

DESIGN OF A NEUTRON DETECTOR CAPABLE OF REPLACING HE-3 DETECTORS UTILIZING THIN POLYMERIC FILMS

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ABSTRACT

There exists a significant need to develop a new neutron detection system which would reduce the dependency on the current He-3 based detectors for Domestic Nuclear Detection Office (DNDO) applications. One of the technologies being developed is the use of Li-6 (thermal cross section of 940 barns) in scintillating polymeric thin films. The purpose of this research is to provide a framework for the characterization of thin polymeric films in terms of meeting the detection requirements set forth by the governing bodies, most notably a detector count rate of 2.5 cps/ng with and only misclassifying a neutron as a gamma once in a million. The performance of some of the best performing fabricated films is simulated with a Monte Carlo transport code (MCNPX) as radiation portal monitors. It is determined that thin polymeric films would have a high enough interaction rate to satisfy the DHS-DNDO requirements while still maintaining the necessary gamma discrimination.

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1. INTRODUCTION

Radiation Portal Monitors (RPMs) are passive radiation detection systems implemented at over a thousand of border crossings [1], designed to determine if cargo contains any special nuclear material in a safe, nondestructive, and effective manner. The existing technologies can be divided into two classes, gamma ray based detectors and neutron based detectors. Gamma ray detectors measure the photon energy spectra of the object in question and then compare it to a known database. Sodium iodide and germanium have been proposed as portal monitor detectors; however, the energy resolution of sodium iodide and the cryogenic requirement of the germanium limit the usefulness of these detectors [2]. Currently the standard for neutron detectors is proportional gas ^3He detectors in which the ^3He is mixed with an inert gas, usually argon with carbon dioxide as a quench gas. These detectors can obtain neutron efficiencies greater than 2.8 cps/ng ^{252}Cf [3] while maintaining the necessary gamma discrimination. Due to the shortage of ^3He [1], replacement technologies are being considered. These options include boron lined straw fibers [4], zinc sulfide paddle detector systems [5] and ^6Li based systems [1].



FIGURE 1 - RADIATION PORTAL MONITOR INSTALLED ALONG THE U.S. BORDER

Neutron detectors register an event when a neutron interaction has occurred and when other conditions are satisfied. It is then desirable for an absorber to have a large cross section such that the interaction is likely to occur, and for the reaction products of the interaction to be highly energetic and easy to detect. Table 1 enumerates some of the more common absorber isotopes used in neutron detection. Of these ^6Li releases the most energy upon absorption of a neutron (4.78 MeV) while still having an appreciable thermal cross section of 940 barns with the least pulse height deficit. The reaction products of $^6\text{Li}(n,^3\text{H})^4\text{He}$ are easily captured in common scintillator materials, contributing to the ^6Li being more efficient than the other reactions at converting the energy from the charged particles into light.

TABLE 1 - SELECTED NEUTRON ABSORPTION REACTIONS AND THERMAL CROSS SECTIONS [6]

Reaction	Q-Value (Mev)	Thermal Cross Section (barns) [7]	Application
${}^3_2\text{He} + n \rightarrow p + {}^3_1\text{H}$	0.756	5,330	Proportional counter gas
${}^6_3\text{Li} + n \rightarrow {}^3_1\text{H} + {}^4_2\text{He}$	4.78	940	Lithium glass scintillators
${}^{10}_5\text{B} + n \rightarrow {}^4_2\text{He} + {}^7_3\text{Li}$	2.31	3,840	
${}^{157}_{64}\text{Gd} + n \rightarrow \gamma$		259,000	

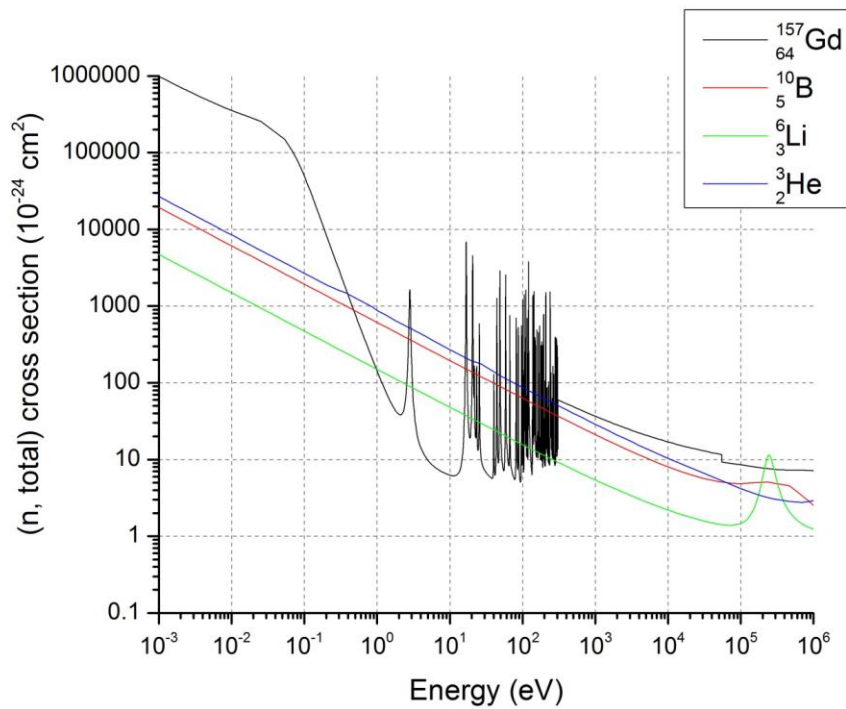


FIGURE 2 - TOTAL NEUTRON CROSS SECTIONS [8]. ${}^6\text{Li}$ HAS A LOWER CROSS SECTION, BUT HAS A HIGHER Q-VALUE, MAKING IT AN ATTRACTIVE ABSORBER FOR REPLACEMENT DETECTOR TECHNOLOGIES.

DETECTOR REQUIREMENTS

The Domestic Nuclear Detection Office within the Department of Homeland Security (DNDO/DHS) in conjunction with Pacific Northwest National Laboratory have outlined a set of criteria that must be met in order for a detector to be a functional replacement (Table 2).

TABLE 2 - FUNCTIONAL SPECIFICATIONS FOR REPLACEMENT RPM NEUTRON DETECTION CAPABILITIES[†] [2]

Parameter	Specification
Absolute neutron detection efficiency	2.5 cps/ng of ²⁵² Cf (in specified test configuration)
Intrinsic gamma-neutron detection Efficiency	$\epsilon_{int\ \gamma n} \leq 10^{-6}$
Gamma absolute rejection ratio for neutrons (GARRn)	$0.9 \leq GARRn \leq 1.1$ at 10 mR/h exposure
Cost	~\$30,000 per system

[†]Electronics and other performance criteria specified in ANSI 42-35

Absolute detection efficiency is defined as the number of counts observed by the detector divided by the quanta of radiation emitted[2] in a given test configuration, regardless of whether the emitted quanta crossed the detector. The DHS/DNDO criteria is 2.5 counts per second per ng ²⁵²Cf in the specified test configuration of the source (²⁵²Cf) surrounded by 0.5 cm of lead and moderated by 2.5 cm of HDPE with the midpoint of the detector located 2 meters away from the source.

$$\epsilon_{abs} = \frac{\# \text{ Counts Observed}}{\# \text{ Quanta of Radiation Emitted}} \quad (1)$$

The intrinsic efficiency is defined as the number of counts registered by the detector, divided by the number of quanta of radiation that cross the detector [2]. For example, if 10 neutrons enter the detector and one count is registered the $\epsilon_{int,n} = 0.1$.

$$\epsilon_{int} = \frac{\#Counts\ Observed}{\#Quanta\ of\ Radiation\ Crossing\ Detector} \quad (2)$$

The gamma absolute detection ratio for neutrons specifies that the performance of the detector should not increase or decrease by more than 10% in the presence of a strong gamma field (10mR/hr) [3]. The GARRn is measured by placing a ^{192}Ir or ^{60}Co source at an appropriate distance to produce a uniform exposure rate of 10 mR/hr across the detector face, with the same neutron source shall be placed at 2m as specified in the neutron configuration. The count rate is then measured and the change in count rate determined.

$$GARRn = \epsilon_{\gamma,abs}/\epsilon_{n,abs} \quad (3)$$

In addition there are several other qualities that a scintillation detector should possess, as quoted from [2]:

- *It should convert the kinetic energy of charged particles into detectable light with a high scintillation efficiency.*
- *This conversion should be linear – the light yield should be proportional to deposited energy over as wide as range as possible.*
- *The medium should be transparent to the wavelength of its own emission for good light collection.*
- *The decay time of the induced luminescence should be short so that fast signal pulses can be generated.*
- *The material should be of good optical quality and subject to manufacture in sizes large enough to be of interest as a practical detector.*
- *Its index of refraction should be near that of glass (~1.5) to permit efficient coupling of the scintillation light to a photomultiplier tube or other light sensor.*

OUTLINE OF THIS DOCUMENT

The focus of this project is the characterization and modeling of polymeric detectors capable of meeting the criteria described above. First the facilities available for spectral characterization are discussed (including a 100 uCi ^{60}Co source and a moderated ^{252}Cf source), followed by facilities for pulse shape discrimination. A brief discussion of pulse shape discrimination follows, followed by an in depth analysis of utilizing a pulse height discriminator for neutron – gamma discrimination. The calculations necessary to compute the intrinsic gamma efficiency are introduced, as well as the necessary modeling and validation. The response of promising characterized films are shown as

examples of what performance can be achieved. Finally detector designs capable of meeting the criteria are proposed, followed by suggestions for further efforts.

2. METHODS

The performance of a given detector is characterized by measurement of its light yield and neutron sensitivity in the characterization laboratory, utilizing the instrumentation and sources present. Having established that a film has scintillation promise, further data analysis of the film is completed. This involves simulating the film in MCNPX in order to calculate the ${}^6\text{Li}(n,t)\alpha$ reaction rate and number of particles crossing the detector in the neutron and gamma irradiator. The response of the film is also simulated in a DHS configuration detector.

INSTRUMENTATION

Samples are characterized based on their pulse height spectra from a variety of sources. The samples are mounted to a Philips XP2202B 10 stage PMT with silicone based optical grease (Saint Gobain BC-630). The PMT is attached to a Canberra 2007P base, which also functions as a preamplifier. The PMT's voltage is supplied by an Ortec 556 high voltage power supply, with the power being supplied to the Canberra 2007P pre amplifier base by the Ortec 571 amplifier. The output signal of the Canberra 2007P base feeds into an Ortec 572A amplifier for pulse shaping and amplification. The amplified signal is then inputted to an Ortec 926 MCB-ADC. The converted signal can then be read using the MAESTRO-32 software. Figure 3 is a schematic of the instrumentation setup used for spectral measurements.

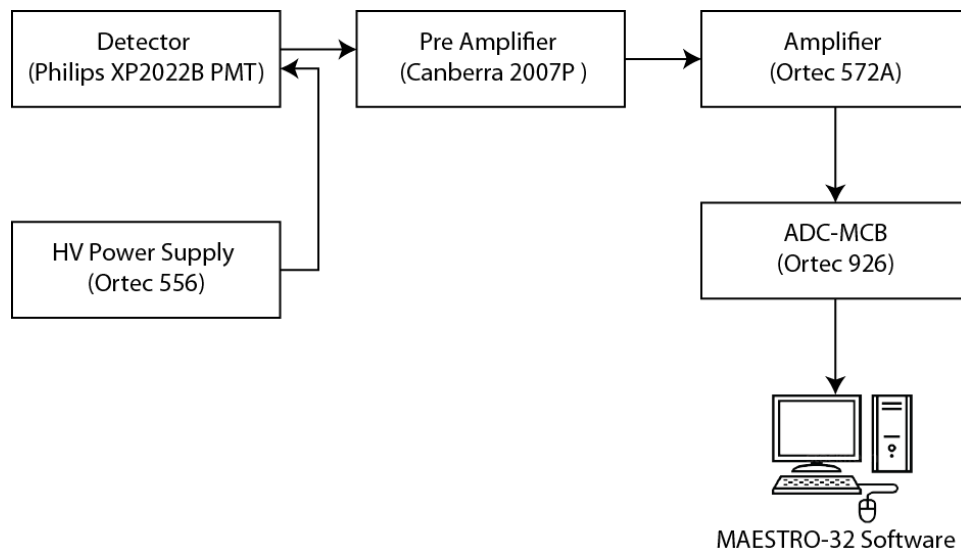


FIGURE 3 – INSTRUMENT FOR SPECTRAL MEASUREMENTS

Voltage pulses from a single radiation event (for pulse shape discrimination) are measured using a Philips XP2020 PMT in conjunction with a S563 base. The signal from the dynode of the S563 base is fed into a MSO-X 3034A Agilent Oscilloscope, triggered on the rising edge. The 2563 base output is attached to the oscilloscope with a T-couple, terminating one of the inputs with a 50 Ohm

impedance to minimize impedance reflections. The capability exists for utilizing a fast digitizer coupled with a fast amplifier. A block diagram of the setup is shown in Figure 4.

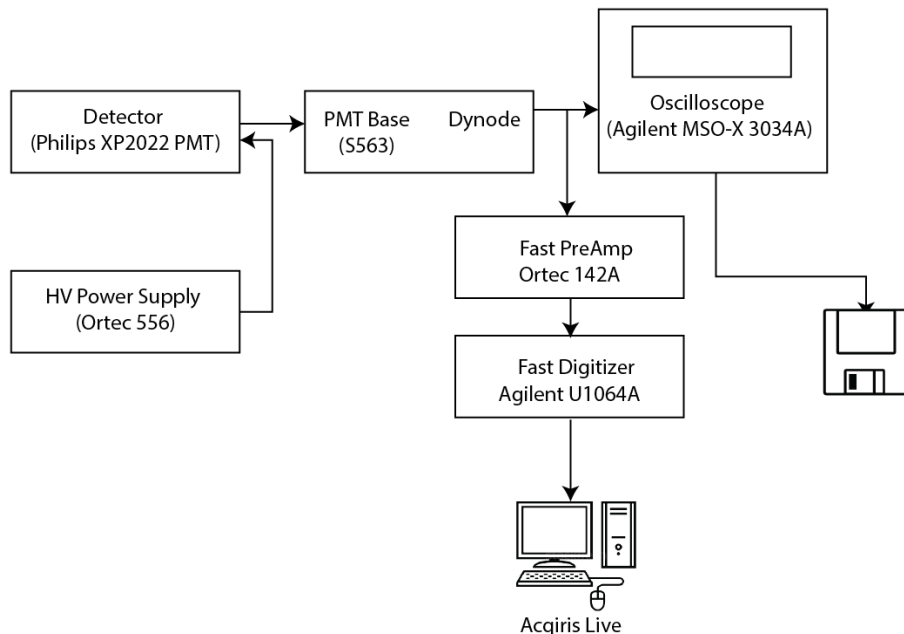


FIGURE 4 - INSTRUMENTATION FOR PULSE SHAPE DISCRIMINATION

AVAILABLE SOURCES

A variety of sources are available for characterization. Button sources exist for the characterization of detector response from alphas (Table 3), betas (Table 4) and button sources of ^{137}Cs and ^{60}Co . The alpha and beta particles have a limited range, and are then best used directly placed on the detector surface.

TABLE 3 - ALPHA SOURCES AVAILABLE FOR CHARACTERIZATION

Source	Half-Life	Alpha Kinetic Energy (MeV)
^{232}Th	$1.4 \times 10^{10} \text{ y}$	4.012
^{240}Pu	$6.5 \times 10^3 \text{ y}$	5.17 (76%), 5.12 (24%)
^{241}Am	433 y	5.48 (85%), 5.44 (12%)
Tri-Nuc (^{239}Pu , ^{241}Am , ^{244}Cm)		

TABLE 4 - BETA SOURCES AVAILABLE FOR CHARACTERIZATION

Source	Half-Life	Endpoint Energy (MeV)
^{14}C	5,730 yr	0.156
^{36}Cl	3.08×10^5 y	0.714
^{63}Ni	92 y	0.067
^{99}Tc	2.12×10^5 y	0.292

The gamma sources consist of button sources (^{137}Cs up to 10 μCi and ^{60}Co up to 1 μCi) as well as a gamma irradiator that produces a 10 mR/hr gamma field across the detector face. The irradiator consist of four 4"x8"x 2" lead bricks on the bottom with and additional four 4"x4"x2" lead bricks encased in an 1/8" metal box. The top four inches is HDPE. The overall dimensions of the detector are 14" by 12" by 12". The source was purchased from Eckert & Ziegler, and was 95.79 μCi ^{60}Co on January 1st, 2012.



FIGURE 5 - CONSTRUCTED GAMMA IRRADIATOR

The neutron irradiator is a custom built $0.59 \mu\text{g}$ ^{252}Cf source encased in 2" blocks of high density polyethylene (HDPE). The HDPE box is approximately 20" long, 12" wide, and 14" tall (Figure 6). There are two detector $1/16"$ thick acrylic detectors wells, one surrounded by a $1/16"$ cadmium to shield out thermal neutrons, and the other surrounded by $1/16"$ of lead to shield out a similar amount of gammas as the cadmium well. The $0.59 \mu\text{g}$ ^{252}Cf source is surrounded by stainless steel, which in turn is contained within a 2" diameter, $1/2"$ thick, $5 \frac{1}{4}"$ tall lead vessel.

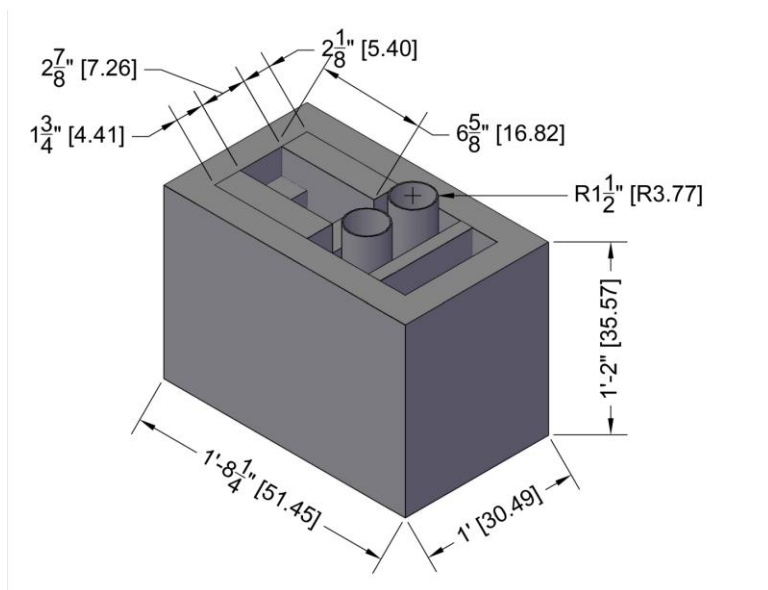


FIGURE 6 – CAD RENDERING OF THE NEUTRON IRRADIATOR.

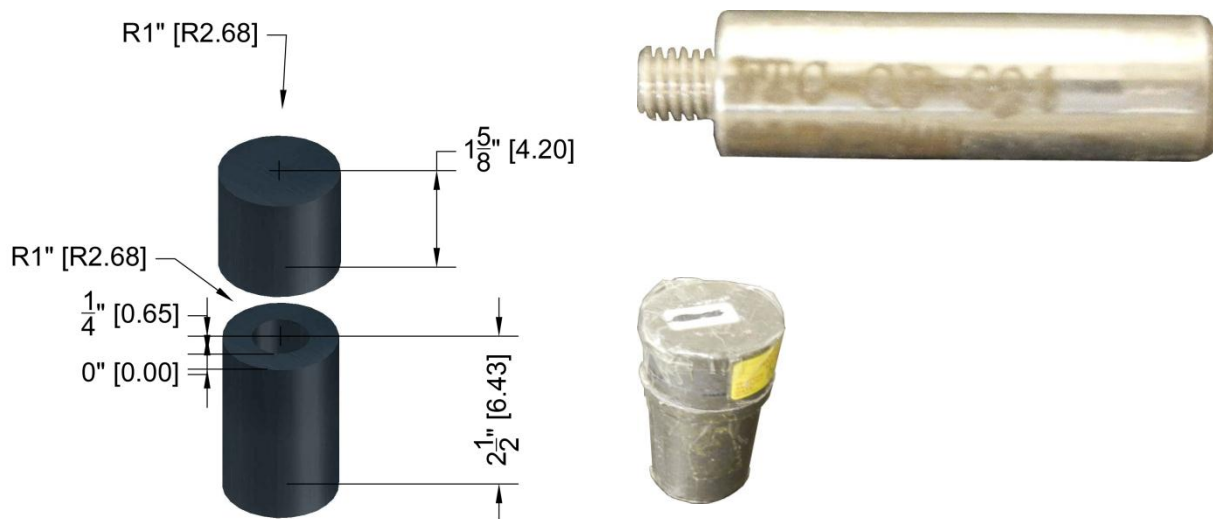
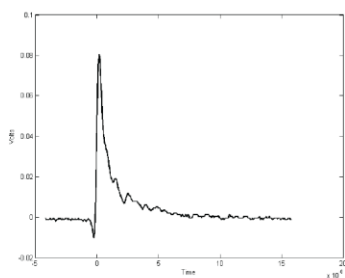


FIGURE 7 - SOURCE AND LEAD PIG FOR THE ^{252}Cf SOURCE. THE LEFT IS A CAD RENDERING, WHILE THE UPPER RIGHT IS THE ACTUALLY ^{252}Cf SOURCE AND THE LOWER RIGHT IS THE LEAD PIG.

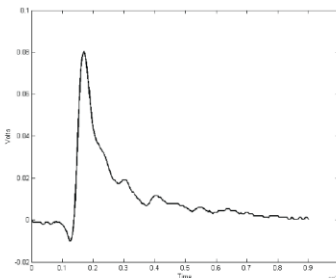
PULSE SHAPE DISCRIMINATION

Pulse shape discrimination was explored as an alternative to a pulse height discriminator for neutron – gamma discrimination. Pulse shape discrimination utilizes the different pulse shapes from neutrons and gammas to classify an unknown pulse into a gamma pulse or neutron pulse. An alpha source was used as a surrogate for a neutron source as the neutron irradiator does not supply a pure neutron source due to (n, γ) interactions in the HDPE and lead and cadmium wells. The gamma source was the ^{60}Co irradiator. The measurement of the pulses was completed using the setup described in Figure 4, where the data were saved for offline analysis. Scripts were written in the MATLAB environment in order to perform the pulse shape analysis. Post-processing of the spectra was completed in order to enhance the pulse shape analysis. This consisted of selecting a region of interest (determined from where the spectra falls by e^{-5} on the left of the peak and e^{-6} on the right of the peak) and band-pass filtering to smooth out high frequency noise.

Spectra from Oscilloscope



Selected ROI of Spectra



Compute
Charge
Ratio

FIGURE 8 - PROCESSING OF A PULSE. FROM LEFT TO RIGHT, THE PULSE IS RECORDED FROM THE OSCILLOSCOPE, AND THEN A REGION OF INTEREST IS SELECTED. FROM THE ROI THE CHARGE RATIO IS COMPUTED.

The charge integration is performed for the total pulse as well as a slow portion (or tail) of the pulse. The start of the slow charge integration was based on the time location where the peak voltage has fallen by a factor of e^{-1} . The integral computation was performed in Matlab with the `trapz` function.

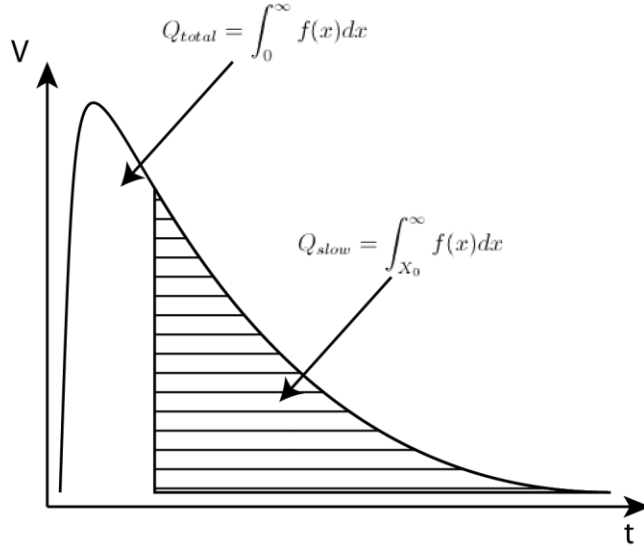


FIGURE 9 - EXAMPLE OF THE CHARGE INTEGRATION. THE TOTAL CHARGE IS ALL OF THE AREA UNDER THE CURVE, WHILE THE SLOW CHARGE IS THE AREA IN THE SHADED REGION.

The charge ratio (4) was then computed for each pulse. A distribution of charge ratios is then obtained for each class of incident radiation (alpha, gamma) and then pulses of unknown class can be classified by computing the charge ratio and computing which distribution the pulse is most likely to belong in.

$$R_c = \frac{Q_{slow}}{Q_{fast}} = \frac{\int_{X_0}^{\infty} f(x)dx}{\int_0^{\infty} f(x)dx} \quad (4)$$

where:

- Q_{slow} is the charge from the slow pulse component,
- Q_{fast} is the charge from the fast pulse component,
- $f(x)$ is the pulse trace,
- and X_0 is the start of the slow pulse integration.

The performance of a film to classify pulses based on the charge ratio was evaluated with Receiver Operator Characteristics (ROC) curves. ROC curves were generated using the built-in `perfcurve` function in Matlab, passing the charge ratio as the score and using the alpha's as the positive class; i.e. testing if every pulse belongs to the alpha class.

TABLE 5 - PULSE SHAPE CLASSIFICATION CLASSES

Hypothesized Class	True Class	
	Alpha	Gamma
	Alpha	Gamma
Alpha	True Positive	False Positive (Type I error)
Gamma	False Negative (Type II error)	True Negative

The false positive rate is then the probability of incorrectly classifying a gamma as an alpha, while the false negative rate is probability of incorrectly classifying an alpha as a gamma. The performance of a classifier can be compared utilizing an ROC curve, which computes the false positive rate versus true positive as a function of a score (or threshold). The score determines how much a given trial belongs to a given class; for example a low charge ratio score is indicative of a gamma event, while a larger charge ratio score is indicative of an alpha.

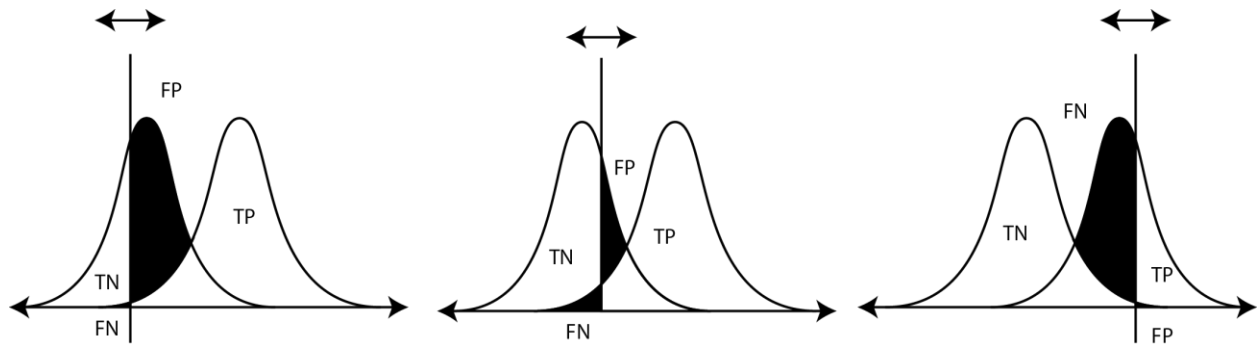


FIGURE 10 - FALSE POSITIVE AND TRUE POSITIVES FOR A GIVEN THRESHOLD. THE FALSE NEGATIVE RATE AND TRUE POSITIVE RATE IS THEN USED TO DETERMINE THE ROC CURVES.

MEASUREMENT PROTOCOLS

Systematic experimental techniques were developed for characterizing scintillation materials for optical and neutron response using a ^{252}Cf neutron source. Several reference scintillation materials including ^6Li -based glass (GS20) and boron based plastic scintillators (EJ-254) serve as benchmarks in assessing the performance of new materials when irradiated with neutrons and gamma rays under similar conditions. The general protocol for evaluating the neutron response for a given sample detector is:

1. Verify that the instrumentation gains are stable by confirming that the GS20 neutron peak is in the same channel as for previous measurements. This is completed by setting the voltage and coarse gain to previously determined values, and then adjusting the fine gain until the peak of the lead spectra measurement occurs in the specified location,
2. obtain a spectrum from an Am-241 alpha source,
3. obtain a spectrum from a Cl-36 beta source,
4. obtain a neutron spectrum from the Pb-shielded tube neutron irradiator,
5. obtain a neutron spectrum from the Cd-shielded tube in the neutron irradiator,
6. obtain a gamma spectrum in the gamma irradiator.

DATA ANALYSIS

Post processing of the spectra is completed in the MATLAB environment in order to calculate the intrinsic efficiency of a given detector. Integrating the resulting spectra as a function of mathematical pulse height discriminator setting (MLLD) and normalizing by the incident photon flux allows for the intrinsic efficiency of a detector to be calculated as a function of pulse height. The necessary mathematical pulse height setting for the gamma discrimination is then determined and the measured neutron spectra is integrated above this value. The steps are as follows:

1. The absolute intrinsic efficiency for gammas is computed as a function of mathematical lower level discriminator, given the number of particles crossing the film from the MCNPX simulation.
2. The MLLD level at which $\epsilon_{int,\gamma} \leq 10^{-6}$ is calculated. This is found by just search the $\epsilon_{int,\gamma}$ values for the first value that is less than 10^{-6} , and then a key-value lookup in order to find the corresponding channel.
3. The count rate for neutrons above the gamma MLLD are calculated by summing the neutron spectra above the gamma MLLD.

The films are evaluated based on their neutron – gamma pulse height discrimination and light yield with the following parameters:

- Total Neutron Counts – provides a measure of how responsive the detector is to neutrons
- Total Neutron Count Rate Per mg Absorber – provides a measure of how well the fabricated detector utilizes the neutron absorber in it. Indirectly this can be a measure of the amount of absorber in the detector
- Gamma LLD – The position (in channel number) of where an LLD would have to be set in order to meet the criteria of $\epsilon_{int,\gamma} \leq 1 \times 10^{-6}$. This calculation is explained in more detail in the following paragraph and in `GammaLLDAlgoReview.docx`.
- Fraction of Total Neutron Count Rate Above the Gamma LLD – this is a measure of how effective the film would be with an LLD set in order to meet the $\epsilon_{int,\gamma}$. This is calculated by summing the counts above the gamma LLD and dividing by the total counts.

- Alpha Peak – provides a clear indication of the light yield of the film from an alpha particle, which is one of the reaction products of the ${}^6\text{Li}$ neutron interaction. The alpha peak is visible in thin films when other features may be lost (due to the range of the secondary electrons exceeding the thickness of the detector) because the range of the alpha is on the order of 30 microns.
- Beta Average – characterizes the response of the film to electrons, account for the possibility that a film may not have a clearly defined feature due to energy escaping. Electrons are generated in the film from scattering events of photon interactions.
- Alpha / Beta – characterizes the relative light yield of the detector from heavy charged particles to electrons.
- Photons per gamma and Photons per beta – a measure of the light yield of the film, or how many photons are produced per energy absorbed.
- Pulse Height Deficit – a measure the apparent energy loss (as seen from the pulse height) of a heavy charged ion compared to an electron. This is measured as the difference between the energy of the heavy ion and its apparent energy from the pulse height. It should be noted that this term closely resembles the phenomena described by pulse height defect as seen in semiconductors.
- Photons per Neutron – a measure of the light yield of the film, or how many photons are produced per energy absorbed.

The average channel number (weighted by the counts) of spectrum where calculated according to (5):

$$\langle \mu \rangle = \frac{\int_0^{\infty} x f(x) dx}{\int_0^{\infty} f(x) dx} \quad (5)$$

where:

- $f(x)$ is the spectrum,
- x is the channel number,
- and the limits of integration are all channels.

The intrinsic efficiency is defined as $\epsilon_{\gamma, \text{int}} = \frac{\text{Counts}}{\text{Particles Incident}}$. For a given channel (acting as the MLLD) the intrinsic efficiency is:

$$\epsilon_{\gamma, \text{int}} = \frac{\int_{MLLD}^{\infty} f(x) dx}{\text{Particles Incident}} \quad (6)$$

where:

- $f(x)$ is the spectra,
- x is the channel number,

- the limits of integration is from a mathematical lower level discriminator (MLLD) to the highest channel,
- and Particles Incident are the particles incident upon the detector.

It is then possible to find the MLLD at which the intrinsic efficiency becomes below a given level, in this case 10^{-6} as set forth by the DHS/DNDO. The pulse height deficit (which determines the effectiveness of creating light for ions compared to electrons) for the neutrons can be calculated as follows:

$$PHD_{GS20} = \frac{n_{peak}/4.78 \text{ MeV}}{CE_{\gamma}/1.038 \text{ MeV}} \quad (7)$$

where:

- n_{peak} is the neutron peak (normalized by the reaction energy),
- and CE_{γ} is the Compton edge (normalized by the average Compton edge).

This also provides a framework for evaluating the pulse height deficit of the samples:

$$PHD_{sample} = PHD_{GS20} \times \frac{\langle n \rangle_{sample}}{\langle n \rangle_{GS20}} \quad (8)$$

where:

- $\langle n \rangle_{sample}$ is the average channel number of the neutron spectra of the sample (defined in (5)),
- and $\langle n \rangle_{GS20}$ is the average channel number of the neutron spectra of GS20.

The light yield (amount of light emitted per unit energy loss of ionizing energy traveling through the material) of the films were measured relative to GS20, when the samples are measured under the same light collection circumstances. GS20 emits 3,800 photons per electron equivalent MeV [2]. The light yield of the various samples is then scaled by the light yield of GS20. Two quantities are computed; the light yield for a light ion (gamma producing electrons (LY_{γ}) or beta source (LY_{β})) and the light yield per neutron (LY_n).

$$LY_{\beta,Sample} = 3,800 \frac{Photons}{MeV} \times \frac{<\beta>_{Sample}}{<\beta>_{GS20}} \quad (9)$$

$$LY_{\gamma,Sample} = 3,800 \frac{Photons}{MeV} \times \frac{<\gamma>_{Sample}}{<\gamma>_{GS20}}$$

where:

- $<\beta>_{Sample}$ is the average channel number of the beta spectrum of the sample (defined in (5)),
- $<\beta>_{GS20}$ is the average channel number of the beta spectrum of GS20,
- $<\gamma>_{Sample}$ is the average channel number of the gamma spectrum of the sample,
- $<\gamma>_{GS20}$ is the average channel number of the gamma spectrum of GS20,
- and 3,800 Photons per MeV is the light yield of GS20.

The light yield per neutron (LY_n) is calculated for GS20 by scaling the ratio of the neutron peak and Compton edge by the pulse height deficit (7):

$$LY_{N,GS20} = 3,800 \frac{Photons}{MeV} \times PHD_N \times 4.78 MeV \quad (10)$$

$$LY_{n,Sample} = LY_{N,GS20} \times \frac{< n >_{Sample}}{< n >_{GS20}} \quad (11)$$

where:

- $< n >_{Sample}$ is the average channel number of the neutron spectra of the sample (defined in (5)),
- $< n >_{GS20}$ is the average channel number of the neutron spectra of GS20,
- and $LY_{n,Sample}$ is the light yield per neutron of the sample.

The alpha over beta ratio was calculated using the measured ^{241}Am alpha peak (5.371 MeV) and the spectra-post processed average beta from ^{36}Cl (0.251 MeV). The alpha over average beta for GS20

was calculated to be between 0.23 and 0.20 which is in good agreement with the published value of 0.23 [9]. The published values, however, are from a ^{137}Cs source Compton edge which is a different measurement than what is expressed in (12).

$$\frac{\alpha}{\beta} = \frac{\alpha_{\text{Peak}}/5.371 \text{ MeV}}{\langle \beta \rangle / 0.251 \text{ MeV}} \quad (12)$$

where:

- α_{Peak} is the peak of the alpha spectra from an ^{241}Am source (average energy of 5.371 MeV(5)),
- and $\langle \beta \rangle$ is the average of the beta spectra from an ^{36}Cl source (average energy 0.251 MeV).

Table 6 provides a reference for the variables defined above.

TABLE 6 - VARIABLE DECLARATIONS

	Description
$LY_{\gamma,i}, LY_{\beta,i}, LY_{N,i}$	Light yield of gamma, beta, and neutrons of sample i , respectively
$\langle n \rangle, \langle \beta \rangle, \langle \gamma \rangle$	Weighted average channel number of the neutron, beta, and gamma spectra
$\epsilon_{int,\gamma}$	Intrinsic efficiency for gammas
PHD_i	Pulse Height Deficit of sample i

MEASUREMENT REPEATABILITY

The measurement repeatability was determined by analyzing the derived factors for six GS20 measurements and from three sets of measurements (by different users) on a thin PEN film. The experiments are described in depth in Appendix A. The neutron peak for GS20 had a variation of 1.4% around the average peak at $3,418 \pm 49$ channels¹. Published values of the light yield per neutron of GS20 range from 6,000 Photons per MeV to 7,000 Photons per MeV [9], while the

¹ In these trials the peak location was set to be 3,460 channels per the measurement protocol, but the subtraction of the cadmium spectra decreases the net spectra average peak location.

calculated light yield of GS20 is on the low end at $6,252 \pm 120$ photons per neutron. However, the measurement is very stable as the standard deviation is 1.9% of the average. The gamma spectra position is slightly less stable, with the standard deviation being 2.4% of the average. The position of the gamma MLLD necessary to various achieve $\epsilon_{int,\gamma}$ was calculated. The intrinsic efficiency is very stable (varying within 3% of the average value) until an intrinsic efficiency of 10^{-6} is approached, at which point standard deviation becomes 7.4% of the average value (MLLD $4,021 \pm 296$ channels).

A stretched PEN film was measured three separate times by two operators (Matthew Urffer and Rohit Uppal) in order to determine the repeatability of thin film measurements. Each of the trials were measured at 50 gain, with the voltage determined by setting the peak position of GS20. The spectra averages, count rate, and MLLD channels were computed and summarized in Table 24 in Appendix A . The third trial had a much higher average neutron spectra had a total count rate that was similar to Trial 1 (in fact they differed by 0.07 cps). The source of the discrepancy in the fraction of neutron counts above the gamma discriminator can be found by looking at the neutron integral spectra (Figure 63). While the spectra weighted average for the gamma's are similar (and the gamma LLD's fall within 2σ of each other), the considerable difference in the neutron count rate above the gamma LLD greatly impacted the fraction of neutron counts above the gamma LLD. Values reported in parentheses are $\pm 2\sigma$, which is roughly a 95% confidence interval (1.96σ is 95% CI for a normal distribution).

TABLE 7 - COMPARISON OF THREE DIFFERENT MEASUREMENTS OF A STRETCHED PEN FILM (49.5% LIF, 1% ADS156FS).

	Gamma Spectra Average (channel number)	Neutron Spectra Average (channel number)	Total Neutron Count Rate (cps)	Gamma such $\epsilon_{int,\gamma} \leq 10^{-6}$ (channel number)	LLD that $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)	Neutron Count rate above $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)	Fraction of neutron counts above $\epsilon_{int,\gamma} \leq 10^{-6}$
Trial 1 (May 22)	290	2,039	30.4 ± 0.02	3,192 (2,706 3,517)	5.7 -	(8.5 - 4.2)	0.19 (0.28 - 0.14)
Trial 2 (Jun 4 RU)	259	2,095	37.1 ± 0.05	2,741 (2,500 3,561)	11.3 -	(13 - 6.5)	0.30 (0.35 - 0.17)
Trial 3 (Jun 4 MJU)	252	2,782	30.4 ± 0.02	2,810 (2,682 3,031)	12.8 -	(13.6 - 11.6)	0.42 (0.45 - 0.38)

INTRINSIC EFFICIENCY

MCNPX was used to determine the dose rate at the detector surface as well as the number of photons incident on the detector. The gamma irradiator was modeled as a thin steel outer box 14" x 12" x 12" (orange) which contains 4" x 8" x 2" lead bricks (light green). The ^{60}Co source (yellow) is contained in 2" of steel, with a 1/8" thick steel cap. The detector well is a 4" outer diameter 14" pipe that is 1/4" thick. A mock up of the geometry is shown in Figure 11.

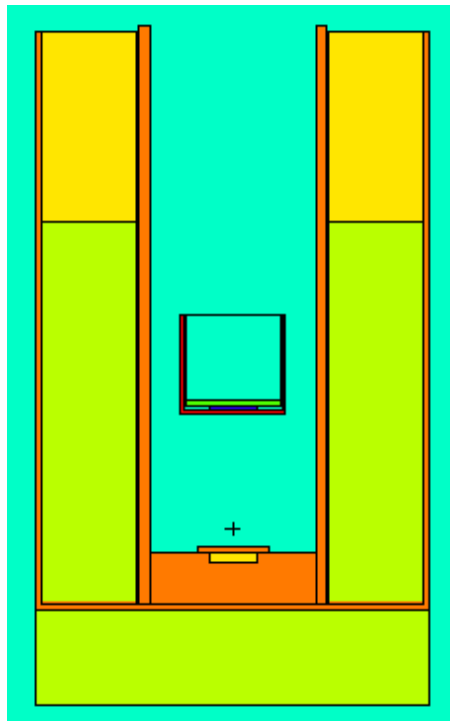


FIGURE 11 –MCNPX MODEL OF THE GAMMA IRRADIATOR

The detector was simulated along with the PMT as its own universe which allowed for easy translations. The thickness of the detector is controlled by translation 602, while the position of the entire PMT (includes the detector) is controlled by translation 6. The cell and surface number is such that anything surface or cell with a '6' as the first letter has to do with the PMT with a '5' as part of the detector.

```

C ##### Cell Cards #####
c ----- Well PMT -----
600  0      -602      trcl=6      fill=6
c ----- PMT Subcells -----
601  3      -1.18    -500          u=6      $ Detector cell
610  440    -1.023   -510          u=6      $ Arcylic Disc Backign
602  388    -2.23    -601          u=6      $ PMT Glass
603  468    -1.406   603          u=6      $ Plastic
604  4      -8.74    -604 605      u=6      $ Metal
605  204    -0.001225 #602 #601 #603 #604 #610 u=6 $Air

C ##### SURFACE CARDS #####
c ----- Detector -----

```

```

c TO CHANGE THE THICKNESS OF THE DETECTOR:
c a) Height of surface 500
c b) Starting position of surface 510
c c) tr602 (sum of height of surface 500 and height of surface 510)
500 rcc 0 0 0 0 0 0.0025 2.54 $ 25 microns thick, 2" Dimeter
510 rcc 0 0 0.0025 0 0 0.3175 2.54 $ 1/8" Aryclic Disc Backing
c ----- PMT -----
601 602 rcc 0 0 0 0 0 0.3178 2.54 $ 2" Diamter, 1/8" Thick (Glass)
602 601 rcc 0 0 0 0 0 5.284 2.8030 $ Plastic Cap Outer
603 601 rcc 0 0 0.189 0 0 5.2651 2.6335 $ Plastic Cap Inner
604 602 rcc 0 0 0.3178 0 0 5 2.54 $ Mu Metal Outer
605 602 rcc 0 0 0.3178 0 0 5 2.535 $ Mu Metal Inner

C ##### DATA CARDS #####
*tr6 0 0 10.3 $ 7" From the top of the well
*tr601 0 0 -0.189 $ PMT Cap (thickness of cap)
*tr602 0 0 0.3200 $ PMT Glass (thickness of detector - 100um+1/8")

```

Photons and electrons were transported in this problem, but significant runtime reduction can be achieved by only transporting photons. Electrons are not born in the source, rather the physics options were set to generate electrons from Bremstrahlung, coherent (Thomson) scattering, and Doppler energy broadening, with the lower level cutoff of 1×10^{-6} MeV. Upon runtime, however, the lower energy cut was raised to ecut min, 1 keV. Electrons are simulated with the MCNPX defaults which are an upper energy limit is 100 MeV, electron production from photons, and electron production of photon. Bremsstrahlung is treated with a tabular angular distribution, with the analog number of bremsstrahlung photons, as is x-ray production, knock-on electrons, and photon induced secondary electrons.

```

C ##### DATA CARDS #####
MODE P E
IMP:P,E 1 15R 0
PHYS:P 3j -1
CUT:P,E j 1E-6

```

The source is treated as a point source located in the middle of a plastic disc, sampling with equal frequency from the two energy distributions of the ^{60}Co .

```

C ##### Cell Cards #####
C ----- SOURCE -----
200 456 -0.93 -400

C ##### SURFACE CARDS #####
C ----- SOURCE -----
200 RCC 0 0 2.2 0 0 0.5 1.27 $ Button Source in Metal

C ##### DATA CARDS #####
SDEF ERG=D1 PAR=p pos=0 0 2.6
SI1 L 1.173 1.332
SP1 D 1.0 1.0

```

The entire input file is available in the Appendix.

Dose Rate

The dose rate over the front of the detector surface was calculated using the dose card and flux to dose conversion factors described in [10], and expressed as an integral over the entire surface, energy range, and angle; where the tally is multiplied by the response function. The DE and DF cards described response function, $\mathfrak{R}(E)$. It should be noted that the resulting flux is not normalized by the source strength; this can either be accomplished by utilizing an energy multiplier card or by post processing.

$$F2 = \frac{1}{A} \int_A dA \int_E dE \int_{4\pi} d\Omega \mathfrak{R}(E) \Phi(\mathbf{r}, E, \Omega) \quad (13)$$

where:

- A is the area of the detector,
- $\mathfrak{R}(E)$ is the response function,
- and $\Phi(\mathbf{r}, E, \Omega)$ is the photon flux.

```
c Multiply each tally by 1000 mrem/rem * 100uCi * 3.7E10 Bq *2 photons / decay
FC12 Photon Flux over Front of Detector Surface
F12:P (500.2<600)
DE12 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6
      0.8 1 1.5
DF12 2.78E-6 1.11E-6 5.88E-7 2.56E-7 1.56E-7 1.20E-7 1.11E-7 1.20E-7 1.47E-7
      2.38E-7 3.45E-7 5.56E-7 7.69E-7 9.09E-7 1.14E-6 1.47E-6 1.79E-6 2.44E-6
```

Using the translation cards a bash script was written to change the distance of the PMT from the source, run MCNPX, and then parse the output for the dose across the detector. The results are plotted in Figure 12, with a dose rate of a 10.07 mrem/hr achieved when the detector is located 10.3 cm from the origin, or 7 cm from the top of the source. The dose rate simulation was validated by measurements completed by the RSO.

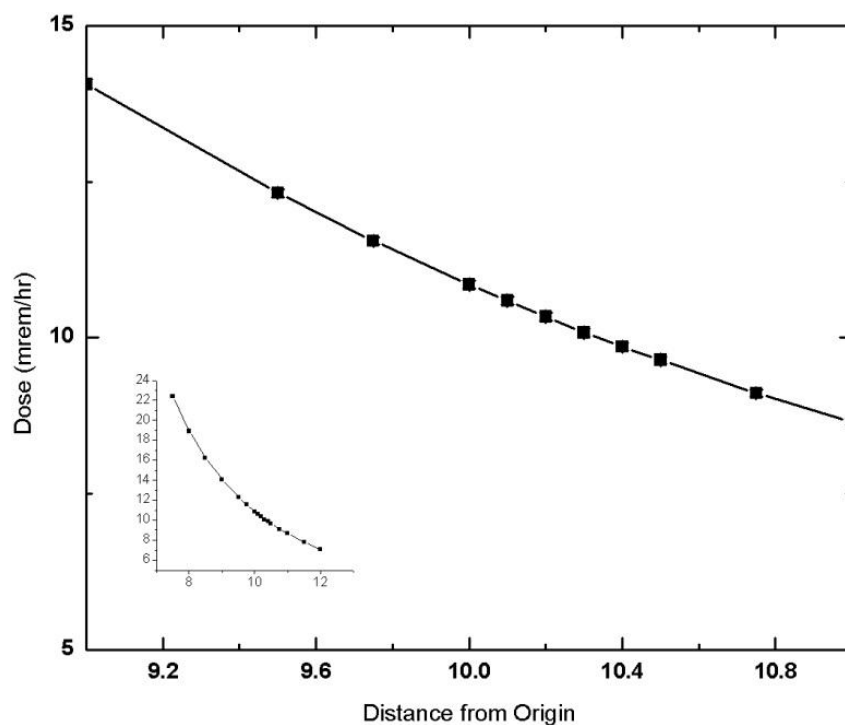


FIGURE 12 – DOSE RATE AT VARIOUS HEIGHTS IN THE GAMMA IRRADIATOR.

TABLE 8 - VALIDATION OF DOSE RATE CALCULATION FROM MEASUREMENT

Measured			Simulated		
Distance	Dose (mRem/hr)	Rate	Distance	Dose (mRem/hr)	Rate
10.2	10		10.2	10.33	
13	5.5		12.76	5.38	
28	2		28	1.80	
28.6	1.7				

Photon Flux

The photon flux across the detector was calculated using a particle crossing tally. Cosine binning is invoked to divide the number crossing between the positive and negative surface sense to calculate the number of photons that enter the cell without including the number of photons that

leave the surface. The surface current is tallied over the three sides of the cylinder, and the union is computed with the T signifier. Once again this tally needs to be normalized with post processing.

```

FCI Photon Tallies Across Detector
F1:P (500.1<600) (500.2<600) (500.3<600) T
C1 0 1

```

The photon flux across a 2" detector and GS20 was calculated for the position necessary to produce a 10 mrem/hr dose rate on the detector.

TABLE 9 - PHOTONS CROSSING GS20 AND A THIN FILM IN THE GAMMA IRRADIATOR

Photons Crossing Detector per Second	
GS20	498,007
25 um	586,970
50 um	685,858

A hand calculation was completed in order to validate the photon flux. In general the photon flux crossing a surface can be found by the ratio of the solid angle that surface subtends to the entire 4π solid angle. An effect of the steel plate was included by simple mass attenuation (14) [2]. It was assumed that the source was 7.5 cm away from a 2.54 radius detector, with 1/8" of steel shielding the source (Figure 13). The mass attenuation coefficient was approximately $0.06 \text{ cm}^2/\text{g}$ for a 1 MeV gamma in iron (density 7.8 g/cm^3). The flux calculation (evaluated in (15)) yielded a flux of 168,000 photons per second crossing the 2" diameter detector. While this is about three times lower than what was calculated in MCNPX, it is believed that the MCNPX calculation is higher due to the pipe effectively making a beam of photons and the inclusion of photons of lower energies.

$$\Phi = S_0 \left(\frac{\Omega}{4\pi} \right) e^{-\mu t} \quad (14)$$

where:

- S_0 is the source strength,
- Ω is the solid angle the detector subtends of the source,
- μ is the mass attenuation coefficient of the shield,
- and t is the thickness of the shield.

Evaluation yields

$$\Phi = \left(2 \times 100 \mu Ci \times \frac{3.7 \times 10^{10} Bq}{Ci} \right) \left(\frac{2\pi (1 - \cos [\tan^{-1} [\frac{2.54}{7.5}]])}{4\pi} \right) e^{-\frac{0.06 cm^2}{g} \times 7.8 \frac{g}{cm^3} \times 0.31 cm} \quad (15)$$

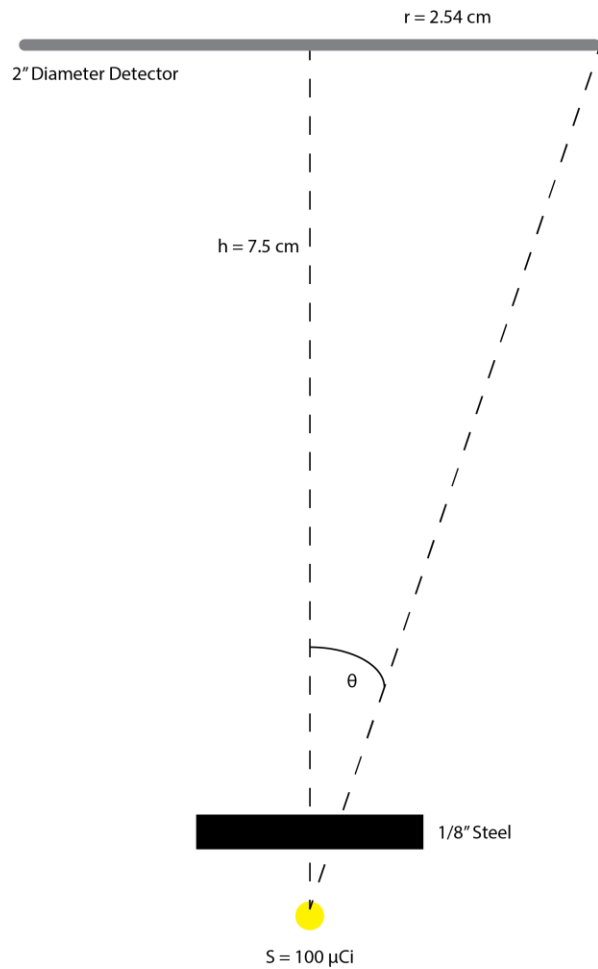


FIGURE 13 - GAMMA FLUX HAND CALCULATION GEOMETRY

Example Gamma Intrinsic Efficiency Calculation

It is illustrative to tie the count rate and intrinsic efficiency computations together with two examples. Suppose a given sample has yielded the gamma and gamma spectra described in Table 10, with 1 million photons crossing the detector.

TABLE 10 - SIMPLE SPECTRA COUNT RATES

Bin	Gamma Count Rate	Neutron Count Rate
0	16000	1
1	400	5
2	20	10
3	1	5
4	0	1

The gamma intrinsic efficiency is calculated as the integral above a mathematical lower level discriminator. Let the first MLLD equal the first bin, zero. The $\int_{MLLD=0}^{\infty} f(x)dx = 16,421$, divided by the photon flux of 1 million yields an intrinsic efficiency of 0.0164. The next MLLD, bin 1, $\int_{MLLD=1}^{\infty} f(x)dx = 421$, yielding a an intrinsic efficiency of 0.00042. This process is repeated until the MLLD is equal to the last bin. The computed intrinsic efficiency values are displayed in Table 11.

TABLE 11 - SIMPLE SPECTRA GAMMA INTRINSIC EFFICIENCY

MLLD	Gamma Intrinsic Efficiency
0	0.016421
1	0.000421
2	0.000021
3	0.000001
4	0

The intrinsic efficiency of 1 in a million occurs at an MLLD equal to 3, so the neutron count rate above that channel is computed, which is the sum of the count rate of channel 3 and channel 4, 6. This process is summarized in Figure 14.

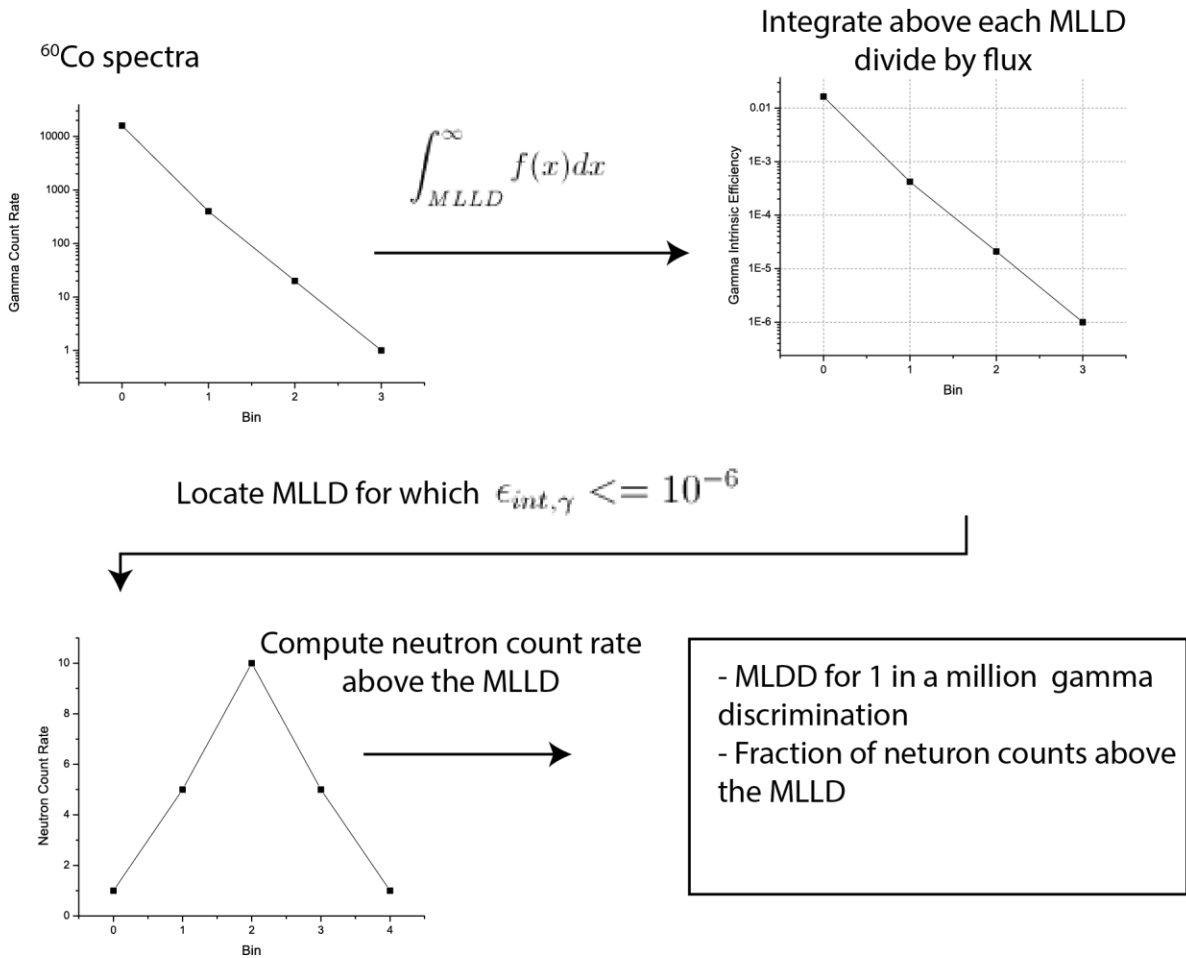


FIGURE 14 - SAMPLE CALCULATION OF INTRINSIC EFFICIENCY AND COUNT RATE BASED ON A SIMPLE SPECTRA.

Figure 15 shows this process applied to the stretched composite PEN film (Figure 59). A 2" diameter sample experiences a photon flux of 39,300 photons per second in the gamma irradiator. For each MLLD (ranging from zero to 8,192) the integral of the spectra is computed, starting at the channel number of the MLLD until the spectra end. This value is then divided by the count time and the photon flux of 39,300.

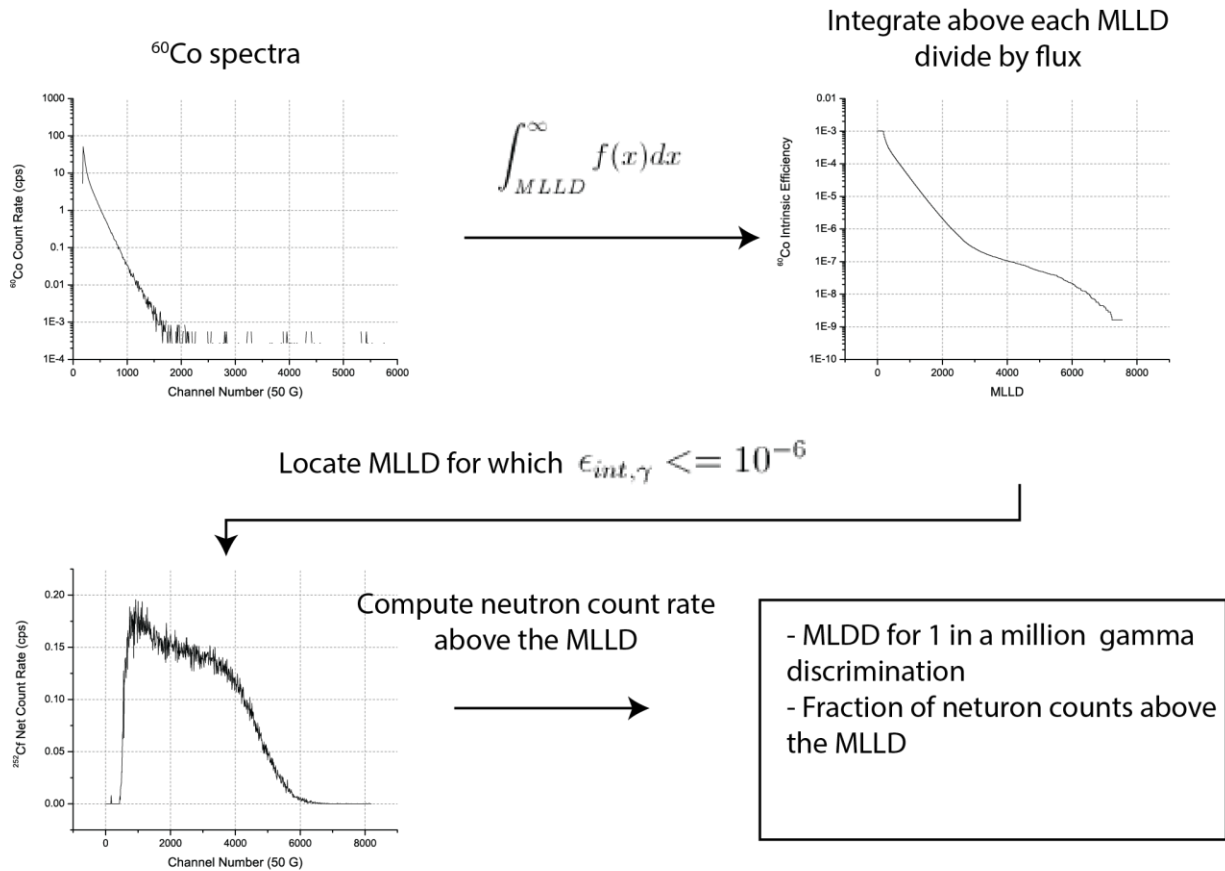


FIGURE 15 - SAMPLE CALCULATION OF INTRINSIC EFFICIENCY AND COUNT RATE BASED ON A MEASURED PEN SPECTRUM

SIMULATION OF DESIGNED DETECTOR FOR SATISFYING THE NEUTRONIC REQUIREMENTS

The evaluation of a detector in the DHS footprint was completed by simulation using MCNPX along with measured material scintillation properties. The basic outline of the simulation is as follows (and graphically in the following figure):

1. A possible film has its gamma and neutron spectra recorded
2. Intrinsic efficiencies are calculated
3. Gamma MLLD is determined, and then the fraction of the counts that deposit energy above the gamma MLLD
4. Film is simulated in a mock-up of a possible detector configuration in the DHS environment
5. The count rate is computed for the detector in the DHS environment

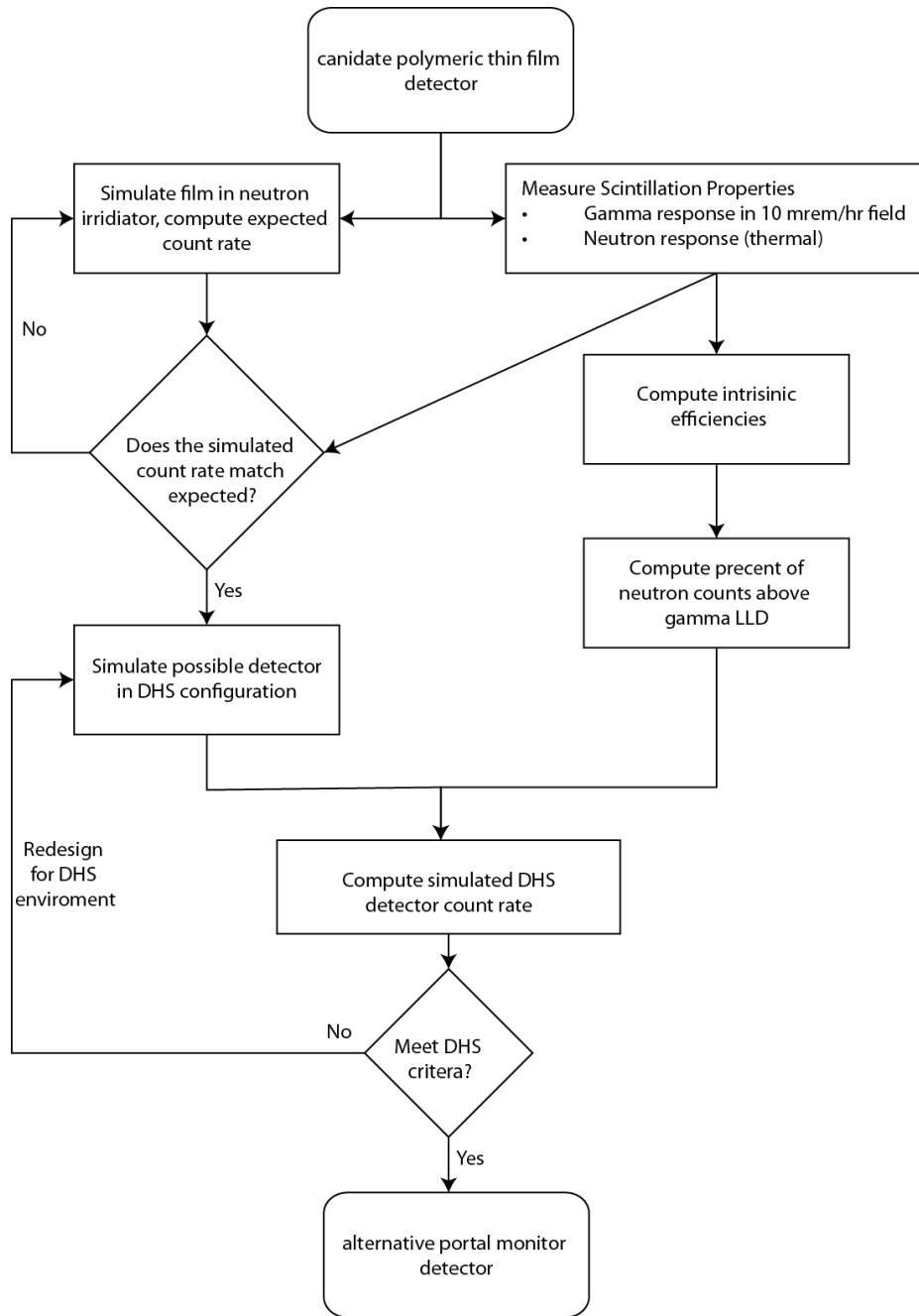


FIGURE 16 - FLOWCHART OF STEPS NEEDED TO SIMULATE A POSSIBLE DHS DETECTOR BASED ON A POLYMERIC FILM

The absolute efficiency of a detector (given the same energy spectra of incident neutrons) can be computed from its intrinsic efficiency and the solid angle of the source it subtends. For example, consider what size a detector would have to be to record 2.5 cps/ng ^{252}Cf that has an $\epsilon_{int,n} = 1.2 \times 10^{-3}$, given that 10 ng ^{252}Cf emits 2.3×10^4 n/s [11]. The count rate c , can be expressed as follows:

$$c = \frac{S_0}{4\pi r^2} (A)(\epsilon_{int,n}) \quad (16)$$

where:

- S_0 is the source strength,
- r is the distance from the source to the film,
- A is the area of the film,
- and $\epsilon_{int,n}$ is intrinsic neutron efficiency of the film.

The size of a detector that captures all of the neutron that cross the surface can be estimated a simple flux based calculation. 1 ng ^{252}Cf emits 2.3×10^4 n/s. At a distance of 2 m, the flux is then 45.7 n/cm² s. To achieve a count rate of 2.5 cps you then need a detector area of 0.0546 m², or about the size of a 8 ½" by 11" sheet of paper. This allows for a bound to be calculated on the possible size of a detector. Evaluation yields $A=45.5$ m², which is the entire surface area of a 2m radius sphere. This establishes a lower bound on the intrinsic neutron efficiency; if $\epsilon_{int,n} < 1.2 \times 10^{-3}$ it will be impossible to build a detector large enough to achieve 2.5 cps/ng ^{252}Cf .

$$A = \frac{4\pi cr^2}{S_0(\epsilon_{int,n})} = 45.5 \text{ m}^2 \quad (17)$$

Finally, this calculation can be run in reverse in order to determine the size of a detector with a non-unity efficiency; all that needs to be completed is to scale by the intrinsic efficiency. For example if a detector with an intrinsic efficiency need to be 0.055 m², then a detector with an intrinsic efficiency of around 1 in 1,000 (about the intrinsic efficiency of a thin film) needs to be 1,000 times bigger, or 55 m², which is clearly bigger than the sphere from which the flux was derived, so such a detector would not have the necessary count rate.

NEUTRONIC CALCULATIONS

MCNPX was used to simulate the interaction rate of a detector in a neutron field. The interaction rate was calculated by multiplying the cell flux by the material cross section. As stated in [10], the tally multiplier card (FM), can be used to calculate any quantity of the form

$$Q = c \int \phi(E) R_m(E) dE \quad (18)$$

Thus a F4 tally is modified with a FM card to record the interaction rate in a cell. The FM card was setup to include the correction from microscopic to macroscopic cross section of the material, and was only used for the cross sections of interest, several are reproduced in Table 12.

```

c ----- Interaction Rate Tallies -----
FC114 Total Neutrons Reactions in Detector in Pb Well
F114:n (601<610)
FM114 -1 3 1
FC154 (n,t) Reactions in Detector in Pb Well
F154:n (601<610)
FM154 -1 3 105
FC214 Total Neutron Reactions in Detector in Cd Well
F214:n (601<620)
FM214 -1 3 1
FC254 (n,t) Reactions in Detector in Cd Well
F254:n (601<620)
FM254 -1 3 105

```

TABLE 12 - NEUTRON REACTIONS AVAILABLE IN MCNPX [10].

Reaction Number (MT)	Reaction Type
101	Sum of MT 102-117
102	(n, γ)
103	(n,p)
104	(n,d)
105	(n,t)
106	(n, ^3He)
107	(n, α)

The interaction rate was then multiplied by the detector cell volume and the source strength. The thermal neutron interaction rate is then the difference of the count rate of the lead well and the cadmium well. The source strength was calculated by applying radioactive decay ($t_{1/2}=2.65$ years) to the number of neutrons emitted per source mass. It was assumed the radiation characterization laboratory neutron source was 0.59 μCi on 1 August 2009.

$$S = (2.314 \times 10^6 \text{ n/s } \mu\text{g}) (\text{mass Cf}^{252})e^{-\lambda t} \quad (19)$$

Validation

Validation of the neutron simulation was completed by comparing the simulated interaction rates for a GS20 detector in a neutron beam of various energies (with various alignments of the beam and detector) and by direct comparison to the observed count rate of detectors. The direct comparison of the MCNPX simulation of a GS20 in a beam allowed for the comparison based on the

published attenuation rates which allowed for the material composition and correct interpretation of the tallies to be verified. Simulating the interaction rate of a detector in the neutron irradiator allowed for the geometry of the irradiator to be verified, as well as providing a verified framework for allowing other detectors to be simulated.

GS20 Beam Configuration

There is sufficient information published about GS20 that makes it an ideal candidate to validate the simulation for simple geometries. There is a large cross section variation for GS20, as shown in Figure 17, and the thickness of the detector allows for the investigation of the interaction rate as it depends on cord length and beam energies ranging from 0.025 eV to 250 keV.

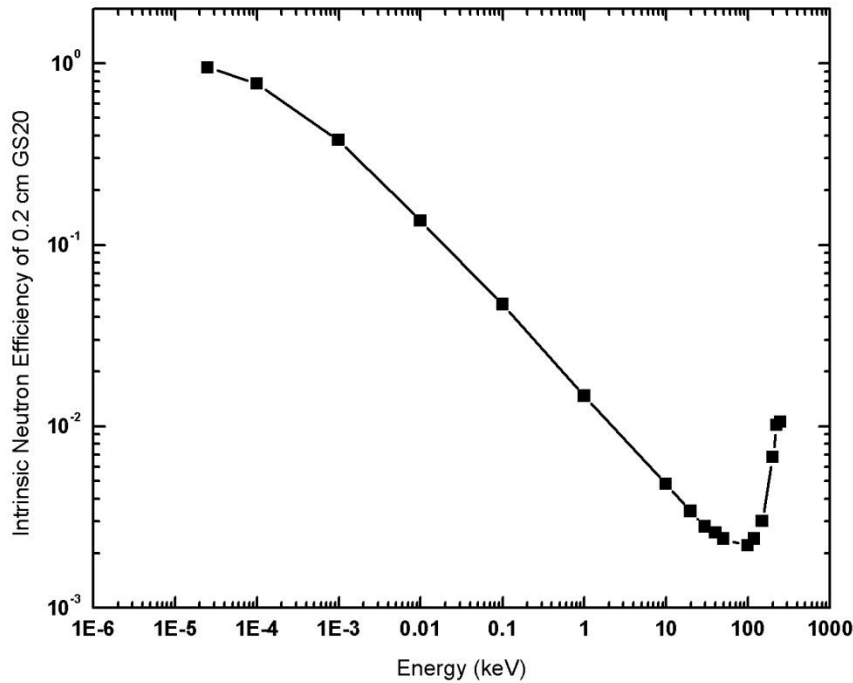


FIGURE 17 – INTRINSIC NEUTRON EFFICIENCY OF 0.2 CM GS20 [9]

The GS20 beam study was arranged in three classes of simulations; the being being oriented 0 degrees from the detector normal, 30 degrees, and 60 degrees as depicted in Figure 18. The 0 degree orientation allowed for a true beam to be validated, while the 30 and 60 degree orientations provided a way to validate that in the irradiator, where the flux would be non-isotropic, that the interaction rate would increase due to the increased path length the neutron travels (20).

$$\eta = 1 - e^{-\Sigma x}$$

$$x = x_0 \cos \theta$$
(20)

where:

- η is the fraction of the beam attenuated,
- Σ is the absorption cross section,
- and x is the projected distance that the neutron travels.

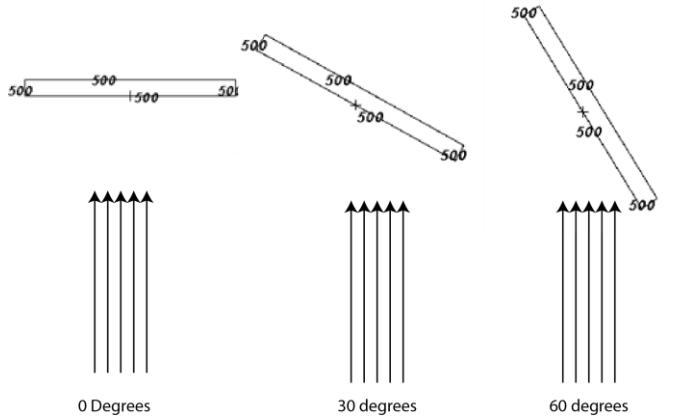


FIGURE 18 - GEOMETRY OF 0 DEGREES, 30 DEGREES, AND 60 DEGREES

For very low neutron energies (less than 1 eV) there was very good agreement (less than 5% relative difference) between the analytical and simulated for all angles. At higher energies the error between the MCNPX simulation and the attenuation calculation grows to around 20%. In all cases the MCNPX simulation had a lower intrinsic efficiency. At larger angles with high energies the effect of the detector (or the orientation of the detector relative to the beam) becomes apparent; as shown in Figure 19 there is a doubling of the interactions from 0 degrees to 60 degrees in the 100 keV range. It should be noted that this only shows the increase in path length and not any effects of projected area as the beam consist of a single neutron vector.

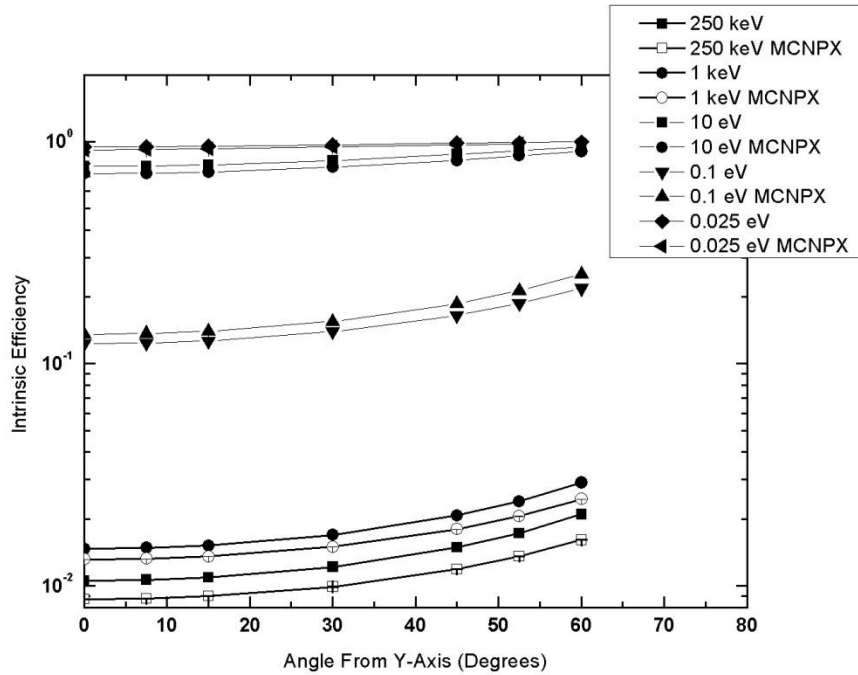


FIGURE 19 - INTRINSIC EFFICIENCY OF 0.2 CM GS20, AS DEPENDENT ON ENERGY AND ORIENTATION IN A BEAM

At low energies (eV range) GS20 has an attenuation coefficient about 100 times that at 1 MeV so varying the thickness of the detector by changing the angle of neutron incidence has very little effect; this is shown by the relative flatness of the curves in Figure 19. The relative difference ($\sigma_{rel} = \frac{Obs-Sim}{Sim}$) was calculated for each simulated error and averaged over all of the beam energies Table 13. For low energies there is excellent agreement, but for higher neutron energies the effects of the neutrons slowing down in the glass cause MCNPX to have a higher count rate than the analytical results.

TABLE 13 - AVERAGE RELATIVE DIFFERENCE OF SIMULATED INTERACTION RATE AND ANALYTICAL REACTION RATES FOR GS20 IN A NEUTRON BEAM.

Beam Energy	Average Relative Difference
0.025 eV	2.3%
0.1 eV	6.3%
10 eV	10.7%
1 keV	12.6%
250 keV	19.7%

Observed Count Rates of Films

The MCNPX simulation was validated by comparing the measured count rate to the simulated count rate for GS20, a PEN film, and a PS film measured in the neutron irradiator.

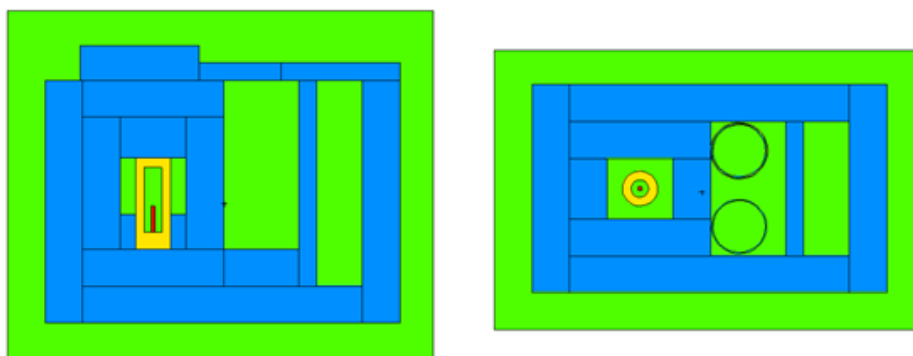


FIGURE 20 - MCNP RENDERING OF THE NEUTRON IRRADIATOR. THE SOURCE IS THE RED CYLINDER.

The simulated interactions rates (per source particle per cm^3) of each of the films are presented in the following table. In general the reaction rate is dominated by the response in the lead well as the lead well contains thermal neutrons.

TABLE 14 - REACTION RATE OF (N,T) REACTIONS PER CM³ PER SOURCE PARTICLE IN THE DETECTOR CELLS

Detector	Lead Well (x10 ⁻³)		Cadmium Well (x10 ⁻⁵)		Net Response (x10 ⁻³)	
GS20	0.767	3.8%	2.50	9.5%	0.742	4.0%
PEN Film, 66 microns	2.00	1.1%	4.15	10.7%	1.96	1.1%
PS Film, 25 Microns	2.01	1.1%	4.24	12.5%	1.97	1.2%
PS Film, 50 Microns	1.93	1.1%	4.05	11.7%	1.89	1.1%

The comparison between the simulated reaction rate and the observed count rate are presented in Table 15. The source strength was taken to be 0.5648 million neutrons per second.

TABLE 15 - COMPARISON BETWEEN SIMULATED COUNT RATE AND PREDICTED (N,T) REACTION RATE

Detector	Volume (cm ³)	Simulated Rate	Count	Observed Rate	Count	Relative Difference $\sigma_{rel} = (obs - sim) / obs$
GS20	1.0130	424.82	3.97%	428 [†]		-0.7%
PEN Film, 66 microns	0.1338	147.81	1.12%			
PS Film, 25 Microns	0.0507	56.23	1.19%	51 ^{†††}		9.5%
PS Film, 50 Microns	0.1013	108.10	1.14%	96		12.6%

[†]Sample measured 1 December 2011, ^{†††}Sample measured 30 January 2012

The incident neutron spectrum was calculated by applying a F1 tally to the surfaces bounding the detector. The net number of particles crossing the detector was calculated by subtracting the number of particles that cross the cadmium well from the number that crossed the lead well.

TABLE 16 - NUMBER OF PARTICLES CROSSING THE DETECTORS (MCNPX).

Detector	Lead Well	Cadmium Well	Net Crossing
GS20	8.50×10^2	3.12×10^2	5.37×10^2
PEN Film, 66 microns	1.12×10^4	4.64×10^3	6.58×10^3
PS Film, 25 Microns	1.12×10^4	4.65×10^3	6.59×10^3
PS Film, 50 Microns	1.12×10^4	4.65×10^3	6.57×10^3

†Source strength is 0.56 million neutrons per second

At the time of measurement 537 neutrons were simulated crossing the GS20 detector in the net spectra (Table 16) and 430 observed counts for a detector efficiency of around 80%. As shown in Figure 17, GS20 can reach detector efficiencies above 80% when the incoming neutrons have energies below an eV. Figure 21 shows the neutron spectra incident upon a GS20 detector in the characterization laboratory's neutron irradiator, where a large majority of the neutrons have been effectively thermalized.

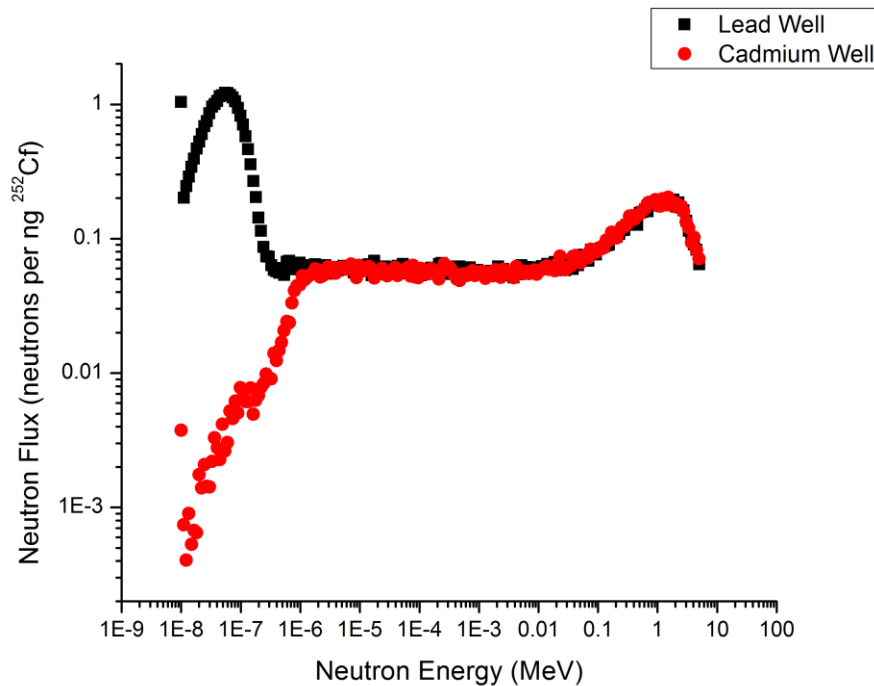


FIGURE 21 - NEUTRON FLUX INCIDENT UPON A GS20 DETECTOR IN THE CHARACTERIZATION LABORATORY IRRADIATOR

3. RESULTS

Three detector materials capable of meeting the DHS-DNDO criteria were modeled; two films (a PEN composite film and a PS composite film) and LiF:ZnS. Three detector designs were examined – a 1mx1m film with varying thickness of moderator and reflector for preliminary design work, a single film in the existing ^3He detectors footprint, and a layered film detector design in the ^3He detector footprint. The detector material (PEN composite, PS composite and LiF:ZnS) were measured for their neutron count rate, gamma lower level discriminator setting, and counts above the gamma LLD.

PERFORMANCE OF SELECTED FILMS

The neutronic performance of five selected films is presented in Table 17 while Table 18 characterizes the light yield. Values reported in parentheses are Poisson counting statistics $\pm 2\sigma$ which is roughly a 95% confidence interval, while the repeatability of these measurements is 30%, based on the analysis of the repeatability (Appendix A) The absorber mass is calculated based on the fraction of material that goes into the film. The actual amount of ^6Li contained in the film may vary due to material losses in the casting process (in the case of PS films) or pellet grinding and heat pressing (in the case of PEN films). Generally the count rate per mg ^6Li is around 6 cps per mg, but varies. It is thought the PEN films, with visible evidence of material domains, might be subject to significant neutron self-shielding. The neutron count rate at $\epsilon_{int,\gamma} \leq 10^{-5}$ and $\epsilon_{int,\gamma} \leq 10^{-6}$ is presented in order to provide an indicator of the shape of the neutron spectra. The light yield (Table 18) per neutron is expressed as a fraction of the calculated light yield per neutron of GS20 (6,250 Photons per MeV).

TABLE 17 – SUMMARY OF DETECTORS DISCRIMINATION PERFORMANCE.

	Absorber mass (mg)	Total Neutron Count Rate (cps)	Total Neutron Count Rate per Absorber (cps/mg)	Gamma such $\epsilon_{int,\gamma} \leq 1 \times 10^{-6}$ (channel number)	LLD that Count above $\epsilon_{int,\gamma} \leq 1 \times 10^{-6}$ (cps)	Neutron Count rate above $\epsilon_{int,\gamma} \leq 1 \times 10^{-5}$ (cps)
PEN 50% LiF 1% ADS156FS Stretched	9.10	53.04	5.89	3,192 (2,704 – 3,571)	11.45 (9.72 - 14.52)	23.81
PEN 70% LiF 25% PPO/POPOP 5% 158 um Annealed	19.6	92.4	4.71	5,053 (5,105 – 5,245)	21.2 (18.15 - 22.72)	41.34
PS LiF 9.66% PPO/POPOP 4.58% 26um annealed	1.37	8.25	6.02	2,899 (2,766 – 3,032)	2.25 (1.93 - 2.6)	4.33
PS LiF 29.9% PPO/POPOP 5.0% 50 um	9.33	82.64	8.86	3,837 (3,264 – 3,961)	1.01 (0.68 - 1.84)	17.59
EJ-426 HD2 (^6LiF in ZnS:Ag)	105	568.3	5.41	3,514 (4,139 – 3,747)	24.56 (17.05 - 30.27)	208.10

TABLE 18 – LIGHT YIELD OF THE SELECTED FILMS

	Alpha Peak (^{241}Am)	Beta Average (^{36}Cl)	$\alpha / < \beta >$	Photons per MeV (Gamma)	Photons per MeV (Beta)	Photons per MeV Neutrons
PEN 50% LiF 1% ADS156FS Stretched	2,592	355	0.34	500	916	1,560
PEN 70% LiF 25% PPO/POPOP 5% 158 um Annealed	2,885	765	0.18	1,398	1,673	2,440
PS LiF 9.66% PPO/POPOP 4.58% 26um annealed	4,074	345	0.55	1,354	1,540	1,500
PS LiF 29.9% PPO/POPOP 5.0% 50 um	3,491	393	0.41	1,141	1,117	1,120
EJ-426 HD2 (^6LiF in ZnS:Ag)	N/A	N/A	N/A	19,745	N/A	26,900

It should be noted that the while the measurements have been repeated on the 26 micron annealed PS film, testing on a 25 micron annealed PS film fabricated later yielded poorer results. In addition, the stretched PEN film has not reproduced.

PERFORMANCE OF A DETECTOR IN THE DHS FOOTPRINT

After determining the detector material response to neutrons and gammas the material was modeled (in MCNPX) in a RPM configuration. The source was modeled as a nano-gram sphere of ^{252}Cf (2.5 micron radius) surrounded by 0.5 cm of lead, and moderator by 2.5 cm of HDPE. This source configuration conforms to the one described in [11]. The modeled detector assembly included four components: the neutron detecting thin film, the front moderator, the rear reflector, and the material encasing the detector. The interaction rate above a gamma intrinsic efficiency of one in a million of the simulated detector assembly was calculated by multiplying the (n,t) reaction rate by the volume of the detector and source strength of 1 ng ^{252}Cf . The effect of a setting a gamma LLD was incorporated by multiplying the interaction rate per ng ^{252}Cf by the fraction η of the neutrons counts that are above the MLLD (21).

$$\text{Detector Interaction Rate} = \#(n, t) \times V \times \frac{2.3 \times 10^3 \text{ n/s}}{1 \text{ ng Cf}^{252}} \eta \quad (21)$$

where:

- $\#(n, t)$ is the number of (n,triton) interactions (per source particle per volume),
- V is the volume of the detector,
- $\frac{2.3 \times 10^3 \text{ n/s}}{1 \text{ ng Cf}^{252}}$ is the source strength of 1 ng of ^{252}Cf ,
- And η is the fraction of neutron counts that occur above the gamma MLLD, as determined from measurement.

Figure 22 shows the incident spectra upon the detector surface. The spectra is almost completely moderated before it is incident upon the portal monitor.

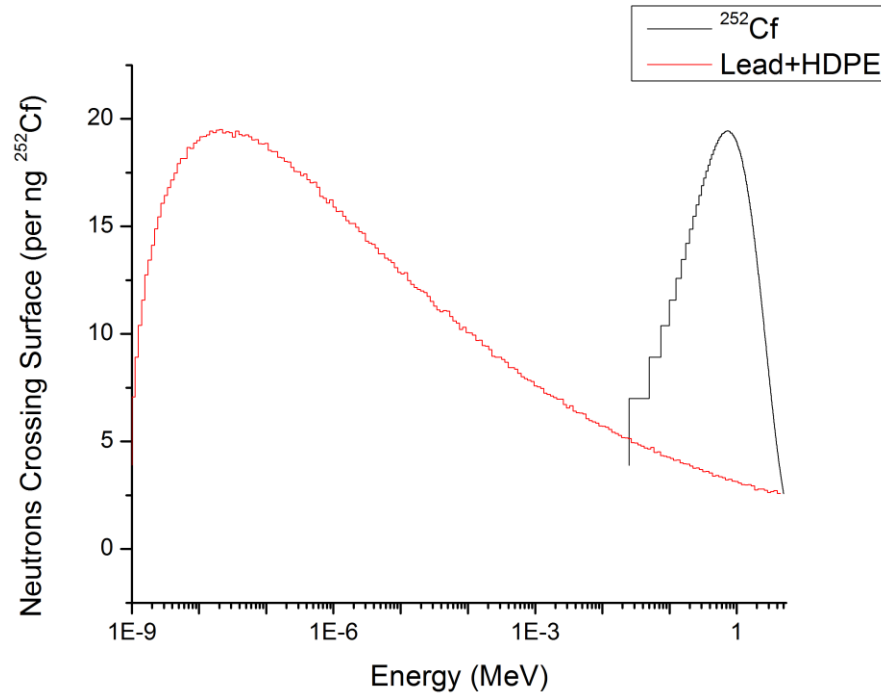


FIGURE 22 - ^{252}Cf WATT FISSION SPECTRA (BLACK) AND THE MODERATED AND SHIELDED SPECTRA (RED) INCIDENT UPON A DETECTOR IN THE RPM8 GEOMETRY

SINGLE FILM WITH VARYING MODERATOR AND REFLECTOR THICKNESS

The detector assembly was modeled as a 1m x 1m 50 micron 30% PS LiF film, with a varying thickness of moderator and reflector. The detector assembly was encased in 1/8" steel, but as shown later the encasing material (even if it is a neutron multiplier) makes little difference on the efficiency of the detector.

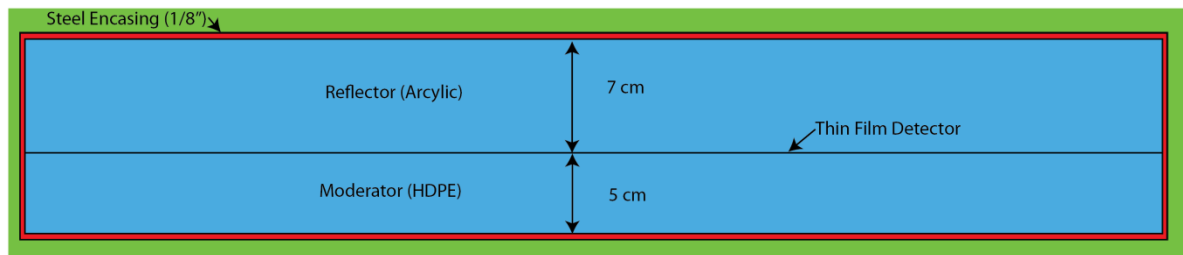


FIGURE 23 - CROSS SECTION OF DETECTOR ASSEMBLY.

A parametric study was completed to determine the optimal thickness of the moderator and the reflector. The moderator serves to slow down the neutron which increases the likelihood of a

capture reaction, while the reflector serves to reflect neutrons that are exiting the detector back towards the film. Too thick of a moderator, however, and it will start to server as the reflector and the detector will see less neutrons.

The results of this study are shown in Figure 24. A reflector thickness greater than 7 cm provides little gain. The moderator needs to be at least 3 cm in order to reduce the neutron energy such that a capture reaction is likely, but past a thickness of 8 cm the presence of the moderator serves to impede the detector performance by reducing the neutron flux. A significant increase (over 60%) can be reached by increasing the reflector from 1 cm to 7 cm.

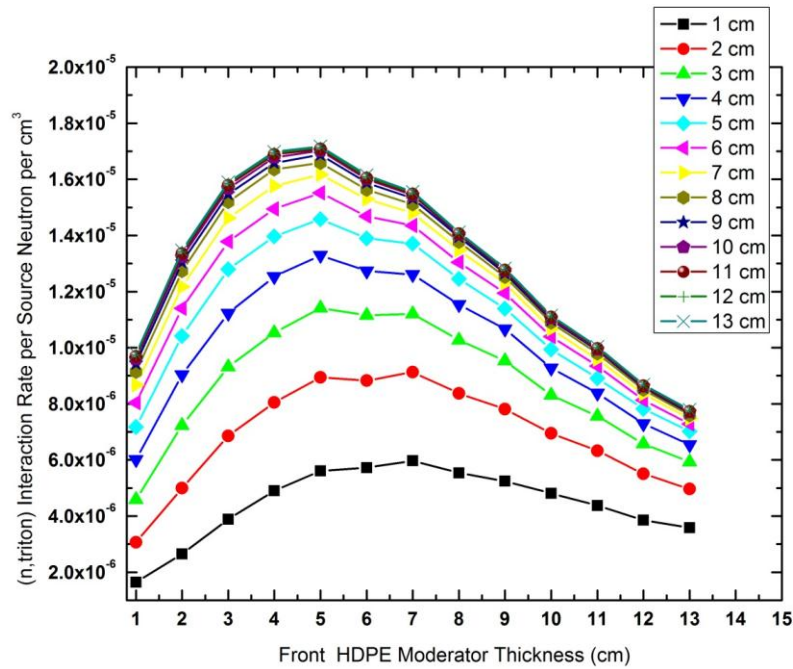


FIGURE 24 - PARAMETRIC STUDY OF REFLECTOR AND MODERATOR THICKNESS FOR A SINGLE FILM. EACH CURVE REPRESENTS A DIFFERENT THICKNESS OF THE REFLECTOR, WHILE THE THICKNESS OF THE MODERATOR IS SHOWN ON THE ABSCISSA.

In addition to the moderator and reflector thickness, the material encasing the detector was investigated. If the detector was encased in a neutron amplifier then number of neutrons crossing the detector would be increased. Two promising amplifier materials are nickel or beryllium because of their (n,2n) reactions. Slight gains were made with Be, but it is thought that those gains do not outweigh the cost and hazards of Be. The results, reported in number of (n,triton) reactions per cm³ per source particle are summarized in Table 19 for a 1m x 1m single film with a 5cm moderator and 7 cm reflector. There is only moderate improvement over having no encasing material for the three materials investigated.

TABLE 19 - ENCASING DETECTOR MATERIAL. MODERATE IMPROVEMENTS ARE MADE FROM THE PRESENCE OF A NEUTRON MULTIPLIER.

	#(n,t) reactions per cm ³ per source particle
Air (no encasing material)	1.45
SS-316	1.46
Beryllium	1.48
HEU	1.96

While the modeled DHS detector assembly has a 63% higher intrinsic efficiency than the film modeled in the characterization laboratory irradiator. If implemented, however, it would have to have a size of 5.8 m², covering 70% of the solid angle in order to have a count rate of 2.5 cps/ng ²⁵²Cf.

LAYERED DETECTOR IN DHS-DNDO FOOTPRINT

Individual films do not possess intrinsic neutron efficiency high enough to satisfy all of the requirements of a DHS-DNDO detector. A layered detector of multiple films was investigated in order to increase the interaction rate. In order not to have prohibitive sacrifices in gamma discrimination the reaction products from a gamma interaction in one film must not create scintillation in another film; if this occurs the gamma LLD will shift to higher channel numbers and the potential benefit of layering multiple films will be outweighed by the hit taken on usable neutron counts.

Experimental Verification

To confirm the extent of this effect an experiment was completed in which four PVT based LiF films were stacked to different heights with different amounts of spacing. Figure 25 shows a significant increase in the neutron count rate, while the gamma spectra (Figure 26) only demonstrates a moderate increase in gamma spectra. Light collection then becomes an integral part of the detector; it was thought that the reason why the neutron count rate did not quadruple with four films relative to the single film was poor light transmission through the films. In the following detector designed it is assumed that the films are transparent to each other, i.e. there is perfect light transmission. This assumption was necessary in order to make the MCNPX model, and will be addressed in future work.

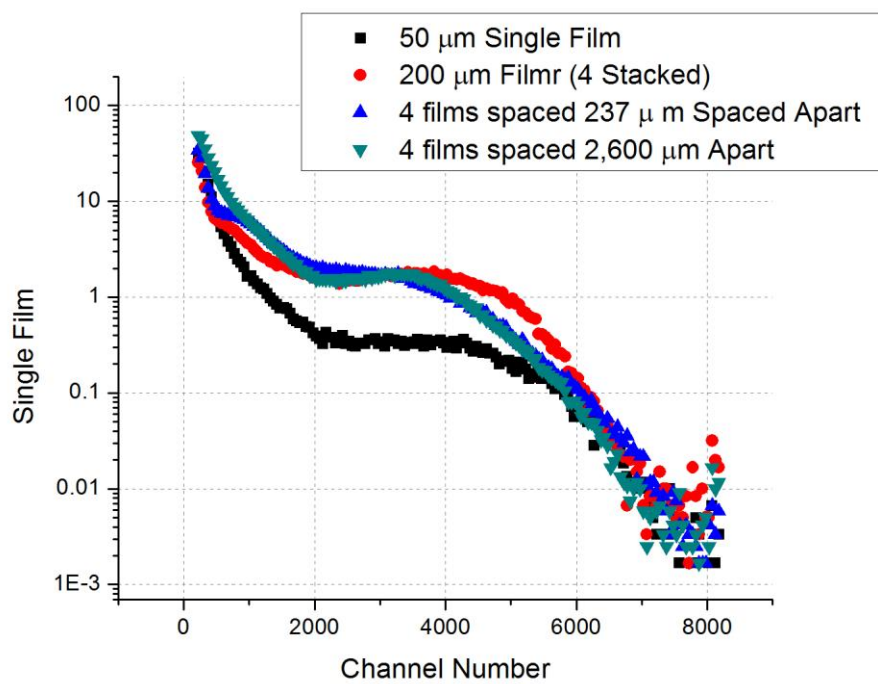


FIGURE 25 - NEUTRON SPECTRA OF STACKED PVT BASED LIF FILMS. HAVING FOUR MORE FILMS INCREASED THE COUNT RATE FROM A SINGLE FILM, WITH LITTLE EFFECT OF THE SPACING BETWEEN THE FILMS

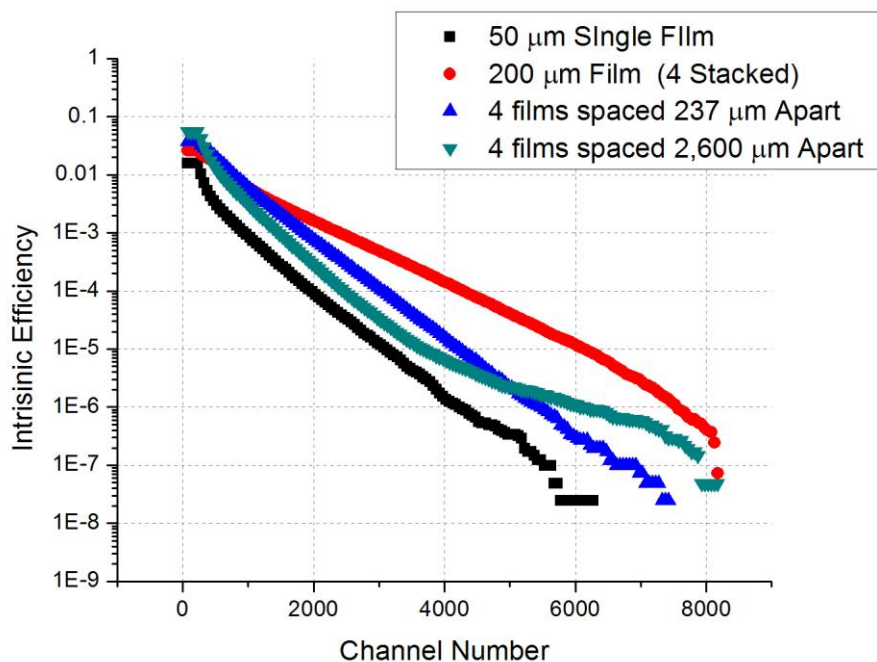


FIGURE 26 - INTRINSIC EFFICIENCY OF DIFFERENT CONFIGURATION OF FILMS. THE FILMS SEPARATED BY A NON(WEAKLY)-SCINTILLATING MATERIAL DID NOT EXPERIENCE THE INCREASE A DRAMATIC INCREASE IN INTRINSIC EFFICIENCY.

LiFZnS:Ag has been evaluated for the film material in a layered detector design. A single EJ-426HD film provided by Dr. Penamadu and measured on 17 June 2012 had a net count rate of 568.3 cps (5.41 cps per mg ^6Li), with a count rate of 24.56 cps above the necessary lower level discriminator to achieve 10^{-6} gamma intrinsic efficiency. The films high light yield (measured at 19,745 photons per electron equivalent MeV and 26,900 photons per neutron) made these films an attractive system to test the layered film concept.

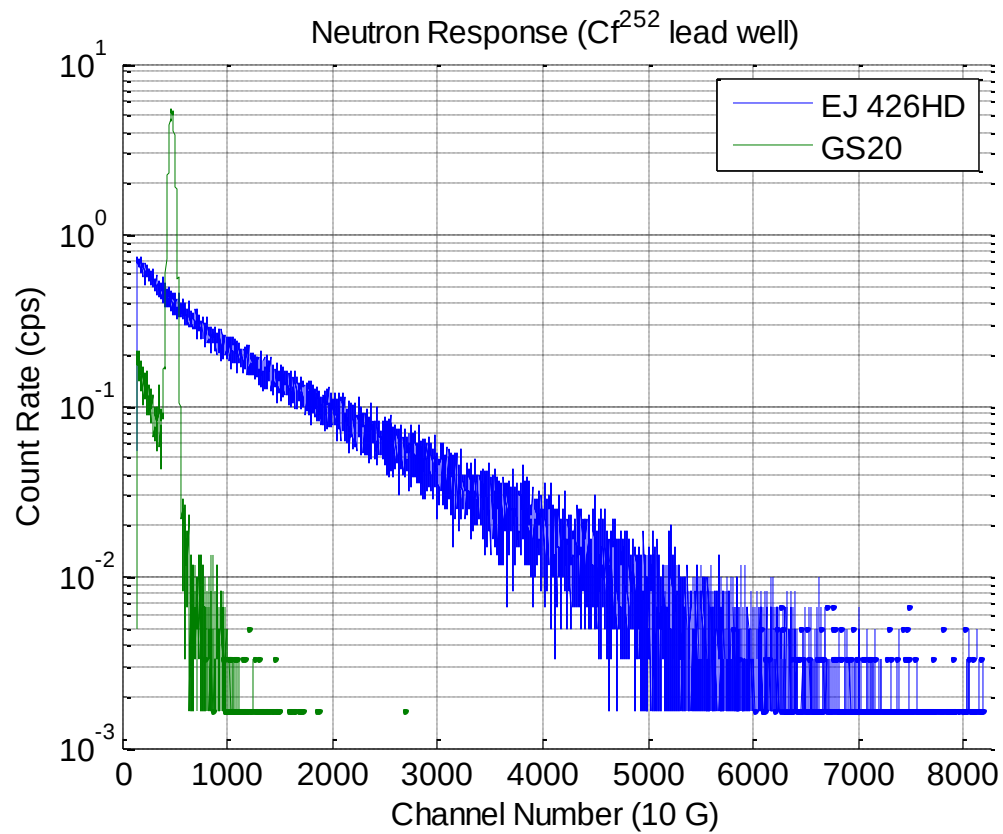


FIGURE 27 - COMPARISON OF NEUTRON RESPONSE OF GS20 AND EJ-426 HD, BOTH MEASURED AT 1,000V AND 10 GAIN. THERE ARE 398.1 CPS IN THE GS20 SPECTRA, AND 599.7 CPS IN THE EJ-426HD.

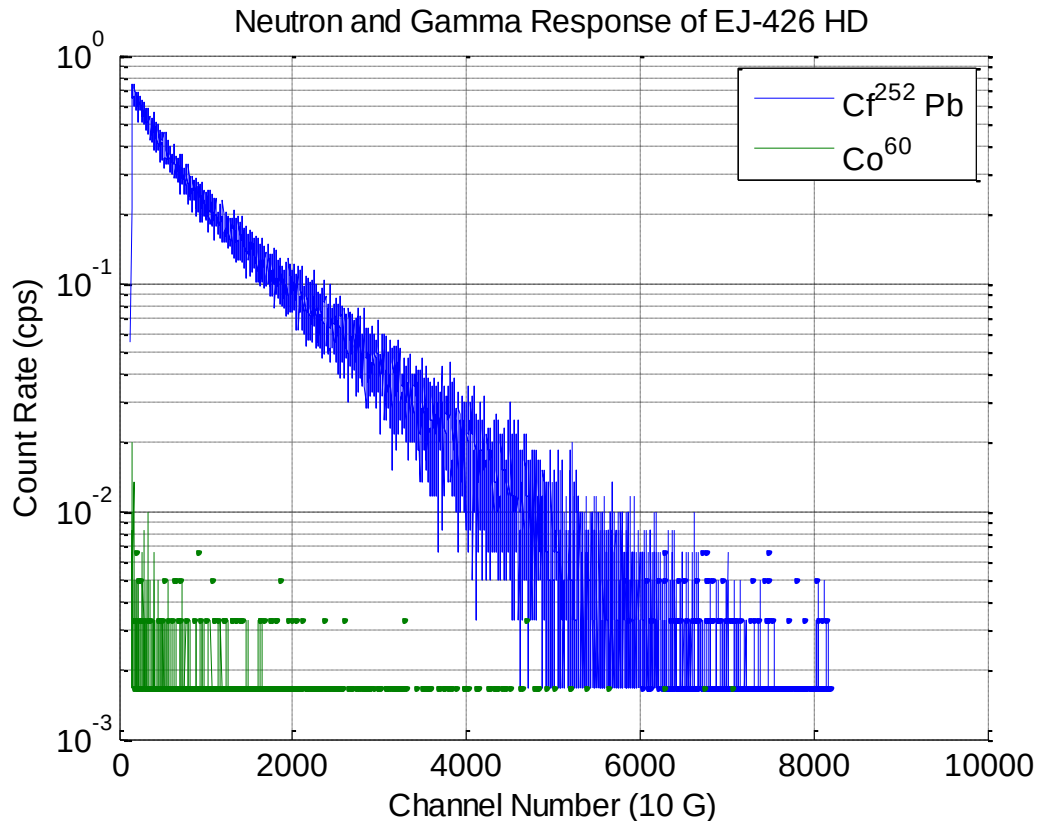


FIGURE 28 - NEUTRON AND GAMMA RESPONSE OF EJ-426 HD FILMS

EJ-426 HD PE screens were acquired from Eljen Technologies based in Sweetwater, Texas. Multiple screens of two sizes were acquired; 4" x 1.4" x 1 mm and 1.4" x 1.4" x 1 mm. PMMA slabs were also provided, measuring 4" x 1.4" x 0.1" and 1.4" x 1.4" x 0.1". The performance of the single film was determined by sandwiching a single 1.4" x 1.4" sheet of EJ426 HD-PE between PMMA slabs atop of the PMT and mounting the slabs to the PMT with optical grease (Figure 29).

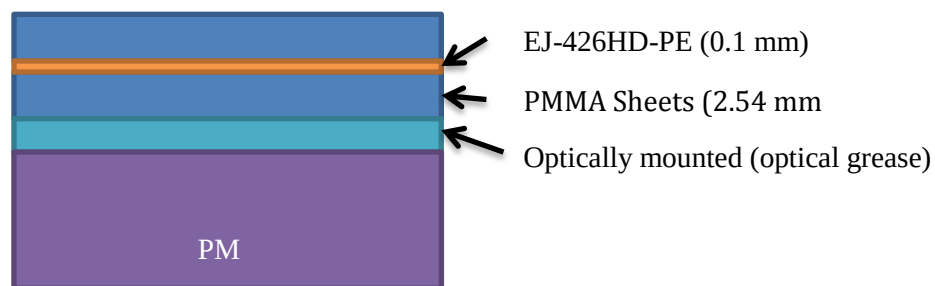
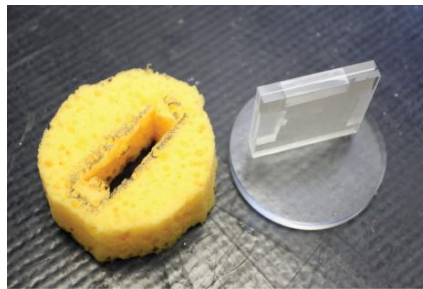


FIGURE 29 - MOUNTING OF SINGLE HORIZONTAL FILM

Another configuration consisted of a single sheet vertically mounted onto a PMT by sandwiching the sheet between two slabs (either PMMA or glass) and wrapping with Teflon tape to increase

light collection and then with gaffers tape to make the system light tight (Figure 30). The system was then optically mounted to the PMT using optical grease. Similarly, four of the EJ-426HD sheets were layered between PMMA slabs, as shown in Figure 31.

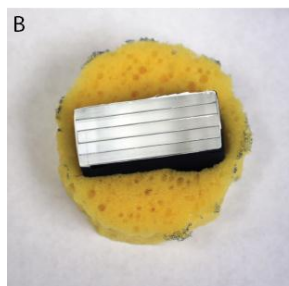
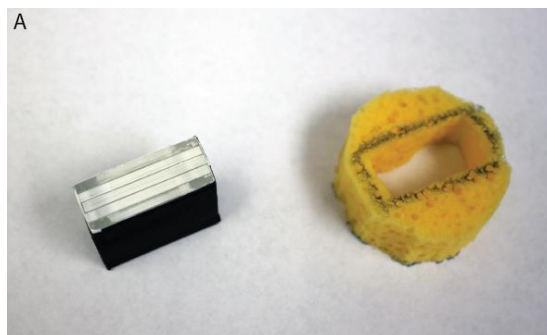


A - Unwrapped Single ^6LiF loaded ZnS:Ag sheet. The sheet is sandwiched between two PMMA slabs, with the narrow edge optically coupled to the PMT. The yellow sponge is provide for support.



B - Single ^6LiF loaded ZnS:Ag Sheet (1.4" x 1.4") wrapped in Teflon tape (white), and gaffer tape (black).

FIGURE 30 -FABRICATED SINGLE WRAPPED SHEET.



A - Four sheets of ^6LiF loaded ZnS:Ag separated by PMMA, already wrapped in Teflon and gaffer tape. B - Assembled detector in sponge for support. C - Assembled detector atop PMT.

FIGURE 31 - FABRICATED MULTIPLE FILMS.

The single film (orientated horizontally on the PMT) had a higher neutron count when glass (about ¼" thick) was used to collect the light compared to the PMMA slabs (0.1" thick), but it also had a decline in the light yield. This is an indicator that the separating material could be optimized for increased light collection. The spectra were also the first spectra of LiFZnS:Ag that displayed a peak. Other LiFZnS:Ag films measured were either 0.32 mm or 0.5 mm; so it is hypothesized that the thicker LiFZnS:Ag films experience a light loss in the film. It should be noted that this does not suggest a preference of one material over the other, but rather there is room for further study.

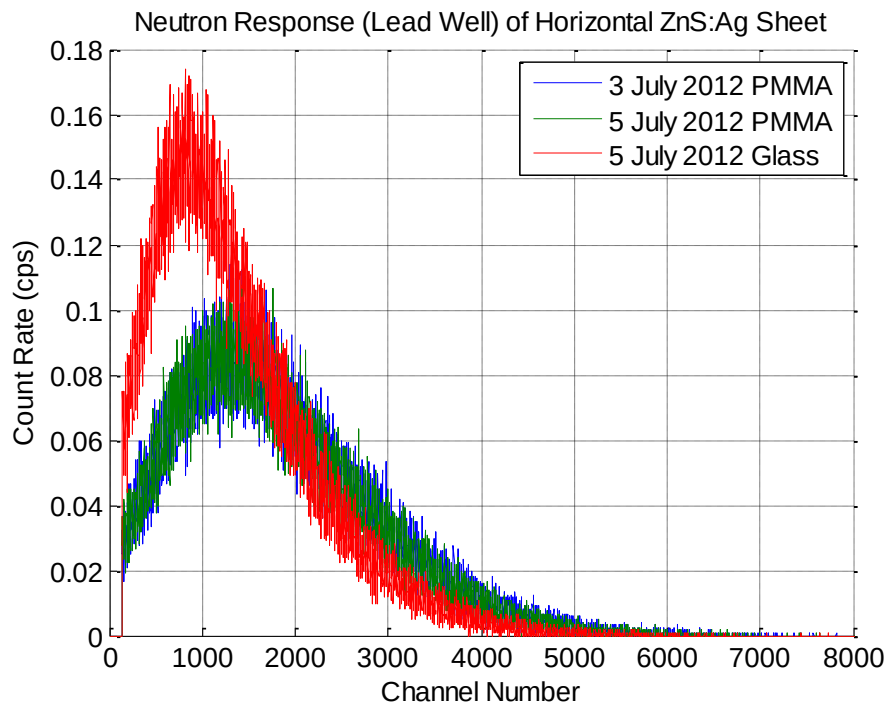


FIGURE 32 - NEUTRON RESPONSE OF HORIZONTAL LIFZNS:AG SHEET

The thickness of the glass plates made it difficult to orient vertically, so only the PMMA sandwiched films were oriented vertically (as shown in Figure 30). A comparison between the neutron performance of the horizontal sheet and vertical sheet is shown in Figure 33. A significant decrease in light output was observed in the vertically oriented sheet with the peak decreasing from 1,190 to 700 channels, while the count rate increased from 202 cps to 245 cps. The increase is due to contributions from the counts on the far side of the sheet in the horizontal orientation that are reflected back into the film instead of the PMT. Exposed to the gamma field the film oriented horizontally atop the PMT had larger amount of counts further out than the film oriented vertically.

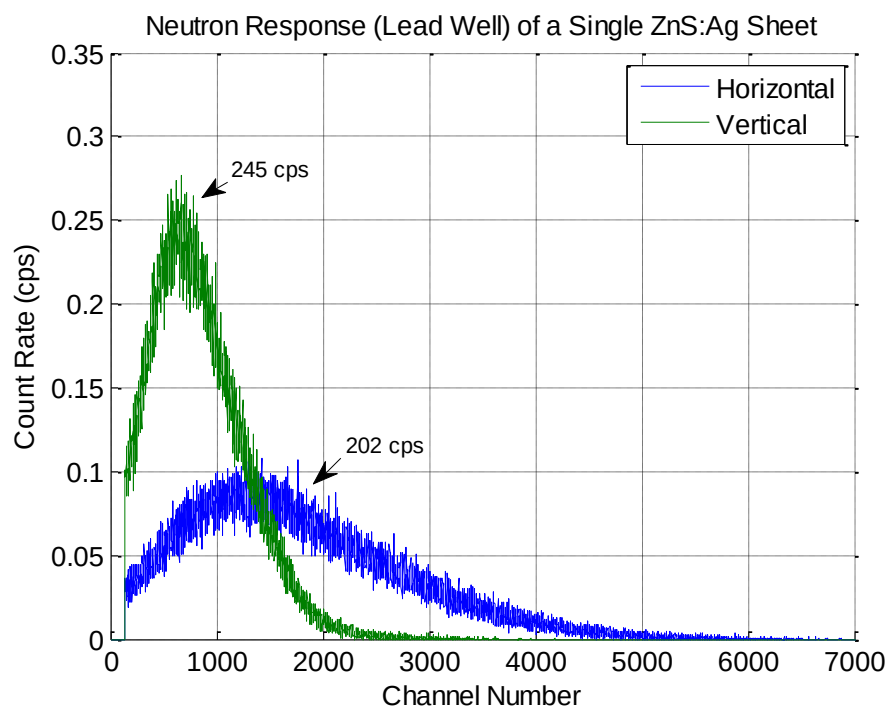


FIGURE 33 - COMPARISON BETWEEN THE HORIZONTAL ORIENTATION AND VERTICAL ORIENTATION OF A SINGLE PMMA FILM. THE VERTICAL FILM HAS A HIGHER COUNT RATE BECAUSE THE HORIZONTAL COUNT RATE FILM WILL LOSE COUNTS THAT OCCUR ON THE SIDE OF THE FILM FARTHEST FROM THE PMT.

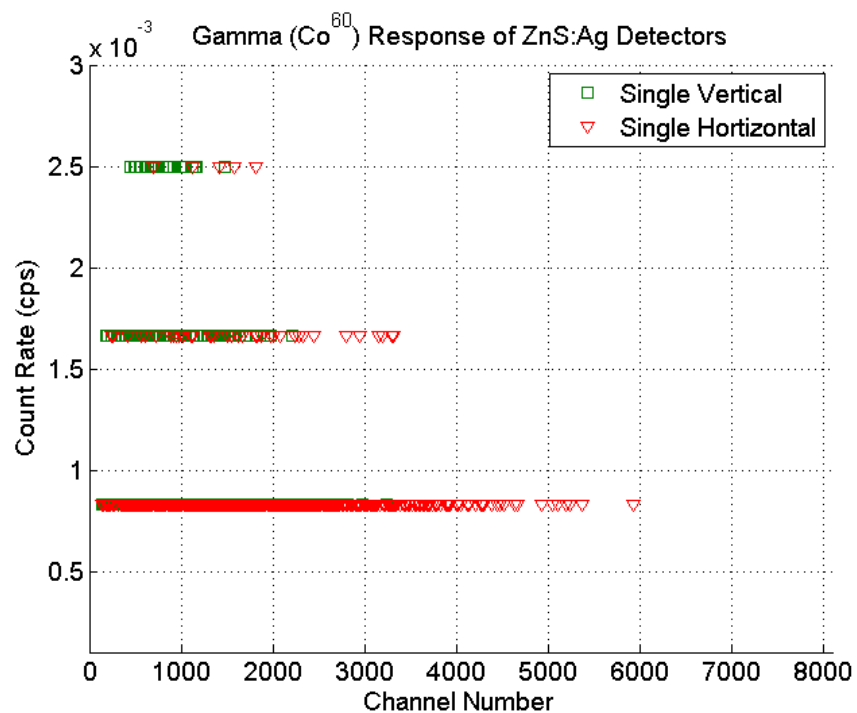


FIGURE 34 - GAMMA RESPONSE OF VERTICAL AND HORIZONTAL LIFZNS:AG SHEETS

The addition of three additional sheets (total of four sheets) each 1.4" x 1.4" in the vertical orientation (as described in Figure 31) showed an increase in the neutron count rate to 692 cps from 245 cps for a single film, with a small decrease in the peak position to 539 channels (the single film oriented vertically was 690 channels) which is attributed to light collection and mounting. It was expected that the count rate for the four films would be four times that of a single film (~980 counts total) but this was not observed and was attributed to self-shielding in the material.

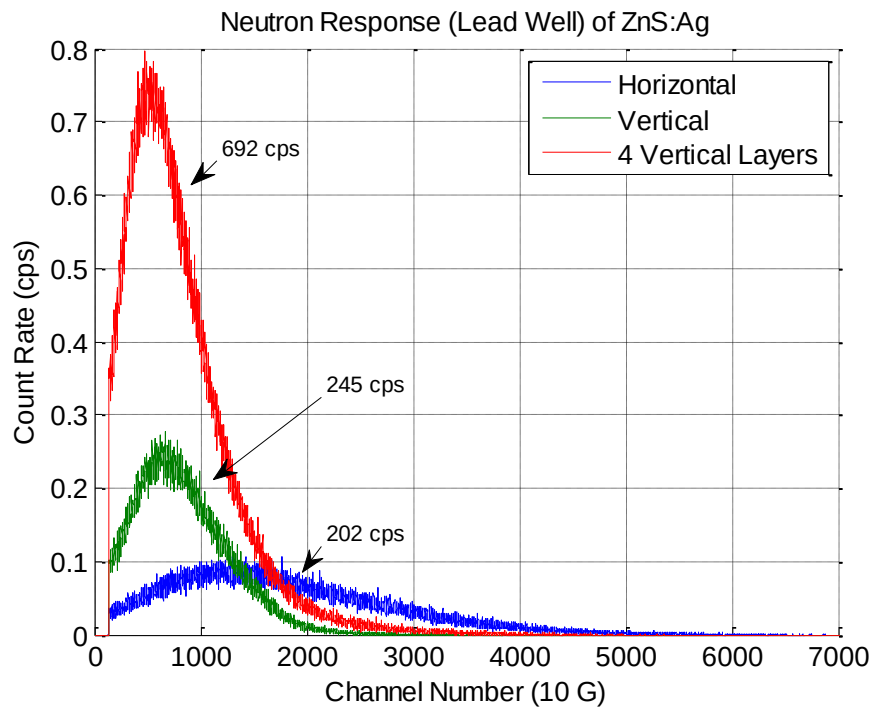


FIGURE 35 - COMPARISON OF THE NEUTRON RESPONSE OF THE 1.4" X 1.4" LIFZNS:AG SHEETS.

The gamma response of the four layered sheets showed an increase in the count rate (especially at the low channels), with more counts in the higher channels than the single vertically oriented sheet, but fewer than the horizontal sheet (Figure 36 and Figure 37).

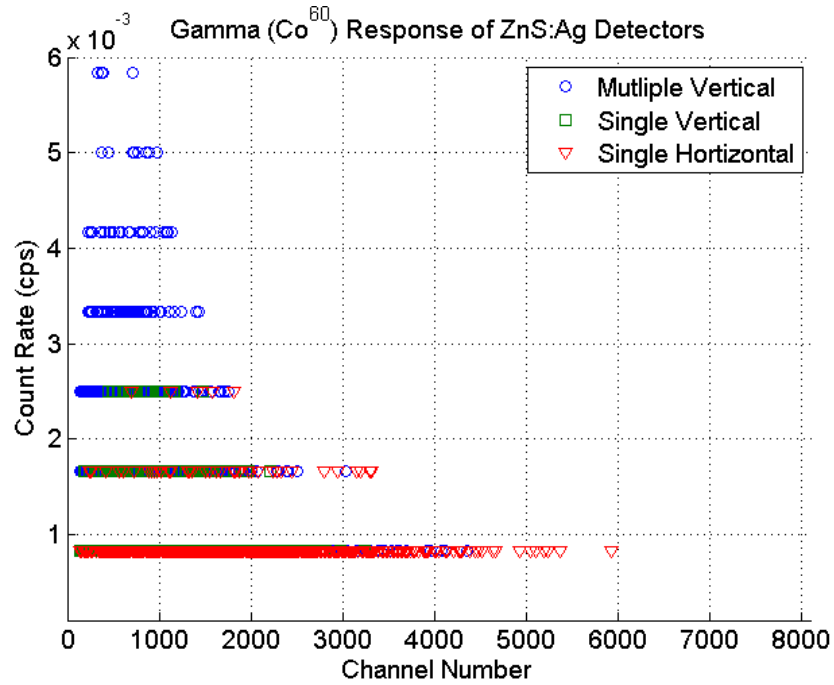


FIGURE 36 - GAMMA RESPONSE OF 1.4" X 1.4" LAYERED LIFZNS:AG SHEETS

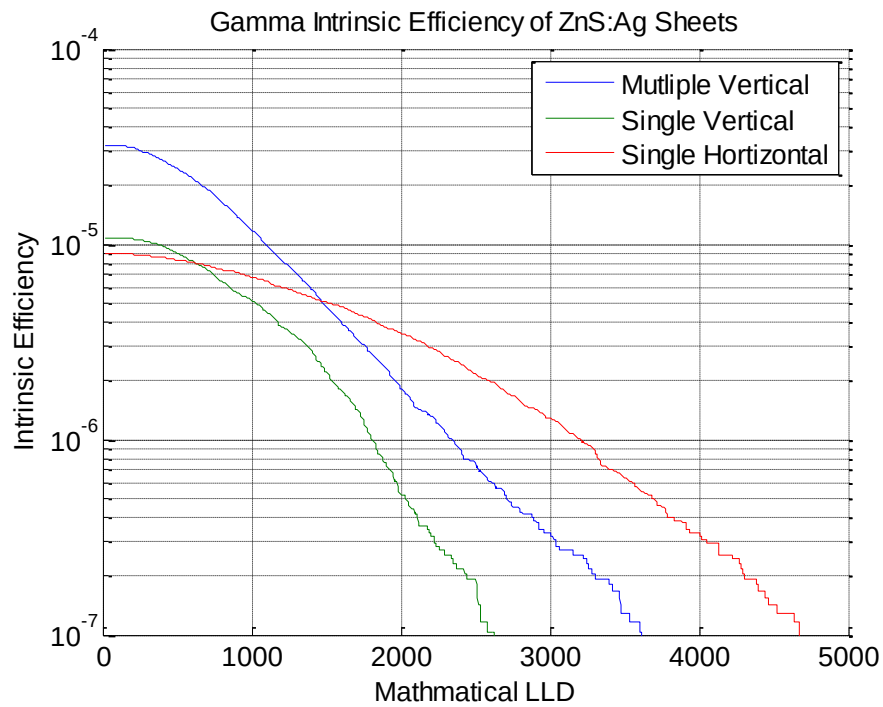


FIGURE 37 - GAMMA INTRINSIC EFFICIENCY OF 1.4" X 1.4" LIFZNS:AG SHEETS

Simulated Detector Performance

The layered detector model consists of films separated by acrylic, rendered by MCNPX in Figure 38. The thickness of the films varied to match the film measured, but the thickness of the acrylic was set at 1 mm. This distance was chosen so that most of the reaction products of gamma interactions would deposit their energy in the non-scintillating acrylic. The rendering shows the films oriented vertically, but horizontally oriented films were also investigated. It was concluded that horizontally oriented films had a 9% decrease in interaction rate, but this orientation could make for easier light collection.

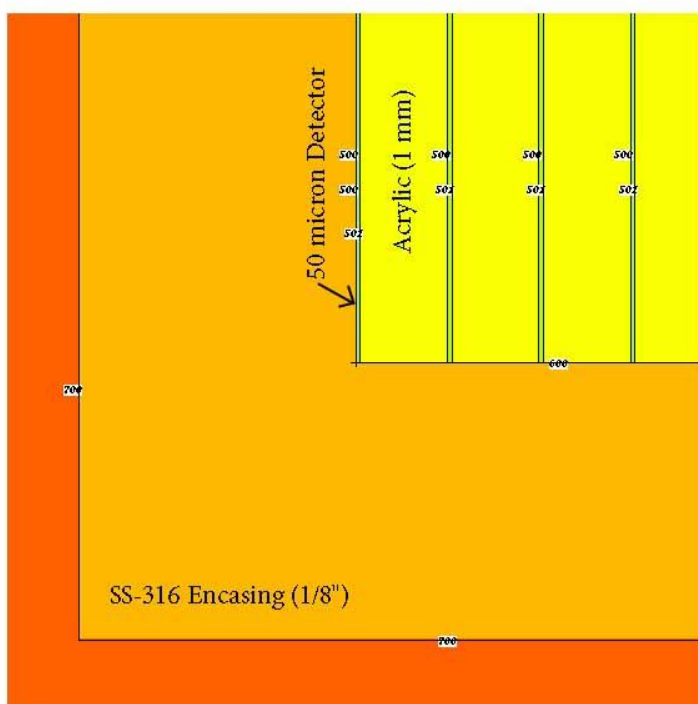


FIGURE 38 - MCNPX MODEL OF LAYERED PS FILMS, RENDERED BY MATERIAL WITH CELL NUMBERS.

The performance of the layered detector was investigated as a function of the layer of the in the detector in order to better understand the detectors performance. Figure 39 shows the neutron spectra for a selected number of films (from the first to the last) in the detector with the source neutron spectra superimposed. It should be recalled that the source spectra is a moderated ^{252}Cf spectra, the difference between the two is shown in Figure 22. It is observed that after about half-way through the detector the neutron's crossing the films have dropped and order to 10, and once they are crossing the last film (12.5 cm) they have dropped almost two magnitudes. It is also noted that the additional films to not serve to thermalize the spectra – as the spectra is already thermalized when it reaches the detector.

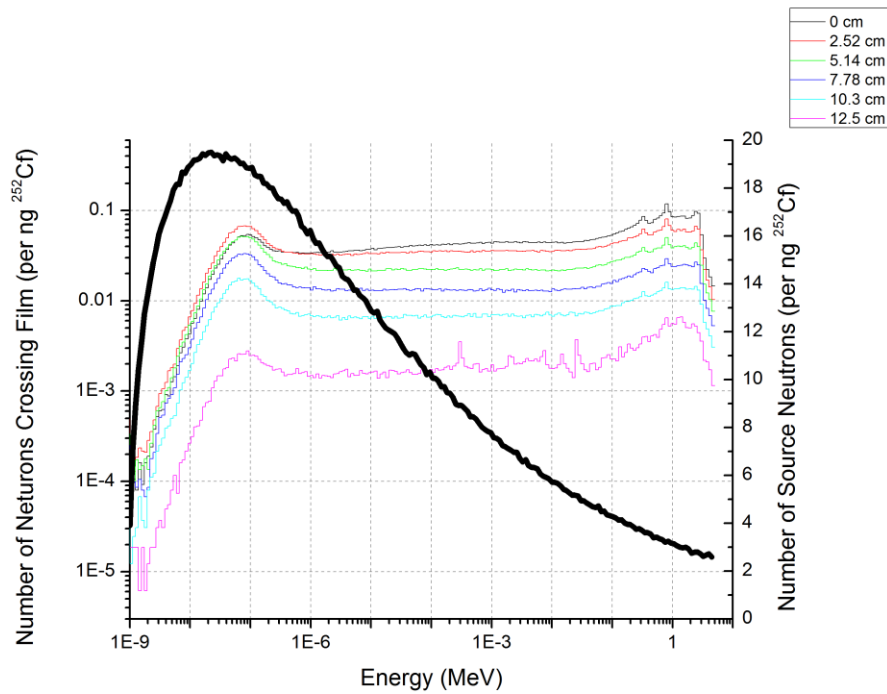


FIGURE 39 - NEUTRON SPECTRA OF PARTICLES INCIDENT UPON DIFFERENT FILMS (WHOSE POSITION IS ENUMERATED IN THE LEGEND) IN THE LAYERED DHS DETECTOR. THE SOLID BLACK LINE IS THE SPECTRA OF NEUTRONS LEAVING THE SOURCE SETUP.

The numbers of reactions are plotted as a function of film position in Figure 40. Films farther away from the front of the detector see fewer neutrons (Figure 39) with little gain in spectra. In addition, as seen in the parameter study of a single film (Figure 24) a five cm thick moderator is a good compromise before neutrons are reflected. This implies that it would be a better use of the material to have the detector thinner and wider.

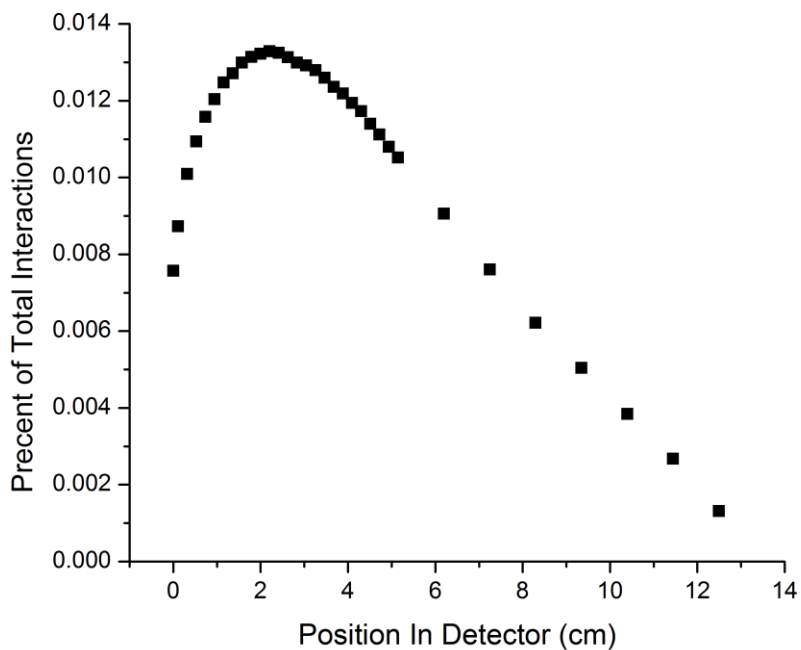


FIGURE 40 - (N,TRITON) INTERACTIONS AS A FUNCTION OF LOCATION IN THE DHS-DETECTOR FOR A PS FILM. OVER 30% OF ALL OF THE INTERACTIONS OCCUR IN THE FIRST FIVE CM OF THE DETECTOR.

Holding the volume of the detector constant the total number of interactions as a function of detector thickness was investigated for a 30% LiF PS film in order to find the optimal use of the detector material. It was found that a 20% increase in the count rates could be achieved if the detector was 6 cm thick instead of 12.7 cm; this of course means that the detector would be 64 cm wide. This effect is due to the depression in flux caused by the absorption of previous layers. This can be best seen in Figure 41.

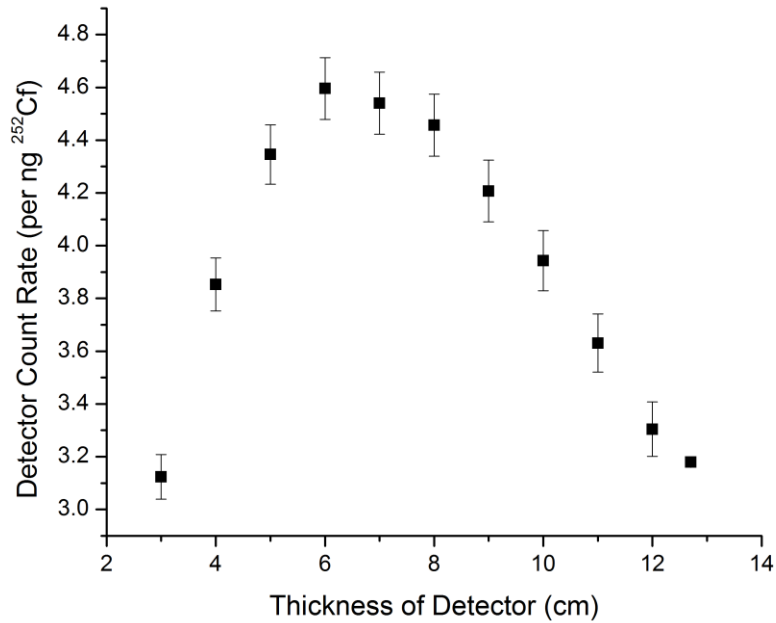


FIGURE 41 - OPTIMAL DETECTOR THICKNESS FOR A 30% LIF PS FILM.

Wrapped Films (Cylinders)

One can imagine a detector fabricated by laying down a sheet of acrylic, layering a ⁶LiF PS or PEN film atop of it, and then rolling up the entire assembly into a cylinder. The PMT would be placed at either end of the cylinder, with the acrylic acting as a light guide for photons generated in the scintillating film. This geometry was modeled for a 5" PMT, which required that the cylinder had a 5" diameter. Two simulations were completed, one with two cylinders oriented vertically and another with 16 cylinders oriented horizontally.

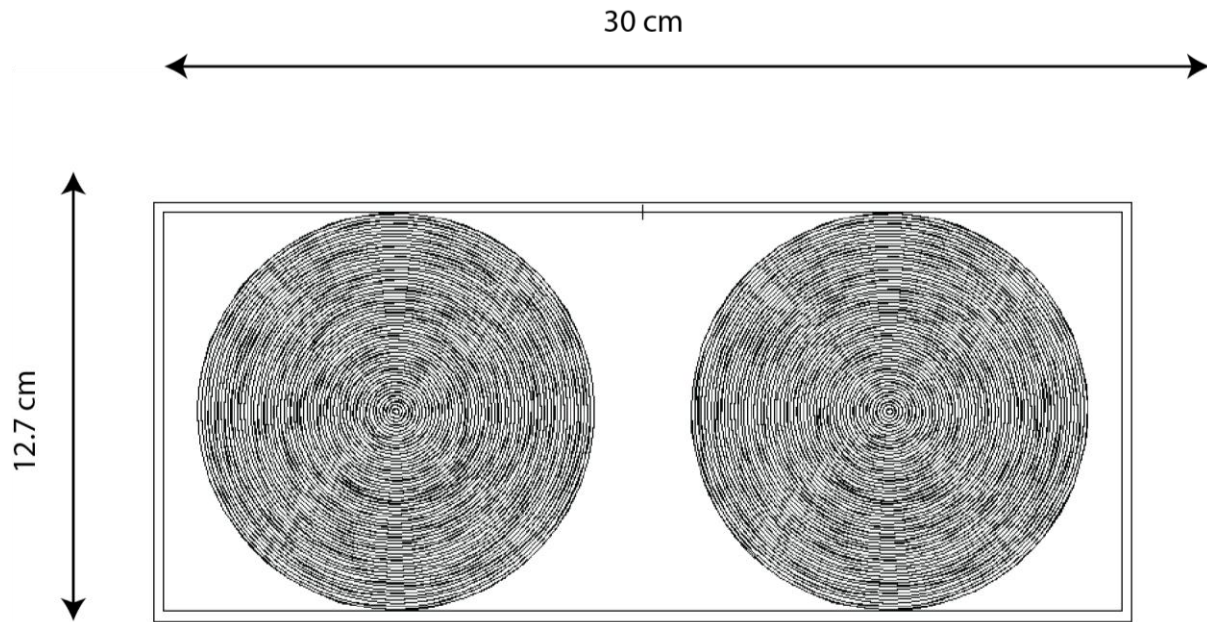


FIGURE 42 - MCNPX RENDERING OF 5" CYLINDER FILMS, SHOWN AS AN X-Y PROFILE.

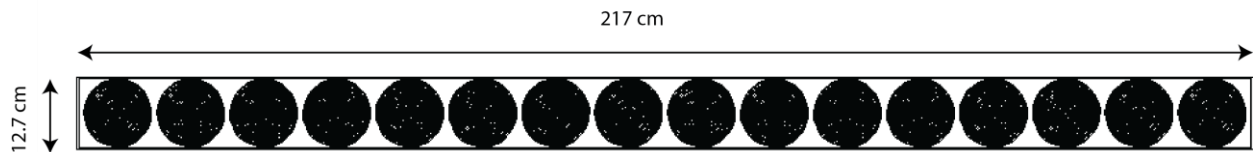


FIGURE 43 - MCNPX RENDERING OF 16 HORIZONTALLY STACKED 5" CYLINDERS SHOWN AS AN X-Z PROFILE

The following table shows the simulated interaction rate in each of the assemblies (50 micron polystyrene films loaded with 30% LiF). Volume normalized the vertical detector almost had twice as many interactions, which is impart due the cylinders on the end of the horizontal configuration not receiving as much flux from the source compared to those in the center.

TABLE 20 - COMPARISON BETWEEN VERTICAL AND HORIZONTAL FILMS FOR A 30% LiF PS FILM WITH AN EFFICIENCY OF 30% ABOVE THE GAMMA LLD. THE CYLINDERS WERE ORIENTED VERTICALLY AND HORIZONTALLY, AND ARE AN INDICATOR OF THE PMT'S NEEDED.

	Number of Cylinders in Detector Volume	Volume of Absorber (cm ³)	Count Rate per ng ²⁵² Cf for 30% LiF PS	Count Rate per ng ²⁵² Cf for 30% LiF PS per Detector Volume (cps per cm ³)
Vertical	2	2,630	2.69	1.02 x 10 ⁻³
Horizontal	16	2,980	1.55	0.250 x 10 ⁻³
6 cm of layered films		4,005	4.59	1.15 x 10 ⁻³

Improved Detector Design

Improved performance of the films (as well as unexpected light yield losses) lead to a small exploration of the parameter space in order to determine the fewest number of layers possible to achieve the necessary count rate (2.1 cps per ng ²⁵²Cf) while still maintaining the gamma discrimination. MCNPX was used to simulate films consisting of 120 layers to 5 layers. Having previously demonstrated the effects of a moderator and reflector for a single film, the geometry was modeled such that the remaining material in the RPM was set to be moderator up to a distance of 4 cm; past a moderator thickness of 4 cm the remaining material was set as the reflector (Figure 44). The results indicate that around 38 layers are needed for the LiF:ZnS films, while the composite PEN film requires 75 layers (Figure 45) for a detector that would fit into the existing RPM8 (12.7 cm x 30 cm x 217 cm).

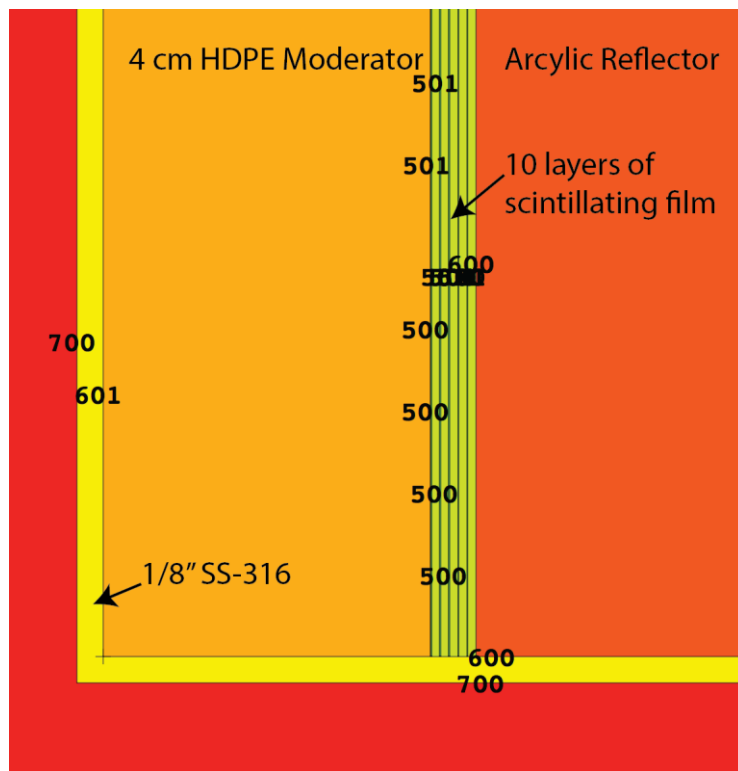


FIGURE 44 - GEOMETRY MODELED FOR LAYER OPTIMIZATION

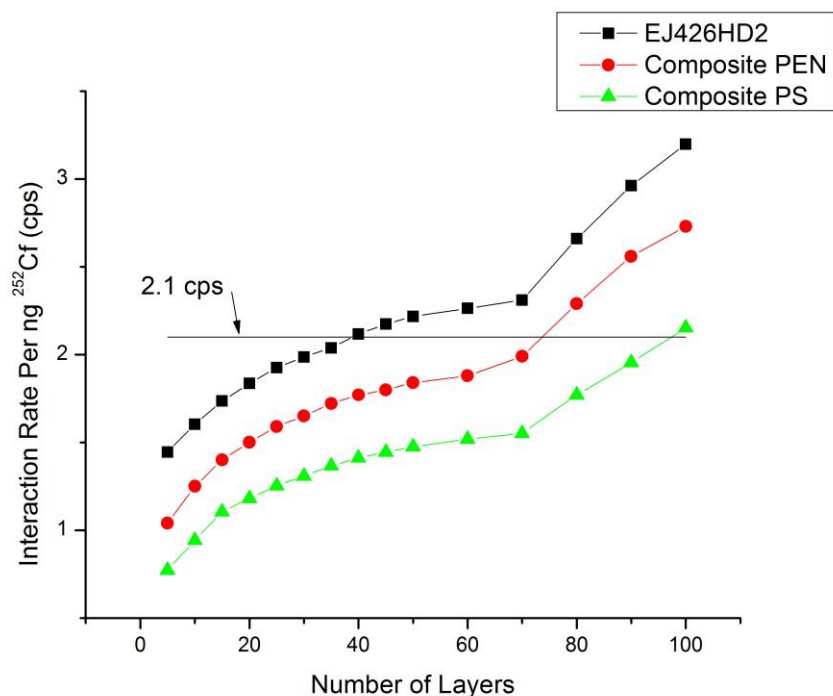


FIGURE 45 - MODELED INTERACTION RATE FOR THE LAYERED OPTIMIZED DETECTOR

ENHANCED DISCRIMINATION THROUGH PULSE SHAPE DISCRIMINATION

Pulse shape discrimination can be used to enhance the gamma discrimination by providing additional information for pulse classification. While the details of such a system have yet to be determined, the ability for polystyrene films to perform pulse shape discrimination exists[12], but experiments on PEN showed little ability. In the following experiments the materials used were previously existing films, and are not at all ideal for pulse shape discrimination [12]. Future work is to reproduce these measurements on films better suited for pulse shape discrimination.

POLYSTYRENE PULSE SHAPE DISCRIMINATION

The distributions of charge ratios are shown for the alphas and gammas in the following three figures for the three films. The 150 micron PS film with 15% PPO displayed the largest separation between the gamma and alpha charge ratios (Figure 46). The addition of 15% of ^6LiF , however, increased the tail of the gammas (Figure 48), leading to less separation in the pulse distributions. Finally having a thinner film (50 microns, loaded with ^6LiF) caused complete overlap between the alpha and gamma charge ratio distributions (Figure 48).

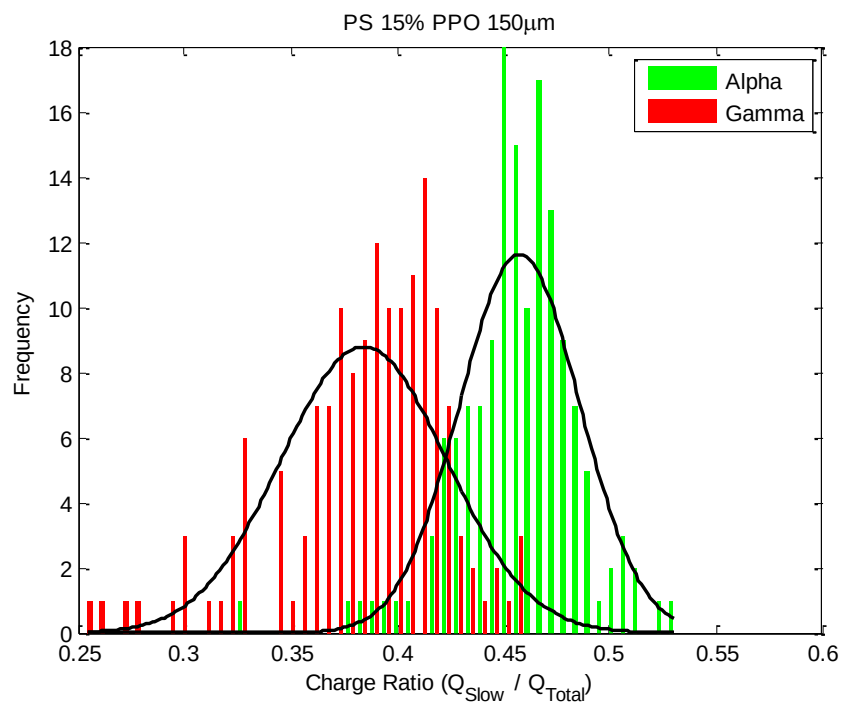


FIGURE 46 - CHARGE DISTRIBUTION OF 150 MICRON PS

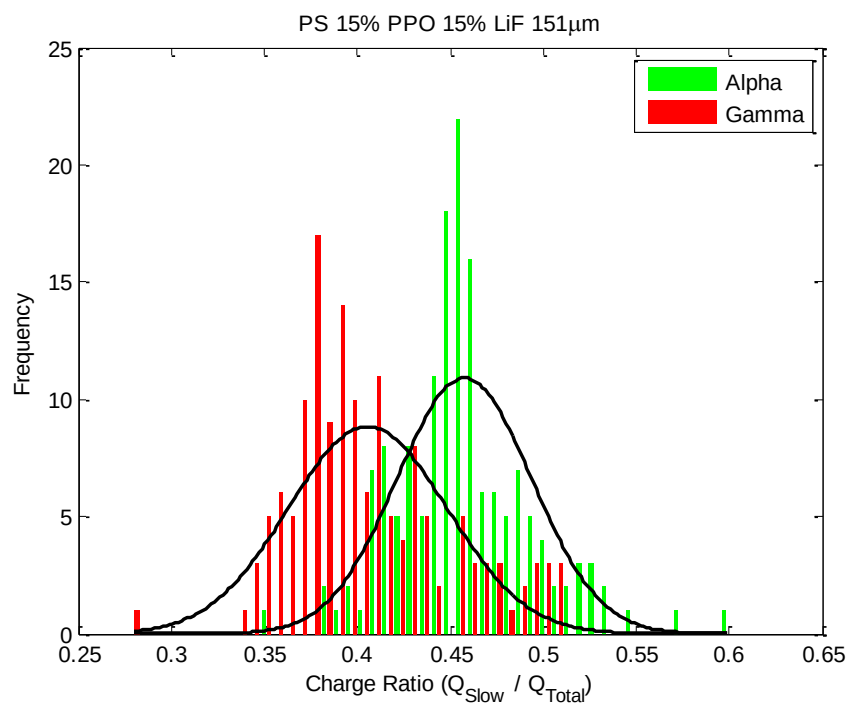


FIGURE 47 - CHARGE DISTRIBUTION OF 150 MICRON PS LOADED WITH LIF

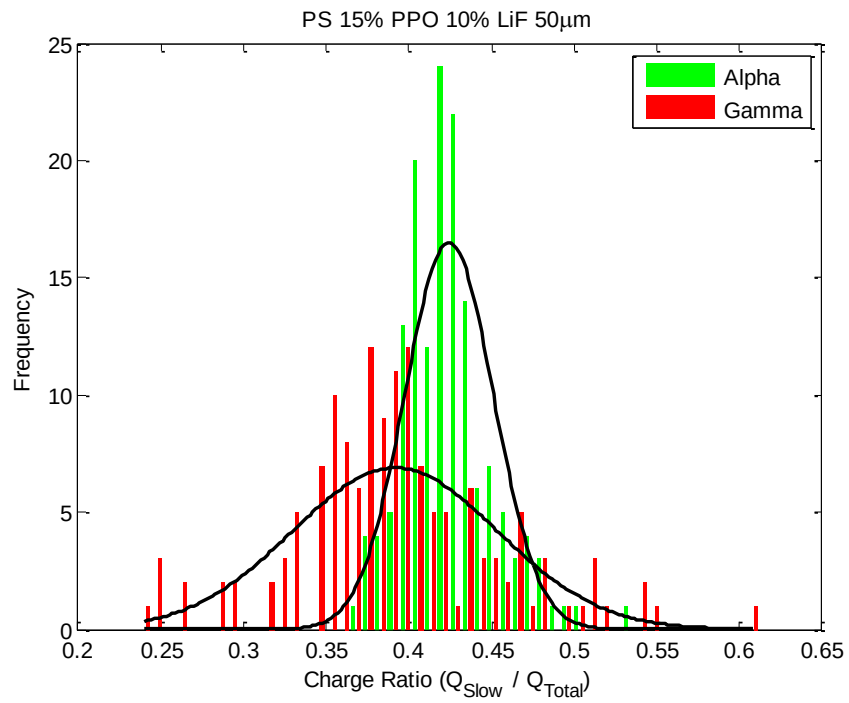


FIGURE 48 - CHARGE DISTRIBUTION OF 50 MICRON PS LOADED WITH LIF

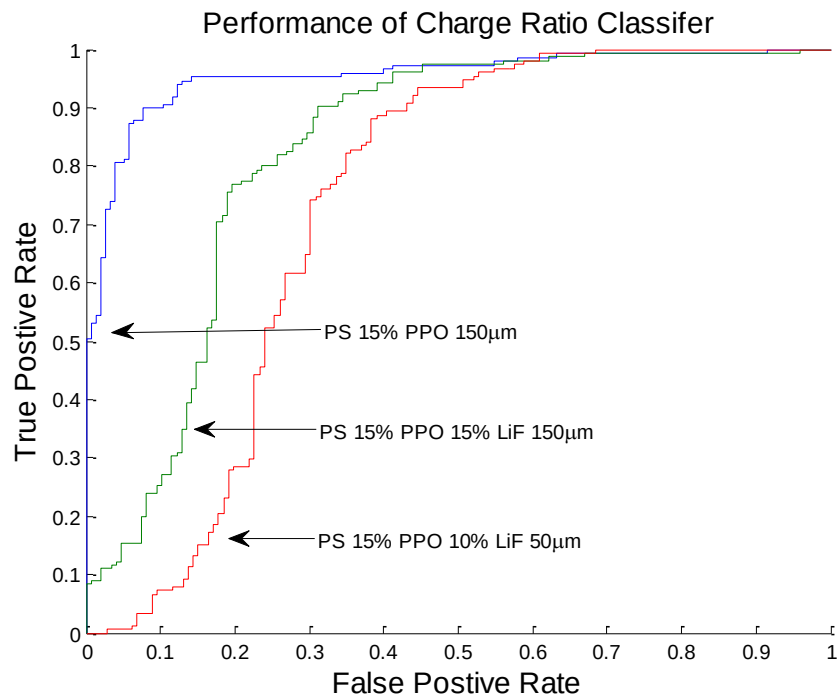


FIGURE 49 - COMPARISON OF CHARGE RATIO CLASSIFIER.

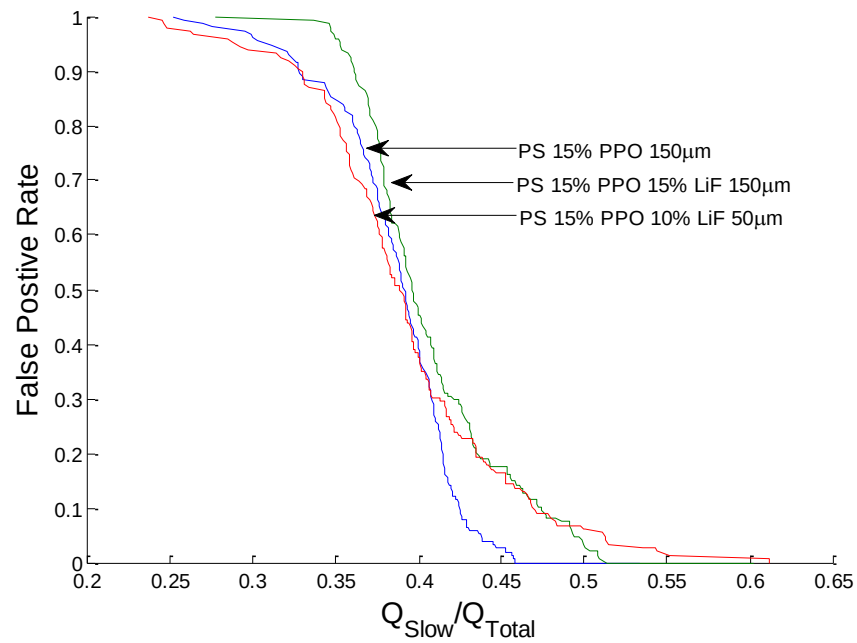


FIGURE 50 - CHARGE RATIO VERSUS FALSE POSITIVE RATE

Initially the false positive rate (classifying a gamma as an alpha) is very high for the charge ratio because gamma's have a lower charge ratio than alphas. After a charge ratio of 0.4 or so there is a knee in the curve and the false positive rate decreases rapidly. The flatness at the foot of the curve indicates the possibility to optimize the performance.

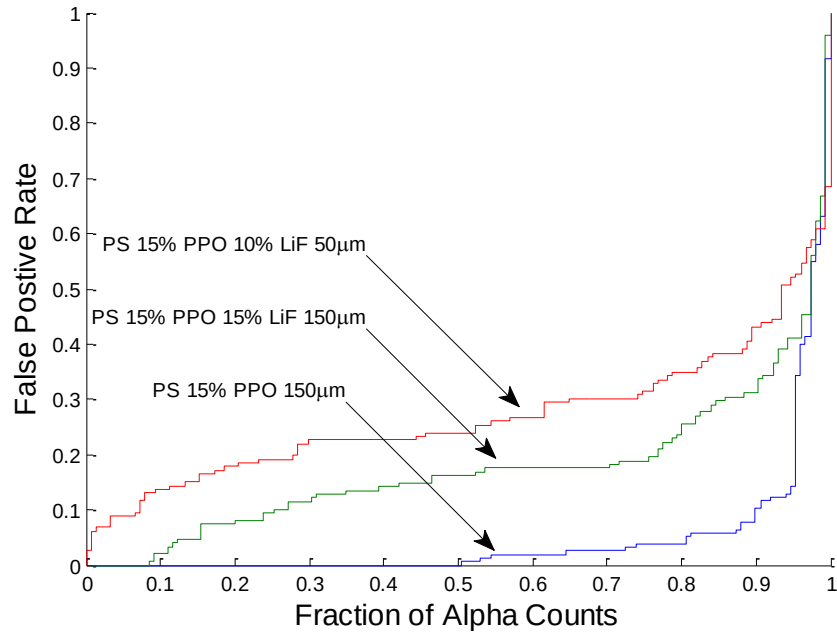


FIGURE 51 – FRACTION OF ALPHA COUNTS AS A FUNCTION OF THE FALSE POSITIVE RATE

The performance of an actual detector system (with alphas as a surrogate for neutrons) can be seen in Figure 51. A very low false positive rate (associated with a high cost of misclassifying a gamma as a an alpha) dictates a prohibitively low fraction of the alpha counts, while allowing a high false positive rate allows for all of the alpha counts to be accepted.

PEN PULSE SHAPE DISCRIMINATION

The PEN films (except for one PEN film) were provide mounted on Kapton as the films could not be removed. The Kapton was tested for scintillation properties by placing an alpha source on it and pulses where observed. Katpon by itself does not possess pulse shape discrimination using the charge ratio method, as evidenced in Figure 52. The scintillation of Kapton makes it difficult to determine if the films still mounted on Kapton have the capability for PSD; instead the capability is determined for the entire system. It is then noted that because of the large overlap between the classes PEN (as measured on Kapton) poses poor pulse shape discrimination.

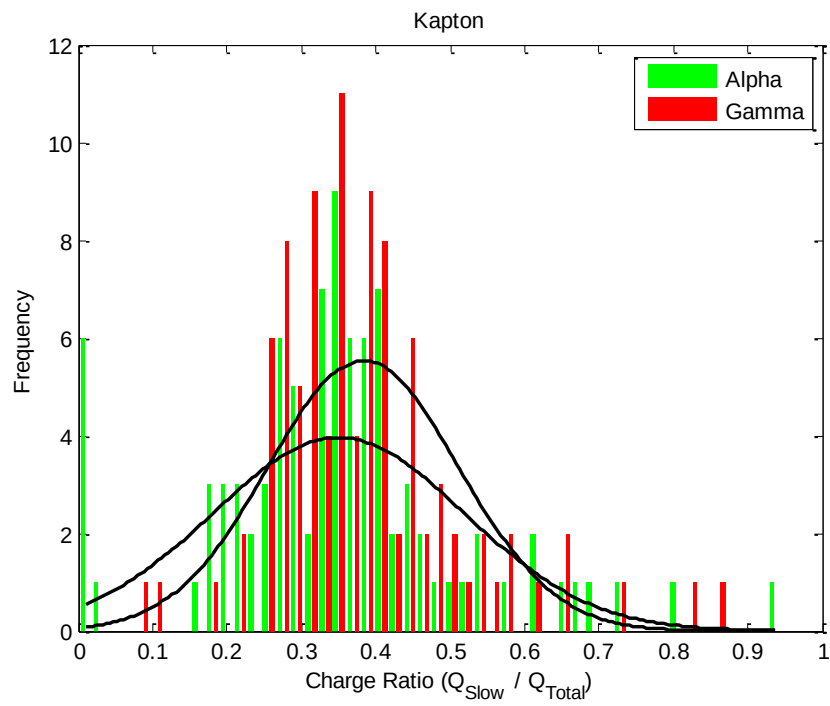


FIGURE 52 - CHARGE RATIO OF KAPTON

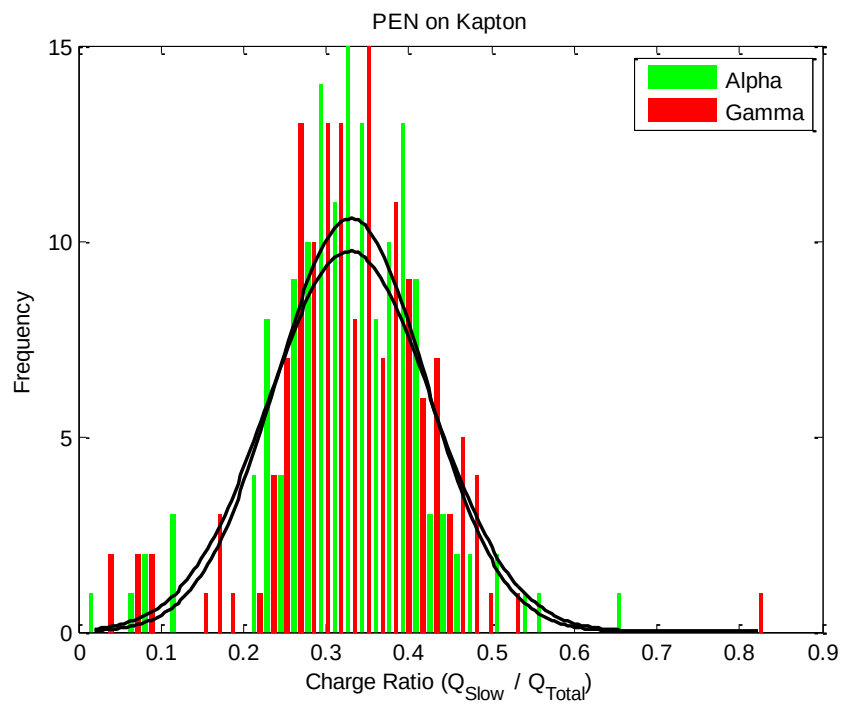


FIGURE 53 - PEN MOUNTED ON KAPTON

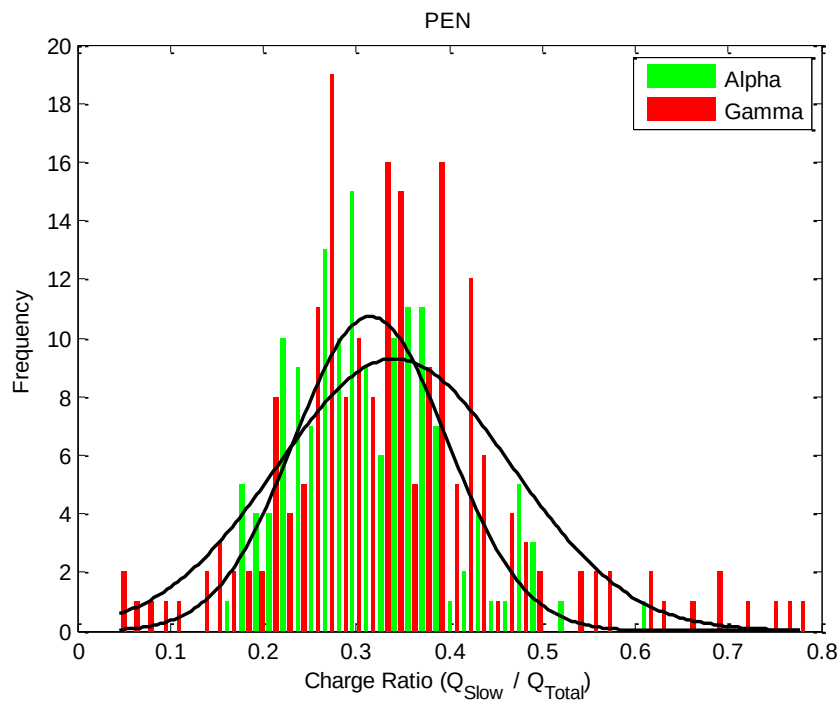


FIGURE 54 - PEN (NOT MOUNTED ON ANYTHING)

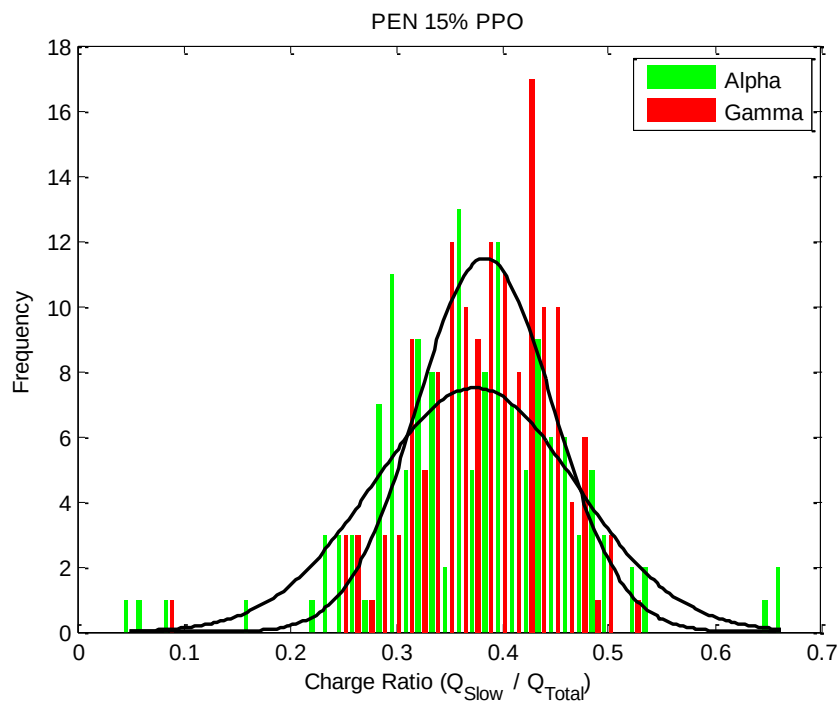
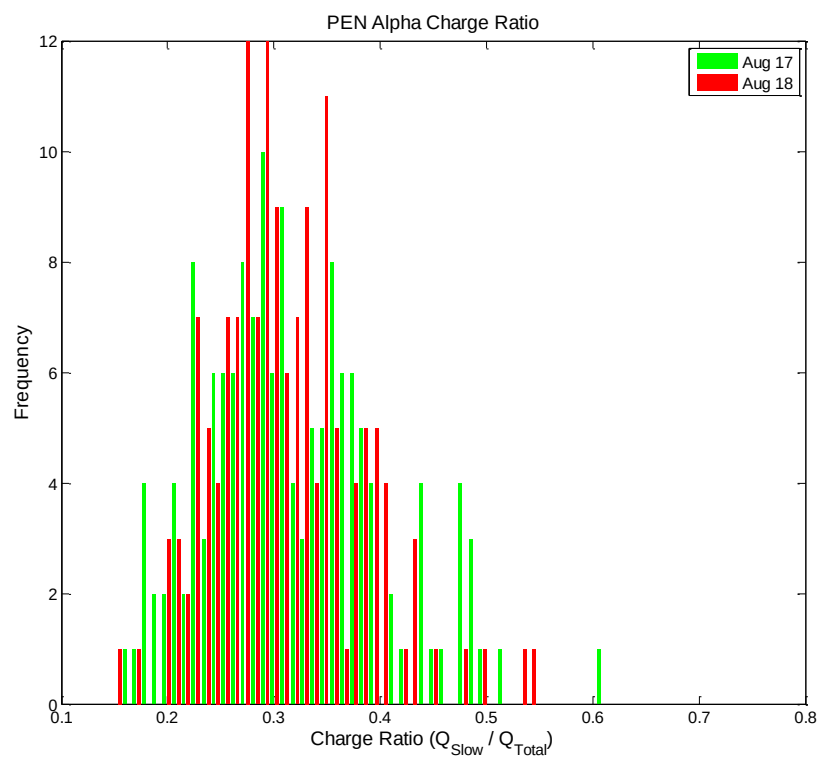


FIGURE 55 - PEN WITH 15% PPO MOUNTED ON KAPTON



4. CONCLUSIONS

This work focused on designing a framework for determining replacement detector technologies for ^3He based radiation portal monitor systems. In order to accomplish this protocols were developed for making repeatable measurements of a film's neutron and gamma spectra. This was assisted by the fabrication of a neutron irradiator that results in the effective measurement of neutrons along with a gamma irradiator from a ^{60}Co source that produces a 10 mR/hr field necessary in order to determine if a film will meet the intrinsic gamma efficiency. Composite polymeric detectors were fabricated and their performance was characterized. Based on those measurements a replacement detector design was proposed and modeled in MCNPX. Optimization was performed on the MCNPX model of a single film system, but the low neutron count rate suggested that a multi-film system would be better suited for meeting the DHS-DNDO requirements. A small (four layer) multi-film system was tested for its gamma discrimination and neutronic properties, and these results were generalized to a multi-film (120 layers) MCNPX model. Basic optimization was performed on this model. If the light can be collected a multi-film system could be an alternative neutron detector. The following sections provide more depth to the topics mentioned above.

MEASUREMENT PROTOCOLS AND DATA ANALYSIS

A protocol has been established that allows for repeatable measurements to be made. It includes:

- 1) verification of the instrument gains,
- 2) measurements of an alpha and beta spectra,
- 3) neutron performance,
- 4) and gamma spectrum in a 10 mR/hr field.

The light yield and alpha over beta ratio are then calculated, as well as the pulse height deficit. Finally, the gamma spectra is summed a function of mathematical lower level discriminator (MLLD) and normalized by the incident flux. The MLLD for an intrinsic efficiency of one in a million is determined, and then the neutron count rate above this value is computed.

MODELING ABILITY

Detectors materials are then modeled in a geometry that replicates the DHS/DNDO test criteria; namely a 1 ng ^{252}Cf source surrounded by 0.5 cm of lead and 2.5 cm of HDPE, intersecting the detector at its midpoint. The interaction rate of the (n,triton) is computed in the MCNPX model, and this interaction rate is scaled by the fraction of counts that are above the MLLD determined from the measured neutron and gamma spectra. When possible these models have been validated by measurements in the lab to agreement within 15% for the neutron interactions, and 30% for the gamma interactions. This allows for the determination if a detector design will meet the DHS/DNDO criteria, purely on interaction rates.

DETECTOR DESIGN

A detector has been designed in which there would be enough neutronics interactions to pass the criteria set forth by the DHS/DNDO. This design consists of a layered polymeric film (either PEN or PS). For the PEN film the count rate would be around 6.1 cps per ng ^{252}Cf , and for the 30% LiF PS film the count rate was 3.4 cps per ng ^{252}Cf . The PS films were modeled rotated 90 degrees for easier light collection, but the count rate dropped 9% to 3.1 per ng ^{252}Cf . The increase in light collection, however, may still make this an option.

FUTURE WORK

Future modeling work can be completed on optimizing the MCNPX model. Different geometries (such as a wrapped cylinder) could be explored, as well as optimizing the amount of material by increasing the surface area of the detector while decreasing the depth in order to avoid the low detection per volume that occurs past 5 cm in the detector.

There is no assurance that the detectors designed based on interaction rate would be feasible to construct; due to their low light output and opaqueness collecting the light from scintillation events would be extremely difficult. Light transport modeling (possibly with Geant4) would provide a way to improve the design to insure adequate light collection for a signal. Advanced modeling could also provide insights into the nature of the secondary electrons. This could lead to detectors designed with an absorption center (such as a high light yield crystal) surrounded by a non-scintillating matrix (example is LYB in PMMA), or perhaps the optimal size of the LiF particles.

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APPENDIX A

While efforts are made to ensure that the instrument gains are stable, the effects of varying amounts of optical grease and Teflon tape were investigated by completing experiments in which the user applied an extreme amount and then by investigating the repeatability of random trials. For the first case, where the user applied an extreme amount, the spectra were recorded from a ^{137}Cs source was applied to a GS20 glass detector. The spectra endpoint (after 600s of counting time was recorded), showing that Teflon tape increases both the light output and the counts, while optical grease has a large effect on the light output and little effect on the count rate, as long as it is applied in a manner such that good optical coupling is achieved. It is then desirable to apply as little amount of optical grease as necessary in order to avoid shifting the light output through optical coupling.

TABLE 21 - MEASUREMENT REPEATABILITY. EFFECTS OF OPTICAL GREASE AND TEFLON TAPE.

Configuration	Spectra Endpoint (^{137}Cs)	Total (600s)	Counts
No optical grease, Teflon tape applied to entire detector	1,930	1,140,000	
No optical grease, Teflon tape applied only to top of detector (side's free)	1,370	1,160,000	
No optical grease, no Teflon tape	1,120	1,770,000	
Copious amounts of optical grease with Teflon tape	2,710	860,000	
Spare application of optical grease with Teflon tape	1,550	1,020,000	
Copious amounts of optical grease, no Teflon tape	1,720	1,050,000	
Poor optical coupling, air bubbles visible between PMT and detector	1,200	710,000	
Good optical coupling	1,830	1,070,000	

GS20 DATA

The repeatability of random trials was investigated by choosing six measurements of GS20 on different days and computing the derived parameters. The spectra are shown below (Figure 56 Figure 57).

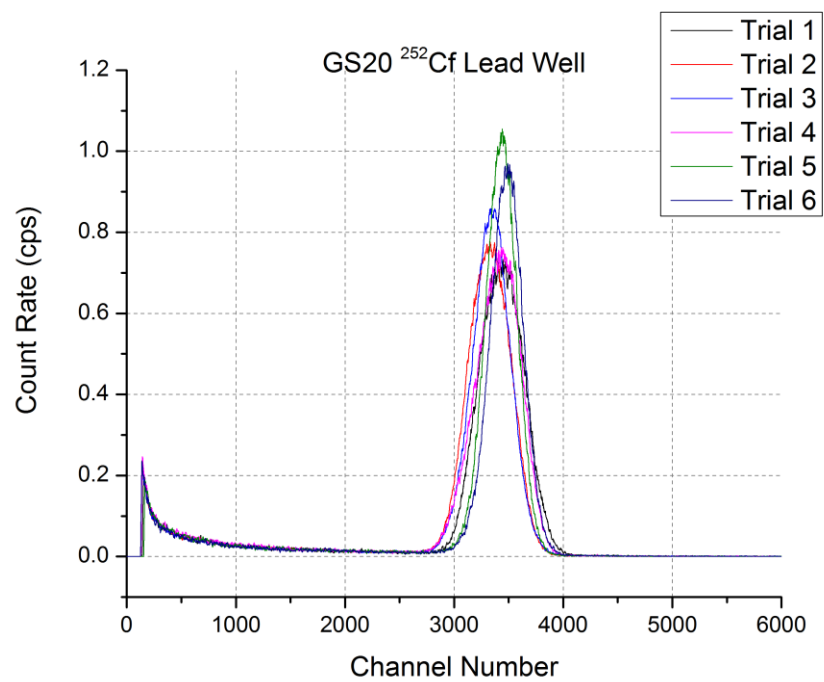


FIGURE 56 - GS20 REPEATED NEUTRON SPECTRA FROM THE LEAD WELL OF THE IRRADIATOR

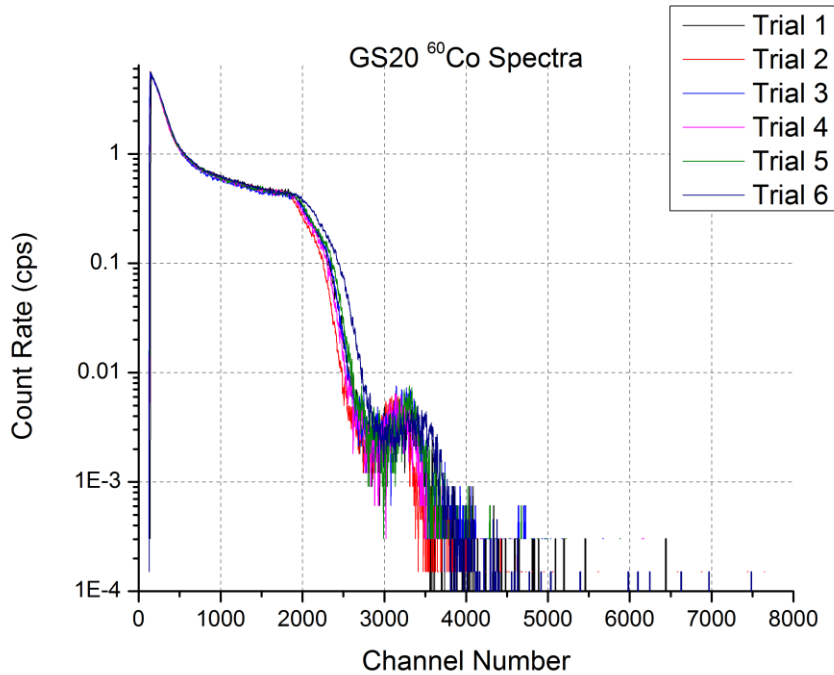


FIGURE 57 - GS20 REPEATED GAMMA SPECTRA FROM A ^{60}Co SOURCE

The pulse height deficit (and corresponding light yield per neutron) were calculated for various GS20 measurements. The standard deviation was computed, and found to be at most 3% of the average. While the peak position was set to occur at 3,460 channels, there seems to be a slight discrepancy in where the final peak location is. This probably arises from the error associated in choosing where the peak occurs in noisy spectra. Published values of the light yield per neutron of GS20 range from 6,000 Photons per MeV to 7,000 Photons per MeV [9].

TABLE 22 - VARIATION OF DERIVED QUANTITIES. THE ERROR (COMPUTED BY THE STANDARD DEVIATION) IS AT MOST 3% OF AVERAGE VALUE.

	Average Neutron (Pb Spectra)	Neutron Peak (Pb Spectra)	Average Gamma	Average Gamma (above channel 750)	Compton Edge	Pulse Height Deficit	Light Yield per Neutron
Trial 1	3,020	3,476	754	1,406	2,188	1,311	6,266
Trial 2	2,909	3,334	708	1,377	2,071	1,328	6,350
Trial 3	2,922	3,380	725	1,418	2,117	1,317	6,298
Trial 4	2,985	3,411	723	1,397	2,115	1,331	6,361
Trial 5	2,958	3,454	735	1,422	2,186	1,304	6,232
Trial 6	3,003	3,451	758	1,455	2,268	1,256	6,002
Average	2,966 $\pm$ 41	3,418 $\pm$ 49	734 $\pm$ 18	1,413 $\pm$ 24	2,158 $\pm$ 64	1,308 $\pm$ 25	6,252 $\pm$ 120
σ/μ	1.4%	1.4%	2.4%	1.7%	3.0%	1.9%	1.9%

The position of the gamma MLLD necessary to various achieve $\epsilon_{int,\gamma}$ was calculated. The intrinsic efficiency is very stable (varying within 3% of the average value) until a very low intrinsic efficiency is approached, at which point standard deviation becomes 7.4% of the average value.

TABLE 23 - GAMMA INTRINSIC EFFICIENCY FOR GS20. EACH COLUMN IS A DIFFERENT INTRINSIC EFFICIENCY SETTING, AND THE ROWS BELOW ARE AT WHICH CHANNEL THE GS20 ACHIEVES THAT SETTING.

	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Trial 1	2,049	2,427	3,336	4,043
Trial 2	1,975	2,342	3,215	3,778
Trial 3	2,056	2,436	3,358	4,540
Trial 4	2,020	2,393	3,262	3,690
Trial 5	2,079	2,464	3,375	4,023
Trial 6	2,164	2,577	3,507	4,051
Average ($\mu \pm \sigma$)	$2,057 \pm 63$	$2,440 \pm 79$	$3,342 \pm 101$	$4,021 \pm 296$
σ/μ	3.1%	3.2%	3.0%	7.4%

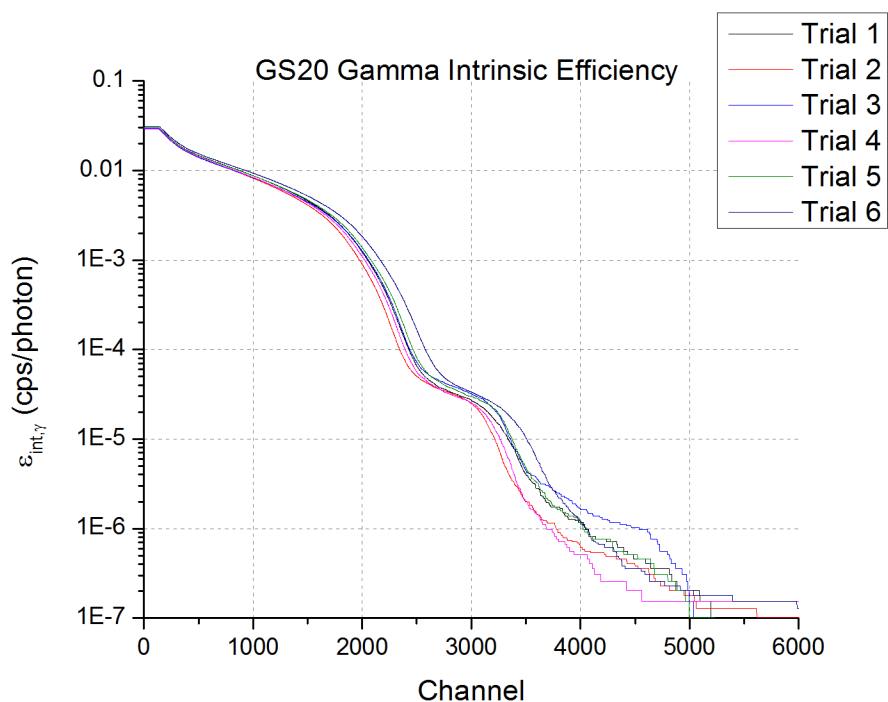


FIGURE 58 – CALCULATED INTRINSIC EFFICIENCIES FOR GS20

PEN DATA

A stretched PEN film, shown below, was measured three separate times by two operators (Matthew Urffer and Rohit Uppal) in order to determine the repeatability of thin film measurements. Each of the trials were measured at 50 gain, with the voltage determined by setting the peak position of GS20.

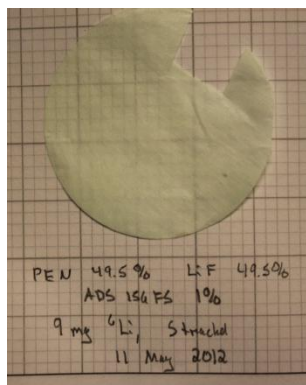


FIGURE 59 - MEASURED PEN FILM

In Figure 59 and Figure 60, where the data has been rebinned in 25 bin increments, it is immediately evident that the neutron spectra have slightly different shapes, while the small gain variations seen in the GS20 gamma spectra (shifts in the photo-peak location) are more apparent. This suggests that a thin film, with smaller counts and lower energy resolution, are more susceptible to small variations in gain and optical mounting.

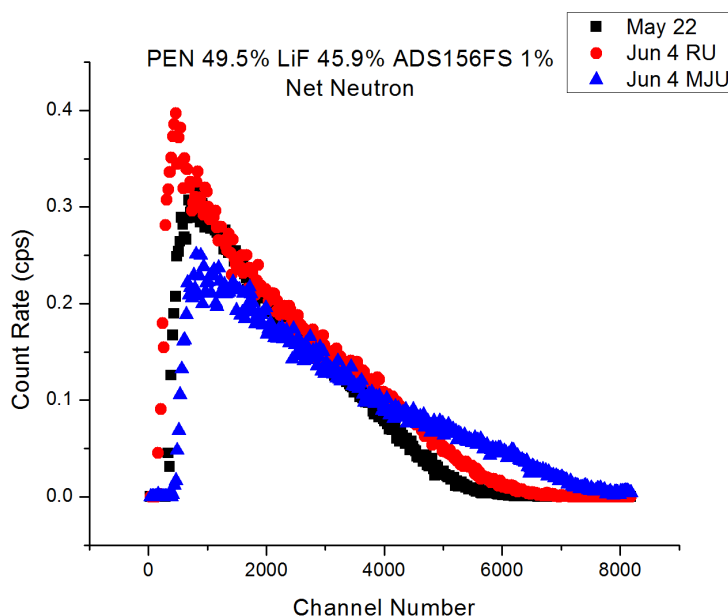


FIGURE 60 – NET NEUTRON SPECTRA OF REPEATED PEN FILMS.

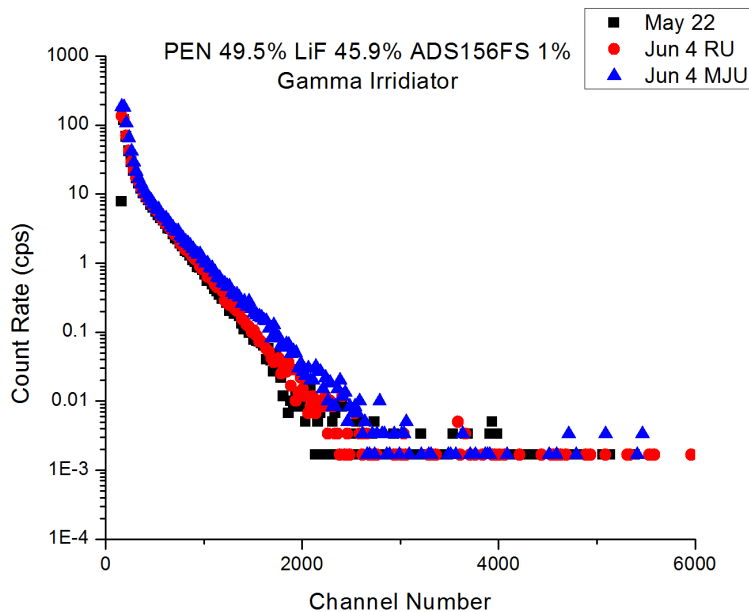


FIGURE 61 - COMPARISON OF GAMMA SPECTRA FOR REPEATED FILMS.

The spectra averages, count rate, and MLLD channels were computed and summarized in Table 24. The third trial had a much higher average neutron spectra had a total count rate that was similar to Trial 1 (in fact they differed by 0.068 cps). The source of the discrepancy in the fraction of neutron counts above the gamma discriminator can be found by looking at the neutron integral spectra (Figure 63). While the spectra weighted average for the gamma's are similar (and the gamma LLD's fall within 2σ of each other), the considerable difference in the neutron count rate above the gamma LLD greatly impacted the fraction of neutron counts above the gamma LLD. Values reported in parentheses are $\pm 2\sigma$, which is roughly a 95% confidence interval (1.96σ is 95% CI for a normal distribution).

TABLE 24 - COMPARISON OF THREE DIFFERENT MEASUREMENTS OF A STRETCHED PEN FILM (49.5% LIF, 1% ADS156FS).

	Gamma Spectra Average (channel number)	Neutron Spectra Average (channel number)	Total Neutron Count Rate (cps)	Gamma such $\epsilon_{int,\gamma} \leq 10^{-6}$ (channel number)	LLD that $\epsilon_{int,\gamma} \leq 10^{-6}$	Neutron rate $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)	Count above $\epsilon_{int,\gamma} \leq 10^{-6}$	Fraction of neutron counts above $\epsilon_{int,\gamma} \leq 10^{-6}$
Trial 1 (May 22)	290	2,039	30.4 ± 0.02	3,192 (2,706 3,517)	-	5.7 (8.5 - 4.2)		0.19 (0.28 - 0.14)
Trial 2 (Jun 4 RU)	259	2,095	37.1 ± 0.05	2,741 (2,500 3,561)	-	11.3 (13 - 6.5)		0.30 (0.35 - 0.17)
Trial 3 (Jun 4 MJU)	252	2,782	30.4 ± 0.02	2,810 (2,682 3,031)	-	12.8 (13.6 - 11.6)		0.42 (0.45 - 0.38)

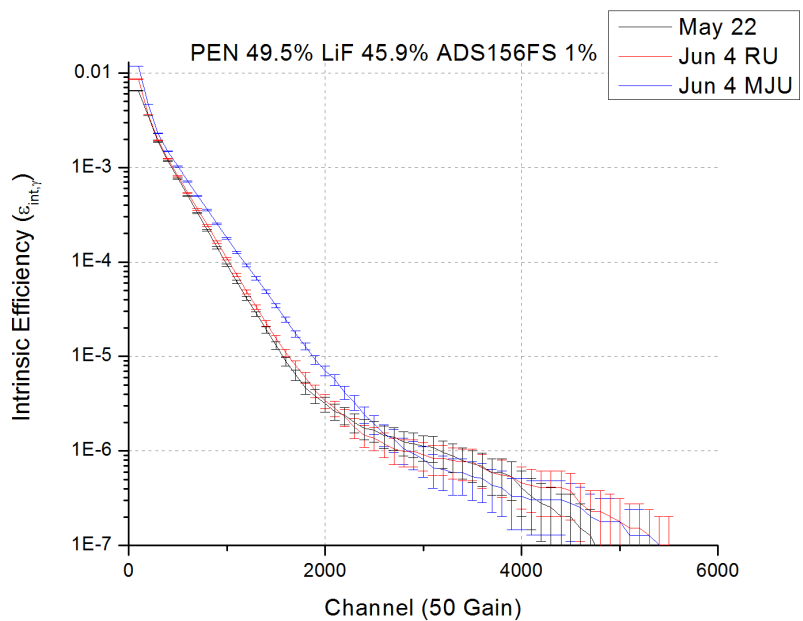


FIGURE 62 – REPEATABILITY OF GAMMA INTRINSIC EFFICIENCY FOR A STRETCHED PEN FILM.

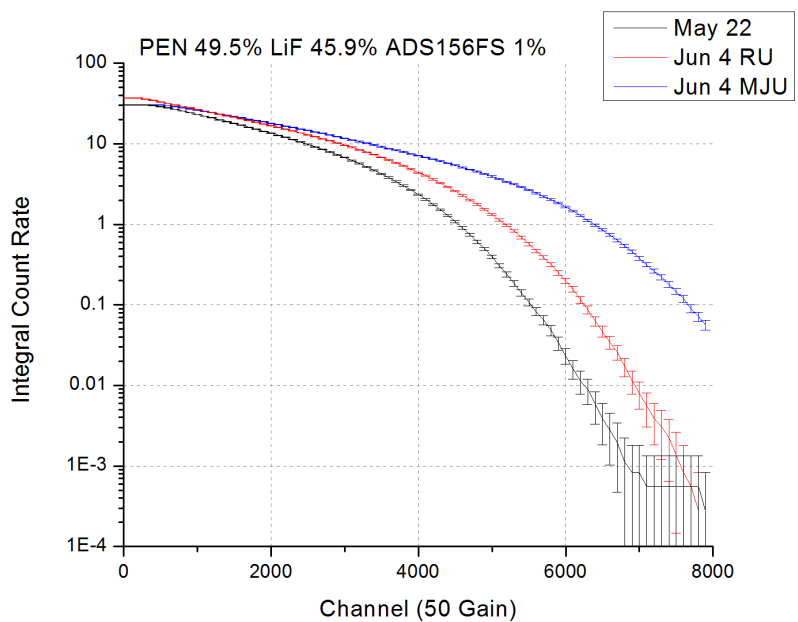


FIGURE 63 - NEUTRON INTEGRAL COUNT RATE AS A FUNCTION OF CHANNEL NUMBER FOR A STREACHED PEN FILM

OPERATING DETECTOR CONFIGURATION

The response was measured of the film in the lead well can gamma irradiator physically setting the gamma LLD to be at 999 channels and 1,801 channels. The results of these trials (where only the lead well neutron response and gamma response was measured) is summarized below.

TABLE 25 - REPEATABILITY OF A SAMPLE SETTING THE LLD TO BE 1,000 CHANNELS AND 1,800 CHANNELS. THE HIGHEST THE GAMMA LLD CAN BE SET IS 1,900 CHANNELS. THE TOTAL NEUTRON COUNT RATE IS NOT REPORTED (NOR IS THE FRACTION) BECAUSE OF THE LLD SETTING.

Physical LLD	Gamma LLD such that $\epsilon_{int,\gamma} \leq 10^{-6}$ (channel number)	Neutron Count rate above $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)
1,801	2,386 (2,103 – 2,721)	12.37 (14.62 - 10.15)
999	2,495 (2,209 – 2,694)	9.97 (12.01 - 8.75)
Trial 1 (May 22)	3,192 (2,706 – 3,517)	5.94 (8.8 - 4.3)
Trial 2 (Jun 4 RU)	2,741 (2,500 – 3,561)	11.61 (13.3 - 6.6)
Trial 3 (Jun 4 MJU)	2,810 (2,682 – 3,031)	13.28 (14.1 - 12)

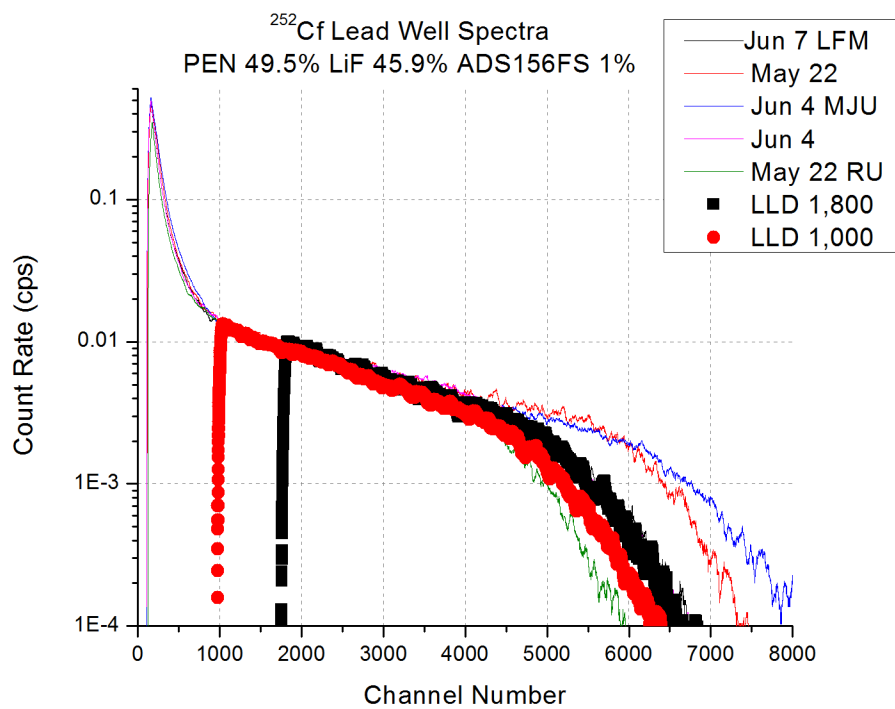


FIGURE 64 - COMPARISON OF THE LEAD NEUTRON SPECTRA. SPECTRA RECORDED AT A HIGHER LLD DID NOT IMPACT WHERE THE SPECTRA ENDED.

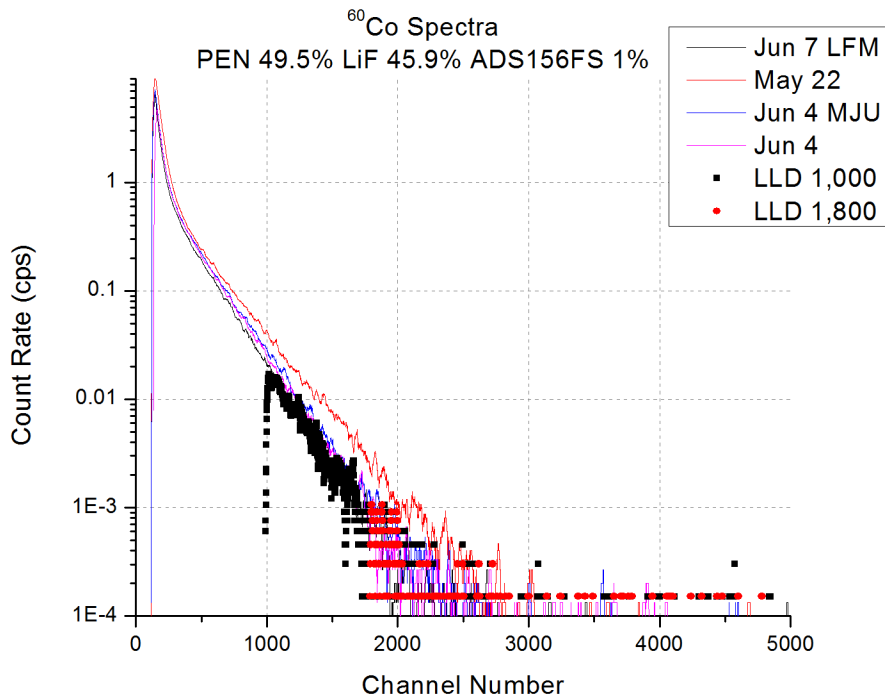


FIGURE 65 - COMPARISON OF THE GAMMA SPECTRA OF THE FILMS. ONE SPECTRA (MAY 22) IS MUCH HIGHER THAN THE REST, WHICH RESULTS IN A HIGHER VALUE FOR THE GAMMA LLD, AND IS REFLECTED IN A LOWER COUNT RATE ABOVE THE GAMMA LLD.

In comparison between the lead well only and the net spectra it is observed that the neutron count rate above the gamma LLD does not change appreciably, due the cadmium well contributing to very few counts at the higher energies. It is the much higher total neutron count rate in the lead well the shifts the fraction of neutron counts below the gamma LLD down for the lead well compared to the subtracted thermal spectra.

TABLE 26 - COMPARISON BETWEEN NEUTRON PERFORMANCE UTILIZING THE SUBTRACTION AND THE LEAD SPECTRA.

Lead Well Only				Thermal Spectra (Subtraction)		
	Total Neutron Count Rate (cps)	Neutron Count rate above $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)	Fraction of neutron counts above $\epsilon_{int,\gamma} \leq 10^{-6}$	Total Neutron Count Rate (cps)	Neutron rate above $\epsilon_{int,\gamma} \leq 10^{-6}$ (cps)	Fraction of neutron counts above $\epsilon_{int,\gamma} \leq 10^{-6}$
Trial 1 (May 22)	77.9 ± 0.1	5.94 (8.8 - 4.3)	0.076 (0.11 - 0.06)	30.4 ± 0.02	5.7 (8.5 - 4.2)	0.19 (0.28 - 0.14)
Trial 2 (Jun 4 RU)	100.8 ± 0.2	11.61 (13.3 - 6.6)	0.115 (0.13 - 0.07)	37.1 ± 0.05	11.3 (13 - 6.5)	0.30 (0.35 - 0.17)
Trial 3 (Jun 4 MJU)	113.3 ± 0.2	13.28 (14.1 - 12)	0.117 (0.12 - 0.11)	30.4 ± 0.02	12.8 (13.6 - 11.6)	0.42 (0.45 - 0.38)

MINIMUM DETECTABLE ACTIVITY

The minimum detectable activity is the level at which it the source spectra has fallen statistically below the background (with a certain confidence). In the following figure (Figure 66) the top curve represents the distribution of net counts when only background is present (distribution is centered around zero), and the bottom curve when the source is present. The point at which the source spectra is statistically different from the background (to within confidence alpha and beta) is shown as the CDL.

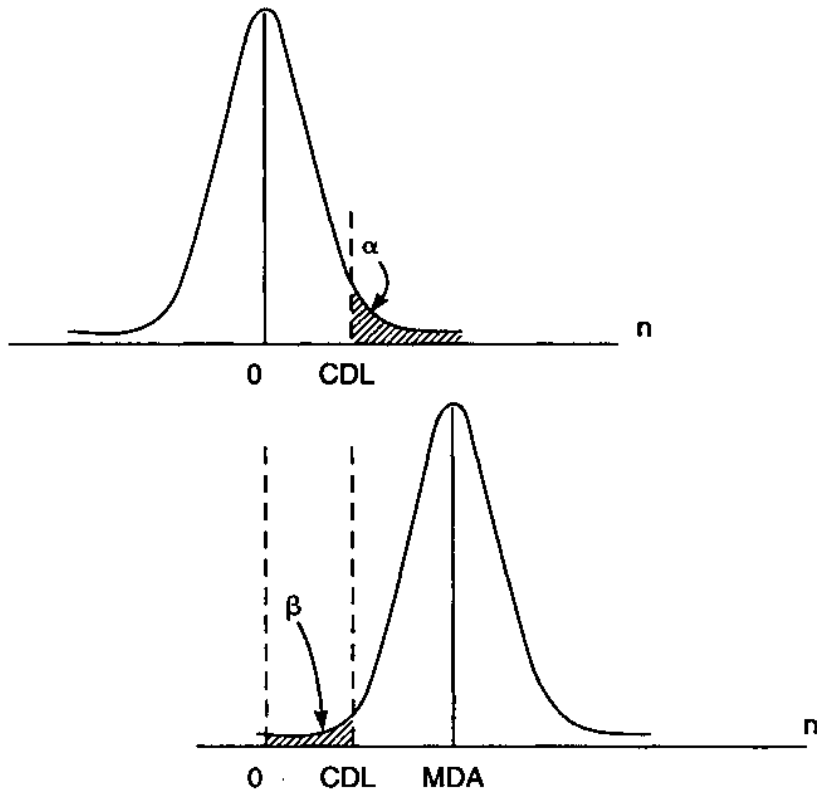


FIGURE 66 - L_c (LABELED AS CDL) WITH THE CONFIDENCE LIMITS DEFINED BY ALPHA AND BETA. FIGURE FROM [13].

If $N_s = N_T - N_B$, where N_s is the net spectra from subtraction, N_T is the gross spectra (source and background), and N_B is the background spectra. Assuming that the errors are independent, propagation of variance yields $\sigma_{N_s}^2 = \sigma_{N_T}^2 + \sigma_{N_B}^2$. Throughout this derivation k will be used to represent the area under the normal distribution, which is representative of the confidence limits. A table of k values is reproduced in Table 27.

TABLE 27 - CONFIDENCE LIMIT AND K-VALUES OF THE NORMAL DISTRIBUTION. REPRODUCED FROM [13].

$\# \sigma (k)$	$p(x > x_a)$	Confidence Limits
0.000	0.500	50.0
1.000	0.159	84.1
1.285	0.100	90.0
1.500	0.067	93.3
1.650	0.050	95.0
2.000	0.023	97.7
2.500	0.006	99.4
3.000	0.001	99.9

The analysis of the minimum detectable activity can be broken into two cases:

Case I: No Activity Present

If no activity is present then $N_T \approx N_B$ which implies $N_S \approx 0$. Then the error on N_S is then $\sigma_{N_S}^2 = 2\sigma_{N_B}^2$. Setting a critical count level $L_C = k\sqrt{2}\sigma_{N_B}$ determines the lower level at which it is possible to be certain of a false positive rate. If $N_S < L_C$, then it is possible to say (with a false positive rate given by k) that no activity is present.

Case II: Activity is Present

Let N_D represent the minimum amount of N_S such that the false-negative rate is below a certain value (determined by k). It is then possible to relate N_D to the error in the background count rate:

$$N_D = L_C + k\sigma_{N_D}$$

It is possible to relate σ_{N_D} to σ_{N_B} by $\sigma_{N_D} = \sqrt{2N_B + N_D}$. If $N_D \ll N_B$ than an expansion can be carried out to equate $\sigma_{N_D} \approx \sqrt{2}\sigma_{N_B} + k$.

The analysis was carried out in both cases for a the stretched PEN film analyzed in the measurement repeatability section. The following plot (Figure 67) shows the N_D and L_C levels as a function of channel for the stretched PEN film. After channel 4,626 the net spectra falls below N_D , at which point the false negative rate is no longer assured to be less than 5%. It is then assured that the gamma counts in the tail end of the spectra are statistically significant.

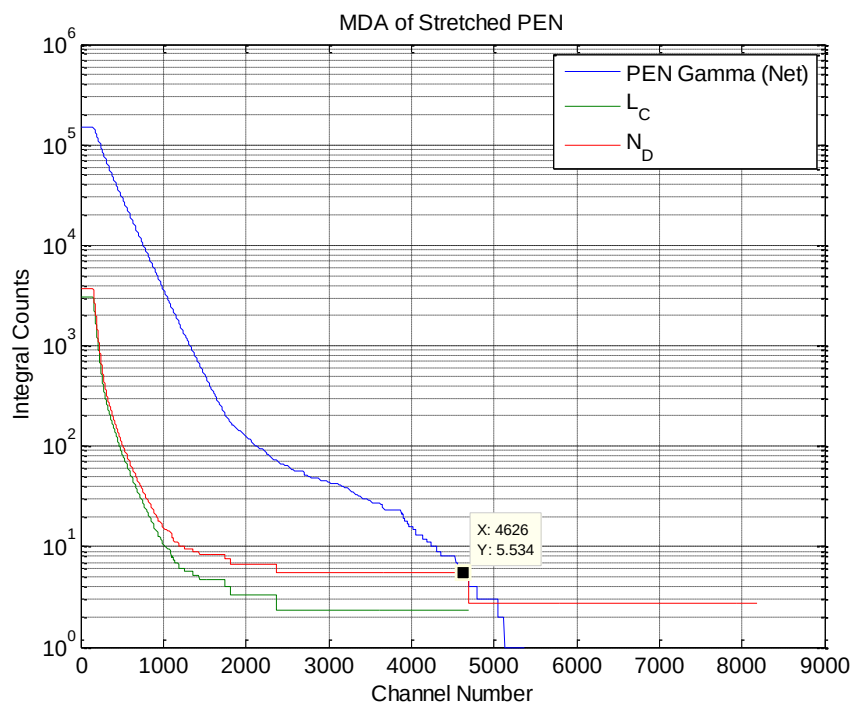


FIGURE 67 - MINIMUM DETECTABLE ACTIVITY OF STRETCHED PEN (49.5% LIF, 1% ADS156FS).

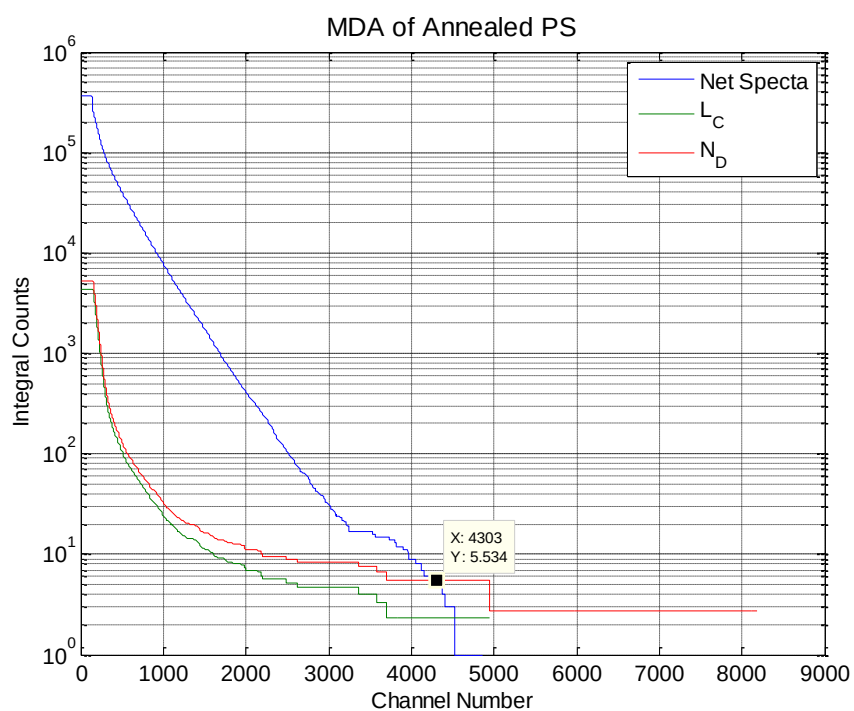


FIGURE 68- MDA OF ANNEALED PS (9.66% LIF, 4.58% PPO/POPOP 26UM) FILM. THE L_c AND N_D HAVE DIFFERENT SHAPES FROM THE PEN BECAUSE THE PEN WAS MEASURED WITHOUT THE ACRYLIC DISC IN THE GAMMA IRRADIATOR.

APPENDIX B

MCNPX INPUTS DECKS

Four MCNPX input decks for the measured material properties are presented here, along with two of the input decks used to simulate a polymeric film DHS-DNDO detector.

MILLER_CONFIG_GS20.MCNP

```

Miller's Poly Box with 0.59 ug (5.9E-7 gram) Cf-252 source
c ***** Cell Cards *****
c ----- Combined all of Martin's HDPE Cells into one -----
  100      456 -0.93      -1 :-2 :-3 :-4 :-5 :-6 :-6 :-7 :-8 :-9 $ HDPE Sheilding
      :-10 :-11 :-12 :-13 :-14 :-15 :-16 :-17 :-18
c ----- Creating a source universe -----
  200      0      -200 fill=3
  201      1 -15.1      -210 u=3      $ Cf252 Spherical Source
  202      488 -7.92      (-206 :-205 )210 u=3 $ Stainless Steel 316 Around Source
  203      406 -11.35      -204 205 u=3      $ Lead Pig
  204      456 -0.93      (-202 :-203 ) 204 u=3 $ HDPE around source
  205      204 -0.001225      (210 202 203 204 ) u=3 $ Air until universe boundary
c ----- Lead Detector Well -----
  300      0      -302 #610 trcl=1 fill=1
  302      204 -0.001225      -300 u=1      $ air
  303      2      -1.18      -301 300 u=1      $ Plastic
  304      406 -11.35      301 u=1      $ Lead
c ----- Cadimium Detector Well -----
  400      0      -402 #620 trcl=2 fill=2
  402      204 -0.001225      -400 u=2      $ air
  403      2      -1.18      -401 400 u=2      $ Plastic
  404      318 -8.65      401 u=2      $ cd
c ----- Lead Well PMT -----
  610      0      -602      trcl=61 fill=6
c ----- Cd Well PMT -----
  620      0      -602      trcl=62 fill=6
c ----- PMT Subcells -----
  601      3      -2.5      -500 u=6      $ Detector cell
  602      388 -2.23      -601 u=6      $ PMT Glass
  603      468 -1.406 603 u=6      $ Plastic
  604      4      -8.74      -604 605 u=6      $ Metal
  605      204 -0.001225 #602 #601 #603 #604 u=6 $Air
c ----- outside world -----
  1000      204 -0.001225      -1000 #100 #200 #300 #400 $ Air inside the world
      #610 #620
  1001      0      1000      $ Outside world
c ***** Surface Cards *****
c ----- Outer HDPE Box -----
  1      rpp 5.3975 45.72 0 30.48 0 5.3975 $ Bottom Cente
  2      rpp 45.72 51.1175 0 30.48 0 35.56 $ Right Side
  3      rpp 0 5.3975 0 30.48 0 35.56 $ Left Side
  4      rpp 5.3975 45.72 0 5.3975 5.3975 35.56 $ Front
  5      rpp 5.3975 45.72 25.0825 30.48 5.3975 35.56 $ Back
  6      rpp 5.3975 25.7175 5.3975 10.795 10.795 35.56 $ Source Cover
  7      rpp 5.3975 25.7175 19.685 25.0825 10.795 35.56 $ Source Cover
  8      rpp 5.3975 25.7175 10.795 19.685 30.1625 35.56 $ Source Cover
  9      rpp 5.3975 25.7175 5.3975 25.0825 5.3975 10.795 $ Source Cover
  10     rpp 5.3975 10.795 10.795 19.685 10.795 30.1625 $ Source Cover
  11     rpp 20.32 25.7175 10.795 19.685 10.795 30.1625 $ Source Cover
  12     rpp 25.7175 36.5125 5.3975 25.0825 5.3975 10.795 $ Detector/Cha
  13     rpp 36.5125 39.0525 5.3975 25.0825 5.3975 35.56 $ Wall behind
  14     rpp 5.08 22.2251 0 30.48 35.56 40.64 $ Block on top
  15     rpp 34.1 51.1175 0 30.48 35.56 38.1 $ Block on top
  16     rpp 22.2251 33.9727 0 5.08 35.56 38.1 $ Block on top
  17     rpp 22.2251 33.9727 13.97 16.51 35.56 38.1 $ Block on top
  18     rpp 22.2251 33.9727 25.4 30.48 35.56 38.1 $ Block on top
c ----- Universe for Inner Source Holder and Source
  200      rpp 10.795 20.32 10.795 19.685 10.795 30.1625

```

```

c ----- Inner Source Holder HDPE -----
202      rpp 10.795 20.32 10.795 19.685 10.795 15.875  $ Block holdi
203      rpp 10.795 20.32 10.795 19.685 24.13 30.1625  $ Block above
c ----- Source Sheilding (Lead) -----
204      rcc 15.5575 15.24 10.795 0 0 13.335 2.54  $ Lead Pig ou
205      rcc 15.5575 15.24 13.305 0 0 9.525 1.27  $ Lead Pig in
206      rcc 15.5575 15.24 13.305 0 0 3.81 0.3175  $ SS 316 Sour
210      s 15.5575 15.24 15.21 2.5914E-04 $ Spherical Point Source
c ----- Lead Well -----
300      rcc 0 0 0.439 0 0 27.726 3.564  $ Inner Well (ID Plastic)
301      rcc 0 0 0.439 0 0 27.726 3.7885  $ Plastic OD / Pb ID
302      rcc 0 0 0 0 0 27.94 4.0025  $ Pb OD
c ----- Cadimium Well -----
400      rcc 0 0 0.418 0 0 27.731 3.7765  $ Inner Well (ID Plastic)
401      rcc 0 0 0.418 0 0 27.731 3.933  $ Plastic OD / cd ID
402      rcc 0 0 0 0 0 27.94 4.142  $ Cd OD
c ----- Detector -----
500      rcc 0 0 1E-6 0 0 0.200 1.27  $ 2.01 thick, 1" Dimeter
c ----- PMT -----
601      602 rcc 0 0 0 0 0 0.3178 2.54  $ 2" Diamter, 1/8" Thick (Glass)
602      601 rcc 0 0 0 0 0 5.284 2.8030  $ Plastic Cap Outer
603      601 rcc 0 0 0.189 0 0 5.2651 2.6335  $ Plastic Cap Inner
604      602 rcc 0 0 0.3178 0 0 5 2.54  $ Mu Metal Outer
605      602 rcc 0 0 0.3178 0 0 5 2.535  $ Mu Metal Inner
c ----- World Boundary -----
1000     rpp -10 60 -10 60 -10 60  $ An oversized box

c ***** Data Cards *****
MODE N P A D E #  $ Type of particles to transport: neutrons, photons, alphas, tritons,
deuterons, & electrons
IMP:N,P,A,D,E,# 1 22r 0
PHYS:N 100 4j -1 2  $ Turned on fission multiplicity "FISM" (-1) and light ion
recoil "NCIA" (2)
PHYS:P 3j -1
CUT:P,A,E,# j 0
CUT:N 2j 0 0  $ Analog Capture for Neutrons - 4th entry
c ----- Weight Windows for Neutrons -----
c ----- Transformations -----
*tr1 29.9 9.68375 10.795  $ Transformations for Wells
*tr2 29.86 20.79625 10.795
*tr601 0 0 -0.189  $ PMT Cap (thickness of cap)
*tr602 0 0 0.201  $ PMT Glass / Body (thickness of detector)
*tr61 29.9 9.68375 12.56  $ PMT Locations
*tr62 29.86 20.79625 12.56
c ----- Source Defination -----
c Simulates the source as emitting spontaneous fission particles of a Watt
c Fission Energy Spectrum, parameters from Appendix H, pg. 3 of the MCNP
c manual.
sdef cel=d1 pos=15.5575 15.24 15.21 rad=d2 par=SF vec=1 0 0 dir=d3
sil L (201<200)  $ Source is bounded by cell 201, inside universe cell 200
spl v
si2 0 2.5914E-04  $ Starting Position
sp2 -21 1
sb3 -31 2.0  $ Source bias in the +x direction
c ----- Number of Particles to Simulate -----
nps 5E6
c ----- Interaction Rate Tallies -----
c Third bin is thermal to 10 eV. Fouth bin is 10 eV to 100 ev. Fifth bin is 100eV
c to 1keV. Sixth bin is 1keV to 1 MeV. Last Bin is 1 MeV to 10 MeV.
C E0 0 0.5E-6 3E-6 10E-6 100E-6 1E-3 1 10
E0 0 1E-9 5E-9 1E-8 5E-8 1E-7 5E-7 1E-6 5E-6
1E-5 5E-5 1E-4 1E-3 5E-3 1E-2 5E-2 1E-1 5E-1 1 10
FC114 Total Neutrons Reactions in Dectector in Pb Well
F114:n (601<610)
FM114 -1 3 1
FC124 Neutron Elastic Reactions in Detector in Pb Well
F124:n (601<610)
FM124 -1 3 2

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FC134 (n,gamma) Radiative Capture Reactions in Detector in Pb Well
F134:n (601<610)
FM134 -1 3 102
FC154 (n,t) Reactions in Detector in Pb Well
F154:n (601<610)
FM154 -1 3 105
FC214 Total Neutron Reactions in Detector in Cd Well
F214:n (601<620)
FM214 -1 3 1
FC224 Neturon Elastic Reactions in Detector in Cd Well
F224:n (601<620)
FM224 -1 3 2
FC234 (n,gamma) Radiative Capture Reactions in Detector in Cd Well
F234:n (601<620)
FM234 -1 3 102
FC254 (n,t) Reactions in Detector in Cd Well
F254:n (601<620)
FM254 -1 3 105
c ----- Source Tallies -----
FC24 Neutron Flux over Source
F24:n 201
SD24 1 $ Equivilant to multiplying by volume
E24 0 200i 5
c ----- Pb Well Tallies -----
FC104 Neutron Flux over Detector in Pb Well (Second is Volume Normalzied)
F104:n (601<610) (601<610)
SD104 j 1
FC184 Photon Flux over Detector in Pb Well
F184:p (601<610)
E184 0 200i 2
c ----- Cd Well Tallies -----
FC204 Neutron Flux over Detector in Cd Well (Second is Volume Normalized)
F204:n (601<620) (601<620)
SD204 j 1
FC284 Photon Flux over Detector in Cd Well
F284:p (601<620)
E284 0 200i 2
c ----- Particle Tallies -----
FC1 Neutron Particle Tallies (Source)
F1:n 210
C1 0 1
FC11 Neutron Particle Tallies (Pb Well)
F11:n (500.1<610) (500.2<610) (500.3<610) T
C11 0 1
FC31 Photon Particle Tally (Pb Well)
F31:p (500.1<610) (500.2<610) (500.3<610) T
C31 0 1
FC21 Neutron Particle Tallies (Cd Well)
F21:n (500.1<620) (500.2<620) (500.3<620) T
C21 0 1
FC41 Photon Particle Tallies (Cd Well)
F41:p (500.1<620) (500.2<620) (500.3<620) T
C41 0 1
c ----- Output -----
PRDMP j j 1 $ Write a MCTAL File
c ----- Material Definations -----
m1 98252 1 $ Cf-252 - rho = 15.1 g/cc - Wiki
c GS20 Detector
c Composition for Dr. Melcher, density from Saint Gobain
m3 3006 -0.0368 3007 -0.0019 8016 -0.2985
12025 -0.0241 13027 -0.0476 14000 -0.2617
58140 -0.0171
m2 6000 3.549E-02 $ Plexiglas - C5H8O2 - rho=1.18 - MCNP Primer
1001 5.678E-02
8016 1.420E-02
m204 7014.70c -0.755636 $air (US S. Atm at sea level) rho = 0.001225
8016.70c -0.231475 18036.70c -3.9e-005 18038.70c -8e-006
18040.70c -0.012842

```

m318	48106.70c	-0.011777	\$Cadmium rho = 8.65 g/cc,		
	48108.70c	-0.008543	48110.70c	-0.122116	48111.70c
	48112.70c	-0.24021	48113.70c	-0.122734	48114.70c
	48116.70c	-0.077225			
m406	82204.70c	-0.013781	\$Lead - rho = 11.32 g/cc		
	82206.70c	-0.239557	82207.70c	-0.220743	82208.70c
m456	1001.70c	-0.143716	\$Polyethylene - rho = 0.93 g/cc		
	6000.70c	-0.856284			
m488	14028.70c	-0.009187	\$Steel, Stainless 316 rho = 7.92		
	14029.70c	-0.000482	14030.70c	-0.000331	24050.70c
	24052.70c	-0.142291	24053.70c	-0.016443	24054.70c
	25055.70c	-0.02	26054.70c	-0.037326	26056.70c
	26057.70c	-0.014024	26058.70c	-0.001903	28058.70c
	28060.70c	-0.031984	28061.70c	-0.001408	28062.70c
	28064.70c	-0.001189	42092.70c	-0.003554	42094.70c
	42095.70c	-0.003937	42096.70c	-0.004169	42097.70c
	42098.70c	-0.006157	42100.70c	-0.002507	
C	\$Glass, Borosilicate (Pyrex),				
m388	5011.70c	-0.040066	8016.70c	-0.539559	11023.70c
	13027.70c	-0.011644	14028.70c	-0.346565	14029.70c
	14030.70c	-0.012481	19039.70c	-0.003086	19041.70c
m468	1001.70c	-0.048382	\$Polyvinyl Chloride,		
	6000.70c	-0.384361	17035.70c	-0.423941	17037.70c
m4	6000.70c	-0.0002	\$Mu Meta		
	25055.70c	-0.005	14000.60c	-0.0035	28000.50c
	42000.66c	-0.42	26000.55c	-0.1913	

GAMMA_CONFIG_GS20.MCNP

Gamma Irradiator (100uCi 60Co) (Larry Miller, UTK)					
C ##### Cell Cards #####					
100	488	-7.92	-100 101	\$ Stainless Steel Outer Box	
110	406	-11.32	-101 200 -201	\$ Pb Sheilding	
120	456	-0.93	-101 200 201	\$ HDPE Sheilding	
130	406	-11.32	-210	\$ Pb Sheilding	
C ----- Source Holder and Detector Well -----					
300	488	-7.92	300 -301 -303 304	\$ Detector Well	
310	488	-7.92	300 -302 -304 400	\$ Metal Source Holder	
320	488	-7.92	-305	\$ Source Cap	
C ----- SOURCE -----					
500	456	-0.93	-400		
c ----- Cd Well PMT -----					
600	0	-602	trcl=6 fill=6		
c ----- PMT Subcells -----					
601	3	-2.50	-500 u=6	\$ Detector cell	
602	388	-2.23	-601 u=6	\$ PMT Glass	
603	468	-1.406	603 u=6	\$ Plastic	
604	4	-8.74	-604 605 u=6	\$ Metal	
605	204	-0.001225	#602 #601 #603 #604 u=6	\$Air	
C ----- Outside World -----					
1000	204	-0.001225	-1000 #100 #110 #120 #130 #300 #310 #320 #500 #600		
1001	0	1000			
C ##### SURFACE CARDS #####					
C ----- HPDE BRICKS, BOX, AND LEAD BRICKS -----					
100	RPP	-10.48	10.48 -10.48 10.48 -0.32 30.48	\$ Outside metal (8.25x8.25x12")	
101	RPP	-10.16	10.16 -10.16 10.16 0 30.48	\$ Inside metal (8x8x12")	
200	RPP	-5.1	5.1 -5.1 5.1 0 30.48		
201	PZ	20.32		\$ Plane dividing Pb and HDPE	
210	rpp	-10.48	10.48 -10.48 10.48 -5.4 -0.32	\$ Pb bricks under metal	
C ----- SOURCE HOLDER AND DETECTOR WELL -----					
300	PZ	0			
301	PZ	30.71		\$ Well 12" tall	
302	PZ	2.7		\$ 1" Solid Steel Block	
303	CZ	5.0		\$ Outer Radius	
304	CZ	4.4		\$ Inner Radius	

```

305 RPP -1.9 1.9 -1.9 1.9 2.7 3.0175          $ Metal Source Cap (1/8")
C ----- SOURCE -----
400 RCC 0 0 2.2 0 0 0.5 1.27          $ Button Source in Metal
c ----- Detector -----
500 rcc 0 0 0 0 0 0.2 1.271          $0.2 cm 1" Diamter
c ----- PMT -----
601      602 rcc 0 0 0 0 0 0.3178 2.54      $ 2" Diamter, 1/8" Thick (Glass)
602      601 rcc 0 0 0 0 0 5.284 2.8030      $ Plastic Cap Outer
603      601 rcc 0 0 0.189 0 0 5.2651 2.6335      $ Plastic Cap Inner
604      602 rcc 0 0 0.3178 0 0 5 2.54      $ Mu Metal Outer
605      602 rcc 0 0 0.3178 0 0 5 2.535      $ Mu Metal Inner
C ----- OUTSIDE WORLD -----
1000 RPP -20 20 -20 20 -10 40      $ World Boundary

C ##### DATA CARDS #####
MODE P E
IMP:P,E 1 14R 0
PHYS:P 3j -1
CUT:P,E j 1E-6          $ Set low KE cutoff to 0 Mev for photons
NPS 1E8
SDEF ERG=D1 PAR=p pos=0 0 2.6
SI1 L 1.173 1.332
SP1 D 1.0 1.0
*tr6 0 0 10.3          $ 7" From the top of the well
*tr601 0 0 -0.189      $ PMT Cap (thickness of cap)
*tr602 0 0 0.2          $ PMT Glass (thickness of detector - 100um+1/8")
C ##### TALLIES (YE HAW) #####
c Multiply each tally by 1000 mrem/rem * 100uCi * 3.7E10 Bq *2 photons / decay
c em0 7.4E9 51r
FC12 Photon Flux over Front of Detector Surface
F12:P (500.2<600)
DE12 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6
      0.8 1 1.5
DF12 2.78E-6 1.11E-6 5.88E-7 2.56E-7 1.56E-7 1.20E-7 1.11E-7 1.20E-7 1.47E-7
      2.38E-7 3.45E-7 5.56E-7 7.69E-7 9.09E-7 1.14E-6 1.47E-6 1.79E-6 2.44E-6
FC22 Photon Flux over Top of Detector Well
F22:p 301
DE22 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6
      0.8 1 1.5
DF22 2.78E-6 1.11E-6 5.88E-7 2.56E-7 1.56E-7 1.20E-7 1.11E-7 1.20E-7 1.47E-7
      2.38E-7 3.45E-7 5.56E-7 7.69E-7 9.09E-7 1.14E-6 1.47E-6 1.79E-6 2.44E-6
FC1 Photon Tallies Across Detector
F1:P (500.1<600) (500.2<600) (500.3<600) T
C1 0 1
FC14 Total Photon Reactions in Detector
F14:p 601
FM14 -1 3 -5
E14 0 20i 0.2 1.5
FC18 Pulse Height Tally
F18:p,e 601
E18 0 200i 1.5
PRDMP j j 1
C ##### MATERIAL CARDS #####
c GS20 Detector
c Composition for Dr. Melcher, density from Saing Gobain
m3      3006 -0.0368      3007 -0.0019      8016 -0.2985
      12025 -0.0241      13027 -0.0476      14000 -0.2617
      58140 -0.0171
m4      6000.70c -0.0002 $Mu Meta
      25055.70c -0.005 14000.60c -0.0035 28000.50c -0.8
      42000.66c -0.42 26000.55c -0.1913
m204    7014.70c -0.755636 $air (US S. Atm at sea level) rho = 0.001225
      8016.70c -0.231475 18036.70c -3.9e-005 18038.70c -8e-006
      18040.70c -0.012842
m388    5011.70c -0.040066 $ Glass, Borosilicate (Pyrex)
      8016.70c -0.539559 11023.70c -0.028191 13027.70c -0.011644
      14028.70c -0.346565 14029.70c -0.018175 14030.70c -0.012481
      19039.70c -0.003086 19041.70c -0.000234

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m440	1001.70c	-0.085	\$Plastic Scintil, Vinyltoluene,			
	6000.70c	-0.915				
m406	82204.70c	-0.013781	\$Lead - rho = 11.32 g/cc			
	82206.70c	-0.239557	82207.70c	-0.220743	82208.70c	-0.525919
m456	1001.70c	-0.143716	\$Polyethylene - rho = 0.93 g/cc			
	6000.70c	-0.856284				
m488	14028.70c	-0.009187	\$Steel, Stainless 316 rho = 7.92			
	14029.70c	-0.000482	14030.70c	-0.000331	24050.70c	-0.007095
	24052.70c	-0.142291	24053.70c	-0.016443	24054.70c	-0.004171
	25055.70c	-0.02	26054.70c	-0.037326	26056.70c	-0.601748
	26057.70c	-0.014024	26058.70c	-0.001903	28058.70c	-0.080873
	28060.70c	-0.031984	28061.70c	-0.001408	28062.70c	-0.004546
	28064.70c	-0.001189	42092.70c	-0.003554	42094.70c	-0.002264
	42095.70c	-0.003937	42096.70c	-0.004169	42097.70c	-0.002412
	42098.70c	-0.006157	42100.70c	-0.002507		
m468	1001.70c	-0.048382	\$Polyvinyl Chloride,			
	6000.70c	-0.384361	17035.70c	-0.423941	17037.70c	-0.143316

MILLER_CONFIG_PS.MCNP

```

Miller's Poly Box with 0.59 ug (5.9E-7 gram) Cf-252 source
c ***** Cell Cards *****
c ----- Combined all of Martin's HDPE Cells into one -----
  100    456 -0.93      -1 :-2 :-3 :-4 :-5 :-6 :-6 :-7 :-8 :-9 $ HDPE Sheilding
      :-10 :-11 :-12 :-13 :-14 :-15 :-16 :-17 :-18
c ----- Creating a source universe -----
  200    0      -200 fill=3
  201    1 -15.1      -210 u=3      $ Cf252 Spherical Source
  202    488 -7.92      (-206 :-205 )210 u=3 $ Stainless Steel 316 Around Source
  203    406 -11.35      -204 205 u=3      $ Lead Pig
  204    456 -0.93      (-202 :-203 ) 204 u=3 $ HDPE around source
  205    204 -0.001225      (210 202 203 204 ) u=3 $ Air until universe boundary
c ----- Lead Detector Well -----
  300    0      -302 #610 trcl=1 fill=1
  302    204 -0.001225      -300      u=1      $ air
  303    2      -1.18      -301 300      u=1      $ Plastic
  304    406 -11.35      301      u=1      $ Lead
c ----- Cadimium Detector Well -----
  400    0      -402 #620 trcl=2 fill=2
  402    204 -0.001225      -400      u=2      $ air
  403    2      -1.18      -401 400      u=2      $ Plastic
  404    318 -8.65      401      u=2      $ cd
c ----- Lead Well PMT -----
  610    0      -602      trcl=61 fill=6
c ----- Cd Well PMT -----
  620    0      -602      trcl=62 fill=6
c ----- PMT Subcells -----
  601    3      -1.281 -500      u=6      $ Detector cell
  602    388 -2.23      -601      u=6      $ PMT Glass
  603    468 -1.406 603      u=6      $ Plastic
  604    4      -8.74      -604 605      u=6      $ Metal
  605    204 -0.001225 #602 #601 #603 #604 u=6 $Air
c ----- outside world -----
  1000    204 -0.001225      -1000 #100 #200 #300 #400 $ Air inside the world
      #610 #620
  1001    0      1000      $ Outside world

c ***** Surface Cards *****
c ----- Outer HDPE Box -----
  1      rpp 5.3975 45.72 0 30.48 0 5.3975 $ Bottom Cente
  2      rpp 45.72 51.1175 0 30.48 0 35.56 $ Right Side
  3      rpp 0 5.3975 0 30.48 0 35.56 $ Left Side
  4      rpp 5.3975 45.72 0 5.3975 5.3975 35.56 $ Front
  5      rpp 5.3975 45.72 25.0825 30.48 5.3975 35.56 $ Back
  6      rpp 5.3975 25.7175 5.3975 10.795 10.795 35.56 $ Source Cover
  7      rpp 5.3975 25.7175 19.685 25.0825 10.795 35.56 $ Source Cover

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8      rpp 5.3975 25.7175 10.795 19.685 30.1625 35.56 $ Source Cover
9      rpp 5.3975 25.7175 5.3975 25.0825 5.3975 10.795 $ Source Cover
10     rpp 5.3975 10.795 10.795 19.685 10.795 30.1625 $ Source Cover
11     rpp 20.32 25.7175 10.795 19.685 10.795 30.1625 $ Source Cover
12     rpp 25.7175 36.5125 5.3975 25.0825 5.3975 10.795 $ Detector/Cha
13     rpp 36.5125 39.0525 5.3975 25.0825 5.3975 35.56 $ Wall behind
14     rpp 5.08 22.2251 0 30.48 35.56 40.64 $ Block on top
15     rpp 34.1 51.1175 0 30.48 35.56 38.1 $ Block on top
16     rpp 22.2251 33.9727 0 5.08 35.56 38.1 $ Block on top
17     rpp 22.2251 33.9727 13.97 16.51 35.56 38.1 $ Block on top
18     rpp 22.2251 33.9727 25.4 30.48 35.56 38.1 $ Block on top
c ----- Universe for Inner Source Holder and Source
200    rpp 10.795 20.32 10.795 19.685 10.795 30.1625
c ----- Inner Source Holder HDPE -----
202    rpp 10.795 20.32 10.795 19.685 10.795 15.875 $ Block holdi
203    rpp 10.795 20.32 10.795 19.685 24.13 30.1625 $ Block above
c ----- Source Sheilding (Lead) -----
204    rcc 15.5575 15.24 10.795 0 0 13.335 2.54 $ Lead Pig ou
205    rcc 15.5575 15.24 13.305 0 0 9.525 1.27 $ Lead Pig in
206    rcc 15.5575 15.24 13.305 0 0 3.81 0.3175 $ SS 316 Sour
210    s 15.5575 15.24 15.21 2.5914E-04 $ Spherical Point Source
c ----- Lead Well -----
300    rcc 0 0 0.439 0 0 27.726 3.564 $ Inner Well (ID Plastic)
301    rcc 0 0 0.439 0 0 27.726 3.7885 $ Plastic OD / Pb ID
302    rcc 0 0 0 0 0 27.94 4.0025 $ Pb OD
c ----- Cadimium Well -----
400    rcc 0 0 0.418 0 0 27.731 3.7765 $ Inner Well (ID Plastic)
401    rcc 0 0 0.418 0 0 27.731 3.933 $ Plastic OD / cd ID
402    rcc 0 0 0 0 0 27.94 4.142 $ Cd OD
c ----- Detector -----
500    rcc 0 0 1E-6 0 0 0.005 2.54 $ 50 micron thick,2" Dimeter
c ----- PMT -----
601    602 rcc 0 0 0 0 0 0.3178 2.54 $ 2" Diamter, 1/8" Thick (Glass)
602    601 rcc 0 0 0 0 0 5.284 2.8030 $ Plastic Cap Outer
603    601 rcc 0 0 0.189 0 0 5.2651 2.6335 $ Plastic Cap Inner
604    602 rcc 0 0 0.3178 0 0 5 2.54 $ Mu Metal Outer
605    602 rcc 0 0 0.3178 0 0 5 2.535 $ Mu Metal Inner
c ----- World Boundary -----
1000   rpp -10 60 -10 60 -10 60 $ An oversized box

c ***** Data Cards *****
MODE N P A D E # $ Type of particles to transport: neutrons, photons, alphas, tritons,
deuterons, & electrons
IMP:N,P,A,D,E,# 1 22r 0
PHYS:N 100 4j -1 2 $ Turned on fission multiplicity "FISM" (-1) and light ion
recoil "NCIA" (2)
PHYS:P 3j -1
CUT:P,A,E,# j 0
CUT:N 2j 0 0 $ Analog Capture for Neutrons - 4th entry
c ----- Weight Windows for Neutrons -----
c ----- Transformations -----
*tr1 29.9 9.68375 10.795 $ Transformations for Wells
*tr2 29.86 20.79625 10.795
*tr601 0 0 -0.189 $ PMT Cap (thickness of cap)
*tr602 0 0 0.020 $ PMT Glass / Body (thickness of detector)
*tr61 29.9 9.68375 12.56 $ PMT Locations
*tr62 29.86 20.79625 12.56
c ----- Source Defination -----
c Simulates the source as emitting spontaneous fission particles of a Watt
c Fission Energy Spectrum, parameters from Appendix H, pg. 3 of the MCNP
c manual.
sdef cel=d1 pos=15.5575 15.24 15.21 rad=d2 par=SF vec=1 0 0 dir=d3
sil L (201<200) $ Source is bounded by cell 201, inside universe cell 200
spl v
si2 0 2.5914E-04 $ Starting Position
sp2 -21 1
sb3 -31 2.0 $ Source bias in the +x direction
c ----- Number of Particles to Simulate -----

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nps 5E6
c ----- Interaction Rate Tallies -----
c Third bin is thermal to 10 eV. Fourth bin is 10 eV to 100 eV. Fifth bin is 100eV
c to 1keV. Sixth bin is 1keV to 1 MeV. Last Bin is 1 MeV to 10 MeV.
C E0 0 0.5E-6 3E-6 10E-6 100E-6 1E-3 1 10
E0 0 1E-9 5E-9 1E-8 5E-8 1E-7 5E-7 1E-6 5E-6
      1E-5 5E-5 1E-4 1E-3 5E-3 1E-2 5E-2 1E-1 5E-1 1 10
FC114 Total Neutrons Reactions in Dectector in Pb Well
F114:n (601<610)
FM114 -1 3 1
FC124 Neutron Elastic Reactions in Detector in Pb Well
F124:n (601<610)
FM124 -1 3 2
FC134 (n,gamma) Radiative Capture Reactions in Detector in Pb Well
F134:n (601<610)
FM134 -1 3 102
FC154 (n,t) Reactions in Detector in Pb Well
F154:n (601<610)
FM154 -1 3 105
FC214 Total Neutron Reactions in Detector in Cd Well
F214:n (601<620)
FM214 -1 3 1
FC224 Neturon Elastic Reactions in Detector in Cd Well
F224:n (601<620)
FM224 -1 3 2
FC234 (n,gamma) Radiative Capture Reactions in Detector in Cd Well
F234:n (601<620)
FM234 -1 3 102
FC254 (n,t) Reactions in Detector in Cd Well
F254:n (601<620)
FM254 -1 3 105
c ----- Source Tallies -----
FC24 Neutron Flux over Source
F24:n 201
SD24 1          $ Equivilant to multiplying by volume
E24 0 200i 5
c ----- Pb Well Tallies -----
FC104 Neutron Flux over Detector in Pb Well (Second is Volume Normalzied)
F104:n (601<610) (601<610)
SD104 j 1
FC184 Photon Flux over Detector in Pb Well
F184:p (601<610)
E184 0 200i 2
FC194 Total Photon Interactions in Pb Well (MT 501)
F194:p (601<610)
FM194 -1 3 -5
c ----- Cd Well Tallies -----
FC204 Neutron Flux over Detector in Cd Well (Second is Volume Normalized)
F204:n (601<620) (601<620)
SD204 j 1
FC284 Photon Flux over Detector in Cd Well
F284:p (601<620)
E284 0 200i 2
FC294 Total Phont Intreactions in Cd Well (MT 501)
F294:p (601<620)
FM294 -1 3 -5
c ----- Particle Tallies -----
FC1 Neutron Particle Tallies (Source)
F1:n 210
C1 0 1
FC11 Neutron Particle Tallies (Pb Well)
F11:n (500.1<610) (500.2<610) (500.3<610) T
C11 0 1
FC31 Electron Particle Tallies (Pb Well)
F31:e (500.1<610) (500.2<610) (500.3<610) T
C31 0 1
FC21 Neutron Particle Tallies (Cd Well)
F21:n (500.1<620) (500.2<620) (500.3<620) T

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C21 0 1
FC41 Electron Particle Tallies (Cd Well)
F41:e (500.1<620) (500.2<620) (500.3<620) T
C41 0 1
c ----- Output -----
PRDMP j j 1      $ Write a MCTAL File
c ----- Material Definations -----
m1  98252  1      $ Cf-252 - rho = 15.1 g/cc - Wiki
m3  1001    -0.0566    $30% LiF, 65% PS, 5% PPO/POPOP
    6000    -0.6912    7014      -0.0067      8016      -0.0076
    3007    -0.0039    3006      -0.0543      9017      -0.2170
m2  6000    3.549E-02    $ Plexiglas - C5H8O2 - rho=1.18 - MCNP Primer
    1001    5.678E-02
    8016    1.420E-02
m4  6000.70c    -0.0002    $Mu Meta
    25055.70c    -0.005    14000.60c    -0.0035    28000.50c    -0.8
    42000.66c    -0.42    26000.55c    -0.1913
m204  7014.70c    -0.755636    $air (US S. Atm at sea level) rho = 0.001225
    8016.70c    -0.231475    18036.70c    -3.9e-005    18038.70c    -8e-006
    18040.70c    -0.012842
m318  48106.70c    -0.011777    $Cadmium rho = 8.65 g/cc,
    48108.70c    -0.008543    48110.70c    -0.122116    48111.70c    -0.126284
    48112.70c    -0.24021    48113.70c    -0.122734    48114.70c    -0.29111
    48116.70c    -0.077225
m406  82204.70c    -0.013781    $Lead - rho = 11.32 g/cc
    82206.70c    -0.239557    82207.70c    -0.220743    82208.70c    -0.525919
m456  1001.70c    -0.143716    $Polyethylene - rho = 0.93 g/cc
    6000.70c    -0.856284
m488  14028.70c    -0.009187    $Steel, Stainless 316 rho = 7.92
    14029.70c    -0.000482    14030.70c    -0.000331    24050.70c    -0.007095
    24052.70c    -0.142291    24053.70c    -0.016443    24054.70c    -0.004171
    25055.70c    -0.02    26054.70c    -0.037326    26056.70c    -0.601748
    26057.70c    -0.014024    26058.70c    -0.001903    28058.70c    -0.080873
    28060.70c    -0.031984    28061.70c    -0.001408    28062.70c    -0.004546
    28064.70c    -0.001189    42092.70c    -0.003554    42094.70c    -0.002264
    42095.70c    -0.003937    42096.70c    -0.004169    42097.70c    -0.002412
    42098.70c    -0.006157    42100.70c    -0.002507
C      $Glass, Borosilicate (Pyrex),
m388  5011.70c    -0.040066    8016.70c    -0.539559    11023.70c    -0.028191
    13027.70c    -0.011644    14028.70c    -0.346565    14029.70c    -0.018175
    14030.70c    -0.012481    19039.70c    -0.003086    19041.70c    -0.000234
m468  1001.70c    -0.048382    $Polyvinyl Chloride,
    6000.70c    -0.384361    17035.70c    -0.423941    17037.70c    -0.143316

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GAMMA_CONFIG_PS.MCNP

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Gamma Irradiator (100uCi 60Co) (Larry Miller, UTK)
C ##### Cell Cards #####
100  488  -7.92  -100 101      $ Stainless Steel Outer Box
110  406  -11.32 -101 200 -201  $ Pb Sheilding
120  456  -0.93  -101 200 201  $ HDPE Sheilding
130  406  -11.32 -210      $ Pb Sheilding
C ----- Source Holder and Detector Well -----
300  488  -7.92  300 -301 -303 304  $ Detector Well
310  488  -7.92  300 -302 -304 400  $ Metal Source Holder
320  488  -7.92  -305      $ Source Cap
C ----- SOURCE -----
500  456  -0.93  -400
c ----- Cd Well PMT -----
600  0    -602      trcl=6      fill=6
c ----- PMT Subcells -----
601  3    -1.18  -500      u=6      $ Detector cell
610  440  -1.023 -510      u=6      $ Arcylic Disc Backign
602  388  -2.23  -601      u=6      $ PMT Glass
603  468  -1.406 603      u=6      $ Plastic
604  4    -8.74  -604 605      u=6      $ Metal

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605 204 -0.001225 #602 #601 #603 #604 #610 u=6 $Air
C ----- Outside World -----
1000 204 -0.001225 -1000 #100 #110 #120 #130 #300 #310 #320 #500 #600
1001 0 1000

C ##### SURFACE CARDS #####
C ----- HPDE BRICKS, BOX, AND LEAD BRICKS -----
100 RPP -10.48 10.48 -10.48 10.48 -0.32 30.48 $ Outside metal (8.25x8.25x12")
101 RPP -10.16 10.16 -10.16 10.16 0 30.48 $ Inside metal (8x8x12")
200 RPP -5.1 5.1 -5.1 5.1 0 30.48
201 PZ 20.32 $ Plane dividing Pb and HDPE
210 rpp -10.48 10.48 -10.48 10.48 -5.4 -0.32 $ Pb bricks under metal
C ----- SOURCE HOLDER AND DETECTOR WELL -----
300 PZ 0
301 PZ 30.71 $ Well 12" tall
302 PZ 2.7 $ 1" Solid Steel Block
303 CZ 5.0 $ Outer Radius
304 CZ 4.4 $ Inner Radius
305 RPP -1.9 1.9 -1.9 1.9 2.7 3.0175 $ Metal Source Cap (1/8")
C ----- SOURCE -----
400 RCC 0 0 2.2 0 0 0.5 1.27 $ Button Source in Metal
c ----- Detector -----
c TO CHANGE THE THICKNESS OF THE DETECTOR:
c a) Height of surface 500
c b) Starting position of surface 510
c c) tr602 (sum of height of surface 500 and height of surface 510)
500 rcc 0 0 0 0 0.0025 2.54 $ 25 microns thick, 2" Dimeter
510 rcc 0 0 0.0025 0 0 0.3175 2.54 $ 1/8" Arycllic Disc Backing
c ----- PMT -----
601 602 rcc 0 0 0 0 0.3178 2.54 $ 2" Diamter, 1/8" Thick (Glass)
602 601 rcc 0 0 0 0 5.284 2.8030 $ Plastic Cap Outer
603 601 rcc 0 0 0.189 0 0 5.2651 2.6335 $ Plastic Cap Inner
604 602 rcc 0 0 0.3178 0 0 5 2.54 $ Mu Metal Outer
605 602 rcc 0 0 0.3178 0 0 5 2.535 $ Mu Metal Inner
C ----- OUTSIDE WORLD -----
1000 RPP -20 20 -20 20 -10 40 $ World Boundary

C ##### DATA CARDS #####
MODE P E
IMP:P,E 1 15R 0
PHYS:P 3j -1
CUT:P,E j 1E-6
NPS 5E6
SDEF ERG=D1 PAR=p pos=0 0 2.6
SI1 L 1.173 1.332
SP1 D 1.0 1.0
*tr6 0 0 10.3 $ 7" From the top of the well
*tr601 0 0 -0.189 $ PMT Cap (thickness of cap)
*tr602 0 0 0.3200 $ PMT Glass (thickness of detector - 100um+1/8")
C ##### TALLIES (YE HAW) #####
c Multiply each tally by 1000 mrem/rem * 100uCi * 3.7E10 Bq *2 photons / decay
c em0 7.4E9 51r
FC12 Photon Flux over Front of Detector Surface
F12:P (500.2<600)
DE12 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6
0.8 1 1.5
DF12 2.78E-6 1.11E-6 5.88E-7 2.56E-7 1.56E-7 1.20E-7 1.11E-7 1.20E-7 1.47E-7
2.38E-7 3.45E-7 5.56E-7 7.69E-7 9.09E-7 1.14E-6 1.47E-6 1.79E-6 2.44E-6
FC22 Photon Flux over Top of Detector Well
F22:p 301
DE22 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6
0.8 1 1.5
DF22 2.78E-6 1.11E-6 5.88E-7 2.56E-7 1.56E-7 1.20E-7 1.11E-7 1.20E-7 1.47E-7
2.38E-7 3.45E-7 5.56E-7 7.69E-7 9.09E-7 1.14E-6 1.47E-6 1.79E-6 2.44E-6
FC1 Photon Tallies Across Detector
F1:P (500.1<600) (500.2<600) (500.3<600) T
C1 0 1
FC14 Total Photon Reactions in Detector

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F14:p 601
FM14 -1 3 -5
E14 0 20i 0.2 1.5
FC18 Pulse Height Tally
F18:p,e 601
E18 0 200i 1.5
PRDMP j j 1
C ##### MATERIAL CARDS #####
m3 1001 -0.0556 $30% LiF, 65% PS, 5% PPO/POPOP
    6000 -0.6800 7014 -0.0070 8016 -0.008
    3007 -0.0036 3006 -0.0684 9017 -0.228
m4 6000.70c -0.0002 $Mu Meta
    25055.70c -0.005 14000.60c -0.0035 28000.50c -0.8
    42000.66c -0.42 26000.55c -0.1913
m204 7014.70c -0.755636 $air (US S. Atm at sea level) rho = 0.001225
    8016.70c -0.231475 18036.70c -3.9e-005 18038.70c -8e-006
    18040.70c -0.012842
m388 5011.70c -0.040066 $ Glass, Borosilicate (Pyrex)
    8016.70c -0.539559 11023.70c -0.028191 13027.70c -0.011644
    14028.70c -0.346565 14029.70c -0.018175 14030.70c -0.012481
    19039.70c -0.003086 19041.70c -0.000234
m440 1001.70c -0.085 $Plastic Scintil, Vinyltoluene,
    6000.70c -0.915
m406 82204.70c -0.013781 $Lead - rho = 11.32 g/cc
    82206.70c -0.239557 82207.70c -0.220743 82208.70c -0.525919
m456 1001.70c -0.143716 $Polyethylene - rho = 0.93 g/cc
    6000.70c -0.856284
m488 14028.70c -0.009187 $Steel, Stainless 316 rho = 7.92
    14029.70c -0.000482 14030.70c -0.000331 24050.70c -0.007095
    24052.70c -0.142291 24053.70c -0.016443 24054.70c -0.004171
    25055.70c -0.02 26054.70c -0.037326 26056.70c -0.601748
    26057.70c -0.014024 26058.70c -0.001903 28058.70c -0.080873
    28060.70c -0.031984 28061.70c -0.001408 28062.70c -0.004546
    28064.70c -0.001189 42092.70c -0.003554 42094.70c -0.002264
    42095.70c -0.003937 42096.70c -0.004169 42097.70c -0.002412
    42098.70c -0.006157 42100.70c -0.002507
m468 1001.70c -0.048382 $Polyvinyl Chloride,
    6000.70c -0.384361 17035.70c -0.423941 17037.70c -0.143316

```

DHS-DNDO_CONFIG_PS.MCNP

```

c ----- Source -----
70 5 -15.1 -70 $ 252Cf source
71 406 -11.34 -71 70 $ Lead around source
72 456 -0.93 -72 71 $ Poly around source
c ----- Detector -----
610 0 -600 fill=1 $ Stacked Detectors
600 0 -510 500 u=1 lat=1 fill=0:120 0:0 0:0
2 120r $ Filling with Universe 2
500 3 -1.281 500 -501 u=2 $ 50 Micron Film
501 10 -1.17 #500 u=2
700 488 -7.92 600 -700 $ SS-316 Encasing
c ----- Outside World -----
1000 204 -0.001225 -1000 #610 #700 #70 #71 #72 $ Atmosphere
1001 0 1000

c ##### Surface Cards #####
c ----- Encasing Bounds (Size of He3) -----
600 rpp 0 12.7 -15.25 15.25 0 217.7 $ Detector Volume
c ----- Detector Bounds -----

500 px 0
501 px 0.005 $ Thickness of Detector
510 px 0.105 $ 1 mm of backing

```

```

c ----- Encasing Material -----
700 rpp -0.3175 13.018 -15.5675 15.5675 -0.3175 218.018
c ----- Source -----
70 s -200 0 108.85 2.510E-04 $ Source
71 s -200 0 108.85 5.0025E-01 $ 0.5 cm lead surrounding source
72 s -200 0 108.85 3.00025 $ 2.5 cm poly surrounding source
c ----- Outside World -----
1000 so 250

c ----- Run Info -----
nps 1E8
IMP:N,H,P,A,D,T,S,E,# 1 8R 0 $ Particle Importances within cells
c ----- Physics -----
MODE N H P A D T S E # $ Type of particles to transport: neutrons, photons, alphas,
deuterons, electrons, & heavy
PHYS:N 100 4j -1 2 $ Turned on fission multiplicity "FISM" (-1) and light ion
recoil "NCIA" (2)
PHYS:P 3j -1 $ Turn on photonuclear particle production - 4th entry
CUT:N 2j 0 0 $ Analog Capture for Neutrons - 4th entry
CUT:P,A,E,#,H,A,S,T j 0 $ Set low KE cutoff to 0 Mev for photons, tritons, alphas,
electrons, & heavy - 2nd entry

c ----- Source Definition -----
c 1 nanogram Cf-252 source = 1E-9 grams = 6.623E-11 cc - modeled as sphere in SS
sdef pos=-200 0 108.85 cel=70 par=SF rad=d1 $ vec=1 0 0 dir=d2
sil 0 2.510E-04
spl -21 1

c ----- Translations -----
*TR1 0 0 200 $ Distance from source to center of detector
c ----- Tallies Yo! -----
C E0 0 1E-9 5E-9 1E-8 5E-8 1E-7 5E-7 1E-6 5E-6
C 1E-5 5E-5 1E-4 1E-3 5E-3 1E-2 5E-2 1E-1 5E-1 1 10
E0 0 200i 5
FC1 Neutron Crossing Source Cell
F1:n 70
C1 0 1
FC11 Neutrons Crossing HDPE Pig Around Source
F11:n 72
C11 0 1
FC31 Photons Crossing HDPE Pig around Source
F31:p 72
C31 0 1
FC41 Neutrons Crossing Detector Front
F41:n 500
C41 0 1
FC4 (n,t) Reactions in Thin Film (Neutron Detector)
F4:n (500<610)
SD4 1
FM4 -1 3 105
FC14 (n,t) Reactions in Selected Thin Films
F14:n (500<600[1]) (500<600[2]) (500<600[4]) (500<600[6]) (500<600[8])
(500<600[10]) (500<600[12]) (500<600[14]) (500<600[16]) (500<600[18])
(500<600[20]) (500<600[22]) (500<600[24]) (500<600[26]) (500<600[28])
(500<600[30]) (500<600[32]) (500<600[34]) (500<600[36]) (500<600[38])
(500<600[40]) (500<600[42]) (500<600[44]) (500<600[46]) (500<600[48])
(500<600[50]) (500<600[60]) (500<600[70]) (500<600[80]) (500<600[90])
(500<600[100]) (500<600[110]) (500<600[120]) T
SD14 1 33r
E14 0 10
FM14 -1 3 105
FC111 Neutrons Crossing Selected Thin Films
F111:n (500<600[1]) (500<600[25]) (500<600[50]) (500<600[75])
(500<600[100]) (500<600[120]) T
SD111 1 6r
C111 0 1
E111 0 1E-9 200ilog 5
c ----- Output -----
PRDMP j j 1 $ Write a MCTAL File

```

c ----- Material Cards -----						
m3	1001	-0.0566	\$30% LiF, 65% PS, 5% PPO/POPOP			
	6000	-0.6912	7014	-0.0067	8016	-0.0076
	3007	-0.0039	3006	-0.0543	9017	-0.2170
m10	1001	-0.080538	\$Lucite (PMMA / Plexiglass)			rho = 1.19 g/cc
	6012	-0.599848	8016	-0.319614		
m204	7014.70c	-0.755636	\$air (US S. Atm at sea level) rho = 0.001225			
	8016.70c	-0.231475	18036.70c	-3.9e-005	18038.70c	-8e-006
	18040.70c	-0.012842				
C	Material 5 is Cf-252 - rho = 15.1 g/cc - Wiki					
m5	98252.66c	1				
m406	82204.70c	-0.013781	\$Lead,			
	82206.70c	-0.239557	82207.70c	-0.220743	82208.70c	-0.525919
m456	1001.70c	-0.143716	\$Polyethylene - rho = 0.93 g/cc			
	6000.70c	-0.856284				
m488	14028.70c	-0.009187	\$Steel, Stainless 316 rho = 7.92			
	14029.70c	-0.000482	14030.70c	-0.000331	24050.70c	-0.007095
	24052.70c	-0.142291	24053.70c	-0.016443	24054.70c	-0.004171
	25055.70c	-0.02	26054.70c	-0.037326	26056.70c	-0.601748
	26057.70c	-0.014024	26058.70c	-0.001903	28058.70c	-0.080873
	28060.70c	-0.031984	28061.70c	-0.001408	28062.70c	-0.004546
	28064.70c	-0.001189	42092.70c	-0.003554	42094.70c	-0.002264
	42095.70c	-0.003937	42096.70c	-0.004169	42097.70c	-0.002412
	42098.70c	-0.006157	42100.70c	-0.002507		
mt3	poly.01t					
mt456	poly.01t					
mt10	poly.01t					

MATLAB SCRIPTS

A toolkit was developed for MATLAB, and the user might find it useful to add a toolkit folder containing the following scripts to their MATLAB path if they intend to use the often; this allows the scripts to be executed out of their source directory. The scripts expect a certain type of input, and limited input error checking has been completed. The user should be aware of this and wary of utilizing the scripts outside of their intended purpose. Finally, in a future release of these scripts the spectra will be rewritten as a class object which will contain both the header and spectra data.

A `Spectra` class has been developed with static methods that allow for a spectra file to be plotted along with the calculation of a variety of derived properties. In addition two Matlab scripts were developed (along with a python script for file name processing) to allow for the comparison of different spectra. These files are `SummerrizeSpectra` and `SummerrizeSpectraPb`.

IMPORTSPE.M

```
function [header spectrum] = importSPE(varargin)

% [header spectrum] = importSPE(filename)

% Reads in SPE files. If no filename is given, prompts the user to enter a
% filename. If the user selects more than one file to be read, the result
```

```

% is returned as a cell array of file headers and spectrum.

%% Getting the Files
if nargin ~=1
    % Prompt user for filenames
    [filename, pathname] = uigetfile({'*'}, 'Choose Spectrum File', 'Multiselect', 'on');
    % [filename, pathname] = uigetfile({'*.spe', '*.Spe'}, 'Choose Spectrum File', 'Multiselect', 'on');
    if ~iscell(filename)
        file{1} = fullfile(pathname, filename);
    elseif isequal(filename, 0) || isequal(pathname, 0)
        error('User Pressed Cancel');
    else
        for i=1:numel(filename)
            file{i} = fullfile(pathname, filename{i});
        end
    end
else
    file{1} = varargin{1};
end

%% Allocating Storage
header = cell(1, numel(file));
spectrum = cell(1, numel(file));

%% Reading in the files
for i=1:numel(file)
    fid = fopen(file{i}, 'r');
    if (fid == -1)
        fprintf(1, 'Cannot read file %s\n', file{i});
    else
        [p f ext] = fileparts(file{i});
    end
end

```

```

        [header{i} spectrum{i}] = readSPE(fid,[f ext]);

        fclose(fid);

    end

end

%% Returning results
if numel(header) ==1
header = header{1};
spectrum = spectrum{1};
end

end

function [h data] = readSPE(fid,filename)

% Main function, where all of the parsing is done.

%% Parsing Constants
HEADERLINES = 12;

%% Calling Helpers
h = readHeader(fid,HEADERLINES,filename);
data = textscan(fid,'%f');

% Conveting into an x,y form
data = cell2mat(data);
data = [h.DATA_RANGE(1):h.DATA_RANGE(2); data'];
end

function h = readHeader(fid,HEADERLINES,filename)

% h = READHEADER(fid,HEADERLINES)

% Reads in number of HEADERLINES, returning a strucutre of the fields and

```

```

% values.

% Reading in header
c = cell(1,HEADERLINES);

for i=1:HEADERLINES

    c{i} = fgetl(fid);

end

% Assigning Field and values

time = sscanf(c{10},'%f %f');

h = struct('FILENAME',filename,'SPEC_ID',c{2},'SPEC_REM',[c{4:6}],...

    'DATE_MEA',c{8},'LIVE_TIME',time(1),'TOTAL_TIME',time(2),...

    'DATA_RANGE',sscanf(c{12},'%d %d'));

end

```

PROCESSSPE.M

```

function [h s dataMatrix] = processSPE(h,s,varargin)

% [h s dataMatrix] = processSPE(h,s,varargin)
% Takes in a header and spectrum structure returned from IMPORTSPE, and
% applies the option specified in varargin to the data, returning the
% modified spectrum and header.  VARARGIN's are:
% 'CountRateScale' - use the count time in header to scale the counts
% 'Plot' - Plots the data
% 'GainScale' - Scales each input by the scale factor specified in either a
% cell array for a multi spectrum case or value in the single spectrum
% case.  The scale factor is DesiredGain/CurrentGain.
% For multiple spectrum the an example is below.
% gain = {20/50,50/20,1,100/10}
% [hScaled sScaled] = processSPE(h,s,'GainScale',gain);
% This would take the 4 spectrum in s and scale the first one to 20 G when
% measured at 50 G, the second from 50G to 20G, the third no scaling, and
% the fifth from 10G to 100G.
% 'CountRate' - can take one or two arguments.  'CountRate' by itself
% calculates the counts over the entire spectrum.  'CountRate' [loc1 loc2]
% calculates the count rate over the spectrum between the two locations.
% 'Rebin',binSize - rebins the data using binSize

%% Checking User Input
if nargin <2
    error('Need to input header and spectrum');
elseif nargin ==2

```

```

    args{1} = 'CountRateScale';
    args{2} = 'Plot';
    fprintf('Applying the Standard Arguments\n');
    disp(args);
else
    args = varargin;
end

%% Turning to cells if single spectrum entered
if ~iscell(h) && ~iscell(s)
    h{1} = h;
    s{1} = s;
end

%% Processing Spectrum
argCount = 1;
while argCount <= numel(args)
    arg = args{argCount};

    switch arg
        case 'GainScale'
            % Gain Scaling is defined as DesiredGain/CurrentGain
            argCount = argCount+1;
            gain = args{argCount};
            for i=1:numel(h)
                s{i}(2,:) = s{i}(2,+)/gain{i};
                s{i}(1,:) = s{i}(1,)*gain{i};
            end
        case 'CountRateScale'
            for i=1:numel(h)
                data = s{i};
                data(2,:) = data(2,+)/h{i}.LIVE_TIME;
                s{i} = data;
            end

        case 'CountRate'
            bounds = zeros(numel(h),2);

            if argCount+1 < numel(args) && ~ischar(args{argCount+1})

                % Using user supplied bounds
                argCount = argCount+1;
                for i = 1:numel(h)
                    bounds(i,:) = args{argCount};
                end
            else
                % Default Bounds are from 1 to end - entire spectrum

```

```

        for i=1:numel(h)
            bounds(i,:) = [1 length(s{i}(2,:))];
        end
    end

    % Computing the sum
    for i = 1:numel(h)
        counts = sum(s{i}(2,bounds(i,1):bounds(i,2)));
        fprintf('Sum of Spectrum %s is %f\n',h{i}.FILENAME,counts);
    end

    case 'Rebin'
        % Rebinning for better statistics
        argCount = argCount+1;
        binSize = args{argCount};
        for i = 1:numel(h)

            % Creating a new bin structure
            bins = floor(numel(s{i}(1,:))/binSize);
            snew = zeros(2,bins);

            % Iterating for the new bin structure
            for j = 1:bins
                snew(1,j) = j*binSize + binSize/2;      % Channel
                binBoundaries = [(j-1)*binSize+1,j*binSize];
                snew(2,j) = sum(s{i}(2,binBoundaries(1):binBoundaries(2))); % Counts
            end
            s{i} = snew;
        end
    case 'Plot'
        figure;
        hold all;
        leg = cell(1,numel(h));
        for i=1:numel(h)
            % scatter(s{i}(1,:),s{i}(2,:));
            plot(s{i}(1,:),s{i}(2,:));
            leg{i} = h{i}.FILENAME;
        end
        legend(leg);
        hold off;
        ylabel('Count Rate (cps)','fontSize',16);
        xlabel('Channel Number','fontSize',16);
        set(gca,'FontSize',16);
        legend boxoff
    otherwise
        fprintf('Argument %s not recongized\n',arg);
    end
    argCount = argCount+1;
end
end

```

```

rows = numel(s{1}(1,:));
cols = numel(h) + 1;
dataMatrix = zeros(rows,cols);
dataMatrix(:,1) = s{1}(1,:);
for i = 1:numel(s)
    dataMatrix(:,i+1) = s{i}(2,:);
end
%% Turning back to single spectrum if single spectrum entered
if numel(h)==1 && numel(s) ==1
    h = h{1};
    s = s{1};
end

```

NGDISCRIM.M

```

function [perf PHDPerf discm PHD nIntEff gIntEff Ch nCounts gCounts] = NGDiscrim(n,g,t,varargin)
% [perf PHDPerf discm PHD nIntEff gIntEff Ch nCounts gCounts] = NGDiscrim(n,g,t,varargin)
% NGDISCRIM - Calculates the discrimination of a sample.
% n - the neutron spectra. Use importSPE, processSPE to generate spectra
% g - the gamma spectra. Use importSPE, processSPE to generate spectra
% t - the name of the spectra. A cell array.
% If n,g,and t are cell arrays then the order of the cells must match; no
% internal checking is completed.
% displayFigures - if this string is present then the figures are displayed.
% saveFigures - if this string is present then the figures are saved.
% Returns several parameters the
% characterize the discrimination performance of the film.
% Format of PHDPerf is PHD Level, gEff at that level, nEfficiency at that
% level.

% If the e_int,g is not meet, than the PHD is returned as the last value in
% the PHD

global displayFigures saveFigures;

if nargin > 3
    for i=1:numel(varargin)
        switch varargin{i}
            case 'displayFigures'
                displayFigures = true;
            case 'saveFigures'
                saveFigures = true;
            otherwise
                warning('Unrecongized option: %s\n',varargin{i});
        end
    end
else
end

% Prompt User For Files

```

```

if nargin == 0
    displayFigures = true;
    saveFigures = true;

    % Prompt user for Neutron Spectra
    [filename, pathname] = uigetfile({'*'}, 'Choose Neutron Spectrum File', 'Multiselect', 'off');
    if isequal(filename, 0)
        error('User selected Cancel');
    else
        [hN sN] = importSPE(strcat(pathname, filename));
        [~, n] = processSPE({hN}, {sN}, 'Rebin', 10, 'CountRateScale');
    end

    % Prompt user for Gamma Spectra
    [filename, pathname] = uigetfile({'*'}, 'Choose Gamma Spectrum File', 'Multiselect', 'off');
    if isequal(filename, 0)
        error('User selected Cancel');
    else
        [hG sG] = importSPE(strcat(pathname, filename));
        [~, g] = processSPE({hG}, {sG}, 'Rebin', 10, 'CountRateScale');
    end

    t = input('Type', 's');
end

%% Input Checking
if numel(n) ~= numel(g) && numel(n) ~= numel(t)
    error('Neutron spectrum, gamma spectrum, and titles should be of the same length\n. ');
end

%% Turning Non Cell Arguments into cells
if ~iscell(n)
    cellN{1} = n;
    cellG{1} = g;
    cellT{1} = t;

    n = cellN;
    g = cellG;
    t = cellT;
end

%% Finding the discrimination of Each Input
% Setting up space
discm = cell(numel(n), 1);
PHD = cell(numel(n), 1);
nIntEff = cell(numel(n), 1);
gIntEff = cell(numel(n), 1);
Ch = cell(numel(n), 1);
nCounts = cell(numel(n), 1);
gCounts = cell(numel(n), 1);
perf = cell(numel(n), 1);
PHDPerf = cell(numel(n), 1);

gammaPerfCriteria = [1E-1 1E-2 1E-3 1E-4 1E-5 1E-6];

```

```

PHDIntrest = [1 1000 2000 3000 4000 5000 6000];
for i = 1:numel(n)
    % Calculating Intrinsic Efficiency
    [discm{i} Ch{i} nCounts{i} gCounts{i} PHD{i} nIntEff{i} gIntEff{i}] = Discrim(n{i},g{i},t{i});

    % Calculating Performance for various gamma effincies values
    perf{i} = CalculatePerformance(gIntEff{i},nIntEff{i},PHD{i},gammaPerfCriteria,n{i});
    PHDPerf{i} = CalculatePHDPerformance(gIntEff{i},nIntEff{i},PHDIntrest);
end

%% Turning Arguments back
if numel(n) ==1
    discm = discm{1};
    PHD = PHD{1};
    nIntEff = nIntEff{1};
    gIntEff = gIntEff{1};
    Ch = Ch{1};
    nCounts = nCounts{1};
    gCounts = gCounts{1};

end
end

function [PHDPerf] = CalculatePHDPerformance(gEff,nEff,PHDIntrest)
PHDPerf = zeros(numel(PHDIntrest),3);
for i=1:numel(PHDIntrest)
    PHDPerf(i,:) = [PHDIntrest(i),gEff(PHDIntrest(i)),nEff(PHDIntrest(i))];
end
end

function [perf] = CalculatePerformance(gEff,nEff,PHD,criteria,nSpectra)

perf = zeros(numel(criteria),4);
i = 1;
for c = criteria

    % Finding what PHD Level Satifies the criteria
    [locG ~] = find(gEff<c,1,'first');
    PHDSetting = PHD(locG);

    % Getting the performance the PHDSetting exist
    if ~isempty(PHDSetting) && PHDSetting < nSpectra(1,end)
        if PHDSetting < nSpectra(1,1)
            locN = 1;
        else
            locN = find(nSpectra(1,:)<PHDSetting,1,'last');
        end
        sumCountRate = sum(nSpectra(2,locN:end));
    end
end

```

```

        % Assigning values
        perf(i,:) = [c,PHDSetting,nEff(locG),sumCountRate];

    else
        perf(i,:) = [0 0 0 0];
    end
    i = i+1;
end

end

function [discm Ch nCounts gCounts PHD gIntEff nIntEff] = Discrim(n,g,t)
global displayFigures saveFigures;

%% DHS Criteria
DHSGamma = 1E-6;
DHSNeutron = 1.2E-3;

%% Incident Radition
% This is calculated by taking the net neutrons crossing the detector
% (MCNFX simulation, the difference in the Lead and Cadmium Well F4
% Tallies) which in this case happens to be 6.23E-3 particles / (cm^2 src).
% We then multiply by the source strength (around 0.86 million neutrons per
% second), and finally by the area of the detector. IF YOU CHANGE THE AREA
% OF THE DETECTOR YOU WILL NEED TO REDO THE MCNFX CALCULATION!

%% Estimating source strength
% massMiller = 0.59;          % Mass of Cf252 in micro grams, from Martin's Disseration
% ageMiller = daysact('01-Aug-2009',now)/365; % Recieved Source in Summer 2009 (Saying June 2009)
% sourceMiller = sourceStrength(massMiller,ageMiller);
% neutronsIncident = (1.98E-2-8.22E-3)*sourceMiller;
% photonsIncident = 687000;
neutronsIncident = particleCrossing('n');
photonsIncident = particleCrossing('p');

% 4.22057E-1 is photons crossing closest surface to source. Assuming a
% 5uCi source, gives 78,081 photons

%% Setting up Count Rate Variables
Ch = n(1,:);
nCounts = n(2,:)./neutronsIncident;
gCounts = g(2,:)./photonsIncident;

% Setting up the PHD
PHD = 1:8100;

% Setting up counts over PHD
nIntEff = zeros(numel(PHD),1);
gIntEff = zeros(numel(PHD),1);

% Finding the scaling factor such that the smallest value is one. We are
% essentially removing the count time scaleing, than reapplying it after it
% the count statistics.
[minGammaValue ~] = min(g(2,g(2,:)>0));

```

```

g(2,:) = g(2,:)./minGammaValue;
[minNeutronValue ~] = min(n(2,n(2,:)>0));
n(2,:) = n(2,:)./minNeutronValue;

for i=1:numel(PHD)
    loc = find(n(1,:)>=PHD(i),1,'first');
    nIntEff(i) = sum (n(2,loc:end)); % Normalized Neutron Spectrum
    if (nIntEff(i) < 2*sqrt(nIntEff(i)))
        nIntEff(i) = 0;
    end

    loc = find(g(1,:)>=PHD(i),1,'first');
    gIntEff(i) = sum (g(2,loc:end)); % Normalized Gamma Spectrum
    if( gIntEff(i) < 2*sqrt(gIntEff(i)) )
        gIntEff(i) = 0;
    end
end

end

gIntEff = gIntEff./photonsIncident.*minGammaValue;
nIntEff = nIntEff./neutronsIncident.*minNeutronValue;

% Output
[nDiscrim gDiscrim] = meetCriteria(DHSGamma, DHSNeutron, PHD, nIntEff,gIntEff);
outputDiscrimPoints(nDiscrim,gDiscrim,PHD,nIntEff,gIntEff,t);
discm = {nDiscrim gDiscrim};

%% Creating Plots of the spectrum
if ~displayFigures
    figure('Visible','Off');
end
figure;
plot(Ch,nCounts,'+');
hold all;
plot(Ch,gCounts,'.');
hold off;
title(sprintf('Radation Response: %s',char(t)),'fontsize',16);
ylabel('Count Rate per Incident Particle','fontsize',16);
xlabel('Channel Number (1200V, 50G)','fontsize',16);
legend('Neutron','Gamma');
set(gca,'YScale','log');
set(gca,'FontSize',16);
if saveFigures
    print(gcf,'-dpng',regexprep(sprintf('Spectrum %s',char(t)), {'\','/'}, ''));
end
end

function outputDiscrimPoints(nDiscrim, gDiscrim,PHD,nCounts,gCounts,t)
% nDiscrim = struct('NeutronDiscriminationLevel',DHSNeutron,'NeutronPHD',phdNLoc,...
% 'GammaEfficiency',gEfficiencyNeutron,'NeutronEfficiency',nEfficiencyNeutron);
% gDiscrim = struct('GammaDiscriminationLevel',DHSGamma,'GammaPHD',phdLocGamma,...
% 'GammaEfficiency',gEfficiencyGamma,'NeutronEfficiency',nEfficiencyGamma);

global displayFigures saveFigures;
%% Plotting Neutron Counts per discrimination scheme
if ~displayFigures
    figure('visibility','off');
end

```

```

figure;
semilogy(PHD,nCounts,PHD,gCounts);
title(sprintf('%s',char(t)),'fontsize',16);
ylim([1E-6 1]);
ylabel('Intrinsic Efficiency','fontsize',16);
xlabel('PHD Setting (Channel Number)','fontsize',16);
legend('Neutron','Gamma');
set(gca,'FontSize',16);

%% Plotting the Gamma Discrimination Values
hold all;
plot(gDiscrim.GammaPHD,gDiscrim.GammaEfficiency...
     ,'h','MarkerEdgeColor','g','MarkerFaceColor','g','MarkerSize',10);
plot(gDiscrim.GammaPHD,gDiscrim.NeutronEfficiency...
     ,'h','MarkerEdgeColor','g','MarkerFaceColor','g','MarkerSize',10);
hold off;

%% Plotting the Neutron Discrimination Values
hold all;
plot(nDiscrim.NeutronPHD,nDiscrim.GammaEfficiency...
     ,'h','MarkerEdgeColor','b','MarkerFaceColor','b','MarkerSize',10);
plot(nDiscrim.NeutronPHD,nDiscrim.NeutronEfficiency...
     ,'h','MarkerEdgeColor','b','MarkerFaceColor','b','MarkerSize',10);
hold off;
if saveFigures
print(gcf,'-dpng',regexprep(sprintf('Discrimination %s',char(t)), {'\','/'}, ''));
end
%% Printing values
fprintf(1,'Discrimination Values for %s\n',char(t));
fprintf(1,'Gamma Discrimination:\n');
disp(gDiscrim);
fprintf(1,'Neutron Discrimination:\n');
disp(nDiscrim);

end

function [nDiscrim gDiscrim] = meetCriteria(DHSGamma, DHSNeutron, PHD, nCounts,gCounts)
% [nDiscrim gDiscrim] = meetCriteria(DHSGamma, DHSNeutron, PHD, nCounts,gCounts)
% Finds the PHD setting where the spectrum meets the DHS criteria. If no
% data is available for the Gammas, an exponential fit (linear on a semilog
% scale) is applied and the value extrapolated. If not data is available
% for the neutrons, the values are not extrapolated.
% Returns two structures:
% nDiscrim = struct('NeutronDiscriminationLevel',DHSNeutron,'NeutronPHD',phdNLoc,...
%   'GammaEfficiency',gEfficiencyNeutron,'NeutronEfficiency',nEfficiencyNeutron);
% gDiscrim = struct('GammaDiscriminationLevel',DHSGamma,'GammaPHD',phdLocGamma,...
%   'GammaEfficiency',gEfficiencyGamma,'NeutronEfficiency',nEfficiencyGamma);

%% Finding the PHD level that accomplished the DHS Criteria For Gamma
phdLocGamma = find((gCounts<DHSGamma),1,'first');

% Need to extrapolate gamma intrinsic efficiency curve
if isempty(phdLocGamma) || gCounts(phdLocGamma) == 0
    if isempty(phdLocGamma)
        phdLocGamma = numel(PHD);
    end
    % Function is in channel number space, not location space
    gFit = fit(PHD(1:phdLocGamma),gCounts(1:phdLocGamma),'exp1');

```

```

f = @(x) feval(gFit,x) - DHSGamma;
phdGamma = fzero(f,phdLocGamma*2);
gEfficiencyGamma = feval(gFit,phdGamma);
phdSettingGamma = uint16(phdGamma);

if phdSettingGamma < PHD(end)
    phdLocGamma = find(PHD==phdSettingGamma,1,'first');
end

else
    gEfficiencyGamma = gCounts(phdLocGamma);
    phdSettingGamma = PHD(phdLocGamma);
end

% Finding the neutron intrinsic efficiency at that setting

if phdSettingGamma < PHD(end) && nCounts(phdLocGamma) > 0
    % Don't need to extrapolate
    nEfficiencyGamma = nCounts(phdLocGamma);
else
    % Need to extrapolate (Using a multi nominal logistic regression.
    % Since the data looks sigmoidal, and the sigmoidal is described by the
    % logistic function, this looked like the best bet.

    % Modifying the data set to remove zero values
    zeroNLocs = find(nCounts==0);
    nonZeronCounts = nCounts;
    nonZeronCounts(zeroNLocs) = [];
    nonZeroPHD = PHD;
    nonZeroPHD(zeroNLocs) = [];

    % Doing the fit
    nFit = fit(nonZeroPHD',nonZeronCounts,'poly1');
    nEfficiencyGamma = feval(nFit,phdGamma);

end

% Creating a structure to hold it all
gDiscrim = struct('GammaDiscriminationLevel',DHSGamma,'GammaPHD',phdSettingGamma,...
    'GammaEfficiency',gEfficiencyGamma,'NeutronEfficiency',nEfficiencyGamma);

%% Finding the Level for which the DHS Neutron Criteria are met
% If a value does not exist, the PHD for the last point in the spectra is
% returned.
phdNLoc = find(nCounts<DHSNeutron,1,'first');

if ~isempty(phdNLoc) && nCounts(phdNLoc) > 0 % A nonzero value that satisfies
    phdSettingNeutron = PHD(phdNLoc);
    nEfficiencyNeutron = nCounts(phdNLoc);

    % Getting the Gamma Discrimination at the Neutron PHD Setting
    if gCounts(phdNLoc) == 0
        % Extrapolating out if value at the location is zero. Uses the fit
        % calculated previously.

        % Function is in channel number space, not location space

```

```

        gEfficiencyNeutron = PHD(end);

    else    % No need to extrapolate
        gEfficiencyNeutron = gCounts(phdNLoc);
    end
else
    nEfficiencyNeutron = 0;
    gEfficiencyNeutron = 0;
end

nDiscrim = struct('NeutronDiscriminationLevel',DHSNeutron,'NeutronPHD',phdSettingNeutron,...
    'GammaEfficiency',gEfficiencyNeutron,'NeutronEfficiency',nEfficiencyNeutron);

end
function [S] = sourceStrength(mass,t)
% Computes the source strength of Cf252 for a given mass in micro grams
% Data from: http://www.ornl.gov/~webworks/cpr/pres/102606.pdf

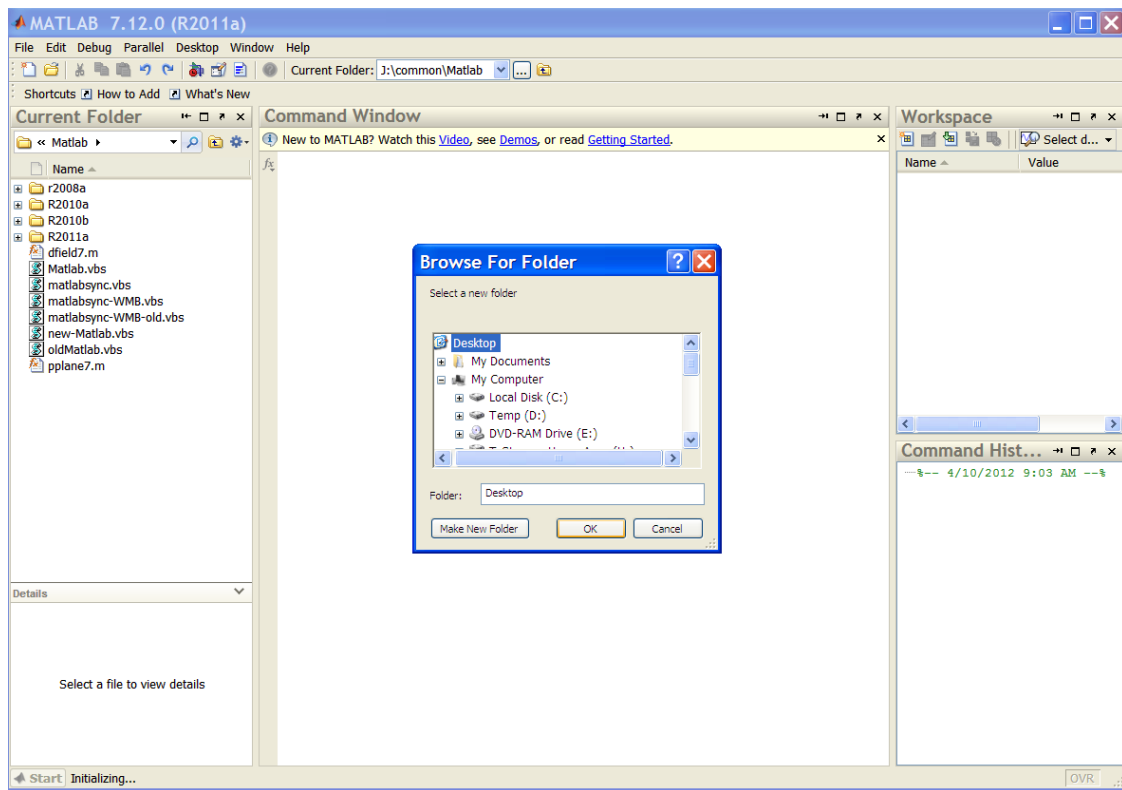
% 2.314E6 n per s per micro gram, so 2.314E3 n/s per nanogram
halfLife = 2.645; % years
S = 2.314E6*mass*exp(-t*log(2)/halfLife);
end

```

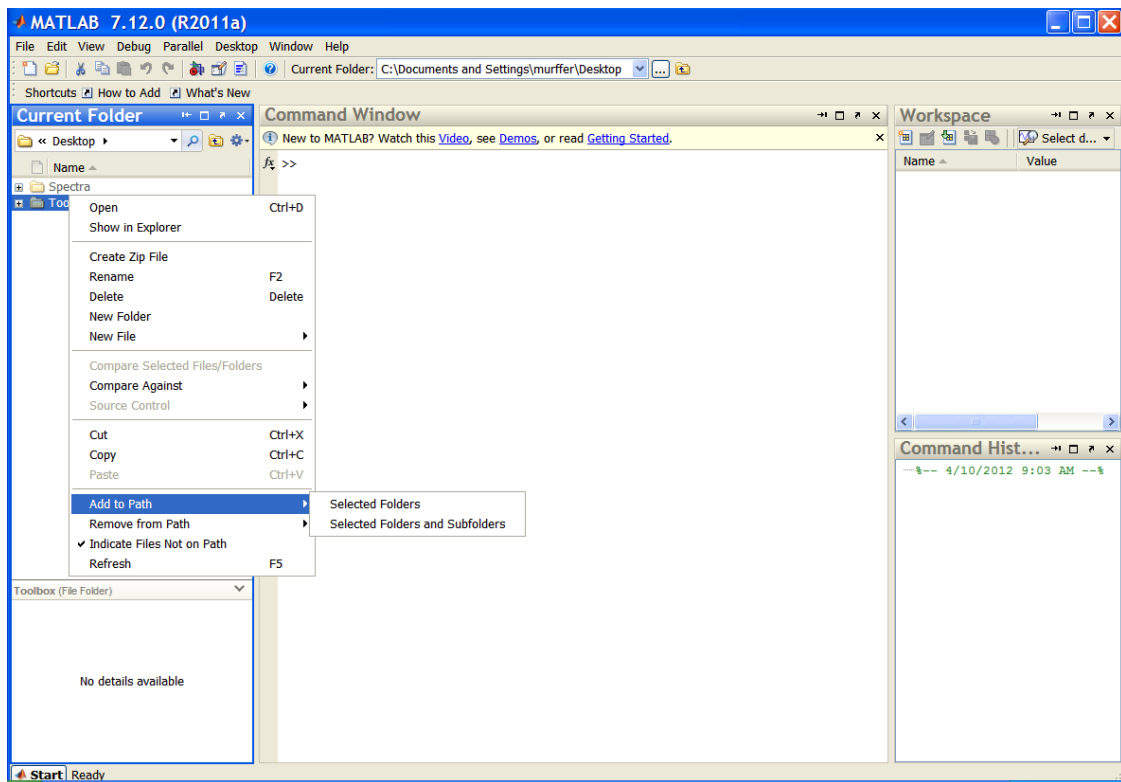
APPENDIX C

ADDING FOLDER TO MATLAB PATH

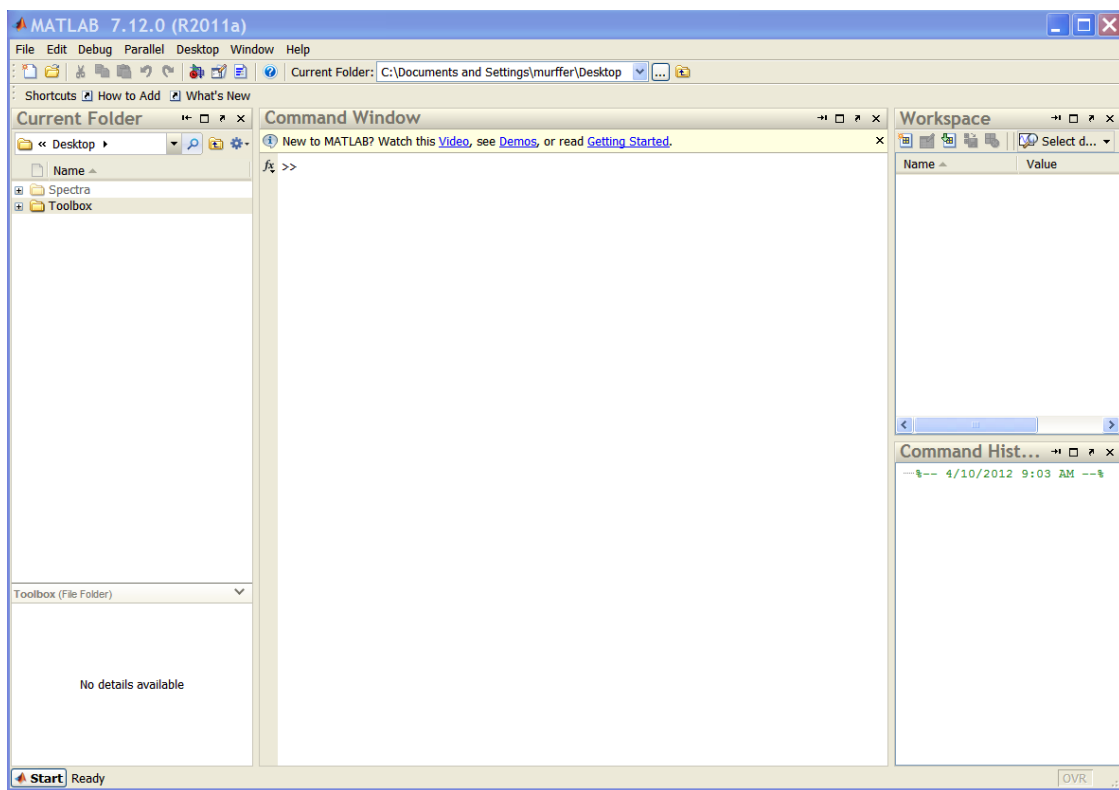
1. Browse to location where the spectra toolbox is located



2. Left click on folder, Select Add to Path, Selected Folders and Subfolders



3. After it has been added to the path the folder should no longer be grayed out.



COMPUTING NEUTRON GAMMA EFFICINCIES

1. Setup the path such that NGDiscrim.m (available in the spectra toolbox) is on the path
2. Browse to the directory that contains the spectra (.spe files)
 - i. `>cd Spectra\`
3. Find out about the NGDiscrim command and arguments with the help command

Command Window

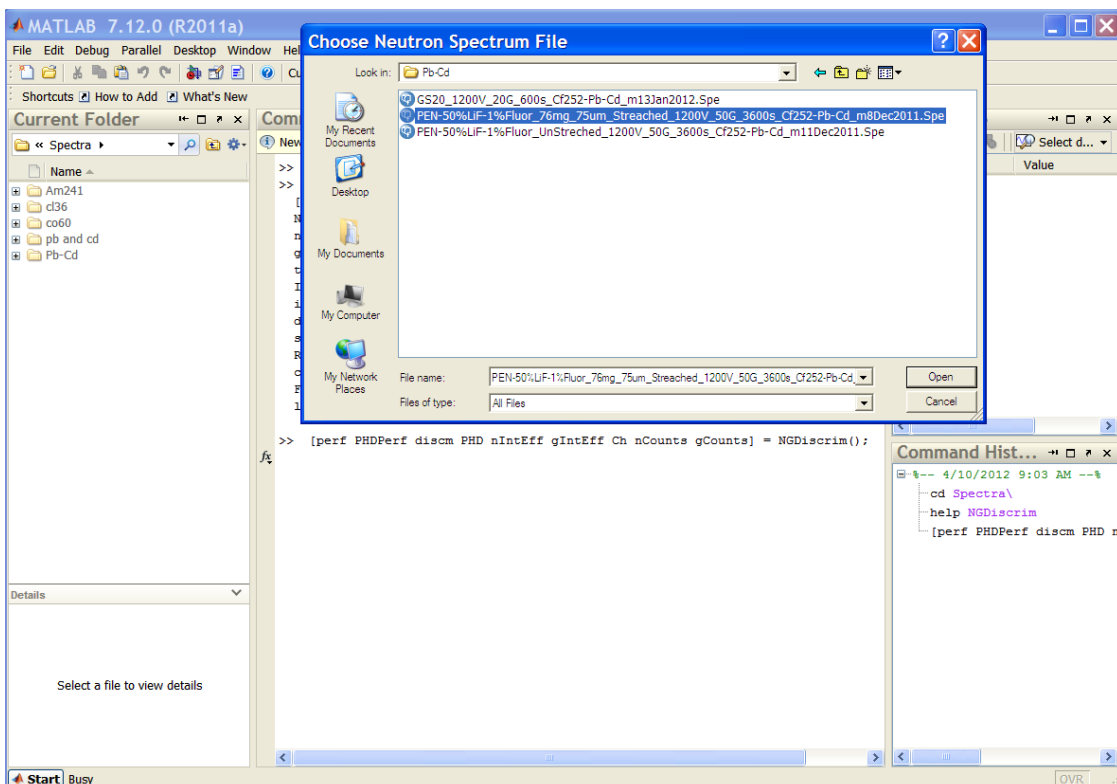
New to MATLAB? Watch this [Video](#), see [Demos](#), or read [Getting Started](#).

```
>> cd Spectra\
>> help NGDiscrim

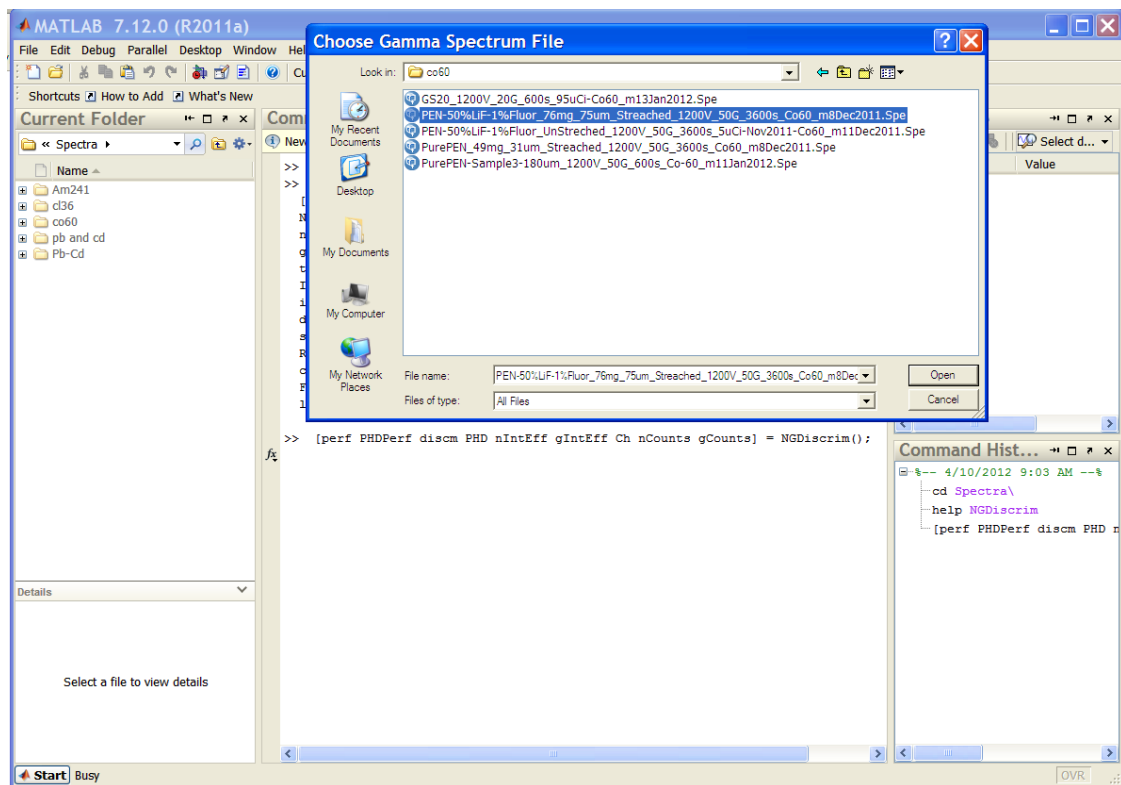
[perf PHDPerf discm PHD nIntEff gIntEff Ch nCounts gCounts] = NGDiscrim(n,g,t,
NGDISCRIM - Calculates the discrimination of a sample.
n - the neutron spectra. Use importSPE, processSPE to generate spectra
g - the gamma spectra. Use importSPE, processSPE to generate spectra
t - the name of the spectra. A cell array.
If n,g,and t are cell arrays then the order of the cells must match; no
internal checking is completed.
displayFigures - if this string is present then the figures are displayed.
saveFigures - if this string is present then the figures are saved.
Returns several parameters the
characterize the discrimination performance of the film.
Format of PHDPerf is PHD Level, gEff at that level, nEfficiency at that
level.
```

fx >>

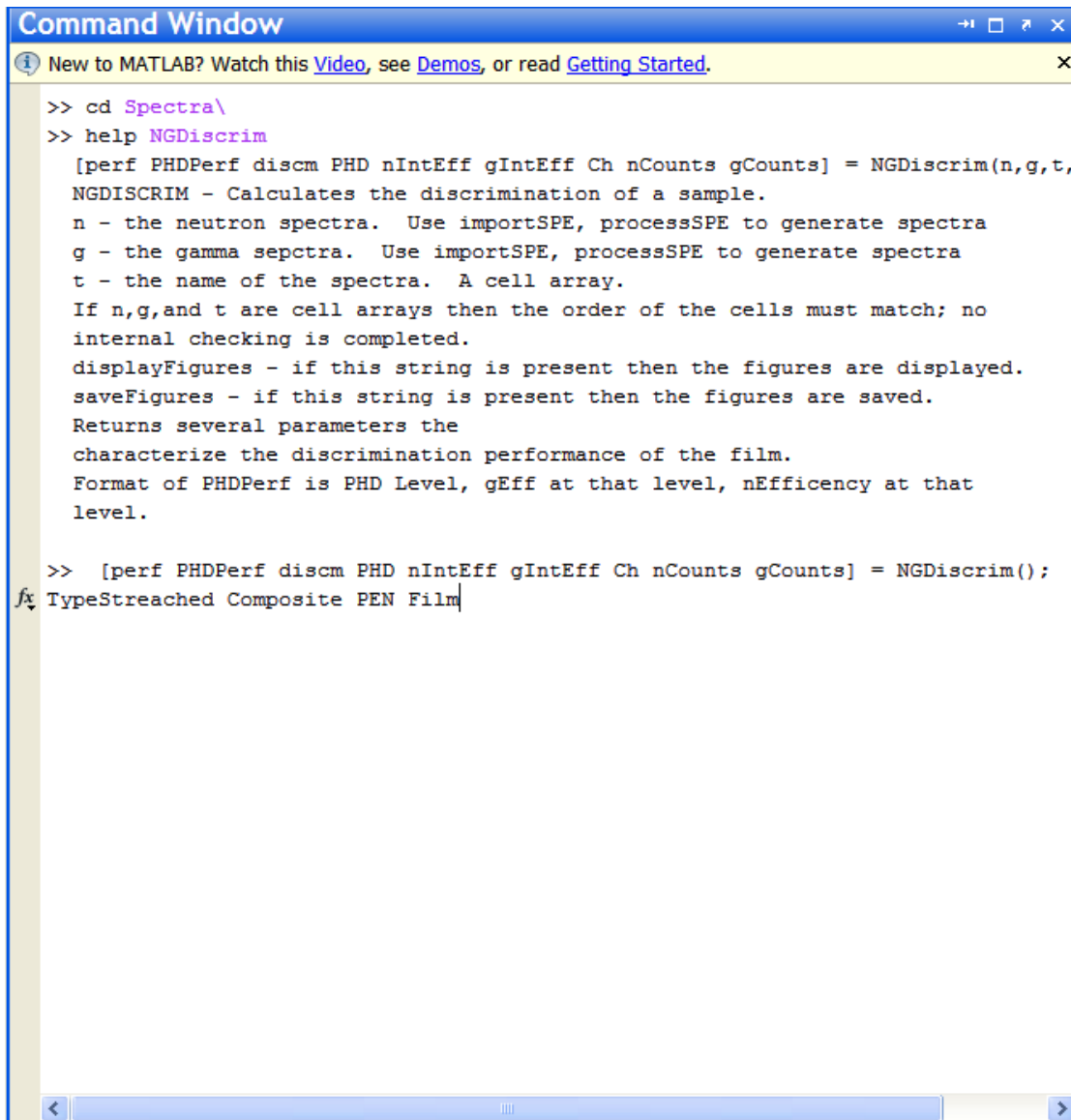
4. Run NGDicrim without any input arguments.
5. Select Neutron Spectra



6. Select Gamma Spectra



7. Enter a short description of the film at the TYPE prompt in the command window



The image shows a MATLAB Command Window. At the top, there is a title bar 'Command Window' and a yellow banner with the text 'New to MATLAB? Watch this [Video](#), see [Demos](#), or read [Getting Started](#).' Below the banner, the user has entered the following commands:

```
>> cd Spectra\  
>> help NGDiscrim
```

The help text for the `NGDiscrim` function is displayed:

```
[perf PHDPerf discm PHD nIntEff gIntEff Ch nCounts gCounts] = NGDiscrim(n,g,t,  
NGDISCRIM - Calculates the discrimination of a sample.  
n - the neutron spectra. Use importSPE, processSPE to generate spectra  
g - the gamma spectra. Use importSPE, processSPE to generate spectra  
t - the name of the spectra. A cell array.  
If n,g,and t are cell arrays then the order of the cells must match; no  
internal checking is completed.  
displayFigures - if this string is present then the figures are displayed.  
saveFigures - if this string is present then the figures are saved.  
Returns several parameters the  
characterize the discrimination performance of the film.  
Format of PHDPerf is PHD Level, gEff at that level, nEfficiency at that  
level.
```

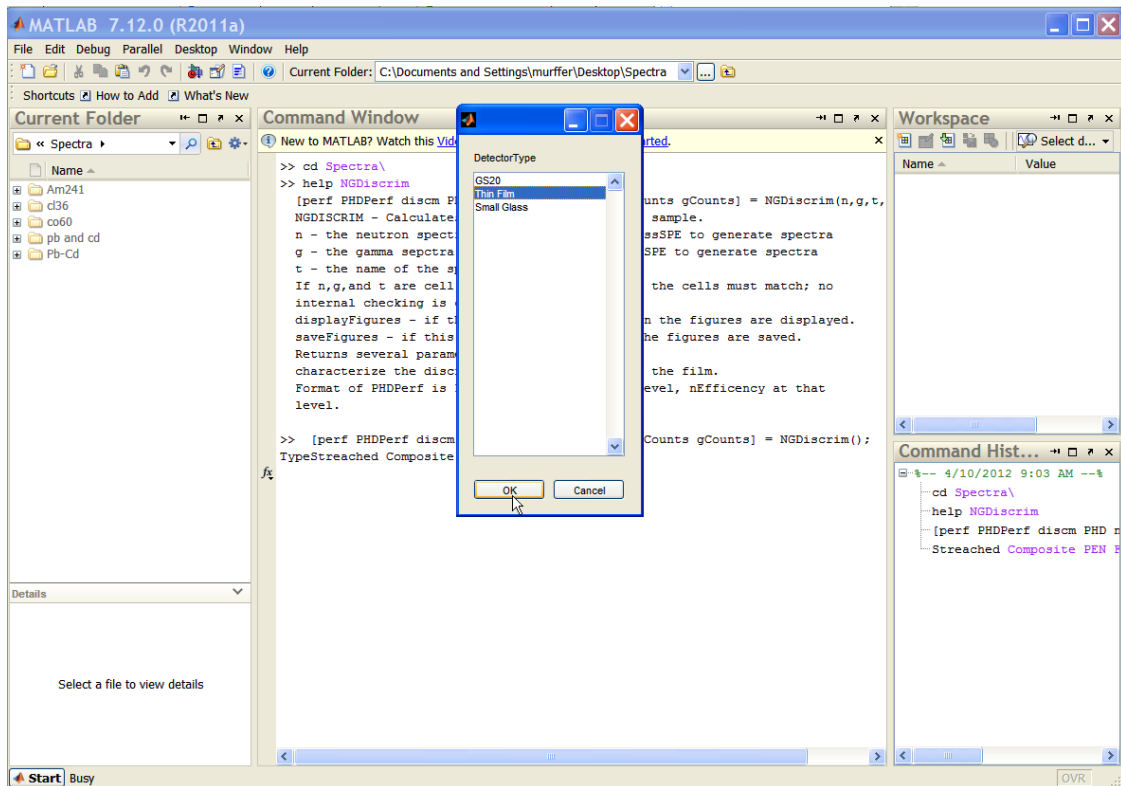
The user then enters the following command:

```
>> [perf PHDPerf discm PHD nIntEff gIntEff Ch nCounts gCounts] = NGDiscrim();
```

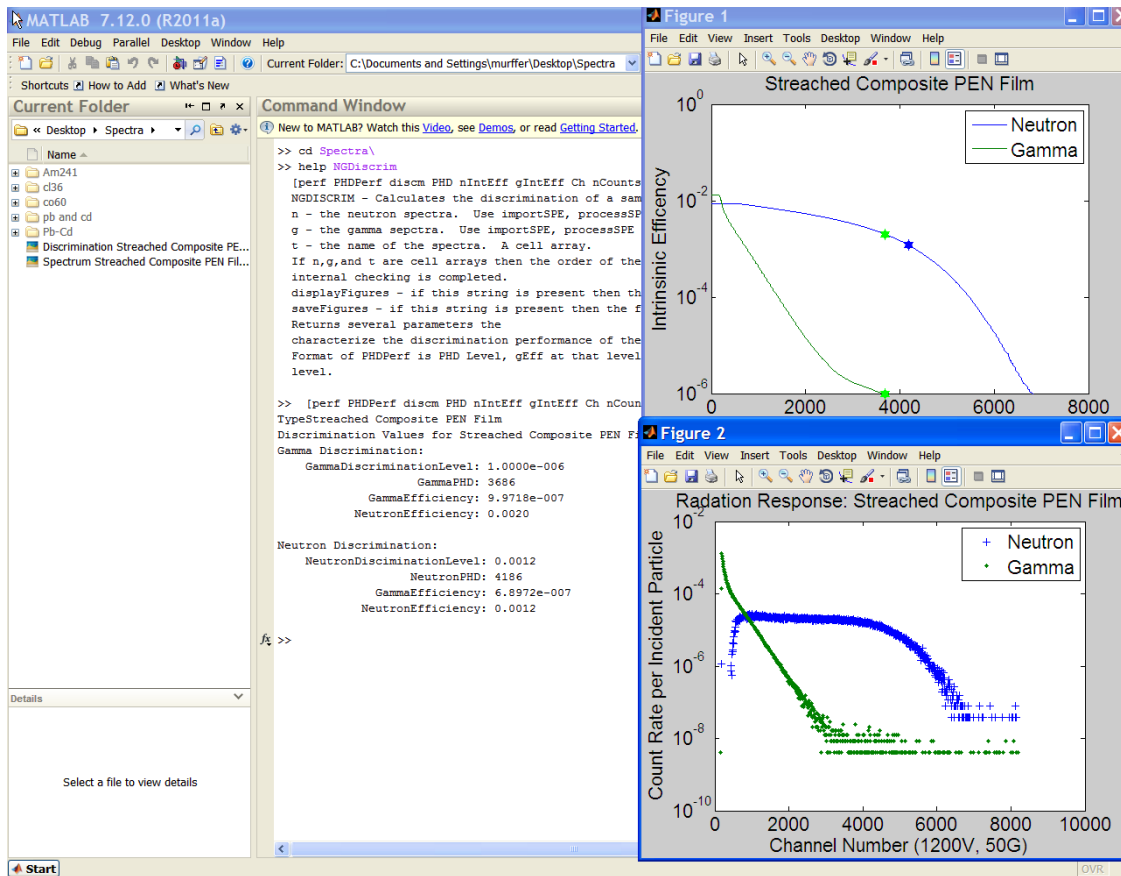
The output of the command is:

```
fx TypeStretched Composite PEN Film
```

8. Select the geometry type from the pop-up menu



9. MATLAB computes the efficiency values, plots the spectra, as well as saves the spectra as .png in the current directory



APPENDIX D

The interaction of charged particles with matter is important to design a detector because it determines how much energy (and where) will be imparted to the detector. One of the most useful parameters is the range of a particle in matter. In the following figure it is observed that the heavy charged particles (protons and alphas) travel about an order of magnitude less than an electron of a similar energy.

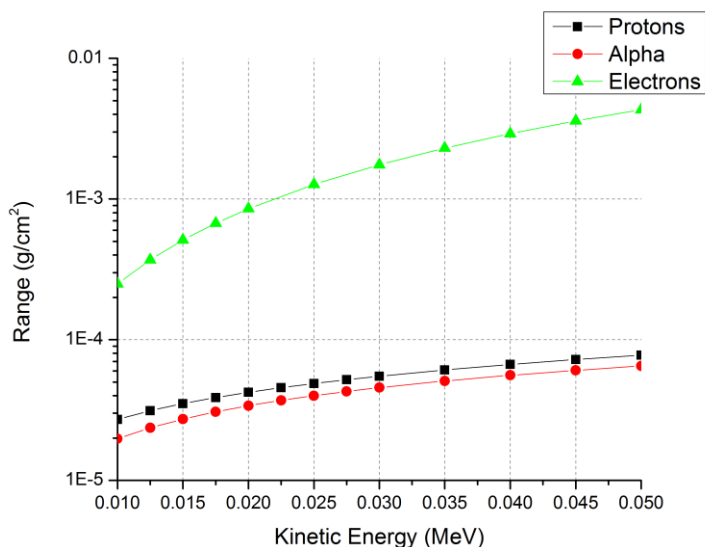


FIGURE 69 - RANGE OF PARTICLES IN A PLASTIC SCINTILLATOR (PVT BASED). DATA FROM NIST

PHOTONS

Photon interactions in matter can be divided into four classes: photoelectric effect, Compton effect, pair production, and photo nuclear absorptions. In general the photons of interest are on the 100's of eV to MeV range, which is much greater than the eV range of the work functions associated with the photoelectric effect so the electrons can be considered at rest. Pair production and photonuclear absorptions can also be neglected because the photons of interest are typically below the range where these reactions are likely to occur. Of the four possible interactions, then, only Compton scattering will be discussed.

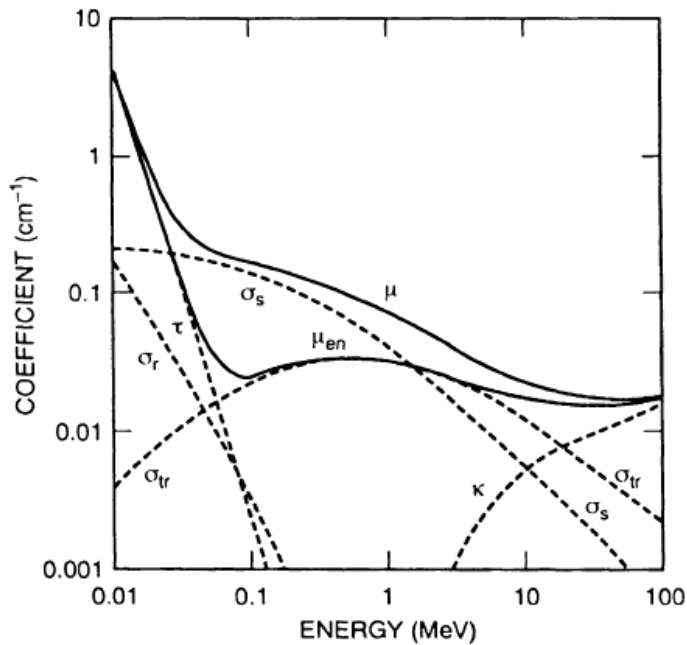


FIGURE 70 - PHOTON ATTENUATION COEFFICIENTS IN WATER. τ IS THE CONTRIBUTION FROM THE PHOTOELECTRIC EFFECT, Σ_s IS THE CONTRIBUTION FROM COMPTON SCATTERING, AND κ IS THE CONTRIBUTION FROM PHOTONUCLEAR ADSORPTIONS. FIGURE FROM [6].

Compton scattering occurs when a photon is incident on an electron (assumed to be free) and scatters off that electron, imparting energy to the electron. This is illustrated schematically in Figure 75.

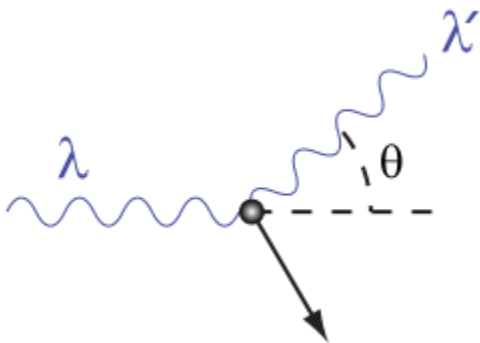


FIGURE 71 - ILLUSTRATION OF COMPTON THE SCATTERING. THE INCOMING PHOTON, λ , IS SCATTERED OFF THE ELECTRON. THIS IMPARTS KINETIC ENERGY TO THE ELECTRON AND CAUSES A CHANGE IN THE WAVELENGTH AND DIRECTION OF THE GAMMA. FIGURE FROM [14].

There is then a range of kinetic energies T that can be imparted to electron which depends on the scattering angle θ and the photons initial energy $h\nu$.

$$T = \frac{1 - \cos \theta}{\frac{mc^2}{hv} + 1 - \cos \theta} \quad (22)$$

The maximum possible kinetic energy that the scattered electron can have occurs at a scattering angle of 180 degrees; when the cosine is negative one. For photon energies $h\nu \gg mc^2$ the maximum energy of the scattered secondary electron approaches the incident photon energy.

$$T = \frac{2h\nu}{2 + \frac{mc^2}{h\nu}} \quad (23)$$

TABLE 28 - MAXIMUM ENERGY OF SECONDARY ELECTRONS FROM ^{60}Co AND ^{137}Cs

	Photon Energy	Maximum Compton Energy
^{137}Cs	0.662	0.478
^{60}Co	1.17, 1.33	0.960, 1.116

In general (described by the Klein-Nishina formula) electrons are more likely to have a higher recoil energy. This is shown in Figure 72.

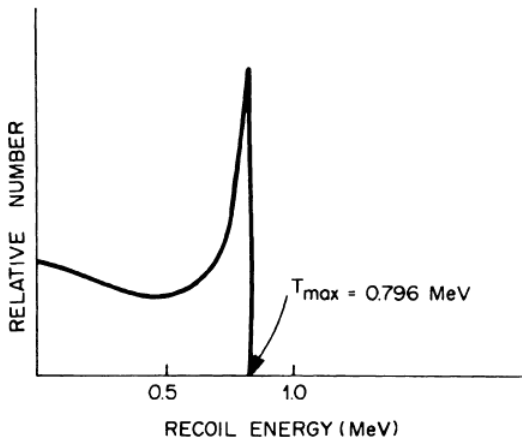


FIGURE 72 - ENERGY DISTRIBUTION OF RECOIL ELECTRONS FROM A 1 MEV PHOTON. FIGURE FROM [6].

All photon interactions of a film are then comparable to a charged particle (electron) interaction in that film (once an interaction has occurred), with the energy of the charged particle being on the order of the energy of the maximum Compton scattered electron.

Most of the samples looked at are very thin, with thickness in the 25-100 micron range. When an incoming photon Compton scatters the energy of the scattered electron is then in the 100's of keV, where the range is around one twentieth of a centimeter; much farther than the thickness of the film. It is then expected that the film will lack a Compton edge, and this is observed in measurement.

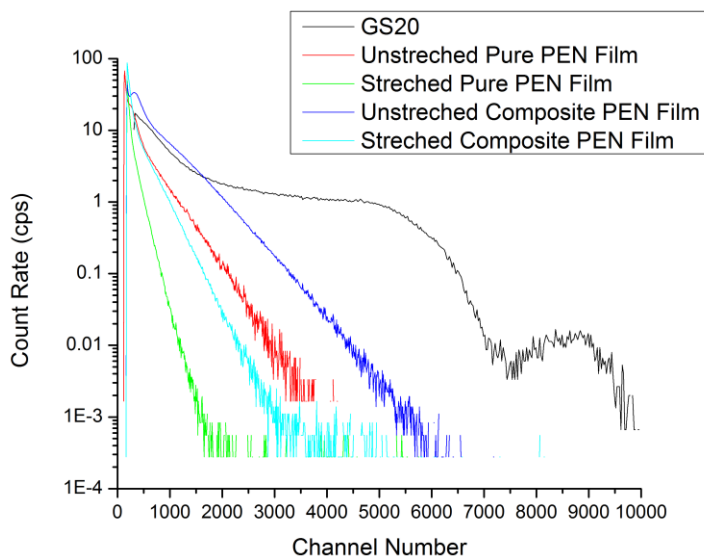


FIGURE 73 - GAMMA SPECTRA FROM THIN (LESS THAN 100 MICRON) PEN FILMS COMPARED TO 2,200 MICRON GS20. THE COMPTON EDGE AND PHOTOPEAK ARE VISIBLE ON THE GS20 BUT NOT THE THIN FILMS

In general the detector size determines how much energy is deposited in the film. In thick samples (samples much thicker than the range of the highest possible scattering event) the detector will absorb most of the energy. In thin samples, however the sample will only absorb a fraction of the energy. This is shown in Figure 74.

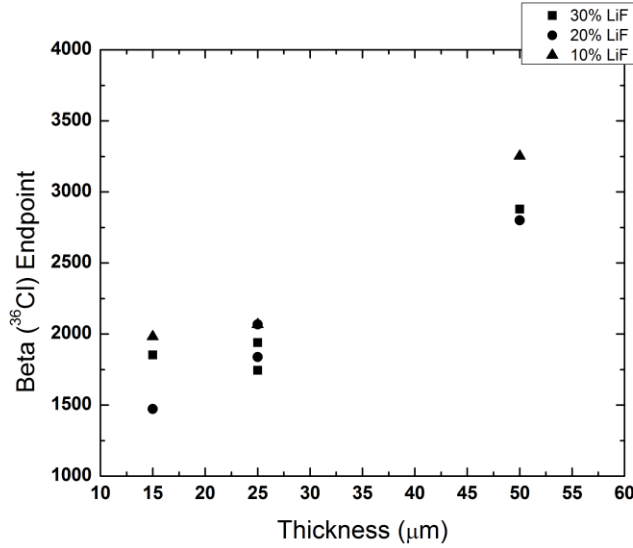


Figure 74 - Beta Endpoint of 5% PS samples according to the Sample Thickness.

CHARGED PARTICLES

The maximum amount of energy any charged particle M of kinetic energy T can transfer in a single collision to a particle of mass m is the product of their masses and kinetic energy divided by the squared sum of masses. The non-relativistic result is given below (24). The only case in which a complete energy transfer could occur is if the incident particle scatters off a particle of the same mass; for example a positron scattering off of an electron.

$$Q_{max} = \frac{4mMT}{(M + m)^2} \quad (24)$$

The following figure describes the probability of single collision energy loss for 50 and 150 eV electrons and 1 MeV protons in water. For reference, a Compton scattered electron from a ^{137}Cs source would have a maximum energy of 478 keV, while ^{60}Co would have 1,116 keV. Turner writes that similar spectra for more energetic electrons lie almost on top of the 150 keV electrons [15].

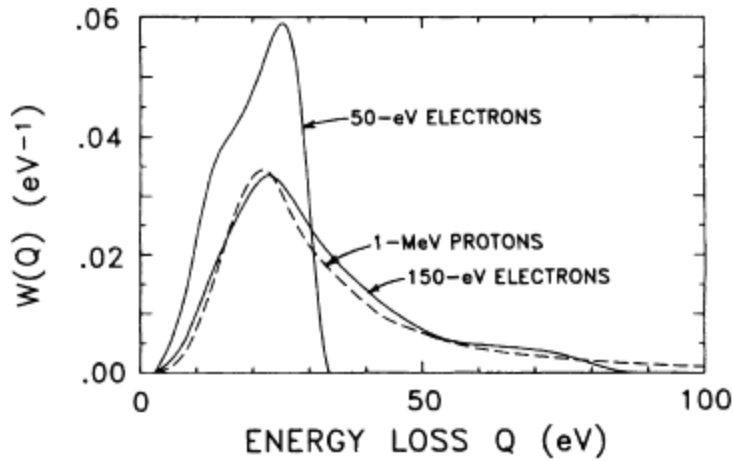


FIGURE 75 - SINGLE COLLISION ENERGY LOSS SPECTRA FOR ELECTRONS AND PROTONS. FIGURE FROM [6].
THICKER SAMPLES ABSORB MORE OF ENERGY, THUS HAVING A HIGHER ENDPOINT.

In certain cases an alpha particle may be used to judge how a neutron might produce light in a film since the (n,triton) reaction in ${}^6\text{Li}$ produces an alpha. The alpha response for four PEN films are shown below; are all typically of thin films. With a range of around 30 microns, most of the alpha's energy will be absorbed in the film leading to the presence of an alpha peak.

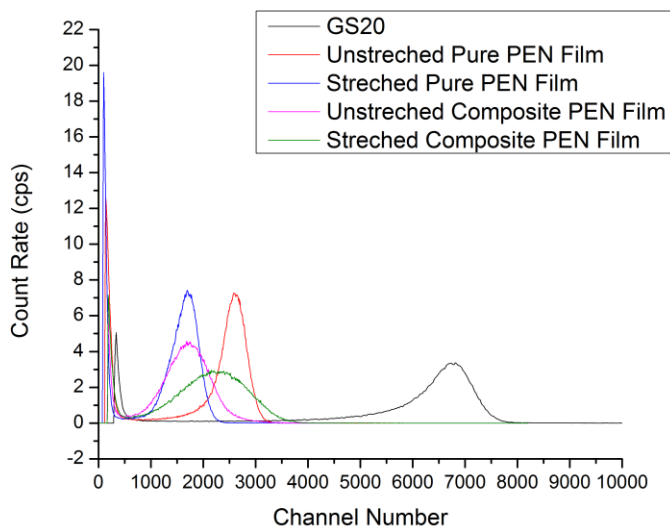


FIGURE 76 - EXAMPLE ALPHA SPECTRA OF PEN FILMS. THE ALPHA PEAK IS A GOOD INDICATION OF THE RESPONSE OF THE FILM TO CHARGED PARTICLES.

APPENDIX E

INTRODUCTION

Receiver Operator Characteristic curve provides a method for judging how well a classifier performs. Each threshold on the classifiers score results in a particular true and false positive rates, as shown in Figure 77.

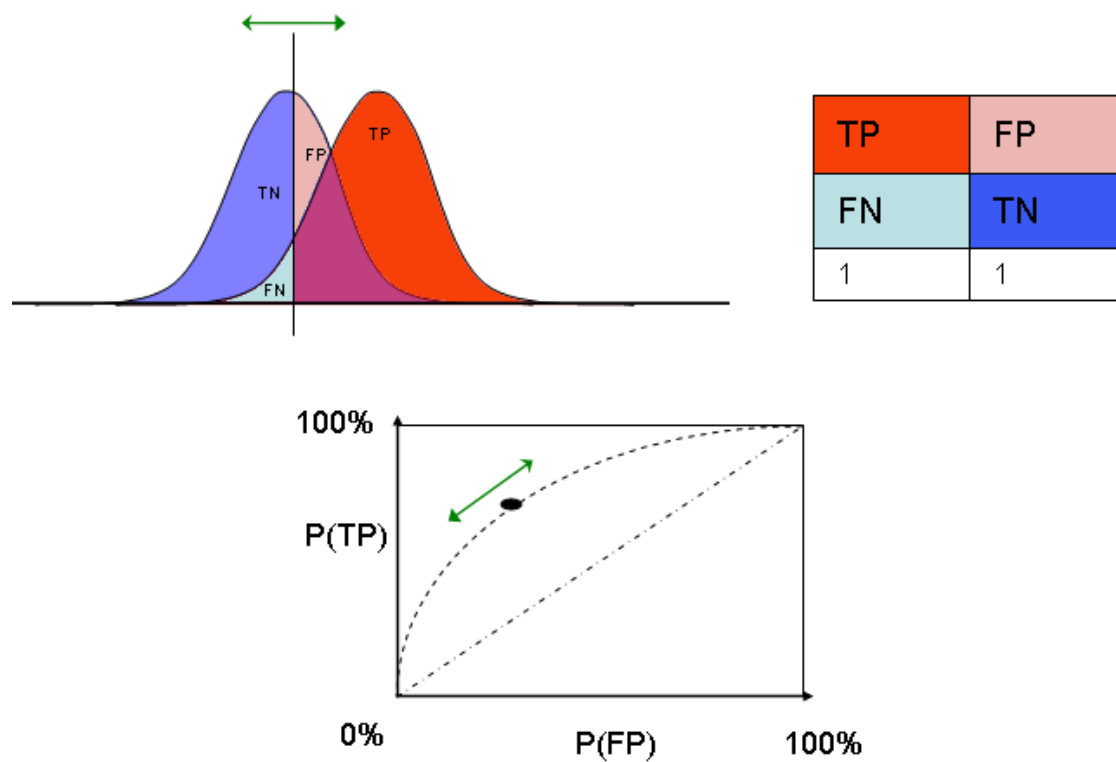
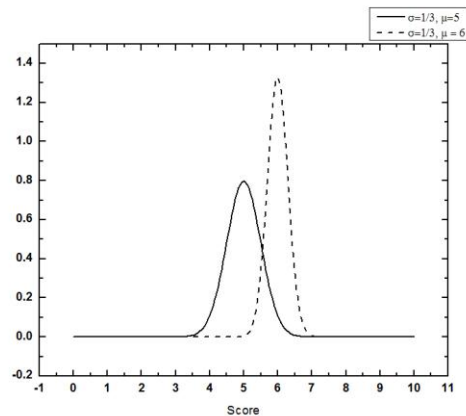
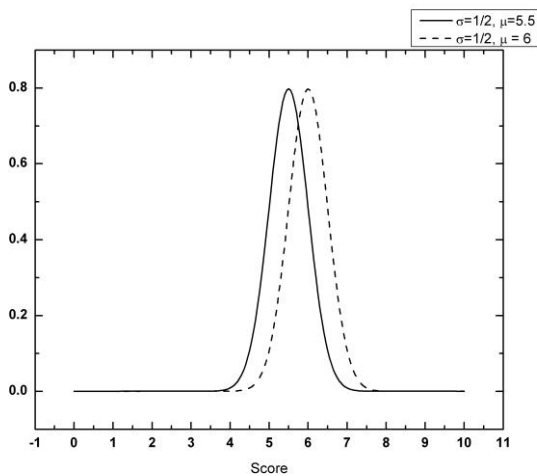


FIGURE 77 - EXAMPLE OF AN ROC CURVE FOR TWO DISTRIBUTIONS. THE THRESHOLD IS SHOWN BY THE VERTICAL LINE BELOW THE GREEN ARROW. (IMAGE FROM WIKIPEDIA)

ROC can also be used to compute the performance of a classifier. Given two classes, P and N, the following table describes the errors that the classifier could make [2].

		True Class	
Hypothesized Class		P (Alpha)	N (Gamma)
	Y	True Positive	False Positive (Type I error)
	N (Gamma)	False Negative (Type II error)	True Negative

The developed functions for calculating ROC curve were tested on four different Gaussian functions (Figure 78). The ROC curves for each of the distributions plotted are shown in Figure 79. Distributions D, with no appreciable cross over, showed perfect classification. As the distributions started to overlap (distributions A, B, and C) the performance of the classification based on score started to suffer. Distributions A, with a large amount of overlap, had the worst performance.



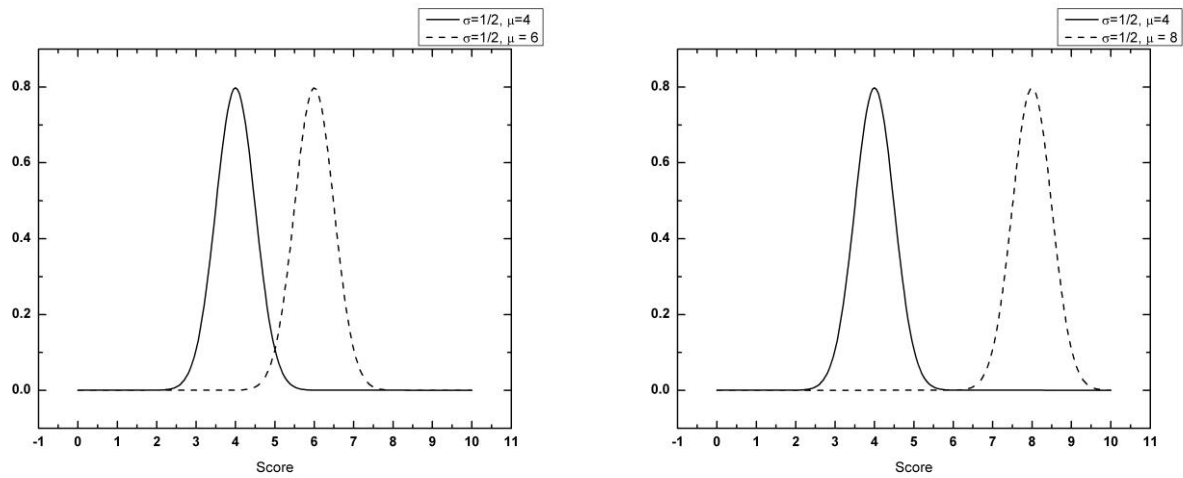


FIGURE 78 – GAUSSIAN DISTRIBUTIONS USED TO TEST THE ROC CURVES. UPPER LEFT IS DISTRIBUTIONS A, UPPER RIGHT IS DISTRIBUTIONS B, LOWER LEFT IS DISTRIBUTIONS C AND LOWER RIGHT IS DISTRIBUTIONS D.

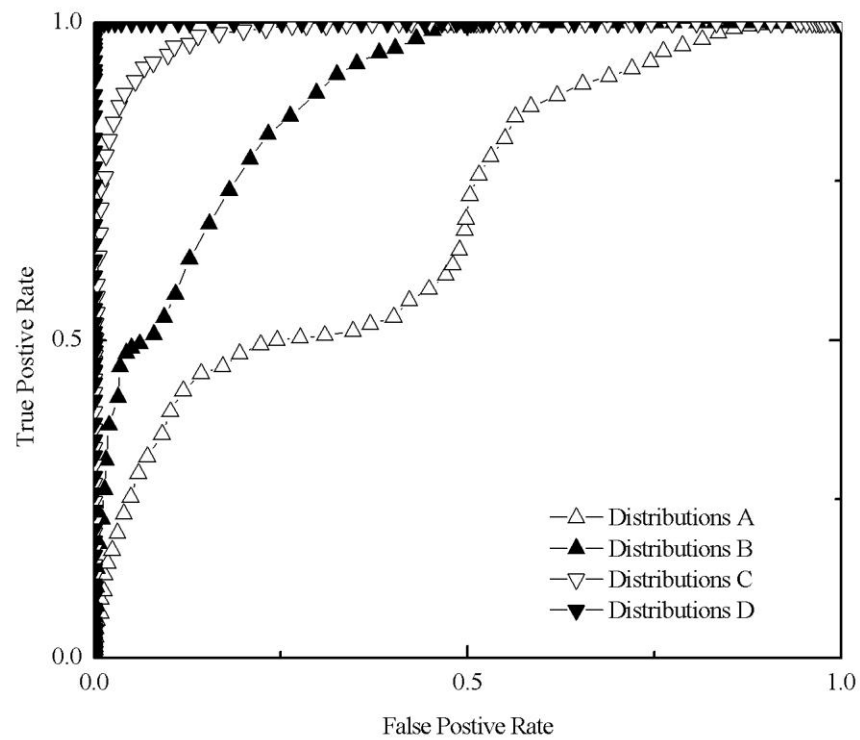


FIGURE 79 - ROC CURVES FOR GAUSSIAN DISTRIBUTIONS.

AREA UNDER THE CURVE (AUC)

The area under the curve (AUC) provides a statistical measure of how well a sample performs; the AUC is the expectation that a uniformly randomly drawn positive receives a higher score than a randomly drawn negative. In the case of Distributions D, there is a 100% expectation that a randomly drawn positive will have a score higher than a negative – this can be seen by because the scores from the distributions do not overlap. In the case of Distributions A, where there is some overlap, a randomly drawn positive score will only have a higher score then a negative one 70% of the time.

TABLE 29

	AUC
Distributions A	0.6966
Distributions B	0.8687
Distributions C	0.9855
Distributions D	1.0

VITA

Matthew J. Urffer was born January, 29, 1988 on a small turkey farm in Coopersburg, Pa. He got his B.S. in physics from Carnegie Mellon University in Pittsburgh, PA. Upon graduation Matthew enrolled at the University of Tennessee, Knoxville where he is currently pursuing a doctorate in nuclear engineering.