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Optimization of the Lead Probe Neutron Detector

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OPTIMIZATION OF THE LEAD PROBE NEUTRON DETECTOR

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ABSTRACT

The lead probe neutron detector was originally designed by Spencer and Jacobs in 1965[§]. The detector is based on lead activation due to the following neutron scattering reactions: ^{207}Pb(n, n')^{207m}Pb and ^{208}Pb(n, 2n)^{207m}Pb. Delayed gammas from the metastable state of ^{207m}Pb are counted using a plastic scintillator. The half-life of ^{207m}Pb is 0.8 seconds. In the work reported here, MCNP[†] was used to optimize the efficiency of the lead probe by suitably modifying the original geometry. A prototype detector was then built and tested.

A "layer cake" design was investigated in which thin (< 5 mm) layers of lead were sandwiched between thicker (~ 1 – 2 cm) layers of scintillator. An optimized "layer cake" design had Figures of Merit (derived from the code) which were a factor of 3 greater than the original lead probe for DD neutrons, and a factor of 4 greater for DT neutrons, while containing 30% less lead.

A smaller scale, "proof of principle" prototype was built by Bechtel/Nevada to verify the code results. Its response to DD neutrons was measured using the DD dense plasma focus at Texas A&M and it conformed to the predicted performance. A voltage and discriminator sweep was performed to determine optimum sensitivity settings. It was determined that a calibration operating point could be obtained using a ^{133}Ba "bolt" as is the case with the original lead probe.

[§] Spencer, C. E., and Jacobs, E. L., "The lead activation technique for high energy neutron measurement," IEEE Transactions on Nuclear Science, NS-12, 407 (1965).
[†] Seagraves, D. T., editor, "Practical MCNP for the Health Physicist, Rad Engineer, & Medical Physicist," Version 4C, Los Alamos National Laboratory, (February 2000).

ACKNOWLEDGEMENTS

This work was originally done by Alan Nelson as a thesis in partial fulfillment of the requirements for the Degree of Master of Science in Nuclear Engineering at the University of New Mexico. It was prepared under the direction of Dr. Gary Cooper, faculty advisor, and Dr. Carlos Ruiz of Sandia National Laboratories. The authors would like to acknowledge Dr. Ray Leeper and Dr. Tom Mehlhorn for providing Sandia National Laboratory support and funding. Also, special thanks go to Dr. Chris Hagen, Steve Molnar, Brent Davis and Irene Garcia of Bechtel/Nevada for constructing and testing the prototype lead “layer cake” neutron detector. Additional thanks go to Dr. Bruce Freeman of Texas A&M University for the availability of the 2.45 MeV DD dense plasma focus neutron calibration source.

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CHAPTER 1

Introduction

The lead activation technique has been utilized to measure the yield of pulsed neutron sources for the past 40 years (Ruby and Rechen 1962). It is based on the neutron reactions of ^{207}Pb(n, n')^{207m}Pb and ^{208}Pb(n, 2n)^{207m}Pb in which delayed gammas from the metastable state of ^{207m}Pb are counted in a plastic scintillator. The half-life of ^{207m}Pb is 0.8 seconds. Spencer and Jacobs developed a detector based on this technique in 1965 and called it the "lead probe," which became a laboratory standard at Sandia National Laboratories for measuring DT neutrons produced via the following Deuterium-Tritium reaction (Spencer and Jacobs 1965):

$$^{2}D + {}^{3}T \rightarrow {}^{4}He\ (3.5\ MeV) + {}^{1}n\ (14.1\ MeV)$$

There are many advantages to using the lead probe for measuring DT neutrons: it has a high sensitivity (1 count per 255 incident neutrons), a low yield detection level of 10^6 neutrons into 4π per pulse, an energy threshold of 1.6 MeV and an accuracy of 10 percent (Spencer and Jacobs 1965). The data is obtained in real time, approximately 3 seconds, and if multi-channel scaling is used, the half-life can be verified to insure the counts represent the "true" signal. A cross-sectional view of the lead probe is shown in Figure 1.

For applications on Sandia National Laboratories' Z machine (Matzen 1997 and Spielman 1995), where Inertial Confinement Fusion (ICF) experiments are performed using deuterium filled capsules, a detector is needed to measure neutron yields from the reaction:

$$^{2}D + {}^{2}D \rightarrow {}^{3}He\ (0.82\ MeV) + {}^{1}n\ (2.45\ MeV)$$

This detector should have as high a sensitivity as possible to measure the lowest possible neutron yields. Unfortunately, the lead probe was designed for measuring DT neutrons, and was determined not to be useful for DD pulsed neutron sources which yield less than 2 x 10^7 neutrons into 4π per pulse (Ruby and Rechen 1967). Therefore, an idea was born that became the subject of this thesis: could one optimize the lead probe in such a way as to increase its sensitivity in detecting DD neutrons without simply increasing the mass of lead? An idea similar to this was thought of by my mentor at Sandia, Dr. Carlos Ruiz,

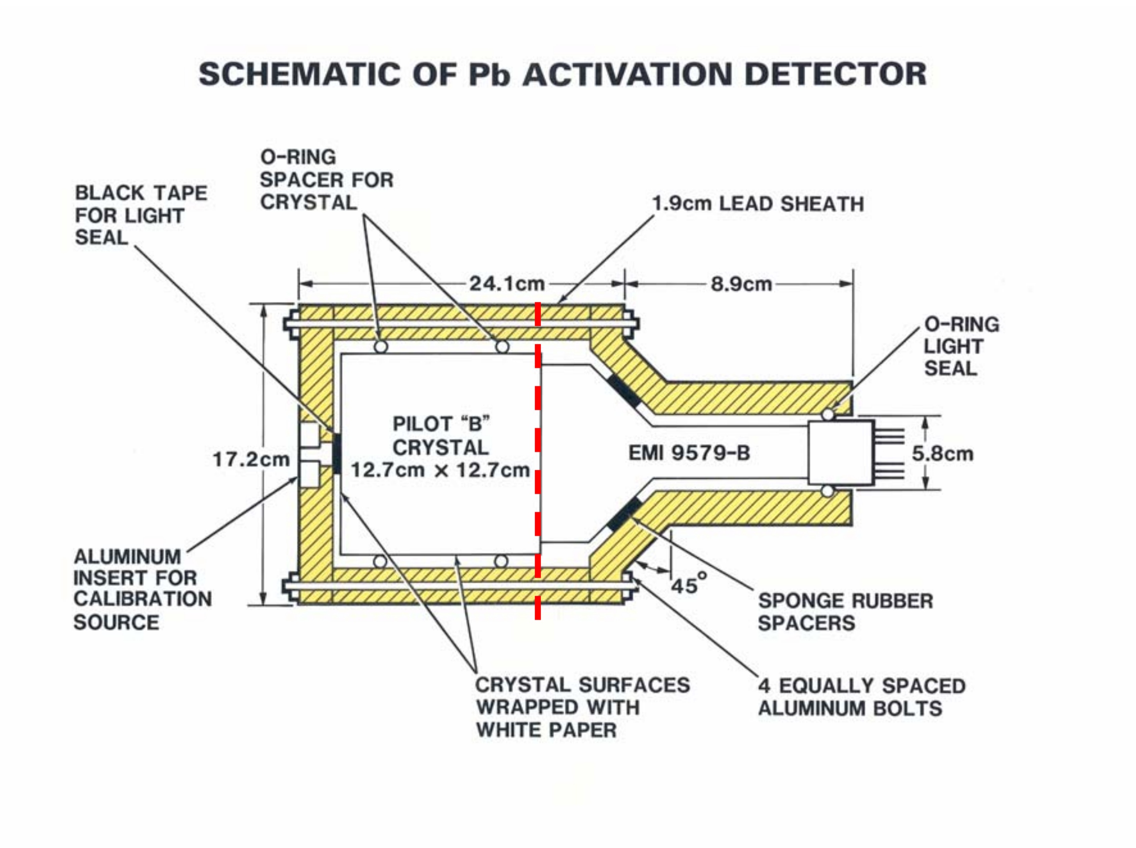


Figure 1. Cross-sectional view of the Original Lead Probe

twenty years ago – that perhaps one could change the geometry of the lead probe by interchanging slices of lead and scintillator to increase its performance. This idea, coupled with the desire to maintain (or reduce, if possible) the overall weight of the detector, became the subject of this thesis.

There was one neutron detector in the literature which was comprised of layers. It consisted of beryllium and scintillator and was based on beryllium activation via the following neutron reaction: $^{9}Be(n, \alpha)^{6}He$ (Rowland 1984). The ^{6}He decays by beta emission; the beta particle is stopped in the scintillator. It was designed analytically for DT neutrons (14 MeV). A prototype was built and tested. However, until now, no one had tried to design a "layer cake" detector with lead for DD neutrons.

The first step was to model the standard lead probe using MCNP (Monte Carlo Neutron Photon) transport code, version 4C (Seagraves 2000), and then investigate alternative geometries via modeling in an attempt to increase the lead probe's efficiency. MCNP is a very versatile and powerful transport code, and can model virtually any kind of geometry imaginable. The original designers of the lead probe relied solely on empirical methods. A great advantage of MCNP is that one can vary the geometry of a design many times without having to physically reproduce each change in the laboratory. This saves considerable expense at not having to build and calibrate intermediate designs along the way.

This work presents just such a scenario. MCNP was used to vary the geometry of the prototype – a "layer cake" design was investigated in which layers of scintillator were sandwiched between layers of lead. "Tallies" were generated by the code – a neutron tally denoted the number of neutron reactions per cm^3 of ^{207m}Pb in the lead. A "counts" tally represented pulses generated in the scintillator by the delayed gammas from ^{207m}Pb, and an "energy deposited tally" denoted the total amount of energy those gammas deposited in the scintillator. A Figure of Merit was derived from the product of the neutron tally, the counts tally, and the volume of the lead in cm^3. This gave a point of comparison between different designs modeled with the same code.

Different geometries of the layer cake were run in which varying widths of lead and scintillator were investigated and compared with the original. It was observed that the mean free path of the gammas were extremely short (~ 0.9 cm) in lead compared with that of scintillator (~ 11.7 cm). A layer cake design was investigated in which thin (< 5 mm) layers of lead were sandwiched between thicker (~ 1 – 2 cm) layers of scintillator. The resulting optimized layer cake detector had 8 layers of lead 0.2 cm thick and 8 layers of scintillator 1.1 cm thick, was 30 cm in diameter, and had the same overall weight as the original lead probe. This produced Figures of Merit which were a factor of 3 greater than the original lead probe for DD neutrons, and a factor of 4 greater for DT neutrons.

To verify the code results, a smaller scale, "proof of principle" prototype was then built by Bechtel/Nevada comprising 8 layers of scintillator 1.5875 cm (5/8") thick, and 9 layers of lead 0.225 cm (0.0886 in) thick. The particular widths were chosen because they consisted of materials in hand. This geometry was modeled using MCNP and its response to DD neutrons was measured using the DD dense plasma focus neutron source at Texas A&M (Freeman 2001). A voltage and discriminator sweep were performed to determine optimum settings during operation. Conclusions are presented which verify the code results.

CHAPTER 2

Monte Carlo Modeling

As a starting point, the original lead probe was modeled with MCNP. (The MCNP input deck used is presented in Appendix A, as well as the input deck for the final, optimized layer cake design.) It consisted of 37 cells and 16 surfaces. A diagram of the model is shown in Figure 2. It should be noted that the lead probe was modeled from the face of the detector to the back edge of scintillator, and included the surrounding lead sheath (note the dashed red line in Figures 1 and 2). The photomultiplier tube was not included or necessary. The code took into account the neutrons interacting with the lead and scintillator, the gammas produced in the lead from neutron activation, the energy the gammas deposited in the scintillator and the counts produced.

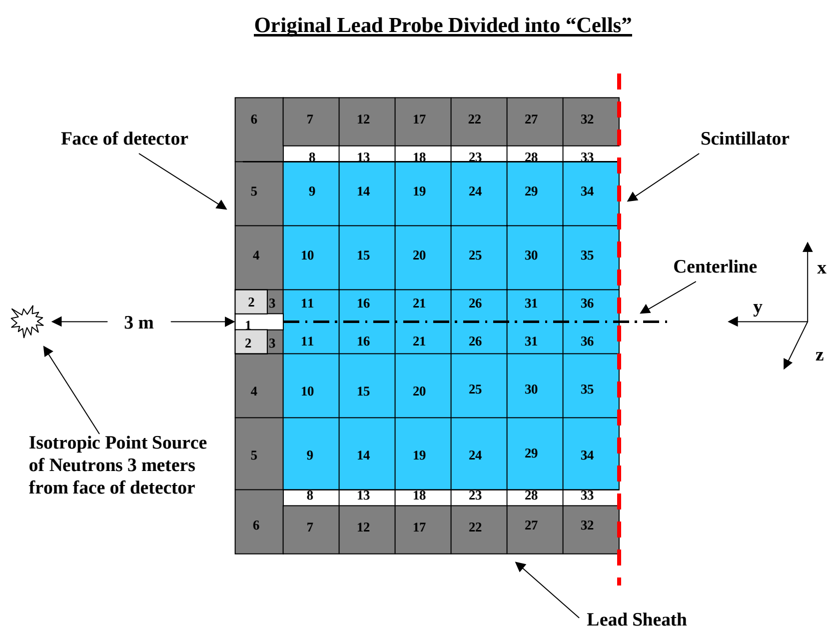


Figure 2. Original Lead Probe Modeled with MCNP

The model was divided into concentric cylinders about the centerline (see Figure

3). Initially, a point source of DD neutrons (2.45 MeV) was placed 3 meters from the

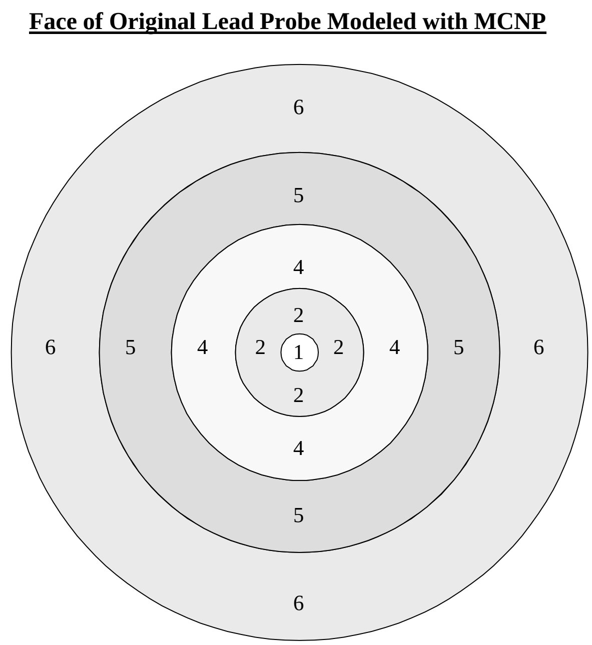


Figure 3. Lead Probe Divided into Concentric Cylinders (Face Shown)

"face" of the lead probe to simulate the distance from a fielded lead probe on the lid of the Z machine to the wire array. Cross sections were input into the code, and were the same as those used by Spencer and Jacobs (Shunk, Wagner and Hemmendinger 1962). The values of the cross sections used are shown in Table I below.

Table I.

$^{207}Pb(n, n')^{207m}Pb$ and $^{208}Pb(n, 2n)^{207m}Pb$ Cross Sections

E_n (MeV)	σ_{207} (mb)	σ_{208} (mb)	E_n (MeV)	σ_{207} (mb)	σ_{208} (mb)
1.8	15.6	…	8.0	905.0	1.8
2.2	68.7	…	9.0	948.8	4.5
3.0	202.4	…	10.0	655.9	173.7
4.0	400.3	…	11.0	476.5	504.2
5.0	749.5	…	14.0	215.7	1313.5
6.0	859.1	…			

Other values of cross sections were found for both reactions (www.nndc.bnl.gov, IAEA 1987) – however, to first order this is a comparison of the layer cake to the lead probe and therefore, as long as the same values were input into each model, an accurate comparison could be made. It was therefore decided to use the original cross sections that Spencer and Jacobs used. A plot of those cross sections are shown in Figure 4.

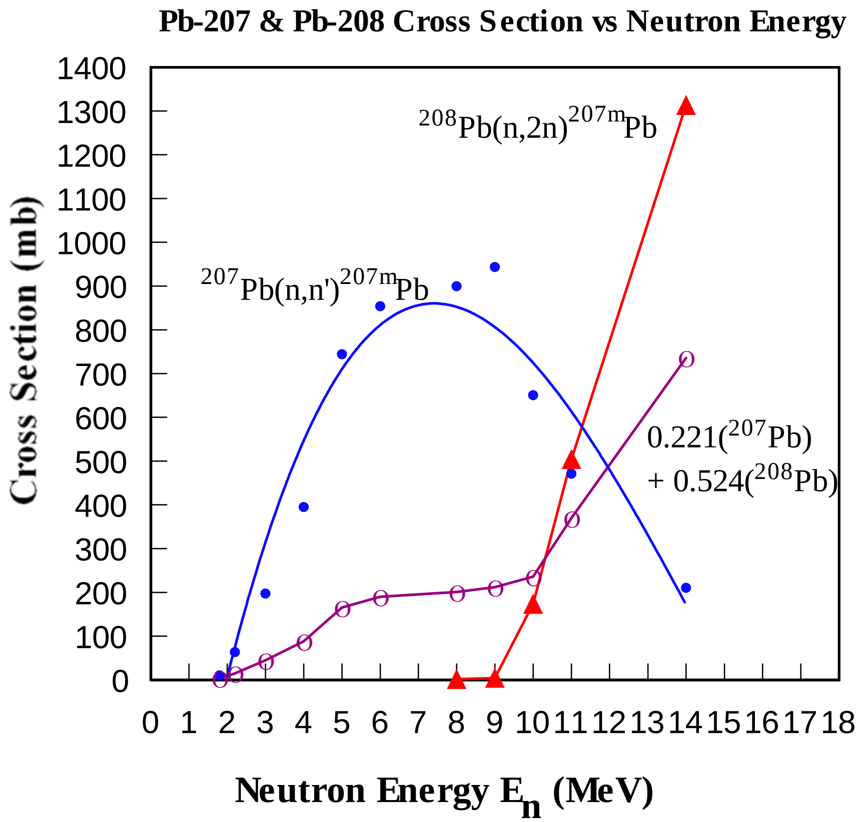


Figure 4. Cross Section Curves for ^{207}Pb(n, n')^{207m}Pb and ^{208}Pb(n, 2n)^{207m}Pb

The cross sections for the production of ^{207m}Pb are shown for ^{207}Pb (blue curve) and ^{208}Pb (red curve). However, due to the isotopic abundance of both isotopes (natural Lead is comprised of 22.1% and 52.4% of ^{207}Pb and ^{208}Pb, respectively), the purple plot shows the effective cross sections that were used in the calculations. As can be seen, at DD neutron energies (2.45 MeV) the values of the effective cross sections are small

(~ 26.9 mb), while at DT neutron energies (14 MeV) they are a factor of 27 greater (~ 735.9 mb), which makes this particular activation technique more suited for DT pulsed neutron sources. (DT neutrons are discussed in Chapter 3.) However, as will be shown, it can be used successfully for DD pulsed neutron sources as well.

Tallies

The tallies used in the calculations consisted of one neutron tally and two photon tallies. The neutron tally was F4 Cell Fluence in units of $\#/cm^2$. The effective cross sections (discussed above, and converted to cm^2) as well as the atomic density of lead ($3.296E10^{22}$ atoms/cm^3) were folded into the code as a multiplier to the F4 tally. This was necessary to convert the F4 tally into units of neutron reactions/cm^3. Thus, fluence ($\#/cm^2$) times cross section (cm^2) times atomic density (atoms/cm^3) yield reactions/cm^3.

Once this first stage was completed, a second modeling step involved treating the lead in the detector as a volumetric gamma source. The delayed gammas from the metastable state of ^{207m}Pb have energies of 0.5697 MeV and 1.0636 MeV, with corresponding branching ratios of 52.5% and 47.5%. These values were input into the code, and the gamma case was run. This produced the photon tallies in the scintillator: F6 Energy Deposition (MeV/gm) and F8 Pulse Height (Counts).

A Figure of Merit was derived as the product of the F4 tally (neutron reactions/cm^3), the F8 tally (counts in the scintillator) and the volume of the lead in cm^3. The resulting units of the Figure of Merit were: (neutron reactions in the lead) x (counts in the scintillator).

Run times for each case (neutron and photon) were determined by the statistics produced in the output. Due to the fact that the geometry of the design was relatively simple, long run times were unnecessary. To obtain statistics less than ten percent with a DD point source at 3 meters a run time of 5 minutes was sufficient for the neutron case, which produced ~10 million particle histories. Three minutes was more than adequate for the gamma case, which produced ~ 800,000 particle histories.

Early on, verification was needed to ensure that the output of the code was similar to the actual performance of the original lead probe. Spencer and Jacobs had produced a plot of the relative neutron sensitivity versus thickness of the lead sheath for the original lead probe. They had done this empirically by running four cases in which four different lead sheaths were analyzed, each having a thickness of 1.27 cm, 1.905 cm, 2.54 cm and 3.175cm (½", ¾", 1", and 1 ¼ ") respectively. Their results are shown in Figure 5.

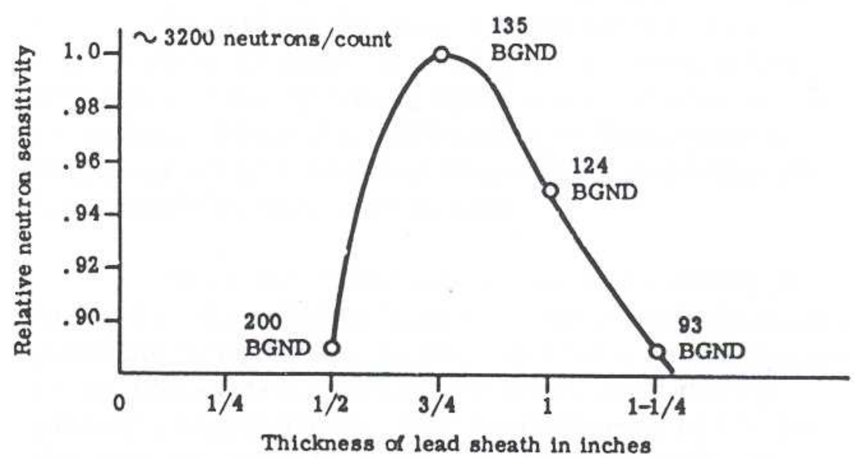


Figure 5. Variation of Neutron Detection Efficiency vs Thickness of Lead Sheath

In an effort to reproduce their data, several cases were run with MCNP in which the thickness of the lead sheath was increased from 1.27 cm to 3.175 cm (1/2" to 1 1/4"), while keeping the volume of the scintillator constant. The results are plotted in Figure 6 and compared with Spencer & Jacobs plot of the original lead probe (Fig. 5) with its 9%

calibration uncertainty (Burns 2003). This good agreement between their data and the MCNP results instilled confidence that other geometries could be modeled that would correctly predict the relative performance of a new detector with respect to the standard lead probe.

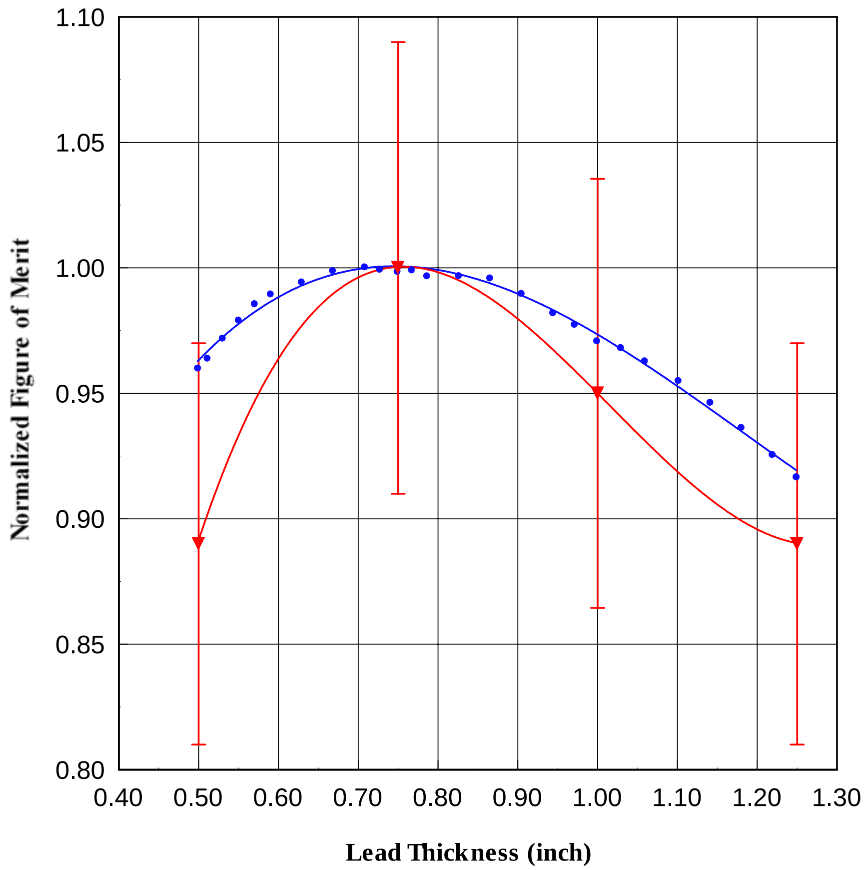


Figure 6. MCNP results of Normalized Figure of Merit vs Lead Thickness compared to Original Lead Probe with 9% Calibration Uncertainty

While running MCNP, it was observed that the delayed gammas from ^{207m}Pb had extremely short mean free paths in the lead compared to their mean free paths in the scintillator. However, the mean free paths of the neutrons in the lead were only slightly larger than their mean free paths in the scintillator, as shown below in Table II.

Table II.

Mean Free Paths of Gammas and Neutrons in Lead and Scintillator

	Lead	Scintillator
Gammas	~ 0.9 cm	~ 11.7 cm
Neutrons	~ 4.0 cm	~ 3.5 cm

This presented an interesting problem: the gammas would rather stop in the lead than in the scintillator, and to a lesser degree, the neutrons would rather stop in the scintillator than in the lead. This was the exact opposite of what was desired. However, the most obvious dissimilarity in the table above are the gamma mean free paths, which differ by more than an order of magnitude in the lead and scintillator. This then was the crux upon which the design criteria would be based – if the lead layers were not thin enough, self attenuation would dominate, and the resulting gamma interactions (F8 tally) in the scintillator would decrease. It was therefore decided that the lead layers in any subsequent design would be less than 0.9 cm to maximize gamma output.

An analysis was performed in which 8 layers of lead of a given mass of 17.1 kg (37.7 lbs) were alternated with 8 layers of scintillator with a constant thickness of 1 cm (0.394 in). A diagram of the model is shown in Figure 7. Note that the layers of lead are labeled as "Front Face, A, B, C," etc., through layer "G"; the layers of scintillator are labeled "1" through "8." Six different cases were analyzed, from 0.6 cm (0.236 in) lead layers to 0.1 cm (0.0394 in) lead layers, with a corresponding increase in radius for the progressively thinner layers of lead to maintain a constant mass of 17.1 kg (37.7 lbs). A point source was placed 3 meters from the face of the detector in each case. F4 and F8 tallies were generated and a Figure of Merit was calculated for each run. The results are in Table III below.

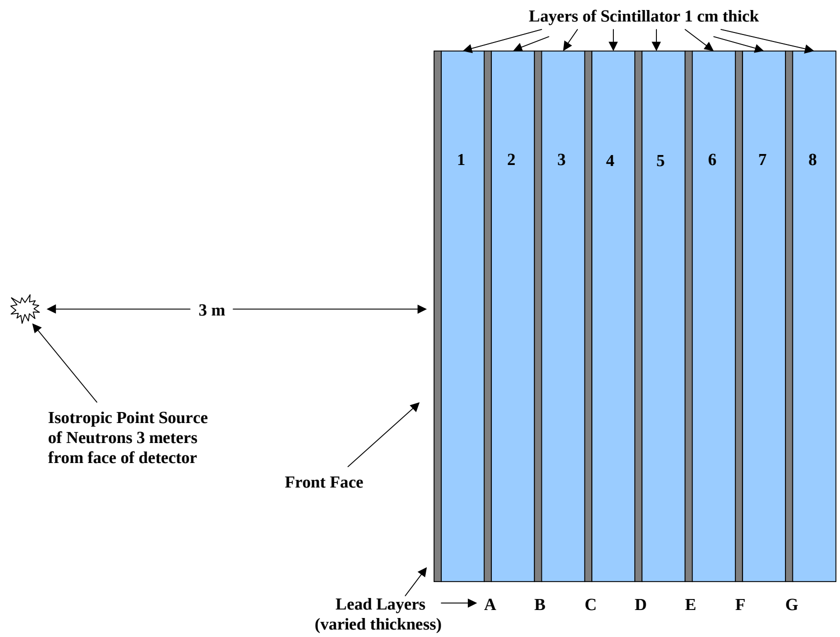


Figure 7. MCNP Model of 8 layers of Scintillator 1 cm thick with 8 layers of lead

As can be seen in Table III, the F4 tallies increase by a modest 7.2 % from a thickness of 0.6 cm (0.236 in) to 0.1 cm (0.0394 in), whereas the largest increases are seen in the F8 tallies and the Figure of Merit. The F8 tallies increase by 187 % from 0.6 cm to 0.1 cm. This is due to two factors: (1) the lead layers are decreasing in thickness, thereby allowing more gammas to escape the lead, and (2) the radius of the detector is increasing, so that more scintillator mass is present to detect the gammas. The Figure of Merit increases by 208 % from 0.6 cm to 0.1 cm – this is primarily due to the increase in the F8 tally. Figure 8 below plots the F4 tally, the F8 tally and the Figure of Merit as a function of lead layer thickness.

Table III.

Lead Layer Thickness vs F4 & F8 Tallies and FOM

for Constant Lead Mass of 17.1 kg (37.7 lbs)

Lead Thickness (cm)	F4 Tally (n reactions/cm^3)	F8 Tally (counts)	Radius (cm)	Figure of Merit (reactions x counts)
0.6	4.72524E-10	0.109192	10	7.7803E-08
0.5	4.84888E-10	0.126695	10.95	9.2635E-08
0.4	4.94024E-10	0.149670	12.25	11.1498E-08
0.3	5.01351E-10	0.183041	14.14	13.8379E-08
0.2	5.01628E-10	0.232290	17.32	17.5707E-08
0.1	5.06483E-10	0.313412	24.49	23.9365E-08

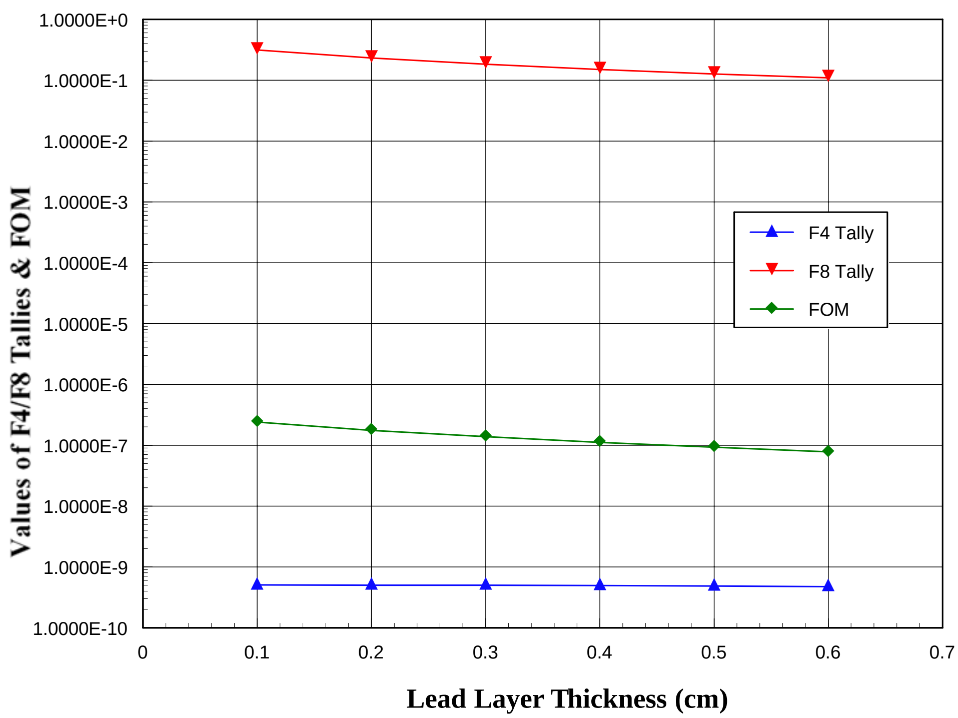
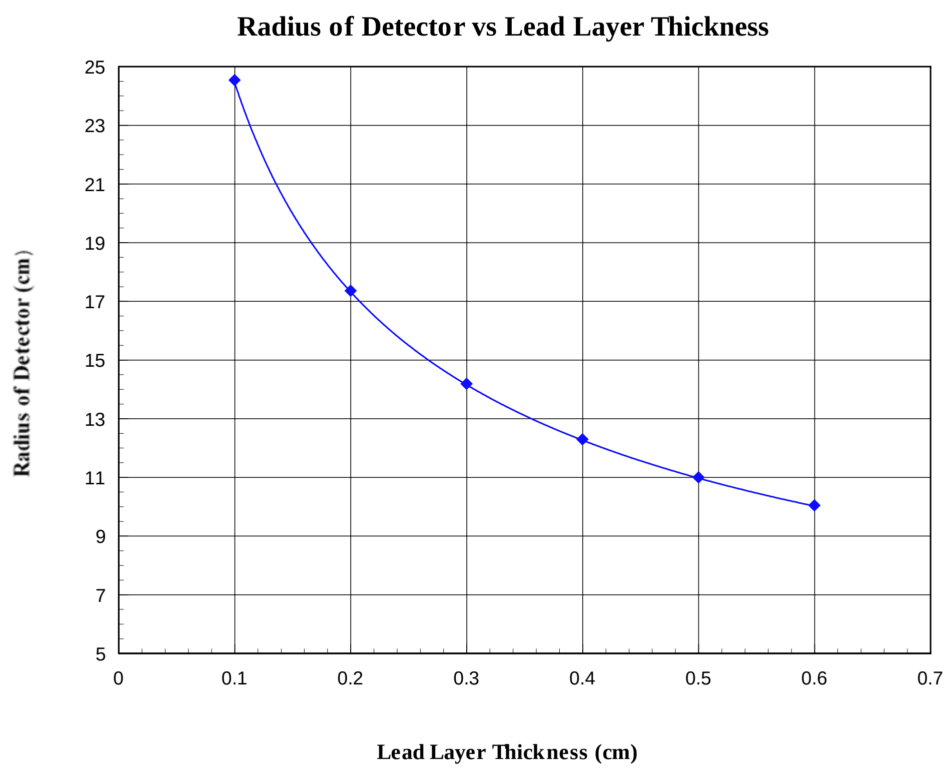


Figure 8. F4 Tally, F8 Tally and Figure of Merit as a Function of Lead Layer Thickness, for Constant Lead Mass and Scintillator Thickness

Figure 9 displays the radius of the detector as a function of the lead layer thickness for the runs described in Table III. What do these figures (8 & 9) reveal? That thinner is better and wider is better for the lead layers. Theoretically, one could keep making the lead layers thinner and wider for a constant lead mass and constant scintillator thickness and the Figure of Merit would steadily increase. However size limitations play a role in practical use, and one must decide how large a detector can ultimately be. For this design, it was decided that a maximum radius of 15 cm (5.9 in) be used for the optimum detector design, giving it a diameter of 30 cm (~1 ft). Anything larger was considered impractical for one person to carry and field by themselves.



<u>Figure 9. Radius of Detector vs Lead Layer Thickness for Constant Lead Mass and Scintillator Thickness</u>

In looking at Figure 9, the values of lead layer thickness above and below a radius of 15 cm (5.9 in) are 0.2 cm (0.0787 in) and 0.3 cm (0.118 in), respectively. A series of runs were performed on both these values in which the scintillator thickness was varied, keeping the lead layer thickness and radius constant, in order to find the thickness of scintillator which would optimize the Figure of Merit for each case. The results for both the 0.3 cm and 0.2 cm lead layer cases are shown in Figure 10 below.

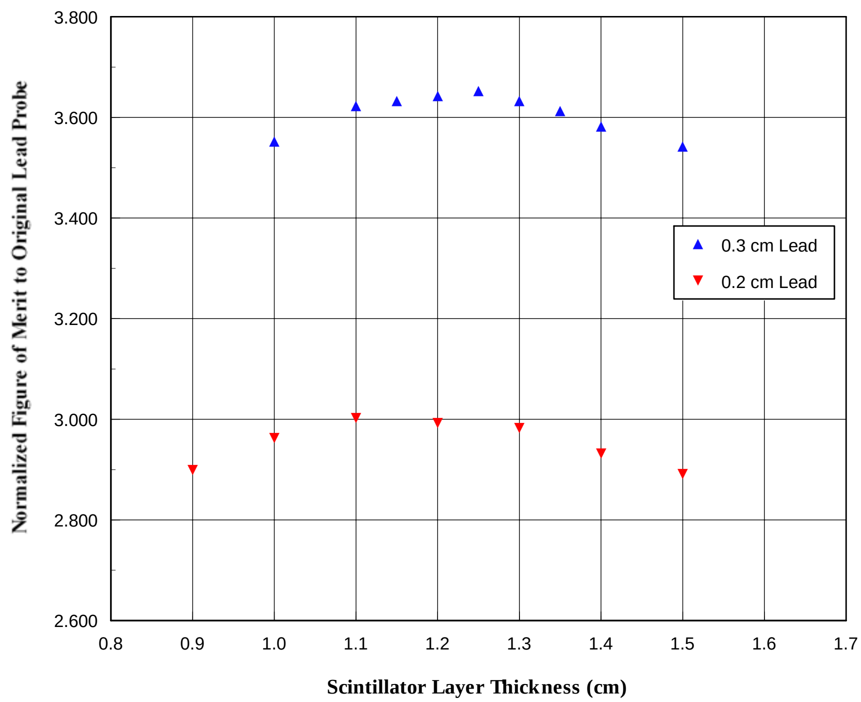


Figure 10. Normalized Figure of Merit vs Scintillator Thickness for 0.3 cm and 0.2 cm lead layer cases

As can be seen in Figure 10, the thickness of scintillator found which would optimize the Figure of Merit in the 0.3 cm lead case was 1.25 cm. This resulted in a Figure of Merit of 3.66 in comparison to the original lead probe. In the 0.2 cm lead case, the thickness of scintillator was found to be 1.1 cm. This optimized the Figure of Merit to a value of 3.0 in comparison to the original lead probe.

The values of the F4 tally, the F8 tally, mass of lead, scintillator, total mass and Figure of Merit are listed in Table IV below for the original lead probe and both the 0.2cm (0.0787 in) and 0.3 cm (0.118 in) lead layer cases, each at their optimized thickness of scintillator. Note that the values in parentheses are normalized to the corresponding values of the original lead probe. As can be seen, the values of the F4 tally drop 4.7% for the 0.2 cm lead case and 11.5% for the 0.3 cm lead case. However, the F8 tallies increase dramatically – 344% for the 0.2 cm case and 290% for the 0.3 cm case.

Table IV.

Comparison between the Original Lead Probe and 0.2 cm and 0.3 cm lead cases

	F4 Tally (reactions/cm^3)	**F8 Tally (counts)**	**Mass of Lead**	**Mass of Plastic**	**Total Mass**	**Figure of Merit (reactions x counts)**
Original Lead Probe	5.1145E-10 (1.0)	0.053917 (1.0)	18.14 kg (40 lbs)	1.66 kg (3.66 lbs)	19.80 kg (43.66 lbs)	4.41E-08 (**1.0**)
0.2 cm Lead, 1.1 cm Scintillator	4.8742E-10 (0.953)	0.239599 (4.44)	12.83 kg (28.28 lbs)	6.42 kg (14.15 lbs)	19.25 kg (42.43 lbs)	13.21E-08 (**3.0**)
0.3 cm Lead, 1.25 cm Scintillator	4.5264E-10 (0.885)	0.210382 (3.90)	19.24 kg (42.42 lbs)	7.29 kg (16.08 lbs)	26.53 kg (58.48 lbs)	16.15E-08 (**3.66**)

It is interesting to note in Table IV that the 0.3 cm lead case has 50% more lead than the 0.2 cm lead case, (19.24 kg vs 12.83 kg), but it has 14% fewer counts in the scintillator (0.210832 vs 0.239599). This is due to the fact that the lead layers are 0.1 cm thinner in the 0.2 cm case than in the 0.3 cm case, allowing less self attenuation in the lead, thereby letting more gammas out into the scintillator, and will be shown below. (The mean free paths of gammas in lead are 0.9 cm; see Table II, p. 11.) A comparison of F4 tallies (reactions/cm^3) times the volume of each layer (cm^3/layer) yielding neutron reactions per layer for both the 0.2 cm and 0.3 cm cases are shown in Table V below.

Table V.

Neutron Reactions per Layer for the 0.2 cm and 0.3 cm lead layer cases

Lead Layers	0.2 cm Lead Layers Neutron Reactions per Layer (x 10^{-8}) (n reactions/cm^3) x (cm^3/layer)	0.3 cm Lead Layers Neutron Reactions per Layer (x 10^{-8}) (n reactions/cm^3) x (cm^3/layer)
Front Face	12.30 (100%)	18.95 (100%)
Layer “A”	10.33 (84%)	15.33 (81%)
Layer “B”	8.66 (70%)	12.22 (64%)
Layer “C”	7.05 (57%)	9.59 (51%)
Layer “D”	5.60 (46%)	7.27 (38%)
Layer “E”	4.71 (38%)	5.89 (31%)
Layer “F”	3.67 (30%)	4.38 (23%)
Layer “G”	2.80 (23%)	3.16 (17%)

In looking at Table V, the 0.3 cm lead case has more neutron reactions per layer than the 0.2 cm lead case. (It has thicker layers of lead, and hence more volume per layer.) However, in looking at the values in parenthesis (which are normalized to the front face value in each case), despite being higher, the neutron reactions/layer for the 0.3

cm case fall off slightly faster from the front face to the last layer ("G"). This seems to indicate, that for the 0.3 cm case, with its thicker layers of scintillator 1.25 cm thick, that more neutron attenuation is occurring as the neutrons travel through to the back layers than in the 0.2 cm case. However, neutron attenuation through the layers of scintillator would be more pronounced if the thickness of scintillator approached the neutron mean free path in scintillator (3.5 cm, Table II, p. 11). (See Appendix B for DD neutron attenuation in 0.2 cm and 0.3 cm cases).

From Table V, it is shown that the 0.3 cm case has more neutron reactions per layer. Thus, more ^{207}Pb atoms are being activated and producing delayed gammas in the 0.3 cm lead case. But are they reaching the scintillator to produce counts? A comparison of F8 tallies for the 0.2 cm and 0.3 cm lead layer cases are shown in Table VI below.

Table VI.

F8 Tallies for the 0.2 cm and 0.3 cm lead layer cases

Scintillator Layers	0.2 cm Lead Layers F8 Tallies (Counts in Scintillator)	0.3 cm Lead Layers F8 Tallies (Counts in Scintillator)
Layer 1	0.044364 (> 2%)	0.043284
Layer 2	0.045144 (> 7%)	0.041991
Layer 3	0.041888 (> 12%)	0.037237
Layer 4	0.037103 (> 18%)	0.031344
Layer 5	0.031769 (> 25%)	0.025365
Layer 6	0.025703 (> 29%)	0.019901
Layer 7	0.020006 (> 36%)	0.014687
Layer 8	0.012889 (> 46%)	0.008815

In Table VI, for every layer of scintillator the F8 tallies are greater in the 0.2 cm lead case than in the 0.3 cm lead case, due to the reasons mentioned above. Namely, that

(1) the lead layers are thinner in the 0.2 cm lead case (0.2 cm vs 0.3 cm), allowing less self attenuation to occur so that more gammas exit the lead. And (2) to a lesser degree, the layers of scintillator are thinner in the 0.2 cm lead case (1.1 cm vs 1.25 cm), thereby attenuating fewer neutrons throughout the detector.

Efficiency

The other photon tally generated by the code was the F6 tally, in units of MeV/gm, *per source particle* (or gamma). The total energy deposited (MeV) in the scintillator was found by multiplying the total mass of scintillator (in grams) by the F6 tally, and also by the number of source particles, or gammas, in the run. The total energy emitted by the lead in the form of gammas, was the number of source gammas multiplied by the weighted average energy of each gamma ray, or 0.8 MeV. The efficiency was then found by dividing the total amount of energy deposited in the detector by the total amount of energy emitted in gamma rays. (And since the number of source gammas was in both the numerator and denominator, simply dividing the energy deposited by 0.8 MeV calculated the efficiency as well.) Table VII lists the efficiency for the original lead probe, the 0.2 cm lead layer case and 0.3 cm lead layer case as well as the energy deposited in each case for both DD and DT neutrons.

Once more, just as the F8 tallies in Table VI are higher for the 0.2 cm lead case, so are the F6 tallies in Table VII. Despite the fact that the 0.3 cm case has more mass of scintillator than the 0.2 cm case (7.29 kg vs 6.42 kg), or (16.08 lbs vs 14.15 lbs), it has a lower F6 tally. The 0.3 cm case has more neutron reactions/layer (as shown in Table V), but its thicker lead layers contribute to more self attenuation, so fewer gammas exit the lead. The net result is less energy is deposited in the scintillator, producing a lower value for efficiency, both for DD and for DT neutrons.

Table VII.

F6 Tallies, Energy Deposited and Efficiencies of Original Lead Probe, and 0.2 cm and 0.3 cm Lead Layer Cases

	F6 Tally (MeV/gm)	Mass of Scintillator	Energy Deposited (MeV)	Efficiency (%) DD Neutrons	Efficiency (%) DT Neutrons
OLP	1.21191E-05	1.66054 kg (3.66 lbs)	0.020124	2.52	2.58
0.2 cm Pb	1.24744E-05	6.41940 kg (14.15 lbs)	0.080078	10.01	10.31
0.3 cm Pb	9.63972E-06	7.29 kg (16.08 lbs)	0.070320	8.79	9.14

As can be seen, the differences in efficiency between DT neutrons and DD neutrons vary by only 2 – 4%, indicating that despite the increase in neutron energy (from 2.45 MeV to 14.1 MeV), similar processes are occurring in the DT case. More will be discussed about DT neutrons in Chapter 3.

A final comparison between the 0.2 cm lead case and the 0.3 cm lead case was to look at the overall mass of lead and scintillator in each case and compare those values with the mass of lead and scintillator in the original lead probe (Table IV). In looking at the total mass of each case, the overall mass of the original lead probe comprising the lead face, lead sheath and block of scintillator is 19.8 kg (43.66 lbs). This value was taken as an upper bound in weight – any new design, however configured, would have to weigh in at that weight or be less than that weight. The 0.3 cm lead case with 1.25 cm layers of scintillator has an overall mass of 26.53 kg (58.48 lbs) making it prohibitively heavy, despite its Figure of Merit being a factor of 3.66 higher than the original lead probe. The 0.2 cm lead case with 1.1 cm layers of scintillator has an overall mass of 19.24 kg (42.42 lbs), which is just under the original lead probe’s overall weight of 19.8 kg (43.66 lbs). This configuration, then, was chosen as the optimum design, with its higher F4 and F8 tallies due to its thinner layers of both scintillator and lead, and having a Figure of Merit 3 times greater than the original lead probe.

CHAPTER 3

DT Neutrons

Since the original lead probe was designed to measure pulsed DT neutron sources (14 MeV), it was only fitting that an analysis be carried out with both the 0.2 cm (0.0787 in) and 0.3 cm (0.118 in) lead cases above to determine how they performed in comparison. As shown in Figure 4, the effective cross sections at DT neutron energies are a factor of 27 greater (~735.9 mb) than those at DD neutron energies (~26.9 mb). This is primarily due to the threshold reaction ^{208}Pb(n, 2n)^{207m}Pb which occurs for neutron energies above about 8 MeV (Spencer & Jacobs, 1965); this threshold value was further analyzed to be 7.38 MeV (Ruby and Rechen, 1967). As is shown in Figure 4, the cross section for the ^{207}Pb(n, n')^{207m}Pb decreases as one increases in neutron energy above 8 MeV, while the ^{208}Pb(n, 2n)^{207m}Pb reaction cross section increases more than a factor of two between 11 MeV (504.2 mb) and 14 MeV (1313.5 mb).

MCNP was used to model a point source of DT neutrons placed 3 meters away from the face of the original lead probe. The neutron case was run for five minutes (generating ~ 10 million particle histories) and the ^{207m}Pb production was calculated (F4 tally). The lead in the detector was then treated as a volumetric gamma source in which a photon case was run that generated a counts tally (F8) in the scintillator from the ~800,000 particle histories generated. The values of the F4 tally, the F8 tally, mass of lead, scintillator, total mass and Figure of Merit are listed in Table VIII. The values in parentheses are normalized to the corresponding values of the original lead probe.

Again, the F8 tallies increase dramatically – 347% for the 0.2 cm lead case and 295% for the 0.3 cm lead case. And, once again, the 0.3 cm case has 50% more lead than

Table VIII.

Comparison between the Original Lead Probe and 0.2 cm and 0.3 cm lead cases

For DT Neutrons (14 MeV)

	F4 Tally (reactions/cm^3)	**F8 Tally (Counts)**	**Mass of Lead**	**Mass of Plastic**	**Total Mass**	**Figure of Merit (reactions x counts)**
Original Lead Probe	1.3697E-08 (1.0)	0.055367 (1.0)	18.14 kg (40 lbs)	1.66 kg (3.66 lbs)	19.80 kg (43.66 lbs)	1.21E-06 (**1.0**)
0.2 cm Lead, 1.1 cm Scintillator	1.7325E-08 (1.26)	0.247316 (4.47)	12.83 kg (28.28 lbs)	6.42 kg (14.15 lbs)	19.25 kg (42.43 lbs)	4.85E-06 (**4.0**)
0.3 cm Lead, 1.25 cm Scintillator	1.6347E-08 (1.19)	0.218956 (3.95)	19.24 kg (42.42 lbs)	7.29 kg (16.08 lbs)	26.53 kg (58.48 lbs)	6.08E-06 (**5.0**)

the 0.2 cm case, but it has 13% fewer counts in the scintillator. This is due to the reasons mentioned above for DD neutrons – the lead layers are 1 mm thinner in the 0.2 cm case than in the 0.3 cm case, which allow less self attenuation to occur so that more gammas exit the lead. And in contrast to the DD case, DT neutrons have more advantageous mean free paths as shown in Table IX below. The mean free paths of 14 MeV neutrons in lead are actually shorter than they are in the scintillator, which is what is desired (as opposed to the DD neutron case, Table II).

Table IX.

Mean Free Paths of 14 MeV neutrons in Lead and Scintillator

	Lead	Scintillator
DT Neutrons	~ 5.2 cm	~ 7.5 cm

A comparison of neutron reactions per layer for both the 0.2 cm and 0.3 cm cases are shown in Table X below. Note that the reactions/layer for DT neutrons are over an order of magnitude greater than the reactions/layer for DD neutrons (Table V). This is due to the higher cross section of the $^{208}Pb(n, 2n)^{207m}Pb$ reaction (Figure 4), and well as the beneficial mean free paths of 14 MeV neutrons in lead and scintillator.

Table X.

Neutron Reactions per Layer for the 0.2 cm and 0.3 cm lead layer cases

For DT Neutrons

Lead Layers	0.2 cm Lead Layers Neutron Reactions per Layer ($\times 10^{-6}$) (n reactions/cm^3) x (cm^3/layer)	0.3 cm Lead Layers Neutron Reactions per Layer ($\times 10^{-6}$) (n reactions/cm^3) x (cm^3/layer)
Front Face	3.13 (100%)	4.70 (100%)
Layer "A"	2.94 (94%)	4.33 (92%)
Layer "B"	2.73 (87%)	3.96 (84%)
Layer "C"	2.54 (81%)	3.65 (78%)
Layer "D"	2.32 (74%)	3.22 (69%)
Layer "E"	2.20 (70%)	2.93 (62%)
Layer "F"	1.96 (63%)	2.64 (56%)
Layer "G"	1.78 (57%)	2.30 (49%)

As was seen for DD neutrons, the neutron reactions/layer for the 0.3 cm case fall off slightly faster from the front face to the last layer ("G"), indicating that more neutron attenuation is occurring in the 0.3 cm case than in the 0.2 cm case. Also, since the 0.3 cm lead case has more neutron reactions per layer than the 0.2 cm lead case, more ^{207}Pb atoms are being activated and producing delayed gammas. To see if these gammas are reaching the scintillator and being counted, a comparison of F8 tallies (Counts) for the 0.2 cm and 0.3 cm lead layer cases are shown in Table XI below.

Table XI.

F8 Tallies for the 0.2 cm and 0.3 cm lead layer cases

For DT Neutrons

Scintillator Layers	0.2 cm Lead Layers F8 Tallies (Counts in Scintillator)	0.3 cm Lead Layers F8 Tallies (Counts in Scintillator)
Layer 1	0.036472 (> 7%)	0.034032
Layer 2	0.040178 (> 9%)	0.036667
Layer 3	0.039946 (> 12%)	0.035492
Layer 4	0.038090 (> 14%)	0.033180
Layer 5	0.036043 (> 18%)	0.030532
Layer 6	0.032212 (> 21%)	0.026605
Layer 7	0.026501 (> 22%)	0.021678
Layer 8	0.017346 (> 29%)	0.013424

As was also seen for DD neutrons, for every layer of scintillator the F8 tallies are greater in the 0.2 cm lead case than in the 0.3 cm lead case, due to the reasons mentioned above. Namely, that (1) the lead layers are thinner in the 0.2 cm lead case (0.2 cm vs 0.3 cm), allowing less self attenuation to occur so that more gammas exit the lead which produces a higher F8 tally (Table VIII). And (2) to a lesser degree, the layers of scintillator are thinner in the 0.2 cm lead case (1.1 cm vs 1.25 cm) or (0.433 in vs 0.492 in), thereby attenuating less neutrons throughout the detector. Overall this produces a Figure of Merit which is a factor of 4 greater than the original lead probe for the 0.2 cm case, and a Figure of Merit which is a factor of 5 greater than the original lead probe for the 0.3 cm case (Table VIII). However, due to weight considerations, the 0.3 cm case is considered prohibitively heavy with its total mass of 26.53 kg (58.48 lbs). The 0.2 cm case is chosen again as the optimized design with its weight of 19.25 kg (42.43 lbs).

CHAPTER 4

The Prototype

The analysis up to this point had provided the optimum “layer cake” design parameters: 0.2 cm lead thickness and 1.1 cm scintillator thickness, with a radius of 15 cm. The overall mass of this model was 19.25 kg (42.43 lbs), which was just under the original lead probe’s mass of 19.80 kg (43.66 lbs), and it produced a Figure of Merit which was a factor of 3 greater than that of the original lead probe for DD neutrons. It was now necessary to build a “proof of principle” prototype, test it experimentally, and compare the experimental results with the code predictions.

A meeting at Bechtel/Nevada in Las Vegas was held to discuss the design of such a prototype. In order to minimize cost, it was decided that the prototype was to be built out of materials at hand and its size reduced. Also, instead of a cylindrical configuration which would require additional machining, a square configuration was chosen instead. The scintillator that was available at Bechtel was in 1.5875 cm (5/8”) sheets. This dimension was not the 1.1 cm (0.433 in) optimized thickness that the code specified; however, once the prototype was built it was modeled with the code to its exact dimensions and the results of the code were compared with experimental data.

In order to reduce background and provide some shielding, it was decided that the prototype have 9 layers of lead and only 8 layers of scintillator; in this way, lead layers would be on each exterior side. Also, it was decided that the size of each layer would be approximately 15.24 cm (6 in) square – the final dimensions were 15.47 cm x 15.37 cm (6.092” x 6.052”).   The lead layers were between 2.2 – 2.3 mm (0.0866 – 0.0906 in) thick. For modeling purposes, a thickness of 2.25 mm (0.0886 in) was chosen. The layers of scintillator were 1.5875 cm (5/8”), and were comprised of BC-400, a general purpose scintillator, equivalent to NE-102. (More specifications of BC-400 can be found in Appendix D.) A photograph of the completed prototype in a steel housing is shown in Figure 11 below.

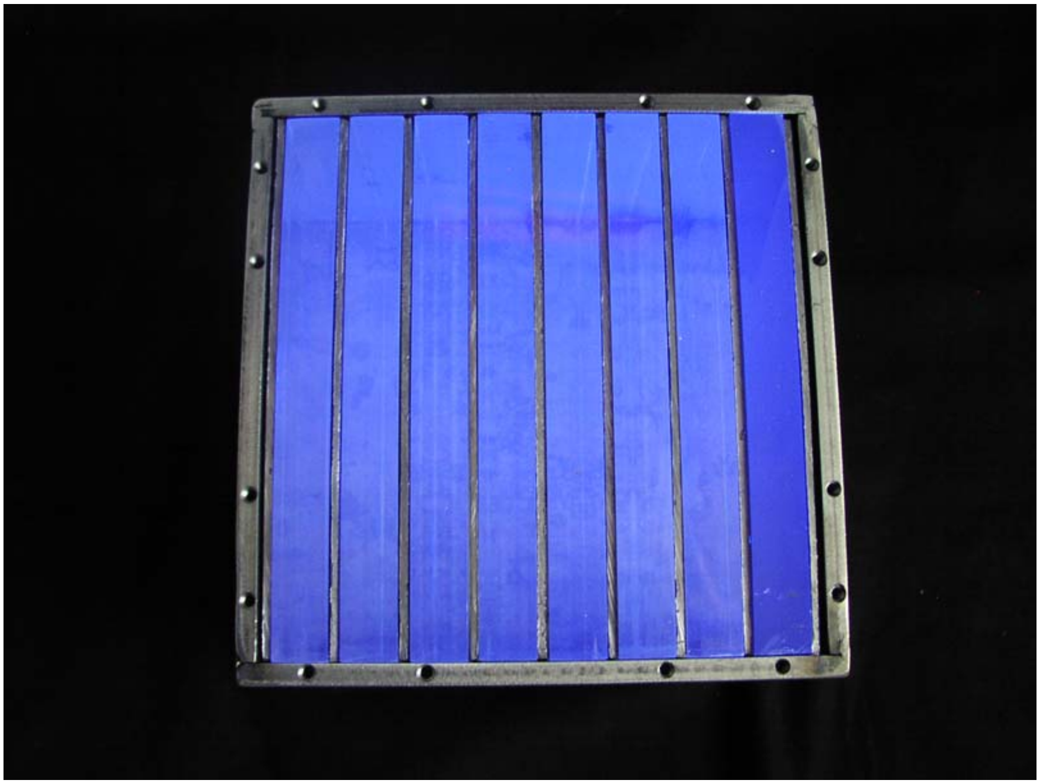


Figure 11. Layer Cake Prototype with 9 layers of lead, 8 layers of scintillator Encased in a steel housing

In order to reduce costs still further, a light guide was deemed unnecessary; instead a 12.7 cm (5 in) Hamamatsu photomulitplier tube was coupled directly to the edge on view via a plate and o-ring as shown in Figure 12. The completed detector assembly with the lead/scintillator section coupled to the photomultiplier tube is shown in Figure 13 below. Specifications on the Hamamatsu R1250 photomultiplier tube can be seen in Appendix C.

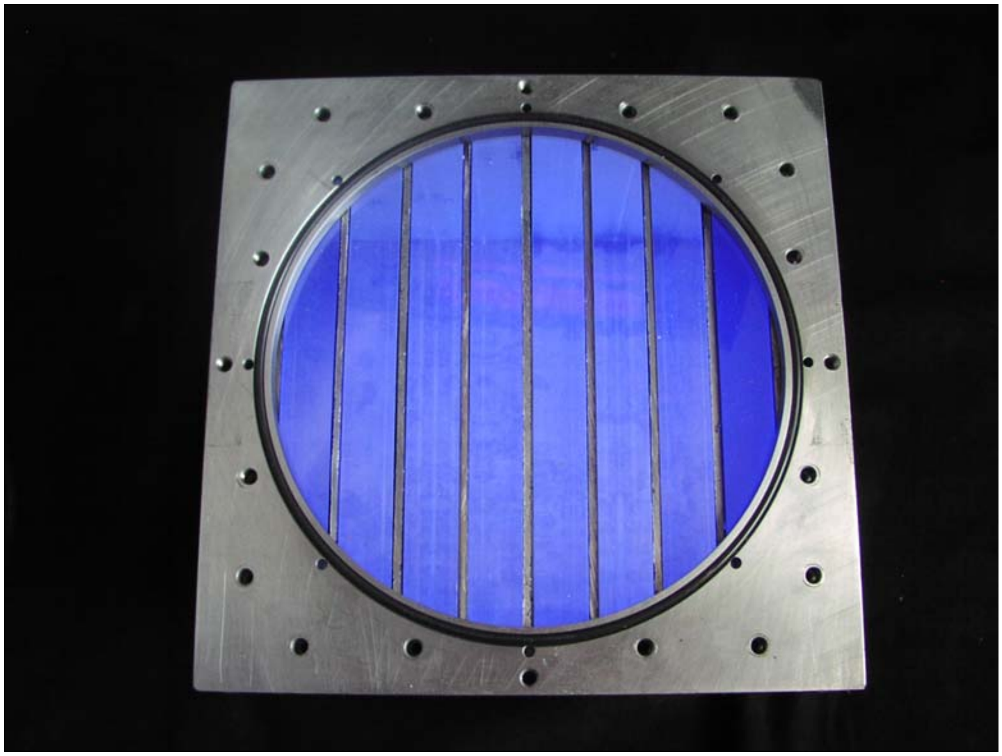


Figure 12. Plate and O-ring on Layer Cake to couple to 12.7 cm (5 in) diameter Hamamatsu Photomultiplier tube

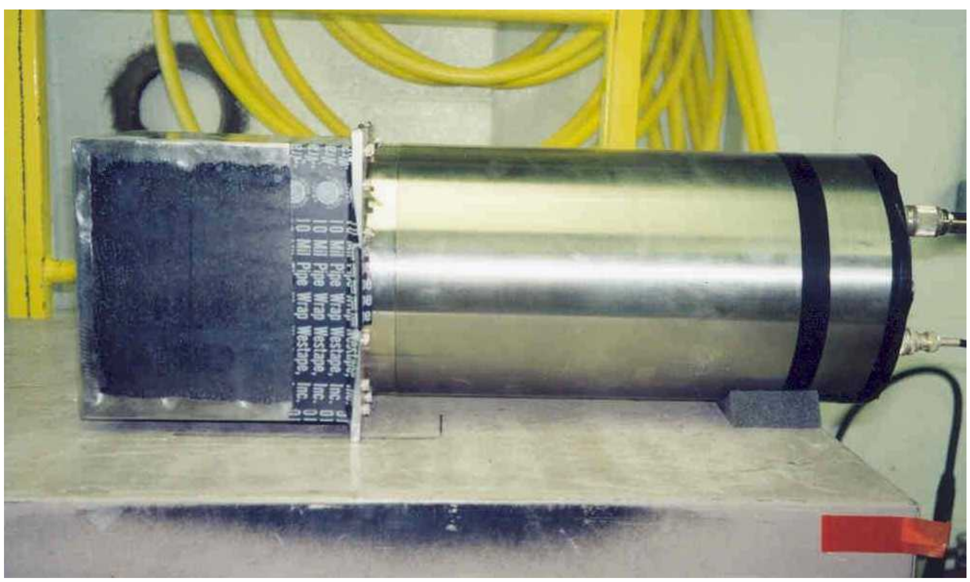
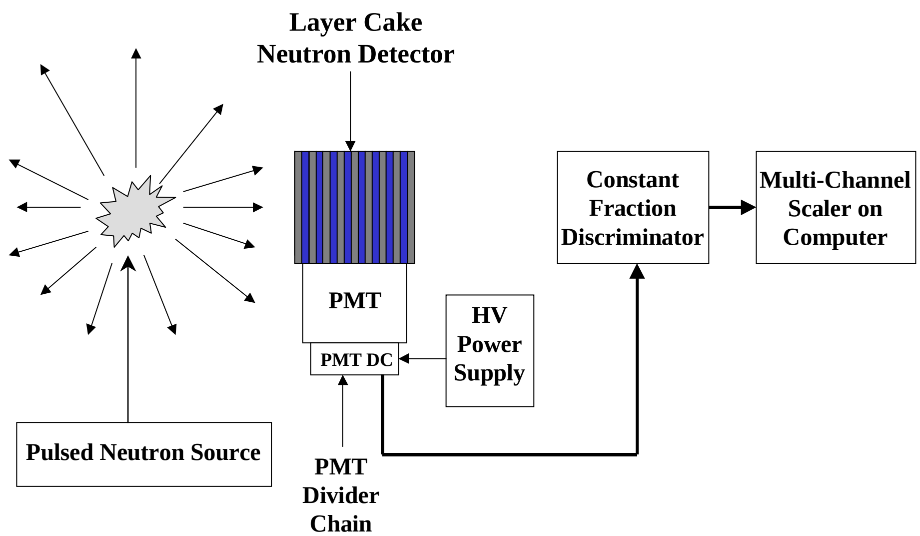


Figure 13. Completed Layer Cake Detector Assembly: Lead/Scintillator Section Coupled to 12.7 cm (5 in) Hamamatsu Photomultiplier Tube

A block diagram of the layer cake prototype detector is shown in Figure 14. It consists of the layer cake, a photomultiplier tube and divider chain, a high voltage power supply, a constant fraction discriminator and multi-channel scaler.



<u>Figure 14. Block Diagram of Layer Cake Prototype Neutron Detector</u>

CHAPTER 5

Experimental Results

Dense Plasma Focus

The neutron source used to calibrate the layer cake prototype was the 480-kJ, 60kV, capacitor driven DD dense plasma focus operated by Dr. Bruce Freeman at Texas A&M University Riverside campus (Freeman 2001). The typical neutron yield for this machine is ~ 3.5 x 10^{10} neutrons (based on indium activation, discussed below) in 100 ns

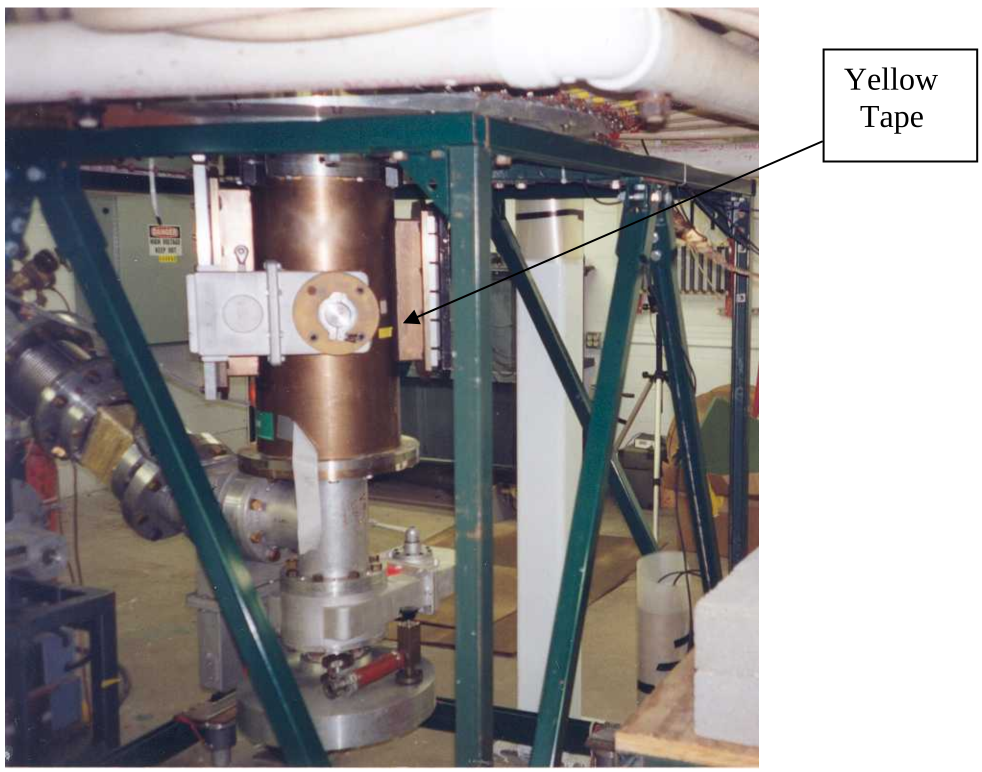


Figure 15. Dense Plasma Focus at Texas A&M; typical neutron yield is ~ 3.5 x 10^{10} neutrons (based on indium activation) in 100 ns (FWHM); center is marked with yellow tape for alignment purposes.

(FWHM). The DPF is shown in Figure 15 (note the small piece of yellow tape on the chamber wall – this denotes the center of the dense plasma focus).

The layer cake was placed on a thin metal table (to minimize neutron scattering) which stood on stacked cinderblocks as shown in Figure 16. This permitted the center of the face of the detector to be 129.54 cm (51 in) above the floor; the center of the dense plasma focus was determined to be 131.45 cm (51 ¾ in) (i.e., marked with yellow tape in Fig. 15).

Figure 16. Layer Cake placed on thin metal table (to minimize neutron scattering) on stacked cinderblocks; at this height the detector was aligned to center of DPF

Also, for $1/R^2$ measurements the table could be rolled towards or away from the DPF on the cinderblocks, depending on the measurement that was desired. Figure 17 shows the layer cake and the original lead probe beneath it while another lead probe from

Bechtel rests on a nearby table. They are all facing the DPF, approximately 1.83 m (6 ft) away.

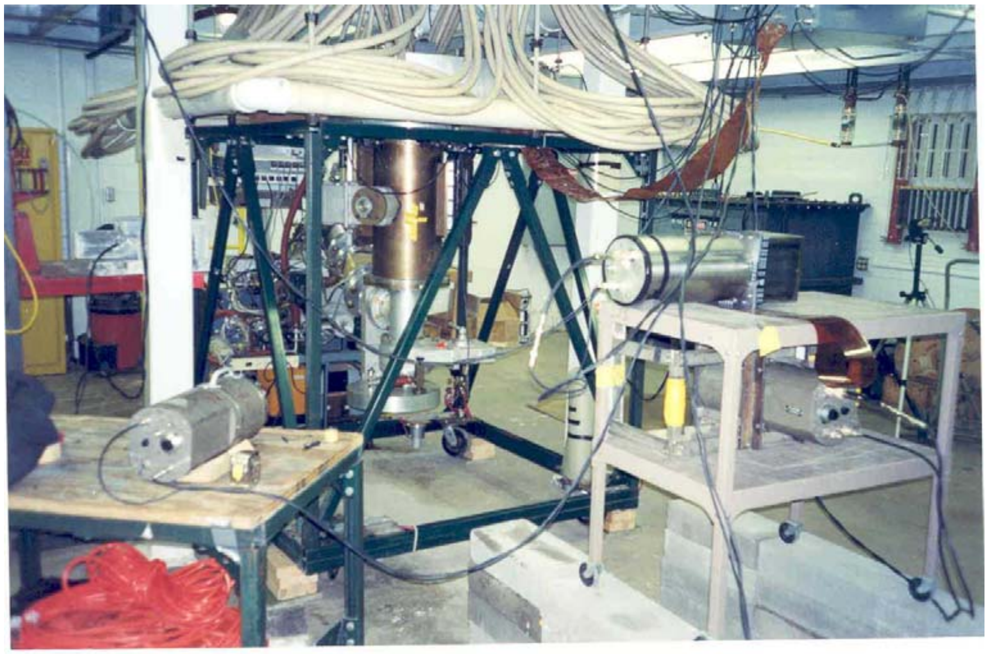


Figure 17. Layer Cake with Original Lead Probe beneath it; another lead probe from Bechtel rests on a table nearby. All are facing the Dense Plasma Focus.

A series of shots were performed with the layer cake at 3 different distances from the chamber wall of the DPF: 243.84 cm (8 ft), 182.88 cm (6 ft) and 106.68cm (42 in). It was noted that the center of the DPF was 15.24 cm (6 in) within the chamber – this was taken into account in the calculations. DD neutron yields were found using activation of nominally 50 gram (1.76 oz) indium samples via the following inelastic neutron scattering reaction: $^{115}In(n,n')^{115m}In$; its threshold is 336 keV (Cooper and Ruiz 2001). The yields were then mass-corrected, and the number of incident neutrons on the face of the detector were calculated.

The data from each shot were taken with a multi-channel scaler. A decay curve of a typical shot is shown in Figure 18, before any analysis was performed. Note the areas of background, the long lived component and the x-ray peak which accompany the neutron pulse. This raw data must be manipulated before a 0.8 second half life can emerge.

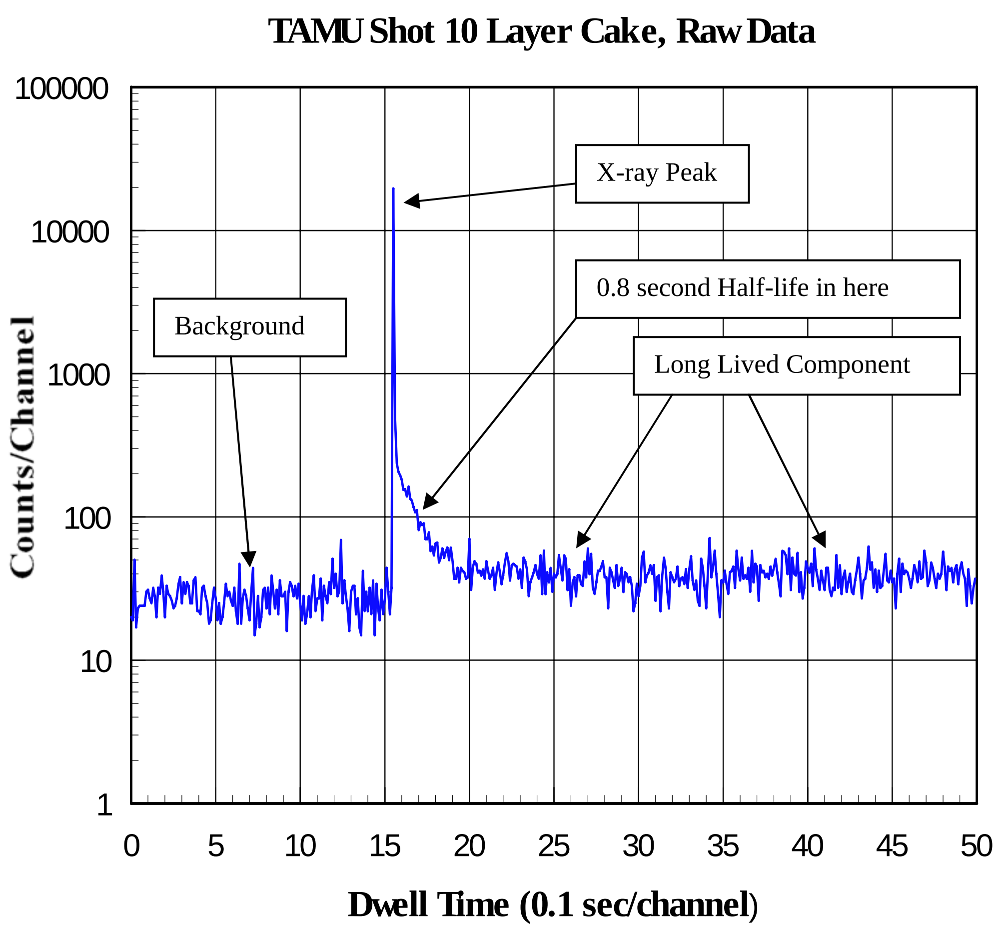


Figure 18. Raw Data taken with Layer Cake on Typical Shot on DPF

Once the background is subtracted, the long lived component is found and subtracted, the x-ray data is removed and a time correction is performed, a least squares fit is performed to determine the initial count rate, A(0), and the corresponding total number of counts, N(0), which is directly proportional to the number of neutrons that interacted with the lead. A plot of a least squares fit that was performed for the raw data in Figure 18 is shown below in Figure 19.

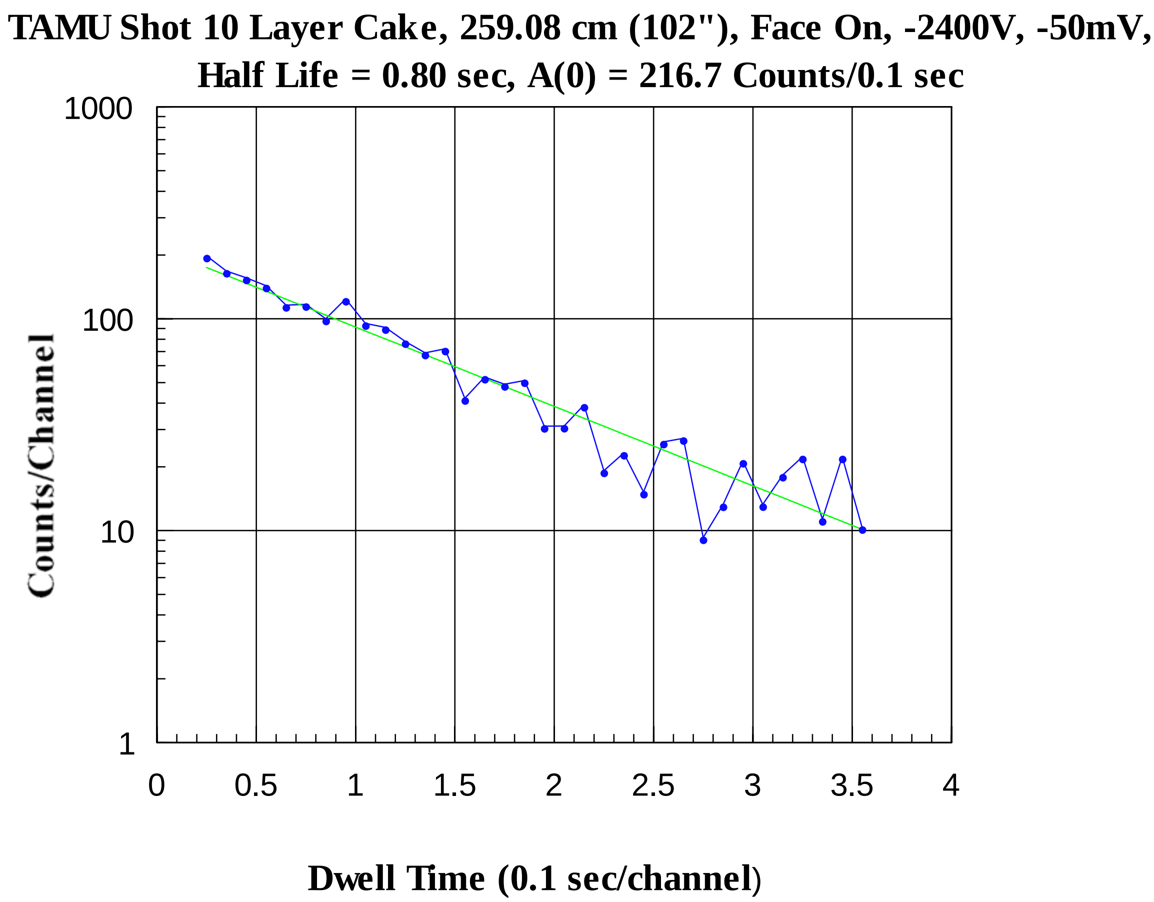


Figure 19. A Least Squares Fit Performed on Data in Figure 17 to Determine A(0), the Relative Initial Activity per unit Time of the Lead

The sensitivity was then determined by dividing the total counts, N(0), by the number of incident neutrons. A voltage sweep and discriminator sweep were performed to determine optimum sensitivity settings. A plot of the sensitivity as a function of photomultiplier tube bias and discriminator setting can be seen in Figure 20. (Note: the values of sensitivity vs tube bias and discriminator setting can be seen in table form in Appendix C.)

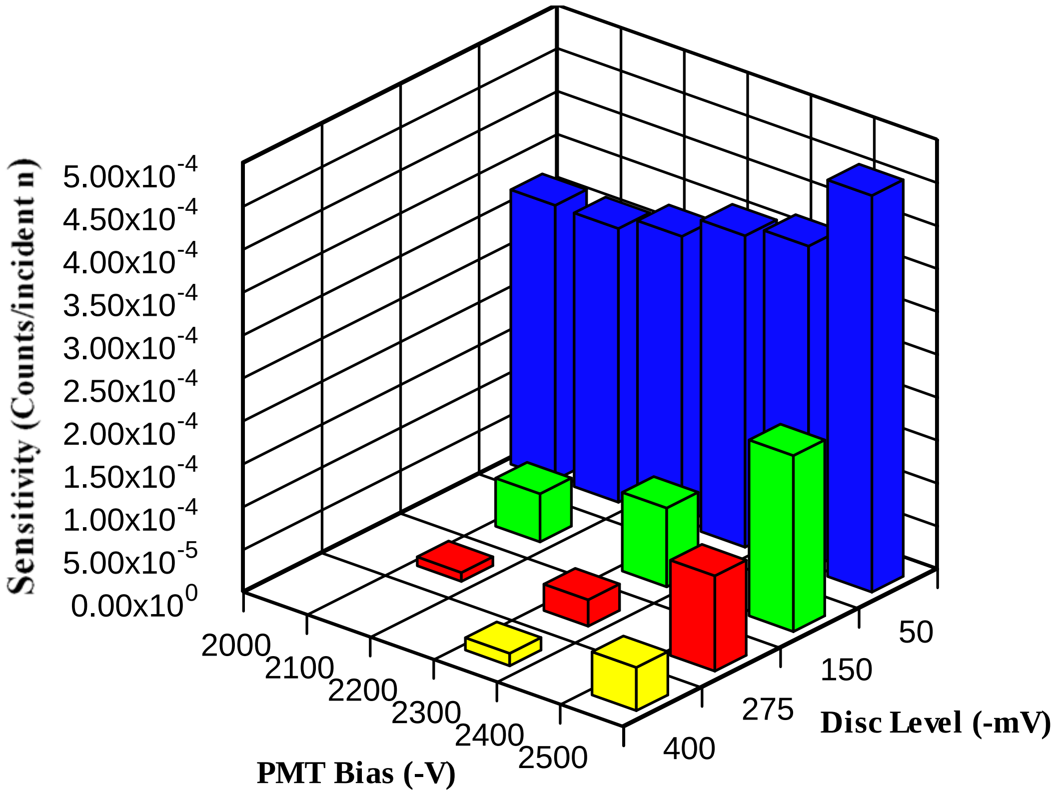


Figure 20. Layer Cake Sensitivity as a Function of Photomultiplier Tube Bias And Discriminator Setting

"Face On" Configuration

An operating voltage of -2200 Volts and a discriminator setting of -50 mVolts (the lowest) was chosen as reasonable for operation of the layer cake. This produced a sensitivity of ~ 3000 incident neutrons/count, which approximated Sandia's lead probe sensitivity of ~ 2635 neutrons/count (from data taken at TAMU's DPF, May 2003). At these settings it was then compared with the original lead probe at a total distance of 198.12 cm (78") from the center of the DPF in a "face on" configuration (i.e., the face of the detector was placed toward the source as shown in Figure 7).

After fielding the detectors at Texas A&M, the prototype layer cake, as it was built by Bechtel – 0.225 cm (0.0886 in) lead layers, 1.59 cm (5/8") scintillator layers, was modeled with MCNP with a point source of DD neutrons at exactly the same distance 198.12 cm (78 in). The run times for each case (layer cake and original lead probe) were equal, both for the first run (which generated a neutron tally) and the second run (which produced a counts tally). The results of the experimental and modeled data of the layer cake compared with the original lead probe are shown in Tables XII and XIII below.

Table XII.

Experimental Data of Layer Cake "Face On" & Original Lead Probe

Detector	Distance	Shot #	A(0) Counts/0.1 sec	LC/OLP
Layer Cake	198.12 cm	27	142.1	142.1/198.6 =
Orig. Lead Probe	198.12 cm	27	198.6	0.715509
Layer Cake	198.12 cm	28	231.6	231.6/321.4 =
Orig. Lead Probe	198.12 cm	28	321.4	0.720597

Ave. Ratio of Layer Cake "Face On" to Original Lead Probe:

(0.715509 + 0.720597)/2 = 0.72 ← Measured Value

Table XIII.

Modeled Layer Cake "Face On" & OLP at 198.12 cm (78 in) from Point Source

Detector	F4 Tally (n reactions/cm^3)	F8 Tally (Counts)	Mass of Lead	FOM (reactions x counts)
Layer Cake	7.8786E-10	0.226469	5.46 kg 12.04 (lbs)	8.5907E-08
Orig. Lead Probe	11.4083E-10	0.053722	18.14 kg 40 (lbs)	9.8036E-08

From Table XIII above, the ratio of Figures of Merit of the Layer Cake "Face On" to Original Lead Probe:

(8.5907)/(9.8036) = 0.88← Calculated Value

"Edge On" Configuration

Another comparison was made of the Layer Cake to the Original Lead Probe comprising a different geometry – the detector was turned such that the "edge-on" view was facing the source as shown in Figure 21 below. It was placed at the same distance of 198.12 cm (78") as was the "face on" evaluation above. Unfortunately, due to time restrictions, only one shot was allowed for a comparison. The experimental data of the Layer Cake in an "edge-on" configuration compared with the Original Lead Probe can be seen in Table XIV below. The modeled data are presented in Table XV.

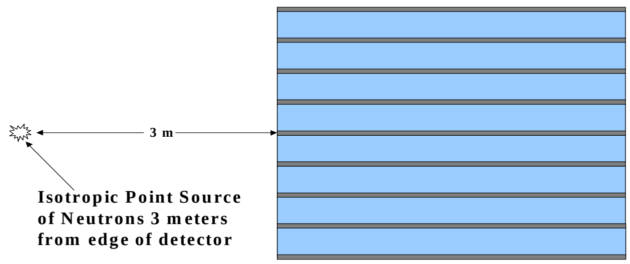


Figure 21. Layer Cake in "Edge On" Configuration to Source

Table XIV.

Experimental Data of Layer Cake "Edge On" & Original Lead Probe

Detector	Distance	Shot #	A(0) Counts/0.1 sec	LC/OLP
Layer Cake	198.12 cm	29	174.8	174.8/257.8 =
Orig. Lead Probe	198.12 cm	29	257.8	0.678045

Ratio of Layer Cake "Edge On" to Original Lead Probe:

0.68 ← Measured Value

Table XV.

Modeled Layer Cake "Edge On" & OLP at 198.12 cm (78 in) from Point Source

Detector	F4 Tally (n reactions/cm^3)	F8 Tally (Counts)	Mass of Lead (lbs)	FOM (reactions x counts)
Layer Cake	6.8945E-10	0.240990	5.46 kg (12.04 lbs)	7.9999E-08
Orig. Lead Probe	11.4083E-10	0.053722	18.14 kg (40 lbs)	9.8036E-08

From Table XV above, the ratio of Figures of Merit of "Edge On" Layer Cake to Original Lead Probe:

(7.9999)/(9.8036) = 0.82 ← Calculated Value

A summary of the comparisons of the experimental data to the modeled data of the "face on" and "edge on" configurations are shown in Table XVI below. The modeled values (0.88 and 0.82) are approximately 20% – 22% higher than the experimental values (0.72 and 0.68), but this is not surprising. The MCNP model is considered an "ideal" detector, which assumes that all the pulses in the scintillator are counted, etc., and is not subject to background or various bias and discriminator settings that an actual detector is subject to. However, what is interesting, are the ratios between the modeled values and the measured ones for the same configurations. The modeled evaluation of the "face on" to "edge on" layer cake is within 1% of the measured "face on" to "edge on" layer cake (1.07 vs 1.06). These results indicate that the code results are valid.

Table XVI.

Comparison of Experimental and Modeled Data of the Layer Cake

"Face On" to "Edge On" at 198.12 cm (78 in) from Point Source

Case	Layer Cake Face On/Edge On
Modeled	0.88/0.82 = 1.07
Measured	0.72/0.68 = 1.06

1/R^2 Measurements

In the three positions mentioned above, namely, 121.92 cm (48 in), 198.12 cm (78 in) and 259.08 cm (102 in) from the DPF, $1/R^2$ measurements were performed with the Layer Cake in the "face on" configuration. A(0) – the initial count rate – was found using a least squares fit to the data. The neutron yields were determined from indium activation (Cooper and Ruiz, 2001) and mass-corrected. The values of A(0) were then normalized using the mass-corrected neutron yields. Figures of Merit were produced from the code at each position and multiplied by a constant to compare with the experimental data. The data – both experimental and calculated – are listed in Table XVII.

Table XVII.

Comparison of Experimental and Calculated Data at 121.92 cm (48 in), 198.12 cm (78 in) and 259.08 cm (102 in)

Distance	Shot #	A(0) Counts/0.1sec	Mass-Corrected Neutron yields	Norm A(0)	FOM $x 10^{-8}$	FOM x K
121.92 cm (48 in)	26	434.1	1.46×10^{10}	627.4	21.77	593.9
198.12 cm (78 in)	27	141.0	1.35×10^{10}	220.4	8.59	234.4
”	28	209.9	1.902×10^{10}	232.9	“	“
”	24	218.7	2.01×10^{10}	229.6	“	“
”	25	191.8	1.59×10^{10}	254.5	“	“
259.08 cm (102 in)	5	172.2	2.11×10^{10}	172.2	5.23	142.6
”	6	162.8	1.98×10^{10}	173.5	“	“

The values of A(0) were normalized to the highest mass-corrected neutron yield of 2.11×10^{10} on shot #5 at a distance of 259.08 cm (102 in). Averages were taken at 198.12 cm (78 in) and 259.08 cm (102 in); their values were 234.4 and 172.9 respectively. The constant K was derived from the average value at 198.12 cm, or 78 in (234.4) divided by the Figure of Merit produced by the code at that distance (8.59×10^{-8}):

$$K = (234.4)/(8.59 \times 10^{-8}) = 2.73 \times 10^{9}.$$

The last column in Table XVII lists the Figures of Merit multiplied by the constant K. The experimental data (i.e., the normalized values of A(0)), the Figures of Merit multiplied by the constant K, and $1/R^2$ values are plotted in Figure 22. Note: the $1/R^2$ values were derived for the data at distances of 121.92 cm (48 in) and 259.08 cm (102 in), using the average normalized A(0) for 198.12 cm (78 in) of 234.4, as follows:

$1/R^2$ at 121.92 cm: $(198.12)^2/(121.92)^2 * (234.4) =$ 619.0, and,

$1/R^2$ at 259.08 cm: $(198.12)^2/(259.08)^2 * (234.4) =$ 137.1

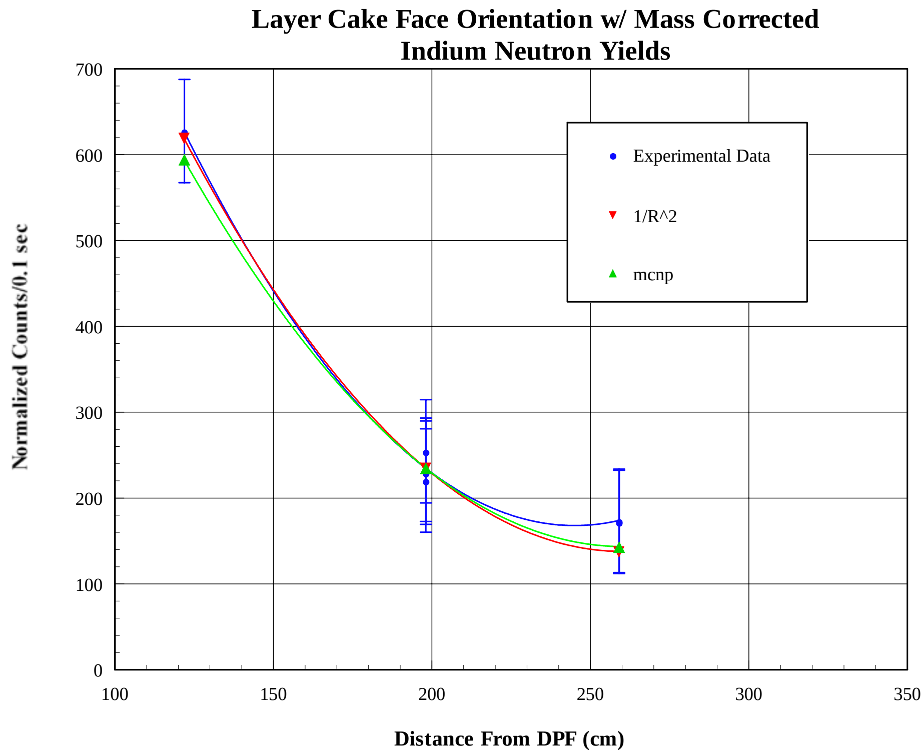


Figure 22. Layer Cake Experimental Data, MCNP Calculations and $1/R^2$ Behavior

The experimental data can be seen to compare well with both the $1/R^2$ behavior (red) and the MCNP calculations (green) – their values fall within the experimental data's standard error bars (blue) of +/- 63.3 counts/0.1 sec.

Calibration

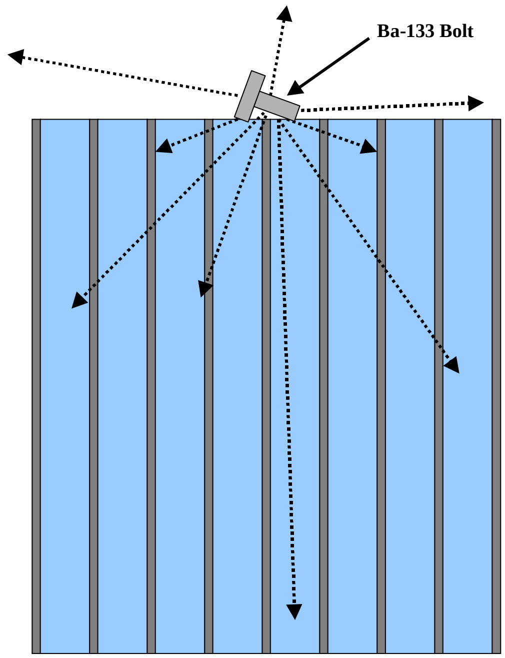
As seen in Figure 20, the sensitivity of the layer cake neutron detector can be adjusted by photomultiplier tube bias as well as pulse height discriminator level. The amplifier gain in the electronics can also be varied to adjust sensitivity. However, at the time of calibration against a known yield of pulsed neutrons (such as at Texas A&M, as mentioned above) these parameters are determined before each pulse, and the system is calibrated by the number of delayed gamma counts in the scintillator. Thus, the neutron sensitivity of the detector is directly related to the gamma scintillation sensitivity. This relationship, then, provides a technique to reset the system gain to the level used during initial calibration.

By using a radioactive source placed at a predefined position on the detector at the time of calibration, the gamma counts in the scintillator can be recorded. Then the photomultiplier tube bias, as well as the pulse height discriminator level can be varied to attain the level of gamma scintillations produced during the primary calibration with a neutron source. In this way the same neutron sensitivity can be achieved when the detector is fielded elsewhere, regardless of the local background and relative settings of the photomultiplier tube bias and discriminator level, as well as any long cable lengths that may be required over which voltage drops could occur.

^{133}Ba was used as the radioactive source for the original lead probe (Spencer & Jacobs, 1965), due to its relatively long half life of 10.53 years and a gamma spectrum of photopeaks with energies below 0.4 MeV. It was produced by taking 20 to 30 microcuries of barium powder (evaporated from a solution), which was then placed in a drilled out bolt and sealed with epoxy. The bolt was then placed in the aluminum insert shown in Figure 1. The rigid mounting of the insert assured that the ^{133}Ba source would always be placed in the same position relative to the scintillator so that the sensitivity could be adjusted to the level determined at the time of calibration. Also, due to slight geometrical discrepancies in source mountings from lead probe to lead probe, a reference source from one probe would not necessarily produce the same ratio of gamma counts to neutron sensitivity in the other. Therefore, it was determined that each lead probe be assigned a ^{133}Ba source at its primary calibration which would then be dedicated to that particular probe throughout its working life.

Initially at Texas A&M, before fielding the detector on neutron shots, it was necessary to determine whether the layer cake could be calibrated in the same fashion as the original lead probe, i.e., with a barium source in a predefined position. Due to the multiple layers of lead in the layer cake, it was unknown whether the low energy gammas from ^{133}Ba would penetrate enough of the scintillator to generate adequate counts to calibrate the detector. The original lead probe, on the other hand, has no lead layers to attenuate gammas; the entire mass of scintillator "sees" the barium source. Therefore, a barium bolt with an activity of 5.1 μCi from a lead probe belonging to Bechtel was placed on top of the Layer Cake in the center, perpendicular to the edges of lead and scintillator as seen in Figure 23.

The voltage applied to the detector at the time was –2000 volts, with the discriminator setting at –50 mV (the lowest). The dwell time was set on the multi-channel scaler to 2.367 sec. The average counts recorded from the barium bolt were ~ 3412 counts/sec. The barium bolt was then taken away and the average background recorded at the same settings was ~200 counts/sec. Since the ratio between source counts and background counts was large (~17) it was determined that a barium bolt similar to those used with lead probes could be used to calibrate the layer cake. Particularly if the bolt was placed in a fixed position (perhaps a nut could be epoxied or welded to the housing of the layer cake such that a barium bolt could be screwed into it, as shown in Figure 24.)



<u>Figure 23. Barium Bolt Placed in center of Layer Cake perpendicular to edges of lead and scintillator.</u>

Also, increasing the gain on the photomultiplier tube would also increase the ratio between source counts and background counts. The operating voltage (as was mentioned above) chosen for the layer cake was –2200 Volts; however, the Hamamatsu photomultiplier tube can be operated up to –3000 Volts (Appendix C). This voltage range is more than adequate for setting system gain to attain the level of gamma scintillations with a ^{133}Ba source to equate to those scintillations produced by neutron activation at the time of calibration.

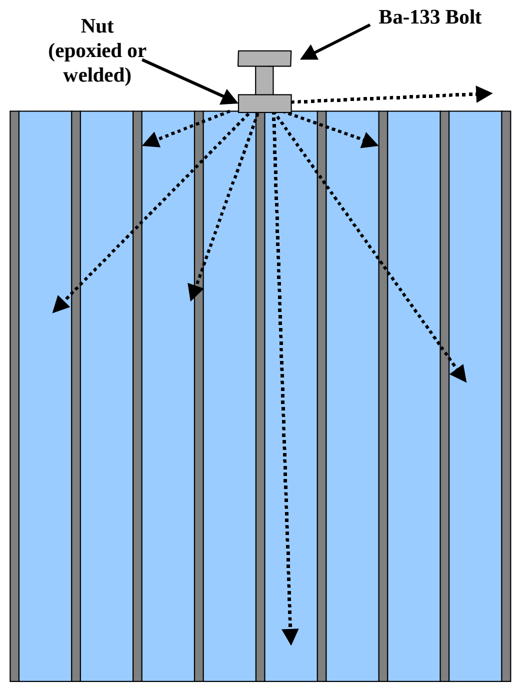


Figure 24. Fixing a position for a Barium Bolt on the Layer Cake in the form of a nut being either epoxied or welded to housing

Chapter 6

Summary

The lead probe neutron detector designed by Spencer and Jacobs in 1965 was optimized using a layer cake design in which thin, 2 mm (0.0787 in) layers of lead were sandwiched between thicker, 1.1 cm (0.433 in) layers of scintillator. The optimized layer cake was 30 cm (11.81 in) in diameter (which was considered the upper design limit on size), and had an equal number of lead and scintillator layers at 8 each. This produced an overall Figure of Merit which was a factor of 3 times greater than the original lead probe for DD neutrons (2.45 MeV) and a factor of 4 times greater for DT neutrons (14 MeV). It has slightly less overall mass – 19.25 kg vs 19.80 kg , (42.43lbs vs 43.66 lbs), and contained 30% less lead.

A smaller, “proof of principle” prototype was built by Bechtel/Nevada out of materials at hand and consisted of 9 layers of lead 0.225 cm (0.0886 in) thick and 8 layers of scintillator (BC-400), 1.5875 cm (5/8 in) thick and was approximately 15.24 cm (6 in) square. In order to reduce background and provide some shielding, it was decided that the prototype have lead layers on each exterior face. To further reduce costs, a light guide was not used; instead a 12.7 cm (5 in) Hamamatsu photomultiplier tube was coupled directly to the edge on view, in line with the layers of lead and scintillator.

The prototype was then calibrated using the 480-kJ, 60kV, capacitor driven DD dense plasma focus operated by Dr. Bruce Freeman at Texas A&M University Riverside campus. A series of shots were performed with the layer cake at 3 different distances from the chamber wall: 106.68 cm, 182.88 cm and 243.84 cm (42 in, 6 ft, and 8 ft). DD neutron yields were found using activation of (nominally) 50 gram (1.76 oz) samples of indium which were mass corrected. The total number of incident neutrons on the face of the detector was found. A least squares fit was performed on the data to determine A(0), the initial count rate. N(0) – the total number of counts from ^{207m}Pb atoms (and therefore the number of neutrons which had interacted with the detector) was found. Sensitivity was determined from dividing N(0) by the number of incident neutrons. A voltage and discriminator sweep was performed to determine optimum sensitivity settings.

The prototype was tested in both a "face on" and "edge on" configuration and compared well in each case with calculations (within 3% – 5%). $1/R^2$ measurements were performed at the three distances mentioned above. The calculations and $1/R^2$ behavior values fell within the experimental data's standard error bars. It was determined that calibration could be accomplished with a standard ^{133}Ba bolt which is used to calibrate the original lead probe.

Future Work

It should be noted that this design process yielded two different pathways one could take. (1) A most efficient case in which the Figure of Merit is a factor of 3 greater than the original lead probe, but the overall weight is the same, or (2) a comparable case in which the performance is the same for a considerable decrease in lead (approximately 68% less lead). The former is advantageous in experiments in which one is attempting to measure marginal neutron yields. The latter is desirable in situations in which one is satisfied with the same sensitivity as the original lead probe, but does not want the added weight: 8.84 kg vs 18.14 kg (19.49 lbs vs 40 lbs). This latter case was discovered during the course of this work. It was analyzed with 11 layers of lead at 0.2 cm (0.0787 in) thick, and 10 layers of scintillator 1.27 cm (½ in) thick, with a face that was 15.24 cm (6 in) square. (Essentially, it has just a few more layers of lead and scintillator than the prototype that Bechtel/Nevada built, which was analyzed above.) This produced a Figure of Merit which approximated that of the original lead probe. MCNP code results of this "comparable case" are listed below in Table XVIII and compared with the original lead probe as well as the optimized layer cake design for DD neutrons.

Table XVIII.

Comparison between Original Lead Probe, "Comparable Case" and Optimized Case for DD neutrons

	F4 Tally (reactions/cm^3)	**F8 Tally (Counts)**	**Mass of Lead**	**Mass of Plastic**	**Total Mass**	**Figure of Merit (reactns x cnts)**
Original Lead Probe	5.1145E-10 (1.0)	0.053917 (1.0)	18.14 kg (40 lbs)	1.66 kg (3.66 lbs)	19.80 kg (43.66 lbs)	4.4112E-08 (**1.0**)
Comparable Case: 0.2 cm Lead, 1.27 cm Scintillator, 15.24 cm (6 in) Square	3.4507E-10 (0.675)	0.246082 (4.56)	5.80 kg (12.78 lbs)	3.04 kg (6.71 lbs)	8.84 kg (19.49 lbs)	4.3432E-08 (**0.985**)
Optimized Case: 0.2 cm Lead, 1.1 cm Scintillator	4.8742E-10 (0.953)	0.239599 (4.44)	12.83 kg (28.28 lbs)	6.42 kg (14.15 lbs)	19.25 kg (42.43 lbs)	13.2127E-08 (**3.0**)

The code used in this analysis was verified to simulate the actual performance of the lead probe (Figs. 5 & 6). The prototype layer cake that was built by Bechtel/Nevada was compared, both with experimental data and modeled data with the original lead probe as well (Table XVI). Then perhaps the comparable case listed above could be considered by those who wish to have the same performance as the original lead probe, but with a 51% reduction in weight.

It also should be noted that, due to the modular design of the layer cake geometry, that the optimized case studied here is only one such solution. The discoveries made during the course of this work, that "thinner is better" could lead to further optimum designs. This could be especially true in looking at even thinner layers of lead in a layer cake design (1mm or less). Of course, those designs would also be constrained by the same parameters as those in this work, namely, overall size, mass of lead and total weight.

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Appendices

Appendix A

MCNP Code Listing of Original Lead Probe

Part 1: F4 Neutron Tally

```
1mcnp     version 4c    ld=01/20/00                      06/04/02 11:11:49
 *************************************************************************
probid =   06/04/02 11:11:49
 inp=xspsna1 outp=xspsna1o

          Pb-207m photons into scintillator
          c          **** MCNP INPUT DECK FOR ORIGINAL LEAD PROBE ****
          c              ****** XSPSNA1 -- POINT SOURCE ****
          c                      ****** 5 MIN RUN ******
          c          **** THIS IS ORIGINAL MODEL OF LEAD PROBE ****
          c                *****  WITH ALUMINUM INSERT ****
          c   **** NOTE: USING SHUNK, WAGNER & HEMMENDINGER CROSS SECTIONS (1962)
          c              THAT SPENCER & JACOBS USED (1965) ****
          c     Looking at a monoenergetic (2.5 MeV) neutron source
          c     striking the lead
          1     0 1 -3 -10
          2     1 -2.7 1 -2 10 -11
          3     2 -11.34 2 -3 10 -11
          4     2 -11.34 1 -3 11 -12
          5     2 -11.34 1 -3 12 -13
          6     2 -11.34 1 -3 13 -15
          7     2 -11.34 3 -4 14 -15
          8     0 3 -4 13 -14
          9     3 -1.032 3 -4 12 -13
          10    3 -1.032 3 -4 11 -12
          11    3 -1.032 3 -4 -11
          12    2 -11.34 4 -5 14 -15
          13    0 4 -5 13 -14
          14    3 -1.032 4 -5 12 -13
          15    3 -1.032 4 -5 11 -12
          16    3 -1.032 4 -5 -11
          17    2 -11.34 5 -6 14 -15
          18    0 5 -6 13 -14
          19    3 -1.032 5 -6 12 -13
          20    3 -1.032 5 -6 11 -12
          21    3 -1.032 5 -6 -11
          22    2 -11.34 6 -7 14 -15
          23    0 6 -7 13 -14
          24    3 -1.032 6 -7 12 -13
          25    3 -1.032 6 -7 11 -12
          26    3 -1.032 6 -7 -11
          27    2 -11.34 7 -8 14 -15
          28    0 7 -8 13 -14
          29    3 -1.032 7 -8 12 -13
          30    3 -1.032 7 -8 11 -12
          31    3 -1.032 7 -8 -11
          32    2 -11.34 8 -9 14 -15
          33    0 8 -9 13 -14
          34    3 -1.032 8 -9 12 -13
          35    3 -1.032 8 -9 11 -12
          36    3 -1.032 8 -9 -11
          37    0 16 -1 -15    $ Cell between point source and face
          38    0 -16:15:9     $ Universe outside detector -- kill zone

          1     py 0
          2     py 1.27
          3     py 1.905
          4     py 4.022
          5     py 6.139
          6     py 8.256
```

```
7      py 10.373
8      py 12.49
9      py 14.607
10     cy 0.3175
11     cy 1.27
12     cy 3.81
13     cy 6.35
14     cy 6.695
15     cy 8.6
16     py -300.1   $ Plane near point source

c      **** Point Source of 2.5 MeV neutrons ****
c      **** 3 meters from face of detector ****
mode  n
sdef  par=1 erg=2.5 pos=0 -300 0
c     Aluminum G-11
m1    13027 1
c     Lead G-23
m2    82000.50c 1   $ <==== NOTE: USING NEUTRON LIBRARY VALUE
c     Plastic
m3    1001 1.1 6000 1
imp:n 1 36r 0
cut:n 10000 0
c     Total F4 Tally
f4:n  3 4 5 6 7 12 17 22 27 32 t
e4    1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em4   0 0.0001 3.448 6.055 9.531 13.008 16.484
      19.9605 23.4369 26.9133
c     **** Front Face Tally (Except Cell 3) ****
f14:n 4 5 6 t
e14   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em14  0 0.0001 3.448 6.055 9.531 13.008 16.484
      19.9605 23.4369 26.9133
ctme 5
```

Effective Cross Sections input into the code as multipliers to the F4 tally – in units of millibarns (Note: they will be converted to cm² later)

```
neutron  activity in each cell
print table 126

                 tracks     population   collisions   collisions     number        flux
average       average
        cell    entering                              * weight     weighted     weighted
track weight   track mfp
                                                    (per history)    energy       energy
(relative)      (cm)

     1     1           3            3            0    0.0000E+00   4.6472E-03
2.3516E+00   9.8729E-01   0.0000E+00
     2     2          78           68           16    1.4947E-06   1.1147E-02
1.9778E+00   9.9599E-01   5.6032E+00
     3     3          71           62            8    7.4730E-07   7.3717E-03
1.6509E+00   9.9103E-01   4.2130E+00
     4     4         591          513          309    2.8461E-05   8.1071E-03
2.0167E+00   9.9341E-01   4.1704E+00
     5     5        1109          984          607    5.6431E-05   1.4260E-02
2.1214E+00   9.9631E-01   4.2533E+00
     6     6        1320         1209          634    5.9049E-05   2.2163E-02
2.2488E+00   9.9815E-01   4.2051E+00
     7     7        1049          932          486    4.5144E-05   1.3678E-02
2.1192E+00   9.9767E-01   4.2397E+00
     8     8         448          392            0    0.0000E+00   8.8022E-03
1.9805E+00   9.9577E-01   0.0000E+00
     9     9        1068          869         1206    1.0854E-04   3.0610E-03
1.6342E+00   9.8974E-01   3.5134E+00
    10    10         658          478          845    7.5151E-05   1.8237E-03
1.4733E+00   9.8214E-01   3.2587E+00
    11    11         126          106          138    1.2242E-05   1.3099E-03
1.3311E+00   9.7747E-01   3.0451E+00
    12    12         922          824          477    4.4043E-05   5.6294E-03
1.8751E+00   9.9381E-01   4.2402E+00
    13    13         489          412            0    0.0000E+00   4.4482E-03
1.8047E+00   9.9113E-01   0.0000E+00
```

```
    14    14         990          756         1404    1.2559E-04   1.5403E-03
1.3278E+00   9.8336E-01   3.0325E+00
    15    15         643          459         1050    9.1521E-05   1.0671E-03
1.1381E+00   9.7320E-01   2.7379E+00
    16    16         127          101          147    1.2798E-05   1.0908E-03
1.0865E+00   9.7475E-01   2.6471E+00
    17    17         680          615          314    2.8939E-05   5.1567E-03
1.7632E+00   9.9286E-01   4.2217E+00
    18    18         384          338            0    0.0000E+00   4.7925E-03
1.8890E+00   9.9303E-01   0.0000E+00
    19    19         823          621         1201    1.0648E-04   1.3030E-03
1.2036E+00   9.8109E-01   2.8368E+00
    20    20         527          375         1100    9.5934E-05   6.4436E-04   9.5028E-
01   9.6810E-01   2.4053E+00
    21    21          87           71          106    9.3406E-06   1.2756E-03
1.0914E+00   9.7083E-01   2.6846E+00
    22    22         548          489          256    2.3631E-05   3.8949E-03
1.6385E+00   9.9118E-01   4.2468E+00
    23    23         350          301            0    0.0000E+00   3.7364E-03
1.7812E+00   9.8872E-01   0.0000E+00
    24    24         610          481          971    8.6269E-05   1.1133E-03
1.1604E+00   9.7911E-01   2.7617E+00
    25    25         371          266          639    5.5589E-05   8.6176E-04
1.0068E+00   9.7111E-01   2.5243E+00
    26    26          70           62          112    9.6740E-06   8.0344E-04   9.2089E-
01   9.5913E-01   2.4394E+00
    27    27         393          352          187    1.7144E-05   3.3804E-03
1.5451E+00   9.8752E-01   4.2649E+00
    28    28         243          208            0    0.0000E+00   4.6232E-03
1.8786E+00   9.8846E-01   0.0000E+00
    29    29         425          342          711    6.2506E-05   1.0740E-03
1.1384E+00   9.7705E-01   2.7247E+00
    30    30         282          212          464    4.0191E-05   1.0150E-03
1.0196E+00   9.7414E-01   2.5622E+00
    31    31          57           48           61    5.0300E-06   1.1952E-03
1.0507E+00   9.6377E-01   2.6576E+00
    32    32         258          242          120    1.1023E-05   5.0877E-03
1.6292E+00   9.9213E-01   4.3163E+00
    33    33         179          160            0    0.0000E+00   8.0697E-03
1.9308E+00   9.9660E-01   0.0000E+00
    34    34         280          245          397    3.5681E-05   1.5742E-03
1.2660E+00   9.8599E-01   2.9428E+00
    35    35         181          150          310    2.7766E-05   1.1117E-03   9.2707E-
01   9.8446E-01   2.4356E+00
    36    36          38           32           63    5.3185E-06   8.2764E-04   8.0772E-
01   9.6288E-01   2.2428E+00
    37    37    10704063     10703567            0    0.0000E+00   2.4691E+00
2.4999E+00   1.0000E+00   0.0000E+00

     total      10720541     10717345        14339    1.2817E-03
tally   4        nps = 10703567
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       3            4            5            6            7
12          17
                         3.01649E+00  7.72222E+01  1.54444E+02  2.01311E+02  1.93783E+02
1.93783E+02  1.93783E+02
                   cell:      22           27           32          total
                         1.93783E+02  1.93783E+02  1.93783E+02  1.59869E+03

 cell  3
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   0.00000E+00 0.0000
    1.8000E+00   0.00000E+00 0.0000
    1.9000E+00   0.00000E+00 0.0000
    2.0000E+00   1.17384E-06 0.5920
```

Total Volume of Lead (cm^3)

Total Mass of Lead:

1,598.69 cm^3 x 11.34 grams/cm^3 = 18,129.14 grams
= 18.129 kg
= 40 lbs

```
   2.1000E+00   9.99652E-08 1.0000
   2.2000E+00   0.00000E+00 0.0000
   2.3000E+00   0.00000E+00 0.0000
   2.4000E+00   0.00000E+00 0.0000
   2.5000E+00   2.30247E-05 0.1697
     total      2.42985E-05 0.1653

cell  4
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   2.36615E-12 0.3189
   1.8000E+00   2.53300E-08 0.5219
   1.9000E+00   2.35333E-07 0.2882
   2.0000E+00   2.28046E-07 0.3966
   2.1000E+00   1.03298E-07 0.5817
   2.2000E+00   7.38223E-09 1.0000
   2.3000E+00   6.71325E-09 1.0000
   2.4000E+00   3.31689E-07 0.6550
   2.5000E+00   2.82430E-05 0.0528
     total      2.91808E-05 0.0532

cell  5
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   9.08009E-13 0.3547
   1.8000E+00   3.74023E-08 0.4143
   1.9000E+00   2.85379E-07 0.2107
   2.0000E+00   1.94187E-07 0.2692
   2.1000E+00   1.61271E-07 0.5731
   2.2000E+00   1.13684E-08 1.0000
   2.3000E+00   0.00000E+00 0.0000
   2.4000E+00   1.73985E-07 0.4007
   2.5000E+00   2.86738E-05 0.0374
     total      2.95374E-05 0.0371

cell  6
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   8.49739E-13 0.4199
   1.8000E+00   1.08713E-08 0.5199
   1.9000E+00   1.22854E-07 0.2274
   2.0000E+00   1.37577E-07 0.2991
   2.1000E+00   3.57402E-08 0.6451
   2.2000E+00   5.64764E-08 0.5343
   2.3000E+00   0.00000E+00 0.0000
   2.4000E+00   1.42200E-07 0.4476
   2.5000E+00   2.77079E-05 0.0328
     total      2.82136E-05 0.0327

cell  7
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   7.99460E-13 0.3715
   1.8000E+00   2.32109E-08 0.4373
   1.9000E+00   8.36041E-08 0.2926
   2.0000E+00   2.13529E-07 0.2799
   2.1000E+00   4.13070E-08 0.4823
   2.2000E+00   9.21588E-08 0.4316
   2.3000E+00   6.59892E-08 0.5549
   2.4000E+00   2.16072E-07 0.3308
   2.5000E+00   2.07155E-05 0.0405
     total      2.14513E-05 0.0398

cell  12
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   7.38961E-13 0.3793
   1.8000E+00   2.23664E-08 0.5174
   1.9000E+00   9.27075E-08 0.2669
   2.0000E+00   1.08517E-07 0.2871
   2.1000E+00   7.94962E-08 0.4182
```

```
   2.2000E+00   5.34230E-08 0.5034
   2.3000E+00   1.41854E-07 0.3783
   2.4000E+00   2.90607E-07 0.2787
   2.5000E+00   1.48222E-05 0.0480
     total      1.56112E-05 0.0466

cell  17
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   8.14344E-13 0.3648
   1.8000E+00   6.77000E-09 0.5950
   1.9000E+00   7.58634E-08 0.3243
   2.0000E+00   8.35715E-08 0.3533
   2.1000E+00   3.00552E-08 0.6693
   2.2000E+00   1.08919E-07 0.4483
   2.3000E+00   1.78733E-07 0.4174
   2.4000E+00   2.63895E-07 0.2878
   2.5000E+00   9.61198E-06 0.0597
     total      1.03598E-05 0.0572

cell  22
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   8.45323E-13 0.4138
   1.8000E+00   2.29847E-08 0.3858
   1.9000E+00   5.31890E-08 0.4282
   2.0000E+00   5.36392E-08 0.4329
   2.1000E+00   1.22919E-08 1.0000
   2.2000E+00   3.49295E-08 0.7267
   2.3000E+00   1.24378E-07 0.4519
   2.4000E+00   2.90133E-07 0.3149
   2.5000E+00   7.01597E-06 0.0714
     total      7.60751E-06 0.0682

cell  27
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   6.44374E-13 0.4581
   1.8000E+00   1.51810E-08 0.4290
   1.9000E+00   3.05121E-08 0.3983
   2.0000E+00   9.31244E-08 0.3476
   2.1000E+00   5.00328E-10 1.0000
   2.2000E+00   4.74862E-08 0.6917
   2.3000E+00   7.17633E-08 0.4942
   2.4000E+00   1.88504E-07 0.3719
   2.5000E+00   4.37446E-06 0.0854
     total      4.82153E-06 0.0815

cell  32
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   3.57477E-13 0.5332
   1.8000E+00   2.42960E-08 0.4613
   1.9000E+00   8.38207E-09 0.7593
   2.0000E+00   4.82805E-08 0.4406
   2.1000E+00   3.04844E-08 0.6399
   2.2000E+00   3.90029E-08 0.5780
   2.3000E+00   8.05038E-08 0.5177
   2.4000E+00   7.19966E-08 0.4916
   2.5000E+00   3.00561E-06 0.1023
     total      3.30856E-06 0.0960

cell union total
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   8.18103E-13 0.1936
   1.8000E+00   2.01222E-08 0.2102
   1.9000E+00   9.61358E-08 0.1345
   2.0000E+00   1.22122E-07 0.1505
   2.1000E+00   4.87904E-08 0.3002
   2.2000E+00   5.41330E-08 0.2692
```

Total F4 Tally, in units of millibarns/cm^2 (Fluence times cross section)

```
    2.3000E+00   8.07155E-08 0.2285
    2.4000E+00   2.10884E-07 0.1594
    2.5000E+00   1.48845E-05 0.0284
      total      1.55174E-05 0.0279
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   4 with nps
=  10703567    print table 160


tally  14        nps = 10703567
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       4            5            6          total
                         7.72222E+01  1.54444E+02  2.01311E+02  4.32978E+02

 cell  4
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   2.36615E-12 0.3189
    1.8000E+00   2.53300E-08 0.5219
    1.9000E+00   2.35333E-07 0.2882
    2.0000E+00   2.28046E-07 0.3966
    2.1000E+00   1.03298E-07 0.5817
    2.2000E+00   7.38223E-09 1.0000
    2.3000E+00   6.71325E-09 1.0000
    2.4000E+00   3.31689E-07 0.6550
    2.5000E+00   2.82430E-05 0.0528
      total      2.91808E-05 0.0532

 cell  5
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   9.08009E-13 0.3547
    1.8000E+00   3.74023E-08 0.4143
    1.9000E+00   2.85379E-07 0.2107
    2.0000E+00   1.94187E-07 0.2692
    2.1000E+00   1.61271E-07 0.5731
    2.2000E+00   1.13684E-08 1.0000
    2.3000E+00   0.00000E+00 0.0000
    2.4000E+00   1.73985E-07 0.4007
    2.5000E+00   2.86738E-05 0.0374
      total      2.95374E-05 0.0371

 cell  6
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   8.49739E-13 0.4199
    1.8000E+00   1.08713E-08 0.5199
    1.9000E+00   1.22854E-07 0.2274
    2.0000E+00   1.37577E-07 0.2991
    2.1000E+00   3.57402E-08 0.6451
    2.2000E+00   5.64764E-08 0.5343
    2.3000E+00   0.00000E+00 0.0000
    2.4000E+00   1.42200E-07 0.4476
    2.5000E+00   2.77079E-05 0.0328
      total      2.82136E-05 0.0327

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.14098E-12 0.2510
    1.8000E+00   2.29137E-08 0.3091
    1.9000E+00   2.00888E-07 0.1480
    2.0000E+00   1.73905E-07 0.2055
    2.1000E+00   9.25664E-08 0.5220
    2.2000E+00   3.16302E-08 0.4889
    2.3000E+00   1.19732E-09 1.0000
    2.4000E+00   1.87333E-07 0.3453
```

Converting F4 tally from millbarns/cm^2 to reactions/cm^3:

(1.55174E-05 millibarns/cm^2) x (10^{-27} cm^2/millibarns) x (3.296 x 10^{22} atoms/cm^3, atomic density of lead)

➔ 5.1145E-10 n reactions/cm^3

```
    2.5000E+00   2.81479E-05 0.0248
      total      2.88583E-05 0.0249
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  14 with nps
=  10703567    print table 160
*****************************************************************************************
******************************
 dump no.    2 on file runtpe       nps =  10703567     coll =          14339     ctm =
5.00     nrn =       27465346


         5 warning messages so far.


 run terminated when it had used    5 minutes of computer time.

 computer time =    5.02 minutes

 mcnp     version 4c    01/20/00                      06/04/02 11:16:50
probid =   06/04/02 11:11:49
```

MCNP Code Listing of Original Lead Probe

Part 2: F8 Counts Tally and F6 Energy Deposited Tally

```
1mcnp     version 4c    ld=01/20/00                      06/04/02 15:20:02
 *************************************************************************
probid =   06/04/02 15:20:02
 inp=xspsga1 outp=xspsga1o

    1-       Pb-207m photons into scintillator
    2-       c        ***** New Cross Sections, Point Source 1 for Gammas *****
    3-       c      **** XSPSGA1 -- 5 MIN RUN TO COMPARE WITH XSPSG1 (1000 MIN RUN) ****
    4-       c      ***** THIS IS THE ORIGINAL MODEL OF THE LEAD PROBE ****
    5-       c               **** WITH ALUMINUM INSERT ****
    6-       c      **** This is a Redo because I want to run it again with
    7-       c      **** an F4 Tally for Cells 4, 5 & 6 to use in normalizing
    8-       c      **** all the lead; also used neutron library value ****
    9-       c      **** ALSO DOING IT WITH USING SHUNK, WAGNER & HEMMENDINGER
   10-       c           CROSS SECTIONS FOR PB-207 THAT SPENCER & JACOBS USED (1965) ****
   11-       c      Looking at Energy Deposited (F6) and Interactions (F8)
   12-       c      in Plastic Scintillator
   13-       1      0 1 -3 -10
   14-       2      1 -2.7 1 -2 10 -11
   15-       3      2 -11.34 2 -3 10 -11
   16-       4      2 -11.34 1 -3 11 -12
   17-       5      2 -11.34 1 -3 12 -13
   18-       6      2 -11.34 1 -3 13 -15
   19-       7      2 -11.34 3 -4 14 -15
   20-       8      0 3 -4 13 -14
   21-       9      3 -1.032 3 -4 12 -13
   22-       10     3 -1.032 3 -4 11 -12
   23-       11     3 -1.032 3 -4 -11
   24-       12     2 -11.34 4 -5 14 -15
   25-       13     0 4 -5 13 -14
   26-       14     3 -1.032 4 -5 12 -13
   27-       15     3 -1.032 4 -5 11 -12
   28-       16     3 -1.032 4 -5 -11
   29-       17     2 -11.34 5 -6 14 -15
   30-       18     0 5 -6 13 -14
   31-       19     3 -1.032 5 -6 12 -13
   32-       20     3 -1.032 5 -6 11 -12
   33-       21     3 -1.032 5 -6 -11
   34-       22     2 -11.34 6 -7 14 -15
   35-       23     0 6 -7 13 -14
   36-       24     3 -1.032 6 -7 12 -13
```

```
25    3 -1.032 6 -7 11 -12
26    3 -1.032 6 -7 -11
27    2 -11.34 7 -8 14 -15
28    0 7 -8 13 -14
29    3 -1.032 7 -8 12 -13
30    3 -1.032 7 -8 11 -12
31    3 -1.032 7 -8 -11
32    2 -11.34 8 -9 14 -15
33    0 8 -9 13 -14
34    3 -1.032 8 -9 12 -13
35    3 -1.032 8 -9 11 -12
36    3 -1.032 8 -9 -11
37    0 -1:15:9      $ Universe outside detector -- kill zone

1     py 0
2     py 1.27
3     py 1.905
4     py 4.022
5     py 6.139
6     py 8.256
7     py 10.373
8     py 12.49
9     py 14.607
10    cy 0.3175
11    cy 1.27
12    cy 3.81
13    cy 6.35
14    cy 6.695
15    cy 8.6

c     **** Volumetric source in the lead sheath ****
c     Based on data from monoenergetic (2.5 MeV) neutron
c     source normal to the face, activating the lead
mode  p
sdef  par=2 erg=d1 axs=0 1 0
      rad=d2 pos=frad=d11 ext=frad=d12
si1   L 0.5697 1.0636 $ gamma energies
sp1   d 0.525 0.475 $ weighted branching ratios
c
c     3 = cell 3; 4 = cells 4, 5 & 6; 5 = cell 7;
c     6 = cell 12; 7 = cell 17; 8 = cell 22;
c     9 = cell 27; 10 = cell 32
c
si2   s 3 4 5 6 7 8 9 10
c     %tage of volume of 3, 4, 5 - 10 times a
c     normalized factor based on cells 4, 5, 6:
sp2   0.001589 0.2708 0.090092 0.065564 0.043509 0.031950 0.020250 0.013895
si3   0.3175 1.27 $ dimensions of 3
sp3   -21 1
si4   1.27 8.6    $ dimensions of 4 (Front Face)
sp4   -21 1
si5   6.695 8.6   $ dimensions of 5; cell 7
sp5   -21 1
si6   6.695 8.6   $ dimensions of 6; cell 12
sp6   -21 1
si7   6.695 8.6   $ dimensions of 7; cell 17
sp7   -21 1
si8   6.695 8.6   $ dimensions of 8; cell 22
sp8   -21 1
si9   6.695 8.6   $ dimensions of 9; cell 27
sp9   -21 1
si10  6.695 8.6   $ dimensions of 10; cell 32
sp10  -21 1
ds11  L 0 1.27 0 0 0 0 0 1.905 0 0 4.022 0 0 6.139 0
      0 8.256 0 0 10.373 0 0 12.49 0
ds12  s 13 14 15 16 17 18 19 20
si13  0 0.635 $ length of 3
si14  0 1.905 $ length of 4
si15  0 2.117 $ length of 5; cell 7
si16  0 2.117 $ length of 6; cell 12
si17  0 2.117 $ length of 7; cell 17
```

```
       si18  0 2.117 $ length of 8; cell 22
       si19  0 2.117 $ length of 9; cell 27
       si20  0 2.117 $ length of 10; cell 32
       c
       c     Aluminum G-11
       m1    13027 1
       c     Lead G-23
       m2    82000 1
       c     Plastic
       m3    1001 1.1 6000 1
       imp:p 1 35r 0
       cut:n 10000 0
       f6:p  9 10 11 14 15 16 19 20 21 24 25 26 29 30
             31 34 35 36 t
       f8:p   9 10 11 14 15 16 19 20 21 24 25 26 29 30
              31 34 35 36 t
       e8     0 1e-10 1.1
       ctme 3

tally   6        nps =  1022359
           tally type 6    track length estimate of heating.            units   mev/gram
           tally for  photons

           masses
                   cell:       9           10           11           14           15
16           19
                         1.77124E+02  8.85621E+01  1.10703E+01  1.77124E+02  8.85621E+01
1.10703E+01  1.77124E+02
                   cell:      20           21           24           25           26
29           30
                         8.85621E+01  1.10703E+01  1.77124E+02  8.85621E+01  1.10703E+01
1.77124E+02  8.85621E+01
                   cell:      31           34           35           36          total
                         1.10703E+01  1.77124E+02  8.85621E+01  1.10703E+01  1.66054E+03

 cell  9
               2.24962E-05 0.0046

 cell  10
               2.11260E-05 0.0068

 cell  11
               1.94816E-05 0.0154

 cell  14
               1.72079E-05 0.0052

 cell  15
               1.61570E-05 0.0075

 cell  16
               1.57686E-05 0.0167

 cell  19
               1.29571E-05 0.0060

 cell  20
               1.24168E-05 0.0084

 cell  21
               1.22486E-05 0.0189

 cell  24
               9.64699E-06 0.0069

 cell  25
               9.37505E-06 0.0096

 cell  26
               8.87250E-06 0.0222
```

Total Mass of Scintillator (grams)

Total Energy Deposited:
(1.21191E-05 MeV/gram) x (1,660.54 grams) = 0.020124 MeV

Efficiency = 0.020124 MeV/0.8 MeV = 0.0252 → 2.52%
(Note: 0.8 MeV is weighted average of both gammas)

```
 cell  29
                7.03477E-06 0.0079

 cell  30
                6.81473E-06 0.0110

 cell  31
                6.48803E-06 0.0257

 cell  34
                4.75525E-06 0.0094

 cell  35
                4.71852E-06 0.0129

 cell  36
                4.56518E-06 0.0305

 cell union total
                1.21191E-05 0.0034
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   6 with nps
=   1022359    print table 160


tally   8        nps =  1022359
           tally type 8    pulse height distribution.                  units   number
           tally for  photons

 cell  9
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   5.72509E-02 0.0040
    1.1000E+00   1.36840E-02 0.0084
      total      7.09350E-02 0.0036

 cell  10
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.65484E-02 0.0060
    1.1000E+00   6.80974E-03 0.0119
      total      3.33581E-02 0.0053

 cell  11
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   5.41493E-03 0.0134
    1.1000E+00   9.43895E-04 0.0322
      total      6.35882E-03 0.0124

 cell  14
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   4.54097E-02 0.0045
    1.1000E+00   1.17082E-02 0.0091
      total      5.71179E-02 0.0040

 cell  15
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.17614E-02 0.0066
    1.1000E+00   5.85900E-03 0.0129
      total      2.76204E-02 0.0059

 cell  16
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   4.78110E-03 0.0143
    1.1000E+00   8.04023E-04 0.0349
      total      5.58512E-03 0.0132

 cell  19
```

Total MeV/gram

```
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   3.58446E-02 0.0051
    1.1000E+00   9.06727E-03 0.0103
      total      4.49118E-02 0.0046

 cell  20
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.78000E-02 0.0073
    1.1000E+00   4.68720E-03 0.0144
      total      2.24872E-02 0.0065

 cell  21
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   3.84699E-03 0.0159
    1.1000E+00   7.21860E-04 0.0368
      total      4.56885E-03 0.0146

 cell  24
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.76899E-02 0.0059
    1.1000E+00   7.07090E-03 0.0117
      total      3.47608E-02 0.0052

 cell  25
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.39520E-02 0.0083
    1.1000E+00   3.74526E-03 0.0161
      total      1.76973E-02 0.0074

 cell  26
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.89918E-03 0.0183
    1.1000E+00   5.23300E-04 0.0432
      total      3.42248E-03 0.0169

 cell  29
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.09545E-02 0.0068
    1.1000E+00   5.09117E-03 0.0138
      total      2.60456E-02 0.0060

 cell  30
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.06822E-02 0.0095
    1.1000E+00   2.79256E-03 0.0187
      total      1.34747E-02 0.0085

 cell  31
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.12450E-03 0.0214
    1.1000E+00   3.80493E-04 0.0507
      total      2.50499E-03 0.0197

 cell  34
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.54124E-02 0.0079
    1.1000E+00   3.35205E-03 0.0171
      total      1.87644E-02 0.0072

 cell  35
      energy
```

```
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   7.96785E-03 0.0110
    1.1000E+00   1.90638E-03 0.0226
      total      9.87422E-03 0.0099

 cell  36
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.50534E-03 0.0255
    1.1000E+00   2.60183E-04 0.0613
      total      1.76552E-03 0.0235

 cell union total
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   6.02098E-02 0.0039
    1.1000E+00   5.39175E-02 0.0041
      total      1.14127E-01 0.0028
```

F8 Tally = 0.114127 – 0.0602098
= 0.053917 ←Counts in Scintillator

```
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   8 with nps
=   1022359    print table 160


dump no.    2 on file runtpe       nps =   1022359     coll =        3776912     ctm =
3.00     nrn =       45365749


         3 warning messages so far.


 run terminated when it had used    3 minutes of computer time.

 computer time =    3.07 minutes

 mcnp     version 4c    01/20/00                      06/04/02 15:23:06
probid =   06/04/02 15:20:02
```

Figure of Merit Calculation for Original Lead Probe

FOM = F4 Tally (reactions/cm^3) x F8 Tally (Counts) x Volume of Lead (cm^3)

FOM = (5.1145E-10 reactions/cm^3) x (0.053917 counts) x (1,598.69 cm^3)

= 4.41E-08 Reactions x Counts

See Table IV, p. 26.

MCNP Code Listing of Optimized Layer Cake

Part 3: F4 Neutron Tally

```
1mcnp     version 4c    ld=01/20/00                      12/09/02 15:14:24
 *************************************************************************
probid =   12/09/02 15:14:24
 inp=xn9qa2a outp=xn9qa2ao

             Pb-207m photons into scintillator
             c              ***** XN9QA2A -- POINT SOURCE -- 5 MIN *****
             c            ***** 15 CM OUTER RADIUS; 28.28 LBS LEAD *****
             c        ***** 8 LAYERS LEAD @ 0.2 CM; 8 PLASTIC @ 1.1 CM *****
             c                    **** NO SHEATH ***
             c      **** USING SPENCER & JACOBS CROSS SECTIONS FOR PB-207
             c      Looking at a monoenergetic point source of DD neutrons
             c      striking the lead
             1      1 -11.34 1 -2 -18
             2      1 -11.34 1 -2 18 -19
             3      1 -11.34 3 -4 -18
             4      1 -11.34 3 -4 18 -19
             5      1 -11.34 5 -6 -18
             6      1 -11.34 5 -6 18 -19
             7      1 -11.34 7 -8 -18
             8      1 -11.34 7 -8 18 -19
             9      1 -11.34 9 -10 -18
             10     1 -11.34 9 -10 18 -19
             11     1 -11.34 11 -12 -18
             12     1 -11.34 11 -12 18 -19
             13     1 -11.34 13 -14 -18
             14     1 -11.34 13 -14 18 -19
             15     1 -11.34 15 -16 -18
             16     1 -11.34 15 -16 18 -19
             17     2 -1.032 2 -3 -18
             18     2 -1.032 2 -3 18 -19
             19     2 -1.032 4 -5 -18
             20     2 -1.032 4 -5 18 -19
             21     2 -1.032 6 -7 -18
             22     2 -1.032 6 -7 18 -19
             23     2 -1.032 8 -9 -18
             24     2 -1.032 8 -9 18 -19
             25     2 -1.032 10 -11 -18
             26     2 -1.032 10 -11 18 -19
             27     2 -1.032 12 -13 -18
             28     2 -1.032 12 -13 18 -19
             29     2 -1.032 14 -15 -18
             30     2 -1.032 14 -15 18 -19
             31     2 -1.032 16 -17 -18
             32     2 -1.032 16 -17 18 -19
             33     0 20 -1 -19    $ Cell between neutron source and face
             34     0 -20:19:17    $ Universe outside detector -- kill zone

             c      **** 0.2 cm Lead; 1.1 cm Plastic ****
             1      py 0.0
             2      py 0.2
             3      py 1.3
             4      py 1.5
             5      py 2.6
             6      py 2.8
             7      py 3.9
             8      py 4.1
             9      py 5.2
             10     py 5.4
             11     py 6.5
             12     py 6.7
             13     py 7.8
             14     py 8.0
             15     py 9.1
```

```
16    py 9.3
17    py 10.4
18    cy 7.5
19    cy 15.0
20    py -300.1    $ Plane near point source

c     **** POINT SOURCE of 2.5 MeV neutrons ****
c     **** 3 meters from face of detector ****
mode  n
sdef  par=1 erg=2.5 pos=0 -300 0
c     Lead G-23
m1    82000.50c 1   $ <====== NOTE: USING NEUTRON LIBRARY VALUE
c     Plastic
m2    1001 1.1 6000 1
imp:n 1 32r 0
cut:n 10000 0
c     f4 tally
f4:n  1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 t
e4    1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em4   0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c
c     f4 tally -- individual sections
c     *** front face ***
f14:n 1 2 t
e14   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em14  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "A" ***
f24:n 3 4 t
e24   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em24  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "B" ***
f34:n 5 6 t
e34   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em34  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "C" ***
f44:n 7 8 t
e44   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em44  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "D" ***
f54:n 9 10 t
e54   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em54  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "E" ***
f64:n 11 12 t
e64   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em64  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "F" ***
f74:n 13 14 t
e74   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em74  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
c     *** Layer "G" ***
f84:n 15 16 t
e84   1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
em84  0 0.0001 3.448 6.055 9.531 13.008 16.4844
      19.9605 23.4369 26.9133
ctme 5
```

```
neutron  activity in each cell
print table 126

                 tracks     population   collisions   collisions     number        flux
average      average
```

	cell	entering			* weight (per history)	weighted energy	weighted energy	track weight (relative)	track mfp (cm)
1	1	2239	1907	140	1.2901E-05	4.0754E-03	1.8945E+00	9.9082E-01	3.9920E+00
2	2	6202	5223	386	3.5571E-05	8.3654E-03	2.0370E+00	9.9553E-01	4.0773E+00
3	3	2469	1810	183	1.6561E-05	1.3067E-03	1.3389E+00	9.8184E-01	4.0126E+00
4	4	6298	4847	472	4.2931E-05	2.5226E-03	1.5706E+00	9.8838E-01	4.0466E+00
5	5	2354	1672	200	1.8175E-05	1.0955E-03	1.1930E+00	9.7899E-01	3.8890E+00
6	6	6111	4424	466	4.2330E-05	1.6376E-03	1.3748E+00	9.8478E-01	4.0509E+00
7	7	2354	1552	255	2.2803E-05	7.1693E-04	1.0003E+00	9.7236E-01	3.9280E+00
8	8	5698	3968	480	4.3328E-05	1.2262E-03	1.2085E+00	9.7919E-01	4.0063E+00
9	9	2208	1418	207	1.8528E-05	7.3541E-04	9.1116E-01	9.7444E-01	3.9001E+00
10	10	5014	3488	451	4.0693E-05	1.0123E-03	1.1173E+00	9.7821E-01	3.9978E+00
11	11	1904	1222	165	1.4567E-05	5.3984E-04	8.8125E-01	9.6177E-01	3.8563E+00
12	12	4359	3050	397	3.5428E-05	1.0093E-03	1.0798E+00	9.7604E-01	3.9904E+00
13	13	1555	1052	157	1.4007E-05	4.8885E-04	8.3766E-01	9.6197E-01	3.8370E+00
14	14	3597	2617	341	3.0777E-05	8.9386E-04	1.0026E+00	9.7775E-01	3.9505E+00
15	15	1201	904	113	1.0094E-05	5.3261E-04	8.8158E-01	9.6810E-01	3.8752E+00
16	16	2705	2192	245	2.2172E-05	9.5063E-04	1.0506E+00	9.8041E-01	3.9626E+00
17	17	2485	1958	2057	1.8147E-04	1.8489E-03	1.5543E+00	9.8359E-01	3.3589E+00
18	18	6484	5236	4527	4.0569E-04	3.4246E-03	1.7231E+00	9.9036E-01	3.6291E+00
19	19	2577	1851	2795	2.4446E-04	1.1586E-03	1.2526E+00	9.7869E-01	2.8917E+00
20	20	6463	4853	5776	5.1236E-04	1.8546E-03	1.4431E+00	9.8571E-01	3.2018E+00
21	21	2526	1731	3291	2.8742E-04	7.7807E-04	1.0583E+00	9.7364E-01	2.5826E+00
22	22	6215	4423	6543	5.8044E-04	1.3581E-03	1.2522E+00	9.8228E-01	2.9062E+00
23	23	2483	1608	3495	3.0721E-04	6.9504E-04	9.3170E-01	9.7407E-01	2.3804E+00
24	24	5647	3970	6700	5.9145E-04	1.0398E-03	1.1228E+00	9.7946E-01	2.6996E+00
25	25	2240	1459	3384	2.9597E-04	6.4486E-04	8.7547E-01	9.6976E-01	2.2974E+00
26	26	4972	3488	6151	5.4022E-04	9.4888E-04	1.0688E+00	9.7686E-01	2.6157E+00
27	27	1896	1265	2956	2.5394E-04	4.7944E-04	8.0432E-01	9.6127E-01	2.1710E+00
28	28	4217	3061	5446	4.7930E-04	8.7512E-04	1.0133E+00	9.7622E-01	2.5307E+00
29	29	1496	1095	2373	2.0533E-04	5.1008E-04	8.0904E-01	9.6437E-01	2.1880E+00
30	30	3320	2596	4157	3.6436E-04	8.2472E-04	1.0153E+00	9.7546E-01	2.5297E+00
31	31	1029	920	1404	1.2195E-04	7.1083E-04	9.3406E-01	9.7244E-01	2.4097E+00
32	32	2360	2180	2627	2.3227E-04	1.1425E-03	1.1020E+00	9.8109E-01	2.6872E+00
33	33	10780161	10778451	0	0.0000E+00	2.1211E+00	2.4995E+00	1.0000E+00	0.0000E+00

```
     total      10892839     10861491        68340    6.0247E-03
tally   4        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       1            2            3            4            5
6            7
                         3.53429E+01  1.06029E+02  3.53429E+01  1.06029E+02  3.53429E+01
1.06029E+02  3.53429E+01
                   cell:       8            9           10           11           12
13           14
                         1.06029E+02  3.53429E+01  1.06029E+02  3.53429E+01  1.06029E+02
3.53429E+01  1.06029E+02
                   cell:      15           16          total
                         3.53429E+01  1.06029E+02  1.13097E+03

 cell  1
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   7.96758E-13 0.3107
    1.8000E+00   3.56337E-08 0.2628
    1.9000E+00   2.00625E-07 0.1627
    2.0000E+00   2.75395E-07 0.2159
    2.1000E+00   1.49410E-07 0.4990
    2.2000E+00   1.79824E-08 0.7073
    2.3000E+00   6.13742E-08 0.5129
    2.4000E+00   5.50582E-08 0.5017
    2.5000E+00   2.59639E-05 0.0327
      total      2.67594E-05 0.0324

 cell  2
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.02775E-12 0.4179
    1.8000E+00   4.11907E-08 0.1704
    1.9000E+00   1.74769E-07 0.0908
    2.0000E+00   3.58269E-07 0.1454
    2.1000E+00   1.79455E-07 0.2825
    2.2000E+00   6.06392E-08 0.6490
    2.3000E+00   2.92439E-08 0.4153
    2.4000E+00   4.98592E-08 0.4553
    2.5000E+00   2.53935E-05 0.0219
      total      2.62870E-05 0.0216

 cell  3
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.38838E-12 0.2477
    1.8000E+00   7.18772E-08 0.2800
    1.9000E+00   2.15433E-07 0.1402
    2.0000E+00   2.11576E-07 0.2088
    2.1000E+00   3.01385E-07 0.3773
    2.2000E+00   4.17086E-07 0.2941
    2.3000E+00   3.81299E-07 0.2444
    2.4000E+00   6.67059E-07 0.1995
    2.5000E+00   2.03280E-05 0.0297
      total      2.25937E-05 0.0295

 cell  4
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.21507E-12 0.1622
    1.8000E+00   7.13489E-08 0.1850
    1.9000E+00   2.32049E-07 0.0894
    2.0000E+00   2.93896E-07 0.1867
    2.1000E+00   2.70886E-07 0.2037
    2.2000E+00   2.32461E-07 0.2013
```

Total Volume of Lead (cm^3)

Total Mass of Lead:

1,130.97 cm^3 x 11.34 grams/cm^3 = 12,825.20 grams
= 12.83 kg
= 28.28 lbs

Percentage Volume per Layer:

Percentage Volume = Volume of lead layer/Total Volume
= 141.372 cm^3/1,130.97 cm^3
= 0.125

Note: All layers have equal volume of lead.

```
   2.3000E+00   4.31349E-07 0.1365
   2.4000E+00   4.95623E-07 0.2344
   2.5000E+00   2.00027E-05 0.0177
     total      2.20304E-05 0.0181

cell  5
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.20560E-12 0.2398
   1.8000E+00   8.85178E-08 0.2279
   1.9000E+00   1.96054E-07 0.1667
   2.0000E+00   2.05535E-07 0.2738
   2.1000E+00   2.45027E-07 0.3156
   2.2000E+00   3.39610E-07 0.4573
   2.3000E+00   7.32551E-07 0.2005
   2.4000E+00   8.80078E-07 0.2591
   2.5000E+00   1.64610E-05 0.0396
     total      1.91483E-05 0.0394

cell  6
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.35555E-12 0.1614
   1.8000E+00   5.88728E-08 0.1562
   1.9000E+00   2.28148E-07 0.1195
   2.0000E+00   2.82931E-07 0.1429
   2.1000E+00   2.54819E-07 0.1526
   2.2000E+00   4.24537E-07 0.2091
   2.3000E+00   5.38689E-07 0.1345
   2.4000E+00   5.80131E-07 0.1087
   2.5000E+00   1.60252E-05 0.0236
     total      1.83934E-05 0.0225

cell  7
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   2.09388E-12 0.2225
   1.8000E+00   6.70966E-08 0.2206
   1.9000E+00   1.84697E-07 0.1643
   2.0000E+00   2.05961E-07 0.2115
   2.1000E+00   3.86885E-07 0.2472
   2.2000E+00   3.40650E-07 0.2610
   2.3000E+00   6.41918E-07 0.1905
   2.4000E+00   6.24680E-07 0.1907
   2.5000E+00   1.32686E-05 0.0457
     total      1.57205E-05 0.0417

cell  8
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.86758E-12 0.1499
   1.8000E+00   7.24271E-08 0.1616
   1.9000E+00   1.82728E-07 0.1046
   2.0000E+00   2.47724E-07 0.1202
   2.1000E+00   2.07763E-07 0.1535
   2.2000E+00   3.33951E-07 0.2017
   2.3000E+00   5.50226E-07 0.1256
   2.4000E+00   6.05770E-07 0.1015
   2.5000E+00   1.27420E-05 0.0324
     total      1.49426E-05 0.0291

cell  9
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   3.24052E-12 0.2297
   1.8000E+00   7.54379E-08 0.2469
   1.9000E+00   2.08430E-07 0.2324
   2.0000E+00   2.08327E-07 0.2148
   2.1000E+00   3.03063E-07 0.2018
   2.2000E+00   2.11187E-07 0.3153
   2.3000E+00   7.27272E-07 0.1777
```

```
   2.4000E+00   6.17600E-07 0.1828
   2.5000E+00   1.01219E-05 0.0473
     total      1.24732E-05 0.0430

cell  10
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.44669E-12 0.1524
   1.8000E+00   6.07937E-08 0.1359
   1.9000E+00   1.82559E-07 0.1020
   2.0000E+00   2.03655E-07 0.1697
   2.1000E+00   2.23606E-07 0.1936
   2.2000E+00   3.39511E-07 0.1902
   2.3000E+00   4.66269E-07 0.1224
   2.4000E+00   5.78470E-07 0.1042
   2.5000E+00   9.80250E-06 0.0260
     total      1.18574E-05 0.0245

cell  11
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   2.66546E-12 0.2052
   1.8000E+00   5.84547E-08 0.2723
   1.9000E+00   1.43710E-07 0.1783
   2.0000E+00   2.71468E-07 0.2614
   2.1000E+00   2.98276E-07 0.2292
   2.2000E+00   3.81729E-07 0.2737
   2.3000E+00   6.24605E-07 0.1912
   2.4000E+00   7.20057E-07 0.1622
   2.5000E+00   8.06277E-06 0.0688
     total      1.05611E-05 0.0572

cell  12
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.31572E-12 0.1677
   1.8000E+00   6.63954E-08 0.1295
   1.9000E+00   1.52926E-07 0.1142
   2.0000E+00   2.59984E-07 0.2696
   2.1000E+00   1.70225E-07 0.1588
   2.2000E+00   3.59322E-07 0.2077
   2.3000E+00   3.65323E-07 0.1564
   2.4000E+00   5.69688E-07 0.1342
   2.5000E+00   8.02274E-06 0.0364
     total      9.96661E-06 0.0333

cell  13
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.42658E-12 0.2597
   1.8000E+00   3.62279E-08 0.2525
   1.9000E+00   1.33599E-07 0.1856
   2.0000E+00   1.74573E-07 0.2606
   2.1000E+00   2.99532E-07 0.2861
   2.2000E+00   4.17762E-07 0.3899
   2.3000E+00   4.77496E-07 0.2254
   2.4000E+00   4.82619E-07 0.2013
   2.5000E+00   6.25023E-06 0.0889
     total      8.27204E-06 0.0740

cell  14
     energy
   1.6000E+00   0.00000E+00 0.0000
   1.7000E+00   1.24474E-12 0.1896
   1.8000E+00   5.72596E-08 0.1320
   1.9000E+00   1.01314E-07 0.1241
   2.0000E+00   1.30239E-07 0.1479
   2.1000E+00   1.94227E-07 0.2208
   2.2000E+00   2.25813E-07 0.1895
   2.3000E+00   3.80784E-07 0.1797
   2.4000E+00   3.84210E-07 0.1270
```

```
    2.5000E+00   6.28080E-06 0.0418
      total      7.75465E-06 0.0370

 cell  15
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   9.92286E-13 0.4405
    1.8000E+00   2.25024E-08 0.3032
    1.9000E+00   9.14423E-08 0.2537
    2.0000E+00   1.66361E-07 0.2482
    2.1000E+00   2.32458E-07 0.4403
    2.2000E+00   1.76953E-07 0.2407
    2.3000E+00   3.65103E-07 0.3356
    2.4000E+00   6.84297E-07 0.3546
    2.5000E+00   4.51014E-06 0.0606
      total      6.24926E-06 0.0654

 cell  16
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   8.31628E-13 0.1834
    1.8000E+00   3.84842E-08 0.1482
    1.9000E+00   8.48031E-08 0.1773
    2.0000E+00   1.18717E-07 0.2407
    2.1000E+00   1.40239E-07 0.2022
    2.2000E+00   2.25609E-07 0.2487
    2.3000E+00   2.65715E-07 0.1951
    2.4000E+00   3.51274E-07 0.1298
    2.5000E+00   4.69070E-06 0.0362
      total      5.91554E-06 0.0344

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.39761E-12 0.0785
    1.8000E+00   5.80020E-08 0.0692
    1.9000E+00   1.68496E-07 0.0522
    2.0000E+00   2.31420E-07 0.0679
    2.1000E+00   2.23116E-07 0.0787
    2.2000E+00   2.78390E-07 0.0863
    2.3000E+00   4.09200E-07 0.0691
    2.4000E+00   4.86766E-07 0.0686
    2.5000E+00   1.29327E-05 0.0155
      total      1.47881E-05 0.0149
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   4 with nps
=  10778451    print table 160


tally  14        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       1            2          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  1
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   7.96758E-13 0.3107
    1.8000E+00   3.56337E-08 0.2628
    1.9000E+00   2.00625E-07 0.1627
    2.0000E+00   2.75395E-07 0.2159
    2.1000E+00   1.49410E-07 0.4990
    2.2000E+00   1.79824E-08 0.7073
    2.3000E+00   6.13742E-08 0.5129
    2.4000E+00   5.50582E-08 0.5017
    2.5000E+00   2.59639E-05 0.0327
      total      2.67594E-05 0.0324
```

Total F4 Tally, in units of millibarns/cm^2
Fluence times cross section

Converting F4 tally from millbarns/cm^2 to reactions/cm^3:

(1.47881E-05 millibarns/cm^2) x (10^{-27} cm^2/millibarns) x (3.296 x 10^{22} atoms/cm^3, atomic density of lead)

➔ <u>4.8742E-10 n reactions/cm^3</u>

```
 cell  2
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.02775E-12 0.4179
    1.8000E+00   4.11907E-08 0.1704
    1.9000E+00   1.74769E-07 0.0908
    2.0000E+00   3.58269E-07 0.1454
    2.1000E+00   1.79455E-07 0.2825
    2.2000E+00   6.06392E-08 0.6490
    2.3000E+00   2.92439E-08 0.4153
    2.4000E+00   4.98592E-08 0.4553
    2.5000E+00   2.53935E-05 0.0219
      total      2.62870E-05 0.0216

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   9.69999E-13 0.3383
    1.8000E+00   3.98015E-08 0.1448
    1.9000E+00   1.81233E-07 0.0797
    2.0000E+00   3.37551E-07 0.1239
    2.1000E+00   1.71944E-07 0.2472
    2.2000E+00   4.99750E-08 0.5940
    2.3000E+00   3.72764E-08 0.3229
    2.4000E+00   5.11589E-08 0.3591
    2.5000E+00   2.55361E-05 0.0185
      total      2.64051E-05 0.0184
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  14 with nps
=  10778451    print table 160


tally  24        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       3            4          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  3
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.38838E-12 0.2477
    1.8000E+00   7.18772E-08 0.2800
    1.9000E+00   2.15433E-07 0.1402
    2.0000E+00   2.11576E-07 0.2088
    2.1000E+00   3.01385E-07 0.3773
    2.2000E+00   4.17086E-07 0.2941
    2.3000E+00   3.81299E-07 0.2444
    2.4000E+00   6.67059E-07 0.1995
    2.5000E+00   2.03280E-05 0.0297
      total      2.25937E-05 0.0295

 cell  4
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.21507E-12 0.1622
    1.8000E+00   7.13489E-08 0.1850
    1.9000E+00   2.32049E-07 0.0894
    2.0000E+00   2.93896E-07 0.1867
    2.1000E+00   2.70886E-07 0.2037
    2.2000E+00   2.32461E-07 0.2013
    2.3000E+00   4.31349E-07 0.1365
    2.4000E+00   4.95623E-07 0.2344
    2.5000E+00   2.00027E-05 0.0177
      total      2.20304E-05 0.0181

 cell union total
```

"Front Face" F4 Tally (points to total 2.64051E-05)

Note: All F4 tallies for layers in thesis have been converted from millibarns/cm^2 to neutron reactions/cm^3

```
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.25840E-12 0.1359
    1.8000E+00   7.14809E-08 0.1688
    1.9000E+00   2.27895E-07 0.0760
    2.0000E+00   2.73316E-07 0.1560
    2.1000E+00   2.78511E-07 0.1965
    2.2000E+00   2.78617E-07 0.1678
    2.3000E+00   4.18837E-07 0.1192
    2.4000E+00   5.38482E-07 0.1736
    2.5000E+00   2.00841E-05 0.0153
      total      2.21712E-05 0.0156
```

Layer "A" F4 Tally

```
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  24 with nps
=  10778451    print table 160


tally  34        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       5            6          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  5
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.20560E-12 0.2398
    1.8000E+00   8.85178E-08 0.2279
    1.9000E+00   1.96054E-07 0.1667
    2.0000E+00   2.05535E-07 0.2738
    2.1000E+00   2.45027E-07 0.3156
    2.2000E+00   3.39610E-07 0.4573
    2.3000E+00   7.32551E-07 0.2005
    2.4000E+00   8.80078E-07 0.2591
    2.5000E+00   1.64610E-05 0.0396
      total      1.91483E-05 0.0394

 cell  6
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.35555E-12 0.1614
    1.8000E+00   5.88728E-08 0.1562
    1.9000E+00   2.28148E-07 0.1195
    2.0000E+00   2.82931E-07 0.1429
    2.1000E+00   2.54819E-07 0.1526
    2.2000E+00   4.24537E-07 0.2091
    2.3000E+00   5.38689E-07 0.1345
    2.4000E+00   5.80131E-07 0.1087
    2.5000E+00   1.60252E-05 0.0236
      total      1.83934E-05 0.0225

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.31806E-12 0.1367
    1.8000E+00   6.62840E-08 0.1289
    1.9000E+00   2.20124E-07 0.1001
    2.0000E+00   2.63582E-07 0.1268
    2.1000E+00   2.52371E-07 0.1400
    2.2000E+00   4.03305E-07 0.2326
    2.3000E+00   5.87154E-07 0.1117
    2.4000E+00   6.55118E-07 0.1133
    2.5000E+00   1.61342E-05 0.0204
      total      1.85821E-05 0.0199
```

Layer "B" F4 Tally

```
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  34 with nps
=  10778451    print table 160
```

```
tally  44        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       7            8          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  7
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   2.09388E-12 0.2225
    1.8000E+00   6.70966E-08 0.2206
    1.9000E+00   1.84697E-07 0.1643
    2.0000E+00   2.05961E-07 0.2115
    2.1000E+00   3.86885E-07 0.2472
    2.2000E+00   3.40650E-07 0.2610
    2.3000E+00   6.41918E-07 0.1905
    2.4000E+00   6.24680E-07 0.1907
    2.5000E+00   1.32686E-05 0.0457
      total      1.57205E-05 0.0417

 cell  8
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.86758E-12 0.1499
    1.8000E+00   7.24271E-08 0.1616
    1.9000E+00   1.82728E-07 0.1046
    2.0000E+00   2.47724E-07 0.1202
    2.1000E+00   2.07763E-07 0.1535
    2.2000E+00   3.33951E-07 0.2017
    2.3000E+00   5.50226E-07 0.1256
    2.4000E+00   6.05770E-07 0.1015
    2.5000E+00   1.27420E-05 0.0324
      total      1.49426E-05 0.0291

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.92416E-12 0.1264
    1.8000E+00   7.10945E-08 0.1340
    1.9000E+00   1.83221E-07 0.0885
    2.0000E+00   2.37283E-07 0.1047
    2.1000E+00   2.52544E-07 0.1421
    2.2000E+00   3.35626E-07 0.1661
    2.3000E+00   5.73149E-07 0.1050
    2.4000E+00   6.10498E-07 0.0900
    2.5000E+00   1.28736E-05 0.0273
      total      1.51371E-05 0.0246
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  44 with nps
=  10778451    print table 160
```

Layer "C" F4 Tally

```
tally  54        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:       9           10          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  9
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   3.24052E-12 0.2297
    1.8000E+00   7.54379E-08 0.2469
    1.9000E+00   2.08430E-07 0.2324
```

```
    2.0000E+00   2.08327E-07 0.2148
    2.1000E+00   3.03063E-07 0.2018
    2.2000E+00   2.11187E-07 0.3153
    2.3000E+00   7.27272E-07 0.1777
    2.4000E+00   6.17600E-07 0.1828
    2.5000E+00   1.01219E-05 0.0473
      total      1.24732E-05 0.0430

 cell  10
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.44669E-12 0.1524
    1.8000E+00   6.07937E-08 0.1359
    1.9000E+00   1.82559E-07 0.1020
    2.0000E+00   2.03655E-07 0.1697
    2.1000E+00   2.23606E-07 0.1936
    2.2000E+00   3.39511E-07 0.1902
    2.3000E+00   4.66269E-07 0.1224
    2.4000E+00   5.78470E-07 0.1042
    2.5000E+00   9.80250E-06 0.0260
      total      1.18574E-05 0.0245

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.89515E-12 0.1351
    1.8000E+00   6.44547E-08 0.1203
    1.9000E+00   1.89026E-07 0.0983
    2.0000E+00   2.04823E-07 0.1425
    2.1000E+00   2.43470E-07 0.1490
    2.2000E+00   3.07430E-07 0.1667
    2.3000E+00   5.31519E-07 0.1012
    2.4000E+00   5.88252E-07 0.0907
    2.5000E+00   9.88235E-06 0.0229
      total      1.20113E-05 0.0215
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  54 with nps
=  10778451    print table 160


tally  64        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:      11           12          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  11
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   2.66546E-12 0.2052
    1.8000E+00   5.84547E-08 0.2723
    1.9000E+00   1.43710E-07 0.1783
    2.0000E+00   2.71468E-07 0.2614
    2.1000E+00   2.98276E-07 0.2292
    2.2000E+00   3.81729E-07 0.2737
    2.3000E+00   6.24605E-07 0.1912
    2.4000E+00   7.20057E-07 0.1622
    2.5000E+00   8.06277E-06 0.0688
      total      1.05611E-05 0.0572

 cell  12
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.31572E-12 0.1677
    1.8000E+00   6.63954E-08 0.1295
    1.9000E+00   1.52926E-07 0.1142
    2.0000E+00   2.59984E-07 0.2696
    2.1000E+00   1.70225E-07 0.1588
```

Layer “D” F4 Tally (pointing to **1.20113E-05**)

```
    2.2000E+00   3.59322E-07 0.2077
    2.3000E+00   3.65323E-07 0.1564
    2.4000E+00   5.69688E-07 0.1342
    2.5000E+00   8.02274E-06 0.0364
      total      9.96661E-06 0.0333

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.65315E-12 0.1309
    1.8000E+00   6.44103E-08 0.1177
    1.9000E+00   1.50622E-07 0.0980
    2.0000E+00   2.62855E-07 0.2174
    2.1000E+00   2.02237E-07 0.1311
    2.2000E+00   3.64924E-07 0.1699
    2.3000E+00   4.30144E-07 0.1214
    2.4000E+00   6.07280E-07 0.1060
    2.5000E+00   8.03275E-06 0.0364
      total      1.01152E-05 0.0318
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  64 with nps
=  10778451    print table 160


tally  74        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:      13            14           total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  13
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.42658E-12 0.2597
    1.8000E+00   3.62279E-08 0.2525
    1.9000E+00   1.33599E-07 0.1856
    2.0000E+00   1.74573E-07 0.2606
    2.1000E+00   2.99532E-07 0.2861
    2.2000E+00   4.17762E-07 0.3899
    2.3000E+00   4.77496E-07 0.2254
    2.4000E+00   4.82619E-07 0.2013
    2.5000E+00   6.25023E-06 0.0889
      total      8.27204E-06 0.0740

 cell  14
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.24474E-12 0.1896
    1.8000E+00   5.72596E-08 0.1320
    1.9000E+00   1.01314E-07 0.1241
    2.0000E+00   1.30239E-07 0.1479
    2.1000E+00   1.94227E-07 0.2208
    2.2000E+00   2.25813E-07 0.1895
    2.3000E+00   3.80784E-07 0.1797
    2.4000E+00   3.84210E-07 0.1270
    2.5000E+00   6.28080E-06 0.0418
      total      7.75465E-06 0.0370

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   1.29020E-12 0.1563
    1.8000E+00   5.20017E-08 0.1211
    1.9000E+00   1.09385E-07 0.1032
    2.0000E+00   1.41323E-07 0.1309
    2.1000E+00   2.20554E-07 0.1752
    2.2000E+00   2.73800E-07 0.1894
    2.3000E+00   4.04962E-07 0.1436
```

Layer "E" F4 Tally (annotation pointing to total 1.01152E-05)

Layer “F” F4 Tally

```
    2.4000E+00   4.08812E-07 0.1074
    2.5000E+00   6.27316E-06 0.0388
      total      7.88399E-06 0.0339
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  74 with nps
=  10778451    print table 160


tally  84        nps = 10778451
           tally type 4    track length estimate of particle flux.
           tally for  neutrons

           this tally is modified by cm, em or tm cards.

           volumes
                   cell:      15           16          total
                         3.53429E+01  1.06029E+02  1.41372E+02

 cell  15
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   9.92286E-13 0.4405
    1.8000E+00   2.25024E-08 0.3032
    1.9000E+00   9.14423E-08 0.2537
    2.0000E+00   1.66361E-07 0.2482
    2.1000E+00   2.32458E-07 0.4403
    2.2000E+00   1.76953E-07 0.2407
    2.3000E+00   3.65103E-07 0.3356
    2.4000E+00   6.84297E-07 0.3546
    2.5000E+00   4.51014E-06 0.0606
      total      6.24926E-06 0.0654

 cell  16
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   8.31628E-13 0.1834
    1.8000E+00   3.84842E-08 0.1482
    1.9000E+00   8.48031E-08 0.1773
    2.0000E+00   1.18717E-07 0.2407
    2.1000E+00   1.40239E-07 0.2022
    2.2000E+00   2.25609E-07 0.2487
    2.3000E+00   2.65715E-07 0.1951
    2.4000E+00   3.51274E-07 0.1298
    2.5000E+00   4.69070E-06 0.0362
      total      5.91554E-06 0.0344

 cell union total
      energy
    1.6000E+00   0.00000E+00 0.0000
    1.7000E+00   8.71792E-13 0.1821
    1.8000E+00   3.44887E-08 0.1335
    1.9000E+00   8.64629E-08 0.1468
    2.0000E+00   1.30628E-07 0.1823
    2.1000E+00   1.63294E-07 0.2038
    2.2000E+00   2.13445E-07 0.2035
    2.3000E+00   2.90562E-07 0.1704
    2.4000E+00   4.34530E-07 0.1603
    2.5000E+00   4.64556E-06 0.0313
      total      5.99897E-06 0.0308
1analysis of the results in the tally fluctuation chart bin (tfc) for tally  84 with nps
=  10778451    print table 160
*****************************************************************************************
******************************
 dump no.    2 on file runtpe       nps =  10778451     coll =          68340     ctm =
5.00     nrn =       28571199


        11 warning messages so far.


 run terminated when it had used    5 minutes of computer time.
```

Layer “G” F4 Tally

```
 computer time =    5.02 minutes

 mcnp     version 4c    01/20/00                      12/09/02 15:19:25
probid =   12/09/02 15:14:24
```

MCNP Code Listing of Optimized Layer Cake

Table XIX.

Determination of Volumetric Gamma Source Values for Lead Layers

Layers	F4 Tally (xE-10) (n reactions/cm^3)	Normalized to “Front Face”	Percentage Volume (p. 80 above)	Values input into Part 4 (p. 92 below)
Front Face	8.70312	1.0	0.125	0.125
Layer “A”	7.30763	0.839656	“	0.104957
Layer “B”	6.12466	0.703731	“	0.087966
Layer “C”	4.98919	0.573264	“	0.071658
Layer “D”	3.95892	0.454886	“	0.056861
Layer “E”	3.33397	0.383078	“	0.047885
Layer “F”	2.59856	0.298578	“	0.037322
Layer “G”	1.97726	0.227190	“	0.028399

Part 4: F8 Counts Tally and F6 Energy Deposited Tally

```
1mcnp     version 4c    ld=01/20/00                   12/09/02 15:45:46
 *************************************************************************
probid =   12/09/02 15:45:46
 inp=xg9qa2a outp=xg9qa2ao

          Pb-207m photons into scintillator
          c            ***** XG9QA2A -- POINT SOURCE -- 5 MIN *****
          c             ***** 15 CM OUTER RADIUS; 28.28 LBS LEAD *****
          c            ***** 8 LAYERS LEAD; 8 PLASTIC *****
```

```
c        ***** 0.2 CM LEAD LAYERS; 1.1 CM PLASTIC LAYERS *****
c                    **** NO SHEATH ***
c      **** USING SPENCER & JACOB CROSS SECTIONS FOR PB-207
c      Looking at Energy Deposited (F6) and Interactions (F8)
c      in Plastic Scintillator
1      1 -11.34 1 -2 -18
2      1 -11.34 1 -2 18 -19
3      1 -11.34 3 -4 -18
4      1 -11.34 3 -4 18 -19
5      1 -11.34 5 -6 -18
6      1 -11.34 5 -6 18 -19
7      1 -11.34 7 -8 -18
8      1 -11.34 7 -8 18 -19
9      1 -11.34 9 -10 -18
10     1 -11.34 9 -10 18 -19
11     1 -11.34 11 -12 -18
12     1 -11.34 11 -12 18 -19
13     1 -11.34 13 -14 -18
14     1 -11.34 13 -14 18 -19
15     1 -11.34 15 -16 -18
16     1 -11.34 15 -16 18 -19
17     2 -1.032 2 -3 -18
18     2 -1.032 2 -3 18 -19
19     2 -1.032 4 -5 -18
20     2 -1.032 4 -5 18 -19
21     2 -1.032 6 -7 -18
22     2 -1.032 6 -7 18 -19
23     2 -1.032 8 -9 -18
24     2 -1.032 8 -9 18 -19
25     2 -1.032 10 -11 -18
26     2 -1.032 10 -11 18 -19
27     2 -1.032 12 -13 -18
28     2 -1.032 12 -13 18 -19
29     2 -1.032 14 -15 -18
30     2 -1.032 14 -15 18 -19
31     2 -1.032 16 -17 -18
32     2 -1.032 16 -17 18 -19
33     0 -1:19:17    $ Universe outside detector -- kill zone

c      **** 0.2 cm Lead; 1.1 cm Plastic
1      py 0.0
2      py 0.2
3      py 1.3
4      py 1.5
5      py 2.6
6      py 2.8
7      py 3.9
8      py 4.1
9      py 5.2
10     py 5.4
11     py 6.5
12     py 6.7
13     py 7.8
14     py 8.0
15     py 9.1
16     py 9.3
17     py 10.4
18     cy 7.5
19     cy 15.0

c      **** Volumetric gamma source in the lead ****
c      **** Based on data from monoenergetic (2.5 MeV) neutron ****
c      **** source normal to the face, activating the lead ****
mode   p
sdef   par=2 erg=d1 axs=0 1 0
       rad=d2 pos=frad=d11 ext=frad=d12
si1    L 0.5697 1.0636   $ gamma energies
sp1    d 0.525 0.475     $ weighted branching ratios
c
c      3 - 10 are Front Face thru Lead Layer "G"
c
```

Volumetric Gamma Source Values listed in Table XIX, p. 90, input into code here

```
si2   s 3 4 5 6 7 8 9 10
c
c     %tage Volume of 3 - 10 times a normalized factor
c     based on cells 1 - 2 (Front Face):
sp2   0.125 0.104957 0.087966 0.071658 0.056861 0.047885 0.037322
      0.028399
si3   15.0    $ Radius of 3 (Front Face)
sp3   -21 1
si4   15.0    $ Radius of "A"
sp4   -21 1
si5   15.0    $ Radius of "B"
sp5   -21 1
si6   15.0    $ Radius of "C"
sp6   -21 1
si7   15.0    $ Radius of "D"
sp7   -21 1
si8   15.0    $ Radius of "E"
sp8   -21 1
si9   15.0    $ Radius of "F"
sp9   -21 1
si10  15.0    $ Radius of "G"
sp10  -21 1
c
c     The following are coordinates of the left side of 3 - 10:
ds11  L 0 0 0 0 1.3 0 0 2.6 0 0 3.9 0 0 5.2 0 0 6.5 0
      0 7.8 0 0 9.1 0
ds12  s 13 14 15 16 17 18 19 20
si13  0 0.2  $ Width of 3 (Front Face)
si14  0 0.2  $ Width of 4 (Layer "A")
si15  0 0.2  $ Width of 5 (Layer "B")
si16  0 0.2  $ Width of 6 (Layer "C")
si17  0 0.2  $ Width of 7 (Layer "D")
si18  0 0.2  $ Width of 8 (Layer "E")
si19  0 0.2  $ Width of 9 (Layer "F")
si20  0 0.2  $ Width of 10 (Layer "G")
c     Lead G-23
m1    82000 1
c     Plastic
m2    1001 1.1 6000 1
imp:p 1 31r 0
cut:n 10000 0
c     Total F6 Tally
f6:p  17 18 19 20 21 22 23 24 25 26 27 28 29 30
      31 32 t
c     Total F8 Tally
f8:p  17 18 19 20 21 22 23 24 25 26 27 28 29 30
      31 32 t
e8    0 1e-10 1.1   $ Counts over all Plastic
ctme 3
```

```
photon   activity in each cell
print table 126

                 tracks     population   collisions   collisions     number        flux
average      average
        cell    entering                               * weight     weighted     weighted
track weight   track mfp
                                                     (per history)    energy       energy
(relative)      (cm)

     1     1       86816       105941        83725    9.7851E-02   7.5875E-01   7.5875E-
01   1.0000E+00   9.1695E-01
     2     2       237587      288425       221039    2.5833E-01   7.6054E-01   7.6054E-
01   1.0000E+00   9.1945E-01
     3     3       95877       114925       101633    1.1878E-01   7.4335E-01   7.4335E-
01   1.0000E+00   8.9475E-01
     4     4       257884      307214       261397    3.0550E-01   7.4570E-01   7.4570E-
01   1.0000E+00   8.9818E-01
     5     5       92317       110736        98694    1.1535E-01   7.3829E-01   7.3829E-
01   1.0000E+00   8.8769E-01
```

```
     6     6      243620       291088       250735    2.9304E-01   7.4225E-01   7.4225E-
01   1.0000E+00   8.9321E-01
     7     7       83763       100317        89458    1.0455E-01   7.3719E-01   7.3719E-
01   1.0000E+00   8.8599E-01
     8     8      218047       260133       222727    2.6031E-01   7.4201E-01   7.4201E-
01   1.0000E+00   8.9283E-01
     9     9       72951        87597        78398    9.1626E-02   7.3729E-01   7.3729E-
01   1.0000E+00   8.8600E-01
    10    10      188034       224089       191543    2.2386E-01   7.4060E-01   7.4060E-
01   1.0000E+00   8.9091E-01
    11    11       62027        74062        65089    7.6071E-02   7.3776E-01   7.3776E-
01   1.0000E+00   8.8669E-01
    12    12      159467       190133       162197    1.8956E-01   7.4174E-01   7.4174E-
01   1.0000E+00   8.9237E-01
    13    13       50452        60299        52326    6.1155E-02   7.3816E-01   7.3816E-
01   1.0000E+00   8.8751E-01
    14    14      128509       152558       127977    1.4957E-01   7.4213E-01   7.4213E-
01   1.0000E+00   8.9304E-01
    15    15       37805        45436        37714    4.4077E-02   7.4470E-01   7.4470E-
01   1.0000E+00   8.9654E-01
    16    16       94945       114020        92125    1.0767E-01   7.4823E-01   7.4823E-
01   1.0000E+00   9.0167E-01
    17    17       70261        67061        13820    1.6152E-02   7.1041E-01   7.1041E-
01   1.0000E+00   1.1755E+01
    18    18      179779       172025        34207    3.9978E-02   7.1684E-01   7.1684E-
01   1.0000E+00   1.1815E+01
    19    19       73517        70049        13911    1.6258E-02   7.0706E-01   7.0706E-
01   1.0000E+00   1.1729E+01
    20    20      186244       178062        34950    4.0847E-02   7.1199E-01   7.1199E-
01   1.0000E+00   1.1775E+01
    21    21       70252        66913        13328    1.5577E-02   7.0415E-01   7.0415E-
01   1.0000E+00   1.1705E+01
    22    22      174779       167136        31960    3.7352E-02   7.1282E-01   7.1282E-
01   1.0000E+00   1.1780E+01
    23    23       63483        60507        11733    1.3713E-02   7.0364E-01   7.0364E-
01   1.0000E+00   1.1699E+01
    24    24      156918       150168        28386    3.3175E-02   7.1106E-01   7.1106E-
01   1.0000E+00   1.1765E+01
    25    25       55041        52495         9965    1.1646E-02   7.0409E-01   7.0409E-
01   1.0000E+00   1.1704E+01
    26    26      135568       129960        24308    2.8409E-02   7.1138E-01   7.1138E-
01   1.0000E+00   1.1768E+01
    27    27       46166        44111         8162    9.5391E-03   7.0591E-01   7.0591E-
01   1.0000E+00   1.1720E+01
    28    28      112990       108396        19534    2.2830E-02   7.1400E-01   7.1400E-
01   1.0000E+00   1.1789E+01
    29    29       36620        35065         6297    7.3594E-03   7.0893E-01   7.0893E-
01   1.0000E+00   1.1746E+01
    30    30       88494        85014        15199    1.7763E-02   7.1481E-01   7.1481E-
01   1.0000E+00   1.1797E+01
    31    31       25205        25094         4205    4.9145E-03   7.3118E-01   7.3118E-
01   1.0000E+00   1.1938E+01
    32    32       59724        59459         9445    1.1039E-02   7.3725E-01   7.3725E-
01   1.0000E+00   1.1995E+01

     total       3645142      3998488      2416187    2.8239E+00
tally   6        nps =   855635
           tally type 6    track length estimate of heating.            units   mev/gram
           tally for  photons

           masses
                   cell:      17           18           19           20           21
22           23
                         2.00606E+02  6.01819E+02  2.00606E+02  6.01819E+02  2.00606E+02
6.01819E+02  2.00606E+02
                   cell:      24           25           26           27           28
29           30
                         6.01819E+02  2.00606E+02  6.01819E+02  2.00606E+02  6.01819E+02
2.00606E+02  6.01819E+02
                   cell:      31           32          total
                         2.00606E+02  6.01819E+02  6.41940E+03
```

Total Mass of Scintillator (grams)

<u>Total Energy Deposited</u>
1.24744E-05 MeV/gram) x (6,419.40 grams)
= <u>0.080078 MeV</u>

Efficiency = 0.080078 MeV/0.8 MeV = 0.1001
➔ <u>10.01%</u>
(Note: 0.8 MeV is weighted average of both gammas)

```
 cell  17
                1.95157E-05 0.0052

 cell  18
                1.65483E-05 0.0031

 cell  19
                1.97346E-05 0.0050

 cell  20
                1.66342E-05 0.0030

 cell  21
                1.83763E-05 0.0051

 cell  22
                1.52682E-05 0.0031

 cell  23
                1.63470E-05 0.0053

 cell  24
                1.34634E-05 0.0032

 cell  25
                1.39843E-05 0.0057

 cell  26
                1.14290E-05 0.0035

 cell  27
                1.15854E-05 0.0062

 cell  28
                9.46601E-06 0.0039

 cell  29
                9.08965E-06 0.0070

 cell  30
                7.29713E-06 0.0044

 cell  31
                5.99111E-06 0.0080

 cell  32
                4.74579E-06 0.0051
```

Total MeV/gram

```
 cell union total
                1.24744E-05 0.0013
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   6 with nps
=    855635    print table 160


tally   8        nps =   855635
           tally type 8    pulse height distribution.                   units   number
           tally for  photons

 cell  17
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   6.48805E-02 0.0041
    1.1000E+00   1.30441E-02 0.0094
      total      7.79246E-02 0.0037

 cell  18
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   1.67485E-01 0.0024
    1.1000E+00   3.23760E-02 0.0059
```

```
     total      1.99861E-01 0.0022

cell  19
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   6.82370E-02 0.0040
   1.1000E+00   1.31154E-02 0.0094
     total      8.13524E-02 0.0036

cell  20
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   1.73800E-01 0.0024
   1.1000E+00   3.30375E-02 0.0058
     total      2.06837E-01 0.0021

cell  21
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   6.51317E-02 0.0041
   1.1000E+00   1.26479E-02 0.0096
     total      7.77797E-02 0.0037

cell  22
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   1.63919E-01 0.0024
   1.1000E+00   3.03295E-02 0.0061
     total      1.94249E-01 0.0022

cell  23
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   5.92402E-02 0.0043
   1.1000E+00   1.10643E-02 0.0102
     total      7.03045E-02 0.0039

cell  24
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   1.47552E-01 0.0026
   1.1000E+00   2.69063E-02 0.0065
     total      1.74459E-01 0.0024

cell  25
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   5.15792E-02 0.0046
   1.1000E+00   9.45146E-03 0.0111
     total      6.10307E-02 0.0042

cell  26
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   1.28000E-01 0.0028
   1.1000E+00   2.30297E-02 0.0070
     total      1.51029E-01 0.0026

cell  27
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   4.35443E-02 0.0051
   1.1000E+00   7.73344E-03 0.0122
     total      5.12777E-02 0.0047

cell  28
     energy
   0.0000E+00   0.00000E+00 0.0000
   1.0000E-10   1.07416E-01 0.0031
   1.1000E+00   1.85488E-02 0.0079
     total      1.25965E-01 0.0028
```

```
 cell  29
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   3.47824E-02 0.0057
    1.1000E+00   5.99087E-03 0.0139
      total      4.07732E-02 0.0052

 cell  30
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   8.43596E-02 0.0036
    1.1000E+00   1.44583E-02 0.0089
      total      9.88178E-02 0.0033

 cell  31
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   2.51544E-02 0.0067
    1.1000E+00   4.04729E-03 0.0170
      total      2.92017E-02 0.0062

 cell  32
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   6.01051E-02 0.0043
    1.1000E+00   9.12071E-03 0.0113
      total      6.92258E-02 0.0040

 cell union total
      energy
    0.0000E+00   0.00000E+00 0.0000
    1.0000E-10   5.02872E-01 0.0011
    1.1000E+00   2.39599E-01 0.0019
      total      7.42471E-01 0.0006
1analysis of the results in the tally fluctuation chart bin (tfc) for tally   8 with nps
=    855635    print table 160
*****************************************************************************************
******************************
 dump no.    2 on file runtpe       nps =    855635     coll =        2416187     ctm =
3.02     nrn =       33356088


         2 warning messages so far.


 run terminated when it had used    3 minutes of computer time.

 computer time =    3.06 minutes

 mcnp     version 4c    01/20/00                      12/09/02 15:48:50
probid =   12/09/02 15:45:46
```

F8 Tally = 0.742471 – 0.502872
= 0.239599 ← Counts in Scintillator

Figure of Merit Calculation for Optimized Layer Cake

FOM = F4 Tally (n reactions/cm^3) x F8 Tally (Counts) x Volume of Lead (cm^3)

FOM = (4.8742E-10 reactions/cm^3) x (0.239599 counts) x (1,130.97cm^3)

= 13.21E-08 Reactions x Counts

See Table IV, p. 26.

Appendix B

DD Neutron Attenuation in 0.2 cm and 0.3 cm Cases

In an effort to see the effects of DD neutron attenuation due to different widths of scintillator (1.1 cm and 1.25 cm), F4 tallies in lead layers with scintillator removed were compared with F4 tallies in lead layers with scintillator present in each case (0.2 cm and 0.3 cm).

Table XX.

0.2 cm Lead Case: F4 Tallies with Scintillator Removed Compared with F4 Tallies with Scintillator Present

F4 Tallies (x E-10)* (n reactions/cm^3)	0.2 cm with 1.1 cm Scintillator	0.2 cm without Scintillator
Total F4 Tally	4.8742	8.0752 (>66%)
Front Face	8.7031	9.0436 (>3.9%)
Layer "A"	7.3076	8.8126 (>20.6%)
Layer "B"	6.1247	8.5596 (>39.8%)
Layer "C"	4.9892	8.2041 (>64.4%)
Layer "D"	3.9589	7.9988 (>102%)
Layer "E"	3.3340	7.8953 (>137%)
Layer "F"	2.5986	7.2788 (>180%)
Layer "G"	1.9773	6.8086 (>244%)

*Neutrons are DD (2.45 MeV).

As can be seen, the F4 tallies with scintillator removed grow increasingly larger toward the back layers of the detector. The last layer, "G", has an F4 tally (without scintillator) which is over 244% greater than its F4 tally with scintillator. These increasingly higher values of F4 tallies in the back layers contribute to the total F4 tally which is over 66% greater (without scintillator) than the total F4 tally with scintillator. The 0.3 cm case is presented in Table XXI below.

Table XXI.

0.3 cm Lead Case: F4 Tallies with Scintillator Removed Compared with F4 Tallies with Scintillator Present

F4 Tallies (x E-10)* (n reactions/cm^3)	0.3 cm with 1.25 cm Scintillator	0.3 cm without Scintillator
Total F4 Tally	4.5264	7.9474 (>75.6%)
Front Face	8.9355	9.3726 (>4.9%)
Layer "A"	7.2273	9.0134 (>24.7%)
Layer "B"	5.7639	8.6278 (>49.7%)
Layer "C"	4.5231	8.2342 (>82%)
Layer "D"	3.4297	7.7981 (>127%)
Layer "E"	2.7769	7.4320 (>167%)
Layer "F"	2.0643	6.8441 (>231%)
Layer "G"	1.4907	6.2574 (>319%)

*Neutrons are DD (2.45 MeV).

In examining the 0.3 cm lead layer case, its thicker, 1.25 cm layers of scintillator attenuate even more neutrons throughout the detector. Its back layer, "G", has an F4 tally (without scintillator) which is over 319% greater than its F4 tally with scintillator. The greater attenuation throughout all the layers produce a total F4 tally (without scintillator) which is over 75% greater than the total F4 tally with scintillator. Since the detector cannot function without scintillator, this data indicates that thinner layers of scintillator attenuate fewer neutrons. To see if lead has any part to play in DD neutron attenuation, Table XXII below compares the 0.2 cm case without scintillator with the 0.3 cm case without scintillator, and displays the F4 tallies of each.

Table XXII.

0.2 cm Lead Case without Scintillator Compared with 0.3 cm Lead Case without Scintillator

Lead Layers*	0.2 cm w/o Scintillator (n reactions/layer) x 10^{-8}	0.3 cm w/o Scintillator (n reactions/layer) x 10^{-8}
Front Face	12.79 (100%)	19.88 (100%)
Layer "A"	12.45 (97%)	19.11 (96%)
Layer "B"	12.10 (95%)	18.30 (92%)
Layer "C"	11.60 (91%)	17.46 (88%)
Layer "D"	11.31 (88%)	16.54 (83%)
Layer "E"	11.16 (87%)	15.76 (79%)
Layer "F"	10.29 (80%)	14.51 (73%)
Layer "G"	9.62 (75%)	13.27 (67%)

*Note: Neutrons are DD (2.45 MeV).

As was seen in Tables V & X, the 0.3 cm case has more reactions/layer, (it has thicker layers of lead, and hence more volume per layer.) But in looking at the values in parenthesis (which are normalized to the front face value in each case), despite being higher, the neutron reactions/layer for the 0.3 cm case fall off slightly faster from the front face to the last layer (“G”). Thus, indeed, thicker layers of lead do attenuate neutrons, although not to the degree that thicker layers of scintillator do. Overall, most of the attenuation is due to the thickness of the plastic scintillator, and a small part of it is due to the thickness of the lead. However, to maximize the Figure of Merit, the adage, “thinner is better” holds true here. The thinner the layers of lead are, the thinner the corresponding layers of scintillator will be. This will provide the least amount of neutron attenuation. Also, thinner layers of lead lead to less self attenuation so that the gammas born in the lead from neutron activation can exit the lead and enter the scintillator where they may be counted.

Appendix C

Layer Cake Prototype Sensitivity Data

Table XXIII.

Layer Cake Prototype Sensitivity (in Counts/Incident Neutron) as a Function of Photomultiplier Tube Bias And Discriminator Setting

	-50 mV	-150 mV	-275 mV	-400 mV
-2000V	3.20E-04*			
-2100V	3.19E-04*	5.60E-05*	1.03E-05*	
-2200V	3.36E-04*			
-2300V	3.63E-04*	9.17E-05*	3.08E-05*	1.45E-05*
-2400V	3.77E-04*			
-2500V	4.62E-04*	2.05E-05*	1.11E-04*	5.03E-05*

*Units of Sensitivity in Counts/incident neutron

Table XXIV.

Layer Cake Prototype Sensitivity (in Incident Neutrons/Count) as a Function of Photomultiplier Tube Bias And Discriminator Setting

	-50mV	-150mV	-275mV	-400mV
-2000V	3125*			
-2100V	3135*	17,857*	97,087*	
-2200V	2976*			
-2300V	2755*	10,905*	32,468*	68,966*
-2400V	2653*			
-2500V	2165*	4878*	9009*	19,881*

* Units of Sensitivity in Incident Neutrons/Count

Appendix D

Hamamatsu Photomultiplier Tube R1250 Data

HAMAMATSU

PHOTOMULTIPLIER TUBE R1250

For High Energy Physics, Fast Time Response, High Pulse Linearity 127mm (5 Inch) Diameter, Bialkali Photocathode, 14-Stage, Head-on Type

GENERAL

Parameter		Description/Value	Unit
Spectral Response		300 to 650	nm
Wavelength of Maximum Response		420	nm
Photocathode	Material	Bialkali	—
	Minimum Useful Diameter	120	mm dia.
Window	Material	Borosilicate glass	—
Dynode	Structure	Linear focused	—
	Number of Stages	14	—
Base		20-pin base	—
Suitable Socket		E678-20A (supplied)	—

MAXIMUM RATINGS (Absolute Maximum Values)

Parameter		Value	Unit
Supply Voltage	Between Anode and Cathode	3000	Vdc
	Between Anode and Last Dynode	500	Vdc
Average Anode Current		0.2	mA
Ambient Temperature		-30 to +50	°C

CHARACTERISTICS (at 25°C)

Parameter		Min.	Typ.	Max.	Unit
Cathode Sensitivity	Luminous (2856K)	55	70	—	μA/lm
	Blue (with CS 5-58 filter)	7.0	9.0	—	μA/lm-b
	Quantum Efficiency at 390nm	—	22	—	%
Anode Sensitivity	Luminous (2856K)	300	1000	—	A/lm
	Blue (with CS 5-58 filter)	—	130	—	A/lm-b
Gain		—	1.4×10^7	—	—
Anode Dark Current (after 30min. storage in darkness)		—	50	300	nA
Time Response	Anode Pulse Rise Time	—	2.5	—	ns
	Electron Transit Time	—	54	—	ns
	Transit Time Spread	—	1.2	—	ns
Pulse Height Resolution with ^{137}Cs		—	8.3	—	%
Gain Deviation	Long Term	—	1.0	—	%
	Short Term	—	1.0	—	%
Pulse Linearity *	2% Deviation	—	160	—	%
	5% Deviation	—	250	—	%

* Measured with special voltage distribution ratios shown in the Table 2.

Table 1: VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrode	K	G1	G2	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	Dy11	Dy12	Dy13	Dy14	P
Ratio		2.5	7.5	0	1.2	1.8	1	1	1	1	1	1	1	1	1.5	1.5	3	2.5

Supply Voltage: 2000Vdc, K: Cathode, Dy: Dynode, P: Anode, G: Grid

Table 2: SPECIAL VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE FOR PULSE LINEARITY MEASUREMENT

Electrode	K	G1	G2	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	Dy11	Dy12	Dy13	Dy14	P
Ratio		2.5	7.5	0	1.2	1.8	1	1	1	1	1.2	1.5	2	2.8	4	5.7	8	5
Capacitors in μF												0.01	0.01	0.02	0.02	0.02	0.04	0.06

Supply Voltage: 2500Vdc, K: Cathode, Dy: Dynode, P: Anode, G: Grid

PHOTOMULTIPLIER TUBE R1250

Figure 1: Typical Spectral Response

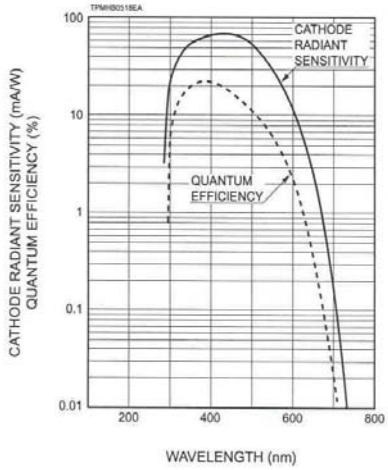


Figure 2: Typical Gain Characteristics

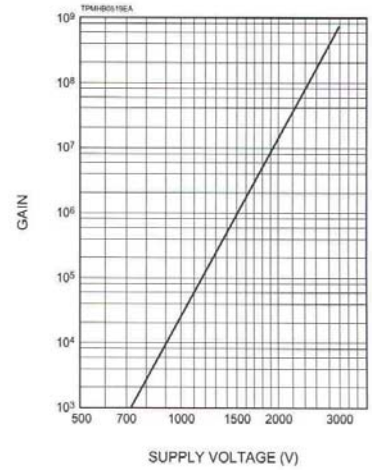
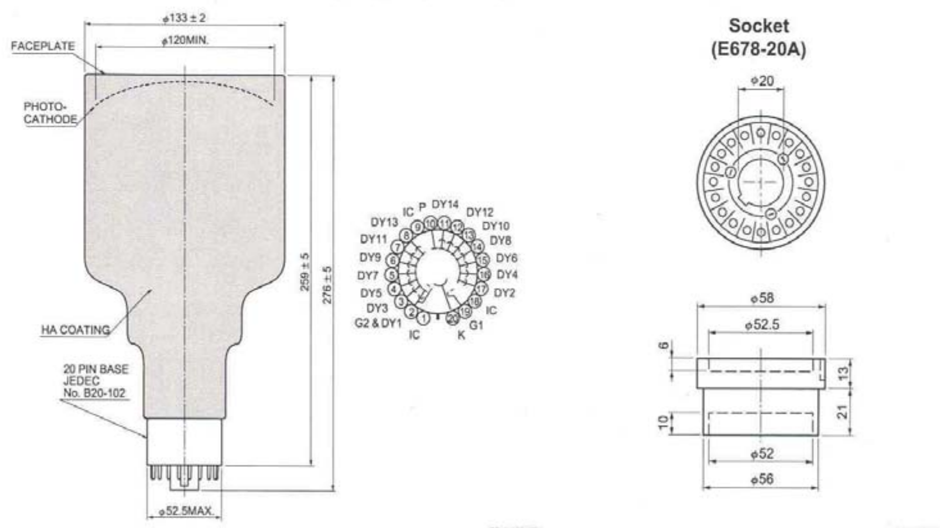


Figure 3: Dimensional Outline and Basing Diagram (Unit: mm)



HAMAMATSU HOMEPAGE URL http://www.hamamatsu.com

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North Europe: Hamamatsu Photonics Norden AB: Smidesvägen 12, SE-171-41 SOLNA, Sweden, Telephone: (46)8-509-031-00, Fax: (46)8-509-031-01

Bechtel Nevada

Photomultiplier Tube Information

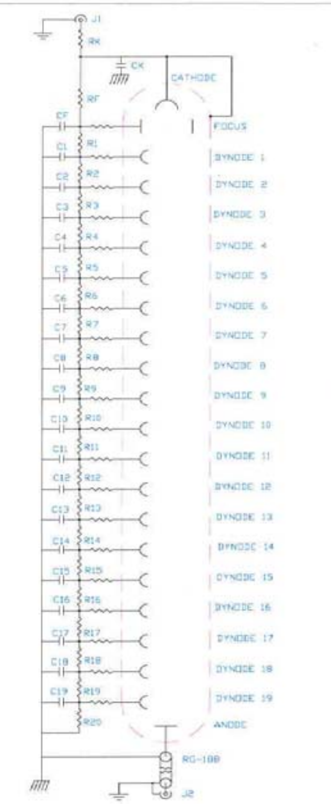
PMT Type	R1250	PMT S/N		Mfg	HAMAMATSU	PMH Type	PMH-315	PMH S/N	

PMT Voltage Distribution Circuit Values

	Kohms		Farads		ohms
RK1	510	CK			
RF		CF			
R1	340	C1		RD1	
R2	1.02M	C2		RD2	
R3	0	C3		RD3	
R4	162	C4		RD4	
R5	246	C5		RD5	
R6	137	C6		RD6	
R7	137	C7		RD7	
R8	137	C8		RD8	
R9	137	C9		RD9	
R10	137	C10		RD10	
R11	137	C11		RD11	
R12	137	C12		RD12	
R13	137	C13		RD13	
R14	203	C14		RD14	
R15	203	C15		RD15	
R16	402	C16		RD16	
R17	340	C17		RD17	
R18		C18		RD18	
R19		C19		RD19	
R20					

PMT Innate Characteristics

Operating Voltage (volts)	Dark Current (Amps)	PMT Gain	Quality Factor QF_{250} (dB)	Max Linearity (v)	Transit Time @30% ampl. (ns)	Band Pass F_{-3dB} (MHz)
-2000						



REMARKS:

Technician: Date

Bechtel Nevada

BD-8DEC1999

Bechtel Nevada

Detector Type		Detector Serial No.		Detector Ass`y Drawing No.		Charge Number		Date	
Fluor Type		No. 1 Det. Head		Head Drawing No.		Customer			
Fluor dia. (in.)		No. 2 Det. Head		Head Drawing No.		Application			
Fluor Length (in.)		No. 3 Det. Head		Head Drawing No.		Transmission Line Information			
Fluor Finish		No. 4 Det. Head		Head Drawing No.		Signal Cable No. 1 Transit Time (ns)			
Fluor Paint Color						Signal Cable No. 2 Transit Time (ns)			

Detector Head Calibrations

Detector Head Position	Detector Head Type	Serial No.	Operating Voltage (volts)	Dark Current @ Operating Voltage (Amps)	Collimation Diameter (cm)	Radiation Flux (R/S)	Detector Optical Filter	Cal. Voltage (volts)	Dark Current @ Calib. Voltage	Radiated Current (Amps)	Sensitivity (A/R/S)	Detector Noise Ratio (Vf/Vn)	Max. Linear Output (volts)	Detector Transit Time (ns)	Misc.

Remarks:

Radiation Calibration by		Date		Detector Technician		Date	
Signature Authorization		Date					

Appendix E

BC-400 Scintillator Data

BC-400,BC-404,BC-408,BC-412,BC-416 Premium Plastic Scintillators

BICRON®

The premium plastic scintillators described in this data sheet include those with the highest light output, as well as the most economical (BC-416). The chart below will direct you to the scintillator suitable for your energy application.

Radiation Detected	BC-400	BC-404	BC-408	BC-412	BC-416
<100keV X-rays			X		
100keV to 5MeV gamma rays				X	
>5MeV gamma rays	X				X
Fast neutrons				X	X
Alphas, betas		X	X		
Charged particles,cosmic rays, muons, protons, etc.			X	X	X
Principal Uses/Applications	general purpose	fast counting	TOF large area	large area	large area economy

Scintillation Properties –	BC-400	BC-404	BC-408	BC-412	BC-416
Light Output, %Anthracene	65	68	64	60	38
Rise Time, ns	0.9	0.7	0.9	1.0	–
Decay Time (ns)	2.4	1.8	2.1	3.3	4.0
Pulse Width, FWHM, ns	2.7	2.2	~2.5	4.2	5.3
Wavelength of Max. Emission, nm	423	408	425	434	434
Light Attenuation Length, cm*	160	140	210	210	210
Bulk Light Attenuation Length, cm	250	160	380	400	400
Atomic Composition –					
No. H Atoms per cc ($\times 10^{22}$)	5.23	5.21	5.23	5.23	5.25
No. C Atoms per cc ($\times 10^{22}$)	4.74	4.74	4.74	4.74	4.73
Ratio H:C Atoms	1.103	1.100	1.104	1.104	1.110
No. of Electrons per cc ($\times 10^{23}$)	3.37	3.37	3.37	3.37	3.37

*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

General Technical Data –

Base .... Polyvinyltoluene

Density (g/cc) .... 1.032 g/cc

Refractive Index 1.58

Expansion Coefficient (per°C,<67°C): 7.8×10^{-5}

Softening Point .... 70°C

Vapor Pressure .... May be used in vacuum

Solubility .... Soluble in aromatic solvents, chlorinated solvents, acetone, etc. Unaffected by water, dilute acids, lower alcohols, alkalis and pure silicone fluids or grease.

Light Output .... At +60°C = 95% of that at+20°C. Independent of temperature from -60°C to +20°C

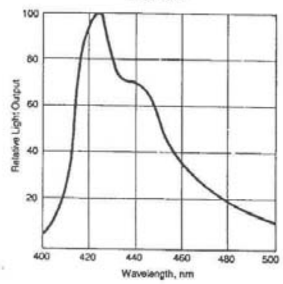
SAINT-GOBAIN
CRYSTALS & DETECTORS

Scintillation Products
Organic Products

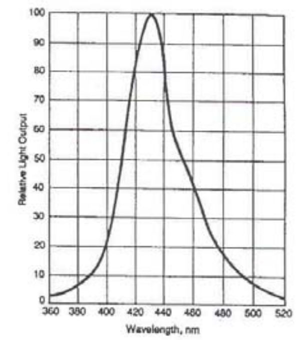
BC-400,BC-404,BC-408,BC-412,BC-416 Premium Plastic Scintillators

Emission Spectra

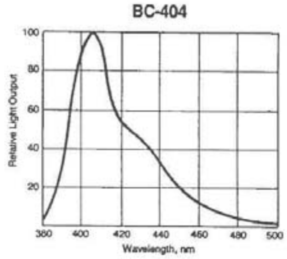
BC-400



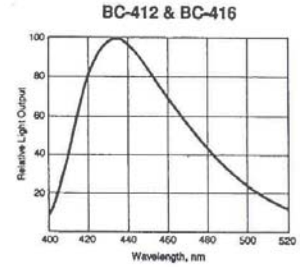
BC-408



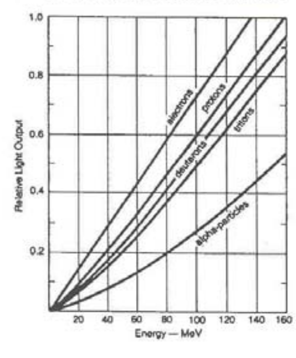
BC-404



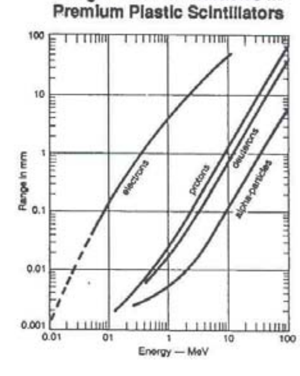
BC-412 & BC-416



Premium Plastic Scintillators Response to Atomic Particles



Range of Atomic Particles in Premium Plastic Scintillators



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Fax: 86 (0) 10 6512 9843

www.detectors.saint-gobain.com

Manufacturer reserves the right to alter specifications.

(06-02)

Plastic Scintillators

A plastic scintillator consists of a solid solution of organic scintillating molecules in a polymerized solvent. The ease with which they can be shaped and fabricated makes plastic scintillators an extremely useful form of organic scintillator.

General Description –

The scintillation emission of a typical plastic scintillator has a maximum around 425 nm. Plastic scintillators are characterized by a relatively large light output — typically 25-30% of NaI(Tl) — and a short decay time of around 2 ns. This makes the material suited for fast timing measurements.

All plastic scintillators are sensitive to X-rays, gamma rays, fast neutrons and charged particles.

Special formulations are available for thermal neutron detection or with improved X-ray efficiency. Plastic scintillators are the most popular scintillation material for use in calorimeters, time of flight detectors, nuclear gauging and large area contamination monitors.

The exact emission wavelength and decay time depend on the type of organic activator and on the host material. A large number of different plastic scintillators are available, each for a specific application. General characteristics of plastic scintillators are presented in another section of this brochure.

Availability –

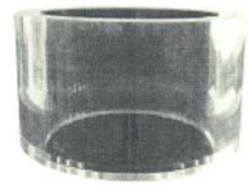
Our plastic scintillators are produced in a wide variety of shapes and sizes. Cast sheet is the most commonly used form.

You can also obtain precision thin sheets, thin film, rods, annuli, ingots and large rectangular blocks, filaments, powders and beads.

We supply most solid scintillators with their surfaces prepared to optimize light collection. For cast sheets, the cast surfaces are untouched, and the edges are machined and polished or diamond milled.

Rods, annuli and blocks are machined and polished, or coated with a diffuse reflector paint such as BC-620. Such a reflector is used only when there are few reflections of the scintillation light off the scintillator surfaces before the light reaches the PMT. Most applications require finished surfaces.

You can also obtain scintillators as finished detector assemblies. These incorporate light guides, photomultiplier tubes, special radiation entrance windows, and light tight wrappings (or metal housings). Monoline or Multiline assemblies can be made as well.



Plastic Scintillator Applications Guide

Scintillator	Distinguishing Feature	Principal Applications
BC-400	NE-102 equiv.	general purpose
BC-404	1.8 ns time constant	fast counting
BC-408	best general purpose	TOF counters; large area
BC-412	longest attenuation length (NE-110 equiv.)	general purpose; large area; long strips
BC-414		use with BC-484 wavelength shifter
BC-416	lowest cost	"economy" scintillator; large volume
BC-418	1.4 ns time constant	ultra-fast timing; small sizes
BC-420	1.5 ns time constant, low self-absorption	ultra-fast timing; for sheet areas > 100mm²
BC-422	1.4 ns time constant	very fast timing; small sizes
BC-422Q	quenched; 0.7 ns time constant	ultra-fast timing, ultra-fast counting
BC-428	green emitter	for photodiodes and CCDs; phoswich detectors
BC-430	red emitter	for silicon photodiodes and red-enhanced PMTs
BC-436	deuterated	fast neutron
BC-440	high temperature up to 100°C	general purpose
BC-440M	high temperature up to 100°C	general purpose
BC-444	slow plastic, 285 ns time constant	phoswich detectors for dE/dx studies
BC-444G	285 ns time constant; green emitter	phoswich detectors for dE/dx studies
BC-452	lead loaded (5%)	x-ray dosimetry (<100 keV); Mossbauer spectroscopy
BC-454	boron loaded (5%)	neutron spectrometry; thermal neutrons
BC-470	air equivalent	dosimetry
BC-490	casting resin scintillator	general purpose
BC-498	applied like paint	beta, gamma detection
BC-480	UV to blue waveshifter	Cerenkov detector
BC-482A	green emitter	waveshifter

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