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RADIANT ENERGY DOSIMETER FOR FIELD USE*

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INTRODUCTION

As pointed out in a subsequent paper (Reference 1), thermal radiation measurements in Project Flambeau fires involved a limited number of conventional radiometers located outside the fire periphery. When, a few weeks before experimental fire 460-7-66, one of us was asked to assist with the thermal radiation measurements, it was decided that even crude supplementary measurements within the 30-acre interior of this fire could be highly useful.

A simple, cheap, easily-fabricated, light-weight, self-contained, rugged dosimeter was desired. It had to withstand a hot-fire environment, including a specific energy input of 5,000 cal/cm^2, and to record the fraction of this energy which was absorbed as thermal radiation from the fire. The short time available before the test limited the effort which could be devoted to the design and fabrication of such instruments and precluded extensive testing or calibrating before the fire. Nevertheless, a few meters were assembled from materials on hand and placed on towers available within the test site.

This paper reports details on the original meter design, describes the crude results obtained during the fire, indicates some of the limitations in such an instrument, and suggests possible improvements for more refined use in the future.

DESIGN AND CALIBRATION

Theory of Operation

Suppose that two thin-walled, vented containers, identical except that one is black (absorptance, $\alpha_b = 1$) and the other totally reflecting ($\alpha_r = 0$), are partially filled with identical known volumes of a boiling liquid and placed side by side in a hot-fire environment. As long as some liquid remains in the containers, the container temperatures are limited by boil-away and remain nearly constant. Heat transfer by convection to the two containers will be essentially equal; therefore, loss of contents from the two containers is given by:

$$W_b = (Q_R + Q_c)/V \qquad (1)$$

and

$$W_r = Q_c/V , \qquad (2)$$

where W_b = weight of liquid lost from black container,

W_r = weight of liquid lost from reflective container,

Q_R = radiant energy dose,

Q_c = convective energy dose, and

V = heat of vaporization.

The radiant dose to the black container then is:

$$Q_r = (W_b - W_r)V \qquad (3)$$

or

$$R = (W_b - W_r)V/A \qquad (4)$$

where R = specific radiant dose, and

A = receiver surface area.

If the respective receivers are not perfectly black and reflecting, a radiant efficiency may be defined as

$$e = \alpha_b - \alpha_r \qquad (5)$$

and the equation for R then becomes

$$R = (W_b - W_r)V/Ae \qquad (6)$$

Description

The prototype meter (Figure 1) consisted of two standard aluminum-end beer cans. Each can was insulated (Figure 2) and filled with a known weight of water. The cans were mounted side by side with exposed ends pointing toward the radiation source. The exposed surface of one can was the original, bare, reflective aluminum. The exposed surface of the other can was enameled with "3M Velvet Coating Optical Black." To limit gas circulation over these receiver surfaces and thus reduce deposition of solids, screens were extended from the ends of the cans. The screens also tended to reduce convective effects and aberrations from random turbulence.

Figure 1. Photograph of mounted meter, showing the exposed receiver ends (one blackened and the other reflective) of the insulated beer cans.

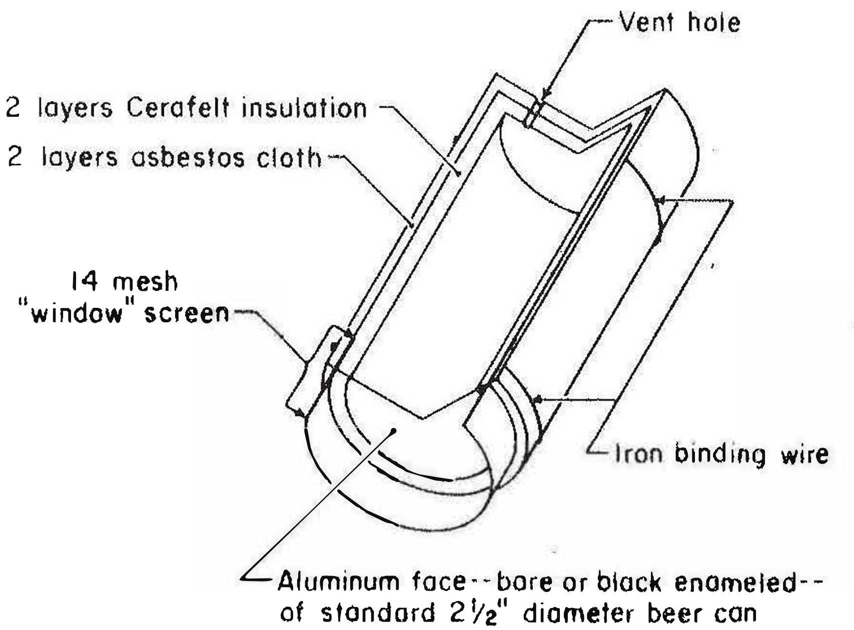

Figure 2. Diagram showing the construction of each dosimeter half.

Calibration

The materials from which the meters were fabricated were chosen largely on the basis of availability, with minimum pre-fire calibration or check-out. After the fire, more detailed spectral reflectivity curves were obtained in the infrared region for the clean receiver surfaces as well as for typical surfaces contaminated during the fire (Figure 3). The range of correction factors for incomplete absorption and reflection of radiant energy is determined by the emission spectrum of the source. For hot fires with wood fuel and for meters whose surfaces remain clean, values of e in the order of 0.8 to 0.9 would seem probable.

By recording the temperature decay of meters in still air, the natural convective transfer rate of the cans was determined to be 2 cal/min °C, with one-quarter of the transfer occurring through the meter face and three-quarters through the insulation. Convective transfer was found to be increased 40 percent by directing an air flow of about 2 m/sec angled toward the receiver surface.

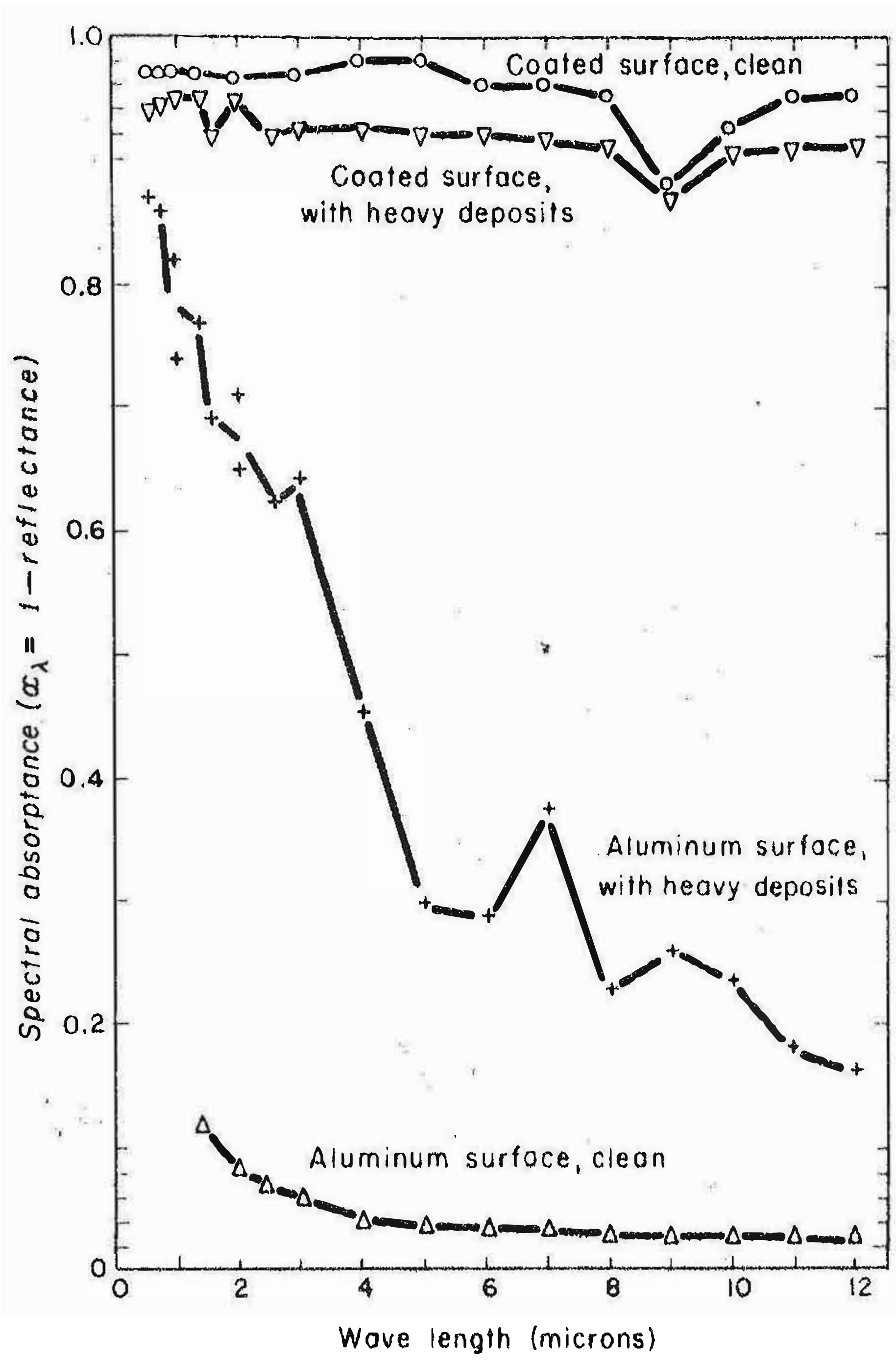

Figure 3. Sprectral absorptance curves for clean and contaminated receiver surfaces.

FIELD USE

Layout

Meters were positioned at the tops of the 20-foot towers and at the 50-foot and 20-foot elevations of the 50-foot towers available in the test area. Because not enough meters were available, a single blackened can was mounted at some locations and a nearby complete meter used to indicate the "background" energy transfer. A total of 13 full meters and 10 blackened half-meters was exposed.

Since the downward hemispherical view from the shorter towers included a disproportionate ratio of bare ground to fuel area, meters on these towers were inclined about 20 degrees from vertical toward a fuel pile. Still, the integrated view of these meters was estimated to have included only about one-half the plot average fuel loading.

Procedure

The day before the experimental fire, meter cans were weighed, filled with water, reweighed, stoppered, and installed. About 2 hours before ignition, the stoppers were removed from the can vent holes. At re-entry time—about 7 hours after ignition—cans were stoppered, removed, and weighed. The asbestos covering had discolored and apparently lost weight during the exposure. Therefore, a final dry weight of each can was obtained in the laboratory.

Results

The recovered meters had a variety of deposits on the receiver surfaces. Nearly all those outside the fire perimeter and those at the 50-foot elevations appeared clean. On the other blackened faces, contamination appeared as a light-gray speckling, and on the bare faces it ranged from light-gray through dark-gray, to a single case of sooty-black. The post-test calibrations with various radiant sources, as well as the spectral reflectance curve measured for the receiver with the heaviest deposits (Figure 3), indicated that the deposited material did not greatly change the absorptance of the blackened receivers. The impact on the spectral reflectance curve for the reflective receivers, however, could be quite severe. One obvious complication in these cases was the absence of a time record of the change in absorptance during the fire.

Of the two full meters and six half-meters placed on the six towers outside the fire perimeter, only the two half-meters at the two elevations on Tower 2—the tower closest to the fire—received sufficient energy to register. All meters within the fire perimeter experienced a detectable water loss, but none came close to the 300 cc which had been placed in each 380-cc-capacity can. With a tare weight of about 200 grams and an initial gross weight of about 500 grams, the largest water losses were 37 grams and 55 grams, respectively, for bare and blackened cans. Changes in tare weight as a result of loss of insulation ranged from less than 1 to almost 20 grams.

Estimates of the specific radiant dose (Tables 1 through 3) were obtained using the following equations:

$$10^{-3}\,Q = (T_v \quad T_a)\,[k\,E_i + (F_i - E_i)] + VW \qquad (7)$$

$$R = (Q_b \quad Q_r)/\,Ae \qquad (8)$$

where F_i = initial weight, g of can plus water,

E_i = initial weight, g , of empty can,

T_v = boiling point, 93 °C at 7, 250 ft. elevation,

T_a = ambient temperature, 20 °C,

k = average heat capacity of can materials, 0.165 cal/g °C,

V = heat of vaporization, 544 cal/g,

and A - receiver area, 31.6 cm^2.

DISCUSSION

Measurements

As used, the meters could provide readings only if the total energy input was in the range 25,000–175,000 cal/cm^2. Furthermore, to minimize the correction due to unequal heat-up time of the two meter halves, energy inputs should be toward the upper end of the measurement range. Unfortunately, in no case were these ideal conditions obtained.

To avoid a major measurement error as a result of convective heat transfer, the meters as used could be effective only when placed in an atmosphere whose temperature was above boiling water temperature during the measurement interval. For example, the convective heat-loss rate for a can at 100 °C in quiescent air at 25 °C is about 6 cal/cm^2 min. Thus an effective radiant input of this rate would just keep the meter at 100 °C without evaporating any water.

Table 1. Results from meters mounted on 50-foot towers.

Tower	Height above ground	Angle from vertical	Face	Assumed rad. eff.	Wt. of water lost	Est. total energy dose	Est. specific radiant dose	Fract. asbestos scorched
	feet	degrees		percent	grams	cal. $x10^{-3}$	cal/cm^2 *	
11	50	0	black bare	80	39.9 1.7	45.6 25.2	810	0.4 .4
[illegible]	50	0	black bare	70	52.4 11.8	52.2 30.4	990	.6 .6
1	20	0	black bare	70	34.4 13.0	42.7 30.9	530	.8 .7
4	50	0	black bare	80	9.5 2.8	29.6 25.8	150	.3 .4
4	20	0	black bare	80	2.8 2.0	25.7 25.4	10	.2 .4

* Can face area 31.6 cm^2.

Table 2. Results from meters mounted on 20-foot towers.

Tower	Height above ground	Angle from vertical	Face	Assumed rad. eff.	Wt. of water lost	Est. total energy dose	Est. specific radiant dose	Fract. asbestos scorched
	feet	degrees		percent	grams	cal. x10^{-3}	cal/cm^{2}*	
8	20	20	black bare	--	1.3 1.7	24.7 25.0	0	0.3 .3
24	20	20	black bare	70	18.8 6.3	34.5 26.5	320	.8 .7
23	20	20	black bare	60	41.5 33.1	46.3 41.8	240	1.0 1.0
10	20	20	black bare	70	17.8 5.5	33.8 27.2	300	.6 .6
3	20	20	black bare	70	17.2 3.0	33.5 26.0	340	.5 .4
32	20	20	black bare	70	55.4 36.9	54.3 44.1	460	.9 .9

* Can face area 31.6 cm^{2}.

Table 3. Results from blackened half meters.

Tower	Height above ground	Angle from vertical	Face	Assumed rad. eff.	Wt. of water lost	Est. total energy dose	Est. specific radiant dose	Fract. asbestos scorched
	feet	degrees		percent	grams	cal. $\times 10^{-3}$	cal/cm^{2} *	
22	20	20	black	--	28.7	39.8	--	0.4
11	20	0	black	--	18.5	34.2	--	.5
3	20	60	black	70	28.9	40.0	630†	.5
4	50	90	black	80	31.1	41.1	610†	.1
2	30	90	black	--	4.6	26.7	--	.0
2	20	90	black	--	12.0	30.8	--	.0

* Can face area 31.6 cm^2.

† Reference "bare" can of "vertical" meter at same location, Tables 1 and 2.

For higher inputs, the meter would continuously read low by this amount.

Within the fire perimeter, most of the measurements indicate that radiation to the receiver faces represented the minor mode of energy transferred to the meters. If the fire behavior is roughly consistent with the pattern indicated by the radiometers (Reference 1) and the radiation/convection partition is assumed constant with time, estimates of transfer are consistent with assumed air temperatures in the 100–300 °C range. However, the low maximum water loss from the meters means that during a significant part of the fire the cans were in a "warm-up" condition. Thus, a sizeable convective heat transfer error exists because during this time the blackened cans were warmer than the bare cans. The magnitude of this error depends upon the assumptions made for the time history of the blackened and unblackened cans, but it may well be as large as a factor of 2.

Despite all of the uncertainties, some noteworthy observations were recorded by the meters within the fire perimeter. The three meters located at 50-foot heights gave radiant energy measurements of 820, 990, and 140 cal/cm^2 at Towers 11, 1, and 4, respectively. The meter at Tower 1, with a nearly full hemispherical view of fuel piles, might have been expected to indicate twice as much radiant transfer as at Tower 11 at the edge of the plot. The high radiant input relative to total energy input at these two meters are consistent with the lower ambient temperatures to be expected at the higher elevation.

The anomalously low reading at Tower 4 is supported by a similarly low reading at its 20-foot level, but the half meter mounted horizontally at the 50-foot level indicates a greater outward than upward radiation flux at this position. The amount and positions of the discolorations in the asbestos coverings of the three cans at this location are consistent with the water loss observed.

At the 20-foot elevation within the interior of the fire, the upward radiant energies estimated from the meter data ranged from 240 cal/cm^2 at Tower 23 to 530 cal/cm^2 at Tower 1. These estimates include very uncertain corrections for the solids deposited on the receiver surfaces. In estimating an over-all average for upward radiant dose at the 20-foot level in the fire, the values recorded could possibly be doubled to compensate for the bias in fuel area viewed by the meters. Supporting this contention are the results obtained by placing a second blackened half-meter at Tower 3 inclined at 60 degrees from the vertical toward the center of the fuel pile to obtain a hemispherical view of fuel, better approximating the plot average. Assuming that "background" transfer to this can was the same as to the "vertical" bare can, the indicated specific radiant dose is 630 cal/cm^2 as compared to 350 cal/cm^2 indicated by the "vertical" meter.

For the 20-foot meters at the periphery of the fire, the anomalous results provide room for considerable speculation. Where full meters were mounted, at Towers 4 and 8, only a minimal water loss was observed for both the black and bare cans. Where only blackened half-meters were exposed, at Towers 11 and 22, the much larger water loss implies either a significant radiant input or a higher than average convective input. Tower 22 is in an area of considerable late fire whirl activity and the difference in readings at Towers 22 and 4 may be attributable to the cool in-drafts at 4 and fire whirls at 22. However, there appears to be no clear explanation for the difference between the readings at 8 and at 11.

To assess the validity of the absolute values of radiant energy estimated by the dosimeters, much more information is needed about such factors as the time history of energy release from the fire and the temperature history of the convection column. Nevertheless, the results obtained provide some worthwhile comparisons. With the modifications discussed below, such dosimeters may provide even more useful information in future fires.

Possible Meter Improvements

Even for the meter as used, a more judicious guess concerning total energy input could have minimized the "warm-up" time (time to reach the boiling point of water) and thus minimized the error due to differential convective transfer to the two halves of the meter. The replacement of water by a lower boiling liquid, preferably with a high heat of vaporization, would also help considerably. If a liquid were selected to minimize warm-up time, it would be desirable to maximize radiant heat transfer and minimize background heat transfer by such means as increasing the ratio of receiver area to container volume, improving the insulation, and adopting a better screen to decrease convective heat transfer. An improved screen* would

* A refinement of elegance would be a screen over the vent hole to exclude "fire bugs," and Melanophila Consputa. The capture rate of these bugs, dry weight range 20 to 30 mg., was about 1 per can.

have the added advantage of being more effective in limiting deposition of solids; and improved insulation, say, by replacing the asbestos cloth by stainless steel foil in the 0.05- to 0.1-mm thickness range, would have the added advantage of reducing tare-weight loss during the fire.

Finally, preliminary experiments indicate the feasibility of adding a crude indicator of maximum radiation rate by attaching a metal strip within the insulation (see Figure 4). To the extent that radiant transfer predominated over convective transfer at the exposed metal tip, an indication of maximum irradiance could be obtained from the peak temperature gradient recorded by the melting of temperature-sensitive shellac painted on the strip.

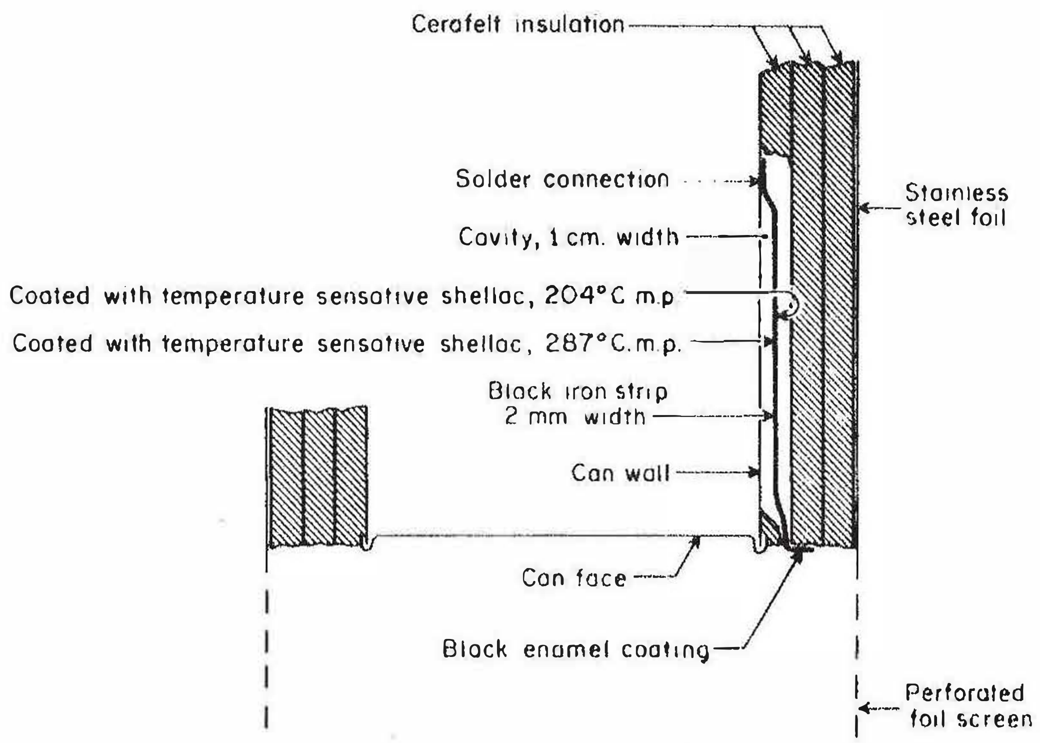

Figure 4. Proposed meter modification including indicator for maximum irradiance.

REFERENCE

1. McCarter, R. J., Thermal Radiation Measurements in Project Flambeau.