An Experimental Study of the Relative Response of Plastic Scintillators to Photons and Beta Particles

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Abstract

A scintillation counting system has been constructed with the use of BC-400 and EJ-212 series plastic scintillators along with a subminiature photomultiplier tube to investigate the effect of increasing plastic scintillator thickness on system integrated counts. Measurements have been carried out using four different gamma sources with different energies ranging from 6keV to 1.332MeV and a Ni-63 beta source of maximum energy of 66keV. A simulation was also carried out in MCNP4a to verify the number of H-3 beta particles with max energy 18.6keV that would reach the plastic scintillator in a vacuum setting as well as in an air medium. Scintillator thicknesses ranged from 10μm to 2500μm. The response of the system was determined by measuring the integrated counts as a function of scintillator thickness. The results of these measurements showed a positive linear correlation between scintillator thicknesses and integrated counts for all the gamma sources while the slopes of the correlations of each gamma source was a function of the source energy. The beta particle response showed an initial increase of counts with scintillator thickness followed by a slight decrease. The MCNP simulation confirmed an analytical calculation of the fraction of H-3 beta particles for a given air concentration that would reach the scintillator. These results in conjunction with the experimental findings will be used to assess the potential of a plastic scintillator system forming the basis of a tritium monitor for the detection of tritium in high energy gamma backgrounds for Canadian nuclear power workers.

Keywords: Plastic scintillator, Tritium, MCNP, gamma photons, beta particles

1. Introduction

Mixed field Dosimetry incorporating low energy beta particle together with high energy gamma radiation has been a challenge in the past continues to be the subject of current investigations. Tritium in particular presents a hazard in nuclear power plants as it is emits low level beta radiation with an average energy of the beta particles being approximately 5.6keV.[1] The beta particles emitted from tritium have a maximum energy of 18.6keV which is considered to be low energy. Although these beta particles cannot penetrate the outer layer of human skin, internal exposure can occur through inhalation and absorption through the skin and can contribute as much as 30% to the occupational exposure of Canadian nuclear energy workers.[2] This exposure is high enough to warrant the development of personal detection methods to monitor and control exposures in high energy gamma backgrounds such as nuclear power plants.

The purpose of this research project is to study the relative response of plastic scintillators to photons and beta particles in order to determine the feasibility of building a tritium monitor that can operate in a high energy gamma background. For this research four gamma sources were used, Iron-55(Fe-55), Americium-241(Am-241), Cesium-137(Cs-137) and Cobalt-60(Co-60). The beta source used for physical experimentation was Nickel-63(Ni-63) while a computer simulation was also created to test the range of tritium particle in air and vacuum settings using the Monte Carlo N-Particle (MCNP) code, version 4A.

2. Materials and Methods

2.1 Experimental Setup

The plastic scintillators chosen for the experiments were the BC-400 series from Saint Gobain Crystals and EJ-212 series from Eljen Technologies. The scintillators absorb the incoming radiation energy emitted from the source and reemit it in the form of light which is then picked up by a photomultiplier tube (PMT). The PMT multiplies the current produced by the light via multiple dynode stages to enable photons to be electronically detected. Both the EJ-212 and the BC-400 series plastic scintillators are used for general purpose type scintillation detection and are sensitive to both gamma photons and beta particles.

The experimental setup consisted of the Hammatsu R7400U miniature PM, chosen due to its vertical mount and easy placement of plastic scintillators directly into the well of the PMT. The PMT featured a 16mm diameter entrance window with a 12mm seated length and the E5780 base connector with three connecting wires. One of these wires was used as a ground, another for the high voltage supply and the third for the outgoing signal which was connected to a preamplifier. A cylindrical aluminum holder was also constructed for proper alignment of the PMT, scintillator and source. To minimize scattering, optical grease was applied onto the well of the PMT and the scintillators. The EJ-550 optical grease was purchased from Eljen Technologies was effective in enhancing the results obtained for each trial.

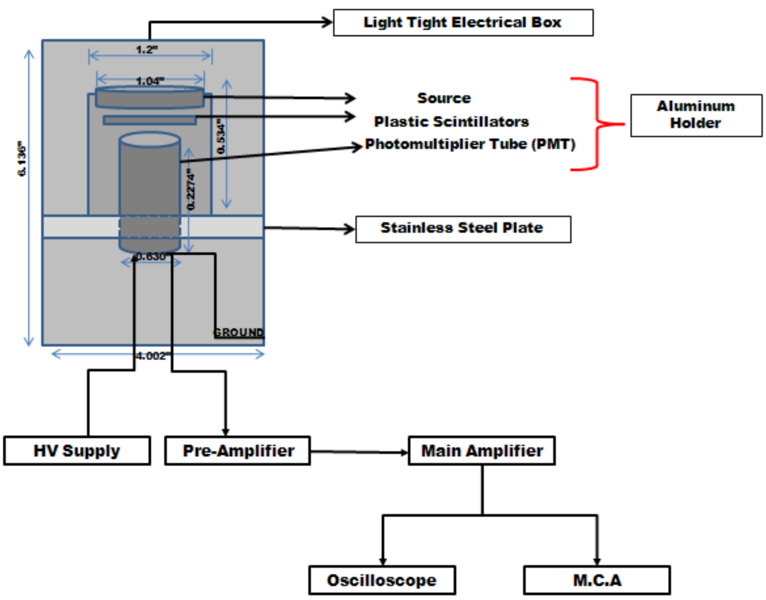

Figure 1: Schematic of detector set up with connections to signal processing electronics

Gamma photon interaction with matter depends on the energy and atomic number of the absorber and results in attenuation while beta particles are essentially electrons which lose energy based on the distance travelled. Considering the range of beta particles and the attenuation of gamma photons, an optimal scintillator thickness is required which limits attenuation for high energy gamma photons yet is thick enough to register beta particles emitted from a specific source. Based on these principles it was hypothesized that the optimal scintillator thickness would need to be thin enough to still register counts from beta particles while being insensitive to most gamma photons.

2.2 Description of Simulation Setup

MCNP 4a was used to simulate the number of tritium beta particles that would interact with the scintillator over a 5 minute period. This was done by building a simple setup which tallied the number of beta particles reaching the PMT. The source was defined as a volumetric source surrounding the PMT inside a given volume. The number of H-3 beta particles detected would then be compared to the number of high energy gamma photons recorded in an identical 5 minute period.

The MCNP4A simulations were compared to the calculated theoretical maximum range of H-3 beta particles which was found through equation 3 given below.

$R\left(\frac{mg}{cm^2}\right) = 412E^{1.265-0.0954 lnE}$ [3] where $0.01 \leq E \leq 2.5MeV$.. (1)

Assuming the density of air to be 1.2041kg/m^3

$$R = \frac{5.86x10^{-4}g}{cm^2} * \frac{1cm^3}{1.2041x10^{-3}g} = 0.486cm * \frac{10mm}{cm} = 4.86mm$$

Using the above formula, the maximum range of a tritium beta particle is calculated to be approximately 5mm in air. This range is used as the height to obtain the volume of air in which H-3 beta particles are able to reach the PMT and was found to be approximately 550mm^3 given the radius of 6mm which resembles the diameter of the scintillation disks. The final step was to determine the number of counts over a 5 minute period which was calculated to be 49.5counts for a concentration of 1 DAC (300kBq/m^3)[4].

This expected number of counts represents a situation where all the H-3 beta particles travel towards the PMT. A realistic assumption would include dividing the counts in half to account for the fact that the beta particles are emitted isotropically and on average only a half of the emitted betas will be travelling towards the PMT. The resulting counts would thus yield approximately 24.7counts over a 5 minute period. In order to confirm these results, an MCNP simulation was needed which would measure the number of H-3 beta particles that would reach the scintillator in an air medium. The MCNP simulation is shown in Figure 2.

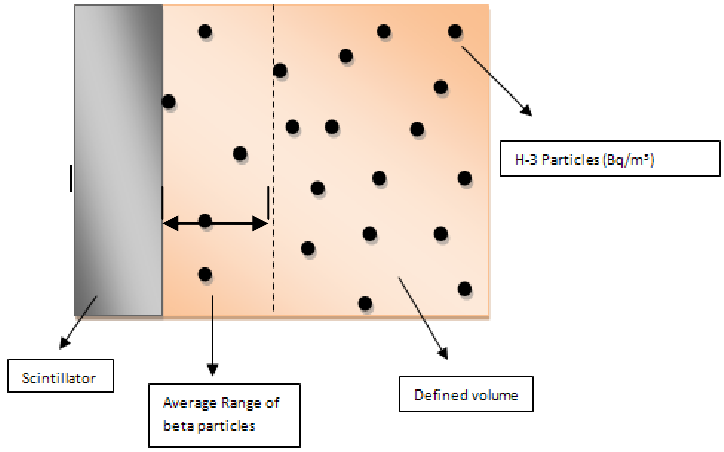

Figure 2: MCNP setup for the determining the number of H-3 beta particles reaching the detector for a given tritium concentration

3. Results and Discussion

3.1 Gamma Sources

The results with the gamma sources were in agreement with the hypothesis and are illustrated in Figure 3. The measurements were repeated for each thickness yielding an uncertainty of 2.6% on each trial.

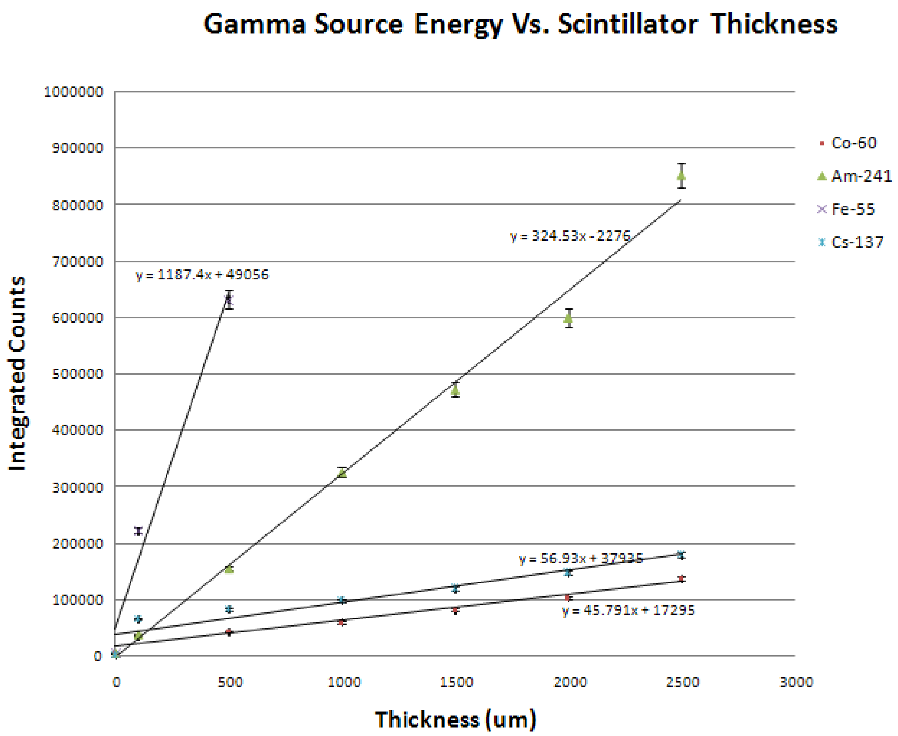

Figure 3: Shows a linear increasing trend with the lowest energy gamma source (Fe-55) having the steepest slope and the highest energy gamma source (Co-60) having the smallest slope.

Figure 3 illustrates an increasing linear correlation as scintillator thickness increases. The integrated counts on the y-axis indicate the number of counts registered by the detector which is the number of photons emitted from each source that interact with the polymer matrix of the scintillators. Since Co-60 has the highest energy it also has the lowest attenuation coefficient ($0.0794cm^{-1}$) and therefore most of the photons emitted from Co-60 pass through the scintillator undetected. Cs-137 has the second highest energy which corresponds to the second lowest attenuation coefficient ($0.1082cm^{-1}$) among the four isotopes tested thus explaining its slope being comparable with Co-60. Am-241 has an even greater slope than either Co-60 or Cs-137 which coincides with it having the second highest attenuation coefficient ($0.255cm^{-1}$) while Fe-55 has the steepest slope due to its attenuation coefficient being higher still ($23.0251cm^{-1}$).

3.2 Beta Source

The beta source used for the experiment was a Ni-63 sealed source having a maximum energy of 65.87keV. The max range for this source was found to be 63.45µm calculated using equation 1. Based on this range, the expected result was to observe a rapid rise in the slope of the counts up to 64µm followed by a plateau at a constant level. At this thickness all the beta particle energy from the source would be converted into scintillation light and registered by the PMT and sufficient to induce a pulse measureable by the multichannel analyzer. Following an initial rise in counts where most of the beta particles are detected, there would not be expected a significant increase or decrease in the integrated counts as none of the beta particles being emitted by the source have an energy or range greater than 65.87keV or 63.45µm respectively. The results are shown in Figure 4.

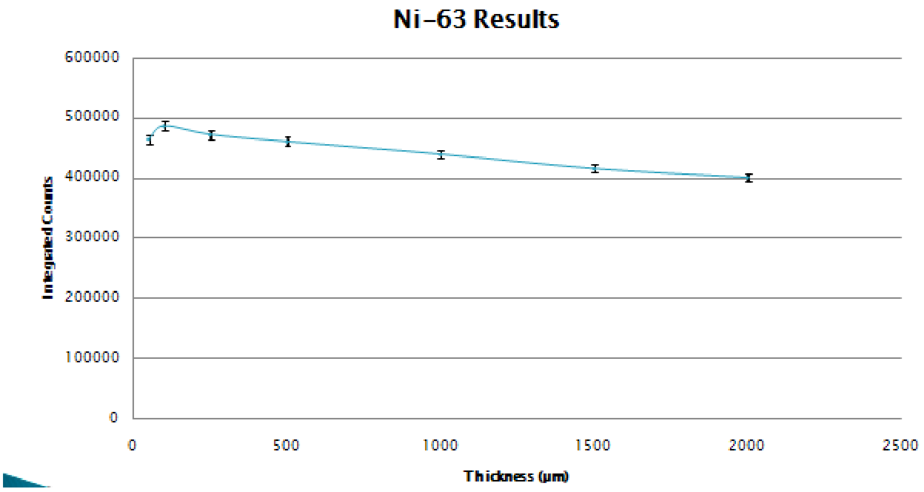

Figure 4: Ni-63 Results for Integrated Counts Vs Increasing Scintillator thickness showing an initial increase in counts up to 50µm followed by a gradual decrease as scintillator thickness increases.

Figure 4 shows an increase in Ni-63 counts up to a thickness of 50µm followed by a constant gradual decrease in the number of counts. Any extra material that is added beyond the maximum range for Ni-63 beta particles acts as an obstruction material limiting the number of light photons reaching the photocathode of the PMT. This explains the gradual decrease in the number of counts as the scintillation thickness increases.

Once a complete set is recorded for Co-60 and Ni-63 through each scintillator thickness an optimal scintillator thickness can be established. Upon analysis, the initial hypothesis of a thin scintillator thickness being optimal was found to be incorrect. This was due to Co-60 counts being distributed over the range of pulse heights as the thickness of the scintillators increased. The distribution in the pulse height spectrum changes as the scintillator thickness changes. To find the optimal scintillator thickness, Co-60 counts were compared to Ni-63 for each scintillator thickness, to find the highest ratio between the counts of the two sources.

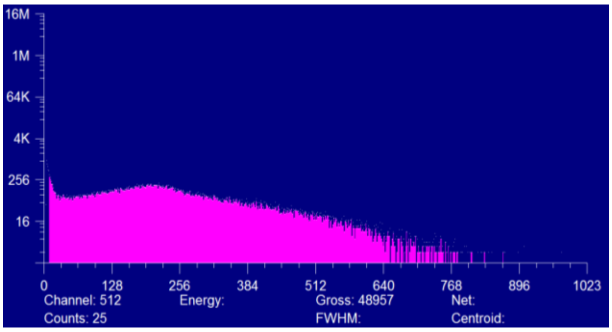

Figure 5: Co-60 spectrum at 500μm scintillator thickness

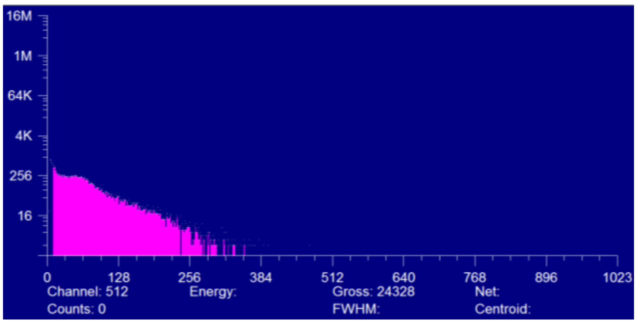

Figure 6: Co-60 at 100μm scintillator thickness

Figure 5 and 6 allow for comparisons between two trials measured for Co-60 at 100μm scintillator thickness and 500μm scintillator thickness. These two trials show how the pulse height spectrum shifts as the thickness of scintillator increases. Co-60 emits photons of energies at 1.332MeV and 1.172MeV, which mainly interacts through Compton scattering. Depending on the thickness of the scintillator, the incoming photons will either generate a single Compton electron with average energy and a range that is greater than the scintillator thickness or will create multiple Compton electrons through more than one scatting interaction. In either case, it is expected that more electron energy would be deposited in the scintillator from a single photon interaction with increasing scintillator thickness. This increase in deposited electron energy per interacting photon will produce pulses of greater height and so the pulse height spectrum is observed to extend to higher channel numbers with increasing scintillator thickness. These shifts in the pulse height spectrum pose a problem in determining optimal scintillator thickness due to the fact that beta emitters result in a constant spread over the spectrum channels.

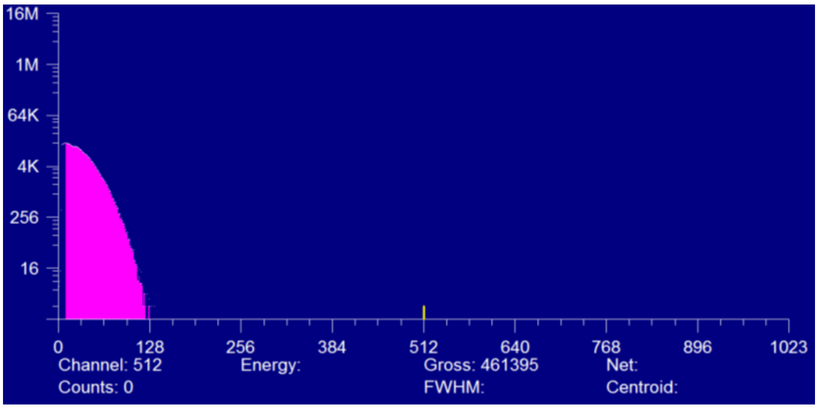

Figure 7: Ni-63 at 500µm scintillator thickness ends at channel 128

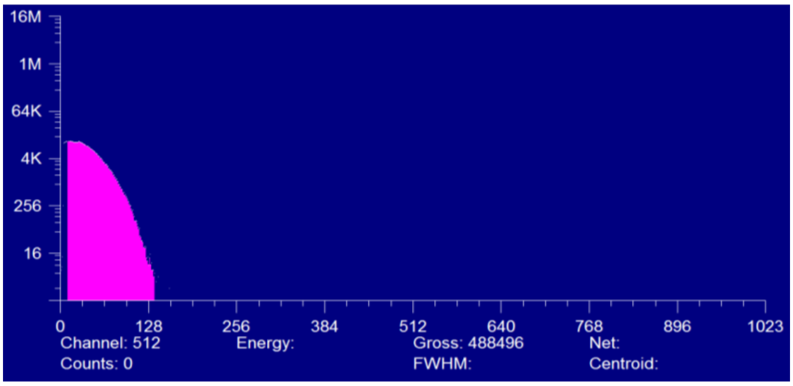

Figure 8: Ni-63 at 100µm scintillator thickness ends at channel 135

Figure 7 and 8 shows the distribution of pulse heights for Ni-63 trials illustrating that there is no significant shift in the pulse heights as the scintillator thickness increases. Taking into account the spectrum shift for high energy gamma photons (Co-60), as well as the consistent channel spread for beta particle emissions from Ni-63, an overlapping of the channels was utilized as a method for obtaining the optimal scintillator thickness. Each scintillator thickness for both sources over the same channel intervals was analyzed by calculating and obtaining a ratio of Ni-63counts to Co-60 counts. The ratio yields the difference for each scintillator thickness between beta particles and high energy photons that result from a given exposure to both sources.

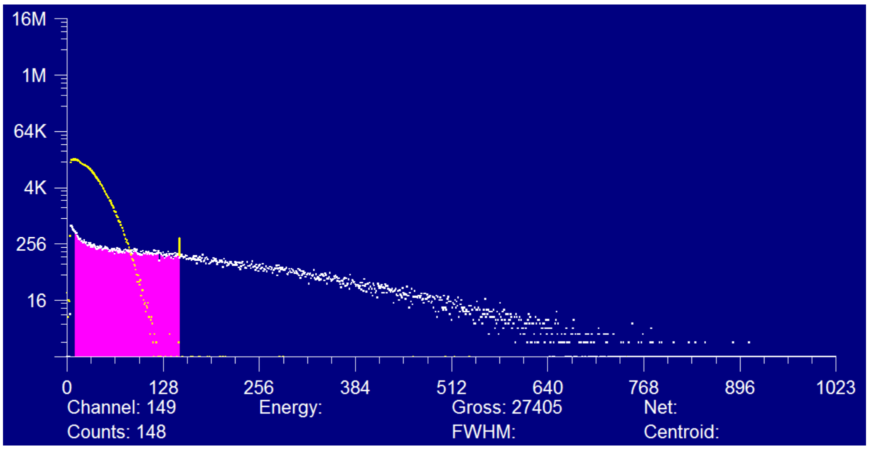

Figure 9: Overlap of Co-60 and Ni-63 counts

Figure 9, shows an overlap of Ni-63 counts over Co-60 counts at a scintillator thickness of 1000µm. The white-dot scatter plot on the figure indicates the pulses from a Co-60 source, while the yellow-dot scatter plot indicates those from the Ni-63 source. The shaded pink region shows the region of interest which extends from channel 11 to channel 149 where counts from both sources are observed. This methodology was used for each scintillator thickness with the results presented in Table 1 and Figure 10.

Thickness(µm)	**Co-60**	**Ni-63**
50	22975	465529
100	21976	488332
250	19157	474018
500	18494	461387
1000	25351	440289
1500	24213	417840
2000	23574	403716

Table1: Co-60 and Ni-63 count comparison

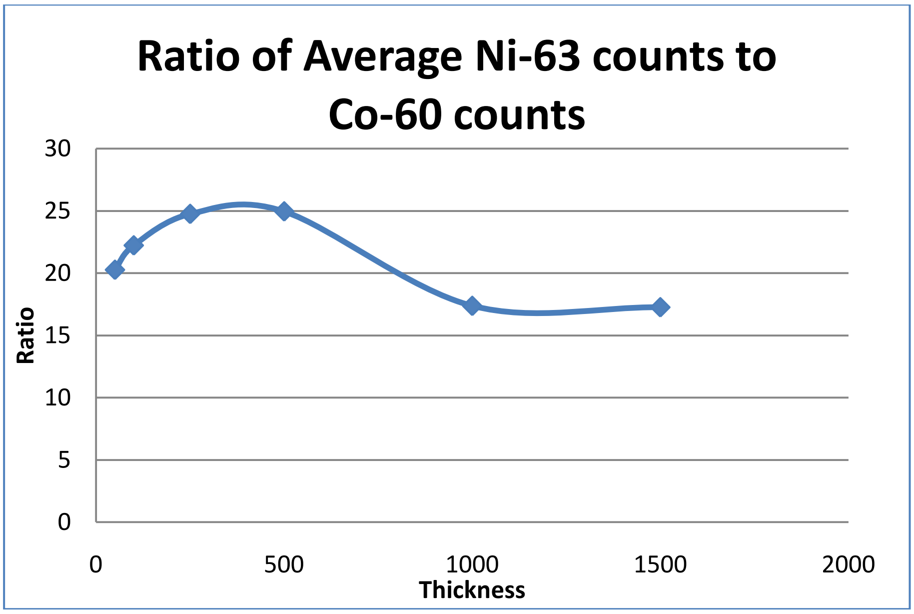

Figure 10: Ratio of Average Ni-63 counts to Co-60 counts

From Figure 10, a ratio of 25 corresponds to two scintillation thicknesses at 250µm and 500µm. The thinner 250µm scintillator is chosen as the optimal thickness since it may be better suited to the experiment as it would provide an increased insensitivity to gamma photons in comparison to the 500µm scintillator thickness and therefore an overall reduction in count rate.

Once this optimal thickness was established, the exposure rate for the Co-60 source over a 5 minute time period was required. This was done using equations 2 and 3 below as well as values for the mass stopping power for plastic scintillators and air from the ICRU Report 44. The activity of the Co-60 source was estimated from the activity at the time of purchase to be $1.75x10^{-3}MBq$.

Exposure at 1m: $\frac{9.19x10^{-19}X}{MBq} * Activity\ of\ Source$ -- (2)
Using the activity of the source, equation 2 and the inverse square, the exposure rate at a distance of $5x10^{-3}m$ was calculated as $\frac{6.433x10^{-6}X}{hr}$.

$X_{plastic} = X_{air} * (\frac{W}{e})_{air} * (\frac{\mu_{en}}{\rho})_{air}^{plastic}$ …………………………………………………………………… (3)

Finally equation 3 and the above calculated values were used to estimate the dose rate as $\frac{2.37x10^{2}\mu Gy}{hr}$

Therefore 19,157 counts over a 5 minute period was found to be equivalent to 237μGy/hr

3.3 Tritium (MCNP4a) Results

The MCNP4a results were in agreement with the calculated results. Two scenarios were attempted in MCNP4a which featured a vacuum and air medium respectively with particles in both scenarios being emitted isotropically. The tally for the vacuum scenario yielded a surface tally of 0.15893, the ratio of the number of beta particles that crossed the PMT surface to the total number of beta particles emitted. In order to obtain the number of counts over a 5 minute period, the ratio obtained from the MCNP run is now used. A volumetric H-3 beta source was simulated with a diameter of 21mm. The photocathode diameter of the PMT was 16mm and an extra 5mm was added in order to ensure the source was a bit larger than the PMT diameter allows for beta particles to reach the PMT from a solid angle of 2π. Using this radius, the volume of the source was found and multiplied by the surface tally and the DAC for tritium to calculate an activity of 50.5 counts over a 5 minute period for 100,000 histories in a vacuum scenario.

The second simulation run for beta particles in a medium of air resulted in the tally through the plastic scintillator to be 0.06728. Using this ratio, the previously calculated volume and the DAC, the activity over a 5 minute period was calculated to yield 21.4 counts.

These counts are in reasonable agreement with the calculated values where beta particles were assumed to travel isotropically in air (24.7 counts).

The simulated value deviates from the calculated value by 15% which can possibly be explained due to the scatter that would have occurred when air is present. The assumption of only half the beta particles reaching the detector was an overestimation as the MCNP version shows that slightly less than half reach the scintillator.

4. Conclusion

The purpose of this research was to obtain experimental data on the gamma ray sensitivities of plastic scintillators as a function of scintillator thickness as well as to gain a better understanding of the interaction of beta particles with these detector materials. A correlation was found between the slope of the number of detected photons as a function of scintillator thickness. The attenuation of gamma rays as a function of energy also supported the experimental data as the attenuation coefficient decreased, fewer photons were stopped for a given scintillator thickness and vice versa. Another objective of the research was to analyze the system's response to beta sources as a function of scintillator thickness and Ni-63 was used for this purpose. An optimal scintillator thickness for greatest photon-beta discrimination was found to be 250μm by comparing integrated counts for the highest energy gamma source (Co-60) to the low energy beta source (Ni-63) over the same number of pulse-height channels. At this thickness, the high energy photon background would result in approximately 19,000 counts being registered by the detector for a dose of 237μGy/ hour over a 5 minute period. For the same photon dose rate, the number of H-3 betas detected would have to be greater than this value for the tritium signal to be discernable over the same interval period of 5 minutes. Using MCNP4a to model the interaction of tritium beta particles with the detector system and any approximate analytical calculations a tritium concentration of 1DAC was calculated to producing approximately 25 counts over a 5 minute interval. Since the H-3 counts were very low in comparison to 19,000 counts from Co-60 a tritium monitor may not be possible; however the optimization of scintillator thicknesses might be applied to other beta-photon mixed field dosimetry situations as well as for low energy gamma radiation such as Fe-55 in a high energy gamma background.

5. References

- Ali, Fawaz. "On The Integration of Computational Fluid Dynamics (CFD) Simulations with Monte Carlo(MC) Radiation Transport Analysis." *UOIT-Library*. UOIT, 1 Dec. 2009. Web. 15 Apr. 2011. <http://ir.library.dc-uoit.ca/dspace/handle/10155/73>.

- Arosio, S., F. Campi, R. A. H Edwards, P. Paceneti, and S. Terrani. "A Personal Discriminating Monitor for Tritiated Water Vapor." Nuclear Instruments and Methods in Physics Research (2000). Print.

- Cember, Herman. Introduction to Health Physics. 3rd ed. New York: McGraw-Hill, Health Professions Division, 1996. Print.

- *Chapter 1: MCNP and the Monte Carlo Method*. Rep. 2000. Print. Primer.

- Cowper, G., and R. V. Osborne. Measurement of Tritium in Air in the Presence of Gamma Radiation. Tech. 45th ed. Vol. R1. Rome: International Radiation Protection Association, 1966. Print

- *MCNP*. Computer software. Vers. 4A. Los Alamos.

- Miramonti, Lino. "A Plastic Scintillator Detector for Beta Particles." Pergamon: Radiation Measurements (2002). Print.

- Pourtangestani, Khadijeh K. *Optimization of Plastic Scintillator Thickness for Online Beta Detection in Mixed Fields*. Thesis. University of Ontario Institute of Technology, 2010.*UOIT*. Web. <https://ir.library.dc-uoit.ca/bitstream/10155/138/4/Pourtangestani_Khadijeh.pdf>.

- Qashua, Nael. "The Effect of High Dose Rate on Tissue Equivalent Proportional Counter Measurements in Mixed Neutron-Gamma Fields." Thesis. University of Ontario Institute of Technology, 2010. *UOIT-Library*. Apr. 2010. Web. <https://ir.library.dc-uoit.ca/bitstream/10155/90/1/Qashua_Nael.pdf>

- RadDecay. Computer software. Vers. 3.6. Web.

- Shu, W. M., M. Matsuyama, T. Suzuki, and M. F. Nishi. "Characteristics of a Promising Tritium Process Monitor Detecting Bremsstrahlung X-rays." Nuclear Instruments and Methods in Physics Research (2004). Print.

- Shultis, J. K., and R. E. Faw. *An MCNP Primer*. Rep. Manhattan: Kansas State University, 2004. Print.

- Thompson, Patsy. *Darlington New Build Project Joint Review Panel*. Rep. no. 2.01. Canadian Nuclear Safety Comission, 29 Mar. 2011. Web. <http://www.ceaa.gc.ca/050/documents/49178/49178F.pdf>.

- *VISED*. Computer software. Vers. 7M. July 2001.

- Waller, Ed. "Introductory MCNP - Using MCNP 4a." NUCL5040 - Monte Carlo Methods. University of Ontario Institute of Technology, Oshawa. Lecture.

- Wood, M. J., and R. A. Surrette. Real Time Tritium-in-Air Monitors for CANDU Facilities. Tech. no. COG-93-427. Chalk River: AECL, 1994. Print.