Title: Criticality Accident Alarm System Analysis Using MCNP6.2 Constructive Solid Geometry/Unstructured Mesh Hybrid

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# CRITICALITY ACCIDENT ALARM SYSTEM ANALYSIS USING MCNP6.2 CONSTRUCTIVE SOLID GEOMETRY/UNSTRUCTURED MESH HYBRID

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## ABSTRACT

*Criticality Accident Alarm System (CAAS) design, analysis, and simulation require a combination of methodologies and techniques used for both criticality and shielding problems. MCNP6.2 is a general-purpose Monte Carlo radiation transport package with continuous-energy neutron and photon physics [1] making it suitable for CAAS analysis and simulation. Use of MCNP6 for analysis of criticality accident alarm systems has typically been done by building constructive solid geometry (CSG) models that may include extensive specification of facilities.*

*The MCNP6 unstructured mesh (UM) capability incorporates a way to specify geometries and conduct simulations on an unstructured mesh, which can be efficient when building complex geometries such as those relevant to CAAS analysis for large, complex facilities. This paper discusses a method that allows users to build a solid geometry or import existing computer aided drawing/computer aided engineering (CAD/CAE) models to create an unstructured mesh for use in MCNP6.2 calculations. Traditional CSG may be combined with UM for embedding an unstructured mesh representation of a geometry and legacy CSG [2] to create a hybrid geometry. An advantage of the CSG/UM hybrid method is the ability to build the facility in the unstructured mesh and specify the critical cells and alarm system detectors in CSG.*

*In this work a constructive solid geometry/unstructured mesh hybrid model is created for use with MCNP6.2. The model is chosen for appropriateness to demonstrate the MCNP6 CSG/UM capability for solving problems relevant to CAAS analysis and for comparison to traditional CSG models used for analyzing criticality accident alarm systems. CAAS problems typically require the use of variance reduction techniques [3]. Methods designed to increase the efficiency of the calculations are discussed. Deterministic variance reduction methods available in Atilla10.0 are applied to the hybrid CSG/UM model [4]. Monte Carlo/deterministic hybrid variance reduction, in which FW-CADIS (forward-weighted consistently adjoint driven importance sampling) is used on the mesh in a deterministic calculation to generate weight windows and source biasing parameters which are applied in the MCNP6.2 simulations [ 5, 6, 7].*

*Results for CAAS analysis are presented and compared for MCNP6.2 unstructured mesh, constructive solid geometry, and unstructured mesh/constructive solid geometry hybrid models. Visualization of MCNP6.2 results, including use of the MCNP6 UM elemental edit output files and FMESH tallies over the geometry under consideration [8], is presented.*

## KEY WORDS

*Criticality accident, unstructured.*

## 1. INTRODUCTION

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## 2. THE HYBRID GEOMETRY METHOD

There are several advantages to using a hybrid geometry method. The first is that a detailed and complicated infrastructure, typical of a facility for which the CAAS analysis is done, may be more straightforward to model either by building solid geometries or importing them from drawings. While it is likely to be the case that facility drawings do not include the criticality cells of interest, it is fairly simple to add these as CSG cells along with unstructured mesh in the MCNP6 input file. Since the goal of CAAS simulations may be the determination of suitable detector locations, adding detector cells as CSG allows them to be relocated without regenerating a mesh. Lastly, adding CSG cells to model a critical system allows for exact preservation of mass and ease in changing dimensions or locations to model various fissile concentrations and material forms.

The series of steps undertaken to complete the hybrid geometry are as follows: 1. Build the facility solid geometry or obtain the facility drawing, 2. Create a mesh for use with the MCNP6 UM capability while preserving void space within the mesh to hold the CSG cells, 3. Specify CSG cells within the MCNP6 input file. Illustration of the aforementioned steps is undertaken with a CAAS example.

### a. Creating the Solid Geometry

The solid geometry may be imported as an already existing file or built from scratch. In this example, SpaceClaim is used to build a solid geometry. Figure 1 shows the solid geometry consisting of a building with concrete walls, floor, and ceiling, along with steel doors. For this case, once the solid geometry model is constructed it is imported into Attila4MC as a parsolid file. There are a variety of solid geometry file types that may be imported into Attila4MC, which are relevant for the case in which a facility model is already in existence.
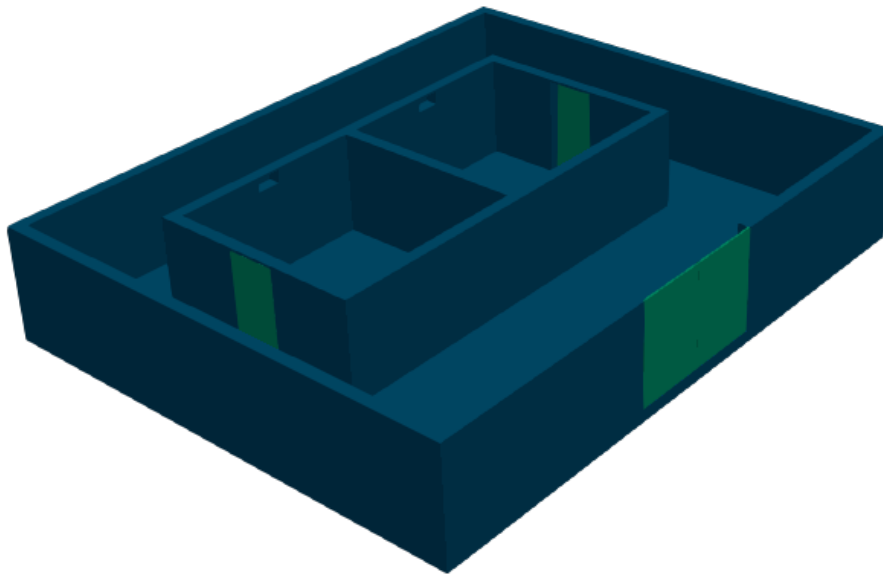


**Figure 1. Solid geometry model of facility. Roof and ceiling removed to show interior detail.**

### b. Creating the Mesh

For this example a mesh is created from the solid geometry using the Mesh Generator in Attila4MC [cite Attila mesh guidance]. An important concept for this example is that the walls, floor, ceiling, and doors are part of the mesh. The option to identify empty regions was not used and therefore the air within the facility "rooms" is not part of the mesh. This concept is important because the CSG cells will be used to fill this space. An illustration of the mesh is shown in Figure 2. The regions are assigned material and density specifications. Calculation parameters are assigned and the MCNP6 input file, along with the Abaqus file describing the unstructured mesh, is created by Attila4MC.
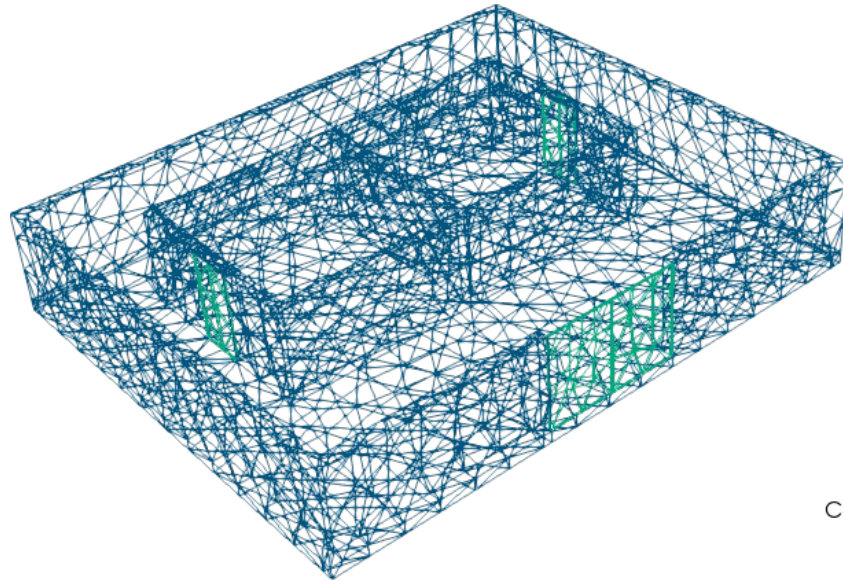
**Figure 2. Mesh model of facility. Roof and ceiling removed to show interior detail.**

c. <u>Creating the CSG/UM Hybrid</u>

Every MCNP UM geometry requires at least one CSG surface to specify space around the mesh plus a buffer region. These surfaces are used to create a cell which is filled with the UM. In this example, cell 9 is the fill cell holding the UM geometry specified in the Abaqus file. The UM geometry cells (u=1) are filled into surface 100. The CSG/UM hybrid specification begins in cell 9 where filling universe 1 outside surfaces 201, 202, 203 creates space to hold the CSG cells. The CSG cells (21, 22, 23) specifying the facility rooms are within surfaces 201, 202, 203. A critical mass of uranium metal is contained in cell 30. The detectors are modeled as cells 40, 41, 42. An MCNP6 illustration, along with the cell cards from the input file with a combination of CSG and UM cells in green text, is shown in Figure 3.
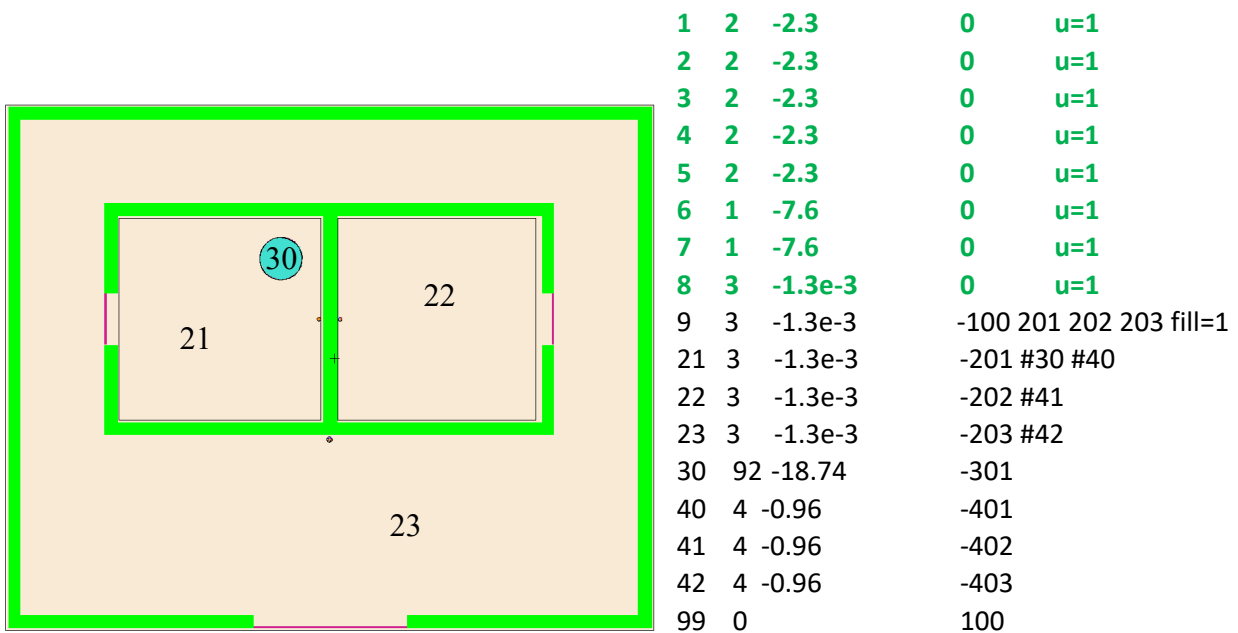


```
1    2   -2.3              0        u=1
2    2   -2.3              0        u=1
3    2   -2.3              0        u=1
4    2   -2.3              0        u=1
5    2   -2.3              0        u=1
6    1   -7.6              0        u=1
7    1   -7.6              0        u=1
8    3   -1.3e-3           0        u=1
9    3   -1.3e-3           -100 201 202 203 fill=1
21   3   -1.3e-3           -201 #30 #40
22   3   -1.3e-3           -202 #41
23   3   -1.3e-3           -203 #42
30  92  -18.74             -301
40   4  -0.96              -401
41   4  -0.96              -402
42   4  -0.96              -403
99   0                     100
```

**Figure 3. MCNP6 plotter illustration and cell cards from input file showing UM and CSG cells**

3. **CAAS ANALYSIS**

There are several steps required for CAAS calculations to determine dose from a criticality accident. The first step is to determine the source to be used for the simulations. This is done by modelling the system in a criticality calculation. Once the source is obtained it is used in fixed source calculations to determine dose.

a.  Criticality calculation

The model is first run as a KCODE calculation in MCNP6 to achieve convergence of k-effective and the fission source distribution. The source file (.src) from the first kcode calculation is used as the starting source in a subsequent kcode calculation, discard cycles are not run because the calculation is starting with an already converged source. In this second KCODE calculation, the SSW card is used to collect the fission source points in the critical cell. Once the fission source points have been collected, they are written to a file and used in subsequent fixed source calculations.

b.  Fixed source calculatiom

Using the same geometry as the previous KCODE calculations, the fission source is read into the cell containing the critical mass. The NONU card is used to turn off fission, which is already acounted for by the use of the SSR.

c.  Variance reduction

CAAS problems require the use of variance reduction to achieve reliable tally results at the detector or location of interest. The use of the unstructured mesh allows for deterministic variance reduction to be applied in an ATTILA calculation. In order to do this there must be a mesh in which the critical cells are present. The solid geometry and mesh for this example are shown in Figures 4 and 5.
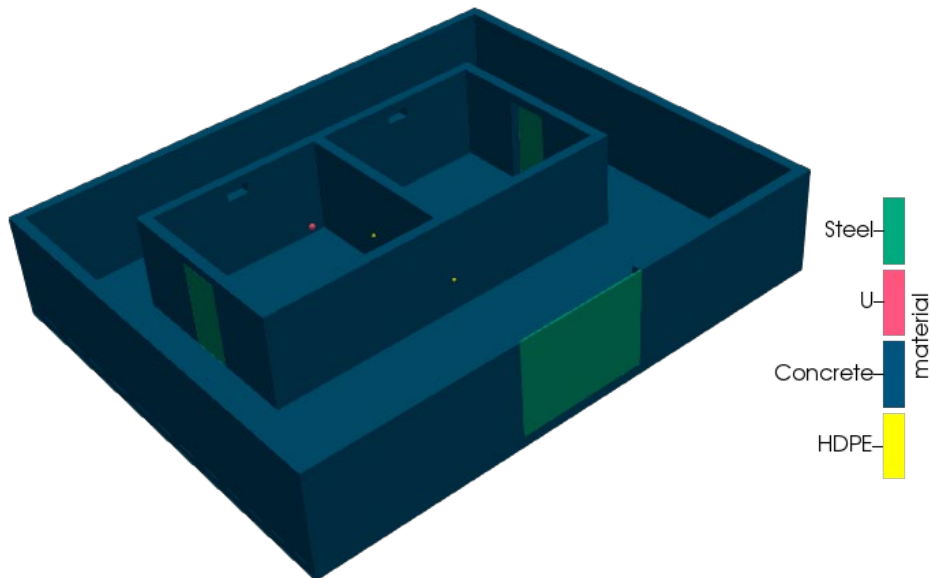


**Figure 4. Solid geometry model of facility with critical and detector cells. Roof and ceiling removed to show interior detail.**
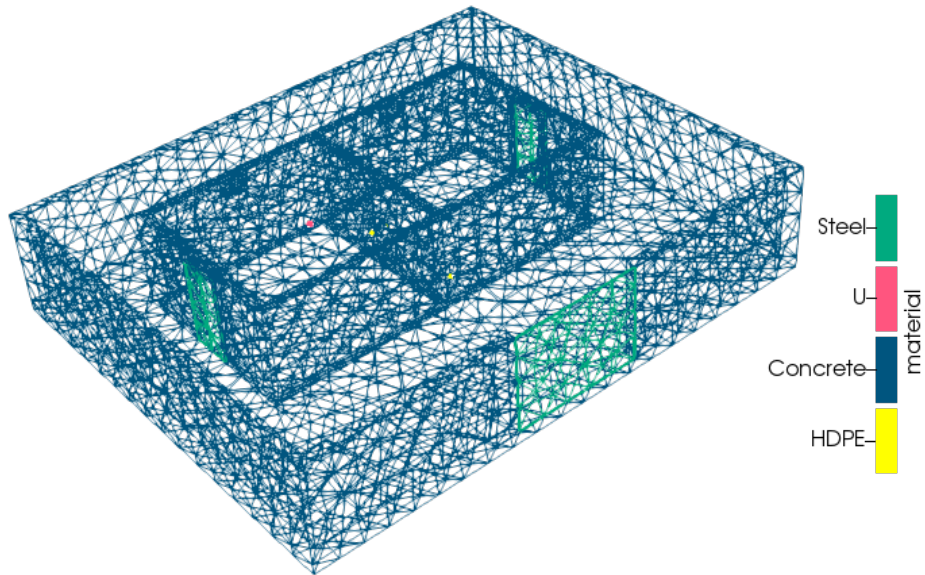
**Figure 5. Mesh model of facility with critical and detector cells. Roof and ceiling removed to show interior detail.**

Subheadings or subsection headings are to be in lower case with initial capitals.

## 4. RESULTS

Neutron and photon absorbed dose results are compared for the CSG, CSG/UM hybrid, and UM geometries. The results presented in Figures 6-8 and Tables I and II are using deterministic variance reduction in Attila4MC in which the full unstructured mesh is used in an FW-CADIS calculation. The weight window file and biased source are used in a subsequent MCNP6.2 calculation. These results have been compared with an analog calculation in which the only variance reduction technique in the MCNP6.2 calculation is implicit capture, which is on by default. In addition, a calculation using only the weight window file generated in the FW-CADIS calculation along with the SSR card reading in the fission source collected in the KCODE calculation. All results were found to be consistent with the three different methods, although the combined weight windows with biased source method was found to be the most efficient for reliable tally results.
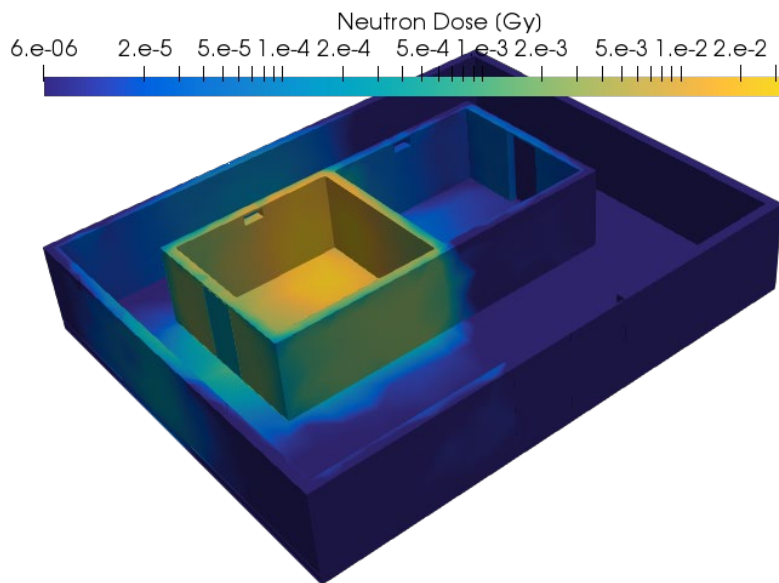
a. Neutron results



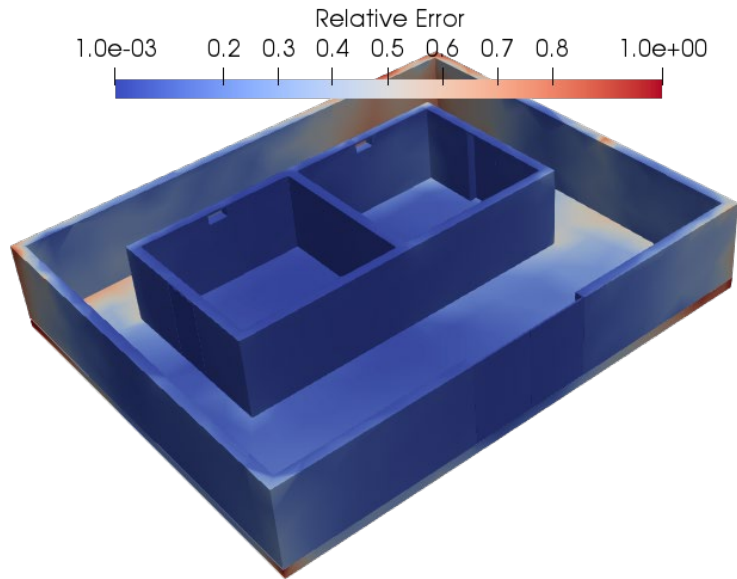**Figure 6. MCNP6.2 neutron energy deposition results for CSG/UM hybrid geometry**

**Figure 7. MCNP6.2 neutron energy deposition relative error for CSG/UM hybrid geometry**

**Table I. Neutron Absorbed Dose Results at Various Detector Locations**

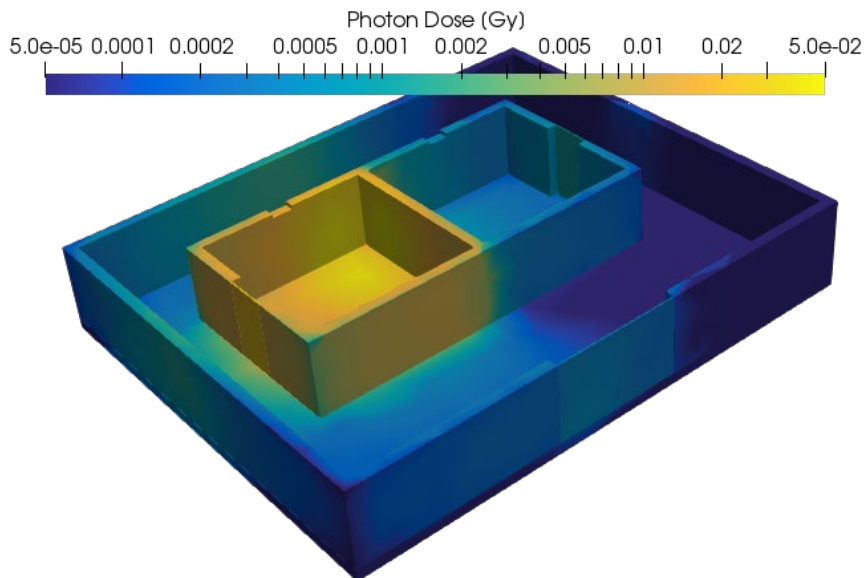| Geometry | Detector 1 Dose in Gy (RE) | FOM > Analog | Detector 2 Dose in Gy (RE) | FOM > Analog | Detector 3 Dose in Gy (RE) | FOM > Analog |
|---|---|---|---|---|---|---|
| **CSG** | $1.48\ 10^{-1}$ (0.01) | 4X | $7.34\ 10^{-4}$ (0.01) | 7879X | $1.47\ 10^{-4}$ (0.06) | 676X |
| **CSG/UM** | $1.47\ 10^{-1}$ (0.01) | 1000X | $7.42\ 10^{-4}$ (0.01) | 1000X | $1.47\ 10^{-4}$ (0.03) | 1000X |
| **UM** | $1.47\ 10^{-1}$ (0.01) | 1000X | $7.42\ 10^{-4}$ (0.01) | 1000X | $1.47\ 10^{-4}$ (0.03) | 1000X |

b. Photon results



**Figure 8. MCNP6.2 photon energy deposition results for CSG/UM hybrid geometry**
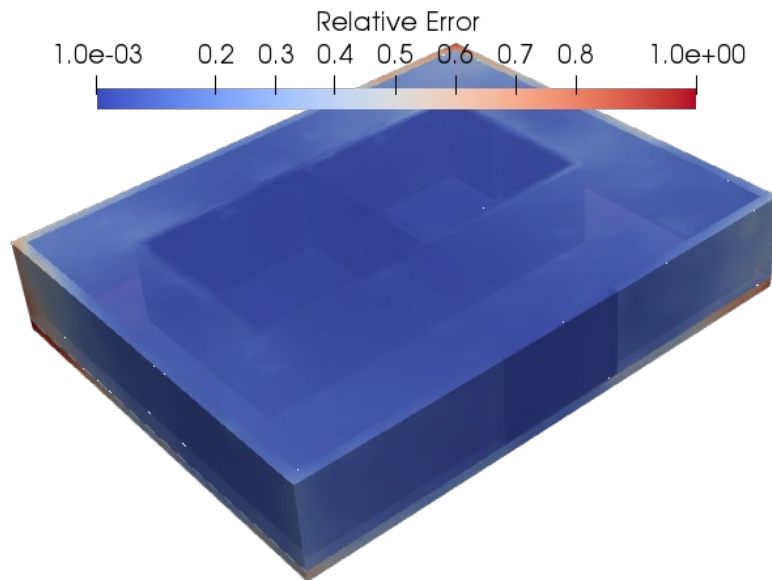
**Figure 9. MCNP6.2 photon energy deposition relative error for CSG/UM hybrid geometry**

**Table II. Photon Absorbed Dose Results at Various Detector Locations**

| Geometry | Detector 1 Dose in Gy (RE) | FOM > Analog | Detector 2 Dose in Gy (RE) | FOM > Analog | Detector 3 Dose in Gy (RE) | FOM > Analog |
|---|---|---|---|---|---|---|
| CSG | $4.64\ 10^{-2}$ (0.02) | 1X | $4.20\ 10^{-3}$ (0.01) | 4X | $1.05\ 10^{-3}$ (0.02) | 7X |
| CSG/UM | $4.60\ 10^{-2}$ (0.02) | 1X | $4.21\ 10^{-3}$ (0.01) | 6X | $1.04\ 10^{-3}$ (0.02) | 7X |
| UM | $4.63\ 10^{-2}$ (0.02) | 1X | $4.29\ 10^{-3}$ (0.01) | 10X | $1.03\ 10^{-3}$ (0.02) | 5X |

## 5. CONCLUSIONS

Results for neutron and photon energy deposition in a facility from a criticality accident are presented for various methods of modeling geometry in MCNP6.2. Comparison of results from a CSG model, a CSG/UM hybrid geometry model and UM geometry model show there is good consistency between geometry modeling methods. There are advantages to modeling CAAS problems with CSG/UM hybrid geometry. One such advantage is the exact preservation of CSG mass/volume for cells with fissionable material or detectors, however it is possible to preserve mass/volume well if attention is given to mesh parameters for these cells.

Analog MCNP6.2 calculations are compared with the application of deterministic weight windows and biased source generated with FW-CADIS. The use of deterministic variance reduction proves more efficient. The use of a cell-based fission source file versus a biased source in this example preserves mean tally results.

Modern visualization methods applied to this example, in which the .eeout file generated for the unstructed mesh is converted to .vtk format for use with Paraview. In addition, fmesh tally results from the MCNP6.2 .msht file are also converted to .vtk format for use with Paraview.

### NOMENCLATURE

| | |
|---|---|
| CSG | constructive solid geometry |
| FW-CADIS | forward weighted- consistently adjoint driven importance sampling |
| SSR | surface source read. A method of reading in fission source into a cell, from points collected using SSW. |

| SSW | surface source write. A method of collecting fission source within a cell during MCNP6.2 kcode calculation. |
|-----|----------------------------------------------------------------------------------------------------------------|
| UM  | unstructured mesh. |

## ACKNOWLEDGMENTS

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