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A CALORIMETRIC RADIATION DOSIMETER FOR
AN ACCELERATOR ENVIRONMENT

by

K.P. Lambert and M.H. Van de Voorde

Abstract

The main concepts of absorbed radiation dose calorimetry are discussed followed by the description of a calorimeter capable of measuring absorbed doses from 2×10^2 to 2.0×10^5 rad. in an accelerator radiation environment.

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1. INTRODUCTION

Calorimeters may conveniently be divided into four categories for nuclear purposes⁽¹⁻⁶⁾: first, radionuclide calorimeters which measure the power of a radioactive source contained in the calorimeter; second, beam calorimeters which measure total power in a particle beam incident on the calorimeter; third, in core calorimeters which are situated inside a nuclear reactor and measure effects due to nuclear radiation, and fourth, local absorbed dose calorimeters which measure the energy deposited in a sample of known mass, composition and geometry.

The last category is of interest in a high energy particle accelerator environment in order to obtain an absolute measurement of absorbed radiation dose. This then enables the secondary dosimeters⁽⁷⁾, which are used on a routine basis around accelerators, to be absolutely calibrated in terms of the complex radiation fields which are characteristic of high energy particle accelerators.

The main problem encountered with using a calorimeter for accelerator dosimetry is the measurement of the small temperature increases associated with the relatively low accelerator dose rates.

Dose rates of 10^6 rad.h^{-1} and upwards occur in nuclear reactors, which correspond to energy deposition rates of $2.78 \times 10^{-3} \text{ W g}^{-1}$ which in turn give a temperature rise of 2.4°C h^{-1} for an absorber with a specific heat of $1 \text{ cal g}^{-1} ^\circ\text{C}^{-1}$. Such temperature changes are easily measured by thermocouples, Chromel-Alumel, for example, produces an EMF of $4 \times 10^{-5} \text{ V}^\circ\text{C}^{-1}$.

High dose rates are rarely present around accelerators except downstream of production targets, injection and ejection regions and at beam dumps. An estimate of the dose rate one meter downstream of target 1 at the CERN Proton Synchrotron, for a 19 GeV beam of 1 pulse per 2.2 sec. with 10^{12} protons per pulse, is $2 \times 10^5 \text{ rad.h}^{-1}$.

Dose values of 10^2 to 10^3 times lower have been measured in quiet areas around the PS and ISR rings⁽⁸⁾. However, by substituting thermistors for thermocouples in a calorimeter, dose rates as low as 10^3 rad.h^{-1} ,

which provides an energy deposition rate of $2.78 \times 10^{-6} \text{ W g}^{-1}$ and results in a temperature rise of $2.4 \times 10^{-3} \text{ }^{\circ}\text{C h}^{-1}$, can be measured.

The absorber of the calorimeter discussed was chosen to be epoxy resin, in order to give an absolute measure of the radiation dose absorbed in the insulating material used for the CERN accelerator magnets. Any material could, however, be chosen as long as it converts all the energy absorbed into heat.

2. CALORIMETER METHODS

2.1 Components of a calorimeter

Figure 1 shows the basic components of a calorimeter, which can be summarized as follows:

TAB - thermally active body, this is the component whose temperature is followed in order to obtain the dose measurement.

JACKET, the defined environment, and its temperature will remain constant or follow that of the TAB depending on the mode of calorimeter operation.

SURROUNDING MEDIUM, which is between the TAB and the JACKET and is the heat transfer medium.

2.2 Basic problems of all calorimetric operating modes

Any thermal effect observed in the TAB is a result of two processes, i.e. evolution of heat in the TAB and heat exchange between the TAB and the JACKET.

The thermal effect observed must be independent of the source of energy input, i.e. the calorimeter must react similarly whether the source of energy is radiation or electrical power.

2.3 Classification of calorimeter systems

This depends on the temperature/time function, which will be a particular case of the general calorimeter equation:

$$\frac{dT}{dt} = \frac{W}{mc} - K (T - T_o) \quad (1)$$

where:

W = heating rate of TAB cal sec⁻¹

mc = heat capacity of TAB cal °C⁻¹

K = heat transfer constant

T = TAB temperature °C

T_o = JACKET temperature °C

Only the ADIABATIC mode, in which our calorimeter operates, will be considered here. The TAB temperature increases with time due to the absorption of radiation energy and in order to prevent heat exchange between the TAB and the JACKET, the latter is maintained at TAB temperature by a suitable control system.

T = T_o, and from equation (1) :

$$\frac{dT}{dt} = \frac{W}{mc} \quad (2)$$

3. CONSTRUCTIONAL DETAILS

A cross-sectional view of the calorimeter is shown in Figure 2. The TAB consists of an epoxy cylinder of length 30 mm and diameter 5 mm which is supported inside the jacket by two polyurethane discs. The jacket is formed from electrically conducting plastic, which by the application of a suitable voltage across it, enables its temperature to follow that of the TAB.

Bead type thermistors of 0.5 mm diameter are used as the temperature sensing elements and are situated as follows:

- Thermistor 1 : inserted into the centre of the TAB
- Thermistor 3 : positioned on the outer surface of the TAB
- Thermistor 4 : positioned on the inner surface of the jacket.

Thermistors 1 and 3 are bonded to the TAB by a high thermal conductivity epoxy and thermistor 4 to the jacket by silicon cement.

A second calorimeter, identical to the one already described with the exception that it contains only two thermistors, Nos. 2 and 5, situated in the positions of thermistors 1 and 3 respectively, is located outside the radiation field. This acts as a dummy calorimeter to compensate for changes in the ambient temperature.

4. CIRCUITS REQUIRED FOR CALORIMETER OPERATION

Thermistors Nos. 1 and 2, which have matched temperature-resistance characteristics, form two arms of a Wheatstone bridge. The bridge output voltage, which is a function of absorbed radiation dose, is monitored by a (y, t) chart recorder. The second pair of matched thermistors, Nos. 3 and 4, form two arms of a further Wheatstone bridge. This bridge output voltage is fed into a D.C. amplifier whose output is applied across the jacket to allow for automatic compensation of the temperature difference between the TAB surface and the inner surface of the jacket.

Due to the slight heat generating properties of the thermistors, thermistor No. 5, which is in contact with the dummy calorimeter TAB, is used to compensate for the heat generated in the dose measuring TAB by thermistor No. 3.

Power for both bridges and thermistor No. 5 is supplied from separate constant voltage sources each consisting of a dry mercury cell with a zener diode regulating circuit.

The D.C. amplifier is a Philips microvoltmeter (type 2436), the range selection determining the heater voltage which in turn determines the response time of the control circuit. If the amplifier gain, as discussed in Appendix 2, is too large, i.e. if the response time is too rapid, an overshoot condition is reached whereby the temperature of the jacket is greater than that of the TAB. A diode in series with the amplifier output then prevents further heating of the jacket until the TAB is again at a higher temperature with respect to the jacket.

5. OPERATIONAL DETAILS

5.1 General scheme of operation

The overall scheme of operation of the calorimeter can be depicted as follows:

5.2 Dose and dose-rate range of the system

Lower limit

The minimum dose limit of the system is a function of the following parameters:

- i) the false dose signal due to bridge drift for zero radiation field;
- ii) the bridge output voltage-dose conversion factor;
- iii) the sensitivity of the data recording system.

The minimum dose rate voltage must be at least equal to the drift signal for meaningful dose readings to be obtained. Drift rates of 1.2 mV h^{-1} have been measured for the calorimeter pair operating in a laboratory environment, which correspond to a noise signal of approximately $4 \times 10^3 \text{ rad h}^{-1}$ using the voltage-dose conversion factor developed in Appendix 1.

With the calorimeter operating in the ISR tunnel, the drift rate is significantly higher due to tunnel temperature fluctuations. A series of temperature measurements performed at two points in the ISR tunnel:

- i) internal beam dump ID1 (radiation area)
- ii) by the inner wall of the ring, 3 m from TL 23 (effectively a non-radiation area),

indicated an average ring temperature of $17.5 \pm 0.5^\circ\text{C}$ over a period of nine days. However, there was a temperature difference between the points of up to 0.5°C which would be reflected as a false dose of approximately $5 \times 10^4 \text{ rad}$.

For this application, a scheme was adopted whereby the dummy calorimeter was replaced by a fixed resistor and the dose measuring calorimeter isolated from ambient temperature fluctuations by surrounding it with polystyrene foam and inserting it into a small glass dewar vessel. After 10 h warm-up time, the bridge drift - for the calorimeter positioned adjacent to ID1 - is between 0.6 and 0.8 mV h^{-1} which corresponds to a noise level of $2.2 \times 10^3 \text{ rad h}^{-1}$ to $2.9 \times 10^3 \text{ rad h}^{-1}$.

It is prudent to set the lower dose-rate detection limit of the device to at least twice the drift rate present prior to dose measurement which, taking the above mentioned drift rates, is about $5 \times 10^3 \text{ rad h}^{-1}$. The minimum integrated dose detectable is, therefore, approximately $200 \pm 15 \text{ rad}$, for a dose-rate of $5 \times 10^3 \text{ rad h}^{-1}$, a recording resolution of $50 \text{ } \mu\text{V}$ and a voltage-dose conversion factor of $0.275 \pm 3.6 \% \text{ } \mu\text{V rad}^{-1}$.

Upper limit

The upper dose limit of the calorimeter depends on two parameters:

- i) the maximum permissible dose rate;
- ii) the maximum value of the temperature rise $\Delta T^{\circ}\text{C}$ of the calorimeter due to absorbed radiation energy.

Operation of the calorimeter at ID1 has shown that the dose signal corresponding to beam dumping, which occurs in a fraction of a second, is a voltage step function. This indicates that for accelerator dosimetry the calorimeter is not dose-rate limited. Figure 3 gives the absorbed dose as a function of $\Delta T^{\circ}\text{C}$ and experience has shown that with the present calorimeter structure a value of 2°C for $\Delta T^{(9)}$, i.e. an absorbed dose value of 2.0×10^5 rad is an acceptable limit in order to retain good adiabatic control.

5.3 Results of dosimetry tests at the ISR

Initial tests of the calorimeter were performed adjacent to the internal beam dump ID1 of the ISR during both a machine development and a physics run. Toshiba RPL and Frické dosimeters were simultaneously exposed with the calorimeter during the runs, the dose values returned being:

Calorimeter	$(0.275 \pm 3.6 \% \mu\text{V rad}^{-1})$	4.0×10^4 rad $\pm 3.6 \%$
Toshiba RPL	$(\pm 20 \%)$	5.3×10^4 rad $\pm 20 \%$
Frické	$(\pm 10 \%)$	4.4×10^4 rad $\pm 10 \%$

Taking the calorimeter dose value, derived from the theoretical voltage-dose conversion factor, as an absolute value, the calibrations of the CERN-ISR Frické and RPL dosimeters are accurate within factors of 1.1 and 1.3, respectively.

A section of the calorimeter recording from the machine development run is shown in Figure 4 and exhibits the following details:

$$\begin{aligned}\text{Drift before irradiation} &= 0.56 \text{ mV h}^{-1} = 2.04 \times 10^3 \text{ rad h}^{-1} \quad \text{noise value} \\ \text{Drift after irradiation} &= 0.54 \text{ mV h}^{-1} = 1.96 \times 10^3 \text{ rad h}^{-1} \quad \text{noise value} \\ \text{True dose rate} &= 7.21 \times 10^3 \text{ rad h}^{-1} \\ \text{True integrated dose} &= \frac{1.79 + (0.70+0.68)}{2} = 9.02 \times 10^3 + 3.0 \times 10^2 \text{ rad.}\end{aligned}$$

At 15.20 h the beam in Ring 1 was dumped⁽¹⁰⁾, shown by the horizontal deflection of the trace.

During the physics run, the dose rate at ID1, apart from during beam dumping, was below the drift limits discussed in section 5.2 rendering it impossible to make any accurate measurement of absorbed dose with the calorimeter.

6. CONCLUSIONS

The feasibility of using a miniature calorimeter for accelerator radiation dosimetry has been demonstrated. The calorimeter is to perform an absolute calibration of the secondary dosimeters⁽⁷⁾ which are used on a routine basis around high energy particle accelerators.

For dose rates above a given threshold, the system allows the remote real-time acquisition of both dose rate and integrated dose. With suitable modifications of the data collection system, several calorimeters feeding into an electronic scanner supported by the recording of data onto magnetic tape would result in long term dosimetry information being available.

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APPENDIX 1.

Absorbed dose as a function of bridge output-voltage

The quantitative relationship between absorbed radiation dose and bridge output-voltage is developed.

By definition, $1 \text{ rad} = \frac{10^{-5}}{4.2} \text{ cal(absorbed)/g of material}$, 1 rad absorbed will, therefore, raise $m \text{ g}$ of material, with a specific heat of $C \text{ cal/g/}^{\circ}\text{C}$, through $\theta^{\circ}\text{C}$ according to

$$\theta^{\circ}\text{C} = \left(\frac{m \cdot 10^{-5}}{4.187} \cdot \frac{1}{m \cdot C} \right). \quad (3)$$

The TAB of the calorimeter under discussion is constructed from epoxy resin with $C = 0.26 \text{ cal/g/}^{\circ}\text{C}$ at room temperature and of mass 0.7 g . From equation (3), 1 rad absorbed will raise the TAB temperature by $9.2 \cdot 10^{-6}^{\circ}\text{C}$. This can be expressed in a more useful manner by:

a 10^{-2}°C increase in TAB temperature results from the absorption of $1.1 \cdot 10^3 \text{ rad}$.

For an ambient temperature of $T^{\circ}\text{C}$, an increase in temperature of $\Delta T^{\circ}\text{C}$ will result in a bridge off-set voltage ΔV which can be determined as follows:

Bridge balance conditions are expressed by

$$\frac{R(T1)}{R3} = \frac{R1}{R2} \quad (4)$$

where $R(T1)$ is the resistance of thermistor $T1$, $R1$ and $R2$ are fixed resistors and $R3$ a variable resistor.

The resistance of a thermistor is expressed as a function of temperature by:

$$R_T = R_0 \exp \left[B \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (5)$$

where:

R_T is the resistance at temperature $T^{\circ}\text{K}$

R_0 is the resistance at temperature $T_0^{\circ}\text{K}$

B expresses the temperature sensitivity of the thermistor ($^{\circ}\text{K}$).

The bridge out of balance voltage, for a change in $R(T_1)$ of $\Delta R(T_1)$ is given by:

$$V = V_{\text{supply}} \left[\frac{R_1}{R_1 + R_2} - \frac{R(T_1) - \Delta R(T_1)}{R(T_1) - \Delta R(T_1) + R_3} \right] \quad (6)$$

For an ambient ISR ring temperature of 17.5°C , see Section 5.2, a 10^{-2}°C increase in the temperature of thermistor T_1 will produce, using equations 4, 5 and 6, an out of balance voltage of $300 \mu\text{V}$ for a bridge power supply of 2.8 V . This particular value of voltage was chosen to avoid any self-heating effect in the thermistor.

Therefore, an absorbed radiation dose of $1.1 \cdot 10^3 \text{ rad}$ will result in an out of balance bridge voltage of $300 \mu\text{V}$, i.e. the system dose/voltage conversion factor is $0.275 \pm 3.6 \mu\text{V rad}^{-1}$, i.e. $3.62 \pm 3.6 \% \text{ rad } \mu\text{V}^{-1}$.

APPENDIX 2

Amplifier gain required to satisfy adiabatic conditions

Adiabatic conditions are maintained by heating the jacket to the same temperature as the TAB. The power required is related to the dose rate by considering that 1 rad s^{-1} deposits 10^{-5} Watt of energy in 1 g of material, i.e.

$$\frac{V^2}{R} = \frac{dD}{dt} \cdot m \cdot 10^{-5}$$

where:

V = voltage across jacket

R = resistance of jacket

$\frac{dD}{dt}$ = dose rate (rad s^{-1})

m = mass of jacket (g)

Table 1 below gives several typical values of dose rate, the corresponding values of V, the out of balance voltage from the bridge V_b , and the required amplifier gain G.

TABLE 1

Amplifier gain as a function of dose rate

Dose rate rad h^{-1}	V Volt	V_b μV after 1 min.	G
10^2	0.075	0.44	1.7×10^5
10^3	0.241	4.40	5.4×10^4
10^4	0.752	44.00	1.7×10^4
10^5	2.41	440.00	5.4×10^3

For dose rates of below approximately $1.5 \times 10^4 \text{ rad h}^{-1}$, i.e. a temperature rise of approximately 0.14°C for the TAB, the heater control circuit has been found to be unnecessary⁽⁹⁾.

APPENDIX 3

Radiation damage of thermistors.

It is necessary that the thermistors employed in calorimeters maintain their resistance-temperature characteristics to within extremely tight tolerances after being subjected to integrated radiation doses in excess of 10^8 rad.

The parameter of importance is $B^{\circ}K$, the temperature sensitivity factor, which is derived from resistance measurements at two specified temperatures. A series of thermistors, Philips type 2322-634-21, were therefore characterized for B computed from resistance values at $46.5 \pm 0.05^{\circ}C$ and $54.5 \pm 0.05^{\circ}C$. The thermistors were then irradiated at the ASTRA Reactor⁽¹¹⁾, Vienna, under the following conditions:

- i) SNIF position, fast neutron fluence of 3.3×10^{14} n cm⁻² (E>1 MeV) 10^6 CH rad.
- ii) EBENE 1 position, 10^7 , 5×10^7 , 10^8 and 5×10^8 CH rad.

The percentage change in B after irradiation as a function of dose was:

	<u>Dose(CH rad)</u>				
	<u>10^6</u>	<u>10^7</u>	<u>5×10^7</u>	<u>10^8</u>	<u>5×10^8</u>
% change in B	-1.26	-3.83	-2.31	-1.08	-0.10

These changes are within the tolerance quoted by the manufacturer so that no change in characteristic can be attributed to radiation damage.

TABLE 2

Calorimeter constructional components

Product	Use	Thermal conductivity $\text{kcal.m}^{-1}\text{h}^{-1}\text{c}^{-1}$	Volume resistivity $\Omega \text{ cm}$	Radiation Damage
CIBA Araldite F + hardener HY 905 + accelerator DY 061	TAB	0.15 - 0.45	6×10^{15}	Mild damage at 5×10^8 rad
Polyurethane foam	TAB supports	0.014 - 0.04	$6 \times 10^{12} - 10^{14}$	Mild damage at 10^9 rad
Expanded polystyrene	thermal insulation of calorimeter	0.03		Mild damage at 10^9 rad
Eccosil X-SV-16 * thickness 0.34 mm	Electrically con- ducting jacket		85	Mild damage esti- mated at 10^8 rad
Stycast 2850 KT *	Bending thermistors to TAB	3.72	10^{15}	Mild damage at $\approx 10^9$ rad
Eccobond 56C *	Bonding Cu leads to jacket for heater supply voltage	4.96	2×10^{-4}	
Eccosil 1776 *	Bonding Eccosil X-SV-16, and thermis- tors to Eccosil X-SV-16		10^{16}	
Thermistors ** Shibaura naked bead	Temperature sensors		$R(25^\circ\text{C}) = 20\text{K}\Omega \pm 2\%$ $B(25^\circ\text{C}) = 3450^\circ\text{K}$	No damage up to 5×10^8 rad

* Emerson and Cuming Europe, Oelvel, Belgium

** Nihon Philips Corporation, Tokyo, Japan

Fig. 1 Basic Calorimeter Components

Fig. 2 Cross Section of the Calorimeter

Fig. 3 Absorbed Dose as a Funtion of
Rise in TAB Temperature

Fig.4 Typical Calorimeter Run