DOSIMETRY TECHNIQUES FOR MEASUREMENTS IN ^{60}Co IRRADIATION FACILITY

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الخلاصة :

اهتم هذا البحث بدراسة الطرق المختلفة المستخدمة للقياسات الإشعاعية في إحدى خلايا التشعيع (GAMMA CHAMBER 4000A) التي تم تركيبها حديثا بالمركز القومي لبحوث وتكنولوجيا الاشعاع في مصر . وقد تم تعيين معدل الجرعة الإشعاعية داخل هذه الخلية باستخدام مقياس الجرعة Fricke Dosimeter وتم أيضا عمل خريطة توزيع منحنيات الإشعاع داخل الخلية باستخدام كلٍّ من مقياس الجرعة GafChromic Dosimetry Media ومقياس الجرعة (CdS) . وتَـمَّ عمل مقارنة بين المقاييس الإشعاعية التي استُخدمت بواسطة الشركة المصنعة والمقاييس التي استُخدمت في هذه الدراسة . وقد تم استخدام برامج الحاسوب لتعيين معدلات الجرعة النسبية وأيضا لرسم المنحنيات المتساوية داخل الخلية .

ABSTRACT

A ^{60}Co irradiation facility, Gamma Chamber 4000A, has recently become available at the National Center for Radiation Research and Technology (NCRRT), Egypt. Dose rate for this irradiation facility was determined by using a Fricke dosimeter. Dose mapping of the radiation field inside the chamber was performed using GafChromic™ Dosimetry Media and CdS photoresistor. Special emphasis is given to comparisons between the dosimetric systems used by the manufacturer and dosimetry systems used in this study. Computer programs were developed for the determination of relative dose rates. A contour plotting routine was then used to obtain the isodose curves.

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INTRODUCTION

The measurement of dose rate and dose mapping for high activity irradiation facilities at the National Center for Radiation Research and Technology (NCRRT), Egypt, started about 13 years ago. The first ^{60}Co irradiation facilities were installed at that time: Gamma Cell-220 (product of the Atomic Energy of Canada Limited) and Egypt's "Mega-Gamma I" facility for radiation processing (type J-6300 Atomic Energy of Canada Limited), mainly used for sterilization [1, 2]. Recently a Chamber 4000A (product of India) was installed to add to the capacity of the irradiation facilities at the NCRRT. The Gamma Chamber 4000A is a compact and self-contained irradiation unit offering an irradiation volume of approximately 4000 cm^3. The activity of this irradiation facility was 10 000 Ci at the time of installation (14 June 1988). The source cage holds the radiation source pencils vertically and symmetrically along its periphery. The cage can hold a maximum of 48 pencils. Each pencil contains seven aluminum-cladded ^{60}Co slugs. The sample chamber is the central part of the central drawer, and has 16 cm inside diameter and 21 cm height, with through holes of 2 cm diameter at the top and the bottom of the sample chamber. The central drawer is raised or lowered by means of an electric motor. The movement of the central drawer is controlled from the control panel of the irradiation chamber, which incorporates an analog timer (Figure 1).

With the development of radiation processing on a commercial scale in Egypt (NCRRT), inexpensive quality control and the development of readily available mass-produced dosimeters has been emphasized by the principal investigator of the present study [1, 3–9]. The aim of the present work is to calibrate and determine the isodose curves of the Gamma chamber 4000A irradiation facility. The latter information was not available to us from the manufacturer. Therefore, GafChromic™ Dosimetry Media [10] and a CdS photoresistor were used to obtain such information, and also, to compare the available data from the manufacturer for dose rate measurements with our results and to test the efficiency of the newly developed GafChromic™ Dosimetry Media and CdS photoresistor for dose distribution studies.

DOSE RATE ASSESSMENT AT THE CENTER OF THE GAMMA CHAMBER USING FRICKE DOSIMETER

The standard ferrous sulfate dosimeter [11], was used for dose rate measurements at the central position of the Gamma chamber 4000A.

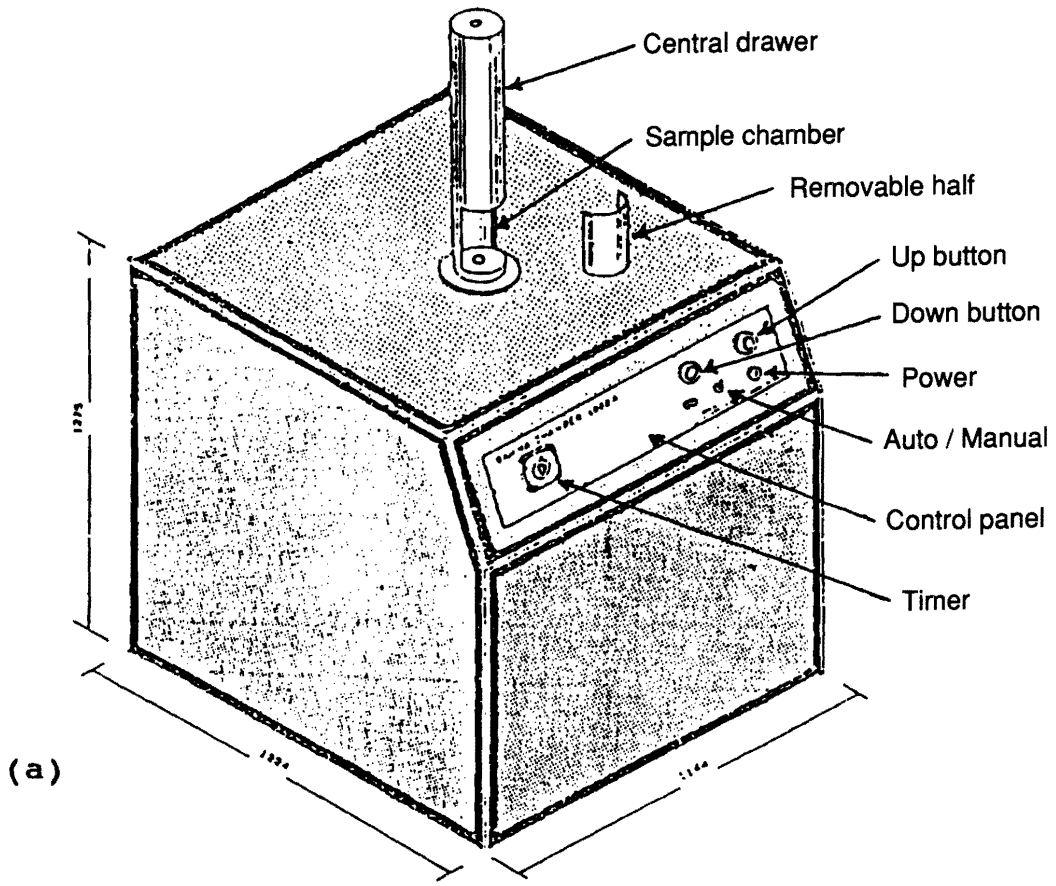
Experimental Procedure

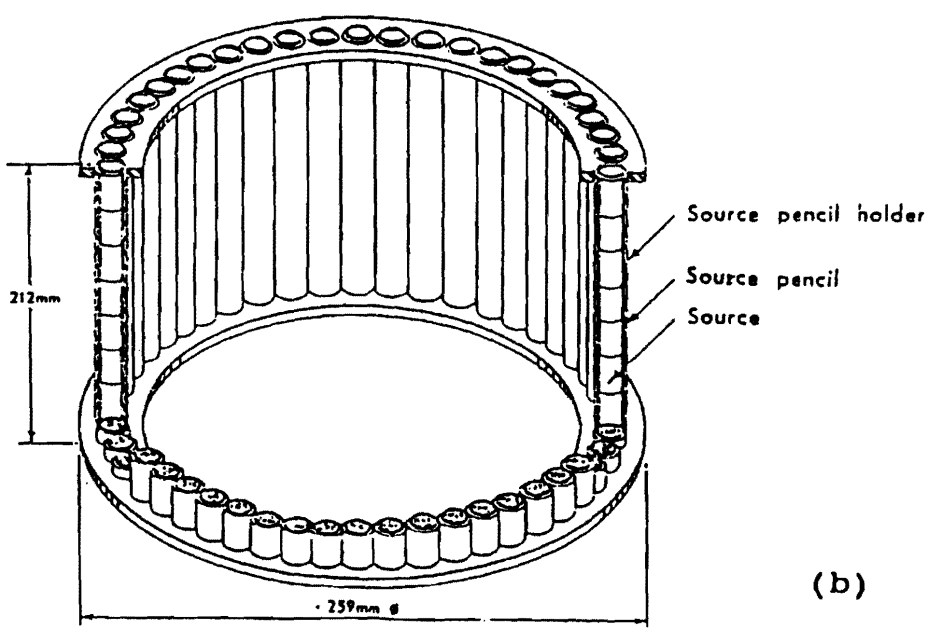
The ferrous sulfate system is particularly sensitive to many organic compounds which can enter into chain reactions and lead to a significant change in yield [12]. Therefore, the glass bottles used for Fricke solution preparation were cleaned using fuming nitric and sulfuric acids, heated up for about 3 hours, and rinsed with triply distilled water many times. The platinum crucible used in weighing ferrous ammonium sulfate was cleaned by placing it in a beaker containing concentrated HCl and heating; then it was dried over a hot flame.

Cylindrical ampoules of neutral glass (wall thickness of 0.5 mm and diameter of 12 mm) were filled with warm detergent, rinsed with water three times, filled again with chromic acid, transferred to a dish and warmed up for one hour and allowed to cool for about one hour. They were then rinsed three times with distilled water and filled with Fricke solution. After transferring to a jar, all ampoules were irradiated in the Gamma Chamber for 4 minutes, to oxidize any organic impurities present, left over night, and rinsed next day with Fricke solution. The cuvettes were boiled for 3 minutes in concentrated HNO_3, then for 3 minutes in distilled water, rinsed with alcohol, and dried using alcohol vapor.

Water is the major constituent of the Fricke dosimeter and can be the prime source of organic contamination. The recognized procedure in radiation chemistry is to redistill water in the presence of an oxidizing agent. This is best done using acid potassium dichromate followed by alkaline potassium permanganate solution [13].

Sulfuric acid comes next in order of concentration and experience has shown that some samples contain impurities, which introduce a negative intercept on the absorbance *versus* dose curve. The presence of H_2SO_4 containing SO_3^{2-} causes errors due to the initial





SOURCE CAGE

Figure 1. Schematic Diagram of Gamma Chamber 4000A and the Source Cage.

oxidation of SO_3^{2-} by radiolysis products in preference to Fe^{2+}. An oxidative pretreatment of the acid with hydrogen peroxide is therefore used [14].

Preparation of Fricke Solution

22 ml concentrated H_2SO_4 microanalytical grade were added to 500 ml triply distilled water in 1 liter volumetric flask, 2 drops of H_2O_2 (1%) were added to oxidize impurities, and potassium permanganate $KMnO_4$ (1 g/l) was added drop by drop until a permanent pink color was obtained. This means that the excess amount of H_2O_2, which did not react with H_2SO_4 species has been consumed in reacting with $KMnO_4$. Ferrous ammonium sulfate, 0.392 g, was added to that solution. The solution is then completed to one liter with triply distilled water. The concentration of H_2SO_4 (0.8 N) in solution was checked by titration against NaOH (1.0 N). The final ferrous ammonium sulfate concentration in Fricke dosimeter is 1×10^{-3} M. This solution is not completely stable, therefore, it was stored in a clean dark brown stoppered bottle at 15–20°C.

Determination of Dose Rate of the Gamma Chamber 4000A at the Central Position Using Fricke Dosimeter

A set of ampoules containing Fricke solution were prepared as mentioned earlier. The ampoules used have an inner diameter of about 8 mm, to avoid undue wall effect (*i.e.* all the secondary electrons contributing to the energy absorption originate in solution). The ampoules were sealed, and each ampoule was placed in the polystyrene jig and irradiated for different periods of time in the gamma chamber, under conditions of electronic equilibrium [15]. The ferric ion yields were measured at 304 nm on a UVIKON 860 spectrophotometer with the cell compartment at a temperature around 25 ºC. Optical density readings were taken directly after irradiation to minimize adventitious oxidation of ferrous ions. All measurements were carried out replicate (5 readings) using one (2 cm length) cuvette in the spectrophotometer against optical air path. The cuvette was filled at the beginning and at the end of every run with water, the optical density (OD) measured and the mean value calculated and subtracted from each sample measurement. Control solutions (unirradiated solutions) were measured in the same way and the mean OD value was subtracted from that of each irradiated solution. In all cases the mean value, the standard deviation and temperature corrections could be evaluated and all data were analyzed statistically. Also, correction was done for transit time (time elapsed during sample transit in and out the gamma cell).

When spectrophotometry is used for Fe^{3+} analysis, the dose is calculated by applying the relation [16]:

$$D = \frac{\Delta(\mathrm{OD})}{\varepsilon(G_{\mathrm{Fe}}^{3+})\rho l}$$

where

$\Delta(\mathrm{OD})$ is the change in absorbance value between irradiated dosimeter and control samples.

ε is the linear molar extinction coefficient for Fe^{3+} at wavelength 304 nm, $\varepsilon(Fe^{3+})_{25°C} = 2194 \pm 10 l\ \mathrm{mol^{-1}cm^{-1}}$.

$G(Fe^{3+})$ is the radiation yield of Fe^{3+} ions $= 1.62 \times 10^{-6}\ \mathrm{mol\ J^{-1}}$.

ρ density of the solution = 1.024 kg l^{-1} for 0.8 N H_2SO_4.

l length of light path in the solution (1 cm).

A UVIKON 860 spectrophotometer with data station was used for the Fricke dosimetry. On this instrument, ε (Fe^{3+}) at 304 nm (25°C) was found to be 2194 ± 10 l $\mathrm{mol^{-1}\ cm^{-1}}$; where the random uncertainty is at 99% confidence level, the systematic uncertainty was estimated to be ± 5%.

Table 1 shows a comparison of dose rate and transit dose values as a result of the present study at the NCRRT and those supplied by the manufacturer. It can be observed from this table that the dose rate value determined in Bhabha Center and NCRRT are in good agreement.

GAFCHROMIC™ DOSIMETRY MEDIA CALIBRATION

GafChromic™ Dosimetry Media has been previously studied as a dosimeter suitable for use in the absorbed dose range from 0.1 to 5 kGy [10]. The effect of various irradiation parameters (absorbed dose rate, irradiation temperature and humidity, and post irradiation stability) have been previously characterized over the absorbed dose range 0.1–5 kGy [10, 17, 18].

In order to calibrate the GafChromic dosimeter in the absorbed dose range from 0 to 1 kGy, a set of 48 dosimeters were prepared for irradiation. The optical of the irradiated films (four films at each dose) were

Table 1. Comparison Between the Experimental Data Determined by NCCRT and that Given by the Manufacturer.

	Dose rate	Transit dose
Date	20-2-1989	
NCCRT	7.105 kGy/h = 197.36 rad/s	904 rad
BARC *	7.105807 kGy/h = 197.384 rad/s	914 rad
Deviation %	−0.01216	−1.09

*Quoted from Bhabha Atomic Research Center report on calibration.

measured at 600 nm wavelength, where the optical density is shown to increase with dose. All films (48) were placed between 2 nm polystyrene strips to ensure that irradiations were performed under conditions of electron equilibrium [15].

The films were subjected to various doses through removing sequentially (4 at each dose) one after another until the highest dose is reached. The optical densities at 600 nm wavelength, for all films were measured 24 hours after the end of the irradiation. Special holders were used to ensure proper orientation of the dosimeters in the cuvette holder during spectrophotometric readout. The response curve was then established representing the optical density

Multiplicative model: $Y = aX^{**}b$

Parameter	Estimate	Standard error	T Value	Prob. Level
Intercept *	1.03443	3.03643×10^{-3}	340.673	0
Slope	0.781123	2.7422×10^{-3}	284.352	0

*Note: The Intercept is equal to log a

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio
Model	3.130	1	3.130	81140.943
Error	0.0003858	10	0.0000386	
Total (Corr.)	3.130557	11		

Correlation Coefficient = 0.999938
Stnd. Error of Est. = 6.21104×10^{-3}

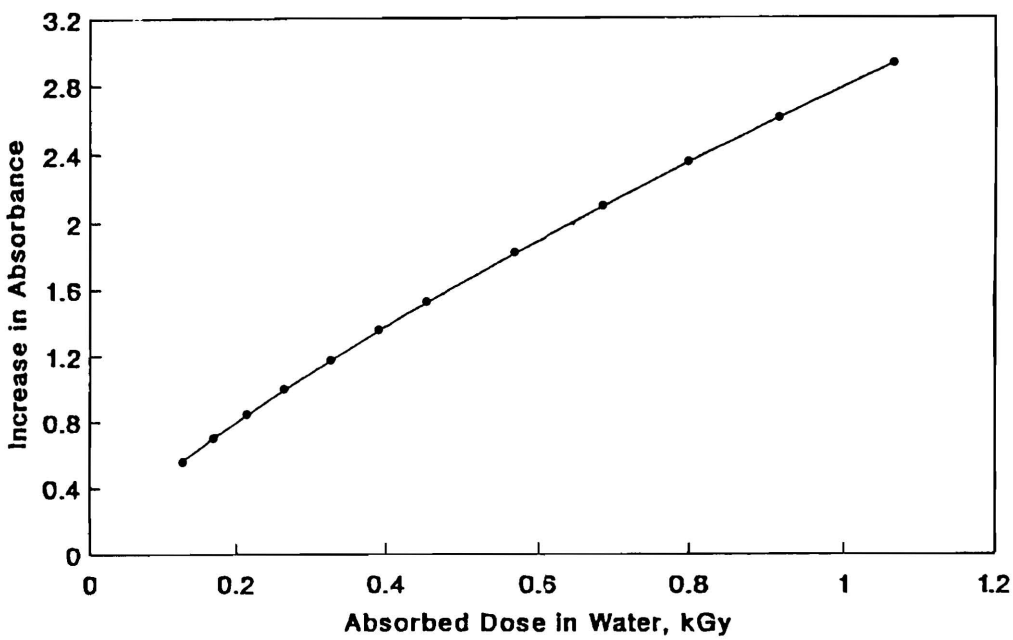


Figure 2. Calibration Curve of GafChromic™ Dosimetry Media. The absorbance was measured at 600 nm wavelength.

versus dose (Figure 2). The stability of the unirradiated GafChromic dosimeters and the good uniformity of the thickness and consistency of the active layer makes it unnecessary to read the optical density or thickness prior to irradiation [17].

DOSE MAPPING USING GAFCHROMIC™ DOSIMETRY MEDIA

A 154 (1×1 cm) films of GafChromic™ Dosimetry Media films were placed in paper envelopes and held between two 2 mm thick perspex sheets (16×20.5 cm) and spaced 1.5 cm apart. The sheets were placed in Gamma chamber in such a way that the film was parallel to cobalt-60 source pencils and it contained the central axis of the chamber. The sheet was irradiated to a dose of 0.625 kGy at the center of the chamber. The optical densities at 600 nm wavelength for all films were read 24 hours after the end of irradiation. The absorbed dose values corresponding to the measured optical density were calculated. Figure 3 shows the relative values of absorbed dose at each point inside the gamma chamber relative to the

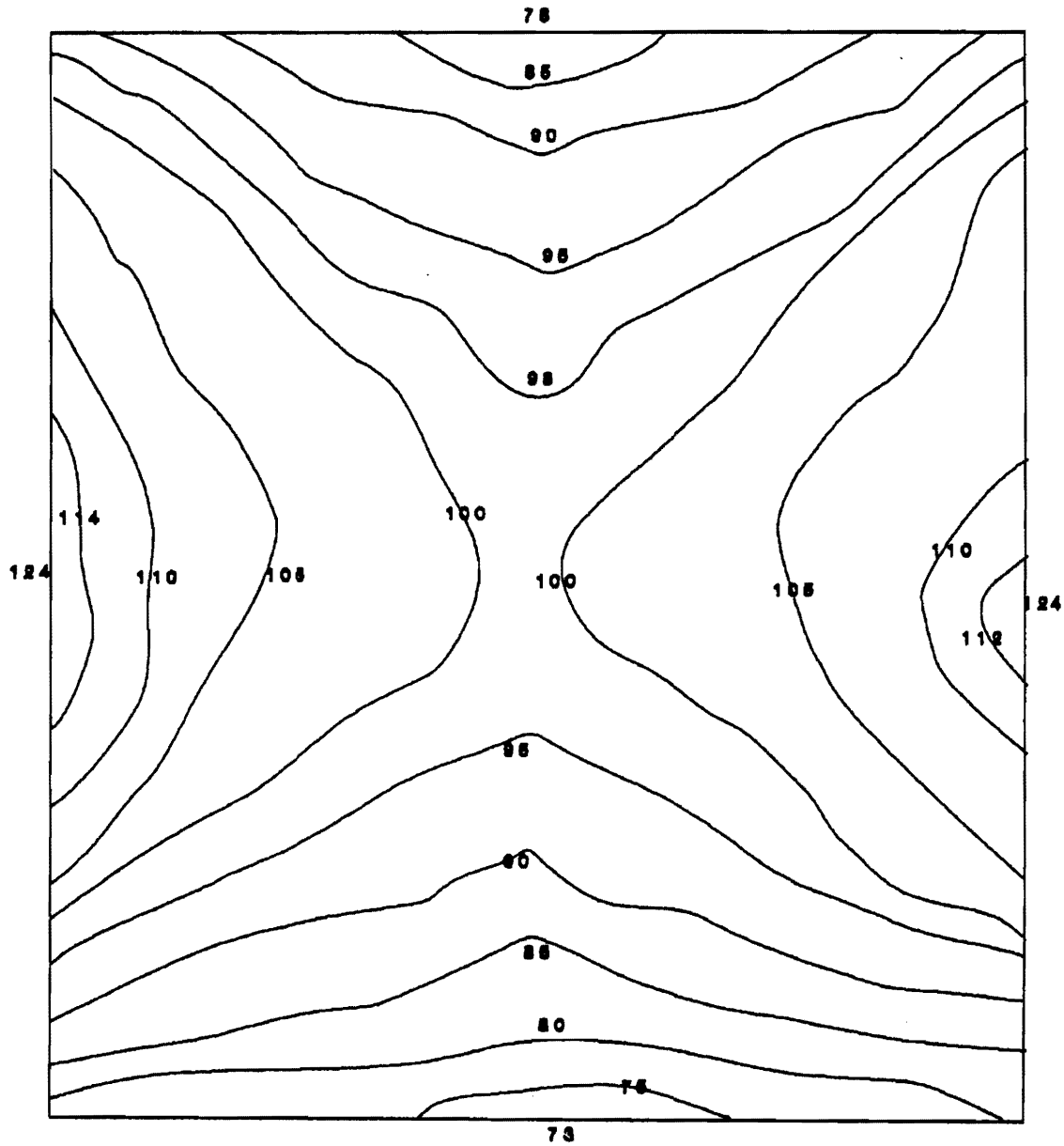


Figure 3. Isodose Curves in the Central Axis of the Gamma Chamber 4000A. The percentage doses are shown relative to that in the center.

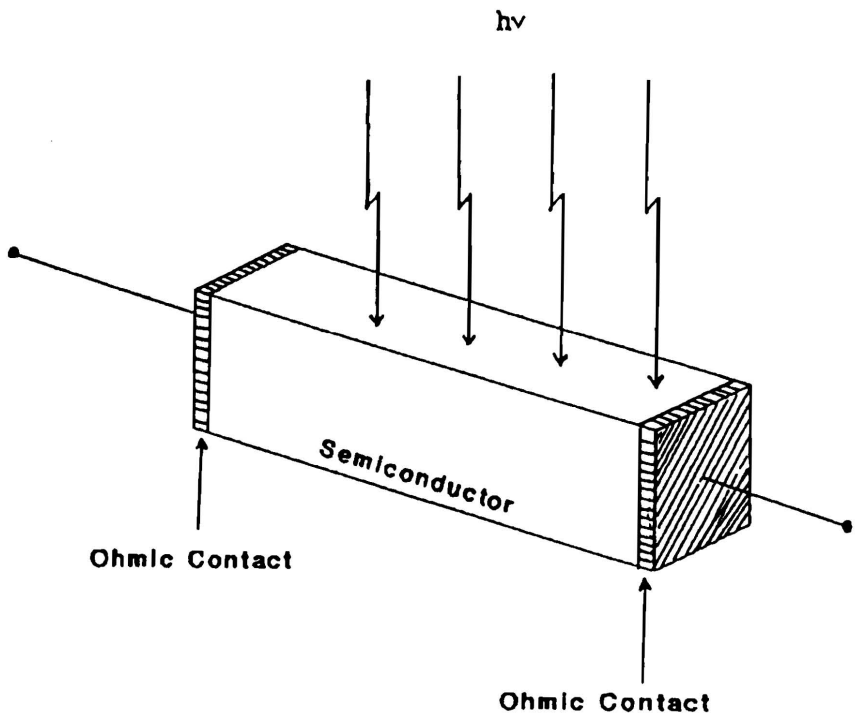


Figure 4. Schematic Diagram of a Photoconductor that Consists of a Slab of Semiconductor and Two Ohmic Contacts at the Ends.

center dose which is called the isodose curves. The results of this study confirm that the GafChromic™ Dosimetry Media is a useful tool for high resolution distribution mapping.

PHYSICAL DOSIMETERS

It is known that the value of current flow in a pn-junction depends on the mode of biasing [19]. When the junction is operating under reverse biasing conditions, the current is due to minority charge carriers only and a much lower conductivity occurs. Investigations [20, 21] have shown that gamma-irradiation of diodes increases the reverse current significantly, while the effect on the forward current is negligible.

On the other hand, a photoconductor consists of a slab of semiconductor (in the bulk or thin-film form) with ohmic contacts affixed to opposite ends (Figure 4). When incident photons fall on the surface of the photoconductor, carriers are generated by band-to-band transition (intrinsic) or by transitions involving forbidden-gap energy levels (extrinsic) resulting in an increase in conductivity.

One of the important properties of the physical dosimeter used in this field is the linear dependence of its photocurrent on the delivered gamma radiation dose-rate [22]. Such a property together with some other advantages, such as high sensitivity, small size, and ease of collection of these devices, recommend their application for dose-rate measurement.

The photoconductivity device with the widest application is the cadmium sulfide (CdS) cell. The sensitive area of the device consists of a layer of chemically deposited CdS, which contain small amount of silver impurities. The primary advantages of CdS photoconductor is its high dissipation capability.

Measurements of gamma radiation dose-rate values were performed by fixing nine RCA 7163, CdS, photoresistor samples at equal distance (1.7 cm apart) on a perspex sheet (16×20.5 cm), in a plane parallel to Cobalt-60 source pencils. The photoresistors with constant voltage value of 30 V were moved up and down within the irradiation cavity (at equal distances) and the output current was measured before and during exposure to gamma radiation.

The values of output current were obtained at each point along the perspex sheet and all values were normalized to that value obtained at the geometrical center of the irradiation chamber. Figure 5 shows the

Simple Regression

Parameter	Estimate	Standard error	T Value	Prob. Level
Intercept	−10.7109	1.96413	−5.45323	0.0121138
Slope	1.10116	0.0177433	62.0606	9.2176×10^{-6}

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio
Model	625.7238	1	625.7238	3851.5135
Error	0.4873854	3	0.1624618	
Total (Corr.)	626.21120	4		

Correlation Coefficient = 0.999611
Stnd. Error of Est. = 0.403066

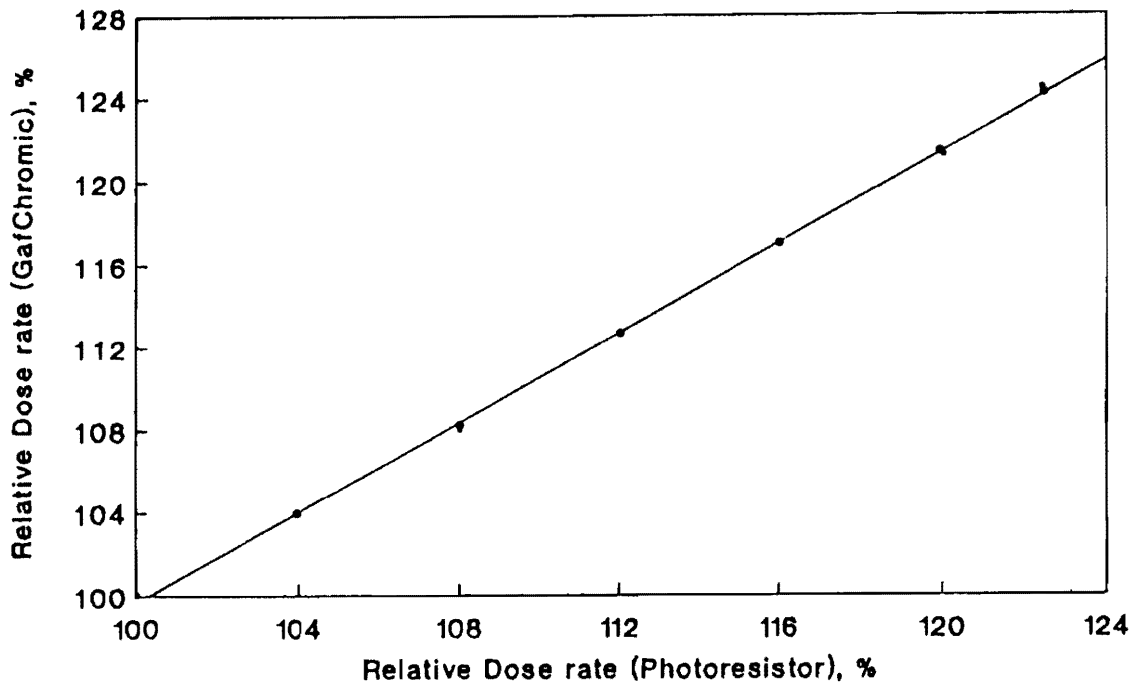


Figure 5. Correlation Between Relative Dose Rate Obtained by Both CdS Photoresistor and GafChromic™ Dosimetry Media Along the Horizontal Central Axis of the Gamma Chamber 4000A. The results are expressed as a percentage relative to that obtained at the geometrical center of the chamber.

Table 2. Dose Rate Assessment of the Gamma Chamber 4000A by Various Dosimetry Techniques Used by Both NCCRT and BARC.

Position	Bhabha Atomic Research Center (BARC)*			National Center for Radiation Research and Technology (NCRRT)		
	Perspex	Fricke	Deviation %	Photoresistor	GafChromic	Deviation %
Top	78.90	78.40	0.63	82.30 ± 0.40	78.900 ± 0.3	4.0
Bottom	76.30	86.60	13.50	76.40 ± 0.80	73.800 ± 1.1	3.4
Left	128.9	125.3	2.79	122.4 ± 1.34	124.46 ± 0.9	1.6
Right	128.9	125.3	2.79	122.4 ± 1.25	124.20 ± 0.8	1.6
Average deviation %			4.53			2.65

*Quoted from Bhabha Atomic Research Center report on calibration.

dose rate distribution obtained by both CdS photoresistor and GafChromic™ Dosimetry Media along the horizontal central axis of the gamma chamber. In this figure the obtained results were analyzed statistically by computer programming and showed a very close agreement between the results obtained by the two techniques.

Table 2 shows the various dosimetry techniques used for dose rate assessment at certain positions inside the gamma chamber by both NCRRT and BARC. This table shows the variation between the results obtained by CdS photoresistor and GafChromic™ Dosimetry Media used by NCRRT as well as the variation between Fricke and Perspex used by BARC. The average deviation between the used techniques by NCRRT (2.65) are less than that obtained by other techniques used by BARC (4.53%).

The reason for such relatively high deviation between the two systems used by BARC is due to the difference in dosimeters type and configuration where the thickness of Fricke ampoules is not less than 8 mm and Perspex is about 3 mm. Thin systems (plastics, glasses, or crystals) are the most widely used for electron beam dosimetry as well as distribution studies [16]. Semiconductor dosimeters such as photoresistor are widely used for dose-rate monitoring in steady-state fields and for mapping of dose rates [23]. Based on the above mentioned informations, we chose to use thin systems such as photoresistor (thickness = 1 mm) and GafChromic dosimeters (thickness = 0.125 mm) for dose mapping of the irradiation facility. The results obtained by these two systems showed better agreement than that obtained by BARC techniques.

SUMMARY

GafChromic Dosimetry Media and CdS photoresistors have been used for dose mapping of ^{60}Co irradiation facility (gamma chamber 4000A). These systems were chosen for dose distribution studies because of their small size and high spatial resolution. They are thin and small in thickness compared to Fricke dosimeter and perspex which were used by the manufacturer. The results obtained by these two systems showed better agreement in dose distribution studies (2.65%) than that obtained by BARC techniques (4.53%).

Dose rate values obtained by Fricke dosimeter at the centre of the irradiation cell, by both laboratories were found to be in excellent agreement. The deviation between the values of transit dose obtained by both laboratories is of the order of 1–2%.

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Paper Received 7 March 1992; Revised 3 August 1992.