DEPTH DOSE DETERMINATION FOR A MIXED RADIATION FIELD USING A THIN PLASTIC SCINTILLATOR DOSIMETRY SYSTEM

by

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Plastic scintillators, due to their favorable characteristics compared with other dosimetry techniques, were used as detectors to estimate dose distributions in high gradient dose fields. In this study, a thin plastic scintillator (type BC-408) was coupled to a photomultiplier tube and multichannel analyzer as a technique for real-time dose measurements. The well-defined beta, gamma, and beta-gamma emitters (^{137}Cs, ^{133}Ba, ^{22}Na, ^{109}Cd, ^{55}Fe, and ^{241}Am) have enabled parallel depth dose measurements with Monte-Carlo calculations to be critically compared. The measurements of doses were made for depths range of 0.1 mm to 5 mm. The MCNP dose results were comparable with the plastic scintillator detector and can be used to approximately estimate the dose rate values from mixed electron-photon fields. The minimum dose rate that can be measured by the plastic scintillator system was ~2 μGy/h and was for ^{109}Cd source of activity 222 Bq.

Key words: plastic scintillator, MCNP code, mixed field radiation, dose

INTRODUCTION

Determining the depth dose distributions of absorbed dose from beta or beta-gamma emitting particles for a variety of boundary conditions and complex geometries has been approached using both experimental measurements and theoretical calculations. Measurements of dose have been carried out using several techniques, namely extrapolation chambers, thermoluminescent dosemeters, and radiochromic dye films [1-3]. During the last decade, there has been increased interest in using plastic scintillators as a means of dose measurements due to their favorable characteristics compared with other dosimetry techniques. Plastic scintillator (PS) due to its very thin thickness is favorable for measuring the high spatial non-uniformity of dose distributions produced by beta and low energy photon emitters. A thin scintillation detector has been coupled to an ICCD camera for potential use in measuring the spatially non-uniform dose distribution around a "hot particle". This imaging system is capable of producing real time measurements considerably quicker than any other available radiation techniques [4, 5]. Plastic scintillators have been successfully applied in radiotherapy as dosimeters for high-energy radiation, at MeV energies [6-8].

Although the introduction of a specific dose limit for localised exposures provided an operational solution to the radiological control of beta-rays and low energy photons, the practical dosimetric difficulties in its applications remain [9]. These primarily arise from the strong attenuation of the beta-rays and low energy photon radiations, which leads to large variations of dose over short distances. An equally important difficulty is the need to measure doses over very thin layers, such as that of basal cells in the skin. To simulate such volumes, a detector must be very thin, with consequent reduction in sensitivity [10]. Similar difficulties arise in assessing the risks associated with low dose exposures to other low energy beta particles encountered in the nuclear industry such as tritium and the long-lived fission products Tc-99 and I-129 where, due to the short range of the beta particles, an inhomogeneous distribution of dose and radiation quality is to be expected. Current methodology in dosimetry does not take into account the non-homogeneous nature of low dose exposure to low energy radi-

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ations and there is a need to develop theoretical and experimental methods of quantifying absorbed dose over small volumes of tissue ranging from micrometers to millimetres.

This study is concerned with dose measurements as a function of plastic scintillator depth when it is exposed to a mixed field of electrons and photons. Monte Carlo simulation is used to determine the electron and photon contributions to the overall dose, and to estimate the dose absorbed by plastic scintillators for a range of energies and for beta, electrons, and photon radiation types. The results of the Monte Carlo dose calculations are then compared with those determined by the PS system. A relationship between the absorbed radiation dose in the scintillator and the final digitized light signal has been established.

MATERIALS AND METHODS

Description of the scintillation dosimetry system

The characteristics of the selected plastic scintillator should pose as high efficiency as possible and its emission spectrum should be close to that of the counting system. This becomes more crucial when dealing with low photon energies and low activity sources (~222-3.7 10^5 Bq). The plastic scintillator should also be water equivalent, easy to handle and easy to cut into different sizes, thus enabling easy preparation of small detector volumes. Figure 1 shows the components of the plastic scintillation dosimetry system. The scintillator material used was the BC-408 plastic scintillator manufactured by Saint-Gobain Ltd. This type is claimed to be more suitable for low energy photons (<100 keV). Because we are dealing with sources of mixed radiation field (beta and gamma), the BC-408 was found to be the only scintillator that is more suitable for beta detection. The physical characteristics of BC-408 are listed in tab. 1. The area where the source and scintillator is located was designed to obtain a better alignment with the PMT photocathode. The PS was coupled to a Hamamatsu R7205-1 photomultiplier tube (PMT), an eleven-stage, head-on PMT with 10 mm cathode diameter and overall length of 92 mm. This PMT was specifically designed for low photon counting applications. It exhibits a very high gain (10^7) with low anode dark current. In addition, the maximum emission spectrum of the BC-408 scintillator closely matches the peak efficiency wavelength of the R7205-1 PMT (420 nm). The PMT and plastics scintillator with a radioactive source and a reflector were tightly packed together using a light tight housing, which must provide total optical isolation. The PMT was connected to a high voltage of 800 V. The output signal was connected to a CANBERRA preamplifier (2005), which is then processed using ORTEC 855 spectroscopy amplifier and the pulse-height spectra are accumulated using an integrated computer spectroscopy system (ISC-PCI 2k – Spectrum Techniques).

Table 1. Physical characteristics of the BC-408 plastic scintillator (Saint-Gobain crystals)

Characteristics	Value
Light output (% anthracene)	64
Decay constant [ns]	2.1
Wavelength of maximum emission [mm]	425
Refractive index	1.58
Density [gcm^{-3}]	1.032
Ratio H:C atoms	1.104
Number of electrons per cubic centimeters	3.37 10^{23}

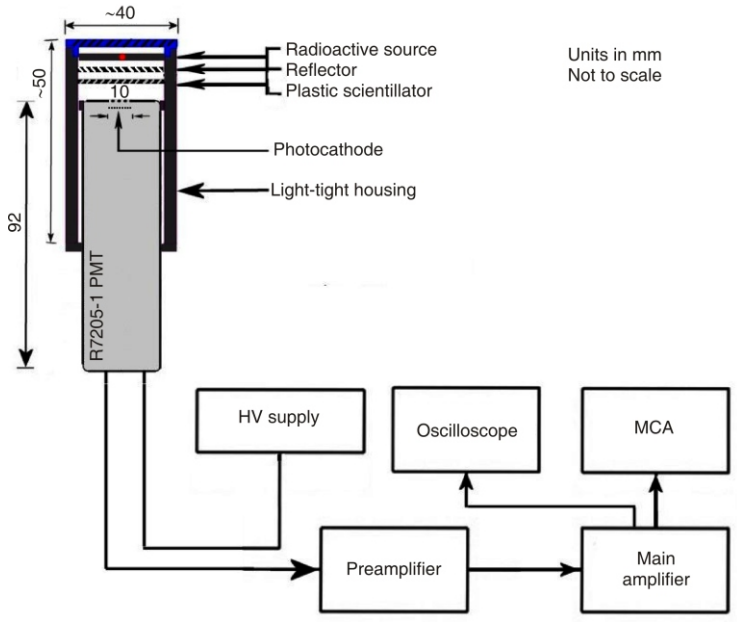

Figure 1. Schematic diagram of the plastic scintillation dosimetry system

Radiation sources

The following sources were used for the investigation: ^{55}Fe, ^{109}Cd, ^{60}Am, ^{133}Ba, ^{22}Na, and ^{137}Cs. These sources cover a wide range of gamma energies, starting from 5.9 keV (^{55}Fe) up to 662 keV (^{137}Cs) and 1275 keV (^{22}Na). Although beta-rays and electrons from these sources are negligible when they are used with gamma detectors such as NaI scintillation detector, they have to be taken into account with a plastic scintillation system. Since this study deals with small-scale dosimetry, the electron dose was also considered in the simulation. The electron energies range from few keV up to 655 keV. The conversion electrons and X- and γ-energies and abundances are given in the National Nuclear Data Centre NUDAT database [11]. Details of the source geometry, dimensions, materials, and densities, which are crucial in the simulation, were obtained directly from the manufacturer (Spectrum Techniques). The RSS8 source set includes ^{137}Cs, ^{22}Na, ^{133}Ba, and ^{109}Cd. Dimensional details of these sources are shown in fig. 2. The radioactive material is evaporated in the bottom of a centered cylindrical hole of 3.175 0.13 mm radius. The source disc is made of plexiglas and the source window's thickness is 0.037 0.013 mm. A schematic view of the ^{55}Fe source is shown in fig. 3. The radioactive material in the ^{55}Fe source is located under the aluminum material opposite the label. The radioactive material is pippetted within the small circle. The window (80 μg per cm aluminized Mylar) is pressed between the two pieces of laminate material. The source is 4 mm diameter and 0.127 mm thick. The radioactive material in the ^{241}Am source is a spherical shape of about 1 mm diameter and located in the centre of the disc. The current radioactivity of these sources also varies from 3.7 10^5 Bq down to 222 Bq.

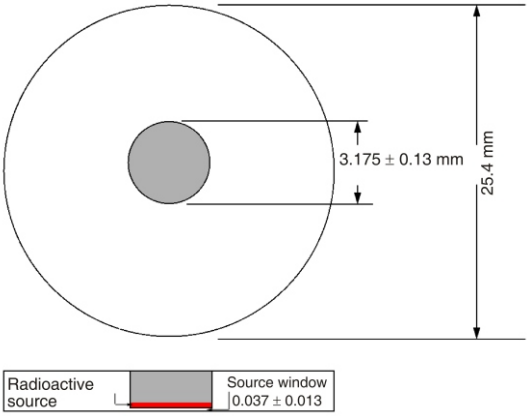

Figure 2. Dimensional details of the RSS8 source set ^{109}Cd, ^{133}Ba, ^{22}Na, and ^{137}Cs (spectrum techniques)

Monte Carlo simulation

Calculation of doses can provide an independent dose assessment in the case of well-known constructed sources. Calculations can be used to predict the depth-dose distributions from beta or beta-gamma emitting particles and, if successful, can be extended to other conditions of interest. The Monte Carlo neutron particle code (MCNP4C) was used to calculate the dose absorbed by plastic scintillators at depths ranging from 10 μm to 5 mm and for photons and electrons emitters, with the default mode being used in all the simulations [12]. The experimental set-ups for both scintillation dosimetry system (fig. 1) and the radioactive sources (figs. 2 and 3) were modeled as realistically as possible. For comparison purposes, all the calculated doses were corrected to the current activity when the measurements were conducted. The geometry, dimensions, and materials' compositions were all taken into account. The energy deposited is scored using the MCNP energy deposition tally *F8 with unit of MeV/particle. The number of photons and electrons tracked was generally sufficient to determine the energy deposition in all cells to within a few percent. The calculated energy deposited (MeV/particle disintegration) in each detector (cell) was converted into mGy per hour using the calculated mass of each detector, the source activity and a decay correction factor, if necessary. All the associated errors R were less than 10%. The dose calculation for all six sources was performed in two separate parts. The first part considered the source as a pure gamma emitter. In the second part of the simulation, beta and conversion electrons or Auger electrons were considered. The radionuclides and emissions taken into consideration are listed in tab. 2. Details about the source geometry and source materials were obtained directly from the manufacturer (Spectrum Techniques).

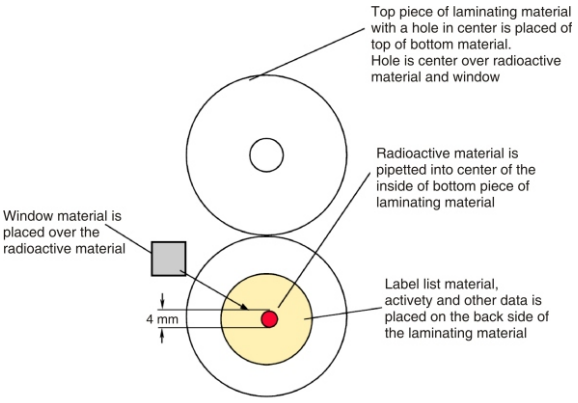

Figure 3. Dimensional details of the ^{55}Fe source (3.7 10^5 Bq). The source is deposited in the center of the disc in an area of about 4 mm and thickness of 0.127 mm (spectrum techniques)

Table 2. Radionuclides and emissions included in the MCNP evaluation

Radionuclide	Emission	Activity [Bq]	Energy [keV]	Intensity [%]
^{55}Fe	X-ray	$3.59\ 10^5$	5.90	16.3
			5.89	8.24
			6.49	3.31
^{109}Cd	Gamma	$2.257\ 10^6$	24.9	11.37
			21.99	18.62
			22.16	35.26
^{241}Am	Gamma	$3.7\ 10^5$	59.94	35.9
			13.9	42.7
^{133}Ba	X-ray	$2.63\ 10^7$	30.63	34.25
			30.97	63.4
			35	22.8
	Gamma		81	32.97
			302.84	17.8
			356.01	60.5
	Conversion electrons		17.17	10.45
			25.5	14.13
			43.64	3.87
			75.28	7.4
			45.01	48.14
			79.78	1.51
			320.02	1.3
^{22}Na	Gamma	$9.4\ 10^6$	1274.5	99.9
			511	179.8
	Positron spectrum		E_{max} = 0.546	89.84
^{137}Cs	Gamma	$3.3\ 10^7$	661.65	89.98
	X-ray		4.47	10.38
			31.82	2.1
			32.19	3.82
			36.4	1.39
	Beta spectrum		E_{max} = 514	0.944
			E_{max} = 1175	0.056
	Conversion electrons		655.66	1.46
			624.21	7.66

RESULTS AND DISCUSSION

Determination of electrons and gamma contributions

It is expected that beta-rays and electrons, depending on their energies and the source window, may dominate doses in the first layer. The depth dose rate distributions from the mixed field sources including ^{137}Cs, ^{22}Na, and ^{133}Ba calculated using MCNP are shown in fig. 4. The dose is averaged over an area of 9 mm diameter. For ^{137}Cs and ^{22}Na sources, it is clearly seen that at the depth of 0.3 mm, beta-rays are predominant by a factor of about 15 comparing with the gamma contribution. This ratio starts to decrease rapidly to about 2 at depth of 5 mm. For ^{133}Ba for which the electron energy is less than that for ^{137}Cs and ^{22}Na, electron contributions to the dose is predominant up to 0.5 mm. After which the gamma contribution becomes grater by a factor of about 2.5. The uncertainty in this calculated ratio is largely affected by the accuracy of the measured source window. According to the manufacture, the tolerance in the measured source window for the RSS8 source set is 0.013 mm. This creates almost 50% difference between the minimum and maximum thicknesses. According to the manufacture, different colors of RSS8 sources also indicate some small differences in dimensions.

Depth dose measurements and calculations

The long-term stability and reproducibility check and background measurements of the scintillation dosimetry system have been investigated in our previous work. For depth dose measurements, a set of plastic scintillator measurements performed for six sources were compared graphically with the corresponding relative MCNP dose rate and presented in fig. 5 (a, b, c, d, e, and f). The total counts for each plastic scintillator thickness is proportional to the energy

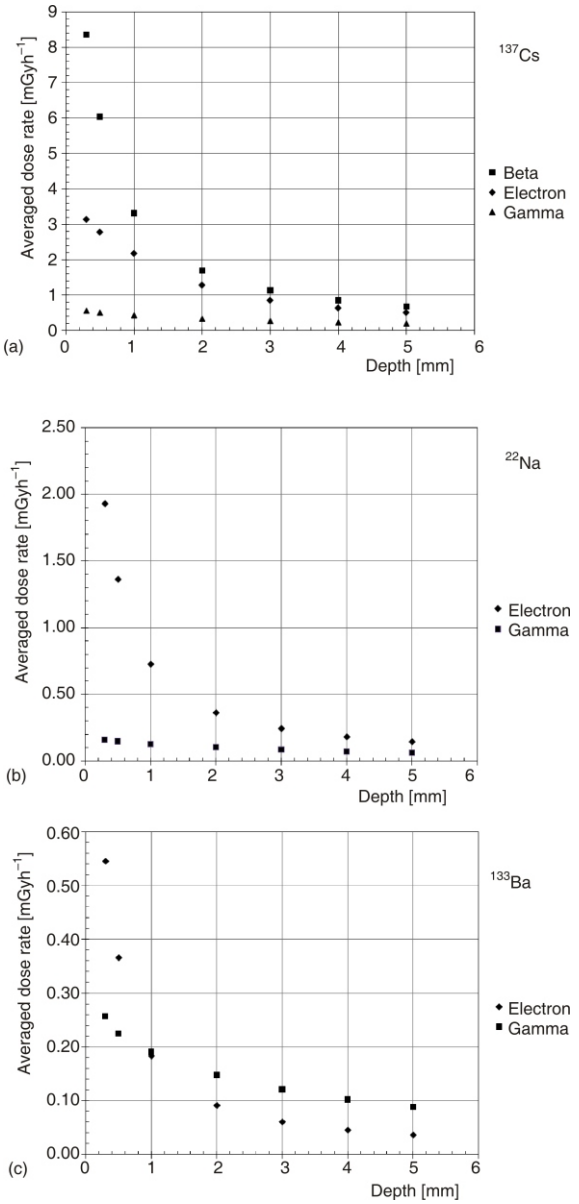

Figure 4. Calculated beta, electron, and gamma doses for ^{137}Cs (a), ^{22}Na (b), and ^{133}Ba (c) sources at various depths of plastic scintillators

absorbed by the plastic scintillator. All dose rates were normalized to the peak dose. The integrated count was taken for depths starting from 0.3 mm to 5 mm and the measurement time was five minutes, which was sufficient to produce statistically acceptable counts. This is a relatively short measurement time for such low activity sources, which is a very desirable characteristic of the detection system. The percentage standard deviation obtained for five consecutive readings was less than 3%. The count rate for each depth was then divided by the mass of the plastic scintillator. In general, the relative dose rates show a systematic increasing deviation with depth. The form of the curve resulting from measurements with the PS resembles that of the MCNP depth-dose curve and the relative depth dose curves generally appear to follow a power function ($Y = AX^B$). It is worth noting that for electron and photon emitters (^{137}Cs, ^{22}Na, and ^{133}Ba), the dose rate falls off rapidly to about 20% at depth of 5 mm. For photon emitters (^{241}Am and ^{109}Cd), the reduction of the dose rates with depth reaches about 50%.

To aid a more critical comparison, ratios of the relative PS values to the relative MCNP dose rates are shown as a function of depth in fig. 6. Generally, maximum deviations between the measured and calculated dose rates were of approximately 20%. This variation reaches its minimum of about 10% at shallow depths (<1 mm). The overall variations may be explained by the decrease of sensitivity of the PS as electron energies decrease with depth. The uncertainty of the source window's thickness may be the major contribution to the variation between the predictions and the measurements, which can produce a maximum disagreement of ~50%. A minor source of this deviation may be attributed to the inaccuracy in aligning the PS with the PMT's photocathode.

Establishing a relationship between the absorbed radiation dose in the scintillator and final digitized light signal is always a challenge. For each radionuclide, an attempt of calibrating the PS system was made by comparing the depth-dose measurements obtained from the PS system with the corresponding calculated MCNP dose rate (fig. 7). Good linearity of dose exists for all radionuclides. It is clearly seen that there are two separate groups: the first group includes the electron-photon emitters (^{137}Cs, ^{133}Ba, and ^{22}Na sources). The measurable dose rates in this group range from ~0.13 mGy/h to 12 mGy/h to. The ratios of the measured light output to the calculated dose rate are 8543, 8541, and 5665 for ^{137}Cs, ^{133}Ba, and ^{22}Na sources, respectively. This difference in ratios may be due to difference in PS response to different beta and electron energies. In the second group (photon emitters only), the light output/dose rate ratios are 38627, 75585 and 14830 for ^{55}Fe, ^{241}Am, and ^{109}Cd, respectively. The difference in ratio for the second group is attributed to the fact that the emission energies for ^{55}Fe, ^{241}Am, and ^{109}Cd are below 100 keV, while the BC-408 is declared for energies above 100 keV. This difference in dose response of the PS system for different radiations reflects the differences in the gamma and electron responses of the plastic scintillators. The dosimetric characteristics of plastic scintillation detectors and its response to different photon and electron energy have been investigated by a number of researchers [14, 15]. However, investigation of the PS sensitivity on the radiation type and radiation energy is outside the scope of this work. The lowest measurable dose rate was 0.002 mGy/h for ^{109}Cd. This means that the PS system is capable of measuring very low dose rates in real time measurements considerably quicker than any other available radiation dosimetry techniques.

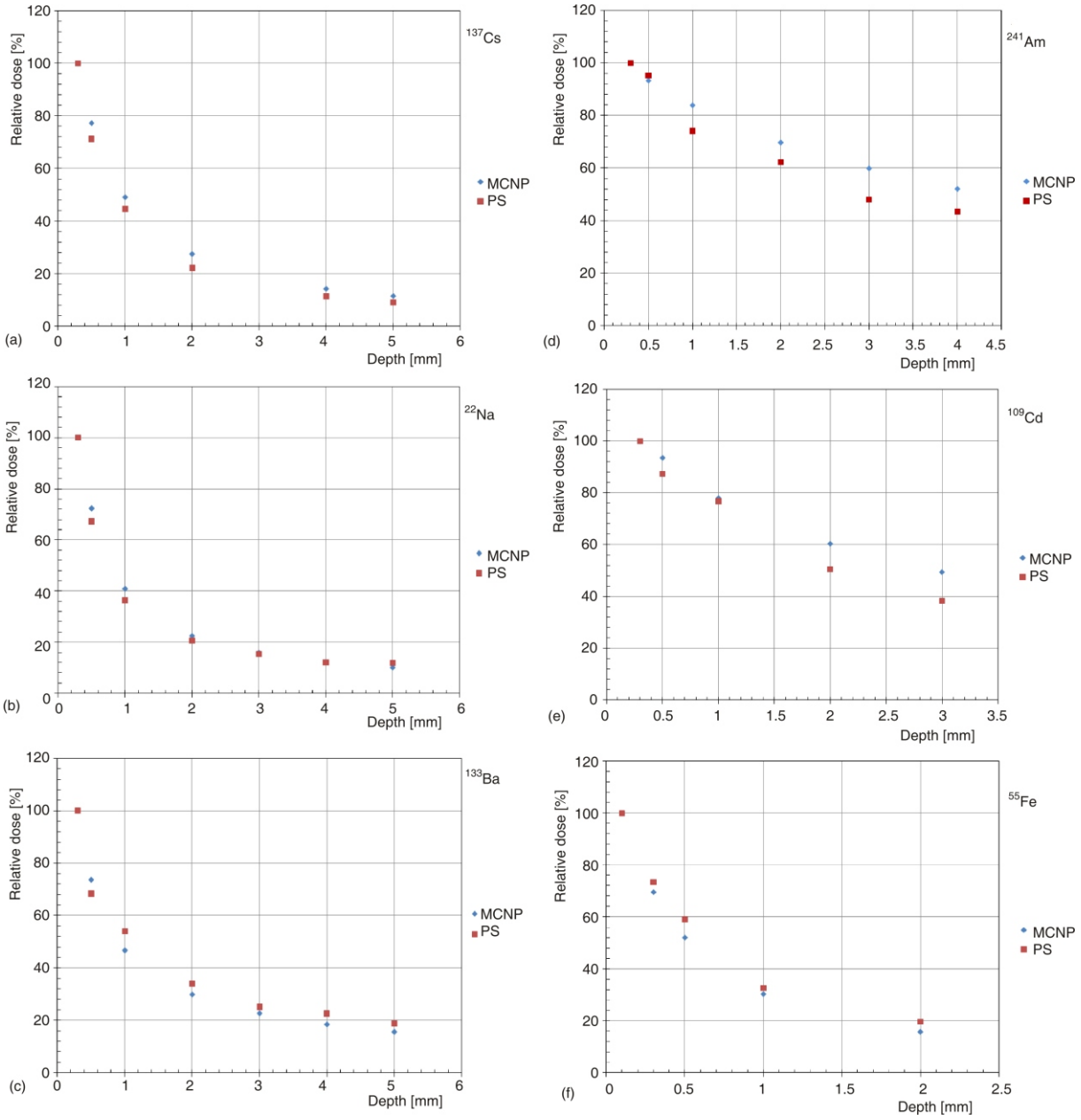

Figure 5. Measured and calculated depth dose distributions for ^{137}Cs (a), ^{22}Na (b), ^{133}Ba (c), ^{241}Am (d), ^{109}Cd (e), and ^{55}Fe (f) sources. distributions are normalized to the peak dose rates at the surface

CONCLUSION

The suitability of the PS system for relative depth-dose measurements was studied for photon and electron emitters. The measurements were made for depths ranging from 0.1 mm to 5 mm. The measurements were compared with the MCNP calculated dose. In general, the PS results prove its capability of measuring doses on a small scale and with high dose gradient. The MCNP dose results are comparable with the PS detector and can be used to estimate the dose rate values from mixed electron-photon fields. Improvement between the measurement and prediction may be possible given more precise information on the source window for each particular source.

Further studies should be directed to study the PS response to electrons and photons as well as to the energy response of PS to low photon energies. An intercomparison study with other measurement techniques may be necessary in order to confirm the predicted dose rates. A preliminary intercomparison study was made between the PS, EBT GafChromic dye films and MCNP for ^{241}Am source. The overall agreement between the relative dose estimates provided by the three techniques was within 10% [13].

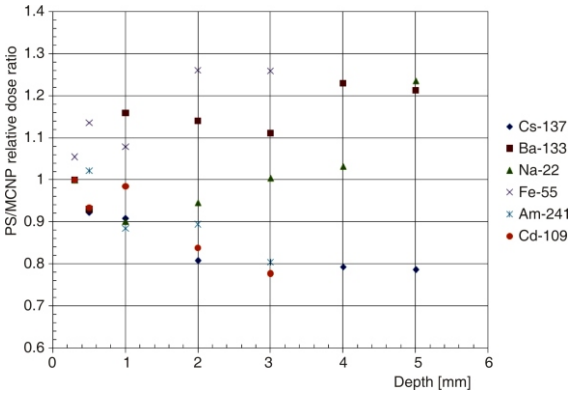

Figure 6. Ratios of measured to the predicted dose rates for ^{137}Cs, ^{22}Na, ^{133}Ba, ^{241}Am, ^{109}Cd, and ^{55}Fe sources

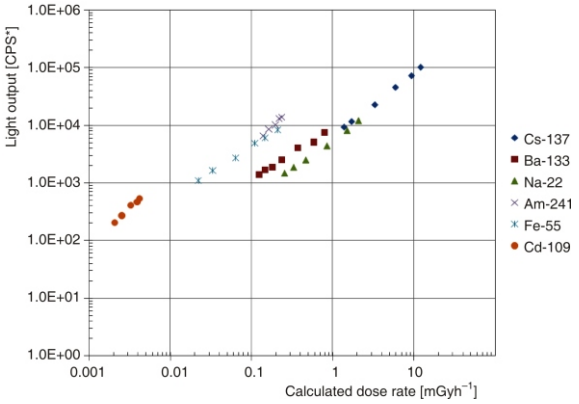

Figure 7. Calibration curves of the PS system for ^{137}Cs, ^{22}Na, ^{133}Ba, ^{241}Am, ^{109}Cd, and ^{55}Fe source
***CPS means count per second**

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КОРИШЋЕЊЕ ТАНКОГ ПЛАСТИЧНОГ СЦИНТИЛАТОРСКОГ ДОЗИМЕТРА ЗА ОДРЕЂИВАЊЕ ДОЗЕ ПО ДУБИНИ ОД МЕШОВИТОГ ЗРАЧЕЊА

Због својих повољнијих карактеристика у односу на друге дозиметријске технике, пластични сцинтилациони детектори користе се за одређивање расподела доза у пољима са великим градијентом дозе. У овом раду, танки пластични сцинтилациони детектор (тип БЦ-408) повезан је са фотомултипликаторском цеви и вишеканалним анализатором ради мерења дозе у реалном времену. Добро дефинисани бета, гама и бета-гама емитери (^{137}Cs, ^{133}Ba, ^{22}Na, ^{109}Cd, ^{55}Fe и ^{241}Am) омогућили су паралелна мерења дозе по дубини уз коришћење Монте-Карло прорачуна за поређење. Дозе су мерене на дубинама од 0.1 mm до 5 mm. Резултати MCNP кода били су упоредиви са мерењима сцинтилационог детектора и могу се користити за апроксимативну процену вредности јачина доза од мешовитих електронско фотонских поља. Минимална јачина дозе коју може мерити пластични сцинтилациони систем је око 2 mGy/h за ^{109}Cd извор активности 222 Bq.

Кључне речи: пластични сцинтилациони детектор, MCNP код, мешовито зрачење, доза