Optimizing Moderators and Shielding
In a Neutron-Pulsing Delayed Gamma Experiment

Part II

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INTRODUCTION

Part I of this report details a number of optimizations of the geometry for a delayed neutron experiment. Recall that the experiment uses a 2.5 MeV D-D neutron generator, which emits 1E8 neutrons per second. These neutrons are moderated to thermal energies, so as to cause fission in a highly-enriched uranium target. (This target is a single HEU pin with a 0.25cm radius, 0.7cm length, 10.97 g/cm^3 material density, and 43% ^{235}U enrichment.) Measurements occur in 10.12 s cycles, with a 100ms irradiation time, a 20ms cool-off, and a 10s counting period.

I concluded that the following design parameters maximize fission probabilities in the irradiated target:

- The neutron generator is surrounded with graphite on 5 of 6 sides.
- Rather than use moderator directly between the D-D source and the target, surround the detectors in a shell of polyethylene. This shell puts 1cm of moderator between the source and the detectors.
- To maximize geometric efficiency, place the detectors as close as possible to the detectors. The shielding limits the degree to which the crystals can be brought in.

Two-dimensional projections of this "optimal" geometry can be found in Appendix A. Simulations of the geometry gave the following results.

Thermal/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)
Estimated Fast Neutron Fluence ($1/cm^2$):	1.98309E+10
Estimated Time for Measurement (days):	6.28409E+02

The "Estimated Fast Neutron Fluence" reflects the total number of fast neutrons that hit a detector during one complete assay of the single HEU pellet. The "Estimated Time for

Measurement", similarly, is the time it will take to create the necessary delayed gamma counts, given our source strength of 1E7 neutrons per 100ms irradiating pulse.

Note the very large fast neutron flux through the detectors. The lack of substantial shielding directly between the HPGe and the D-D sources leaves this as no surprise. For every ^{235}U fission event, approximately 4 fast neutrons pass through the HPGe crystals. This is significant, because the detectors can be damaged by high neutron fluences on the order of 1E9 neutrons/cm^2.

In Part I of this report, I estimated that we need 1.7E14 source neutrons to assay the ^{235}U content of a single HEU pin to 1% uncertainty. That many source neutrons would expose the HPGe crystals to 5E10 neutrons per cm^2, a factor of 50 above the limit for radiation damage. Clearly, this is far from ideal—a single measurement puts a big dent in the detectors.

We could easily reduce the number of fast neutrons that impinge on the crystals by placing more moderating shielding around them. However, as the simulations show, the more shielding used, the fewer fissions produced, and therefore the smaller our measured signal. This occurs because of the protium in the polyethylene moderator, which has a significant thermal neutron absorption coefficient.

Fortunately, there is a similarly effective moderating material which does absorb thermal neutrons—heavy water, or D_2O. Deuterium is much more stable than protium with regards to neutron absorption, and still has a small enough mass to slow neutrons in a collision.

This second part of the geometry optimization explores the effects of D_2O moderator in our experiment. The basic setup is somewhat simpler than before. The D-D generator is still surrounded by graphite (a good neutron reflector), but on one side, a large body of heavy water sits between the source and the target. In addition, D_2O tanks fill each corner of the irradiation chamber, leaving space enough for the target and four detectors. See Appendix B for illustrations of the new geometry.

I again used the Lawrencium computer cluster to obtain high-precision simulation results. Each run tracked 2.5E8 source neutrons, giving uncertainties less than 2% for most tallies.

RESULTS: MODERATOR THICKNESS

As my first task, I revisited the question of optimum moderator thickness. While we want to maximize the likelihood that a source neutron will cause fission in the target, we must also consider the effects of fast neutron radiation in the detectors.

In previous simulations, I varied the moderator thickness from 0cm to 16cm (using polyethylene). For the D2O tests, I decided to use a much wider range—4cm to 52cm. We are not limited by thermal neutron absorption in heavy water, so making a very thick moderator does not reduce fission probabilities very much. In addition, since D_2O contains deuterium instead of hydrogen, it is less effective than polyethylene at slowing down neutrons. Therefore, we need to place more heavy water between the source and the target. And of course, the more moderating material, the less radiation hazard posed to the detectors.

Table 1 gives information on the fission probabilities for each of the simulations. Neutron flux through the detectors is addressed in Table 2. All fluxes and fission probabilities are normalized per source neutron, and uncertainties are given in parentheses where available. Best results for each given quantity are highlighted in red.

To calculate "Estimated Fast Neutron Fluence" and "Estimated Time for Measurement", I did the following. Let the **F** represent the fission probability per source neutron and **X** be the fast flux through the detectors. In addition, consider the delayed gamma response over time, which we'll call **R**. For the 1.50777g HEU sample, the delayed gamma response dropped off to 0.002 gammas per 1000 fissions per 50ms time bin, in a 3 keV energy window.

To obtain a 1% uncertainty in the counts registered in any given time/energy bin, we must detect 1E4 gammas. Assuming that ALL emitted delayed gammas are detected (which is far from realistic), we'll then need a number of fissions equal to **10000 / R** .

Given the fission probability, we'll need **10000 / R F** source neutrons to obtain the required signal. This corresponds to a fast neutron flux in the detectors of:

$$\textbf{Dose} = 10000\ X / R\ F \qquad \text{(neutrons per cm}^2\text{)}$$

Then, given a pulse duty cycle of **t** seconds, with a source strength of **N** neutrons per pulse, it will take

$$\textbf{Time} = 10000\ t / N\ R\ F \qquad \text{(seconds)}$$

$$= 0.1157\ t / N\ R\ F \qquad \text{(days)}$$

to produce the required source neutrons.

MODERATOR THICKNESS	SUB-MeV/FAST NEUTRON RATIO	TOTAL NEUTRON FLUX	^{235}U FISSION PROBABILITY	^{235}U / ^{238}U FISSION RATIO
4 cm	2.21681	**1.07750E-03 (0.0036)**	5.12250E-05 (0.0074)	183.559
8 cm	**2.59797**	8.61480E-04 (0.0041)	**5.55357E-05 (0.0073)**	283.198
12 cm	2.56066	6.84487E-04 (0.0047)	5.52025E-05 (0.0074)	350.000
16 cm	2.29486	5.34528E-04 (0.0053)	5.28437E-05 (0.0077)	393.036
20 cm	2.01349	4.12619E-04 (0.0061)	4.70897E-05 (0.0083)	413.202
24 cm	1.78626	3.25073E-04 (0.0069)	4.15762E-05 (0.0089)	426.904
28 cm	1.57903	2.50868E-04 (0.0078)	3.55164E-05 (0.0097)	438.017
32 cm	1.39839	1.93143E-04 (0.0089)	2.89076E-05 (0.0108)	434.862
36 cm	1.32268	1.48740E-04 (0.0101)	2.35218E-05 (0.0119)	439.895
40 cm	1.25977	1.13274E-04 (0.0115)	1.83547E-05 (0.0133)	443.706
44 cm	1.23526	8.67404E-05 (0.0129)	1.46885E-05 (0.0149)	455.802
48 cm	1.12816	6.73989E-05 (0.0147)	1.15547E-05 (0.0167)	443.509
52 cm	1.14901	4.97742E-05 (0.0169)	8.89654E-06 (0.0192)	**458.167**

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

The first column gives the ratio of Sub-MeV neutrons to fast (> 1MeV) neutrons that hit the target. This quantity should be as large as possible to minimize the background effects of ^{238}U fissions (which have a threshold energy of very close to 1 MeV). The ^{235}U/^{238}U fission ratio is another measure of this background.

The total neutron flux given in table 2 applies to the target, and is given in units of neutrons per cm^2 per source neutron. The higher this number, the better, because more neutrons generally yield more fissions (and hence a more intense delayed gamma signal).

The sub-threshold fission probability (in fissions per source neutron) peaks at 8cm moderator thickness. It may be useful to run more simulations with a moderator thickness between 4cm and 12cm, so we can determine the peak more precisely.

MODERATOR THICKNESS	TOTAL NEUTRON FLUX	FAST NEUTRON FLUX	ESTIMATED FAST NEUTRON FLUENCE	ESTIMATED MEASUREMENT TIME
4 cm	9.15668E-04 (0.0002)	2.95996E-04 (0.0007)	2.88918E+10	1.14329E+03
8 cm	7.09082E-04 (0.0002)	1.51777E-04 (0.0010)	1.36648E+10	**1.05454E+03**
12 cm	5.37082E-04 (0.0003)	7.60849E-05 (0.0014)	6.89144E+09	1.06091E+03
16 cm	4.03017E-04 (0.0003)	3.79204E-05 (0.0019)	3.58798E+09	1.10826E+03
20 cm	3.01040E-04 (0.0004)	1.88896E-05 (0.0028)	2.00570E+09	1.24369E+03
24 cm	2.24913E-04 (0.0004)	9.39472E-06 (0.0039)	1.12982E+09	1.40861E+03
28 cm	1.68182E-04 (0.0004)	4.73895E-06 (0.0056)	6.67150E+08	1.64895E+03
32 cm	1.26193E-04 (0.0005)	2.40615E-06 (0.0078)	4.16179E+08	2.02593E+03
36 cm	9.49416E-05 (0.0006)	1.23226E-06 (0.0108)	2.61940E+08	2.48981E+03
40 cm	7.15729E-05 (0.0006)	6.49191E-07 (0.0147)	1.76845E+08	3.19073E+03
44 cm	5.40717E-05 (0.0008)	3.50037E-07 (0.0196)	1.19153E+08	3.98712E+03
48 cm	4.09529E-05 (0.0008)	2.00055E-07 (0.0252)	8.65687E+07	5.06848E+03
52 cm	**3.10177E-05 (0.0009)**	**1.12511E-07 (0.0323)**	**6.32330E+07**	6.58288E+03

TABLE 2: DETECTOR DAMAGE AND MEASUREMENT TIME AS FUNCTIONS OF MODERATOR THICKNESS

Here, neutron fluxes are taken through the detector crystals (and again given in neutrons per cm^2 per source neutron). In terms of radiation damage, “fast” neutrons include all those with more than 100keV of kinetic energy.

Table 2 attempts to quantify what “ideal” means in terms of moderator thickness. As mentioned earlier, we cannot simply go by maximized fission probability—the condition of the HPGe crystals is also of concern. The “Estimated Fast Neutron Fluence” reflects the total number of fast neutrons that hit a detector during one complete assay of the single HEU pellet. The “Estimated Time for Measurement”, similarly, is the time it will take to create the necessary delayed gamma counts, given our source strength of 1E7 neutrons per 100ms irradiating pulse.

CONCLUSIONS

Varying the moderator thickness gives a clear trade-off between measurement time and radiation damage to the detectors. With a larger amount of D_2O between the neutron generator and the target, the fewer fast neutrons hit the detectors. However, beyond about 8cm of moderator thickness, the fission probability begins to decrease.

While thermal neutrons are not absorbed within the heavy water, neutrons still leave the system. The graphite reflectors in place around the moderating layer are far from ideal; many neutrons are not reflected back into the heavy water or irradiation chamber. The probability of escape increases as the distance between source and target increases. (The D-D generator emits particles in a nearly isotropic manner, so total flux is expected to drop off somewhere between $1/r^2$ and $1/r$.)

Unfortunately, none of the tested moderator thicknesses gave an acceptable measurement time or dose to the detectors. Note that the dose is independent of measurement time (i.e. source strength). We could conceivably use a very large amount of moderator to minimize the damage, and then simply use a much stronger neutron source. At 52cm of heavy water, the 1E8 neutron/s generator we currently have would take 6500 days to assay an HEU pellet. A 1E14 neutron/s source (i.e. a reactor) would make the same measurement in 560 seconds. The HPGe crystals could take roughly 15 such measurements before requiring thermal annealing.

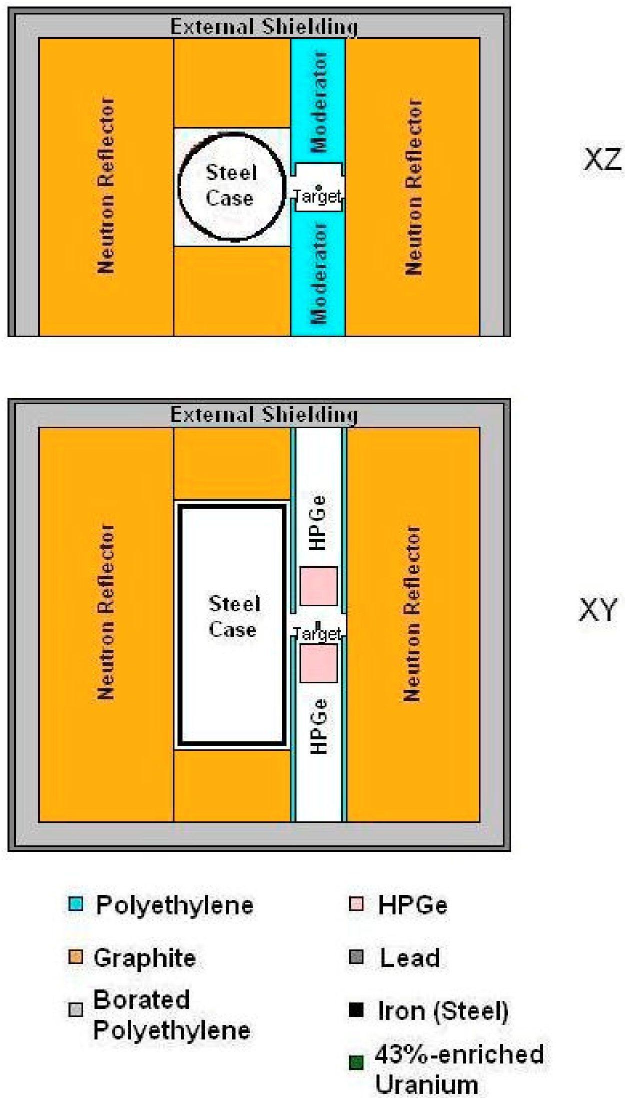
That being said, the proposed experimental geometry is not feasible for a delayed gamma measurement. It is unlikely that any static setup could produce a strong enough gamma signal without also greatly damaging nearby detectors.

A mobile source might address these limitations. This would allow samples to be irradiated far away from the detectors, and then rapidly shuttled into a different position for delayed gamma measurement. Note, though, that we have a time constraint, since we're attempting to measure delayed gamma signatures in the first few seconds following irradiation. Transit time between irradiation chamber and the detectors must be on the order of a second. This limits travel distance, as well as the masses of the samples.

Determining the ideal dimensions of a shuttling system is left for further study. For now, Appendix C shows a generic geometry with a mobile source.

APPENDIX A: "OPTIMAL" GEOMETRY, USING POLYETHYLENE MODERATOR

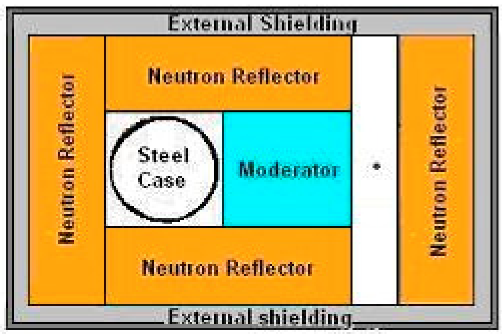
Below is the geometry optimized for greatest fission yield, using polyethylene as moderator. While this model gives the highest fission yield of any geometry tested (including those with heavy water moderator), it does not properly shield the HPGe detectors.



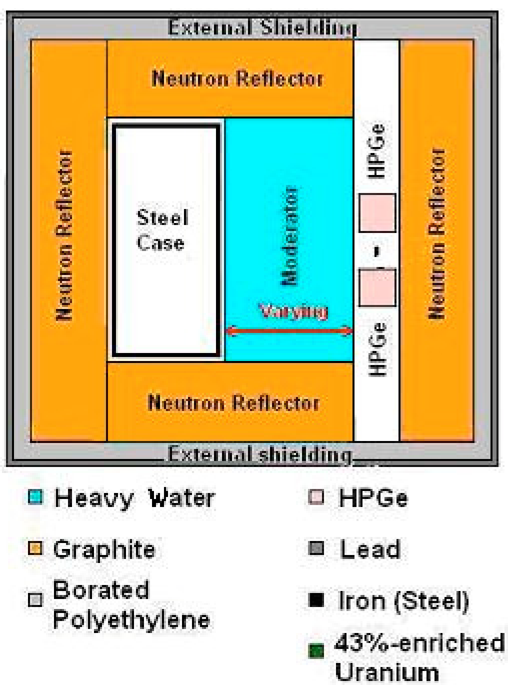
APPENDIX B: GEOMETRY USING HEAVY WATER MODERATOR

Use of heavy water instead of polyethylene nearly eliminates thermal neutron absorption within the moderator. However, we needed to retest for the optimal thickness of the moderator itself. D_2O does not slow down neutrons quite so well as polyethylene, because deuterium has twice the mass of a neutron. A neutron imparts less energy to deuterium than to hydrogen during a collision.

However, we are also concerned with the amount of neutron leakage through the geometry. Adding too much moderator between the target and the source reduces the thermal flux.



XZ



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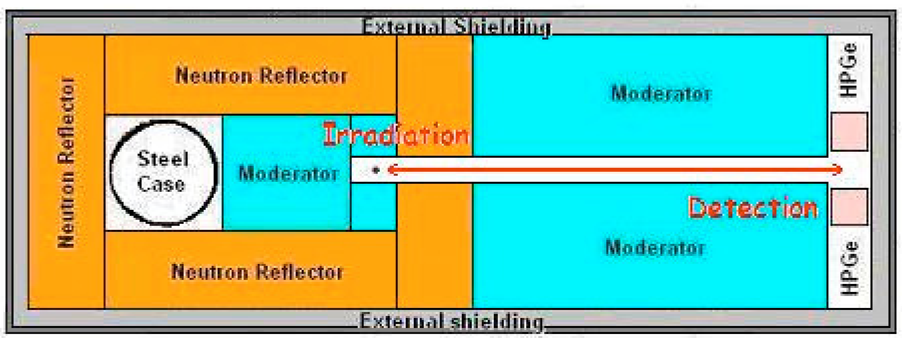
APPENDIX C: AN ASSAY SYSTEM WITH A MOBILE SOURCE

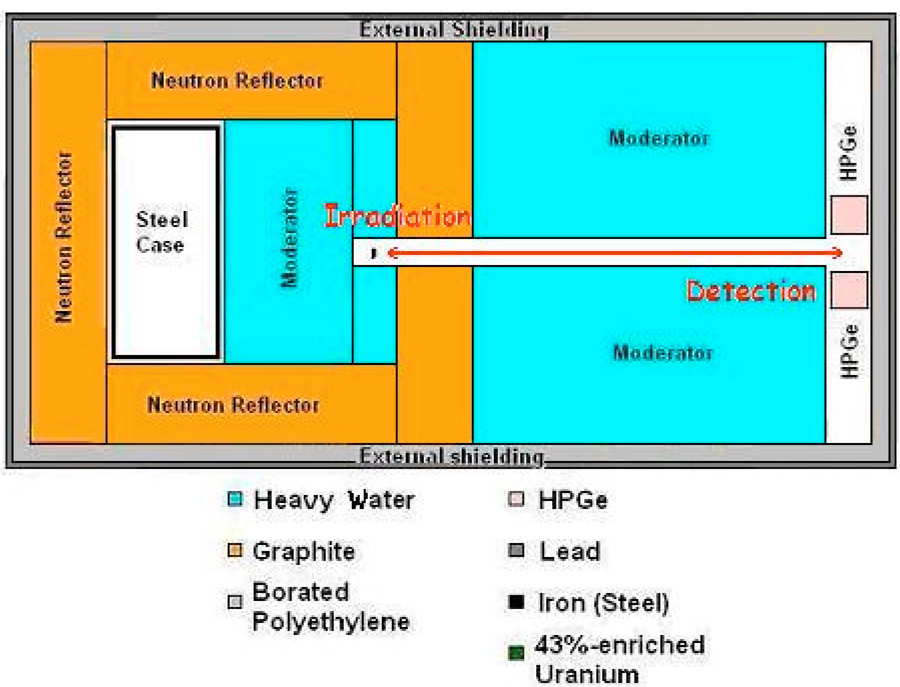
The setup below makes use of a rapid shuttling system to move an assay target between an irradiation position and a detection position. With such a system, it is possible to obtain very high fission yields in the sample, without exposing the detectors to large fast neutron fluxes.

However, the sample must be able to travel between positions rather quickly, within 1 second perhaps. Also, the shuttle must be able to reset with each pulse, and reverse direction. The mass of the sample limits its speed, as well. The geometry below is best used for small targets.

Note that this setup also makes use of 4 HPGe detectors for maximum counting efficiency.



XZ



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