

## Investigation of Thin Plastic Scintillators for Real-Time Small Scale Dosimetry

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### Abstract

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<sup>(1-3)</sup>. In this study, the possible use thin plastic scintillators (10 $\mu$ m to 1mm, type BC-408) for real-time small scale dosimetry has been investigated and developed. The well-defined low energy sources (<sup>55</sup>Fe and <sup>241</sup>Am) have enabled parallel measurements with radio sensitive film and Monte-Carlo calculations to be critically compared. EBT GafChromic films have the advantage of producing a two-dimensional profile of the dose distribution as well as the depth dose distribution. The depth dose relationship was successfully confirmed using EBT GafChromic films and the MCNP code. The overall agreement between the relative dose estimates provided by the three techniques was within 10%. The relationship between the count rates obtained from the plastic scintillator system and the MCNP calculated absorbed dose rate was established, with a discrepancy of about 5%. The minimum dose rate that can be measured for <sup>55</sup>Fe source (10 $\mu$ Ci) using the plastic scintillator system is 20 $\mu$ Gy h<sup>-1</sup>.

**Keywords:** Plastic scintillator, GafChromic films, MCNP, low energy photons

## 1. Introduction

### 1.1 Dosimetric difficulties associated with low energy photons and betas

Although the introduction of a specific dose limit for localised exposures provided an operational solution to the radiological control of betas and low energy photons, the practical dosimetric difficulties in its applications remain<sup>(4)</sup>. These primarily arise from the strong attenuation of the beta and low energy photons 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<sup>(5)</sup>. 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 internal dosimetry does not take into account the non-homogeneous nature of low dose exposure to low energy radiations 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.

In this work, we employ a thin plastic scintillator (10 $\mu$ m to 1mm, type BC-408) coupled to a photomultiplier tube and multichannel analyzer as technique for real-time dose measurements around low energy photons. Depth dose measurements have also been conducted using EBT GafChromic films and MCNP4C for comparison purposes.

## 2. Materials and Methods

### 2.1 Description of the scintillation dosimeter

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 we are dealing with low photon energies and low activity sources ( $\sim 10 \mu\text{Ci}$ ). 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 system. The scintillator material used was the BC-408 plastic scintillator manufactured by Saint-Gobain Ltd. This type is claimed to be more efficient for low energy photons ( $<100 \text{ keV}$ ). The physical characteristics of BC-408 are listed in Table 1. Three different thicknesses of plastic scintillator were obtained, 10, 500 and 1000  $\mu\text{m}$ . The area where the source and scintillator is located was designed to obtain a better alignment with the PMT's 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 700 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).

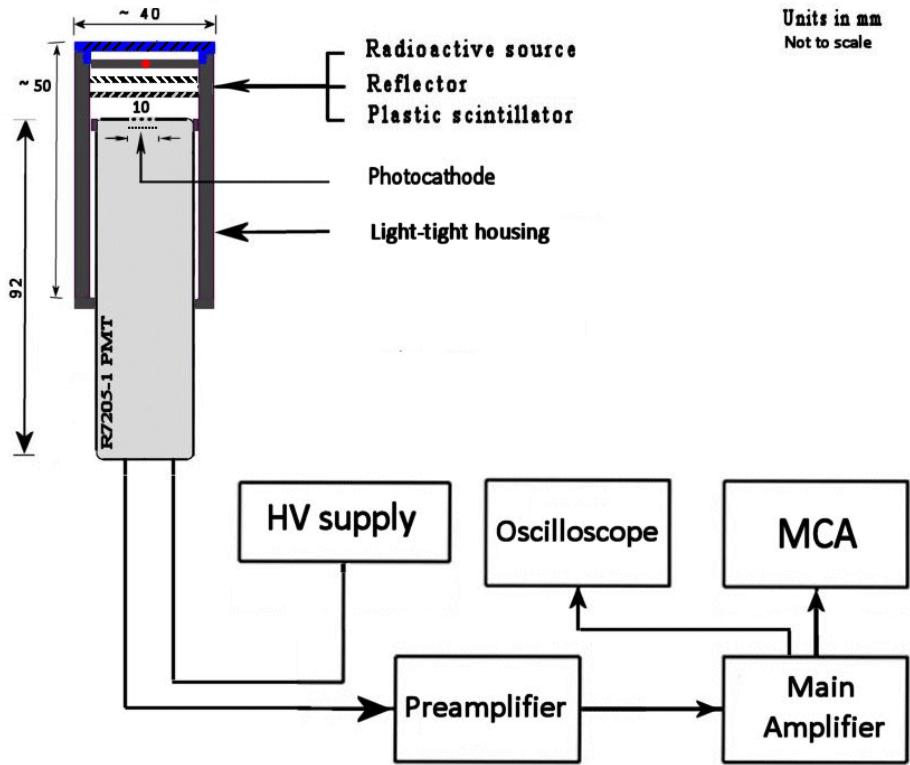


Figure 1: Schematic diagram of the plastic scintillation dosimetry system.

Table 1: Physics characteristics of the BC-408 plastic scintillator

Characteristics	Value
Light output (% anthracene)	64
Decay constant (ns)	2.1
Wavelength of maximum emission (nm)	425
Refractive Index	1.58
Density (g cm <sup>-3</sup> )	1.032
Ratio H:C Atoms	1.104
No. of electrons per cc	3.37 x 10 <sup>23</sup> (water: 3.34 x 10 <sup>-23</sup> )

## 2.2 Radiochromic dye film dosimeters

The GAFCHROMIC® EBT dosimetry film has been designed for the measurement of absorbed dose in the 1cGy to 800 cGy dose range. The response to photons has been found to be energy-independent in the MeV range and measurements at energies down to about 30 keV reveal that the sensitivity changes by less than 10%. The films develop a distinctive and characteristic blue color upon exposure to ionising radiation, which requires no processing to stabilise. By measuring the optical density of the exposed films using densitometers or spectrophotometers or flat-bed scanner, these films can be used directly for dosimetric measurements such as in radiation protection, dose distribution mapping, food irradiation, radiotherapy and radiography<sup>(6)</sup>. The characteristics that make these films widely used in many qualitative and quantitative applications are their relatively broad dose range, good reproducibility in a given batch, high spatial resolution over 1200 lines/mm and equivalent response to photons and electrons, and dose rate independence. The configuration of GAFCHROMIC® EBT film is shown in Figure 2. GAFCHROMIC® EBT is made by laminating two film coatings each having an active layer approximately 17 µm thick and a surface layer approximately 3 µm thick. The active layers are mounted from both sides on a 97 µm thick polyester base. The total mass thickness of one EBT film is approximately 31 mg cm<sup>-2</sup> <sup>(7)</sup>. The experimental set up for the depth-dose measurement using the EBT films is shown in Figure 3. The source was placed in contact with the stack. During the exposure all stacks were kept in the dark to further ensure avoidance of any possible spurious increase in optical density due to light exposure. Because of the low activity of the sources, the films have to be exposed for several days.

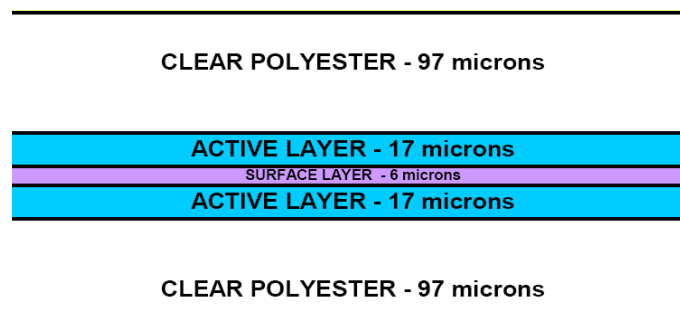


Figure 2: GafChromic™ dye film (type EBT) construction with manufacturers' specified dimensions<sup>(7)</sup>.

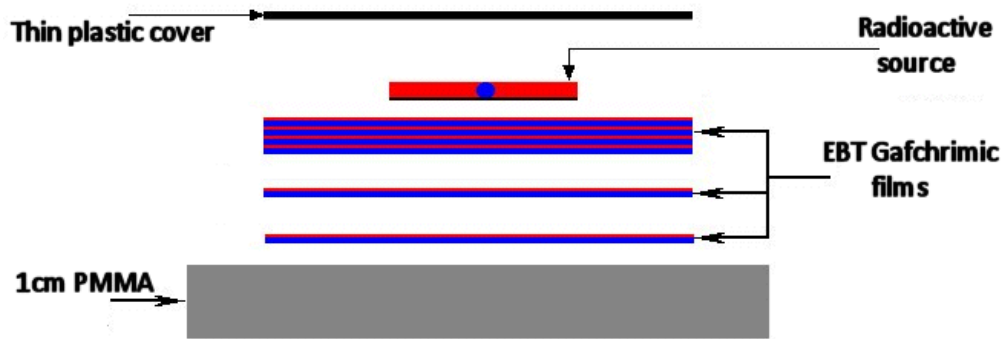


Figure 3: Schematic view of the experimental set up for the area and depth dose measurements using GafChromic EBT films.

### 2.3 Monte Carlo Simulation

The Monte Carlo Neutron Particle code (MCNP4C) was used to calculate the depth dose distribution as well as the area dose distribution for low energy photons, with the default mode being used in all the simulations<sup>(8)</sup>. The experimental setups for both scintillation dosimetry system (Figure 1) and GafChromic EBT dosimetry system (Figure 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 tracked was generally sufficient to determine the energy deposition in all cells to within a few percent. The dose calculation was performed for <sup>55</sup>Fe and <sup>241</sup>Am sources. Details of these two sources are shown in Table 2 and Table 3. Details about the source geometry and source materials were obtained directly from the manufacturer (Spectrum Techniques).

Table 2: <sup>55</sup>Fe source information used in the Monte Carlo calculation

<b>Source</b>	<sup>55</sup> Fe
<b>Radiation type</b>	Gamma
<b>Energy (keV)</b>	5.9
<b>Intensity</b>	0.163
<b>Half life(y)</b>	2.7 (June 2007)
<b>Activity</b>	10 $\mu$ Ci
<b>Source material</b>	The source is a ferric chloride (FeCl <sub>3</sub> )
<b>Source dimension</b>	Source deposited in the center of the disc in an area of about 4 mm and thickness of 0.127 mm.
<b>Disc material</b>	Vinyl
<b>Source window</b>	Aluminized Mylar with a density of 80 $\mu$ g cm <sup>-2</sup> .

**Table 3:  $^{241}\text{Am}$  source information used in the Monte Carlo calculation**

<b>Source</b>	$^{241}\text{Am}$
<b>Radiation type</b>	Gamma
<b>Energy (keV)</b>	59.9
<b>Intensity</b>	0.359
<b>Half life(y)</b>	432 (11/01/2007)
<b>Activity</b>	10.15 $\mu\text{Ci}$
<b>Source material</b>	Americium
<b>Source dimension</b>	Source deposited in the centre of the disc of (25.3 radius X 3.15) mm
<b>Disc material</b>	Polyethylene
<b>Source window</b>	None

### 3. Results and Discussion

#### 3.1 Reproducibility check

Before any measurement was taken, the long-term stability and reproducibility of the scintillation dosimetry system was investigated over a period of time and at different experimental settings. Since measurements require changing the source and the PS, it is necessary to assure that the radioactive source and the PS are in a good alignment with the PMT's window. Under good alignment settings, the coefficient of variation for a series of repeated measurements was less than 5%. The reproducibility was improved when the aluminum light-tight housing was made and a proper source mount was designed, which led to better alignment for both the source and the scintillator with the PMT's window. It is highly recommended to have optical grease between the PMT glass's window and the plastic scintillator. Poor contact might reduce the overall light measured.

#### 3.2 Background measurements

Any signal is produced other than the signal produced in the plastic scintillator is considered to be a noise or a background signal. A good detection system should exhibit a high signal to noise ratio (S/N). In our scintillation system, there are two sources of background that have to be taken into account: PMT dark current (will be referred to as BG), and scintillation-induced PMT currents (will be referred to as SI-PMT). The dark current is always there and it depends on the characteristic of the PMT and the high voltage applied to it. The SI-PMT background is the dominating background source and is generated in the presence of a radioactive source but no plastic scintillator. This light may be reduced if a collimator is used, and thus avoiding radiation reaching the whole PMT. For each source used in this study, two sets of measurements were conducted to measure the BG and SI-PMT backgrounds. Figure 4 shows two pulse height spectra for the two mentioned backgrounds and one for an  $^{55}\text{Fe}$  source taken with a 10  $\mu\text{m}$  plastic scintillator. As it can be seen, the magnitude of the BG spectrum is negligible compare to the

other two spectra. The PMT high voltage and the gain were optimized in away the S/N ratio obtained is as high as possible. In all subsequent measurements, the noise band counts were excluded.

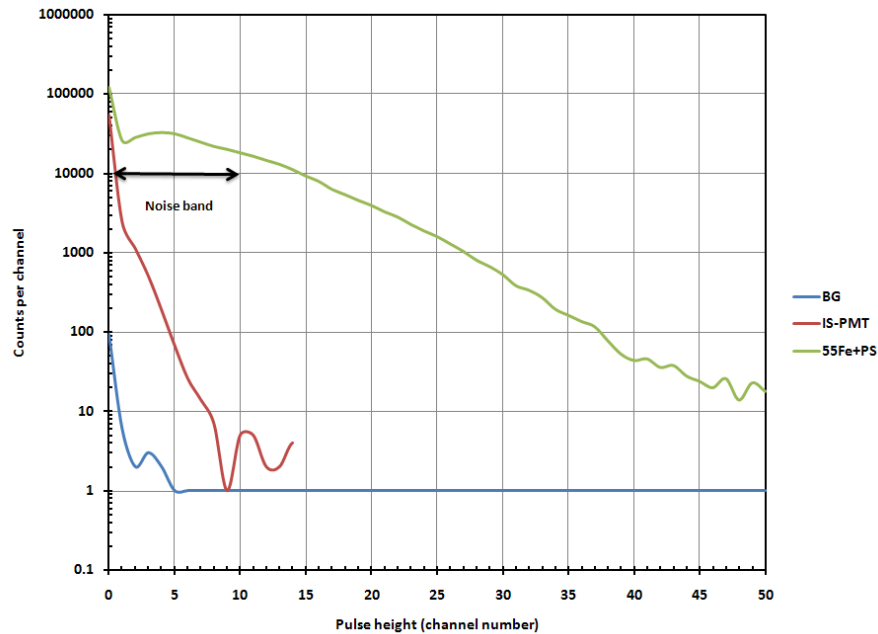


Figure 4: Measured pulse height spectrum of  $^{55}\text{Fe}$  source only (IS-PMT) and of  $^{55}\text{Fe}$  coupled to the 10  $\mu\text{m}$  BC-408 plastic scintillator, the counting time is 300 sec.

### 3.3 Depth dose distribution measurements and calculations

The dose distribution measurements for  $^{55}\text{Fe}$  and  $^{241}\text{Am}$  sources, over various areas and several depths, were carried out using the GafChromic EBT dosimetry technique. Doses were measured at depths of 15.5, 46.5, 77.5, 108.5, 139.5 and 170.5  $\text{mg cm}^{-2}$ . In order to adequately define the dose profile at increasing radial distance, the films were exposed for six days. This was just sufficient to get some reasonable results for the first four depths. For deeper depths and for large radial distances, longer times would be required. In order to allow the films to stabilize, all films were read-out 48 hours post irradiation. The readout of the irradiated GafChromic EBT films was performed using a Canon flatbed scanner (Model 8800F). Figure 5 shows the false color optical density map for the surface film (15.5  $\text{mg cm}^{-2}$ ) and produced by the  $^{241}\text{Am}$  source. The image is generated by the red color and displayed using the radial dose distribution software (RADODS)<sup>(9)</sup>. The scale of the image was calculated using the resolution at which the scanned film was taken. Figure 6 shows the area averaged relative dose distributions for  $^{241}\text{Am}$  source at different depths. The area-averaged optical density starts to fall off at radius of 0.5 mm for the shallow depth and at radius of 1.5 mm for deep depths. The steepness of the radial variation is a strong function of depth and particle size.

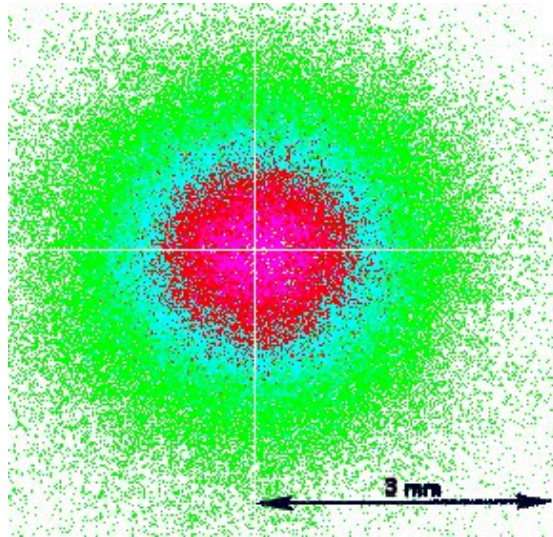


Figure 5: False colour optical density map for  $^{241}\text{Am}$ , generated by red colour image and displayed using RADODS software.

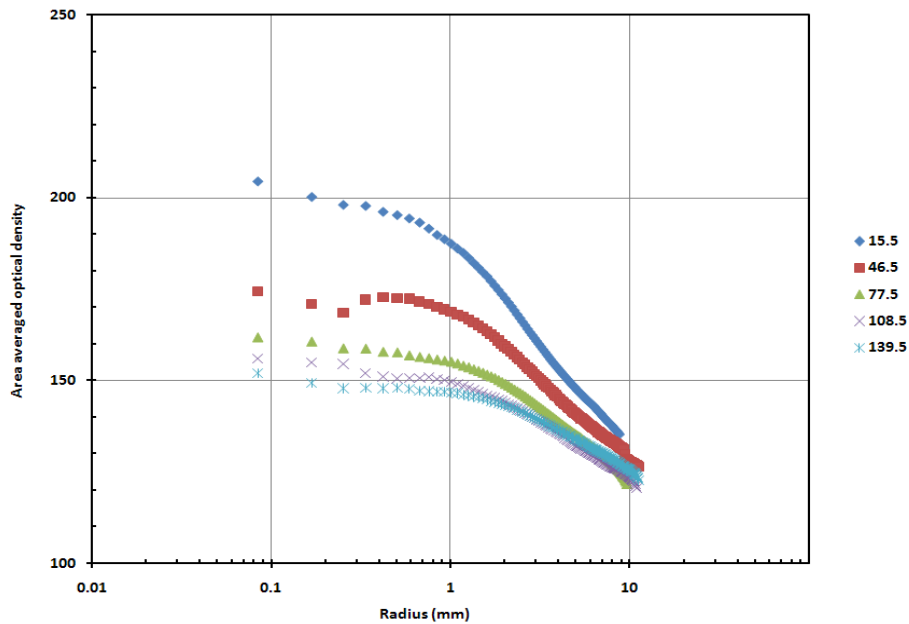


Figure 6: Area-averaged optical density for  $^{241}\text{Am}$  source at various depths using EBT Gafchromic films, readout using Canon 8800F flatbed scanner (number in the legend gives depths in  $\text{mg cm}^{-2}$ )

The relative accumulated dose obtained for  $^{241}\text{Am}$  source and measured using EBT Gafchromic films and plastic scintillators is shown in Figure 7. With plastic scintillator system, the accumulated dose starts to increase linearly with depth up to about 1 mm, then starts to saturate at about 3 mm. The EBT GafChromic films' results show very good agreement for depths between 0.217mm to ~ 1mm. The depth of 0.217 mm is the minimum depth that can be obtained

for EBT GafChromic films. In order to obtain measurements at depth above 1mm for such low activity source, longer exposure time is required, possibly weeks. Similar comparison was made for  $^{55}\text{Fe}$  source using plastic scintillator system and MCNP code, and presented in Figure 8. From 10 to 100  $\mu\text{m}$  depth range, both techniques show very good agreement with overall relative error less than 10%. This depth range is adequate to show that the MCNP result can efficiently be used to evaluate the dose rate for plastic scintillator system, and it follows similar kind of pattern in terms of dose gradient.

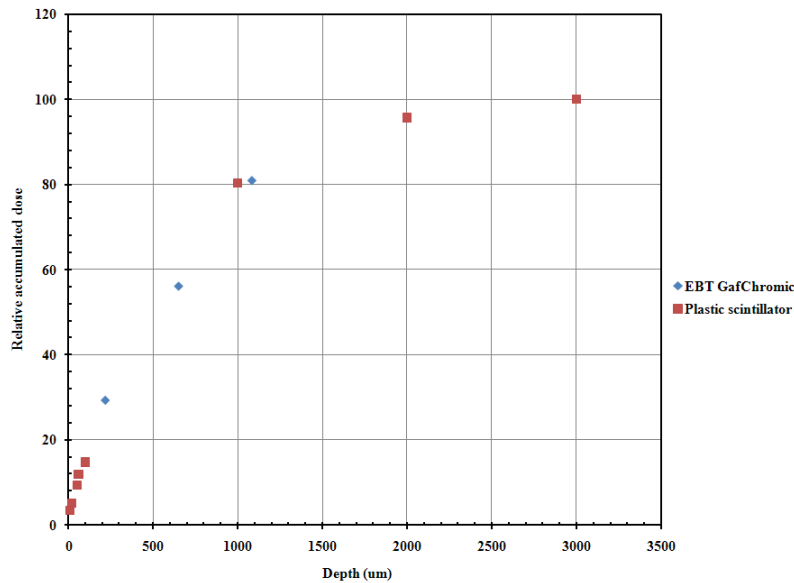


Figure 7: Relative accumulated dose for  $^{241}\text{Am}$  source measured using EBT GafChromic films and plastic scintillators.

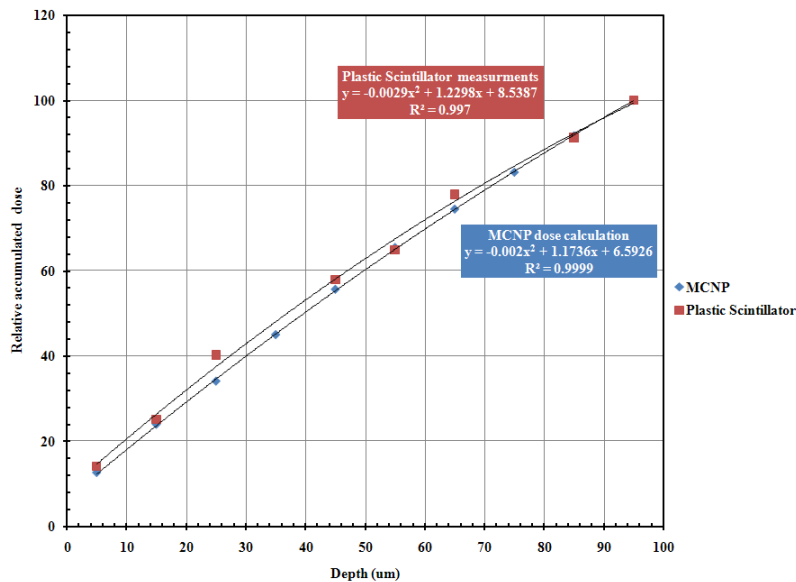


Figure 8: Relative accumulated dose for  $^{55}\text{Fe}$  source measured using Plastic scintillator system and MCNP code.

Based on the information of the  $^{55}\text{Fe}$  and  $^{241}\text{Am}$  sources provided in Table 2 and Table 3, the energy deposited (MeV/particle dis.) in each detector (cell) was calculated and converted into  $\text{Gy h}^{-1}$  using the calculated mass of each detector, the source activities and a decay correction factors, if necessary. Figure 9 presents three dimensional surface dose distribution for  $^{241}\text{Am}$  source, calculated using MCNP. It is clearly seen the large variation in dose as one moves out radially from the centre, which introduce some complications in dose measurements as well as in radiological control of such low energy sources. The dose rate estimated for  $^{55}\text{Fe}$  over  $1\text{ cm}^2$  fall down from  $19.4\text{ }\mu\text{Gy h}^{-1}$  at  $5\text{ }\mu\text{m}$  to about  $9\text{ }\mu\text{Gy h}^{-1}$  at  $200\text{ }\mu\text{m}$ .

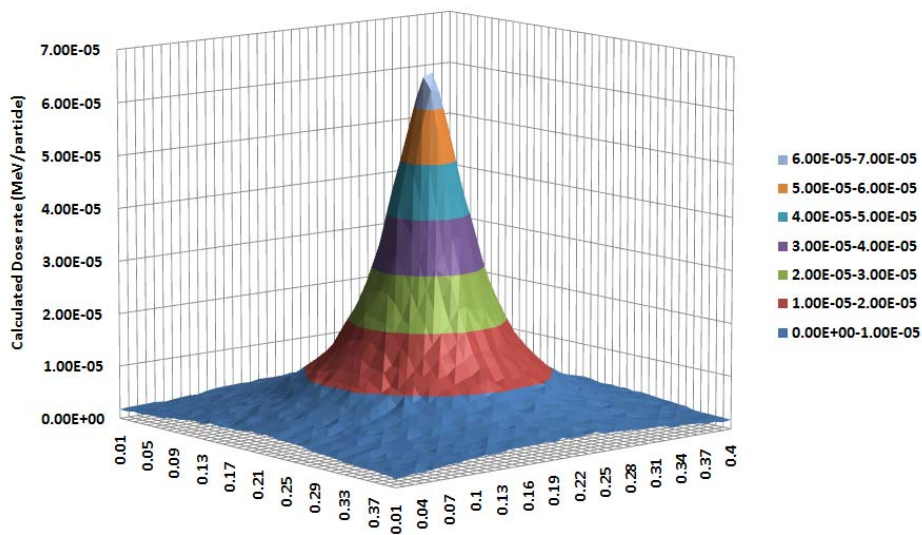


Figure 9: Three-dimensional dose distribution for  $^{241}\text{Am}$  source at depth of  $5\text{ }\mu\text{m}$ , calculated using MCNP.

### 3.4 Dose response relationship

By combining the previous measurements and calculations, a relationship between the integrated counts, optical density and the absorbed dose were established for both  $^{55}\text{Fe}$  and  $^{241}\text{Am}$  sources. The photon emissions in the plastic scintillator indicate the absorbed dose in the scintillator material. The optical density value is proportional to the energy deposited in the EBT GafChromic films. The dose linearity of the scintillation detector output was investigated by comparing the signal from the plastic scintillation system to that obtained from MCNP calculated dose rate. Figure 10 presents a comparison between the count rates measured by the plastic scintillator system and the dose rate calculated using MCNP code for  $^{55}\text{Fe}$  source. The calibration curve produced shows good linearity between the two systems. A similar curve is produced for the  $^{241}\text{Am}$  source. The count rate produced for each source would represent the energy deposited in the plastic scintillator, regardless of the plastic thicknesses. Each calibration curve is specific to each source. Further investigation is required to study the energy dependence

on the dose rate measured in the plastic scintillator. Measurements could also be done using calibrated EBT GafChromic films to confirm the MCNP dose rate calculations.

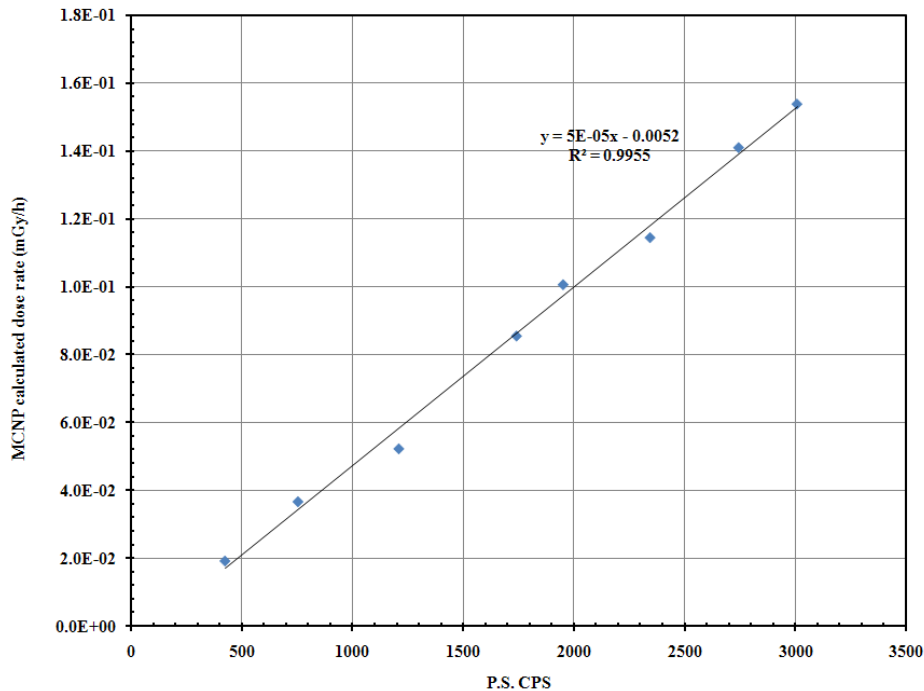


Figure 10: Calibration curve of the plastic scintillation system, for  $^{55}\text{Fe}$  source and using a stack of 100  $\mu\text{m}$  BC-408 plastic scintillators.

## 4. Conclusion

We have developed a real time dosimetry system using thin plastic scintillators coupled to a photomultiplier tube. The focus in this study was for  $^{55}\text{Fe}$  and  $^{241}\text{Am}$  gamma sources. The depth dose relationship was successfully confirmed using EBT GafChromic films and the Monte-Carlo MCNP code. The MCNP depth dose calculations were in good agreement with that obtained with the plastic scintillator, with a discrepancy of less than 10%. The EBT GafChromic films have the advantages of providing two-dimensional profiles of the dose distribution as well as the depth dose distribution. However, the low activity of the sources and relatively low sensitivity of the films compared to the plastic scintillator system make it difficult to measure doses at depths beyond a few millimeters. According to the MCNP dose calculations, the minimum dose rate that can be measured for  $^{55}\text{Fe}$  source (10 $\mu\text{Ci}$ ) using the plastic scintillator system is 20 $\mu\text{Gy h}^{-1}$ . Further investigation is required to work out the range of dose rate that can be measured using the plastic scintillator system. The issue of S/N ratio has been dramatically improved by eliminating the noise band from the actual counts.

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