ANS NCSD 2013 - Criticality Safety in the Modern Era: Raising the Bar
Wilmington, NC, September 29–October 3, 2013, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2013)

GUIDANCE DETAILING METHODS TO CALCULATE CRITICALITY ACCIDENT ALARM SYSTEM DETECTOR RESPONSE AND COVERAGE

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ABSTRACT

This paper is an extended summary of a guidance document that was produced by Oak Ridge National Laboratory on the subject of computational analyses of Criticality Accident Alarm Systems (CAAS). This full guidance document reviews ANSI/ANS-8.3-1997 and provides examples on how to calculate the fission rate that produces the minimum accident of concern, how to calculate the response of a CAAS detector, and how to evaluate the coverage of a CAAS detector. Discussing a strategy on how to perform CAAS placement analysis concludes the full guidance document. All of the examples in the full guidance document are performed with SCALE 6.1 and MCNP5, and the full input files for both are provided. This extended summary of the full guidance document only reviews ANSI/ANS-8.3-1997, calculates the fission rate that produces the minimum accident of concern for a simple example, and provides an example for one of the approaches suggested in the CAAS placement analysis strategy that uses a forward Monte Carlo transport calculation.

Key Words: CAAS, Detector response, Alarm coverage, Minimum accident of concern

1 INTRODUCTION

Oak Ridge National Laboratory (ORNL) has published a guidance document on the subject of computational analyses of Criticality Accident Alarm Systems (CAAS) [1]. The full guidance document provides a brief overview of ANSI/ANS-8.3-1997 [2], the standard that the United States Department of Energy uses to guide the placement of CAAS detectors, with a focus on the parts of the standard that are most applicable to calculating CAAS detector responses and evaluating CAAS detector coverage. This overview is followed by a brief discussion of how CAAS detector response calculations differ from eigenvalue calculations normally performed by criticality safety practitioners. Next, several computational examples are provided to demonstrate how to determine the minimum accident of concern according to ANSI/ANS-8.3-1997, how to calculate the response of a CAAS detector due to a specific criticality accident, and how to evaluate the coverage of a CAAS detector for criticality accidents. These practical examples are solved applying SCALE 6.1 [3] and MCNP5 [4], but the methodologies can be applied to other radiation transport codes with similar capabilities, including deterministic codes. Finally, an analysis strategy to determine the optimum placement of the minimum number of CAAS detectors is described and a few examples are provided. Complete input files are provided for all the example SCALE and MCNP calculations.

This paper provides an extended summary of reference 1, and will only focus on part of the content of the full guidance document. The definition of the minimum accident of concern in ANSI/ANS-8.3-1997 will be applied to calculate the fission rate that produces the minimum accident of concern for a simple example. Also, an example of one of the different approaches proposed in the CAAS placement analysis strategy, and a new SCALE utility, will be summarized.

2 SCOPE AND LIMITATIONS

The scope of this guidance covers just the CAAS detector response calculations. A few important aspects of CAAS evaluations are not discussed in this guidance, such as the determination of credible accidents and credible accident locations, which will vary between different applications and facilities, specific CAAS detectors, nor the appropriate flux-to-dose-rate conversion factors for any specific CAAS detectors. The flux-to-dose-rate conversion factors convert the calculated fluxes to the units measured by a detector, often dose like Gy or Sv. It is advisable that practitioners work with all stakeholders involved, including operations staff, instrumentation and controls staff, and regulators, to define the credible accidents, locations, and appropriate flux-to-dose-rate conversion factors before beginning a detailed CAAS analysis. This “buy in” from all stakeholders will address issues during the analysis and should lead to a smoother review of the CAAS evaluation.

Other issues that will not be addressed by this guidance document are the kinetic behavior of a criticality accident and the excursion shutdown mechanism. Nor will initial evacuation zones be specifically addressed. However, the same methods that are used to determine CAAS detector responses over a large area using mesh tallies can also be used to calculate human dose response over large areas, which will be part of the analysis required to determine initial evacuation zones.

3 MINIMUM ACCIDENT OF CONCERN

The detection criterion stated in section 5.6 of ANS/ANS-8.3-1997 can be paraphrased as follows.

A CAAS shall respond immediately to the minimum accident of concern, which may be assumed to deliver the equivalent of an absorbed dose rate in free air of 0.2 Gy/min at 2 meters.

For the purposes of this guidance, a critical assembly of material generating a radiation dose rate of 0.2 Gy/min in free air at 2 meters from the outer surface of the critical assembly will be the assumed minimum accident of concern. Notice that the standard does not state whether the dose rate is due to neutrons or photons, so it is reasonable to assume this refers to total dose. However, most simple detection systems, like those typically used in CAAS, only respond to neutrons or photons. The standard does not state what flux-to-dose-rate conversion factors should be used to calculate the absorbed dose in air, so this guidance will use the air kerma factors provided by the International Commission on Radiation Units and Measurements (ICRU) [5,6] and the ANSI/ANS-6.1.1-1977 flux-to-dose conversion factors [7]. The standard does state that a different minimum accident of concern may be used, but additional documentation is required in such cases. This guidance will not discuss justifying a different minimum accident of concern, but the principles presented here can be applied to any minimum accident of concern.

Section 5.8 of ANSI/ANS-8.3-1997 discusses the spacing and placement of the CAAS detectors. The standard states the following.

"The location and spacing of detectors should be chosen to minimize the effect of shielding by massive equipment or materials."

Evaluation of the coverage of a CAAS detector can most accurately be performed via a radiation transport calculation. The results of such an evaluation will provide direct insight into the effects of location and spacing of CAAS detectors and will directly address section 5.8 of ANSI/ANS-8.3-1997 in a straightforward and conclusive manner.

Once a credible accident and accident location have been established, the minimum accident of concern needs to be determined. A practitioner will quickly realize that the definition of the minimum accident of concern from ANSI/ANS-8.3-1997 is not overly prescriptive. Different critical configurations could meet this criterion of a minimum accident of concern with dramatically different fission rates, so establishing a minimum accident of concern based on a set number of fission events or fission rate will not equally address the risk to personnel due to exposure to radiation. Therefore, the practitioner needs to determine the fission rate that produces the minimum accident of concern for their specific credible accident. This determination can be done by two different methods.

First, an experimental measurement could be performed to determine the required fission rate for a dose rate of 0.2 Gy/min in air 2 meters from the critical assembly. However, this is likely to be an expensive proposition and not likely to be very practicable. The second option is to calculate the fission rate required to produce a dose rate of 0.2 Gy/min in air 2 meters from the critical assembly. The drawback to this second option is that the practitioner needs to use an appropriate set of flux-to-dose-rate conversion factors to calculate what neutron and photon flux produces a measurement of 0.2 Gy/min in air two meters from the critical assembly. Selection of a set of flux-to-dose-rate conversion factors is one of the decisions the practitioner should get buy in from all the stakeholders. In this example the air kerma factors provided by the ICRU will be used to convert between calculated flux and calculated dose rate. For a little historical perspective, the Criticality Slide Rule used the Henderson flux-to-dose-rate conversion factors, which are appropriate because the detector for that application is a human [8].

3.1 Minimum Accident of Concern – SCALE and MCNP Example

The following example demonstrates how to calculate the fission rate that produces the minimum accident of concern using SCALE and MCNP with the ICRU air kerma factors. This procedure consists of calculating the neutron and photon dose rate per fission rate at 2 m from the critical assembly. Then the fission rate required to produce a dose rate of 0.2 Gy/min at 2 m can be calculated. First, a simple credible accident needs to be introduced. The credible accident consists of Jezebel (PU-MET-FAST-001 [9]) in a simple block building, which is 1200 cm long, 600 cm wide, and 300 cm high above the ground. The exterior and interior walls are all made of a double layer of typical concrete blocks (total of 40 cm thick). The floor is made of poured concrete, extending 60 cm into the ground. The roof and the exterior door (120 cm wide and 210 cm tall) are made of 0.3175 cm thick steel. The center of Jezebel is 100 cm above the concrete floor of this building. The building and Jezebel (red sphere in left room) can be seen in Figures 1 and 2. Also visible in Figure 2 is part of a spherical shell (purple) with an inner radius that is 2 meters from the outer surface of Jezebel. This spherical shell marks where the dose rate per fission rate will be calculated to determine the minimum accident of concern. Since the top and bottom of the purple spherical shell extend above the roof and into the concrete floor, the top and bottom have been cut off. The dose rate per fission rate will only be considered for locations that have direct line of sight (unshielded) to the critical assembly. Note that the building surrounding Jezebel will also contribute to the calculated dose rate per fission rate.

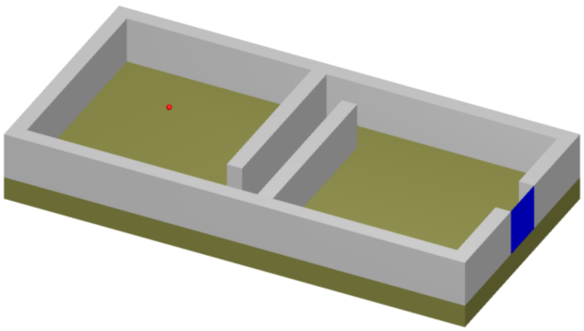

Figure 1. Block building with Jezebel, top half removed

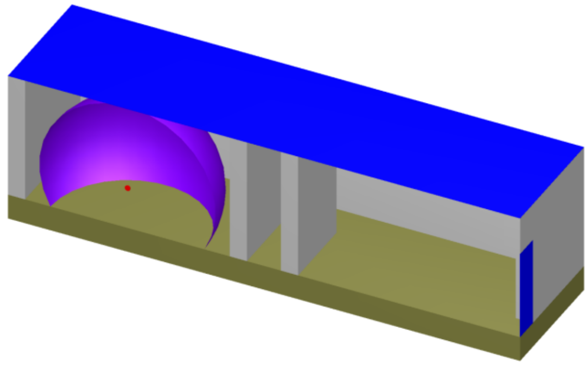

Figure 2. Block building with Jezebel and 2 meter tally sphere, front half removed

To calculate the minimum accident of concern with SCALE, the SCALE CAAS analysis capability [10] is applied, which consists of the following steps.

1) Run KENO-IV [3] to calculate the spatial- and energy-dependent distributions of neutrons created by fission, which is saved as a mesh tally file.
2) The neutron mesh tally file is converted to a spatial- and energy-dependent neutron fixed source file using the MT2MSM [3] utility.
3) The SCALE MAVRIC sequence is used to run the fixed-source Monte Carlo code Monaco to calculate the CAAS detector response, with the options to model fission photon production and use the CADIS or FW-CADIS variance reduction methodology [3].

Some of the features of the MAVRIC/Monaco input that are needed in addition to the geometry and materials provided in the KENO-IV input are the fixed source and source strength (1 fission per second or $\bar{\nu}$ neutrons per second), selection of the ICRU air kerma factors as the detector response function (i.e., flux-to-dose-rate conversion factors), a region tally for the spherical shell that is 2 meters from Jezebel (including the volume), and multiplication must be turned off via the "noFissions" keyword.

To calculate the minimum accident of concern with MCNP, the tally and response functions must also be included in the MCNP input. However, other additional MCNP input requirements depend on how the problem is simulated using MCNP. In SCALE the CAAS analysis capability that links KENO-IV to MAVRIC/Monaco is needed because KENO-IV cannot easily tally the air kerma 2 m from the surface of Jezebel. Tallies can be included in an MCNP eigenvalue calculation, which eliminates the requirement to enter a description of the fixed source and the "nonu" keyword (analog to "noFissions"). However, some variance reduction techniques, for example weight windows, cannot be used with an eigenvalue calculation to bias particle transport toward the minimum accident of concern tally and still reliably converge the fission source and accurately calculate the system eigenvalue. This is not a significant issue for this example, but it likely will be when calculating a CAAS detector response when there is significant distance and/or shielding between the critical assembly and the CAAS detector. For those situations, a fixed-source calculation with variance reduction is preferred, and will require all the additional input included in MAVRIC/Monaco to be entered into MCNP. To determine the fixed source using MCNP, the same technique is used, which is to run an MCNP eigenvalue calculation and tally the fission neutron production with a mesh tally. There is no officially released MCNP utility that converts a mesh tally to a fixed source, so an SDEF description or source subroutine will have to be written by the practitioner.

Below, in Table I, are the neutron and photon air kerma rates, K_N and K_P, calculated by MAVRIC/Monaco and MCNP due to a single fission event per second in Jezebel. Also included in Table I is the minimum accident of concern, N_{MAOC}, for this system due to these calculated kerma rates. The fission rate that produces the minimum accident of concern based on the ANSI/ANS-8.3-1997 definition is calculated using the following equation.

$$N_{MAOC} = \frac{0.2\ Gy/min}{K_N + K_P} \tag{1}$$

Table I. Determination of the minimum accident of concern for Jezebel in a simple block building

Result	MAVRIC/Monaco	MCNP
Neutron air kerma (Gy/min per fission/sec)	1.83133E-15 ± 0.074%	1.8352E-15 ± 0.02%
Photon air kerma (Gy/min per fission/sec)	5.85128E-16 ± 0.183%	6.6624E-16 ± 0.05%
Minimum accident of concern (fissions/sec)	8.2766E+13	7.9954E+13

3.2 Minimum Accident of Concern – Summary

The MAVRIC/Monaco neutron air kerma rate per fission rate, reported in Table I, is statistically the same as that calculated by MCNP. However, the MCNP photon air kerma rate per fission rate, reported in Table I, is about 14% higher than the reported MAVRIC/Monaco value. This is due to some differences between photon transport physics in MCNP and MAVRIC/Monaco, which primarily are a lower photon cutoff energy in MCNP (1 keV instead of 10 keV) and the MCNP thick target bremsstrahlung model that accounts for low-energy photons produced by electrons during the electromagnetic cascade [3,4]. Turning off these additional photon physics options in MCNP produces results that agree very well with MAVRIC/Monaco. The difference in the Table I photon air kerma rates produces an MCNP minimum accident of concern that is about 3.5% lower than the MAVRIC/Monaco value.

4 CAAS PLACEMENT ANALYSIS STRATEGY AND EXAMPLES

Determining the optimum placement of the minimum number of CAAS detectors that can detect a critical assembly anywhere in a large facility is a complex problem. Typically there are a target number of detectors that are desired to cover a given zone of a facility. A study to determine detector placement typically begins with stakeholders' initial selection of the placement of the detectors, and is followed by either predictive calculations of accidents at specific locations or adjoint calculations using the detectors as sources.

If the number of credible accident locations, *A*, is much less than the number of detector locations, *D*, then forward simulations may be more convenient and less time-consuming. If *D* is much less than *A*, then adjoint calculations may be more efficient. Forward calculations employing a mesh tally are useful if the accident type and location are fixed, but the CAAS detector type and location are unknown. Adjoint calculations employing a mesh tally can be even more advantageous since they do not rely on a list of specific accidents, which may not have included every possible accident location, but require more information about the type and location of the CAAS detector.

Depending on the geometry of the problem, the number of detectors, and the number of accident sites, different approaches to CAAS placement studies can be taken. These are summarized in Table II. In the full guidance document [1], all eight of these approaches are discussed, but in this summary only approach 4 will be discussed.

Table II. Different approaches for CAAS detector placement studies

Detector locations *D* and Accident sites *A*			Geometry	Approach			
Comparison	*A*	*D*			Direction	Biasing	Tallies
A<*D*	small	small	sparse	1.	forward	analog	standard tallies
A<*D*	small	large	sparse	2.	forward	analog	mesh tally
A<*D*	small	small	dense	3.	forward	CADIS	standard tallies
A<*D*	small	large	dense	4.	forward	FW-CADIS	mesh tally
D<*A*	small	small	sparse	5.	adjoint	analog	standard tallies
D<*A*	large	small	sparse	6.	adjoint	analog	mesh tally
D<*A*	small	small	dense	7.	adjoint	CADIS	standard tallies
D<*A*	large	small	dense	8.	adjoint	FW-CADIS	mesh tally

In Table II, the "Direction" column refers to whether the calculation is a forward or adjoint transport calculation. Biasing referred to as "analog" does not truly have to be analog. In this context analog means no automated variance reduction like CADIS or FW-CADIS is applied. Note that CADIS is a variance reduction method intended to optimize the response of a single tally, that is, one volume tally or point detector with a single response. FW-CADIS is a variance reduction method intended to optimize the response of multiple tallies or a single tally with multiple responses, that is, a mesh tally, so FW-CADIS can provide global variance reduction. Finally, standard tallies refer to any tallies other than mesh tallies, typically region (volume) or point detector tallies.

To test the different approaches to analyze CAAS detector placement, a simple example problem was created. The problem consists of a fuel storage room filled with 18 storage racks. Each rack consists of an array of 80 double-sided steel storage bins, each side containing a cuboid of about 21 kg of natural UO_2. Each storage bin is a cube of 30.48 cm. The basic geometry is shown in Figures 3–5.

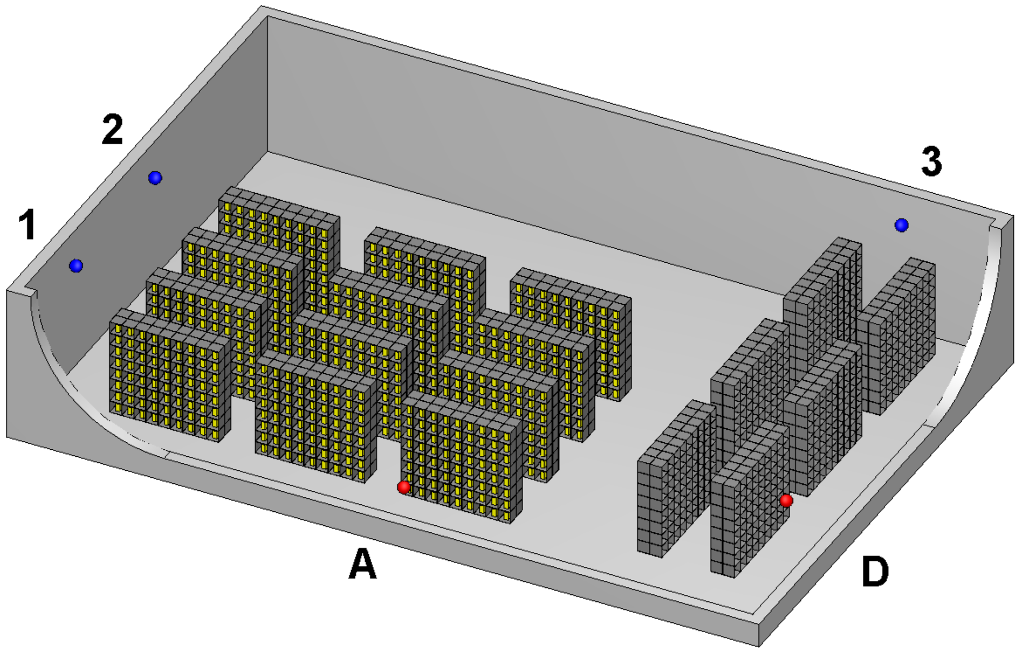

Figure 3. The storage room (ceiling and walls removed for visualization) showing the detector locations (blue, 3 m above floor) and some accident locations (red). Accident locations B and C are between the racks and not visible in this view

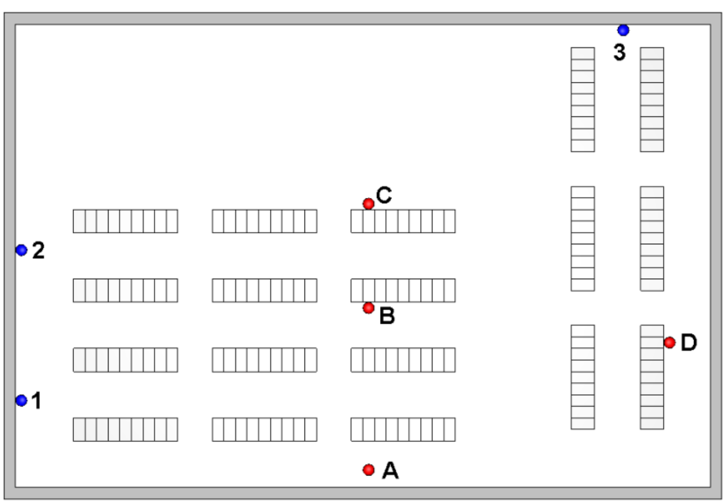

Figure 4. Overhead view of the storage room showing three detector locations (blue) and four accident sites (red)

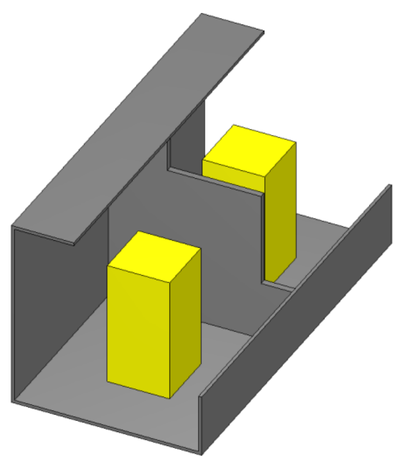

Figure 5. Close-up view of the double-sided storage bin, with sides removed

For the purposes of this example, it is assumed that the minimum credible accident produces 2.5×10^{15} neutrons and *no* photons, which can be modeled as a point isotropic source with an energy distribution of a generic ^{235}U Watt spectrum in a single burst. It is also assumed the

CAAS detector will only respond to photons and that the alarm set point is a photon dose of 0.150 rem. Note that this is an equivalent dose, not absorbed dose in air, so a different detector response function must be applied. In this case, the 1977 ANSI/ANS photon flux-to-dose-rate conversion factors are applied. Note that when MAVRIC/Monaco and MCNP use the 1997 ANSI/ANS photon flux-to-dose-rate conversion factors to calculate dose rates (rem/hr) they must use a steady state source (neutron/sec). Since this study models a single burst (source units are neutrons), the 1977 photon flux-to-dose-rate conversion factors ((rem/hr)/(photons/cm2/sec)) are multiplied by 1 hr/3600 sec. Hence, the tally results will be doses and have units of rem.

4.1 Forward Placement Analysis Approach 4: Forward Simulation, FW-CADIS, Mesh Tallies

For dense geometries with large numbers of detectors or unknown detector locations, approach 4 uses the FW-CADIS variance reduction method to compute a mesh tally over the entire facility with biasing parameters designed to obtain uniform relative uncertainties in the gamma dose for both high- and low-dose areas. Using this approach, the gamma dose mesh tallies in Figures 6–9 were produced by a source at each accident locations depicted in Figures 3 and 4. The mesh tallies in Figures 6–9 were generated by MAVRIC/Monaco for the plane that includes the detector locations depicted in Figures 3 and 4. Similar plots are generated for the MCNP mesh tallies, but they are not shown here for brevity.

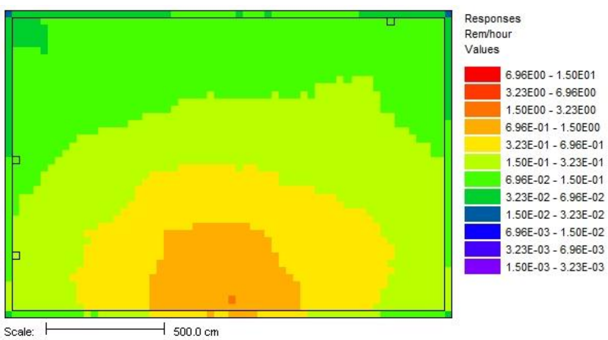

Figure 6. Gamma dose mesh tally from source A

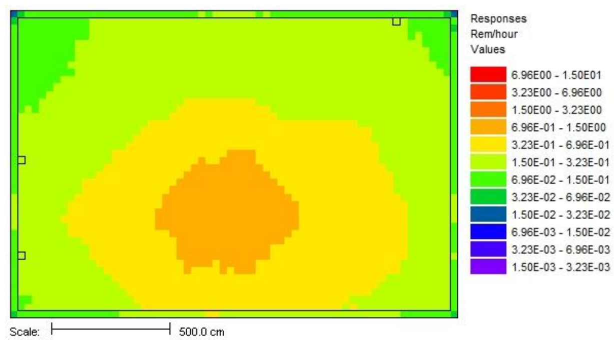

Figure 7. Gamma dose mesh tally from source B

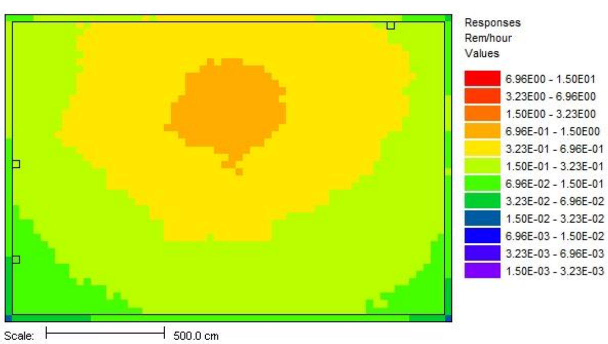

Figure 8. Gamma dose mesh tally from source C

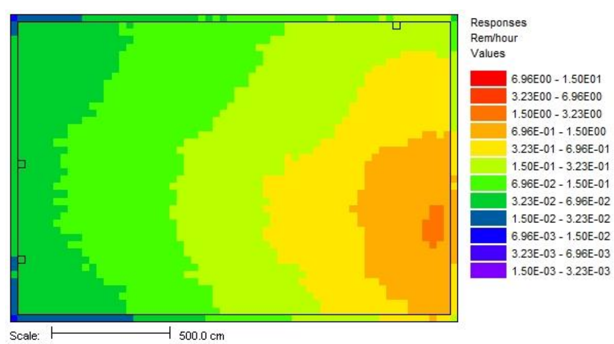

Figure 9. Gamma dose mesh tally from source D

The FW-CADIS methodology was applied with MCNP for this problem via the code ADVANTG [11]. In order to compare the MAVRIC/Monaco and MCNP results, the doses from the mesh tallies at the detector locations in Figures 3 and 4 are compared in Table III.

Table III. Comparison of detector location calculated doses (rem)

Source or Accident Site	Detector	MAVRIC/Monaco	MCNP	Ratio: MAVRIC / MCNP
A	1	1.81E-1 ± 2.55%	2.40E-1 ± 0.49%	0.75 ± 0.02
A	2	1.06E-1 ± 2.00%	1.50E-1 ± 0.46%	0.71 ± 0.01
A	3	9.55E-2 ± 2.45%	1.22E-1 ± 0.48%	0.78 ± 0.02
B	1	1.91E-1 ± 2.38%	2.43E-1 ± 0.51%	0.78 ± 0.02
B	2	1.77E-1 ± 2.26%	2.35E-1 ± 0.48%	0.75 ± 0.02
B	3	1.59E-1 ± 2.46%	2.01E-1 ± 0.52%	0.79 ± 0.02
C	1	1.12E-1 ± 2.24%	1.46E-1 ± 0.47%	0.77 ± 0.02
C	2	1.93E-1 ± 2.25%	2.64E-1 ± 0.45%	0.73 ± 0.02
C	3	2.99E-1 ± 2.36%	3.89E-1 ± 0.50%	0.77 ± 0.02
D	1	4.78E-2 ± 3.06%	6.29E-2 ± 0.68%	0.76 ± 0.02
D	2	5.72E-2 ± 4.22%	7.17E-2 ± 0.83%	0.80 ± 0.03
D	3	2.44E-1 ± 2.15%	3.25E-1 ± 0.52%	0.75 ± 0.02

The MAVRIC/Monaco results in Table III are consistently 20 to 30 percent less than the MCNP results. Turning off the additional MCNP photon physics (lower cutoff energy and thick target bremsstrahlung model) did not significantly affect the difference between MCNP and MAVRIC/Monaco. Investigations have concluded that these differences are primarily due to the multi-group representation of the photon cross sections used in the MAVRIC/Monaco calculations. The multi-group library used was the 200-neutron group/47-gamma group SCALE library based on ENDF/B-VII.0. A few of the results in Table III were recomputed using a continuous-energy version of MAVRIC/Monaco in the beta version of SCALE 6.2 [12], which produced MAVRIC/Monaco results that were between 6 and 12 percent lower than MCNP.

Note that the standard FW-CADIS method may not be what the practitioner wants – the method attempts to provide low relative uncertainties, even in areas below the CAAS alarm set point. For CAAS placement studies, the practitioner's area of interest may only be the region where the calculated dose is above that which will trigger an alarm. MAVRIC/Monaco in SCALE 6.2 will contain keywords within the normal FW-CADIS input for the importance map block to reduce the area of mesh tally optimization to those areas that are above some minimum estimated response, below some maximum estimated response, or both. This new option for FW-CADIS will improve the biasing parameters and provide a speedup over the standard FW-CADIS methodology.

With the dose mesh tally maps produced by this approach, filtering and adding the dose maps can determine areas where detectors could see multiple accidents. SCALE 6.2 will include new MAVRIC utilities that perform the mesh tally filtering and adding operations described next. Consider the dose maps computed for each accident site shown in Figures 6–9. Each dose map was filtered to show where a detector would alarm or not within the plane of the detectors. These filtered dose maps are shown in Figures 10–13, with the red color indicating areas where a detector would alarm due to an accident at the particular site and purple indicating that a detector would not alarm. Summing these new alarm/not alarm plots creates the plot in Figure 14, which shows for any given location (i.e., potential detector location) how many of the four accidents could be seen at that location. This strategy is very useful in determining detector placement if there are only a few credible accident locations.

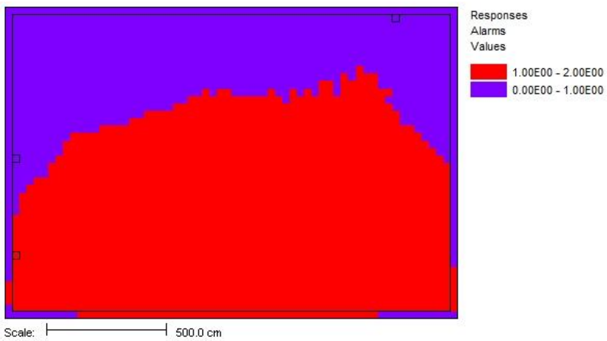

Figure 10. Areas that would alarm for accident site A

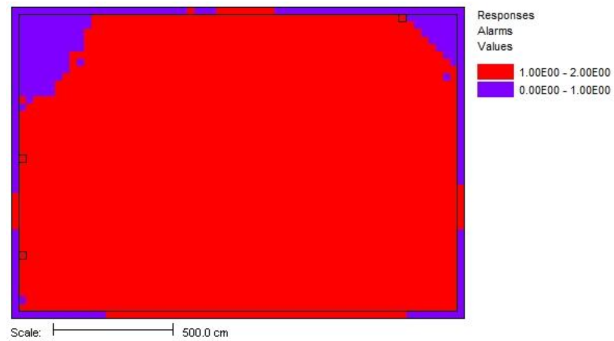

Figure 11. Areas that would alarm for accident site B

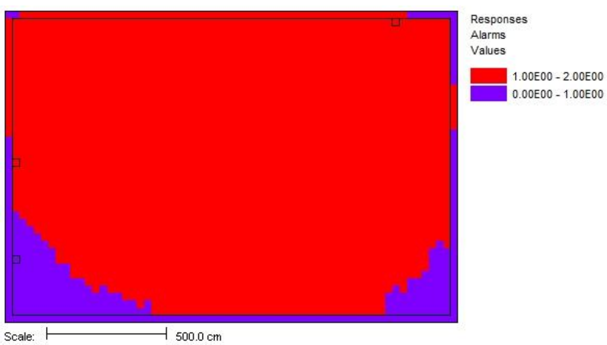

Figure 12. Areas that would alarm for accident site C

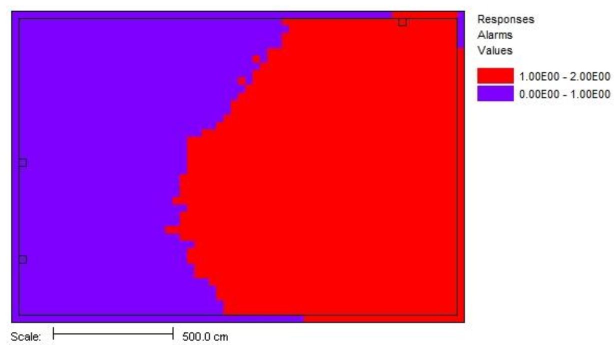

Figure 13. Areas that would alarm for accident site D

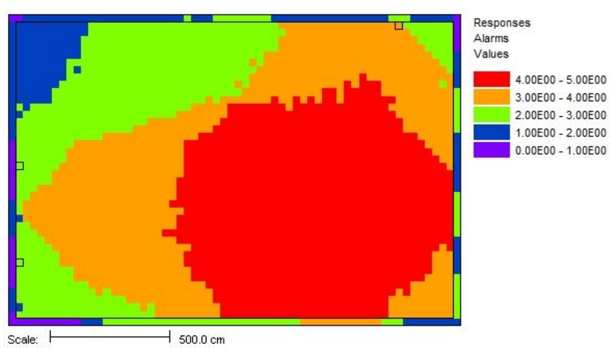

Figure 14. The number of accidents that can be seen from any given position in the plane of the detectors

5 CONCLUSIONS

Reference 1 provides an overview of ANSI/ANS-8.3-1997 as it relates to computational analysis of CAAS detector responses. In particular, the process of determining the minimum accident of concern is discussed, which is followed by basic examples of how to calculate CAAS detector responses using the 3D Monte Carlo radiation transport capabilities of SCALE and MCNP. Then, an example of how to calculate the coverage of a CAAS detector is provided. Finally, a strategy to determine the optimum placement of the minimum number of CAAS detectors is described. This strategy accounts for the number of credible accident locations relative to the number of potential CAAS detector locations, and recommends applying forward and adjoint transport simulations in different situations.

This paper has provided an extended summary of the original CAAS guidance document [1]. This includes reviewing the definition of the ANSI/ANS-8.3-1997 minimum accident of concern, and calculating the fission rate that produces the minimum accident of concern for a simple example. Finally, a combination of realistic geometry and credible accident locations is used to illustrate one of the suggested approaches to determine CAAS detector placement using a forward Monte Carlo transport calculation.

6 ACKNOWLEDGMENTS

The work documented in this paper was performed with support from the US Department of Energy Office of Environmental Management and Nuclear Criticality Safety Program.

This manuscript has been authored by the Oak Ridge National Laboratory, managed by UT-Battelle LLC under Contract No. DE-AC05-00OR22725 with the US Department of Energy. The US Government retains and the publisher, by accepting the article for publication, acknowledges that the US Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US Government purposes.

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