

Methods for Detector Placement and Analysis of Criticality Accident Alarm Systems

Douglas E. Peplow¹ and Larry L. Wetzel²

(1) Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6170, peplowde@ornl.gov

(2) Babcock & Wilcox Nuclear Operations Group Inc., P.O. Box 785, Lynchburg, VA 24505, llwetzel@babcock.com

INTRODUCTION

Determining the optimum placement to minimize the number of detectors for a criticality accident alarm system (CAAS) in a large manufacturing facility is a complex problem. There is typically a target for the number of detectors that can be used over a given zone of the facility. A study to optimize detector placement typically begins with some initial guess at the placement of the detectors and is followed by either predictive calculations of accidents at specific locations or adjoint calculations based on preferred detector locations.

Within an area of a facility, there may be a large number of potential criticality accident sites. For any given placement of the detectors, the list of accident sites can be reduced to a smaller number of locations at which accidents may be difficult for detectors to detect. Developing the initial detector placement and determining the list of difficult accident locations are both based on the practitioner’s experience.

Simulations following fission particles released from an accident location are called “forward calculations.” These calculations can be used to answer the question “where would an alarm be triggered?” by an accident at a specified location. Conversely, ‘adjoint calculations’ start at a detector site using the detector response function as a source and essentially run in reverse. These calculations can be used to answer the question “where would an accident be detected?” by a specified detector location.

If the number of accidents, P , is much less than the number of detectors, Q , then forward simulations may be more convenient and less time-consuming. If Q is large or the detectors are not placed yet, then a mesh tally of dose

observed by a detector at any location must be computed over the entire zone. If Q is much less than P , then adjoint calculations may be more efficient. Adjoint calculations employing a mesh tally can be even more advantageous because they do not rely on a list of specific difficult-to-detect accident sites, which may not have included every possible accident location.

Analog calculations (no biasing) simply follow particles naturally. For sparse buildings and line-of-sight calculations, analog Monte Carlo (MC) may be adequate. For buildings with internal walls or large amounts of heavy equipment (dense geometry), variance reduction may be required. Calculations employing the CADIS [1] method use a deterministic calculation to create an importance map and a matching biased source distribution that optimize the final MC to quickly calculate one specific tally. Calculations employing the FW-CADIS [2] method use two deterministic calculations (one forward and one adjoint) to create an importance map and a matching biased source distribution that are designed to make the MC calculate a mesh tally with more uniform uncertainties in both high-dose and low-dose areas.

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 I.

SCALE 6.1 [3] contains the MAVRIC sequence, which can be used to perform any of the forward-based approaches outlined in Table I. For analog calculations, MAVRIC simply calls the Monaco MC code. For CADIS and FW-CADIS, MAVRIC uses the Denovo [4] discrete ordinates (S_N) deterministic code to generate the importance map and biased source used by Monaco.

Table I. List of Different Situations and What Computational Approach to Use

P Accident sites and Q Detectors				Approach		
Comparison	P	Q	Geometry	Direction	Biasing	Tallies
$P < Q$	small	small	sparse	1. forward	none	standard tallies
		large	sparse	2. forward	none	mesh tally
		small	dense	3. forward	CADIS	standard tallies
		large	dense	4. forward	FW-CADIS	mesh tally
$Q < P$	small	small	sparse	5. adjoint	none	standard tallies
		large	sparse	6. adjoint	none	mesh tally
		small	dense	7. adjoint	CADIS	standard tallies
		large	dense	8. adjoint	FW-CADIS	mesh tally

An adjoint capability is currently being added to Monaco and should be available in the next release of SCALE. An adjoint-based approach could be performed with Denovo alone – although fine meshes, large amounts of memory, and long computation times may be required to obtain accurate solutions. Coarse-mesh S_N simulations could be employed for adjoint-based scoping studies until the adjoint capability in Monaco is complete.

CAAS placement studies, especially those dealing with mesh tallies, require some extra utilities to aid in the analysis. Detectors must receive a minimum dose rate in order to alarm; therefore, a simple yes/no plot could be more useful to the analyst than a standard dose rate contour plot. Alarm systems that require several detectors to alarm simultaneously for a given accident would need to combine several yes/no plots in order to show accident sites where multiple detectors would be triggered. This could require a plot of “areas of coverage” that is mapped over the building geometry.

Several new utilities (which will be part of SCALE 6.2) were created to help with CAAS analysis.

DESCRIPTION OF THE ACTUAL WORK

A simple test problem for CAAS detector placement studies was created to demonstrate the different approaches and use of the new utilities. 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. Three detector locations (1, 2, and 3) are at a height of 290 cm above the floor (close to the ceiling). Four accident sites (A, B, C, and D) are located 100 cm above the floor. The basic geometry is shown in Fig. 1.

For this study, an accident was modeled as a point isotropic source, emitting 2.5×10^{15} neutrons with an energy distribution of a generic Watt spectrum in a single burst with no gamma component in the source. All gammas considered in this analysis are generated from

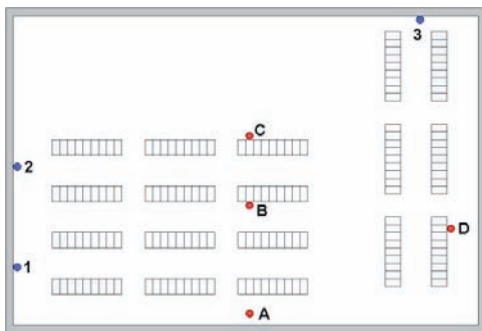


Fig. 1. Overhead view of the storage room showing three detector locations (1-3) at $z=290$ cm and four accident sites (A-D) at $z=100$ cm.

neutron interactions. For this study, a detector must observe a gamma dose of 0.150 rem to trigger. (Note: This is not intended to represent a minimum accident. It is used for demonstration purposes only.)

RESULTS

The transport calculations for this study all used SCALE 6.1. The new utilities were used to work with the final MC mesh tallies or S_N flux files.

Forward Approaches

Approach 1: Forward, Analog MC, Standard Tallies

In this approach, a forward simulation is performed for each of the four accident locations. This approach works well for a small number of potential accident sites, a small number of detector locations and a sparse geometry.

Each of the four simulations (600 minutes each) calculated the dose at all three detector locations. Doses for this approach are shown in the first part of Table II.

Approach 2: Forward, Analog MC, Mesh Tally

For a small number of accident sites but a large number of detector locations (or unknown detector locations), this approach calculates a mesh tally over the entire room. This can then be used to show where detectors would be triggered from the given accident.

Table II. Results Using Approaches 1 and 3 (values in boldface indicate that the alarm would be triggered)

Source/ Detector	1. Analog Gamma Dose		3. CADIS Gamma Dose	
	rem	rel unc	rem	rel unc
A	1	0.1757 3.0%	0.1802 2.8%	
	2	0.1092 3.8%	0.1083 2.5%	
	3	0.0968 4.1%	0.0928 3.5%	
B	1	0.1858 3.1%	0.1799 2.4%	
	2	0.1777 3.2%	0.1790 2.4%	
	3	0.1441 3.5%	0.1543 3.3%	
C	1	0.1061 3.8%	0.1168 3.3%	
	2	0.1961 2.9%	0.1904 2.4%	
	3	0.2976 2.3%	0.2901 2.6%	
D	1	0.0535 5.7%	0.0467 4.1%	
	2	0.0571 5.3%	0.0566 4.0%	
	3	0.2440 2.6%	0.2430 2.0%	

As an example, the dose mesh tally for source location D, which took 600 minutes to calculate, is shown in Fig. 2. The figure is for the plane $z=290$ cm that includes the detector locations. Note that the values in the mesh tally for the detector locations correspond to the values in Table II. The minimum dose contour of 0.150 rem is between the two light green colors ().

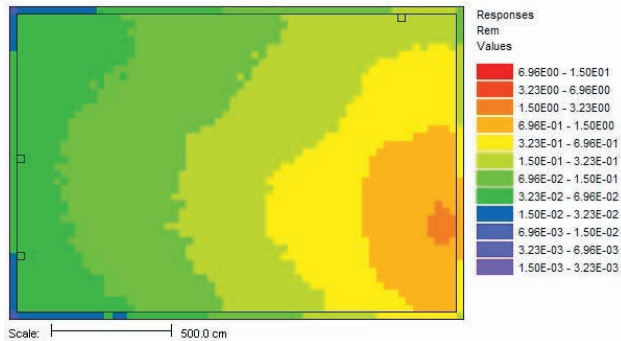


Fig. 2. Doses (rem) from accident location D.

Approach 3: Forward, CADIS, Standard Tallies

For dense geometries, CADIS may be required to accelerate the MC calculation of detector responses. For a small number of potential accident sites, P , and a small number of detector locations, Q , this approach requires one simulation for each of the PQ combinations.

The results, similar to those using the analog approach, are also shown in Table II. Each of the 12 calculations employing CADIS required 25 minutes for the S_N and 190 minutes for the MC. The total time to compute all accident/detector combinations with 12 input files (40 hours) was the same as the total time for the 4 analog inputs.

Note that the CADIS and analog dose values agree well. Only source B/detector 3 obtained a different result for alarm/not alarm because each calculated value is about one standard deviation above/below the 0.150 rem trigger.

Approach 4: Forward, FW-CADIS, Mesh Tally

For dense geometries and a large number of detectors or unknown detector locations, this approach uses the FW-CADIS method to compute a mesh tally over the entire facility, with biasing parameters designed to obtain more uniform relative uncertainties in the gamma dose for both high- and low-dose areas.

Using this approach, each of the gamma dose mesh tallies from the four accident sites was similar to those produced by approach 2, but with more uniform relative uncertainties across the storage room. The values at the three detector locations also compared well to those in Table II from approaches 1 and 3.

Detector Placement Using Forward Approaches

With either of the forward approaches that result in dose mesh tally maps (approaches 2 and 4), areas where detectors could see multiple accidents can be determined by filtering and adding the dose maps. Consider the dose map computed for accident site D shown in Fig. 2. This dose map was filtered to show where a detector would alarm or not, and is shown in Fig. 3; the red color indicates that a detector would be triggered by an accident at the particular site and white indicates that a detector would not be triggered. Summing the alarm/not alarm plots from all four accident sites gives the plot shown in Fig. 4, which shows for any given location how many of the four accidents could be seen at that location.

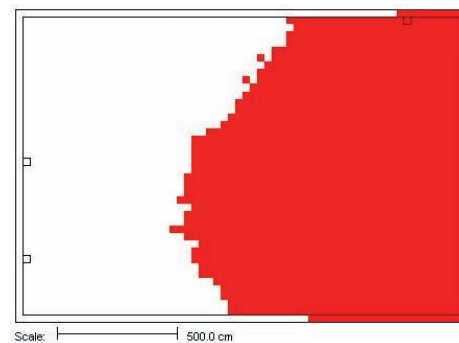


Fig. 3. Detector locations ($z=290$ cm) that would alarm for an accident at location D.

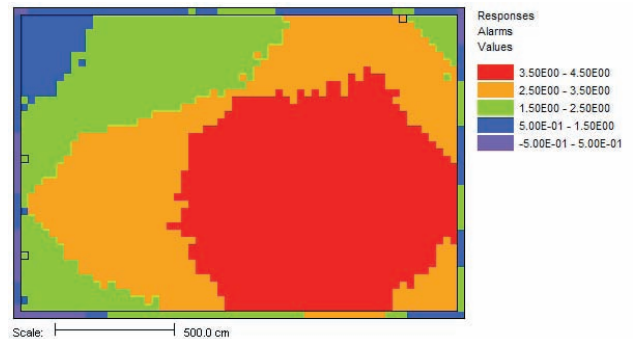


Fig. 4. Number of the four accidents that a detector ($z=290$ cm) at a given location would see.

Adjoint Approaches

For CAAS detector placement studies or for existing detector placements checks, adjoint MC calculations would be quite useful in determining the area of coverage for a particular detector location. Until the adjoint capability is added to Monaco, S_N -based solutions could still be used for scoping studies where high accuracy is not needed. With only the S_N code to work with, there are

no differences among approaches 5–8: one adjoint calculation per detector location is needed.

The mesh used was fairly coarse, $112 \times 89 \times 33 \approx 0.33 \times 10^6$ voxels, and consisted of planes with spacing of 30.48 cm, with extra planes that delineated all of the important concrete and steel surfaces. Note that this was the same mesh used by Denovo in the importance maps for approaches 3 and 4 above. The only result of a Denovo calculation currently available through SCALE is the scalar flux file. Utility programs were created to combine the adjoint scalar fluxes with the accident source spectrum, integrate those values into a dose response, and then multiply them by the appropriate constants to create a map of detector response for a source at any location. This is shown for detector location 1 in Fig. 5.

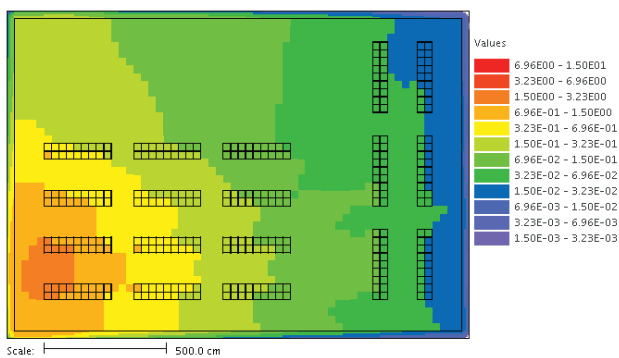


Fig. 5. Doses (rem) at detector location 1 for any given accident location ($z=100$ cm).

Coverage Analysis

The new utilities were used to show the coverage from the detectors. This was done by filtering the dose values (Fig. 5) and keeping only those above the 0.150 rem minimum dose. That result was further processed by setting non-zero values to 1 to show those areas where an accident would trigger the detector; this is shown in Fig. 6. The coverage areas for all three detectors were then added together (Fig. 7) to find the number of detectors triggered for an accident in any location. For systems that require at least two detectors to be triggered for any accident, Fig. 7 shows that only the left half of the room (yellow and red areas) qualifies. Accidents in the green areas will trigger only one detector. Accidents in the purple areas will trigger none of the three detectors.

ACKNOWLEDGMENTS

The authors would like to thank Babcock & Wilcox Nuclear Operations Group, Inc., for funding this work.

Oak Ridge National Laboratory is managed and operated by UT-Battelle, LLC, for the U.S. Department of Energy under contract No. DE-AC05-00OR22725.

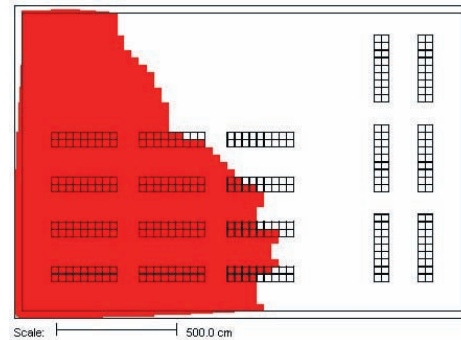


Fig. 6. Accident locations ($z=100$ cm) where detector 1 would trigger.

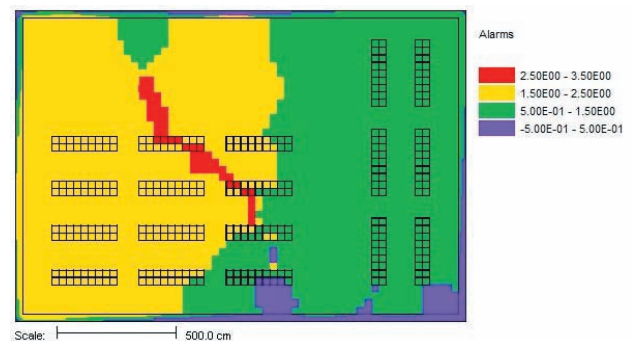


Fig. 7. Number of detectors that would trigger for an accident at a given location.

REFERENCES

1. A. HAGHIGHAT and J. C. WAGNER, "Monte Carlo Variance Reduction with Deterministic Importance Functions," *Progress in Nuclear Energy*, **42(1)**, 25–53 (2003).
2. D. E. PELOW, T. M. EVANS, and J. C. WAGNER, "Simultaneous Optimization of Tallies in Difficult Shielding Problems," *Nuclear Technology* **168(3)**, 785–792 (2009).
3. *SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design*, ORNL/TM-2005/39, Version 6.1, June 2011. (Chapters S6 – MAVRIC and F23 – Monaco.) Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.
4. T. M. EVANS, A. S. STAFFORD, R. N. SLAYBAUGH, and K. T. CLARNO, "Denovo: A New Three-Dimensional Parallel Discrete Ordinates Code in SCALE," *Nucl. Technol.* **171**, 171–200, 2010.