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A CALORIMETER FOR LARGE FIELDS OF ACCELERATED ELECTRON BEAM

C.Oproiu, S.Marghitu, D.Martin, D.Toader, G.Craciun, F.Scarlat

Abstract
This paper is presenting the experimental results obtained with a quasi-adiabatic calorimeter that can be used for measuring the absorbed dose from non-homogenous electron beams with energies from 2 to 10 MeV. The main calorimeter body is made of glass and it has dimensions big enough to be used in large irradiation fields, giving precise results for doses between 10 and 100 kGy.

1. Introduction

The calorimeter for large irradiation fields was made for emphasizing a precise and easy method to determine the value of the absorbed energy on the surface and in the depth of a material exposed to electron beam treatment.

In the second part of the presentation we will include general considerations regarding the determination of the absorbed dose by using calorimeter devices and the particularities of this method. We also discuss the functioning principle of a calorimeter and the specific elements that we took into account when conceiving the device. The mathematical expressions used for processing the experimental data are also introduced. After this we will present the calorimeter device made in our laboratory with all its characteristics, the measurements we made using it and their results. These results were obtained with the calorimeter system for large irradiation fields made especially for measuring the dose in electron beam with average energies between 2 and 10 MeV.

Our aim was to construct a device useful to the process of electron beam irradiation for the calibration of secondary dosimeters as well as for obtaining a good precision in measurements that should be simple and easy to do. The calorimeter for large irradiation fields needs minimum manufacturing work, very few auxiliary devices and it is made according to the requests of an adiabatic system, characterized through minimum thermal exchange between the calorimeter body and the envelope of the system. Practically, these requests are very hard to realize so the system actually works in quasi-adiabatic conditions.

2. General considerations

The absorbed dose in a material exposed in electron beam depends on the dimension the density and the configuration of the material as well as on the beam parameters, energy and intensity. A large number of methods and techniques to determine the absorbed energy and the dose distribution on the surface and in the depth of different materials exposed to accelerated electron beam or to ionizing radiation have been studied so far [1], [2], [3], [4], [5], [6] .

Calorimetry is one of the methods for measuring the absorbed dose. With it we can determine the quantity of heat generated in the absorbent material supposing that the whole energy dissipated by the beam is transformed in heat. Comparing to other dosimeters used in electron beam, for calorimeters we have to take into account when measuring the dose a few particularities regarding the dimensions, the homogeneity and the chemical stability of the calorimeter material [6].

The dimensions of the calorimeter body are established taking into account the electron range inside the material. The irradiation in electron beam is always accompanied by quick variations of the dose at the surface and in the depth of the material, dependent on the electrons energy and on the irradiation technique used. The non-homogeneities and the inclusions inside the composition of the calorimeter influence the value of the measured dose and that is why the calorimeter body is usually chosen to be made of a unique material. The main element of the calorimeter device is usually water, a material that possesses well known physical characteristics that are included in the formula of the absorbed energy. From the point of view of the chemical stability most materials with molecular structure are suffering chemical transformations when they are being exposed to the action of a radiation field. A fraction of the energy absorbed by the material will be consumed in the chemical reactions produced and in this case the thermal effect that takes place in the calorimeter body will not show the exact total quantity of the absorbed energy.

For example, in water a part of the energy given by the beam will be consumed to dissociate the molecules in the radiolysis process. For metals the quantity of energy consumed to produce atomic dislocations is extremely reduced, representing approximately 0.001% from the quantity of absorbed energy. For this reasons metals can be used for making the calorimeter body in bremsstrahlung dosimetry.

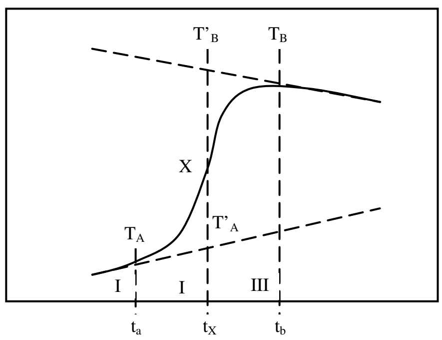
2.1. The functioning principle of the calorimeter

For measuring the dose in electron beam we chose an adiabatic calorimeter system, characterized by minimum thermal change between the calorimeter body and the envelope of the system. If the heat capacity of the calorimeter body and the rhythm of dissipating energy are constant then the temperature increase speed remains constant and its variation in time is given by the next expression:

$$\frac{dT}{dt} = \frac{W}{mc} \qquad (1)$$

where "m" and "c" are the mass and the specific heat of the absorbent and W is the absorbed energy.

The proportionality factor 1/mc is determined from the mass and the specific heat of the calorimeter body or experimentally by using calibration.



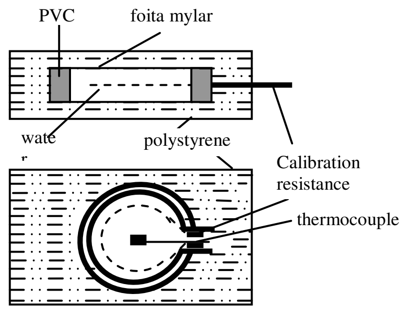


Fig. 1 – The evolution in time of the calorimeter	*Fig.2 – The construction of the body temperature calorimeter*

From the experimental point of view reaching purely adiabatic conditions is extremely difficult, and so, practically the system works in quasi-adiabatic regime. In this mode of operation, the experimental conditions are adjusted in such a way that one can obtain graphically or by using numerical calculations, the ideal adiabatic case. Generally the evolution in time of the calorimeter body temperature is similar to the one shown in fig.1. It is pointed out that there are three intervals of temperature variation with time. In regions I and III the temperature detector shows the thermal exchange between the calorimeter body and the surroundings in the absence of the radiation field. In region II the calorimeter body absorbs energy in the time interval $t_b - t_a$, therefore we will have a temperature variation $\Delta T = T_B - T_A$. The real temperature variation for the ideal adiabatic case is obtained by extrapolating in temperature region II the liniar variation of the characteristic curves in intervals I and III supposing that the whole quantity of energy is absorbed instantly in the material at moment t_x.The line $T'_B T'_A$ has to be fitted in such a way that surfaces $T_A T_{A'} X$ and $T_{BB'X}$ are equal.

2.2. Construction of the calorimeter

When constructing a calorimeter system it has to be taken into account the following specific elements for the electron beam treatment. At the liniar accelerator that we posses the irradiation field is restrained to a few teens of centimeters. To measure the dose in a certain point of the field, the dimensions of the calorimeter have to be reduced on the surface as well as in thickness. Also, the electron range for the energy of 7 MeV is aproximately 3.5 cm for materials with density $\rho = 1\ g/cm^3$, so the thickness of the calorimeter body will not exceed 2 cm. At the same time the dependence of the range on the energy sets the choise of materials with low density for the insulation for ensuring small energy losses through penetrating the thermic protection envelope of the device.

Realized in a simple, constructive manner, the device is easy to use when the energy absorbtion from the primary beam takes place in a short time interval and when the calorimeter body temperature before and after the irradiation is not too high comparing to the surrounding temperature.

We represented in fig.2 the configuration of a calorimeter device realized in the laboratory. In an air-proof cylindrical container with rigid lateral walls made of P.V.C. is introduced a well determined quantity of distilled water.The detector for the continous monitoring of the temperature variations in time is fixed in the middle of the calorimeter body.

The average absorbed dose is determined by using the formula:

$$\Delta D\,[kGy] = 10\,K \cdot \Delta T \qquad (2)$$

where ΔT reprezents the temperature variation (in ºC) of the calorimeter body when it is exposed in electron beam, and K is the characteristic constant of the calorimeter:

$$K = \frac{\sum_i m_i c_i}{\sum_i m_i s_i \cdot 2.389} \qquad (3)$$

in which: m_i – the mass in grams of the „i" component; c_i – the specific heat of the „i"component;

s_i – the proportion relation of the stopping power of the „i" comp. to the water, or:

$$s_i = \frac{\left(\frac{dE}{dX}\right)_{ioniz}^{(i)}}{\left(\frac{dE}{dX}\right)_{ioniz}^{(apa)}}$$

The factor 2,389 reprezents the number of calories equivalent to 1 g · 10^4 Gy or 10^8 ergs.

3. The calorimeter for large irradiation fields

The device for dose measurements in large surface irradiation fields was made of an air-proof glass cylinder with a diameter of 92 mm and 25 mm height; the glass thickness is 2 mm and the glass lid thickness is 1 mm.The insulation was made of expanded polystyrene with an average thickness of 30 mm. With this thickness we ensured thermic stability good enough for the entire system; calorimeter body temperature variation at 30 C is 0.01 ºC per minute. Experimentaly we observed that for polystyrene insulations of 5 mm thickness, the temperature variation is much bigger than 0.2 ºC per minute

3.1. The electrical calibration

Knowing the values of the specific heats c_i, the masses m_i, of the „i"components and the temperature variation during the time of the irradiation and using relations (2) and (3) we can determine suficiently precise the absorbed dose into the calorimeter body at the electron beam irradiation. Because the specific heat of the different components of the calorimeter system is not known precise enough, it was necessary to realize an electrical calibration of the entire calorimeter for the experimental determination of the quantity $\sum_i m_i c_i$. By calibrating we transfer to the system a well precised quantity of electrical energy and we determine the coresponding temperature variation By measuring the exact time and the electrical current that crosses the ohm resistence as well as the temperature variation ΔT_{el}, the electrical energy given to the calorimeter can be determined from the following calorimeter equation:

$$\Delta T_{el} = \frac{\sum_i m_i c_i}{0,2389} \cdot \Delta T_{el} \qquad \text{[Joule]}$$

Knowing the electrical current, I(ampers), the ohmic resistence R(ohm) and the time t(sec) during which the electrical energy is applied, we can determine the value of

$\sum_i m_i c_i$: $$\sum_i m_i c_i = \frac{0{,}2389 \cdot i^2 \cdot R \cdot \Delta t}{\Delta T_{el}} \qquad (5)$$

The final expresion of the relation for the absorbed dose in water is:

$$\Delta D_{(apa)}[kGy] = \frac{I^2 \cdot R \cdot \Delta t_{el}}{10^2 \cdot \sum_i m_i s_i} \cdot \frac{\Delta T_{rad}(°C)}{\Delta T_{el}(°C)} \qquad (6)$$

in which $m_i s_i$ reprezents product between the mass of the „i" component and the stopping power of the electrons through that component.

4. The experimental results

In the following we will point out the experimental results obtained with this calorimeter for large irradiation fields, made of glass with 9.2 cm in diameter and 2.5 cm in height.

In table I we give the main components of the calorimeter.

Table I

Component	**Value**
Water mass (grams)	82.03
Electrical resistance (ohm)	40.78
Calorimeter body mass (grams)	119.31
Electrical resistance mass(grams)	0.33
Diode mass (grams)	0.09
Insulation thickness(cm)	3.0
total mass (grams)	241.6

Table II

Parameters	**Ist Calibration**	**IInd Calibration**
Electrical Current (A)	0.75	0.75
Electrical resistance (ohm)	40.78	40.78
Room temperature (°C)	22	22
ΔΩ / °C (ohm/°C)	0.159	0.159
Test time (sec)	120	60
ΔΩ (ohm)	1.003	0.348
ΔT_{el} (°C)	6.269	2.919
$\sum_i m_i c_i$	104.89	112.6

The irradiation was made in vertical unscanned beam with the 10 MeV liniar accelerator at the surrounding temperature of 22 ºC. The average energy of the electrons used for irradiation was 7 MeV. We made two succesive electrical calibrations and three completely absorbed dose measurements. The main experimental parameters in the electrical calibrations are given below in table II. One of the calorimeter curves realised in the electrical calibrations is represented in fig.4.

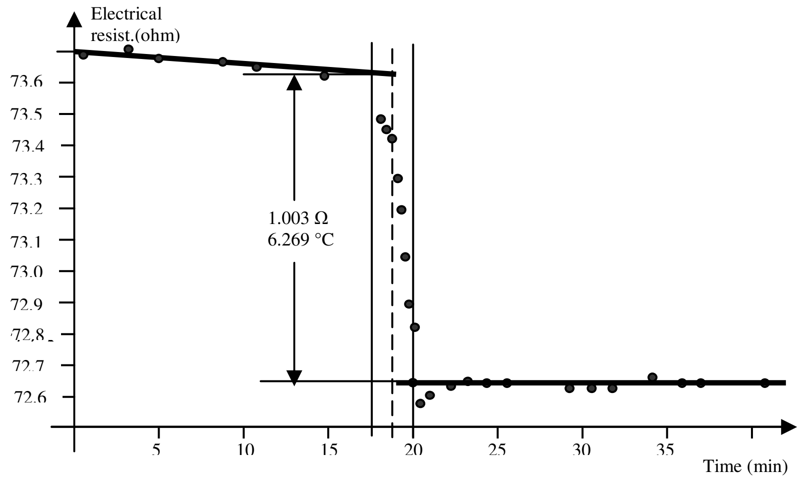


Fig. 4 – The electrical calibration

In fig.5 it is represented the calorimeter curve obtained for one of the dose measurements made in vertical beam of electrons. The dosimetric system was irradiatted from a distance of 40cm from the exit window of the electrons in the accelerator.

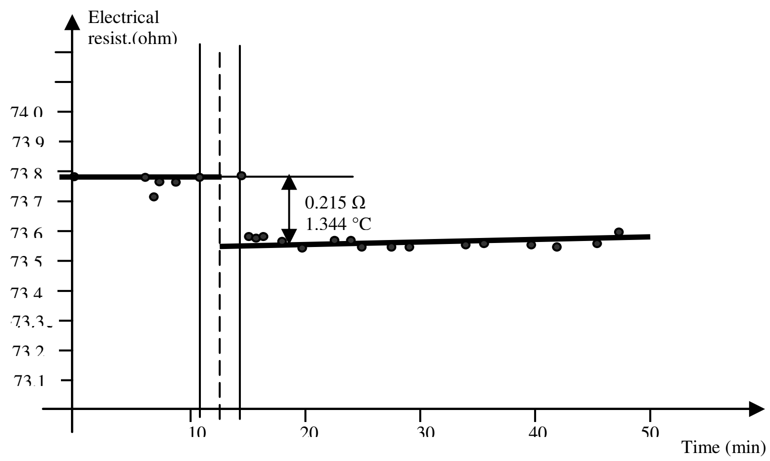


Fig. 5 – The calorimeter calibration curve

The experimental results are given in table III.

Table III

Parameters	**Experiment Nb.1**	**Experiment Nb. 2**	**Experiment Nb. 3**
Room temperature (ºC)	20	20	20
Water average temp. (ºC)	25	23	26
$\Delta\Omega$ / ºC	0.159	0.159	0.159
$\Delta\Omega$ (ohm)	0.215	0.215	0.215
Δt_{irad} (sec)	240	180	60
ΔT_{irad} (ºC)	1.535	1.344	0.362
$\sum_i m_i c_i$	105.2	105.2	105.2
$\sum_i m_i s_i$	187.9	187.9	187.9
Absorbed dose (kGy)	35.9	31.4	0.84

The measurements we made are affected by an error up to 3%.

5. Conclusions

In the paper we present the construction mode of a calorimeter device for large irradiation fields made in our laboratory, the calibration methods and the results obtained with it. This quasi-adiabatic device made according to our own ideeas was used for calibrating secondary devices with dosimetric film and also for making usual dosimetric mesurements in electron beam.

The advantages shown by this device are the simple construction and the facility it proovedin manipulation. The temperature measurements can be made before and after the irradiation and they take a short time of exposure of 1-2 minutes. Such a device can be used for many times in measuring doses of 10 to 100 kGy. It is preferred that the calorimeter body temperature do not excced 30°C over the initial value.

The calorimeter was made with the aim of finding a practical and very advantageous method for establishing the absorbed dose level in the material and the dose distribution on the surface as well as in the depth of the material exposed in electron beam.

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