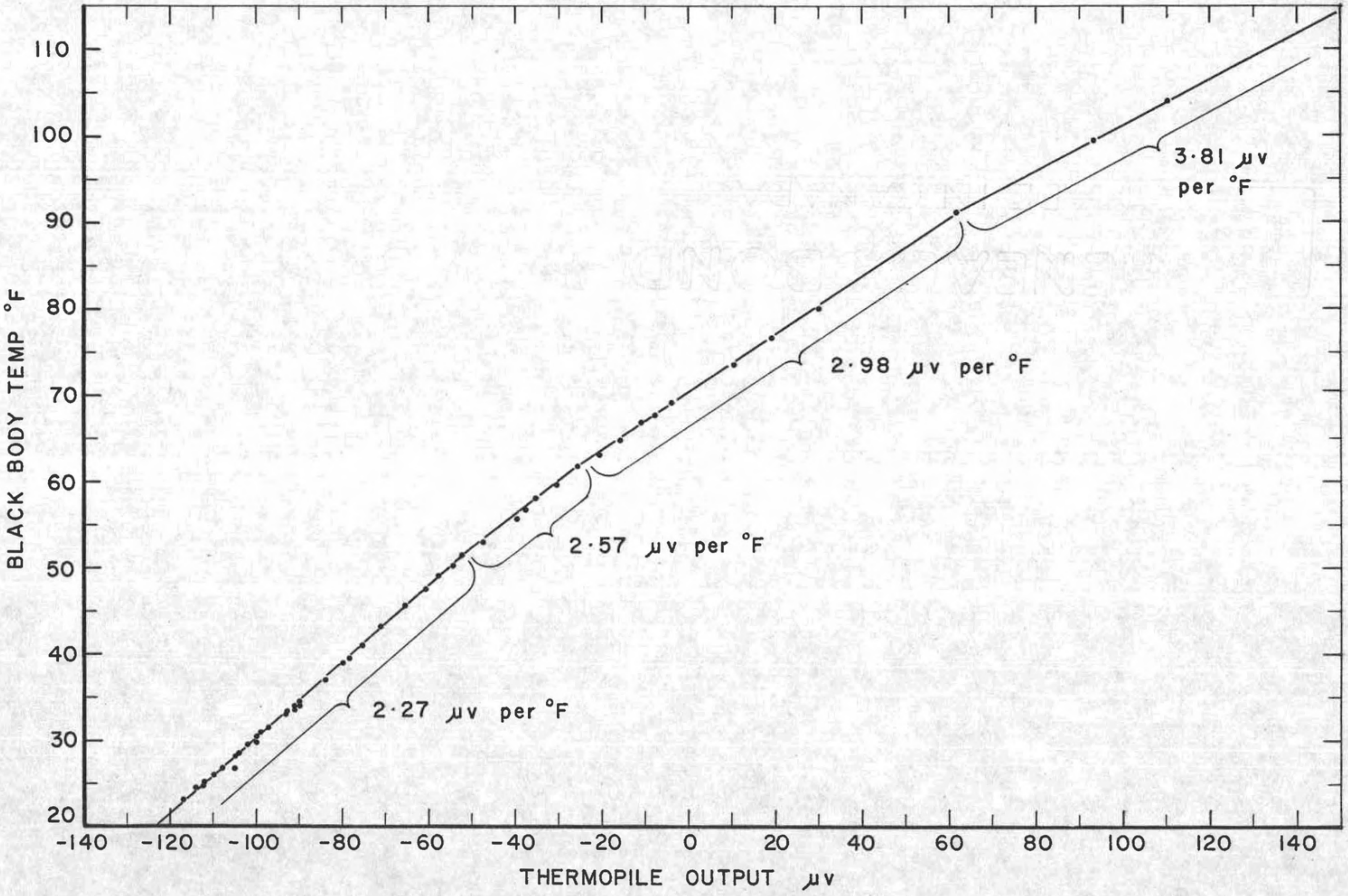


FIGURE I CALIBRATION OF CAMBRIDGE RADIATION THERMOPILE

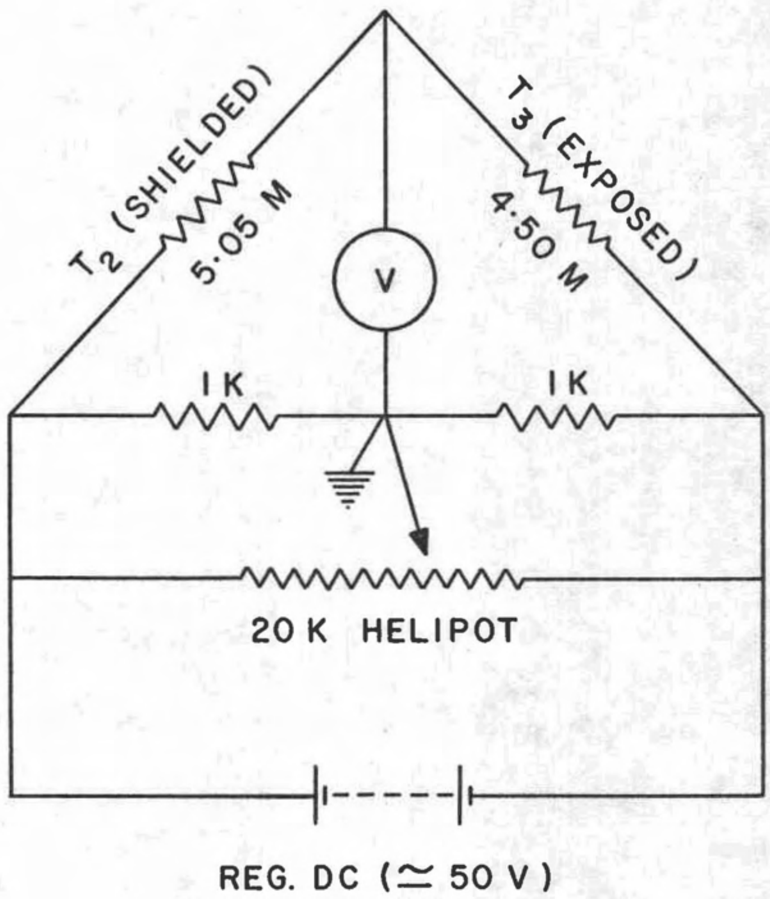


FIGURE 2

THERMISTOR RADIOMETER CIRCUIT FOR SURFACE TEMPERATURE MEASUREMENTS