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Concrete Shielding of Spent Fuel Gamma Rays

Using Importance-Weighted Monte Carlo Calculations

By

Seth Alexander Robison

A thesis

Submitted in partial fulfillment

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Seth Robison find it satisfactory and recommend that it be accepted.

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Vita

Seth Robison was born on May 18, 1991 in Corvallis, Oregon. He received his undergraduate degree in Nuclear Engineering from Idaho State University (ISU) in December 2014. Upon finishing his undergraduate studies, Seth was accepted to the Master's program of Nuclear Science and Engineering at ISU. While at ISU, Seth rewrote and updated the undergraduate reactor lab manual, assisted in hazard table development, and reviewed technical documents.

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Abstract

The research in this thesis focuses on concrete shielding of gamma radiation from spent nuclear fuel. Various nuclear fuel configurations were depleted using ORIGEN-ARP and the resulting gamma spectra were used as source particles for shielding calculations in MAVRIC. The research includes a study on the effects of burnup and enrichment on resulting spectrum, a parametric study of shielding thickness vs. dose rate, the importance of including self-shielding in physical models, and a determination of the thickness required to sufficiently attenuate the most hazardous spectrum from the ORIGEN-ARP calculations. Dose rate from depleted fuel was found to have a positive relationship with burnup, but a slight negative relationship with enrichment. Shielding effectiveness was shown to follow an exponential decay pattern with regard to thickness. Inclusion of self-shielding was found to reduce the dose rate by an order of magnitude. The final concrete thickness required to attenuate the most hazardous gamma spectrum down to under 0.005 mSv/hr at a detector 1 cm from the surface was 113 cm. All Monte-Carlo calculational uncertainties were below 1%.

1. Introduction

All spent nuclear fuel emits gamma radiation that presents a significant safety challenge. Without shielding in place, that gamma radiation will cause significant problems for the surrounding areas. Shielding must be used to limit the amount of radiation escaping to the surrounding areas. It is vital to know how much and what type of shielding must be in place to reduce exposure rates to acceptable levels. The research in this document provides basic shielding analysis of gamma spectra using concrete as the shielding medium. The research includes 1) depletion analysis of Westinghouse 17x17 and Combustion Engineering 16x16 fuel designs of various burnups and enrichments, 2) a determination of the bounding gamma spectrum (i.e. which fuel type results in the highest exposure rate after burnup), 3) a parametric shielding study of concrete ranging from 0-1.5 m in thickness, 4) a self-shielded dose rate calculation using the bounding spectra with 1.5 m of concrete, 5) a determination of how thick the concrete must be to reduce the bounding spectra to 0.005 mSv/hr with self-shielding included, and 6) a validation model.

2. Literature Review

Concrete shielding of gamma radiation is not an altogether new concept. The first use of concrete in gamma-ray shielding dates back all the way to the Manhattan Project and thickness requirements were largely guesses.[1] It was known that hydrogenous materials were desired for neutron attenuation and dense materials for gamma attenuation, but wartime pressures overruled any detailed investigation to thickness requirements.

Since then, much research has been done on gamma-ray attenuation properties of concrete for use in reactor design. The early stages of this research consisted primarily of pointkernel methods.[1]-[3] Researchers developed buildup factor tables and used empirical formulas to evaluate shielding effectiveness. The next widely used method for evaluating shielding effectiveness was the discrete-ordinate method of evaluating the transport equation, widely referred to as the S_N method. In 1965, F. Mynatt and W. Engle of Oak Ridge National Laboratory developed ANISN.[1] ANISN implemented differencing and convergence techniques which made the S_N method more applicable for shielding applications. ANISN is still somewhat useful for 2-D calculations and is still used by some enthusiasts, but the primary technique for evaluating radiation shielding problems is currently the Monte Carlo method.

The Monte Carlo method was originally applied to radiation shielding in 1950 by H. Kahn of Rand Corporation.[1] Kahn was, however, ahead of his time. Monte Carlo techniques for radiation shielding almost necessarily require the use of a powerful digital computer and digital computers were not readily available in 1950. Now, in 2017, Monte Carlo methods dominate almost all nuclear engineering calculations.

The majority of Monte Carlo shielding research involving concrete has been applied to reactor shielding design, such as that performed by M. Matijević et.al. where PWR containment shielding calculations were performed.[4] The other primary use of concrete in shielding research has been dry cask storage, such as that done by S. L. Morton et.al. of the Idaho National Laboratory where they investigated the concrete shielding performance of the VSC-17 spent nuclear fuel cask.[5]

Much less research has been done on concrete shielding of spent nuclear fuel as it is being prepared for reprocessing. This is probably because reprocessing is not as widely used as dry cask storage or reactors. The research in this document focuses on shielding spent fuel after it has undergone a 10 year "cool-down" period after use in a reactor. The spent fuel is located on the opposite side of a concrete barrier from a point detector. One possible application of this research is in pyro-processing, where spent nuclear fuel will typically be located inside an inert atmosphere hot cell made of concrete and workers will be nearby the opposite side of the concrete boundary.

3. Methodology and Descriptions

The SCALE 6.2 software package was used for all calculations except where noted otherwise.

3.1 Shielding Hand Calculations

Lamarsh and Baratta[3] show in Chapter 9 of Introduction to Nuclear Engineering that without a shield the exposure rate from a beam of gamma rays is

$$\dot{X}_0 = 0.0659\phi_0 E_0 \left(\mu_a/\rho\right)^{air} \; mR/hr \tag{1}$$

Where, $\dot{X}_0$ is exposure rate in mR/hr, ϕ_0 is flux in $\frac{\gamma - ray}{cm^2 - sec}$, E_0 is energy in MeV, and $\left(\mu_a/\rho\right)^{air}$ is mass absorption coefficient of air at energy E in cm^2/g.

If the flux is a monodirectional beam and there is no interaction with matter, ϕ_0 may be constant and equation 1 can be relatively straightforward. If there is shielding, however, the flux will be attenuated and ϕ_0 cannot be treated so simply.

When gamma rays interact with matter they may be scattered or absorbed. Scattered gamma rays lose some energy and scatter in a different direction. Absorbed gamma rays can cause the shield to produce secondary gammas via pair production and annihilation radiation. These interactions complicate the solution and force equation 1 to be solved in integral form.

The result of which can be written, for an isotropic point source surrounded by a spherical

$$\dot{X} = 0.0659 \int_{0}^{E_0} \phi_0(E) E_0 \left(\mu_a/\rho\right)^{air} dE \;\; mR/hr \tag{2}$$

shield, as

$$\dot{X} = \dot{X}_0 B_p(\mu R) e^{-\mu R} \; mR/hr \tag{3}$$

Where $\dot{X}$ is the exposure rate, $\dot{X}_0$ is the exposure rate without a shield (equation 1), $B_p(\mu R)$ is the point isotropic exposure buildup factor, R is the distance from the point source, and μ is the total attenuation coefficient at energy E_0.[3]

An example calculation of this type is included in Appendix B. Note that for gamma-rays, exposure rate, absorbed dose, and dose equivalent essentially share units.[6] Thus, for this calculation, the units on equations 1-3 may be interchanged with mrem/hr.

3.2 Monte Carlo

Monte Carlo methods in nuclear engineering involve evaluating “random” variables with random numbers.[7] Random is put in quotation marks because nuclear physicists will argue that there are physical processes involved that can be evaluated, but nuclear engineers instead use cross sections that represent probabilities of interaction. A full description of Monte Carlo shielding of gamma radiation is far beyond the scope of this thesis, but a brief overview of analog Monte Carlo is provided in this section.

The first step in a Monte Carlo simulation is to birth a particle. Assuming a point source, this particle will be located at the point and will be assigned random numbers to determine direction and energy. Direction is determined by “mapping” the random numbers to directional angles. For example, if all azimuthal angles are equally probable from 0 to 2π and the random number ranges from 0 to 1, multiply the random number by 2π to determine azimuthal direction.[7] Similarly, to map the next random number to the polar angle, multiply the random number by π. To determine particle energy, some kind of energy probability distribution function must be sampled.

Now that energy, direction, and initial location are known, travel length must be determined. Travel length is determined by sampling the first collision probability distribution function.[3]

$$p(x) = \mu_t e^{-\mu_t x} \tag{4}$$

Integrating Equation 4 from 0 to x yields

$$F(x) = 1 - e^{-\mu_t x} \tag{5}$$

The result of Equation 5 is a value between 0 and 1. A random number, ζ, is assigned to F(x) and x is solved for. [7]

$$x = -\frac{\ln \zeta}{\mu_t} \tag{6}$$

Now that distance traveled is known it must be determined if the particle has penetrated the shield or if a collision has occurred. If x > thickness, the particle passed through without interaction. If x< thickness, however, the isotope collided with, type of collision, and whether the particle entered a new material must now be determined. If the particle entered a new material a new x must be calculated using the new μ_t and a new random number.

The isotope collided with is determined by comparing atom density ratios and assigning a random number. For example, consider a material with 4 isotopes of atom densities: N_1, N_2, N_2, and N_4.[7]

If $$0 < \zeta \le \frac{N_1}{N_{Total}} \qquad Select\ Isotope\ 1$$

If $$\frac{N_1}{N_{Total}} < \zeta \le \frac{N_1 + N_2}{N_{Total}} \qquad Select\ Isotope\ 2$$

If $$\frac{N_1 + N_2}{N_{Total}} < \zeta \le \frac{N_1 + N_2 + N_3}{N_{Total}} \qquad Select\ Isotope\ 3$$

If $$\frac{N_1 + N_2 + N_3}{N_{Total}} < \zeta \le \frac{N_1 + N_2 + N_3 + N_4}{N_{Total}} \qquad Select\ Isotope\ 4$$

With isotope determined it is now necessary to determine type of collision. The type of collision is determined similarly to isotope, except instead of comparing atom densities we compare cross sections.[7]

Gamma rays may interact with matter via photoelectric absorption, Compton scattering, or pair production and subsequent annihilation.[8] If scattering occurs or secondary gammas are produced, new directions and energies must be determined. This process is repeated until the particle is absorbed by the material or penetrates the shield, or the code reaches a user-specified parameter indicating for it to stop calculations and report results.

3.3 MAVRIC

MAVRIC[9] (Monaco with Automated Variance Reduction using Importance Calculations) is a fixed-source radiation transport sequence designed to apply automated variance reduction capabilities to the fixed-source Monte Carlo code Monaco to solve deep penetration problems with low uncertainties in reasonable times. MAVRIC uses user-inputted data to construct a Denovo adjoint problem. Denovo is a deterministic 3-D S_N code that generates the adjoint flux for use in the CADIS (Consistent Adjoint Driven Importance Sampling) methods in MAVRIC. The goal of the Denovo calculations is to generate a quick estimate of the adjoint flux, not to calculate a highly accurate solution. The adjoint flux represents the importance of a particle in contributing to a detector. Adjoint flux is calculated by starting with an event and back calculating how that event happened, rather than of starting with a particle and tracking where it goes. The MAVRIC sequence then uses CADIS methodology to generate a biased source distribution and importance map (weight window target values) from the Denovo adjoint flux. In Monaco, the biased source distribution and importance map cause source particles to be born with a weight matching the target weight of the region/energy they are born into. This causes Monaco to spend less computational time on particles that are not likely to reach the detector and more time on the particles that are likely to reach the detector (i.e. the important particles) and greatly reduces the computational time necessary to achieve low uncertainties.[9]

Other Monte Carlo shielding codes were considered for this research. MAVRIC was selected as the code of choice due to its convenient automated variance reduction capabilities. Variance reduction is very simple in MAVRIC when compared to other codes like MCNP and gives MAVRIC an advantage for deep penetration research.

3.3.1 Variance Reduction and CADIS

The goal of variance reduction techniques is to reduce the uncertainty of complex problems to compute accurate solutions to complex problems. This is generally done by either decreasing the variance or decreasing the time spent on each particle.[10] Unfortunately, decreasing the variance usually involves spending more time on each particle and decreasing the time spent on each particle usually increases variance. There are, however, techniques that provide enough benefit with little enough drawback to be useful.

The first techniques[10] discussed are splitting and Russian roulette. Splitting/roulette involves dividing the geometry into cells and assigning importances I_N to each cell. When a particle crosses from cell i to cell j, the weight ratio, ν is calculated and one of three events happens:

$$\nu = {}^{I_i}\!/_{I_j}$$

If $\nu = 1$ $\quad$ $Continue\ transport$

If $\nu < 1$ $\quad$ $Play\ Russian\ roulette$

If $\nu > 1$ $\quad$ $Split\ the\ particle\ into\ \nu = {}^{I_i}\!/_{I_j}\ tracks$

Russian roulette[10] occurs when the particle crosses from a higher-importance cell to a lower-importance cell. Less particles are desired in low-importance regions so the particle plays Russian roulette. The particle's survival probability is ν and if it survives it is given a new weight, ν^{-1}. The particle's termination probability is 1- ν and if the particle is terminated it is no longer tracked. Russian roulette generally increases variance, but decreases time per history significantly enough to be worth using.

Splitting[10] occurs when the particle crosses from a lower-importance region to a higher-importance region. More particles are desired in high-importance regions so the particle is split into ν subparticles with accordingly reduced weights. Splitting generally increases the time per history, but decreases the variance enough to be worth using.

The weight window technique[10] is an advanced application of the splitting/roulette techniques. Instead of comparing region importances and splitting/rouletting accordingly, weight boundaries (w_{min}, w_{max}) are specified and particle weight is compared to the window boundaries. If the particle's weight is above the upper limit, the particle is split so all the particles are within the weight window. If the particle's weight is below the lower bound, the particle is rouletted and its weight is either increased to be within the boundary or the particle is terminated.

Weight windows[10] are space and energy dependent. Without a biased source, it is possible that a particle may be started with a weight not within the boundaries for its region. This would lead to immediate splitting/rouletting of source particles and would waste computational time. A biased source distribution is developed to match the weight windows and prevent unnecessary splitting/roulette.

CADIS methodology[9] uses the estimated adjoint flux from the Denovo problem to construct approximate weight windows and a biased source distribution. Consider a source-detector problem with source distribution $q(\vec{r}, E)$ and detector response function $\sigma_d(\vec{r}, E)$.

Typically, to find total detector response, R, the forward scalar flux $\phi(\vec{r}, E)$, must be known and R is found by integrating the product of $\phi(\vec{r}, E)$ and $\sigma_d(\vec{r}, E)$.

$$R = \int_{V_d} \int_E \phi(\vec{r}, E) \sigma_d(\vec{r}, E) \, dE \, dV \tag{7}$$

It has been shown,[9]-[12] however that if an estimate of the adjoint scalar flux, $\phi^+(\vec{r}, E)$, is known then an estimate of the total detector response can be found by integrating the product of $q(\vec{r}, E)$ and $\phi^+(\vec{r}, E)$ over the source volume, V_s.

$$R = \int_{V_s} \int_E \phi^+(\vec{r}, E) q(\vec{r}, E) \, dE \, dV \tag{8}$$

A biased source distribution, $\hat{q}(\vec{r}, E)$, and weight windows, $\overline{w}(\vec{r}, E)$, can then be constructed using the estimated detector response and adjoint scalar flux.

$$\hat{q}(\vec{r}, E) = \frac{1}{R} \, q(\vec{r}, E) \phi^+(\vec{r}, E) \tag{9}$$

$$\overline{w}(\vec{r}, E) = \frac{R}{\phi^+(\vec{r}, E)} \tag{10}$$

The use of a biased source distribution causes Monaco to simulate more particles with correspondingly lower weights in the more important regions of the problem.[11],[12] The weight windows specify an importance map that tells Monaco the upper and lower importance bounds for that region. If a particle has a weight that does not fall into the weight window, it is either split into more particles with lower weights or plays Russian roulette and is either killed or assigned a new, higher weight. If the particle's weight falls within the weight window boundaries, no splitting or roulette is performed. The weight windows and source biasing from CADIS cause source particles to be born with a weight corresponding to the importance of that region. The use of weight windows and source biasing greatly reduces the amount of splitting/roulette occurring in the Monaco calculation and, in turn, reduces the time necessary to achieve low uncertainties.

3.3.2 Constructing MAVRIC Input Files Used in this Thesis

This section provides a guide on how a self-shielded input file used in this thesis was constructed and the reasoning behind the input. The purpose of this section is to give the reader enough information to replicate the self-shielded MAVRIC input and understand why the input was constructed the way it was. The reader should then be capable of using the information in the descriptions to replicate the rest of the input files. The full self-shielded input file examined in this section may be found with comments in Appendix A, 6.1 and without comments in Appendix A, 6.20. This section is not intended to be a full guide on how to run MAVRIC. Most capabilities and input options that were not used in this thesis are not discussed here and can be found in the SCALE user's manual.[9]

MAVRIC input files begin with three lines of code designating to SCALE that MAVRIC is the sequence to be run, the title of the problem, and the cross-section library to be used.[9] In this thesis, the ENDF/B-VII.0 200 neutron/47 gamma (v7-200n47g) was used for every input file because it was the highest resolution multigroup library available. For the input file being examined here, these three lines were written as:

```
=mavric
w17x17ss60gwd4pct1.5m
v7-200n47g
```

There are four optional blocks and two required blocks following the first three lines of text that must be in order.[9] Of these blocks, only the two required blocks, composition and geometry, were used in this thesis. The composition block must come directly after the first three lines. The composition block specifies materials that may be used by other blocks. Material input requires an identification number, a density multiplier, and a temperature in Kelvin. A specific density (in $g/_{cm^3}$) may be inputted, but a multiplier for that density must still be included. The materials used in this problem were regulatory concrete and half-density UO_2. The concrete density can be found in Appendix D. The UO_2 was half-density because it was used to represent chopped fuel pellets randomly placed in a large cylinder, modeled as a homogeneous structure. The input for these two materials was written as:

```
read composition
 reg-concrete 1             1 300   end
 uo2          2 den=5.485 1 300   end
end composition
```

The geometry block must come directly after the composition block if no celldata block is included.[9] The geometry block defines shapes and sizes and then fills the shapes with materials specified in the composition block. Geometry input is based on “units” that function as building blocks. These building blocks each have an identification number and may be stacked on each other by constructing an array and placing the array in the global unit. The global unit specifies the overall geometry of the problem. For this research, only one unit was used and it was specified as the global unit. Within the units, shape information and what material to fill the shapes with is specified.

Shapes in MAVRIC are defined by a shape type, identification number, and sizing/location information.[9] All shape units are in cm. This research used three types of shapes: a cuboid to represent the concrete, a sphere to represent the problem’s boundary, and a zcylinder to represent the container of half-density UO_2. The cuboid boundaries were specified by planes of the form (X_{max} X_{min} Y_{max} Y_{min} Z_{max} Z_{min}). Sphere input consisted of an identification number and a radius in cm. Zcylinder specifies a cylinder oriented on the z-axis. Zcylinder input consisted an identification number, planes of the form (Z_{min} Z_{max}), a radius, and an optional origin input specifying where in the x and y directions the center of the zcylinder should be. The full shape input is shown below:

```
read geometry
global unit 1
cuboid 1    500       0     150       0    500       0
 sphere 2    1000
 zcylinder 3 32.05 132.05 67.95 origin x=250 y=232.05
```

Materials within the shapes were specified using media cards.[9] Media cards consist of numbers referencing which material to be used, its bias id, and which shape to fill with the material. The bias id is set to 1 if no additional biasing is used. The numbers after bias id represent logical AND commands. A positive number indicates the material is located inside the shape and a negative number indicates the material is located outside the shape. For example a specification of -1 2 -3 indicates the material is located everywhere outside of shape 1 AND inside of shape 2 AND outside of shape 3. This is useful when there are shapes within other shapes, such as if shapes 1 and 3 were located within shape 2 in the previous example. The media cards for this input were written as:

```
 media 1  1   1
 media 0  1  -1  2  -3
 media 2  1   3
```

The last part of the geometry block is the boundary.[9] The boundary tells MAVRIC which shape is the boundary of the system. If particles travel outside the boundary they are no longer tracked and assumed to be lost. The boundary for this model was shape 2 and it was written as:

```
boundary 2
end geometry
```

After the blocks that must be in order, there are five optional blocks and one required block that can come in any order.[9] The blocks, in the order they appear in this thesis, are definitions, sources, tallies, parameters, importance map, and biasing. Two of these blocks are mutually exclusive. If an importance map block is included, the biasing block will be completely ignored by MAVRIC. This thesis used an importance map so a biasing block was not included.

The definitions block specifies certain types of information that can be used by other blocks.[9] The information can include locations, detector response functions, distributions, grid geometries, cylindrical geometries, energy bin boundaries, and time bin boundaries. In application to the research presented here, only the location, detector response function, grid geometry, and distribution capabilities were used.

Location merely specifies a point in space in (x, y, z) coordinates with units of cm.[9] One way a location may be used is by the tallies block, specifying a point detector location. The location specification for the point detector in this problem is shown below:

```
read definitions
 location 1
  position 250 -10 100
 end location
```

Next in the definitions block is the detector response function. Response function will be referenced by the tallies block and determines what will be reported in the output file along with flux at the detector location.[9] There are many ways response functions can be defined, but for this research only gamma-ray flux-to-dose-rate conversion factors were required. MAVRIC is programmed with a few built-in detector response functions, including ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate conversion factors. In this research ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate factors were used because they were the most recent flux-to-dose-rate factors included with MAVRIC. The built-in identification number for ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate factors is 9505 and the input for the response used in this research is:

```
response 9505
   specialdose=9505
end response
```

Distributions in the definitions block will be referenced by the sources block to represent the source distribution.[9] As with response functions, there are a few ways distributions can be defined. For this research, a user-input binned histogram type distribution was used to model the resulting gamma spectrum from the depletion calculations. SCALE has the capability of importing depletion results from ORIGEN to MAVRIC, but these capabilities were challenging to utilize. It was much more convenient to manually input the n+1 bin boundaries in eV and n intensities in 1/s for each bin. The binned-histogram approach actually calls for a probability density function evaluated at each bin, but if numbers that do not add up to 1 are used, MAVRIC is capable of normalizing the user-input data to 1. The input for a binned-histogram type distribution consists of an identification number, the keyword abscissa followed by n+1 bin boundaries, and the keyword truepdf followed by n values corresponding to each bin. The input file examined in this section used the gamma spectrum resulting from the Westinghouse 17x17 60 GWd 4 wt% depletion case and it was implemented by inputting:

```
distribution 1
   abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
   2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
   300000 200000 100000 50000 10000 end
   truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
         9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
         2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
         5.1501E+14 6.9451E+14 2.5462E+15 end
 end distribution
```

A grid geometry is required to be included if MAVRIC is to utilize its automated variance reduction capabilities.[9] Grid geometries are rectangular 3-D meshes that overlay parts of the physical geometry. The grid geometry will be referenced by the importance map block and will be the geometry used by Denovo for the S_N calculation. Recall that the goal of the Denovo calculation is not a completely accurate solution. The goal is a quick, approximate solution to be used with the CADIS methods to determine an approximate importance map and accelerate the forward Monte Carlo calculation. Thus, even though S_N practitioners suggest mesh sizes of about one mean free path for S_N calculations, much larger meshes may be used for the approximate Denovo solution. There becomes a balancing problem within MAVRIC that the user must solve – to lower uncertainty by simulating more particles or to decrease the mesh size. Larger mesh sizes reduce the time necessary for Denovo to complete its approximation, but also reduce the fidelity of the importance map. If the meshes are too large, the importance map will not noticeably accelerate the forward

Monte Carlo calculation. If the meshes are too small, the Denovo calculation might require too much random-access memory and crash the user's computer or take so long to compute that the user would have been better off just running more particles with an analog Monte Carlo code. This balancing is problem-specific and is the user's prerogative. If given enough time, the code will find an accurate solution to the problem. It is up to the user to make that accurate solution be found in as little time as possible. In addition to the balancing problem, there are some mesh guidelines included in the SCALE user's manual that should be considered:[9]

- The true source regions should be included in the mesh with mesh planes at their boundaries
- For point or very small sources, place them in the center of a mesh cell, not on the mesh planes
- Any region of the geometry where particles could eventually contribute to the tallies (the "important" areas) should be included in the mesh
- Point adjoint sources (corresponding to point detector locations) in standard CADIS calculations do not have to be included inside the mesh. For FW-CADIS, they must be in the mesh and should be located at a mesh cell center, not on any of the mesh planes.
- Volumetric adjoint sources should be included in the mesh with mesh planes at their boundaries.
- Mesh planes should be placed at significant material boundaries.
- Neighboring cell sizes should not be drastically different.
- Smaller cell sizes should be used where the adjoint flux is changing rapidly, for example, toward the surfaces of adjoint sources and shields (rather than their interiors).

Taking all of these factors into account, a grid geometry was constructed for use in this specific input file. The grid geometry includes the self-shielded source, covers all regions that have a possibility of contributing to the flux at the detector, has planes at material and source boundaries, has smaller mesh sizes near the adjoint source, has smaller meshes in the y-direction (shielding direction), and is coarse enough for Denovo to finish its calculation in approximately 10 minutes.

Input for a grid geometry consists of an identification number and specifications for the plane locations.[9] The planes may be specified individually in any order or a keyword "linear" can be used to specify equally spaced planes between two locations. The keyword "end" must be used at the end of individual plane specifications, but not at the end of linear plane specifications. A plot of the grid geometry can be drawn by including the keyword "make3dmap." The grid geometry for the model being examined in this section consisted of 63 x-bins, 71 y-bins, and 55 z-bins and the input is shown below:

```
    gridGeometry 5
  xLinear 20 0 200
  xLinear 9 200 245
  xLinear 9 255 300
  xLinear 20 300 500
  xplanes 217.05 249 251 282.05 end
  yLinear 50 0 150
  yLinear 11 155 265
  yplanes -11 -9 -7 -5 -3 -1 152 200 264.1 end
  zLinear 10 0 95
  zLinear 39 110 500
  zplanes 67.95 99 101 105 132.05 end
 make3dmap
end gridGeometry
```

end definitions

A top-down plot of this grid geometry at Z=100 cm is shown in Figure 1 and a side-view plot at X=250 is shown in Figure 2.

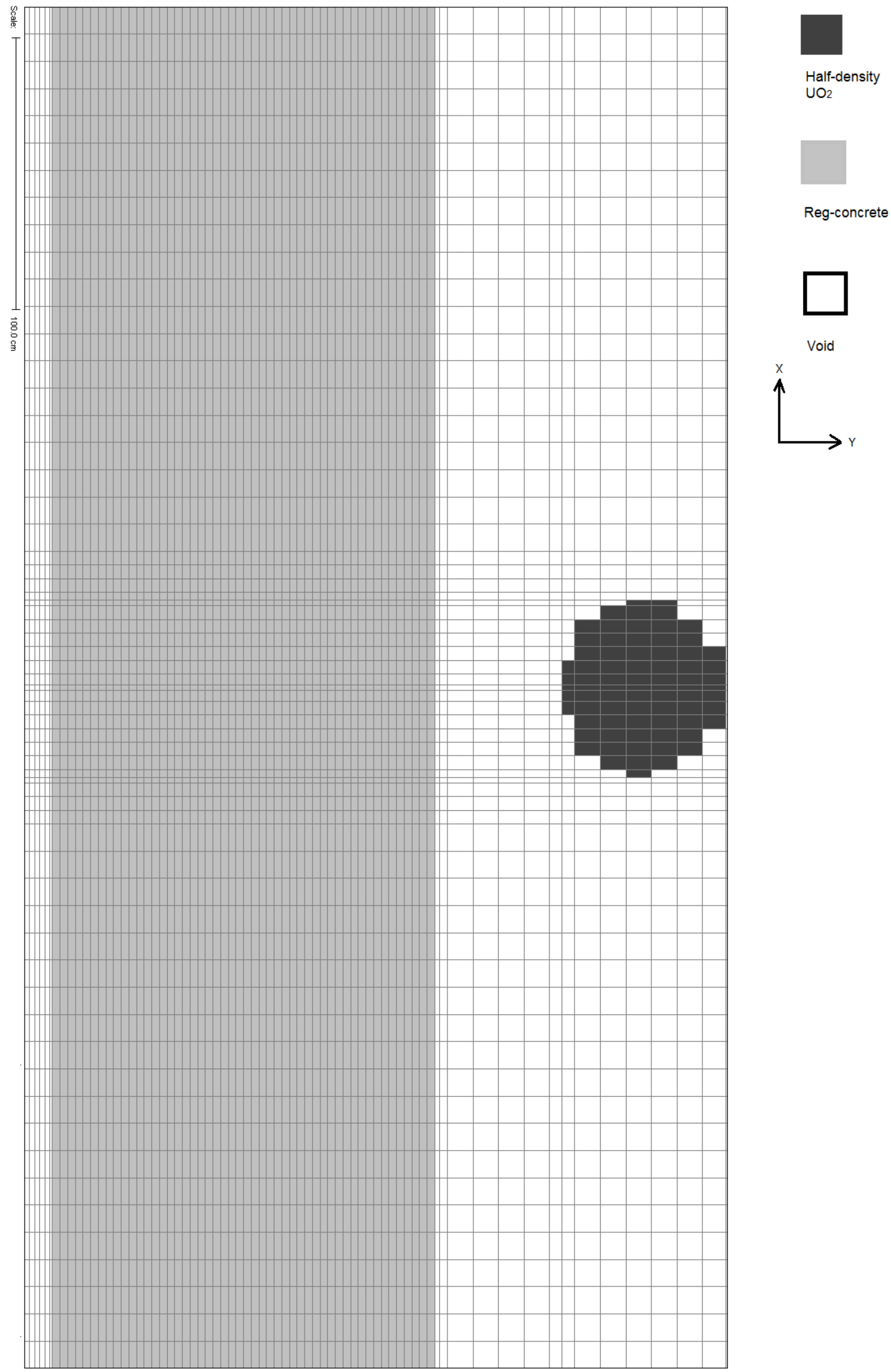

Figure 1: X-Y top-down view of grid geometry

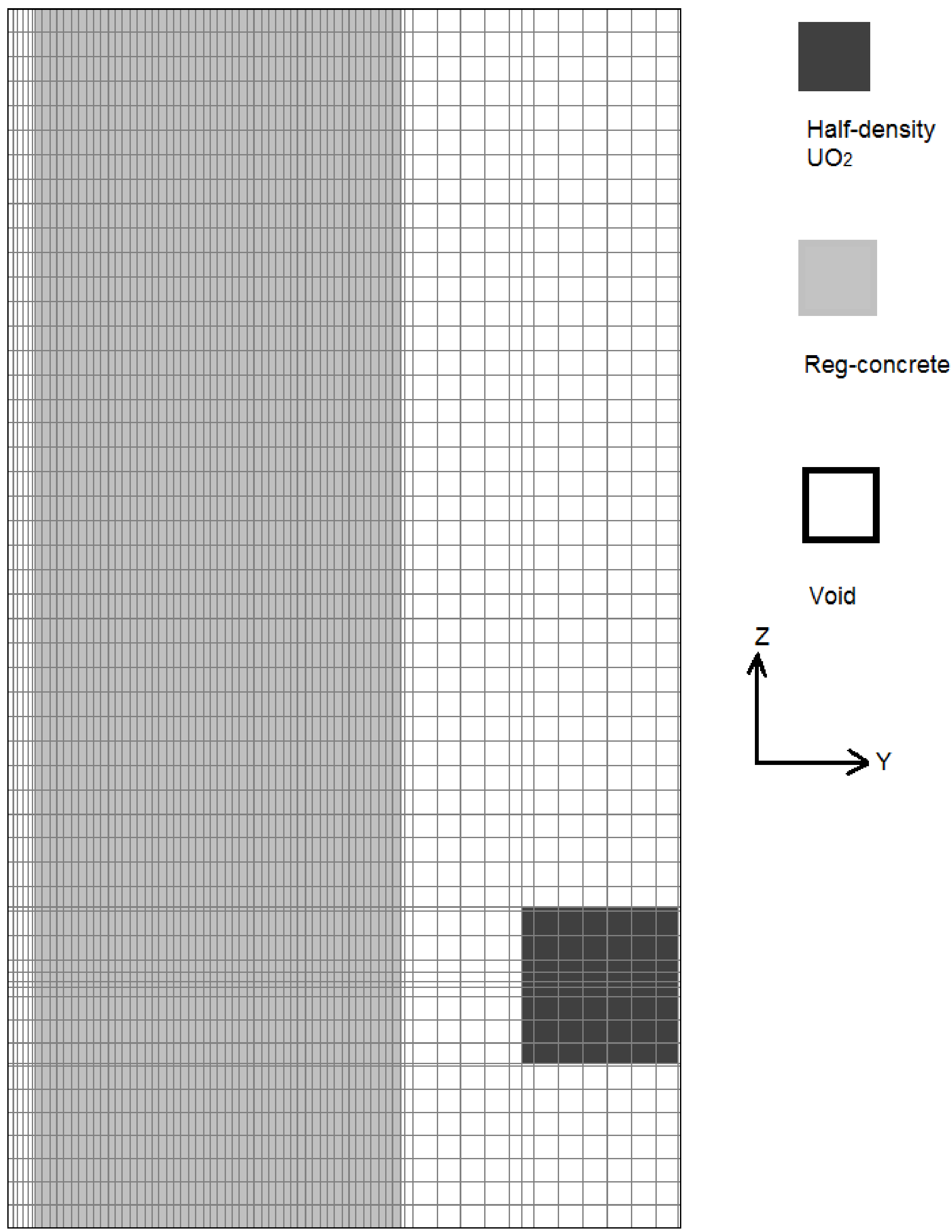

Figure 2: Y-Z side-view of grid geometry

The sources block specifies the total source strength (intensity), what type of particles the source is emitting, the location and/or shape of the source, and the energy distribution of the source.[9] The source strength is in 1/s and is just one number. The energy distribution will reference a distribution from the definitions block and will be applied to the source strength to create the source gamma spectrum. The location and shape of the source can be specified using the same shape rules from the geometry block, or with a keyword “origin x= y= z=” for a point detector. Particle type was specified by the keyword “photon.” The input for the source block used in this section’s example is:

```
read sources
  src 1
    strength=1.0048E+16
    photons
    zcylinder 32.05 132.05 67.95 origin x=250 y=232.05
    edistributionid=1
  end src
end sources
```

The tallies block tells the code where to calculate the flux and what to report along with the flux.[9] All tallies in this thesis were point detector tallies counting gamma-rays. Point detectors in MAVRIC estimate the flux at the detector location using a ray-trace from every collision during the life of the particle. Point detector tally input consists of an identification number, a keyword “neutron” or “photon” for particle type, a location ID referencing a location in the definitions block, and a response function ID from the definitions block. The input for the point detector tally in this example was:

```
read tallies
  pointDetector 1
    photon
```

```
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
```

The parameter block specifies the parameters for the Monte Carlo calculation in Monaco.[9] Parameters set in this thesis include initial random number, the number of histories per batch, and the number of batches. The rest of the parameters were left to their default values. The initial random number was specified by a 16-digit hexadecimal number and was the same for every input file in this thesis. Number of histories per batch and number of batches determine how many particles the forward Monte Carlo calculation will simulate. This is where the other half of the time balancing problem is solved. More particles simulated will result in less uncertainty, but will take more time to calculate. Particle histories and grid geometry mesh spacing should be balanced to give an accurate result, with low uncertainty, in a reasonable time. After much trial-and-error balancing with the grid geometry, the number of histories per batch was set to 250,000 and the number of batches was set to 50. The input for the parameter block was:

```
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
```

The final block included in these input files was the importance map block. Without an importance map block, MAVRIC can be used as a convenient way to run Monaco.[9] Note that if using MAVRIC without an importance map, file names may include spaces, but if an importance map is used and a space is present, MAVRIC will display an error stating only “this is not a Denovo adjoint flux file” and terminate, causing great frustration to the user. The importance map block for a problem with a point detector requires an adjoint source identification number, a location ID that must match the location referenced by the point detector, a detector response function matching that of the point detector, and a grid geometry identification number referencing a grid geometry in the definitions block. Note also that the use of an importance map will morph the source into a biased, mesh-based source. The mesh source should be an accurate enough representation of the true source, but it is something to consider if the results do not make sense and the grid geometry is very coarse. The input for the importance map was written as:

```
read importanceMap
   adjointSource 1
   locationID=1
   responseID=9505
   end adjointSource
   gridGeometryID=5
end importanceMap
```

The input file is then ended by telling MAVRIC it has reached the end of the input file:[9]

```
end data
end
```

3.4 Depletion Calculations

The ORIGEN-ARP GUI in SCALE 6.1 was used to generate input files that were run using Fulcrum in SCALE 6.2. Depletion calculations were performed for CE 16x16 and W 17x17 fuel types. Diagrams of these fuel types can be found in Appendix C. The basis for the calculations (mass of heavy metal depleted) was 1 MTHM. The initial composition of the fuel was simplified to consist only of UO_2. The depletion calculations included 6 stages: 3 stages of 540 day burnups, 2 intermediate 30 day decay periods, and a final 10 year decay period following the third burnup phase. During burn up, the reactor power was assumed to be constant. Calculations were performed for 40, 50, and 60 GWd burnups and enrichments of 4, 5, and 6% wt% U-235 for a total of 18 depletion calculations. The range of the enrichment-burnup combinations exceeds traditional commercial operating envelopes. The range was selected to help develop a clear understanding of the relationship between enrichment, burnup, and resulting gamma spectrum. Example output from the Westinghouse 17x17 60 GWd 4 wt% case may be found in Appendix E.

3.5 Parametric Shielding Thickness Study

Calculations were performed using MAVRIC. The concrete composition used in the shielding calculations was reg-concrete. The cross-section library used was ENDF/B-VII.0 200 neutron/47 gamma (v7-200n47g) because of its high resolution. The gamma spectrum used was the resulting spectrum from the CE 16x16 60 GWd 6 wt% depletion case. ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate factors were used since they are the latest ones included in MAVRIC. A grid geometry was created to utilize MAVRIC's automated variance reduction capabilities. For all calculations there were 250,000 histories per batch and 50 total batches. This means the Monte Carlo portion of MAVRIC simulated 250,000 source particles 50 times. Calculations were performed for concrete thicknesses of 0 cm, 5 cm, 10 cm, 25 cm, 50 cm, 75 cm, 100 cm 125 cm, and 150 cm. For all calculations the source was a point source located at x=250 cm, y=151 cm, z=100 cm and the detector was a point detector located at x=250 cm, y=-1 cm, z=100 cm. The point source and point detector were 152 cm apart; 150 cm of concrete between them for the thickest shielding case and 1 cm away from the concrete on either side. The concrete was 5 m thick in the x-direction, 0-150 cm thick in the y-direction and 5 m thick in the z-direction. A geometry plot would be included, but point detectors and point sources do not show up in SCALE 6.2 plots so the plot only shows a block of concrete.

Point sources and detectors were used because the scope of this study was only to demonstrate the relationship between thickness and effectiveness, not to realistically model the components as they may be set up in a reprocessing or storage facility.

3.6 Determination of the Bounding Gamma Spectrum

All 18 gamma spectra from the depletion calculations were simulated in MAVRIC models identical to the parametric shielding study model with 150 cm of concrete in the y-direction. The resulting dose rates were compared and the spectra that resulted in the highest dose rate was selected as the bounding spectra.

3.7 Self-Shielded Calculations

Calculations were performed with MAVRIC. The concrete composition used was reg-concrete. The source was modeled as a distributed cylinder source of half density UO_2 (5.485 g/cm^3) to represent small cylinders (chopped fuel pellets) randomly placed in a large cylinder (64.1 cm long, 64.1 cm diameter). The cylinder source was a z-cylinder with its origin at x=250 cm, y=232.05 cm, z=0 cm and a radius of 32.05 cm. The cylinder source extended from z=67.95 cm to z=132.05 cm. The cylinder is just large enough for 1 MTHM of half density fuel to fit. The point detector was located at x=250 cm, y=-10 cm, z=100 cm. The point detector and center of the distributed source were located 242.05 cm apart. The cross-section library used was ENDF/B-VII.0 200 neutron/47 gamma (v7-200n47g) due to its high resolution. The gamma spectrum used was the resulting spectrum from the

60 GWd 4 wt% depletion case because it is the bounding spectrum. ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate factors were used because they are the latest included in MAVRIC. A grid geometry was created to utilize MAVRIC's automated variance reduction capabilities. There were 250,000 histories per batch and 50 total batches. The concrete was 5 m thick in the x-direction, 150 cm thick in the y-direction, and 5 m thick in the z-direction. An example self-shielded input file is included in Appendix 6.1. A plot is shown in Figure 1. For illustrative purposes, a 5 cm radius sphere was added to the plot to represent the point detector.

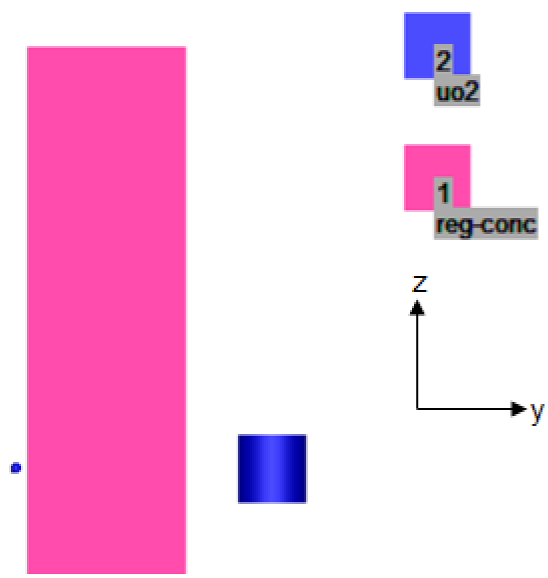

Figure 3. Self-shielded MAVRIC model.

A non-self-shielded calculation was performed with a point source located at x=250 cm, y=232.05 cm, z=100 cm to compare the self-shielded results to non-self-shielded results since in the self-shielded model the detector was moved from y=-1 cm to y=-10 cm and the source was changed from a point source at y=151 cm to a distributed cylinder ranging from y=200 cm to y=264.1 cm.

The thickness of the concrete in the self-shielded model was reduced in the y-direction until a dose rate just under 5 x 10^{-6} Sv/hr was achieved. This dose rate was selected because it corresponds to an annual occupational dose of 1 rem/yr. The annual limit on total occupational effective dose equivalent for adults is 5 rem/yr according to 10 CFR 20.1201 so this value provides a factor of safety of 5.[13]

3.8 Validation Model

A MAVRIC calculation was performed and compared to hand calculations of the same model. The goal of the model was to calculate the dose rate at the surface of an aluminum sphere with a point source of 1 MeV gamma rays located at the center of the sphere. The sphere's radius was 6.032 cm. The point source was located at x=0 cm, y=0 cm, z=0 cm and the point detector was located at x=0 cm, y=0 cm, z=6.032 cm. The source strength was 1 x 10^8 γ/sec. The cross-section library used was ENDF/B-VII.0 200 neutron/47 gamma (v7-200n47g) due to its high resolution. ANSI/ANS-6.1.1-1991 gamma-ray flux-to-dose-rate factors were used since they are the latest included in MAVRIC. A grid geometry was created to utilize MAVRIC's automated variance reduction capabilities. There were 1,000,000 histories per batch and 25 total batches.

4. Results and Discussion

4.1 Depletion Calculations

The activities of the depletion calculations are tabulated in Table 1. The specific group-by-group results are shown in Figure 2 and Figure 3. All total intensities were between 6.6 x 10^{15} and 1.03 x 10^{16} γ/s and total activity increased with both enrichment percent and burnup. All spectra had relatively similar intensities in the low energy gamma groups, but in the high-energy groups there were, in some cases, order of magnitude differences. Lower enrichments had higher intensities in the high-energy groups as can be seen in Figures 2 and 3. It will be shown in Section 4.3 that even though the 4% enriched cases had lower total source intensity, their dose rates were higher than the 5% and 6% enriched cases. In Figures 2 and 3, a large peak can be seen in the 600 – 800 keV group. This peak is due to Cs-137. Cs-137 is the primary contributor to the total gamma intensity and it releases a 661 keV gamma when it decays. More depletion results can be found in Appendix 11.

Table 1. Activities of Spent Fuels after 10 Year Decay

Depletion Results 1 MTHM			
CE 16x16		W 17x17	
Fuel	Intensity (γ/s)	Fuel	Intensity (γ/s)
40GWd 4%	6.612E+15	40GWd 4%	6.624E+15
40GWd 5%	6.672E+15	40GWd 5%	6.683E+15
40GWd 6%	6.709E+15	40GWd 6%	6.720E+15
50GWd 4%	8.324E+15	50GWd 4%	8.339E+15
50GWd 5%	8.419E+15	50GWd 5%	8.434E+15
50GWd 6%	8.479E+15	50GWd 6%	8.494E+15
60GWd 4%	1.003E+16	60GWd 4%	1.005E+16
60GWd 5%	1.017E+16	60GWd 5%	1.018E+16
60GWd 6%	1.026E+16	60GWd 6%	1.028E+16

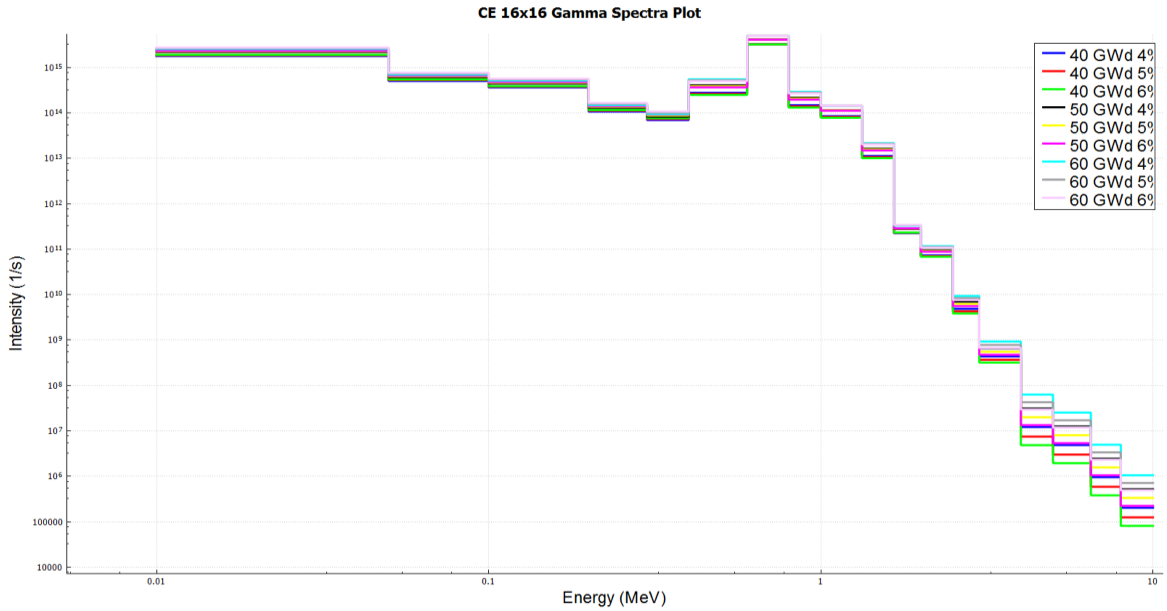

Figure 4. Combustion Engineering 16x16 gamma spectra plot, 10 yr decay

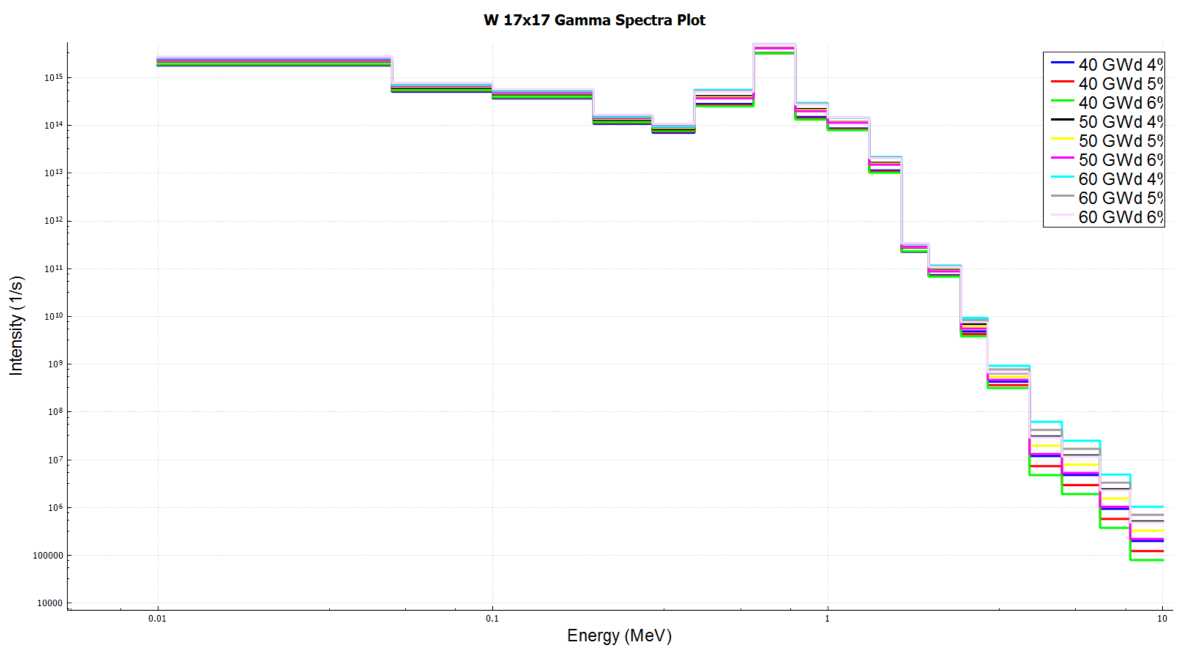

Figure 5. Westinghouse 17x17 gamma spectra plot, 10 yr decay

4.2 Parametric Shielding Thickness Study

Results of the parametric shielding study are tabulated in Table 2 and plotted on a log-linear scale in Figure 4. Dose rate decreased exponentially with increased shielding thickness.

Table 2. Parametric Shielding Thickness Study Results

Parametric Shielding Thickness Study Spectrum: 60 GWd 6 wt%		
Concrete Thickness (cm)	Dose Rate (Sv/hr)	Relative Uncertainty
0	2.757E+02	0
5	1.944E+02	0.00789
10	1.160E+02	0.00784
25	1.986E+01	0.00598
50	7.536E-01	0.00442
75	2.589E-02	0.00439
100	9.549E-04	0.00506
125	4.011E-05	0.00610
150	1.947E-06	0.00696

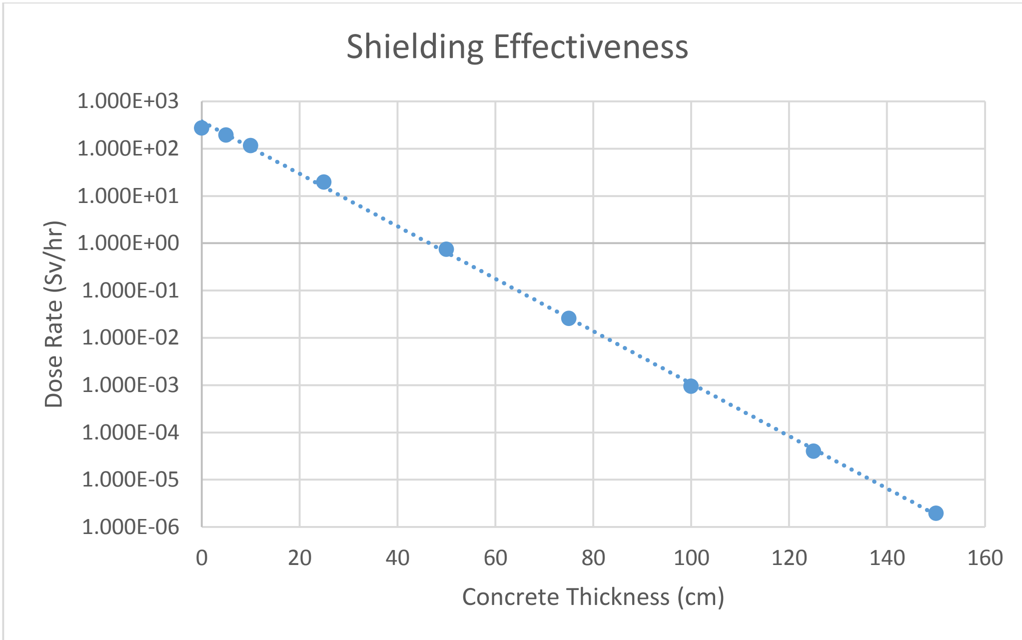

Figure 6. Dose vs. concrete thickness CE 16x16 60 GWd 6 wt%

4.3 Determination of the Bounding Gamma Spectrum

Results of the dose rates of the various gamma spectra evaluated with 1.5 m of concrete are tabulated in Table 3 and plotted as a histogram in Figures 5 and 6. The dose rates increased with increasing burnup and decreased with increasing enrichment. These results indicate that although higher enrichments resulted in higher total source intensity, the higher energy gamma spectra from lower enriched fuels resulted in a higher dose rate. Enrichment, however, was clearly the secondary factor when compared to burnup. The 60 GWd 6 wt% case had nearly double the dose rate of the 40 GWd 4 wt% case for both CE 16x16 and W 17x17 fuel types. The bounding spectrum was determined to be the W 17x17 60 GWd 4 wt% case since its dose rate of 2 x 10^{-6} Sv/hr was the highest.

Table 3.Dose Rates of All Spectra Shielded by 1.5 m of Concrete

Shielding Study of Spectra Shielded by 1.5 m of Concrete 10 yr decay					
CE 16x16			W 17x17		
Fuel	Dose Rate (Sv/hr)	Relative Uncertainty	Fuel	Dose Rate (Sv/hr)	Relative Uncertainty
40GWd 4%	1.125E-06	0.00689	40GWd 4%	1.135E-06	0.00691
40GWd 5%	1.089E-06	0.00693	40GWd 5%	1.099E-06	0.00696
40GWd 6%	1.042E-06	0.00692	40GWd 6%	1.052E-06	0.00687
50GWd 4%	1.561E-06	0.00699	50GWd 4%	1.570E-06	0.00702
50GWd 5%	1.529E-06	0.00687	50GWd 5%	1.537E-06	0.00689
50GWd 6%	1.478E-06	0.00686	50GWd 6%	1.492E-06	0.00687
60GWd 4%	1.992E-06	0.00685	60GWd 4%	2.009E-06	0.00687
60GWd 5%	1.964E-06	0.00697	60GWd 5%	1.980E-06	0.00698
60GWd 6%	1.947E-06	0.00696	60GWd 6%	1.960E-06	0.00694

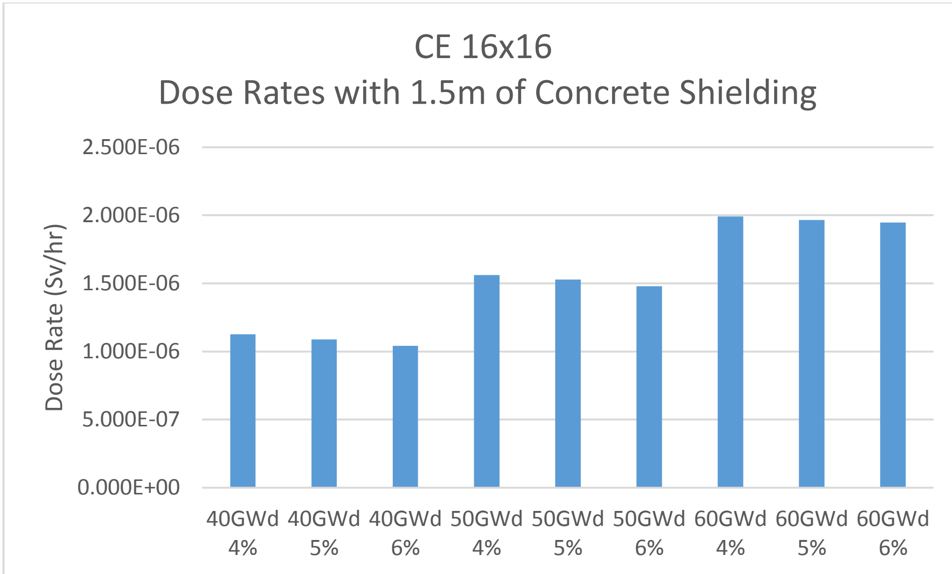

Figure 7. CE 16x16 dose rates with 1.5 m of shielding, 10 yr decay, 1 MTHM

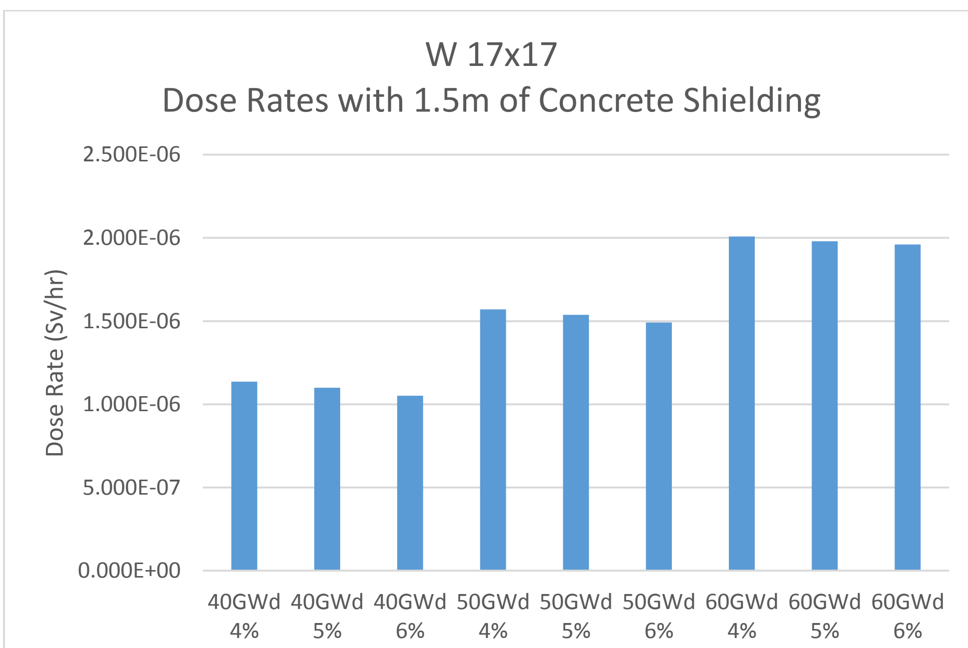

Figure 8. W 17x17 dose rates with 1.5m of shielding, 10 yr decay, 1 MTHM

4.4 Self-Shielded Calculations

Results of the self-shielded calculation and comparison point source calculation are tabulated in Table 4. Including self-shielding lowered the dose rate by an order of magnitude. The non-self-shielded 1.5 m result in this section differed from the result in section 3.3 because the source and detector locations were changed for this study.

Table 4. Self-Shielded and Comparison Results

Self-Shielded Calculations		
Configuration	Dose Rate (Sv/hr)	Relative Uncertainty
Self-shielded 1.5 m thick concrete	5.496E-08	0.00634
Non-self-shielded 1.5 m thick concrete	7.031E-07	0.00581
Self-shielded 1.13 m thick concrete	4.590E-06	0.00589
Non-self-shielded 1.13 m thick concrete	6.390E-05	0.00485
Self-shielded 1.12 m thick concrete	5.239E-06	0.00569
Non-self-shielded 1.12 m thick concrete	7.182E-05	0.00470

4.5 Validation Model

The hand calculation of the aluminum sphere model resulted in a dose rate of 2.999 mSv/hr. The MAVRIC model resulted in a dose rate of 2.656 mSv/hr with a relative uncertainty of 0.00194. The percent error between these methods is 11.4% which can be attributed to more modern flux-to-dose conversion factors being used in the MAVRIC calculation.

5. Conclusion

This thesis provides basic shielding analysis of gamma spectra from spent nuclear fuel utilizing concrete as the shielding medium. The spent fuel gamma ray emission spectrum was determined for 18 spent fuel arrangements. Using a fixed concrete shield thickness the bounding gamma spectrum was identified. A parametric shielding study of concrete ranging from 0-1.5 m in thickness was also included. Point source and self-shielded sources were also compared.

The bounding fuel was determined to be the Westinghouse 17x17 60 GWd 4 wt%. Dose rate increased with burnup and decreased slightly with enrichment. The effectiveness of additional shielding decreased exponentially as thickness increased. Inclusion of self-shielding decreased dose rate by an order of magnitude. For the W 17x17 60 GWd 4 wt% gamma spectrum, when considering self-shielding, the concrete thickness needed to achieve a dose rate under 0.005 mSv/hr is 113 cm.

6. References

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7. Appendix A

7.1 Example Self-Shielded Input File with Comments

```
=mavric
'Title
w17x17ss60gwd4pct1.5m
' Cross-section library is ENDF/B-VII.0
v7-200n47g
'Compositions block
read composition
'Regulatory concrete is mixture 1, the density multiplier is 1, and ‘temperature of 300K
 reg-concrete 1 1 300   end
'UO2 is mixture 2, it has a density of 5.485 g/cc, a density ‘multiplier of 1, and
temperature of 300K
 uo2          2 den=5.485 1 300   end
end composition
'Geometry Block
read geometry
global unit 1
com="Unit 1"
'Geometry 1 is a cuboid ranging from x=0 cm, y=0 cm, z=0 cm to x=500 ‘cm, y=150 cm,
z=500 cm
 cuboid 1     500        0      150        0     500        0
'Geometry 2 is a sphere with a radius of 1000 cm
 sphere 2    1000
'Geometry 3 is a cylinder on the z-axis with a radius of 32.05 cm.
'Its base is at z=67.95 cm and its top is at z=132.05 cm. The ‘cylinder's origin is x=250
cm, y=232.05, z=0 cm.
 zcylinder 3 32.05 132.05 67.95 origin x=250 y=232.05
'Material 1’s bias id is 1 and is located inside of geometry 1
 media 1 1 1
'Material 0’s (void) bias id is 1 and is located inside of geometry 2, ‘but outside of
geometries 1 and 3
 media 0 1 -1 2 -3
'Material 2’s bias id is 1 and is located inside geometry 3.
 media 2 1 3
```

```
'The boundary of the model is geometry 2.
 boundary 2
end geometry
'Definitions block
read definitions
'Location 1 is located at x=250 cm, y=-10 cm, z=100 cm
'Location 1 will be referenced later on
'Title is optional
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
'Response will be referenced later on by the detector and importance ‘map.
'Response 9505 is specialdose 9505
'Specialdose 9505 tells the detector to convert gamma-ray flux to dose ‘rates using
'ANSI/ANS-6.1.1-1991 Gamma-ray flux-to-dose-rate factors
  response 9505
    specialdose=9505
  end response
'Distribution 1 will be referenced by the source so the source ‘particles are sampled
according to the distribution
  distribution 1
    title="60gwd4pct origen"
'19 histrogram boundaries for 18 bins
'These are the boundaries for the 18GroupSCALE5 gamma group structure
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
'truepdf values will automatically be normalized to add up to 1
'These values are the gamma intensity results from an ORIGEN ‘calculation
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
'Grid geometry will be referenced for importance map calculation
'planes should be located at material boundaries
'point detectors should be placed in the middle of two planes
  gridGeometry 5
'20 x-planes spaced evenly apart between x=0 cm and x=200 cm (10 cm ‘between planes)
```

```
   xLinear 20 0 200
'9 x-planes spaced evenly apart between x=200 cm and x=245 cm (5 cm ‘between planes)
   xLinear 9 200 245
'9 x-planes spaced evenly apart between x=255 cm and x=300 cm (5 cm ‘between planes)
   xLinear 9 255 300
'20 x-planes spaced evenly apart between x=300 cm and x=500 cm (10 cm ‘between
planes)
   xLinear 20 300 500
'x-planes located at x=217.05 cm, x=249 cm, x=251 cm, x=282.05 cm
   xplanes 217.05 249 251 282.05 end
'50 y-planes spaced evenly apart between y=0 cm and y=150 cm (3 cm ‘between planes)
   yLinear 50 0 150
'11 y-planes spaced evenly apart between y=155 cm and y=265 cm (10 cm ‘between
planes)
   yLinear 11 155 265
'y-planes located at y=-11 cm, y=-9 cm, y=-7 cm, y=-5 cm, y=-3 cm, y=-‘1 cm, y=152
cm, y=200 cm, y=264 cm
   yplanes -11 -9 -7 -5 -3 -1 152 200 264.1 end
'10 z-planes spaced evenly apart between z=0 cm and z=95 cm (9.5 cm ‘between planes)
   zLinear 10 0 95
'39 z-planes spaced evenly apart between z=110 cm and z=500 cm (10 cm ‘between
planes)
   zLinear 39 110 500
'z-planes located at z=67.95 cm, z=99 cm, z=101 cm, z=105 cm, z=132.05 ‘cm
   zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
'Sources block
read sources
'Source 1 has a strength of 1.0048E16 photons/sec
  src 1
   strength=1.0048E+16
   photons
'Source 1 is distributed in a cylinder on the z-axis with a radius of ‘32.05 cm
'Source 1's base is at z=67.95 cm and its top is at z=132.05 cm. The ‘source's origin is
x=250 cm, y=232.05, z=0 cm.
   zcylinder 32.05 132.05 67.95 origin x=250 y=232.05
'Source particles will be distributed as indicated by distribution 1.
   edistributionid=1
  end src
```

```
end sources
'Tallies block
read tallies
'Point detector 1 is a photon detector titled "point"
  pointDetector 1
    photon
    title="point"
'Point detector 1 is located at Location 1
    locationID=1
'Point detector 1 responds to photons according to response 9505 ‘(ANSI/ANS-6.1.1-
1991 Gamma-ray flux-to-dose-rate factors)
    responseID=9505
  end pointDetector
end tallies
'Parameters block
read parameters
'The first random seed is 0000000100000001, there are 250,000 ‘histories per batch, and
50 total batches
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
'Importance map block
read importanceMap
'Adjoint source must have same responseID as the detector it is ‘optimizing
'for point detectors the LocationID must also be the same as the ‘detector
'The grid geometry used to optimize detector 1 will be gridGeometry5
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.2 CE 16x16 40 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
40gwd4pct1.5m
v7-200n47g
read composition
```

```
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 2.0353E+05 9.5868E+05 4.8878E+06 1.2181E+07 4.3582E+08
    4.8682E+09 7.2888E+10 2.2542E+11 1.1251E+13 8.4800E+13 1.4762E+14
    3.2594E+15 2.7724E+14 6.9735E+13 1.0717E+14 3.6376E+14 5.0413E+14
    1.7863E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
```

```
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.6117E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.3 CE 16x16 40 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
40gwd5pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
```

```
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.2511E+05 5.8937E+05 3.0053E+06 7.4906E+06 3.6809E+08 4.2863E+09
            7.0205E+10 2.2950E+11 1.0631E+13 8.1516E+13 1.3857E+14 3.2429E+15
            2.6172E+14 7.3667E+13 1.1210E+14 3.7769E+14 5.2579E+14 1.8471E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.6720E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
```

```
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.4 CE 16x16 40 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
40gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
```

```
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 8.1121E+04 3.8219E+05 1.9491E+06 4.8591E+06 3.1960E+08 3.8462E+09
            6.8189E+10 2.3237E+11 1.0095E+13 7.8203E+13 1.3085E+14 3.2292E+15
            2.4897E+14 7.6563E+13 1.1562E+14 3.8733E+14 5.4103E+14 1.8910E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.7091E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
```

```
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.5 CE 16x16 50 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
50gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
```

```
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 5.1936E+05 2.4462E+06 1.2470E+07 3.1074E+07 6.5533E+08
            6.9755E+09 9.4391E+10 2.7780E+11 1.6269E+13 1.1552E+14
            2.1653E+14 4.1378E+15 4.0479E+14 8.2797E+13 1.2924E+14
            4.4252E+14 6.0373E+14 2.1744E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=8.3240E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
```

```
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.6 CE 16x16 50 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
50gwd5pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      150       0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
```

```
  300000 200000 100000 50000 10000 end
  truepdf 3.3466E+05 1.5763E+06 8.0364E+06 2.0027E+07 5.5056E+08
      6.1987E+09 9.0756E+10 2.8364E+11 1.5564E+13 1.1427E+14
      2.0570E+14 4.1162E+15 3.8342E+14 8.8184E+13 1.3638E+14
      4.6386E+14 6.3517E+14 2.2597E+15 end
 end distribution
 gridGeometry 5
  xLinear 49 0 245
  xLinear 49 255 500
  xplanes 249 251 end
  yLinear 100 0 150
  yplanes -2 152 end
  zLinear 19 0 95
  zLinear 39 110 500
  zplanes 99 101 105 end
 end gridGeometry
end definitions
read sources
 src 1
  title="point source midpoint x, 1.51m y, 1m z"
  strength=8.4189E+15
  photons
  origin x=250 y=151 z=100
  edistributionid=1
 end src
end sources
read tallies
 pointDetector 1
  photon
  title="point"
  locationID=1
  responseID=9505
 end pointDetector
end tallies
read parameters
  randomSeed=0000000100000001
  perBatch=250000
  batches=50
end parameters
read importanceMap
```

```
   adjointSource 1
   locationID=1
   responseID=9505
   end adjointSource
   gridGeometryID=5
end importanceMap
end data
end
```

7.7 CE 16x16 50 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
50gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
   title="detector 1cm from wall, half way x direction, 1m z dir"
   position 250 -1 100
  end location
  response 9505
   specialdose=9505
  end response
  distribution 1
   abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
   2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
   300000 200000 100000 50000 10000 end
   truepdf 2.2374E+05 1.0539E+06 5.3737E+06 1.3392E+07 4.7398E+08
       5.5822E+09 8.7899E+10 2.8780E+11 1.4896E+13 1.1200E+14
       1.9570E+14 4.0970E+15 3.6474E+14 9.2270E+13 1.4164E+14
       4.7912E+14 6.5819E+14 2.3233E+15 end
```

```
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=8.4792E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
```

```
end importanceMap
end data
end
```

7.8 CE 16x16 60 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
60gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      150       0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0555E+06 4.9710E+06 2.5340E+07 6.3140E+07 9.2967E+08
            9.3161E+09 1.1675E+11 3.2864E+11 2.1627E+13 1.4293E+14
            2.9142E+14 5.0312E+15 5.4874E+14 9.4589E+13 1.4914E+14
            5.1347E+14 6.9366E+14 2.5429E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
```

```
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=1.0030E+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.9 CE 16x16 60 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
```

```
60gwd5pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 7.1422E+05 3.3639E+06 1.7149E+07 4.2730E+07 7.8154E+08
            8.3829E+09 1.1229E+11 3.3641E+11 2.0928E+13 1.4441E+14
            2.8003E+14 5.0069E+15 5.2340E+14 1.0139E+14 1.5856E+14
            5.4259E+14 7.3485E+14 2.6519E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
```

```
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=1.0165E+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.10 CE 16x16 60 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
60gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
```

```
read geometry
global unit 1
com="Unit 1"
 cuboid 1    500       0     150       0    500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
```

```
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.11 W 17x17 40 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
40gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      150       0     500       0
```

```
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 2.0100E+05 9.4678E+05 4.8271E+06 1.2030E+07 4.3408E+08
            4.8581E+09 7.2819E+10 2.2566E+11 1.1352E+13 8.5799E+13
            1.4895E+14 3.2616E+15 2.7906E+14 6.9876E+13 1.0748E+14
            3.6497E+14 5.0493E+14 1.7893E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.6236E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
```

```
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.12 W 17x17 40 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
40gwd5pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
```

```
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.2349E+05 5.8173E+05 2.9663E+06 7.3935E+06 3.6637E+08
           4.2748E+09 7.0130E+10 2.2971E+11 1.0725E+13 8.2451E+13
           1.3982E+14 3.2450E+15 2.6343E+14 7.3802E+13 1.1239E+14
           3.7884E+14 5.2652E+14 1.8500E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.6833E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
```

```
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.13 W 17x17 40 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
40gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
```

```
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 8.0097E+04 3.7736E+05 1.9245E+06 4.7978E+06 3.1798E+08
            3.8348E+09 6.8115E+10 2.3256E+11 1.0185E+13 7.9085E+13
            1.3204E+14 3.2311E+15 2.5060E+14 7.6688E+13 1.1590E+14
            3.8840E+14 5.4168E+14 1.8937E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=6.7197E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
```

```
read parameters
   randomSeed=0000000100000001
   perBatch=250000
   batches=50
end parameters
read importanceMap
   adjointSource 1
   locationID=1
   responseID=9505
   end adjointSource
   gridGeometryID=5
end importanceMap
end data
end
```

7.14 W 17x17 50 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
50gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1    500       0     150       0    500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
   title="detector 1cm from wall, half way x direction, 1m z dir"
   position 250 -1 100
  end location
  response 9505
   specialdose=9505
  end response
  distribution 1
   abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
```

```
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 5.1434E+05 2.4226E+06 1.2350E+07 3.0773E+07 6.5339E+08
        6.9701E+09 9.4330E+10 2.7808E+11 1.6412E+13 1.1686E+14
        2.1843E+14 4.1409E+15 4.0748E+14 8.2941E+13 1.2959E+14
        4.4395E+14 6.0459E+14 2.1777E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=8.3393E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
```

```
read importanceMap
   adjointSource 1
   locationID=1
   responseID=9505
   end adjointSource
   gridGeometryID=5
end importanceMap
end data
end
```

7.15 W 17x17 50 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
50gwd5pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      150       0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
   title="detector 1cm from wall, half way x direction, 1m z dir"
   position 250 -1 100
  end location
  response 9505
   specialdose=9505
  end response
  distribution 1
   abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
   2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
   300000 200000 100000 50000 10000 end
   truepdf 3.3112E+05 1.5596E+06 7.9513E+06 1.9815E+07 5.4851E+08
         6.1897E+09 9.0678E+10 2.8391E+11 1.5702E+13 1.1556E+14
         2.0752E+14 4.1193E+15 3.8600E+14 8.8337E+13 1.3674E+14
```

```
        4.6530E+14 6.3605E+14 2.2632E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=8.4341E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
```

```
  gridGeometryID=5
end importanceMap
end data
end
```

7.16 W 17x17 50 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
50gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 2.2136E+05 1.0427E+06 5.3164E+06 1.3250E+07 4.7197E+08
            5.5718E+09 8.7814E+10 2.8804E+11 1.5030E+13 1.1327E+14
            1.9746E+14 4.0999E+15 3.6721E+14 9.2421E+13 1.4199E+14
            4.8053E+14 6.5904E+14 2.3267E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
```

```
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=8.4940E+15
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.17 W 17x17 60 GWd 4 wt% 1.5m thick concrete input file

```
=mavric
60gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
```

```
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=1.0048E+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.18 W 17x17 60 GWd 5 wt% 1.5m thick concrete input file

```
=mavric
60gwd5pct1.5m
v7-200n47g
read composition
```

```
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 7.0792E+05 3.3343E+06 1.6997E+07 4.2354E+07 7.7921E+08
            8.3785E+09 1.1221E+11 3.3672E+11 2.1109E+13 1.4604E+14
            2.8244E+14 5.0109E+15 5.2689E+14 1.0155E+14 1.5896E+14
            5.4426E+14 7.3583E+14 2.6557E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
```

```
  src 1
    title="point source midpoint x, 1.51m y, 1m z"
    strength=1.0184E+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.19 W 17x17 60 GWd 6 wt% 1.5m thick concrete input file

```
=mavric
60gwd6pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
```

```
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 4.8905E+05 2.3035E+06 1.1743E+07 2.9264E+07 6.6674E+08
            7.5870E+09 1.0848E+11 3.4236E+11 2.0397E+13 1.4641E+14
            2.7115E+14 4.9873E+15 5.0271E+14 1.0692E+14 1.6629E+14
            5.6666E+14 7.6764E+14 2.7412E+15 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0277E+16
    photons
    origin x=250 y=151 z=100
```

```
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.20 W 17x17 60 GWd 4 wt% 1.5m thick concrete self-shielded input file

```
=mavric
w17x17ss60gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2          2 den=5.485 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150        0     500        0
 sphere 2    1000
```

```
 zcylinder 3 32.05 132.05 67.95 origin x=250 y=232.05
 media 1 1 1
 media 0 1 -1 2 -3
 media 2 1 3
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 152 200 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
  src 1
    strength=1.0048E+16
```

```
    photons
    zcylinder 32.05 132.05 67.95 origin x=250 y=232.05
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.21 W 17x17 60 GWd 4 wt% 1.5m thick concrete comparison input file

```
=mavric
w17x17noss60gwd4pct1.5m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2          2 den=5.485 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
```

```
 cuboid 1     500        0      150        0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 152 200 231.05 233.05 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
  src 1
    strength=1.0048E+16
```

```
    photons
    origin x=250 y=232.05 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.22 W 17x17 60 GWd 4 wt% 1.12m thick concrete self-shielded input file

```
=mavric
w17x17ss60gwd4pct1.12m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2          2 den=5.485 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
```

```
 cuboid 1     500        0      112      0     500       0
 sphere 2    1000
 zcylinder 3 32.05 132.05 67.95 origin x=250 y=232.05
 media 1 1 1
 media 0 1 -1 2 -3
 media 2 1 3
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 112 152 200 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
```

```
  src 1
    strength=1.0048E+16
    photons
    zcylinder 32.05 132.05 67.95 origin x=250 y=232.05
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.23 W 17x17 60 GWd 4 wt% 1.12m thick concrete comparison input file

```
=mavric
w17x17noss60gwd4pct1.12mPointSrc
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2          2 den=5.485 1 300   end
end composition
read geometry
global unit 1
```

```
com="Unit 1"
 cuboid 1    500       0     112     0    500      0
 sphere 2   1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 112 152 200 231.05 233.05 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
  src 1
```

```
    strength=1.0048E+16
    photons
    origin x=250 y=232.05 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.24 W 17x17 60 GWd 4 wt% 1.13m thick concrete self-shielded input file

```
=mavric
w17x17ss60gwd4pct1.13m
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2        2 den=5.485 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
```

```
 cuboid 1     500        0      113      0     500       0
 sphere 2    1000
 zcylinder 3 32.05 132.05 67.95 origin x=250 y=232.05
 media 1 1 1
 media 0 1 -1 2 -3
 media 2 1 3
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 152 200 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
```

```
  src 1
    strength=1.0048E+16
    photons
    zcylinder 32.05 132.05 67.95 origin x=250 y=232.05
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.25 W 17x17 60 GWd 4 wt% 1.13m thick concrete comparison input file

```
=mavric
w17x17noss60gwd4pct1.13mPointSrc
v7-200n47g
read composition
 reg-concrete 1 1 300   end
 uo2          2 den=5.485 1 300   end
end composition
read geometry
global unit 1
```

```
com="Unit 1"
 cuboid 1     500        0      113      0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 10cm from wall, half way x direction, 1m z dir"
    position 250 -10 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 1.0470E+06 4.9314E+06 2.5138E+07 6.2636E+07 9.2747E+08
            9.3159E+09 1.1671E+11 3.2894E+11 2.1806E+13 1.4452E+14
            2.9382E+14 5.0353E+15 5.5226E+14 9.4727E+13 1.4950E+14
            5.1501E+14 6.9451E+14 2.5462E+15 end
  end distribution
  gridGeometry 5
    xLinear 20 0 200
    xLinear 9 200 245
    xLinear 9 255 300
    xLinear 20 300 500
    xplanes 217.05 249 251 282.05 end
    yLinear 50 0 150
    yLinear 11 155 265
    yplanes -11 -9 -7 -5 -3 -1 152 200 231.05 233.05 264.1 end
    zLinear 10 0 95
    zLinear 39 110 500
    zplanes 67.95 99 101 105 132.05 end
  end gridGeometry
end definitions
read sources
  src 1
```

```
    strength=1.0048E+16
    photons
    origin x=250 y=232.05 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.26 CE 16x16 60 GWd 6 wt% 0 m thick concrete input file

```
=mavric
60gwd6pct0cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     5       0      1       0     500       499
```

```
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
```

```
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.27 CE 16x16 60 GWd 6 wt% 5 cm thick concrete input file

```
=mavric
60gwd6pct5cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      5        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
```

```
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
```

```
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.28 CE 16x16 60 GWd 6 wt% 10 cm thick concrete input file

```
=mavric
60gwd6pct10cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      10       0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
```

```
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
```

```
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.29 CE 16x16 60 GWd 6 wt% 25 cm thick concrete input file

```
=mavric
60gwd6pct25cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500       0      25       0     500       0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
```

```
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
```

```
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.30 CE 16x16 60 GWd 6 wt% 50 cm thick concrete input file

```
=mavric
60gwd6pct50cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1    500      0     50      0    500      0
 sphere 2   1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
```

```
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
```

```
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.31 CE 16x16 60 GWd 6 wt% 75 cm thick concrete input file

```
=mavric
60gwd6pct75cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      75        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
```

```
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
```

```
   end adjointSource
   gridGeometryID=5
end importanceMap
end data
end
```

7.32 CE 16x16 60 GWd 6 wt% 100 cm thick concrete input file

```
=mavric
60gwd6pct100cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      100        0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
```

```
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
```

end

7.33 CE 16x16 60 GWd 6 wt% 125 cm thick concrete input file

```
=mavric
60gwd6pct125cm
v7-200n47g
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1    500       0     125       0    500       0
 sphere 2   1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
```

```
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.34 CE 16x16 60 GWd 6 wt% 150 cm thick concrete input file

```
=mavric
60gwd6pct150cm
v7-200n47g
```

```
read composition
 reg-concrete 1 1 300   end
end composition
read geometry
global unit 1
com="Unit 1"
 cuboid 1     500        0      150       0     500        0
 sphere 2    1000
 media 1 1 1
 media 0 1 -1 2
 boundary 2
end geometry
read definitions
  location 1
    title="detector 1cm from wall, half way x direction, 1m z dir"
    position 250 -1 100
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="60gwd6pct origen"
    abscissa 1e+007 8e+006 6.5e+006 5e+006 4e+006 3e+006 2.5e+006
    2e+006 1.66e+006 1.33e+006 1e+006 800000 600000 400000
    300000 200000 100000 50000 10000 end
    truepdf 493650 2.3251e+006 1.1854e+007 2.9538e+007 6.6912e+008
    7.5944e+009 1.0857e+011 3.4207e+011 2.0220e+013 1.448e+014
    2.6879e+014 4.9833e+015 4.9930e+014 1.0675e+014 1.6588e+014
    5.6498e+014 7.6664e+014 2.7373e+015 end
  end distribution
  gridGeometry 5
    xLinear 49 0 245
    xLinear 49 255 500
    xplanes 249 251 end
    yLinear 100 0 150
    yplanes -2 152 end
    zLinear 19 0 95
    zLinear 39 110 500
    zplanes 99 101 105 end
  end gridGeometry
```

```
end definitions
read sources
  src 1
    title="point source midpoint x, 1.01m y, 1m z"
    strength=1.0258e+16
    photons
    origin x=250 y=151 z=100
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=250000
    batches=50
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

7.35 Validation aluminum sphere input file

```
=mavric
Validation
v7-200n47g
read composition
 al 1 1 300   end
end composition
read geometry
```

```
global unit 1
com="Unit 1"
 sphere 1    6.032
 sphere 2    10
 media 1 1 1
 media 0 1 -1 2
boundary 2
end geometry
read definitions
  location 1
    position 0 0 6.032
  end location
  response 9505
    specialdose=9505
  end response
  distribution 1
    title="monoenergetic 1mev gammas"
    discrete 1e6 end
    truePDF 1 end
  end distribution
  gridGeometry 5
    xPlanes -6.032 -5.5 -5 -4.5 -4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5
             0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6.032 end
    yPlanes -6.032 -5.5 -5 -4.5 -4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5
             0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6.032 end
    zPlanes -6.032 -5.5 -5 -4.5 -4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5
             0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3 3.25
             3.5 3.75 4 4.25 4.5 4.75 5 5.25 5.5 5.75 6.032 end
  end gridGeometry
end definitions
read sources
  src 1
    title="point source at origin"
    strength=1e8
    photons
    edistributionid=1
  end src
end sources
read tallies
  pointDetector 1
```

```
    photon
    title="point"
    locationID=1
    responseID=9505
  end pointDetector
end tallies
read parameters
    randomSeed=0000000100000001
    perBatch=1000000
    batches=25
end parameters
read importanceMap
    adjointSource 1
    locationID=1
    responseID=9505
    end adjointSource
    gridGeometryID=5
end importanceMap
end data
end
```

8. Appendix B

8.1 Validation Model Hand Calculations

$$\dot{X} = \dot{X}_0 B_p(\mu R) e^{-\mu R} \left[\frac{mrem}{hr}\right]$$

Given:
$S = 10^8$ γ/sec
$E_0 = 1$ MeV
$R = 6.032$ cm
$\rho = 2.7$ g/cm^3

$$\dot{X}_0 = 0.0659\, \phi_0 E_0 \left(\frac{\mu_a}{\rho}\right)^{air}$$

$$\left(\frac{\mu_a}{\rho}\right)^{air} = 0.028\ \frac{cm^2}{g}$$

$$\phi_0 = \frac{S}{4\pi R^2}$$

$$\mu/\rho = 0.0614\ \frac{cm^2}{g}$$ [Table 11.4 ref. 1]

$$\mu = \left(0.0614\ \frac{cm^2}{g}\right)\left(2.7\ \frac{g}{cm^3}\right)$$

$$\mu = 0.16578\ cm^{-1}$$

$$B_p(\mu R) = 2.02$$ [Table 10.2 ref 1]

$$\dot{X} = \frac{0.0659\left(10^8\ \frac{\gamma}{s}\right)(1\ MeV)\left(0.028\ \frac{cm^2}{g}\right)(2.02)\, e^{-(0.166)(6.032)}}{4\pi(6.032\ cm)^2}$$

$$\dot{X} = 299.899\ \frac{mrem}{hr}$$

$$\dot{X} = 2.99899\ \frac{mSv}{hr}$$

9. Appendix C

9.1 Fuel Assembly Diagrams

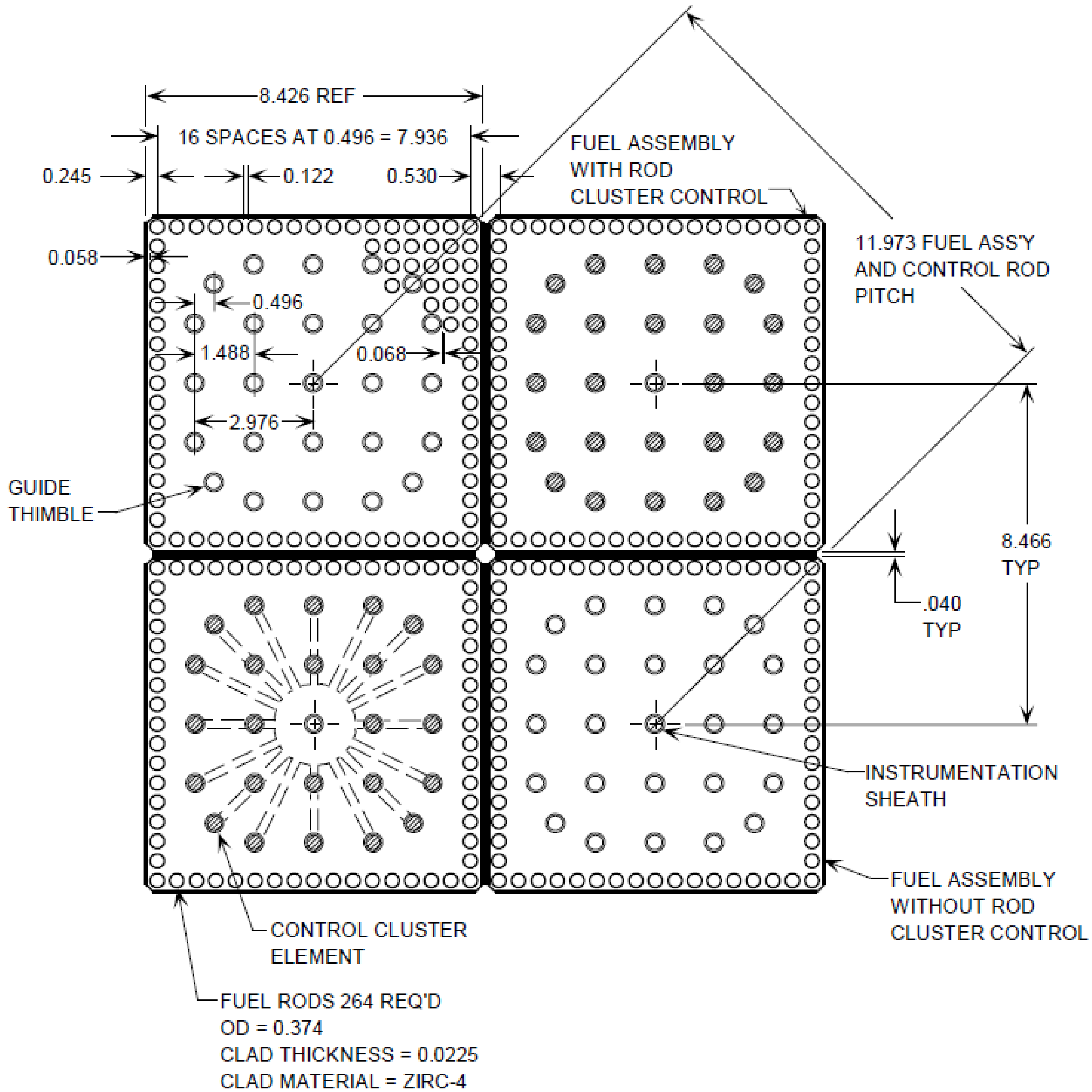

Figure 9: Westinghouse 17x17 Cross Section[14]

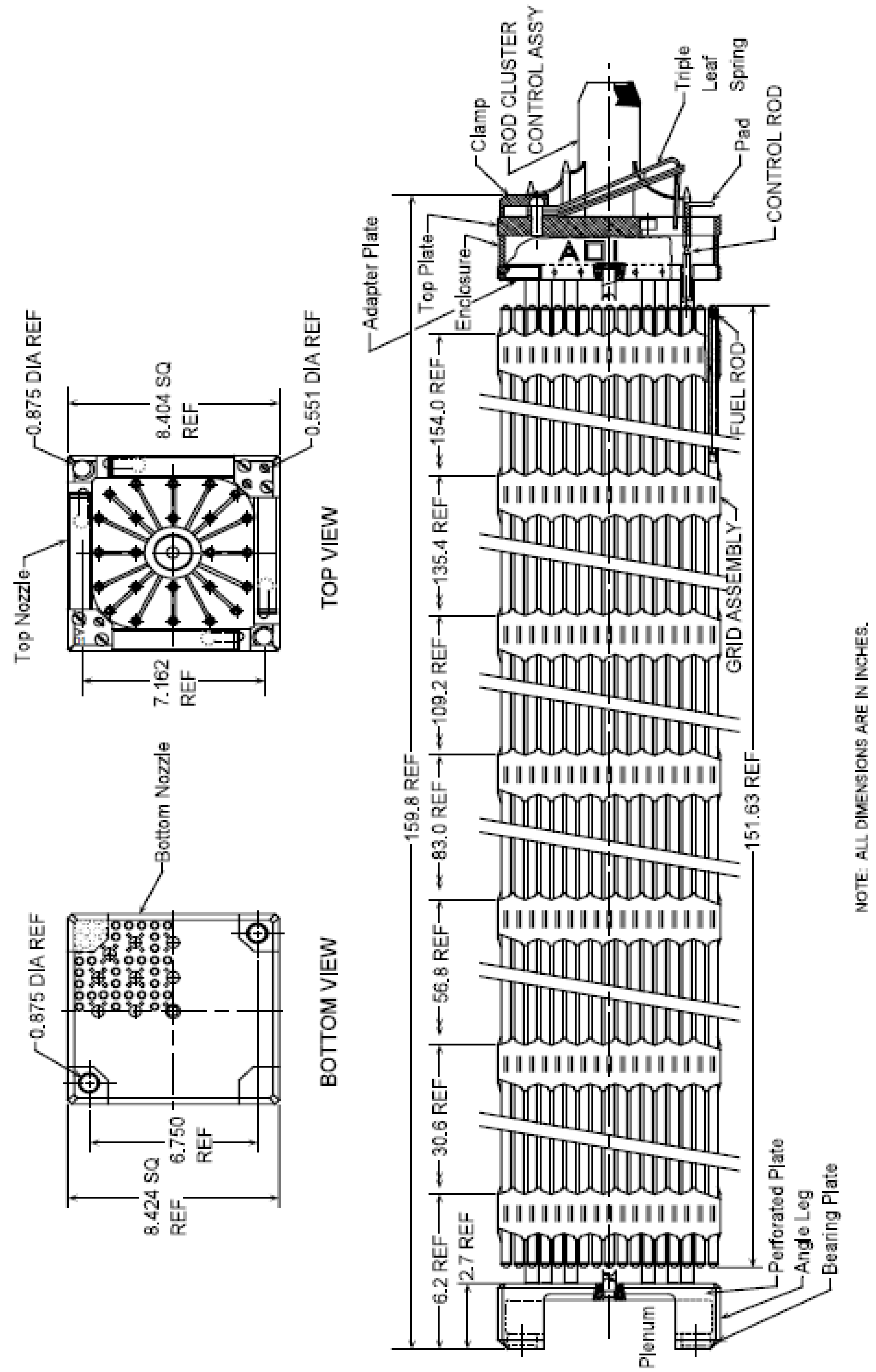

Figure 10: Westinghouse 17x17 Fuel Assembly Outline [14]

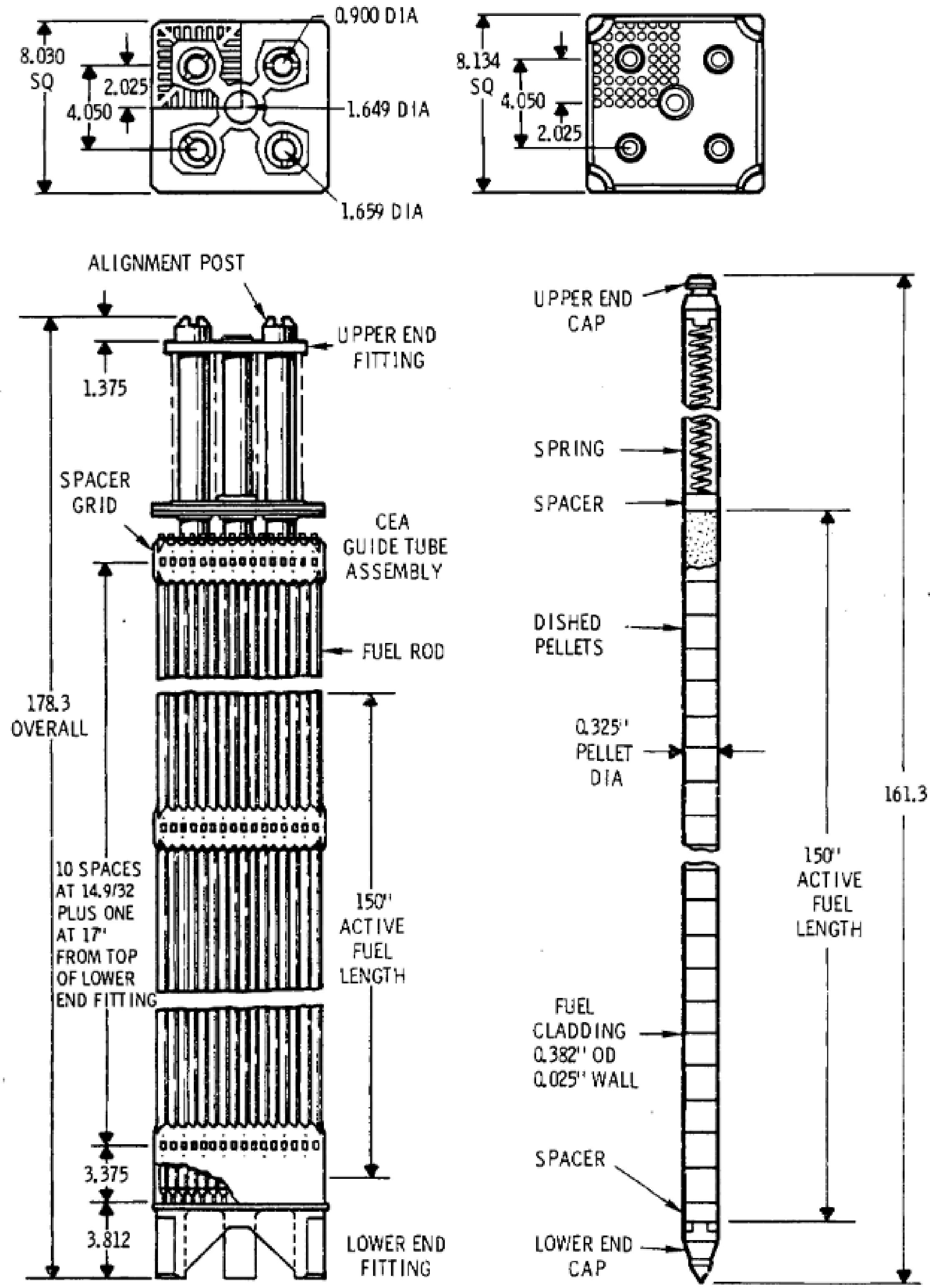

Figure 11: Combustion Engineering 16x16 Fuel Assembly [15]

10. Appendix D

10.1 Concrete Composition

Table 5: Regulatory Concrete Composition [9]

Regulatory Concrete (developed for U.S. NRC)	
Element	**Weight %**
Iron	1.4
Hydrogen	1
Aluminum	3.4
Calcium	4.4
Oxygen	53.2
Silicon	33.7
Sodium	2.9
Total:	100
Density:	2.3 g/cm^3

11. Appendix E

11.1 Depletion results for the Westinghouse 17x17 60 GWd 4 wt% case

For these tables the rightmost column represents the fuel after the 10 year decay period and is the only column used in the MAVRIC input.

```
===============================================================================================
=   Nuclide concentrations in grams, light elements for case '6' (#6/6)                       =
=   case 6 (Basis: 1 MTU)                                                                     =
-----------------------------------------------------------------------------------------------
  (relative cutoff; concentration at step     0 >   5.00E-02 % of sum of all concentrations at that step)
.
                 0.000d      0.500d      1.000d      3.000d     10.000d     30.000d    100.000d    300.000d   1000.000d   3000.000d   3652.000d
  o-16        1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05  1.3408E+05
  o-18        3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02  3.0252E+02
------------
  totals      1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05  1.3446E+05
===============================================================================================
=   Nuclide concentrations in grams, actinides for case '6' (#6/6)                            =
=   case 6 (Basis: 1 MTU)                                                                     =
-----------------------------------------------------------------------------------------------
  (relative cutoff; concentration at step     0 >   5.00E-02 % of sum of all concentrations at that step)
.
                 0.000d      0.500d      1.000d      3.000d     10.000d     30.000d    100.000d    300.000d   1000.000d   3000.000d   3652.000d
  u-235       4.1177E+03  4.1177E+03  4.1177E+03  4.1177E+03  4.1177E+03  4.1177E+03  4.1177E+03  4.1178E+03  4.1181E+03  4.1191E+03  4.1194E+03
  u-236       5.7695E+03  5.7695E+03  5.7695E+03  5.7695E+03  5.7695E+03  5.7695E+03  5.7695E+03  5.7697E+03  5.7704E+03  5.7722E+03  5.7728E+03
  u-238       9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05  9.1362E+05
  np-237      8.0546E+02  8.0614E+02  8.0679E+02  8.0908E+02  8.1423E+02  8.1851E+02  8.1916E+02  8.1926E+02  8.1993E+02  8.2437E+02  8.2650E+02
  pu-238      5.2986E+02  5.3037E+02  5.3082E+02  5.3210E+02  5.3402E+02  5.3662E+02  5.4367E+02  5.5430E+02  5.5508E+02  5.3206E+02  5.2462E+02
  pu-239      5.9149E+03  5.9294E+03  5.9419E+03  5.9769E+03  6.0151E+03  6.0207E+03  6.0206E+03  6.0206E+03  6.0204E+03  6.0198E+03  6.0196E+03
  pu-240      3.1744E+03  3.1744E+03  3.1744E+03  3.1744E+03  3.1746E+03  3.1750E+03  3.1766E+03  3.1811E+03  3.1959E+03  3.2326E+03  3.2429E+03
  pu-241      1.9714E+03  1.9712E+03  1.9711E+03  1.9706E+03  1.9688E+03  1.9635E+03  1.9454E+03  1.8944E+03  1.7262E+03  1.3236E+03  1.2138E+03
  pu-242      1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03  1.3054E+03
------------
  totals      9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05  9.3818E+05
===============================================================================================
```

= Nuclide concentrations in grams, fission products for case '6' (#6/6) =
= case 6 (Basis: 1 MTU) =

(relative cutoff; concentration at step 0 > 5.00E-02 % of sum of all concentrations at that step)

	0.000d	0.500d	1.000d	3.000d	10.000d	30.000d	100.000d	300.000d	1000.000d	3000.000d	3652.000d
br-81	3.5661E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01	3.5662E+01
se-82	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01	5.7332E+01
kr-83	5.7952E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01	5.7963E+01
kr-84	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02	1.9609E+02
kr-85	3.8574E+01	3.8575E+01	3.8572E+01	3.8559E+01	3.8511E+01	3.8376E+01	3.7905E+01	3.6590E+01	3.2339E+01	2.2724E+01	2.0254E+01
rb-85	1.6698E+02	1.6700E+02	1.6701E+02	1.6702E+02	1.6707E+02	1.6721E+02	1.6768E+02	1.6899E+02	1.7324E+02	1.8286E+02	1.8533E+02
kr-86	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02	3.0678E+02
rb-87	4.0251E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02	4.0252E+02
sr-88	5.5846E+02	5.5850E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02	5.5851E+02
y-89	7.1945E+02	7.1961E+02	7.1977E+02	7.2039E+02	7.2245E+02	7.2734E+02	7.3689E+02	7.4244E+02	7.4282E+02	7.4282E+02	7.4282E+02
sr-90	8.6084E+02	8.6082E+02	8.6079E+02	8.6068E+02	8.6028E+02	8.5915E+02	8.5519E+02	8.4399E+02	8.0593E+02	7.0639E+02	6.7667E+02
zr-90	5.7378E+01	5.7408E+01	5.7438E+01	5.7555E+01	5.7957E+01	5.9091E+01	6.3047E+01	7.4250E+01	1.1232E+02	2.1188E+02	2.4161E+02
y-91	3.7867E+01	3.7795E+01	3.7637E+01	3.6800E+01	3.3873E+01	2.6727E+01	1.1663E+01	1.0910E+00	2.7311E-04	1.4008E-14	6.1925E-18
zr-91	9.4185E+02	9.4207E+02	9.4230E+02	9.4318E+02	9.4611E+02	9.5325E+02	9.6832E+02	9.7889E+02	9.7998E+02	9.7998E+02	9.7998E+02
zr-92	1.0837E+03	1.0838E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03	1.0839E+03
zr-93	1.2026E+03	1.2028E+03	1.2029E+03	1.2030E+03	1.2030E+03	1.2030E+03	1.2030E+03	1.2030E+03	1.2030E+03	1.2030E+03	1.2030E+03
zr-94	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03	1.3197E+03
zr-95	6.8896E+01	6.8532E+01	6.8162E+01	6.6702E+01	6.1834E+01	4.9797E+01	2.3341E+01	2.6783E+00	1.3708E-03	5.4250E-13	4.6684E-16
nb-95	3.7786E+01	3.7783E+01	3.7779E+01	3.7743E+01	3.7397E+01	3.5031E+01	2.1876E+01	3.1066E+00	1.6515E-03	6.5365E-13	5.6248E-16
mo-95	1.1618E+03	1.1621E+03	1.1625E+03	1.1640E+03	1.1692E+03	1.1836E+03	1.2233E+03	1.2627E+03	1.2685E+03	1.2685E+03	1.2685E+03
zr-96	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03	1.4098E+03
mo-96	1.1471E+02	1.1471E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02	1.1472E+02
mo-97	1.4126E+03	1.4130E+03	1.4132E+03	1.4134E+03	1.4135E+03	1.4135E+03	1.4135E+03	1.4135E+03	1.4135E+03	1.4135E+03	1.4135E+03
mo-98	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03	1.4922E+03
tc-99	1.3281E+03	1.3286E+03	1.3290E+03	1.3303E+03	1.3319E+03	1.3322E+03	1.3322E+03	1.3322E+03	1.3322E+03	1.3322E+03	1.3322E+03
mo-100	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03	1.6894E+03
ru-100	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02	2.7704E+02
ru-101	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03	1.3725E+03
ru-102	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03	1.5404E+03
ru-103	5.6965E+01	5.6466E+01	5.5969E+01	5.4027E+01	4.7744E+01	3.3536E+01	9.7409E+00	2.8481E-01	1.2174E-06	5.5593E-22	5.5469E-27
rh-103	6.9351E+02	6.9402E+02	6.9451E+02	6.9646E+02	7.0275E+02	7.1697E+02	7.4079E+02	7.5025E+02	7.5054E+02	7.5054E+02	7.5054E+02
ru-104	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03	1.1141E+03
pd-104	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02	6.0884E+02
pd-105	7.8040E+02	7.8075E+02	7.8104E+02	7.8172E+02	7.8213E+02	7.8215E+02	7.8215E+02	7.8215E+02	7.8215E+02	7.8215E+02	7.8215E+02
ru-106	2.6677E+02	2.6652E+02	2.6628E+02	2.6529E+02	2.6185E+02	2.5226E+02	2.2140E+02	1.5249E+02	4.1347E+01	9.9321E-01	2.9452E-01
pd-106	5.6642E+02	5.6667E+02	5.6692E+02	5.6791E+02	5.7135E+02	5.8093E+02	6.1180E+02	6.8070E+02	7.9184E+02	8.3219E+02	8.3289E+02
pd-107	4.7350E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02	4.7351E+02
pd-108	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02	3.2245E+02
ag-109	1.5324E+02	1.5336E+02	1.5342E+02	1.5349E+02	1.5350E+02	1.5350E+02	1.5350E+02	1.5350E+02	1.5350E+02	1.5350E+02	1.5350E+02
pd-110	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02	1.0924E+02
cd-110	1.1582E+02	1.1583E+02	1.1583E+02	1.1584E+02	1.1586E+02	1.1593E+02	1.1616E+02	1.1660E+02	1.1710E+02	1.1719E+02	1.1719E+02
cd-111	5.5159E+01	5.5186E+01	5.5213E+01	5.5307E+01	5.5527E+01	5.5730E+01	5.5767E+01	5.5768E+01	5.5768E+01	5.5768E+01	5.5768E+01
sn-126	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9675E+01	3.9674E+01	3.9674E+01
i-127	8.0579E+01	8.0612E+01	8.0644E+01	8.0750E+01	8.0946E+01	8.1101E+01	8.1349E+01	8.1665E+01	8.1787E+01	8.1788E+01	8.1788E+01
te-128	1.7699E+02	1.7700E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02	1.7701E+02
i-129	2.8872E+02	2.8879E+02	2.8882E+02	2.8889E+02	2.8911E+02	2.8959E+02	2.9031E+02	2.9053E+02	2.9054E+02	2.9054E+02	2.9054E+02
te-130	6.8906E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02	6.8907E+02
xe-131	6.2485E+02	6.2521E+02	6.2554E+02	6.2678E+02	6.2982E+02	6.3288E+02	6.3358E+02	6.3358E+02	6.3358E+02	6.3358E+02	6.3358E+02
xe-132	2.1680E+03	2.1685E+03	2.1689E+03	2.1703E+03	2.1723E+03	2.1728E+03	2.1728E+03	2.1728E+03	2.1728E+03	2.1728E+03	2.1728E+03
cs-133	1.8353E+03	1.8360E+03	1.8367E+03	1.8391E+03	1.8443E+03	1.8475E+03	1.8477E+03	1.8477E+03	1.8477E+03	1.8477E+03	1.8477E+03
xe-134	2.7299E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03	2.7300E+03
cs-134	3.0244E+02	3.0231E+02	3.0218E+02	3.0162E+02	2.9969E+02	2.9423E+02	2.7590E+02	2.2958E+02	1.2066E+02	1.9204E+01	1.0549E+01
ba-134	1.7199E+02	1.7213E+02	1.7227E+02	1.7283E+02	1.7476E+02	1.8022E+02	1.9855E+02	2.4487E+02	3.5378E+02	4.5524E+02	4.6389E+02
cs-135	6.9006E+02	6.9033E+02	6.9056E+02	6.9078E+02	6.9079E+02	6.9079E+02	6.9079E+02	6.9079E+02	6.9079E+02	6.9079E+02	6.9079E+02
xe-136	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03	4.2102E+03
ba-136	5.0616E+01	5.0646E+01	5.0675E+01	5.0783E+01	5.1083E+01	5.1521E+01	5.1749E+01	5.1755E+01	5.1755E+01	5.1755E+01	5.1755E+01
cs-137	2.1643E+03	2.1643E+03	2.1642E+03	2.1639E+03	2.1630E+03	2.1602E+03	2.1507E+03	2.1238E+03	2.0320E+03	1.7911E+03	1.7189E+03
ba-137	1.1698E+02	1.1705E+02	1.1712E+02	1.1739E+02	1.1835E+02	1.2108E+02	1.3060E+02	1.5756E+02	2.4931E+02	4.9020E+02	5.6238E+02
ba-138	2.3249E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03	2.3250E+03
la-139	2.1548E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03	2.1549E+03
ce-140	2.2087E+03	2.2093E+03	2.2100E+03	2.2124E+03	2.2194E+03	2.2294E+03	2.2344E+03	2.2345E+03	2.2345E+03	2.2345E+03	2.2345E+03
ce-141	5.4434E+01	5.4114E+01	5.3571E+01	5.1339E+01	4.4221E+01	2.8868E+01	6.4894E+00	9.1233E-02	3.0059E-08	9.0670E-27	8.3133E-33
pr-141	1.9027E+03	1.9033E+03	1.9039E+03	1.9061E+03	1.9132E+03	1.9286E+03	1.9510E+03	1.9574E+03	1.9575E+03	1.9575E+03	1.9575E+03
ce-142	1.9882E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03	1.9883E+03
nd-142	6.1071E+01	6.1107E+01	6.1131E+01	6.1166E+01	6.1173E+01	6.1173E+01	6.1173E+01	6.1173E+01	6.1173E+01	6.1173E+01	6.1173E+01
nd-143	1.1100E+03	1.1105E+03	1.1110E+03	1.1130E+03	1.1188E+03	1.1274E+03	1.1321E+03	1.1323E+03	1.1323E+03	1.1323E+03	1.1323E+03
ce-144	3.9433E+02	3.9385E+02	3.9337E+02	3.9146E+02	3.8485E+02	3.6657E+02	3.0917E+02	1.9006E+02	3.4615E+01	2.6674E-01	5.4601E-02
nd-144	2.1707E+03	2.1711E+03	2.1716E+03	2.1735E+03	2.1801E+03	2.1984E+03	2.2558E+03	2.3749E+03	2.5304E+03	2.5647E+03	2.5649E+03
nd-145	1.0929E+03	1.0931E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03	1.0932E+03
nd-146	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03	1.3306E+03
pm-147	2.0913E+02	2.0930E+02	2.0946E+02	2.1003E+02	2.1128E+02	2.1120E+02	2.0189E+02	1.7471E+02	1.0529E+02	2.4777E+01	1.5460E+01
sm-147	1.2313E+02	1.2321E+02	1.2328E+02	1.2359E+02	1.2465E+02	1.2771E+02	1.3819E+02	1.6539E+02	2.3480E+02	3.1532E+02	3.2463E+02
nd-148	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02	6.6765E+02
sm-148	3.2329E+02	3.2340E+02	3.2350E+02	3.2383E+02	3.2458E+02	3.2533E+02	3.2602E+02	3.2631E+02	3.2632E+02	3.2632E+02	3.2632E+02
nd-150	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02	3.3291E+02
sm-150	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02	5.3316E+02
sm-152	1.5082E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02	1.5083E+02
eu-153	2.0310E+02	2.0335E+02	2.0356E+02	2.0411E+02	2.0458E+02	2.0463E+02	2.0463E+02	2.0463E+02	2.0463E+02	2.0463E+02	2.0463E+02
sm-154	7.6205E+01	7.6205E+01	7.6205E+01	7.6205E+01	7.6205E+01	7.6205E+01	7.6205E+01	7.6205E+01	7.6207E+01	7.6209E+01	7.6210E+01
eu-154	5.2804E+01	5.2798E+01	5.2792E+01	5.2769E+01	5.2688E+01	5.2456E+01	5.1652E+01	4.9422E+01	4.2349E+01	2.7239E+01	2.3589E+01
gd-156	2.7072E+02	2.7093E+02	2.7114E+02	2.7194E+02	2.7422E+02	2.7784E+02	2.8017E+02	2.8027E+02	2.8027E+02	2.8027E+02	2.8027E+02
gd-158	5.0222E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01	5.0223E+01
totals	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04	6.1849E+04

```
=====================================================================================================
=   Nuclide concentrations in curies, light elements for case '6' (#6/6)                            =
=   case 6 (Basis: 1 MTU)                                                                           =
-----------------------------------------------------------------------------------------------------
  (relative cutoff; concentration at step      0 >   5.00E-02 % of sum of all concentrations at that step)
.
                 0.000d      0.500d      1.000d      3.000d     10.000d     30.000d    100.000d    300.000d   1000.000d   3000.000d   3652.000d
  h-3          4.0975E-01  4.0972E-01  4.0969E-01  4.0956E-01  4.0912E-01  4.0786E-01  4.0349E-01  3.9125E-01  3.5125E-01  2.5812E-01  2.3346E-01
  c-15         1.1863E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  n-16         6.3891E+02  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  o-19         5.1069E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
------------
  totals       6.4562E+02  4.1120E-01  4.1117E-01  4.1104E-01  4.1060E-01  4.0934E-01  4.0497E-01  3.9273E-01  3.5273E-01  2.5960E-01  2.3493E-01
=====================================================================================================
=====================================================================================================
=   Nuclide concentrations in curies, actinides for case '6' (#6/6)                                 =
=   case 6 (Basis: 1 MTU)                                                                           =
-----------------------------------------------------------------------------------------------------
  (relative cutoff; concentration at step      0 >   5.00E-02 % of sum of all concentrations at that step)
.
                 0.000d      0.500d      1.000d      3.000d     10.000d     30.000d    100.000d    300.000d   1000.000d   3000.000d   3652.000d
  u-235m       4.1272E+04  1.9045E-04  8.7879E-13  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  u-237        1.1154E+06  1.0596E+06  1.0065E+06  8.1966E+05  3.9944E+05  5.1232E+04  4.3654E+01  4.8231E+00  4.3949E+00  3.3698E+00  3.0903E+00
  u-239        2.4402E+07  1.3966E-02  7.9934E-12  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  np-238       7.6247E+05  6.4733E+05  5.4957E+05  2.8552E+05  2.8857E+04  4.1382E+01  4.9267E-02  4.9134E-02  4.8674E-02  4.7381E-02  4.6967E-02
  np-239       2.4347E+07  2.1163E+07  1.8268E+07  1.0142E+07  1.2935E+06  3.6712E+03  7.1387E+01  7.1383E+01  7.1370E+01  7.1334E+01  7.1322E+01
  np-240m      3.4891E+04  2.9016E-06  2.9016E-06  2.8902E-06  2.8886E-06  2.8879E-06  2.8879E-06  2.8879E-06  2.8879E-06  2.8879E-06  2.8879E-06
  pu-241       2.0460E+05  2.0458E+05  2.0457E+05  2.0451E+05  2.0432E+05  2.0378E+05  2.0190E+05  1.9660E+05  1.7915E+05  1.3736E+05  1.2597E+05
  pu-243       9.8208E+05  1.8334E+05  3.4228E+04  4.1577E+01  6.4814E-06  6.4788E-06  6.4788E-06  6.4788E-06  6.4788E-06  6.4788E-06  6.4788E-06
  am-242       1.7060E+05  1.0151E+05  6.0400E+04  7.5791E+03  1.5978E+01  1.0694E+01  1.0684E+01  1.0655E+01  1.0555E+01  1.0275E+01  1.0185E+01
  am-244m      5.1759E+05  2.3884E-03  1.1021E-11  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  am-244       3.4589E+04  1.5180E+04  6.6622E+03  2.4717E+02  2.4313E-03  3.6051E-07  3.5522E-07  3.4055E-07  2.9379E-07  1.9264E-07  1.6788E-07
  cm-242       1.1637E+05  1.1636E+05  1.1625E+05  1.1544E+05  1.1208E+05  1.0294E+05  7.6433E+04  3.2647E+04  1.6702E+03  8.8345E+00  8.4597E+00
------------
  totals       5.2778E+07  2.3520E+07  2.0275E+07  1.1605E+07  2.0674E+06  3.9091E+05  3.0773E+05  2.5859E+05  2.0947E+05  1.6383E+05  1.5178E+05
=====================================================================================================
```

Table 6: Nuclide Concentrations in Curies, Fission Products

Nuclide Concentrations in curies following 10 year decay, fission products for case '6' Only nuclides with curies > 10^{-7} included	
Nuclide	Curies
Sr-90	9.3458E+04
Y-90	9.3482E+04
Ru-106	9.7671E+02
Rh-106	9.7671E+02
Ag-109m	2.9292E-03
Ag-110	3.5034E-03
Te-127	6.2779E-07
Cs-134	1.3637E+04
Cs-137	1.4922E+05
Ba-137m	1.4131E+05
Ce-144	1.7388E+02
Pr-144	1.7389E+02
Pm-147	1.4340E+04
Total	5.2652E+05

Table 7: Gamma Source Intensity

Gamma source intensity (1/s) for case '6' following 10 year decay	
Energy bin boundaries (MeV)	Source Intensity (γ/s)
1.000E+01 - 8.000E+00	1.0470E+06
8.000E+00 - 6.500E+00	4.9314E+06
6.500E+00 - 5.000E+00	2.5138E+07
5.000E+00 - 4.000E+00	6.2636E+07
4.000E+00 - 3.000E+00	9.2747E+08
3.000E+00 - 2.500E+00	9.3159E+09
2.500E+00 - 2.000E+00	1.1671E+11
2.000E+00 - 1.660E+00	3.2894E+11
1.660E+00 - 1.330E+00	2.1806E+13
1.330E+00 - 1.000E+00	1.4452E+14
1.000E+00 - 8.000E-01	2.9382E+14
8.000E-01 - 6.000E-01	5.0353E+15
6.000E-01 - 4.000E-01	5.5226E+14
4.000E-01 - 3.000E-01	9.4727E+13
3.000E-01 - 2.000E-01	1.4950E+14
2.000E-01 - 1.000E-01	5.1501E+14
1.000E-01 - 5.000E-02	6.9451E+14
5.000E-02 - 1.000E-02	2.5462E+15
Total:	**1.0048E+16**