Optimizing Moderators and Shielding

In a Neutron-Pulsing Delayed Gamma Experiment

Part I

Robert Crabbs

1-12-2009

INTRODUCTION

For the past several months, we have simulated an experiment which measures delayed gamma emissions to determine the fissile composition of a sample. The measurements occur in 10.12 s cycles, with a 100ms irradiation time, a 20ms cool-off, and a 10 s counting period. Neutrons are created by a 2.5 MeV D-D neutron generator with a strength of 1E8 neutrons per second. To increase the measurement sensitivity, we tailor the source spectrum with a layer of moderating material between the generator and the irradiation cavity containing the sample. This creates a flux of thermal neutrons which cause fissions within the target. Two HPGe detectors within the cavity then register the gamma rays released by the fission products created.

Recent calculations of fission rates in our proposed experimental geometry have shown some rather disappointing numbers. In light of the results, I double checked the simulations we completed earlier on which we based our optimized geometry. I also systematically tested various aspects to further optimize the thermal fissions rates in an HEU target.

Without any optimizations in place, we obtained the following results with the original design.

Sub-MeV/Fast Neutron Ratio at Target:	1.46941
Total Neutron Flux at Target:	9.15870E-05 (0.0113)
^{235}U Fission Probability:	8.09496E-06 (0.0147)
^{238}U Fission Probability:	3.03348E-08 (0.0153)
Total Neutron Flux at Detectors:	8.72953E-06 (0.0020)
Fast Neutron Flux at Detectors:	2.76449E-06 (0.0072)

The first set of MCNPX calculations were all very fast (about five minutes long), and therefore showed poor statistical uncertainties. I then submitted much longer jobs on the Lawrencium computer cluster to obtain better results. This write-up is based on the more precise results.

The HEU target remained constant between all the runs, as a single 1.50777 g cylindrical pin. This UO_2 pin had a radius of 0.25 cm, a length of 0.7 cm, a mass density of 10.97 g/cm^3, and a ^{235}U enrichment of 43%.

RESULTS: MODERATOR THICKNESS

As my first task, I verified original results pertaining to the optimum thickness of polyethylene moderator around the neutron generator. Note that the previous calculations optimized for combination of thermal/fast fission ratio and neutron flux. I have reported related quantities in Table 1 below.

Appendix A shows 2D projections of the experimental geometry used. This geometry is identical in function to the one that Jeremy Lorenzo used for the initial optimizations. He found that a 12 cm polyethylene thickness was best for maximizing the thermal/fast neutron ratio, while maintaining a high total flux at the target. (A high thermal/fast neutron ratio improves differentiation between ^{235}U and ^{238}U fissions, while total neutron flux relates to the strength of the delayed-gamma signal.)

For calculating thermal to fast neutron flux ratios, “thermal” neutrons are any which have energy below the 238U fission threshold (nearly 1 MeV). Fast neutrons, then, have energy greater than 1 MeV. Note that the flux has units of neutrons/cm^2/source neutron, and is tallied over the surface area of the target (1.49 cm^2).

Relative uncertainties are given in parentheses. The longer simulations tracked 2.5E8 source particles, which kept uncertainties under 3%.

MODERATOR THICKNESS	SUB-MeV/FAST NEUTRON RATIO	TOTAL NEUTRON FLUX	^{235}U FISSION PROBABILITY	^{238}U FISSION PROBABILITY
0 cm	0.90737	4.07964E-04 (0.0057)	3.46902E-05 (0.0088)	1.89671E-07 (0.0077)
1 cm	1.02561	3.79894E-04 (0.0059)	3.34343E-05 (0.0091)	1.62151E-07 (0.0082)
2 cm	1.12099	3.60749E-04 (0.0061)	3.32063E-05 (0.0091)	1.44687E-07 (0.0087)
3 cm	1.19914	3.26957E-04 (0.0064)	3.22994E-05 (0.0094)	1.25286E-07 (0.0092)
4 cm	1.22939	2.96774E-04 (0.0067)	3.07960E-05 (0.0096)	1.11305E-07 (0.0097)
5 cm	1.25972	2.66749E-04 (0.0071)	2.93874E-05 (0.0099)	9.76260E-08 (0.0103)
6 cm	1.28043	2.29325E-04 (0.0076)	2.60806E-05 (0.0102)	8.32861E-08 (0.0110)
7 cm	1.29042	2.03066E-04 (0.0080)	2.43051E-05 (0.0106)	7.31852E-08 (0.0116)
8 cm	1.30053	1.72638E-04 (0.0087)	2.12137E-05 (0.0113)	6.15451E-08 (0.0124)
9 cm	1.25282	1.42074E-04 (0.0095)	1.82351E-05 (0.0122)	5.20332E-08 (0.0136)
10 cm	1.26973	1.19340E-04 (0.0103)	1.56754E-05 (0.0130)	4.32497E-08 (0.0147)
11 cm	1.26852	9.73456E-05 (0.0113)	1.30891E-05 (0.0141)	3.50776E-08 (0.0161)
12 cm	1.26190	8.29570E-05 (0.0123)	1.10059E-05 (0.0153)	3.02603E-08 (0.0173)
13 cm	1.25472	6.54085E-05 (0.0138)	8.91634E-06 (0.0170)	2.38378E-08 (0.0195)
14 cm	1.26057	5.13498E-05 (0.0154)	6.95613E-06 (0.0187)	1.87547E-08 (0.0215)
15 cm	1.30745	4.16787E-05 (0.0170)	5.95400E-06 (0.0204)	1.47388E-08 (0.0239)
16 cm	1.25566	3.30046E-05 (0.0189)	4.82529E-06 (0.0228)	1.21635E-08 (0.0268)

TABLE 1: NEUTRON FLUX AND FISSION AS FUNCTIONS OF MODERATOR THICKNESS

The sub-threshold fission probability (in fissions per source neutron) does not peak at 12cm moderator thickness. Indeed, it even seems that using polyethylene moderator is detrimental to thermal fission! It does, however, serve to slow fast neutrons. Clearly, there are some significant neutron absorption issues with polyethylene that make it less than ideal for our purposes.

RESULTS: DISTANCE FROM TARGET TO DETECTORS

For the initial simulations, we did not account for detection efficiency of any sort. The two HPGe crystals we included in the geometry both started much too far away from the target to be practical. The fission rates due to our pulsed 1 x 10^8 neutron/s generator are quite small, so very few delayed gammas are released during the course of a duty cycle. We want the detectors to count as many of the gamma emissions as possible.

The next set of simulations varied the position of the detectors relative to the HEU target. In the first calculations, the detectors were placed 22.24 cm from the sample. The HPGe crystals were protected by a two layers of shielding, so as to reduce fast neutron flux through them. This shielding was composed of 10 cm of polyethylene around a 5 cm shell of lead directly surrounding the detectors. The shielding extended 1.76 cm beyond the faces of the detectors closest to the target. See Appendix B for 2D projections of this geometry.

Note that these crystals become damaged after sustaining a total fast neutron fluence of 10^9 neutrons/cm^2. Radiation damage to the detectors is discussed in a later section.

DISTANCE TO DETECTORS	SUB-MeV/FAST NEUTRON RATIO	TOTAL NEUTRON FLUX	^{235}U FISSION PROBABILITY	^{238}U FISSION PROBABILITY
22.24 cm	1.26189	8.29570E-05 (0.0123)	1.10059E-05 (0.0153)	3.02603E-08 (0.0173)
12 cm	1.26278	7.54413E-05 (0.0127)	1.00563E-05 (0.0157)	2.75129E-08 (0.0181)
11 cm	1.22274	7.05781E-05 (0.0131)	9.36563E-06 (0.0164)	2.62403E-08 (0.0184)
10 cm	1.24369	6.64661E-05 (0.0135)	8.87748E-06 (0.0166)	2.44133E-08 (0.0189)
9 cm	1.20530	6.20819E-05 (0.0139)	8.28780E-06 (0.0173)	2.32898E-08 (0.0197)
8 cm	1.23600	5.42408E-05 (0.0148)	7.16388E-06 (0.0188)	2.02229E-08 (0.0209)
7 cm	1.14857	4.74933E-05 (0.0158)	6.02977E-06 (0.0198)	1.81304E-08 (0.0220)
6 cm	1.11993	3.74382E-05 (0.0177)	4.80844E-06 (0.0221)	1.49419E-08 (0.0247)
5 cm	1.15149	2.86998E-05 (0.0201)	3.55233E-06 (0.0250)	1.12212E-08 (0.0281)
4 cm	1.12301	2.08125E-05 (0.0236)	2.52073E-06 (0.0297)	8.36096E-09 (0.0327)

TABLE 2: EFFECTS OF DETECTOR SHIELDING ON FISSION PROBABILITIES

RESULTS: RECONFIGURATION OF SHIELDING

Neutron flux and thermal fission rate were further improved by other changes in the experimental geometry. For example, borated polyethylene in the irradiation cavity is counterproductive. However, we had been using it in previous simulations, which necessitated the use of lead shielding around the HPGe detectors. (The ^{10}B thermal neutron capture reaction releases a 480keV gamma ray.) One of the changes replaced the Pb shielding with additional polyethylene.

All the different test cases are listed below. Each change has a corresponding abbreviation.

- **MODIFICATION A**: Remove Pb gamma shielding from around the detectors, replacing it with polyethylene.
- **MODIFICATION B**: Encase the setup with a neutron reflecting material (graphite). Fewer neutrons escape, thereby increasing flux within the test chamber, and decreasing the fast neutron radiation hazard.
- **MODIFICATION C**: Use iron instead of graphite for neutron reflection.
- **MODIFICATION D**: Use polyethylene instead of graphite for neutron reflection.

Some of the MCNPX simulations used combinations of the above options. All of the tests are variations on the design with detectors 4 cm from the target, surrounded by 15 cm of mixed polyethylene and lead shielding. (See Appendix C for the illustrations of the changes made.)

Again the neutron fluxes are taken at the sample, with "fast neutrons" being any over 1MeV in energy.

SHIELDING MODIFICATIONS	SUB-MeV/FAST NEUTRON RATIO	TOTAL NEUTRON FLUX	^{235}U FISSION PROBABILITY	^{238}U FISSION PROBABILITY
None	1.12301	2.08125E-05 (0.0236)	2.52073E-06 (0.0297)	8.36096E-09 (0.0327)
A	0.95902	1.60978E-05 (0.0268)	2.12689E-06 (0.0347)	7.10827E-09 (0.0360)
B	1.16701	3.00051E-05 (0.0194)	3.84486E-06 (0.0236)	1.16684E-08 (0.0268)
A+B	1.00712	1.96440E-05 (0.0240)	2.76778E-06 (0.0300)	8.46696E-09 (0.0325)
C	1.10479	2.13977E-05 (0.0232)	2.64135E-06 (0.0289)	8.61083E-09 (0.0322)
D	1.12856	2.04636E-05 (0.0238)	2.51392E-06 (0.0298)	8.20490E-09 (0.0331)

TABLE 3: MATERIALS OPTIMIZATIONS

RESULTS: DISTANCE FROM NEUTRON GENERATOR TO TARGET

The previous sections show that the presence of excess polyethylene is detrimental to neutron fluxes and fission probabilities in the target. Polyethylene moderates fast neutrons, making them more likely to cause fissions. However, polyethylene contains light hydrogen nuclei, which tend to absorb neutrons. Thus, there are two competing effects in our spectrum-tailoring assembly. We want to minimize the neutron absorption, while also creating a sufficient thermal neutron flux at the target.

In addition, neutrons produced in the D-D generator are emitted more or less isotropically. Therefore, the flux through the target can be maximized by minimizing the distance between source and target. Naturally, this distance must be at least as large as the thickness of the moderator used.

However, we also need to consider the radiation effects of fast neutrons on the detectors. We placed additional polyethylene around the HPGe crystals to minimize radiation damage. This shielding put the target/detector plane farther from the source.

Table 4 gives the results of another series of simulations, for which the thickness of shielding was reduced incrementally from 15 cm to 0 cm. The crystals are each 4 cm from the target. The lead shielding was also replaced with polyethylene (material option A in the previous section). See Appendix D for a figure depicting the geometry.

SHIELDING THICKNESS	SUB-MeV/FAST NEUTRON RATIO	TOTAL NEUTRON FLUX	^{235}U FISSION PROBABILITY	^{238}U FISSION PROBABILITY
14.7 cm	0.95902	1.60978E-05 (0.0268)	2.12689E-06 (0.0347)	7.10827E-09 (0.0360)
13.7 cm	0.95360	1.87439E-05 (0.0250)	2.53353E-06 (0.0316)	8.38699E-09 (0.0341)
12.7 cm	1.00320	2.14158E-05 (0.0230)	3.02544E-06 (0.0282)	9.22982E-09 (0.0317)
11.7 cm	0.98703	2.44282E-05 (0.0218)	3.34081E-06 (0.0277)	1.05200E-08 (0.0298)
10.7 cm	1.01241	2.87175E-05 (0.0202)	3.88748E-06 (0.0252)	1.20763E-08 (0.0274)
9.7 cm	1.00019	3.42909E-05 (0.0185)	4.61133E-06 (0.0228)	1.43990E-08 (0.0255)
8.7 cm	1.01054	3.89260E-05 (0.0174)	5.23654E-06 (0.0217)	1.61408E-08 (0.0236)
7.7 cm	1.06709	4.58997E-05 (0.0160)	6.48004E-06 (0.0195)	1.88012E-08 (0.0221)
6.7 cm	1.08581	5.29472E-05 (0.0150)	7.48242E-06 (0.0182)	2.14462E-08 (0.0206)
5.7 cm	1.13407	6.38801E-05 (0.0137)	9.15230E-06 (0.0167)	2.52476E-08 (0.0188)
4.7 cm	1.18366	7.48244E-05 (0.0127)	1.03940E-05 (0.0157)	2.86973E-08 (0.0177)
3.7 cm	1.19377	9.03491E-05 (0.0116)	1.23116E-05 (0.0142)	3.41605E-08 (0.0163)
2.7 cm	1.19451	1.06454E-04 (0.0107)	1.47816E-05 (0.0133)	4.02552E-08 (0.0148)
1.7 cm	1.25770	1.28792E-04 (0.0098)	1.79775E-05 (0.0120)	4.76501E-08 (0.0138)
0.7 cm	1.26724	1.52673E-04 (0.0091)	2.08371E-05 (0.0112)	5.55002E-08 (0.0128)
0 cm	1.37757	1.51611E-04 (0.0093)	1.83214E-05 (0.0121)	5.20616E-08 (0.0136)

TABLE 4: EFFECTS OF SHIELDING ON FISSION PROBABILITIES

The data above shows a clear trend – decreasing the amount of shielding around the detectors improves the probability that a source neutron will cause fission. The improvement is almost an order of magnitude between the setup with 15 cm of polyethylene versus the one with no additional shielding.

However, we must still consider how the shielding affects the neutron flux through the detectors. This is the subject of a later section.

A NEW, OPTIMIZED GEOMETRY

Though by no means exhaustive, the simulations described in this paper have led to a more optimized experimental geometry. That is, we have found a setup which yields a significantly better fission probability per source neutron released from the D-D generator.

The original geometry (Appendix A) produced a total neutron flux of 8.1E-5 at the target, with a thermal to fast neutron ratio of 6.38. Note, however, that this early model almost completely ignored geometric efficiency. The detectors were placed on the far walls of the irradiation cavity, and therefore very little shielding interfered with the neutron flux at the target. The new geometry has improved both the fission probability and the geometric efficiency.

Several improvements have been made, based on maximizing the ^{235}U fission probability.

- Replacing borated polyethylene with pure polyethylene as shielding around the HPGe detectors.
- Removing the Pb shielding layer around the detectors
- Decreasing the thickness of the polyethylene shielding from 15 cm to 1 cm
- Surrounding the neutron generator on 5 sides with a neutron reflecting block rather than moderator
- Reducing the moderator thickness from 12 cm to 8 cm
- Replacing graphite with iron as the neutron reflector

With these optimizations in place, we obtained the following results.

Sub-MeV/Fast Neutron Ratio at Target:	1.02588
Total Neutron Flux at Target (1/cm^2):	1.21534E-03 (0.0034)
^{235}U Fission Probability:	9.31954E-05 (0.0056)
^{238}U Fission Probability:	5.22787E-07 (0.0047)
Total Neutron Flux at Detectors (1/cm^2):	8.89545E-04 (0.0002)
Fast Neutron Flux at Detectors (1/cm^2):	3.69629E-04 (0.0006)

The geometry optimizations resulted in an order of magnitude increase in the 235U fission probability, while also increasing the dose to the detectors by a factor of approximately 100.

For future revisions, we will test the effects of using D_2O (heavy water) in place of polyethylene as both moderator and detector shielding. The deuterium in heavy water does not absorb thermal neutrons like ^{1}H does. Therefore, we may be able to use more shielding without significantly decreasing the neutron flux in the target.

See Appendix E for an illustration of the final optimized geometry.

RESULTS: FAST NEUTRONS AND DAMAGE TO THE DETECTORS

As I mentioned earlier, HPGe crystals can withstand a certain amount of fast neutron exposure before radiation damage in the crystal lattice decreases performance. The threshold is approximately 1E9 total fast neutrons / cm^2. (Here, all neutrons with energy above 100keV are counted as "fast".) Naturally, since detectors are expensive, we don't want to expose them to non-reversible damage in one or two measurements! It is possible to repair crystals through thermal annealing, though this is time consuming, and may not fully repair the lattice structure of the HPGe.

Reductions in the amount of polyethylene present in the experimental geometry have been shown to increase fission probabilities. However, this goes hand-in-hand with increased radiation exposure to the detectors.

Table 5 summarizes the fast neutron fluxes through the HPGe crystals for most of the simulations. Note that all of the readings are averages over both detectors. Again, in this context, a fast neutron is any with energy greater than 100keV.

Since several different parameters were varied throughout the simulations, I will use abbreviations to describe geometries. The abbreviations are as follows:

- modXX
  For tests optimizing the thickness of the moderator between the neutron generator and the irradiation cavity. XX is the thickness (in cm) of the polyethylene.
  All of these runs use the 15 cm Pb/polyethylene shield around the detectors, which are 22 cm from the target.
- distXX
  Corresponds to the simulations that dealt with the distances between the HPGe detector crystals and the target. XX is the distance between a detector's front face and the target.
  The moderator thickness is held constant at 12 cm, with the same shielding as the modXX runs.
- MatYY
  Specifies the configuration options used in the runs dealing with shielding and reflector materials. YY is a list of the options used.
  The moderator thickness is held constant at 12 cm, and the detectors are placed 4 cm from the target.
- shldXX
  For runs varying the thickness of polyethylene shielding around the HPGe crystals. XX is the thickness of the shielding layer on either side of a crystal.
  The moderator thickness is held constant at 12 cm, and the detectors are placed 4 cm from the target. In addition, all Pb shielding around the detectors was replaced by polyethylene.

No exposure tallies were made for the modXX simulations.

See the previous page for an explanation of the abbreviations for “Geometry Used”.

GEOMETRY USED	TOTAL NEUTRON FLUX	FAST NEUTRON FLUX		GEOMETRY USED	TOTAL NEUTRON FLUX	FAST NEUTRON FLUX
dist22	2.86039E-05 (0.0010)	4.64759E-06 (0.0055)		**shld14**	5.69553E-06 (0.0023)	5.68571E-07 (0.0149)
dist12	2.72000E-05 (0.0011)	4.30735E-06 (0.0058)		**shld13**	6.97506E-06 (0.0021)	7.13937E-07 (0.0133)
dist11	2.57272E-05 (0.0011)	4.07305E-06 (0.0059)		**shld12**	8.54845E-06 (0.0018)	9.02760E-07 (0.0118)
dist10	2.40379E-05 (0.0011)	3.80358E-06 (0.0062)		**shld11**	1.05230E-05 (0.0017)	1.14159E-06 (0.0105)
dist09	2.20472E-05 (0.0012)	3.50640E-06 (0.0064)		**shld10**	1.29677E-05 (0.0016)	1.45530E-06 (0.0093)
dist08	1.97463E-05 (0.0012)	3.16666E-06 (0.0067)		**shld09**	1.60255E-05 (0.0014)	1.85859E-06 (0.0082)
dist07	1.72299E-05 (0.0013)	2.78692E-06 (0.0072)		**shld08**	1.98225E-05 (0.0013)	2.37595E-06 (0.0073)
dist06	1.45307E-05 (0.0014)	2.36218E-06 (0.0078)		**shld07**	2.45786E-05 (0.0011)	3.05268E-06 (0.0064)
dist05	1.18944E-05 (0.0016)	1.94642E-06 (0.0086)		**shld06**	3.04894E-05 (0.0010)	3.94834E-06 (0.0057)
dist04	9.64685E-06 (0.0018)	1.60553E-06 (0.0095)		**shld05**	3.79055E-05 (0.0009)	5.10796E-06 (0.0050)
MatA	4.68605E-06 (0.0025)	4.54320E-07 (0.0166)		**shld04**	4.71872E-05 (0.0008)	6.65440E-06 (0.0044)
MatB	1.52689E-05 (0.0013)	2.19425E-07 (0.0082)		**shld03**	5.88793E-05 (0.0008)	8.72754E-06 (0.0039)
MatAB	6.08605E-06 (0.0021)	5.15390E-07 (0.0156)		**shld02**	7.36066E-05 (0.0007)	1.15351E-05 (0.0034)
MatC	9.67549E-06 (0.0018)	1.62097E-06 (0.0095)		**shld01**	9.22289E-05 (0.0006)	1.55328E-05 (0.0029)
MatD	9.18196E-06 (0.0018)	1.55872E-06 (0.0097)		**shld00**	9.91258E-05 (0.0006)	2.24857E-05 (0.0025)

TABLE 5: DETECTOR NEUTRON EXPOSURES

Note that the HPGe crystals, with 4 cm radii and 8 cm lengths, have surface areas of 301.6 cm^2.

SIGNAL STRENGTHS VERSUS NEUTRON EXPOSURE TO THE DETECTORS

From the sets of simulations discussed, we can make the following general observations.

- Decreasing the thickness of moderator between the generator and the target improves the thermal neutron flux at the target, and hence increases the fission probability. This only applies down to a certain size, but the moderator tests showed a steady improvement down to 8 cm thickness. However, decreasing the amount of moderator also increases the fast neutron flux through the detectors.
- The neutron generator should be surrounded on five sides by a neutron reflector, rather than polyethylene. This increases the number of fissions in the HEU target by about a factor of 2. The radiation exposure to the detectors is similarly increased.
- Using iron rather than graphite as neutron reflector yields a very slight performance improvement, on the order of 5%.
- If we are to put the HPGe detectors closer to the target, then we must also vastly decrease the thickness of the shielding surrounding them. The extra polyethylene absorbs much of the thermal neutron flux that would otherwise cause fission in the target. Of course, doing so results in much higher fast neutron fluxes in the detector crystals.

Disregarding the radiation damage to the detectors for now, consider the following. In our simulations of delayed gamma responses, we determined the gamma yields per 1000 fissions, separated in 50ms time bins over a 10s counting period. Generally, the minimum yields are on the order of 0.002 gammas per 1000 fissions per 50ms.

If we want to achieve a maximum 1% uncertainty in any of the time bin, we need to measure 10,000 counts in that channel. Given our gamma yields, we would then need 5E9 fissions to obtain the desired precision.

The maximum fission probability for this geometry is on the order of 3E-5 fissions per source neutron, when combining all of the optimizations discussed so far.

Thus, we'll need to generate 1.7E14 source neutrons to make the measurement on a 1.50777g HEU pin. The fast neutron flux through either HPGe crystal is approximately 3E-4 neutrons per cm^2 per source neutron. Thus, 1.7E14 source particles results in a fast neutron exposure of 5E10 neutrons per cm^2. (This is 50 times greater than the "lethal" dose for the crystals.)

Also, assume we use a neutron generator of strength 1E8 neutrons per second, with a 10.12s duty cycle and 100ms pulse length. Then we'd obtain 1E7 neutrons per pulse, and we would need to measure over 1E7 counting periods. Such a measurement would take roughly 2000 days.

OTHER FACTORS AND LIMITATIONS

We may be able to reduce the number of source neutrons needed to run a measurement. Consider the time binning of the gamma yields. While we had calculated the gamma signals for 50ms time windows, we will not need such fine resolution. The extra information gained by the time dependence serves to define the shape of the gamma response, which depends on the nucleus that fissioned.

However, it does not take 200 points (10 seconds split into 50ms bins) to accurately define a gamma response curve. In fact, we may be able to use as few as 10 time bins, thereby reducing the required fission amount by a factor of 20.

Furthermore, all of the simulations use a single, 1.50777 g uranium oxide pellet to determine fission probabilities. Increasing the fissionable mass of the target would result in a roughly linear increase in the number of fissions, and hence emitted delayed gammas. We currently have 12 identical HEU pellets (18.1 grams total), which lends another factor of 12 in reducing the number of source neutrons.

We may also be able to make a geometrical improvement in the shape of the target. Because the cross-section for thermal fission in ^{235}U is very large (on the order of 1000 barns), fission events are more likely to occur near the surface of an HEU pellet. (Given that the UO_2 pellets have a mass density of 10.97 g/cm^3, with 43% enrichment in ^{235}U, the skin depth for thermal neutrons is roughly 0.09 cm.)

If we were the melt the 12 pellets into a foil of thickness equal to the skin depth, it would cover a cross-sectional area of 18 cm^2. The pellets themselves are 0.5 cm in diameter and 0.7 cm long, so each shows a maximum cross-section of 0.35 cm^2. Thus, 12 pellets have a combined cross-sectional area of 4.2 cm^2. Exposing a larger surface to the interrogating neutrons would result in a higher fission probability per source neutron.

However, there are other factors that decrease the sensitivity of our measurements. First, we have neglected the detection efficiency of the HPGe detectors, instead assuming that all the emitted delayed gamma rays are counted. For high gamma ray energies, the intrinsic efficiency of our crystals is on the order of 10%. Furthermore, the geometric efficiency of our setup is close to 33%. So, perhaps as few as 1 in 30 emitted gammas are actually detected.

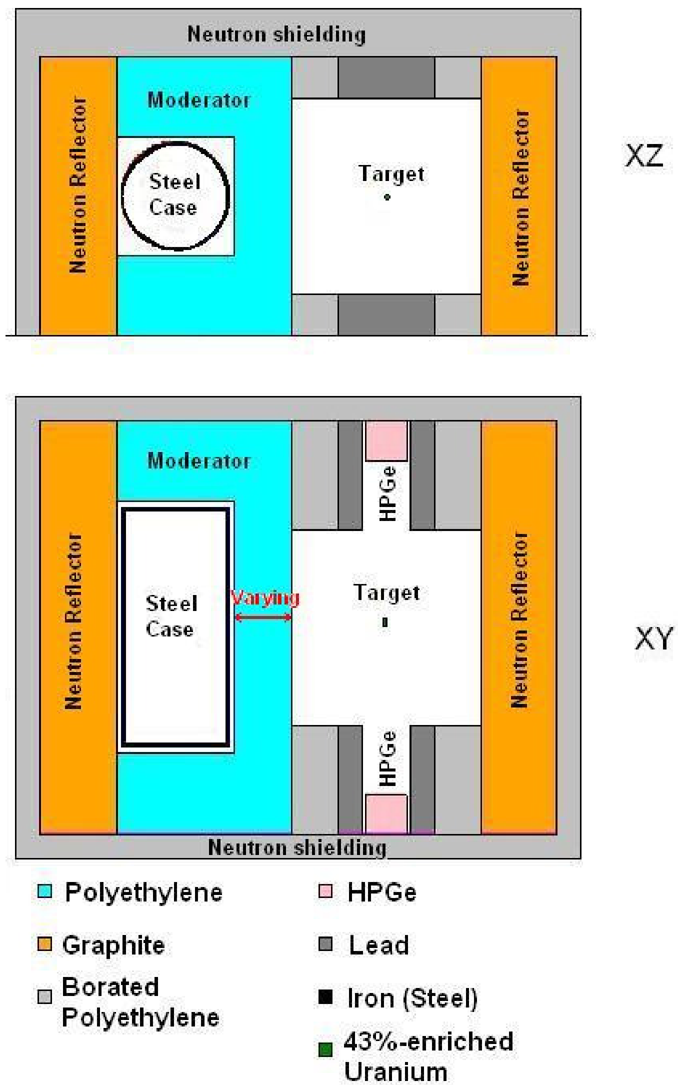
Consider, too, that this experiment aims to determine the amounts of multiple fissionable nuclides in a mixed sample. While our current target contains only ^{235}U and ^{238}U, we want to apply the delayed gamma technique to samples that may also contain ^{239}Pu. To do so, we would need to precisely characterize the <u>difference</u> between ^{235}U and ^{239}Pu gamma responses. This requires a much higher level of statistics, and therefore a much stronger neutron source.

In the end, our current geometry is unlikely to be useful for spent fuel measurements. However, given a much stronger neutron source, combined with better neutron shielding, we might yet make the more complex measurements on spent fuel. A reactor equipped with a sample shuttling system would fulfill both requirements.

APPENDIX A: ORIGINAL DESIGN

The original design surrounds a neutron generator with polyethylene moderator on 3 sides, with a graphite neutron reflector on the final side. Two HPGe detectors sit within the irradiation cavity, and are shielded from source neutrons by borated polyethylene and Pb bricks. Another graphite reflector on the far right side of the setup helps to keep neutrons within the testbed. The entire setup is surrounded by a layer of borated polyethylene to minimize neutron exposure outside.

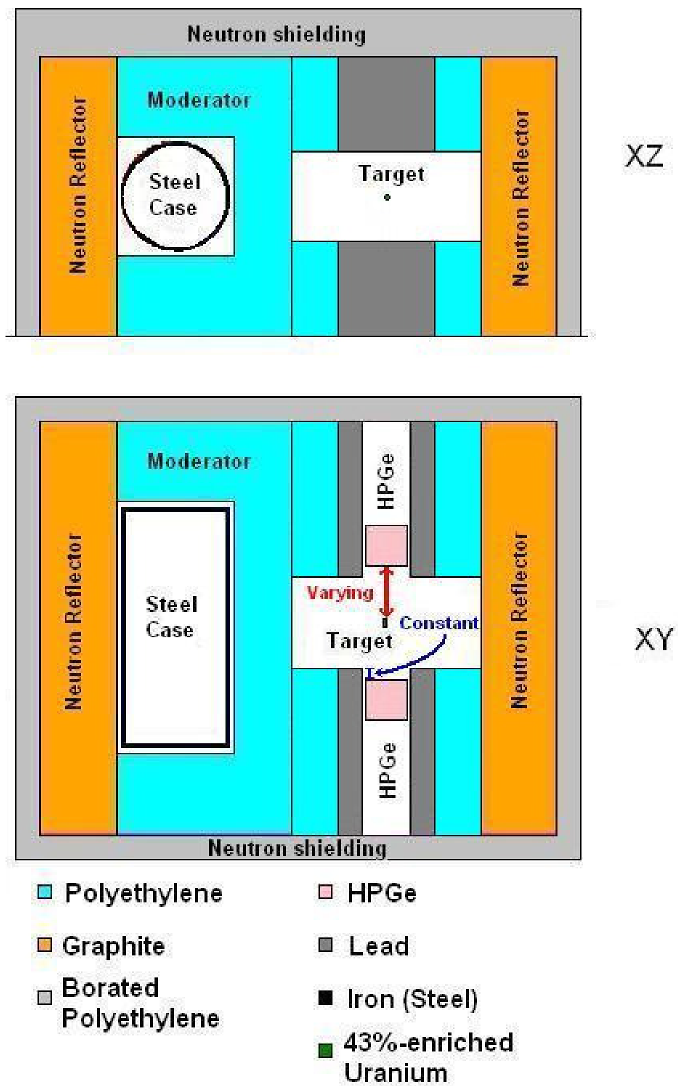
Jeremy Lorenzo determined that the optimum moderator thickness between the source and the target should be 12 cm. In a separate series of simulations, I varied this thickness myself found that 8cm of moderator produced a greater thermal neutron flux at the target.



APPENDIX B: MOVING DETECTORS CLOSER TO THE TARGET

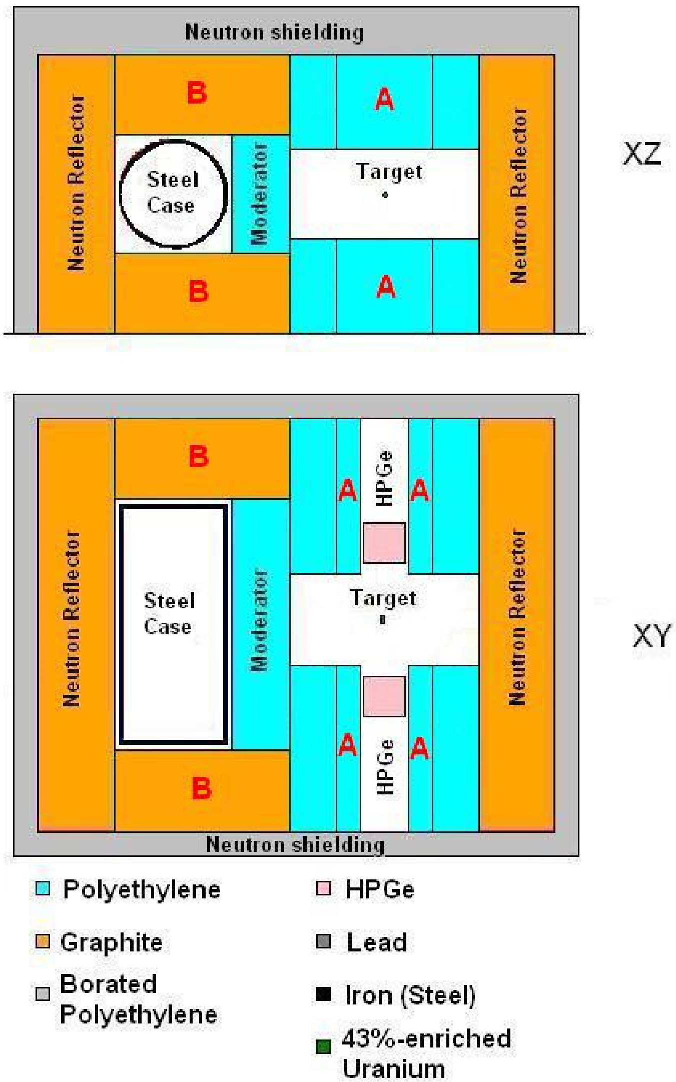
For the second series of simulations, I studied the effects of the shielding around the detector. In the first revision of the geometry, the HPGe crystals were placed fairly distant (22.24 cm) from the HEU sample target. Such a setup has very low geometric efficiency.

For these tests, I moved the crystals towards the target in 1 cm increments, while also extending the shielding to remain 1.76 cm beyond the front face of the crystal. In doing so, as the distance between the detectors shrank, so too did the size of the irradiation cavity (which retained a square YZ cross-section).



APPENDIX C: OTHER CHANGES TO THE EXPERIMENTAL GEOMETRY

The third set of simulations made changes to the material types used, rather than geometrical aspects of the experimental setup. There are four main modifications that I considered, shown in the figure below.



Modification A
Substitute polyethylene for the Pb shielding around the detectors.

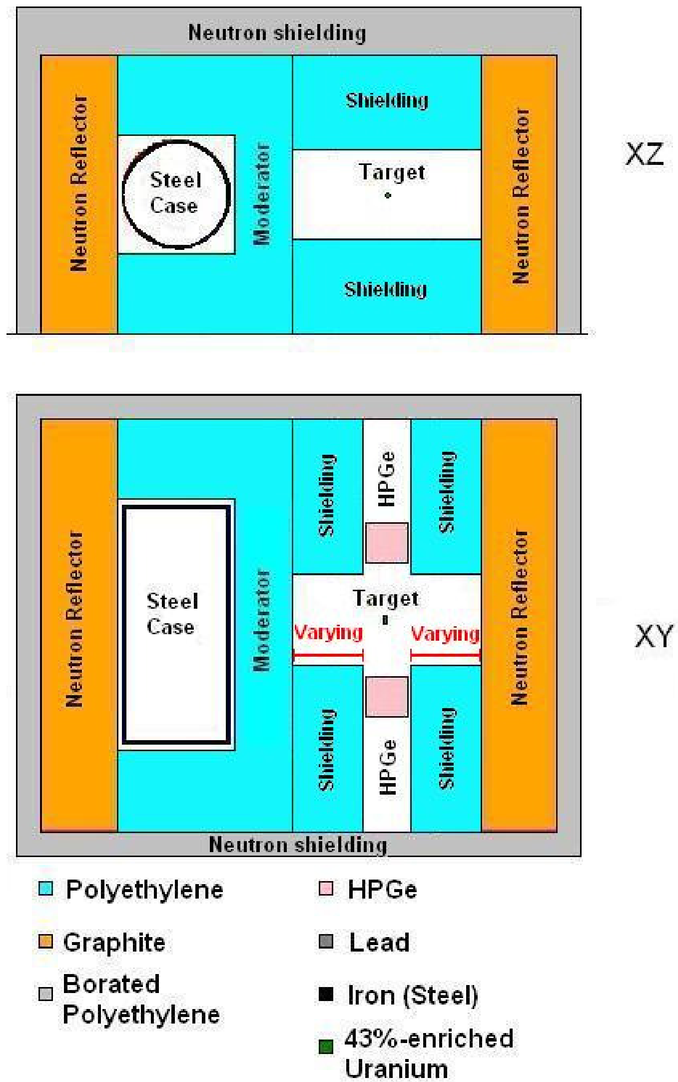
Modification B
Use reflectors instead of moderator around the sides of the neutron generator.

Modification C
Use iron in place of graphite for reflectors.

Modification D
Use polyethylene in place of graphite for reflectors.

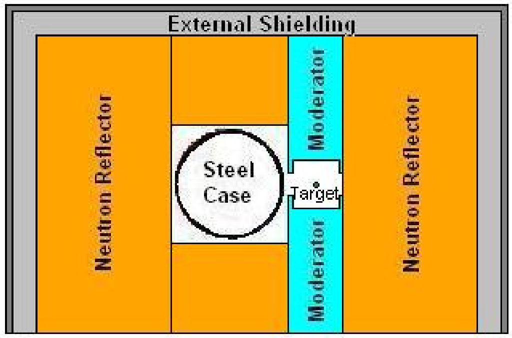
APPENDIX D: REDUCING SHIELDING AROUND THE DETECTORS

We also wanted to see how much we could increase the neutron flux through the HEU target by bringing it closer to the neutron generator. This required decreasing the thickness of polyethylene shielding around the detector crystals.

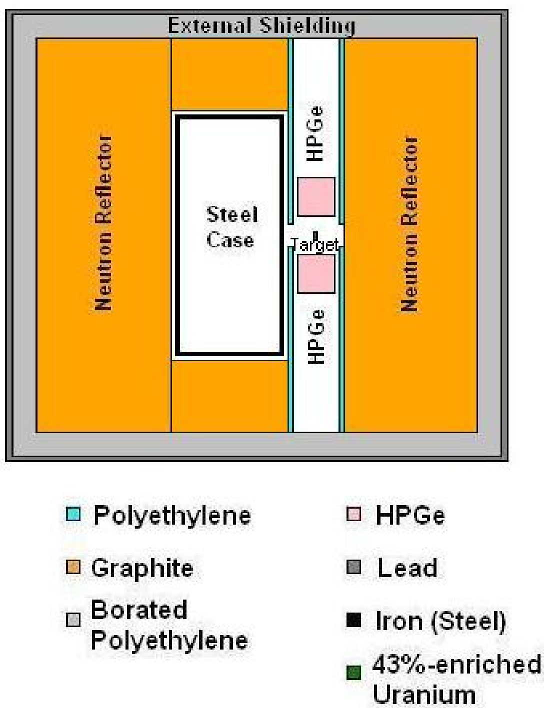


APPENDIX E: THE OPTIMIZED GEOMETRY

Below is the geometry yielding the highest fission probability. Not that it does not account well for shielding the HPGe detectors. Future revisions will most likely substitute heavy water in place of all polyethylene, so as to increase moderation without also increasing thermal neutron absorption.



XZ



XY