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COMPARISON OF HIGH-DOSE DOSIMETRY SYSTEMS FOR RADIATION DAMAGE STUDIES IN COLLIDER DETECTORS AND ACCELERATORS

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Abstract

Measurements of absorbed dose in accelerator tunnels around primary beam areas are carried out on a routine basis at CERN. Dosimetric surveillance of high-energy particle accelerators has a great importance for the assessment of the radiation induced damage to materials and components used in high-level radiation areas. Standard dosimeters used at CERN for this purpose are polymer-alanine dosimeters (PAD) and radiophotoluminescent glass dosimeters (RPL). Ethanol-chlorobenzene dosimeters (ECB) for high-dose dosimetry, developed at the Ruder Boskovic Institute (RBI), have several interesting properties making their use in future multi-TeV colliders and detectors promising. These and RPL dosimeters were compared using the CERN alanine dosimetry as the reference system and ^{60}Co gamma rays as the reference radiation. A very good agreement between the ECB and PAD was obtained for ^{60}Co gamma irradiation whereas RPL overestimated the dose by about 20%. The suitability of the ECB system as a transfer standard for gamma irradiation was established. In mixed accelerator radiation fields the combination of the three dosimeters allows for an estimate of the total dose and of the contribution of the individual components of the radiation field.

1. INTRODUCTION

The intense research and development work for large detector systems devoted to future colliders, LHC, SSC and alike, includes extensive studies of radiation damage induced in their components. To be able to compare tests performed at different radiation sources - reactors, gamma ray sources and accelerator beams - it is of great importance to be able to perform accurate dosimetry measurements. Accurate dosimetry of various radiations (electromagnetic, neutrons, pions, etc.) requires detailed knowledge of the dosimeter response as a function of the radiation quality (type and energy), and the knowledge of the relative contributions of radiations of various types and energies to the total dose. Several dosimetry systems have been calibrated to radiations of various qualities. One group of dosimeters (alanine [1] and ethanol-chlorobenzene (ECB) [2]) have been developed mainly for high-dose dosimetry in radiation processing, whereas dosimetry systems of higher sensitivity have been developed specifically for radiation protection and therapy purposes (alanine [3] and chlorobenzene-ethanol-trimethylpentane (CET) [4]. Their common property is that all are very nearly tissue equivalent over a wide range of electromagnetic radiation energies, which makes them suitable for the measurement of doses to low-Z organic materials. Organic liquid chemical dosimeters are especially interesting because of their relative insensitivity to impurities. They can be used in a built-in dosimetry system to follow up radiation ageing of detector components. The dosimetric solution may be injected, via tubes, inside the equipment to be controlled for irradiation, and portions withdrawn for readout during the operation. The reading of the ECB and CET dosimeters is easy and can be done at low cost and with portable instruments.

Solid-state dosimetry is also attractive because of the large dose range covered, reusability and small size of the dosimeters. Radiophotoluminescence (RPL) dosimetry with silver - activated aluminophosphate glass has been routinely used at CERN for twenty years [5].

In the past, two intercomparisons of high-dose dosimetry systems used in the accelerator fields were carried out at CERN [6-8]. More recently the intercomparison of the two independent alanine dosimetry systems was performed between the Istituto Superiore di Sanità (ISS) in Rome and CERN [9]. That intercomparison has shown a very good consistency of the alanine dosimetry systems manufactured and evaluated at different locations, and

has established the suitability of the system as a transfer standard. The present paper reports the results of a collaboration programme study between CERN and the Ruder Boskovic Institute (RBI) carried out to compare the characteristics of the ECB and RPL dosimetry systems, using the alanine dosimetry as the reference dosimetry and ^{60}Co gamma radiation as the reference radiation field.

2. MATERIALS AND METHODS

2.1. High-dose dosimetry systems

The basic principles of the dosimeters used in this study are briefly reviewed below and their main characteristics are given in Table 1.

2.1.1. CERN dosimeters

The high-dose dosimetry systems in use at CERN have already been described in several papers [6-8].

Polymer-alanine dosimetry (PAD) is based on the formation of stable free-radicals in irradiated alanine [1, 10-14]. One of the big advantages is that dosimeters can be manufactured in the form of a cable which can be inserted in places with a difficult access, such as around accelerator magnet coils or in very large future detectors. The ones used in this study were 3 cm long pieces cut from an extruded cable (Elcugray), diameter 4.8 mm, made of a mixture of 33% ethylene-propylene rubber and 67% of alanine powder [7, 8]. The readout of the irradiated dosimeters was performed with a Varian E-3 electron spin resonance spectrometer at CERN.

Radiophotoluminescent (RPL) dosimetry is based on the formation of stable colour centres in irradiated silver-activated aluminophosphate glass [5,15]. The dosimeters used in this study were of the type DOS-2 produced by Schott and read by means of a Toshiba FGD-6 reader at CERN.

2.1.2. The ECB Dosimetry System

The ethanol-chlorobenzene (ECB) dosimeters consist of aqueous alcoholic solutions of monochlorobenzene [16, 17]. Radiation-induced

electrons and positive ions are rapidly scavenged by chlorobenzene and ethanol, respectively. Chloride ions are produced by dissociative electron attachment to chlorobenzene (CB) and then stabilized in the system by solvation [18]. Positive ions of the ethanol molecule undergo a fast hydrogen atom transfer conferring ultimate stability to $\text{C}_2\text{H}_5\text{OH}_2^+$. The measured radiolytic product is hydrogen chloride. The HCl yield for a given absorbed dose is a function of CB concentration, but at any constant CB concentration, it is independent of the dose rate up to $10^5 \text{ Gy} \cdot \text{h}^{-1}$ [19] and independent of the dose up to about 100 kGy in partially evacuated ampoules [20]. The effects of temperature in the range 293 to 360 K [21] and of dose at any given CB concentration can be found directly in the literature or by interpolation based on the literature data. The system can be utilized in the dose range between 10 Gy to over 1 MGy using various evaluation methods [22]. The dosimetric solutions can be stored for a long time with the only limitation that exposure to UV light should be avoided during storage.

Absolute ethanol and triply distilled water were combined to prepare 96 vol. % ethanol. It was then used for topping appropriate amounts of chlorobenzene to obtain dosimetric solutions containing 4, 10, 20, 25 and 40 vol. % of CB. The use of dosimeters with various formulations is recommended for cross-checking of the internal consistency of the measurements. The five formulations have been extensively used in the past and their characteristics are well known.

Commercial pharmaceutical ampoules (15 mm outer diameter) were filled with 5 ml of dosimetric solution. ECB solutions were partly deoxygenated by bubbling with nitrogen for 1 minute immediately before flame sealing. Sealed dosimeters were stored in the dark.

It is important to point out that the dimensions and volume of the dosimeters allow for electron equilibrium. The vessel is usually glass, but other suitable materials may also be used (quartz, stainless steel, etc.). Of course, the shape and volume may be adapted to any requirement.

Irradiated dosimeters were analysed for the HCl concentration by at least one of the available readout methods : oscillometry [22], mercurimetric titration [23] and spectrophotometry [24] at RBI. Of these, oscillometry (high-frequency conductivity) is not necessarily restricted to being performed in a laboratory, and is particularly suitable for field work. It uses an inexpensive

portable instrument, and the readout does not even require a galvanic contact with the solution, so that dosimeters may be evaluated without breaking open the ampoules.

2.2. Irradiation conditions

2.2.1. Cobalt 60 at RBI

Five PAD, 5 RPL and three ECB dosimeters of various concentrations (20%, 25% and 40% CB) were irradiated together at any one time with the nominal doses of 0.1, 0.4, 1, 4, 10, 40 and 100 kGy, at a dose rate of about 1 kGy/h, in the well-type irradiator of the Ruder Boskovic Institute [23]. The irradiation was in air at room temperature.

2.2.2. Cobalt 60 at Conservatome

Five PAD, 5 RPL and one ECB (10% CB) dosimeter were irradiated together at any one time with the nominal doses of 50, 100, 500 and 1000 Gy, at a dose rate of 350 Gy/h, at a distance of 1.10 m from the centre of the source in the panoramic irradiation facility.

Five PAD, 5 RPL and one ECB (10% CB) dosimeter were irradiated together at any one time with the nominal doses of 3, 10 and 30 kGy, at a dose rate of 6.7 kGy/h, in the centre of the cylindrically shaped source of the same panoramic irradiation facility. The irradiation was in air at ambient temperature.

2.2.3 CERN accelerators

Routine high-dose dosimetry is carried out at the main CERN accelerators: PS (Proton Synchrotron), PS Booster, SPS (Super Proton Synchrotron), LEP (Large Electron Positron collider) and in related target areas [25].

For this intercomparison study, irradiation positions were chosen so as to cover a wide energy range and different types of radiation; mainly gammas and neutrons in the proton accelerators and X-ray synchrotron radiation in LEP.

Two ECB (40 %), 2 PAD and 2 RPL were irradiated together in various accelerator positions (items 1 to 26 listed in Table 2) and illustrated in Figure 1. Five ECB, 4 PAD and 6 RPL were irradiated in the PS-ACOL Irradiation Facility (PSAIF) [28] (item 23 in Table 2).

The radiation field around the proton accelerators consists mainly of gamma rays and neutrons. The neutron contribution is expected to be less than 10% of the flux with an important contribution of low-energy neutrons in the accelerator tunnels (items 1 to 12 in Table 2) [26, 27].

The neutron dose has a higher contribution around the targets where high-energy particles are also expected (items 13 to 16 and 23 in Table 2). The neutron spectrum has an important low-energy part [28].

The radiation field in LEP (items 17-22 and 24-26 in Table 2) has a dominant contribution of X-rays from the synchrotron radiation. At the current energy of LEP (2×45 GeV), the mean energy of the synchrotron radiation is a few tens keV and the maximum energy is 1 MeV [29].

The dosimetry and the neutron fluence measurements in PSAIF (item 23) have been well established [28]. About 20% of the total dose in tissue comes from the fast neutrons, and about 10% from the low-energy neutrons.

3. RESULTS AND DISCUSSION

3.1. Cobalt 60 irradiations

The readings for each type of dosimeter were averaged if more than one piece of this type of dosimeter was used for ^{60}Co gamma ray dosimetry. The results expressed as dose to water are shown in Table 3 and the response of ECB and RPL versus PAD is plotted in Fig. 2.

Throughout the investigated dose range, 0.5-30 kGy, the ECB is in an excellent agreement with the alanine dosimetry, independently of the dose rate. The correspondence between the results obtained with the two systems, ECB vs. PAD, is 1.03 ± 0.04 , which is practically unity within the experimental

uncertainty. In the same dose range the RPL dosimetry yields about 18% higher readings, the uncertainty being about 20%. One should bear in mind that these results are in agreement with specific properties of RPL in the measured dose range [3]. A smaller discrepancy is observed in the dose range extending down to 50 Gy which was not covered by the ECB dosimetry in this experiment.

3.2. Accelerator irradiations

The dose measured with ECB and RPL as a function of the dose measured with PAD in various accelerator environments is shown in Fig. 3. The readings of the individual dosimeters are shown, rather than the mean values, to show the span of the obtained results. In some cases, the results of any single type of dosimeters differ by a factor of almost 2. The explanation for this is that dosimeters were placed inside boxes which have finite dimensions, that no two dosimeters occupied exactly the same position, and that radiation fields may have been non-uniform. The effect of the dose gradient across the box has been shown by exposing six ECB dosimeters along with 2 PADs in PSAIF (item 23 in Table 2). The results for the neighbouring pairs ECB-PAD are shown in the box 23 in the Figure 3 by filled circles. The results for the 4 ECBs remaining between the two pairs are contained inside box 23.

The larger dimensions of the ECB dosimeters as compared to PADs are probably the additional reason for the generally larger span of results in Figure 3 along the D_{ECB} axis than along the D_{PAD} axis. This is further corroborated by the generally smaller span of the results obtained with tiny RPL dosimeters.

Having explained the observed differences in the same type of dosimeters we observe marked differences among the three types of dosimeters that cannot be explained on the grounds of geometry of irradiation.

All dosimeters used in this work are of the integrating type, i.e. their readings are proportional to the absorbed doses. The proportionality factor, however, is different for different radiations. If dosimeters are exposed to more than one type of radiation, which is the case in proton accelerator environments (items 1-16 and item 23 in Table 2), they will respond to

various radiations with different efficiencies, and the resulting integral dose will be different. The response of alanine dosimeters has been calibrated to neutrons of various energies and the decreased response was found for decreasing neutron energy [30]. The response of the ECB to neutrons has not been calibrated, but, based on mechanistic considerations [18] and by analogy with the related CET system [4], we expect that the response to neutrons of the ECB is constant over a range of neutron energies. This would explain consistently higher readings of the ECB dosimetry as compared to PAD in all cases where mixed $n + \gamma$ fields were measured. Stronger dependence of the RPL response to the decreasing neutron energy [5], as compared to the PAD, would explain the consistently lower readings obtained with this system in mixed $n + \gamma$ fields compared to the PAD results.

As expected [5], RPL shows a much higher sensitivity to low energy electromagnetic radiation as compared to PAD (items 17 to 22 and 24 to 26). The increased readings of ECB at the same location apparently do not stem from the same cause since the independence of the ECB response has been measured down to 50 KeV [31].

4. CONCLUSIONS

The irradiations in ^{60}Co gamma fields have demonstrated an excellent agreement between the ECB and the alanine dosimetry, whereas the RPL shows a relatively large ($\sim 20\%$) systematic overestimation of the dose.

The suitability of the alanine dosimetry system as a transfer standard dosimetry system has been proven for high, as well as for low-dose dosimetry [14]. This study has established the suitability of the ECB dosimetry system as a transfer standard for gamma irradiation using alanine as a standard.

The irradiations in accelerator environments may be grouped into two categories:

- a) neutron + electromagnetic radiation in proton accelerators,
- b) low energy electromagnetic radiation from synchrotron radiation in LEP.

From Figure 3 we can conclude that compared to PAD:

- the RPL dosimeters overestimate by a factor up to 10 in LEP,
- the ECB reads in general higher both in LEP and proton accelerator,
- the RPL dosimeter reads in general lower in proton accelerator environment.

The discrepancy observed in proton accelerators between the three dosimeter types ECB, RPL and PAD may be explained by their different responses to neutrons.

It is also evident by comparison of Figs. 2 and 3 that, unlike in the case of a cobalt source, one must be cautious to use alanine as standard dosimeter around accelerators when high precision is required because of its lower sensitivity for neutrons and low-energy electromagnetic radiation. It confirms, however, that alanine is a valuable dosimeter over a wide range of dose.

The difference of response of the three dosimeters to energy and/or radiation kind open the interesting possibility to use a simple combination of them for a simultaneous characterization of the radiation field and dose determination.

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Table 1

Main characteristics of the utilised dosimetry systems

Type	Alanine [7] Elcugray	RPL glass [5] Toshiba FD-R1-1 Schott DOS 2	ECB [16] RBI
Dimensions (mm)	Dia.: 4.8, length: 30	Dia.: 1, length: 6	Dia.: 15, length: 80
Composition (%)	Alanine: 67 Polymer: 33 (by weight)	O: 53.7, P: 33.4 Al: 4.6, Ag: 3.7 Li: 3.7, B: 0.9 (by weight)	chlorobenzene (4 to 40 vol. %) in 96 vol. % aqueous ethanol
Physical characteristics	$Z_{\text{eff}} \approx 7.2$	A: 19, Z: 10	A ~ 15, Z_{eff} 6.2-7.6
Range (Gy)	$5 - 5 \times 10^5$	10^{-1} - 10^6	$50 - 2 \times 10^6$
Uncertainty (%)	± 4 up to 50 Gy $\pm (4-10)$ above	± 20	± 5 up to 1 kGy ± 3 between 1 and 100 kGy
Fading	Absent at 15-25°C and 40-60 % RH	1% per 3 months at 25°C. Accelerated by exposure to sunlight	Negligible
Energy dependence (electromagnetic)	Underestimation 0.8 at 0.05 MeV 0.95 at 0.1 MeV Ref. 8	Overestimation 7.0 at 0.05 MeV 2.0 at 0.2 MeV 1.2 at 0.5 MeV Ref. 5	0.05-1.5 MeV gam- mas: none 4-10 MeV e: none
Neutron sensitivity compared to gamma	0.4 at 1.0 MeV 0.6 at 8.0 MeV 0.7 at 14.0 MeV Ref. 30	0.9 for thermal Ref. 32 0.01 for fast Refs. 5 and 33	to be measured, see text
Readout	Electron spin resonance	RPL excited by UV at 365 nm	oscillometry titration spectrophotometry

Table 2
Selected positions at the CERN accelerators

Item	Pos. No	Description of position	Absorbed dose in Gy	Dose rate (Gy/h)
450 GeV-SPS (1532 h)				
1	18	Coil: 2.17.01	4.68×10^3	3.00
2	25	Coil: 3.24.01	4.68×10^2	0.31
3	19	BLM 2.18.01	1.25×10^4	8.16
4	15	BLM: 3.14.01	5.31×10^2	0.35
26 GeV-PS (1842 h)				
5	5	Vacuum chamber: pos. 5	1.73×10^3	0.94
6	3	Vacuum chamber: pos. 3	1.40×10^4	7.60
7	2	Vacuum chamber: pos. 2	1.39×10^3	0.75
8	26	Vacuum chamber: pos. 26	1.85×10^2	0.10
800 MeV-PSB (1961 h)				
9	51	Ring 3: BR3.BHZ 72 U	2.26×10^1	0.01
10	54	Ring 3: BR3.BHZ 81 D	3.98×10^3	2.03
11	58	Ring 3: BR3.BHZ 82 D	8.45×10^1	0.04
12	52	Ring 3: BR3.BHZ 72 D	1.69×10^1	0.01
Transfer tunnel TCC 2 (1560 h)				
13	93	Target 2	4.29×10^4	27.5
14	90	Target 4	6.04×10^4	38.7
15	92	Target 6	1.10×10^4	7.05
16	81	Behind concrete shielding	3.50×10^2	0.22
45 GeV - LEP				
17	D.C. 132	dipole (e ⁻)	1.51×10^2 (1)	0.22
24	D.C. 132	dipole (e ⁻)	8.65×10^2 (2)	0.98
18	D.C. 132	Q-pole (e ⁻)	1.11×10^1 (1)	0.02
25	D.C. 132	Q-pole (e ⁻)	6.70×10^1 (2)	0.08
19	D.C. 132	synchr. rad.	6.5×10^2 (1)	0.95
26	D.C. 132	synchr. rad.	1.20×10^2 (2)	0.13
20	D.C. 169	dipole (e ⁺)	1.22×10^3 (1)	1.79
21	D.C. 169	Q-pole (e ⁺)	1.09×10^1 (1)	0.02
22	D.C. 169	synchr. rad. (e ⁺)	1.64×10^2 (1)	0.24
23	[n - 11]	PSAIF (75 h)	3×10^3	40

(1) 682 h

(2) 887 h

Table 3

Comparison of high-dose dosimetry systems for ^{60}Co gamma rays

Nominal Dose (Gy)	Dose Rate kGy h^{-1}	Dose to water (Gy)		
		Alanine	ECB	RPL
5×10^1	0.3	5.00×10^1	.	5.36×10^1
10^2	0.3	1.01×10^2		1.13×10^2
10^2^*	1	1.04×10^2		1.19×10^2
$4 \times 10^2^*$	1	3.94×10^2		4.34×10^2
5×10^2	0.3	4.89×10^2	5.36×10^2	5.13×10^2
10^3	0.3	1.04×10^3	1.03×10^3	1.19×10^3
10^3^*	1	0.88×10^3	0.90×10^3	1.50×10^3
3×10^3	6	2.89×10^3	2.98×10^3	3.49×10^3
$4 \times 10^3^*$	1	3.47×10^3	3.74×10^3	5.60×10^3
10^4	6	1.02×10^4	1.01×10^4	1.13×10^4
10^4^*	1	0.98×10^4	0.98×10^4	1.13×10^4
3×10^4	6	3.26×10^4	3.24×10^4	3.26×10^4
10^5^*	1	1.00×10^5		0.96×10^5

* Irradiations carried at RBI Zagreb, the others at Conservatome.

PS

5 - 8

PSB

9 - 12

SPS

1 - 4

LEP

17 - 22

24 - 25

● Dosimeter position

Figure 1. Irradiation positions in CERN accelerators. The numbers identify items in Table 2.

Figure 2. The ^{60}Co gamma dose measured by the ECB (open circles) or RPL (filled circles) as a function of dose measured by the PAD.

Figure 3. The dose measured by the ECB (shaded boxes) or RPL (dark boxes) as a function of dose measured by the PAD (all relative to ^{60}Co gammas) in various locations of CERN accelerators. The numbers identify items in Table 2.