Criticality Accident Alarm System Modeling Made Easy With SCALE 6.1

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INTRODUCTION

A new capability in SCALE allows users to quickly and easily model both the criticality and deep-penetration shielding portions of criticality accident alarm system (CAAS) problems in fully 3-D Monte Carlo. The SCALE CAAS capability uses both KENO-VI for simulating the criticality accident (to determine the fission distribution) and MAVRIC for radiation transport through thick shields using automated variance reduction. This paper demonstrates the CAAS capability with examples of calculating single detector responses and for calculating dose rates over large areas.

A wide variety of methods are currently in use to calculate the response of CAAS, with many drawbacks. Fast, approximate techniques typically model the criticality source as a point source and make use of one-dimensional, point-kernel, or build-up factor approximations for estimating transport over long distances and through thick shielding. Multidimensional discrete ordinates methods have been widely used [1,2] but require separate calculation of the critical system and the shielding systems as well as geometric approximations due to the orthogonal mesh.

Standard Monte Carlo codes using detailed models and detailed physics can simulate radiation transport more accurately than point-kernel or build-up factor codes but can suffer from the long run times required to calculate detector responses with reasonably low levels of stochastic uncertainty. This is especially true for simulating systems that require tallies at many points. Similarly, Monte Carlo codes can accurately model the complex geometry necessary for CAAS problems, but typical variance reduction techniques are tailored to criticality or shielding problems, and as a result, CAAS problems are broken into multiple steps which can be unnecessarily complicated.

Many variance reduction methods have been used in Monte Carlo codes to reduce calculation times, typically involving iteration and a great deal of experience to use. Over the past decade, progress has been made in developing hybrid methods that use approximate discrete ordinates solutions to generate space- and energy-dependent weight windows [3,4]—widely considered to be one of the most effective variance reduction techniques. These hybrid approaches greatly improve calculation times and have been automated in MCNP (Monte Carlo N-Particle) [5] and the MAVRIC (Monaco with Automated Variance Reduction using Importance Calculations) sequence in SCALE [6]. Both use the CADIS (Consistent Adjoint Driven Importance Sampling) method, which forms an importance map and biased source distribution from the results of a coarse-mesh adjoint discrete ordinates calculation. The MAVRIC sequence in SCALE 6 uses the new functional modules Denovo, an S_N code using a Koch-Baker-Alcouffe parallel sweep algorithm and nonstationary Krylov methods, and Monaco, a derivative of the MORSE (Multigroup Oak Ridge Stochastic Experiment) multi-group Monte Carlo code with many improvements.

Recent work with MAVRIC has demonstrated [7,8] that an importance map and biased source distribution can be formed that will calculate multiple tallies or a large mesh tally with low relative uncertainties simultaneously. This extension of CADIS uses the results of a forward discrete ordinates calculation to form the source for the adjoint calculation. This approach, called forward-weighted CADIS (or FW-CADIS), has been completely automated in the MAVRIC sequence.

METHODS

The CAAS capability in SCALE is a two-step approach using KENO-VI and MAVRIC. The first step is the determination of the source distribution, typically done with the CSAS6 (Criticality Safety Analysis Sequence) control sequence, which uses the KENO-VI functional module. Along with calculating the system k_{eff}, KENO-VI has been modified to accumulate the fission distribution over the nonskipped generations. This information is collected on a three-dimensional Cartesian mesh that overlays the physical geometry model and is saved as a Monaco mesh source.

The mesh source is then used in the second step as a source term in MAVRIC. The absolute source strength is set by the user based on the total number of fissions (based on the total power released) during the criticality excursion. Further neutron multiplication is prevented in the MAVRIC transport calculation. MAVRIC can be optimized to calculate one specific detector response at one location using CADIS or to calculate multiple responses/locations with roughly the same relative uncertainty using FW-CADIS. For calculating mesh tallies of fluxes or dose rates, MAVRIC also uses FW-CADIS to help balance the Monaco Monte Carlo calculation such that low flux voxels are computed with about the same relative uncertainty as high flux voxels.

With this two-step approach, users will have a great deal of flexibility in modeling CAAS problems. The CSAS6 step and the MAVRIC step could both use the same geometry and materials definitions or could include different levels of detail. For best results, a possible scheme would be to model the critical system geometry with only the closest surrounding materials but in fine detail. The transport geometry could leave out small details but would include the large building-level components. The fission source distribution from one CSAS6 calculation could be used in a number of different MAVRIC building/detector models, with each MAVRIC calculation optimized for a given type of detector.

RESULTS

Consider the following example problem based on a critical assembly of an aqueous uranyl nitrate solution. A 48 inch diameter, unreflected aluminum sphere is filled with a ^{233}U solution. Assume that a criticality excursion involving 10^{18} total fissions occurs in the upper level of the two-story experimental facility. This example uses one KENO-VI calculation to determine the fission distribution and three MAVRIC calculations to find (a) the total dose at the detectors in the lower level of the control room, (b) the total dose at the detectors in the upper level inside the experimental area, and (c) the total dose on a mesh covering the inside and the areas just outside the experimental bay.

KENO-VI was used to find the fission distribution on a $13 \times 13 \times 13$ mesh covering a cube of 122.022 cm surrounding the fissionable material, which is shown in Fig. 1. Note that the fission spatial distribution should be symmetrical, but it shows some statistical noise. Even though the value of k_{eff} has converged well, the numbers of fissions within each voxel of the grid have not yet converged. Depending on the fineness of the grid resolution, the criticality calculation may need to be run longer than a typical k_{eff} calculation in order to reduce the statistical variation in the computed mesh source.

For the various MAVRIC transport calculations, the critical assembly model was added to a building model (Fig. 2) 160 cm above the floor of the upper level. The fission mesh source is read by MAVRIC for both the spatial and energy distribution of the starting neutrons. Fission photons can also be added when importing a mesh source.

For calculation of doses seen by the detectors on the lower level of the control room, MAVRIC was optimized for transport of neutrons and photons to these detectors. First, MAVRIC used Denovo to calculate the adjoint fluxes from an adjoint source located over an area surrounding the three detectors using an energy spectrum corresponding to the flux-to-dose conversion factors for both neutron and photons. This adjoint S_N solution

required 23 min. From the adjoint fluxes, MAVRIC created the space- and energy-dependent weight window and source biasing parameters, which were then passed to the Monaco Monte Carlo code. The Monaco calculation ran for 15 h, and the final doses at the detectors are shown in Table I.

Table II gives the results for the detectors on the upper level of the assembly room. Similar to the calculation described above, MAVRIC used an adjoint source covering all three detectors, ran an adjoint S_N calculation, constructed an importance map and biased source, and then ran Monaco. The Denovo adjoint calculation took 26 min and Monaco took 2.7 h.
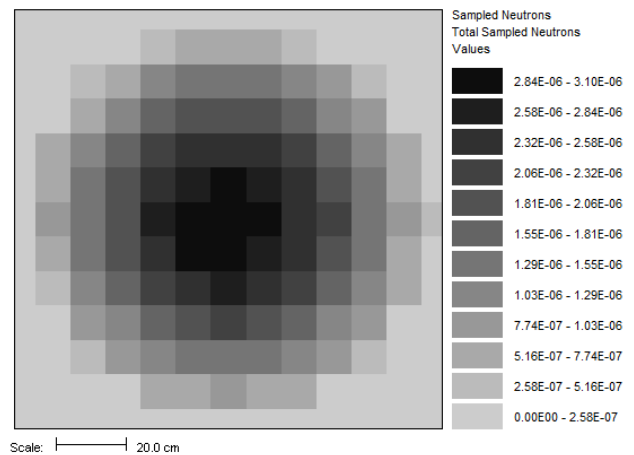

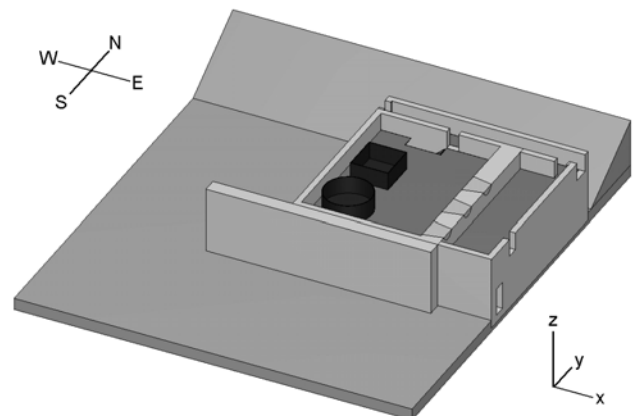Fig. 1. Fission spatial distribution from KENO-VI for the sphere of uranyl nitrate.

Fig. 2. Cut-away view of the two-story building and surrounding area where the criticality excursion occurs.

Table I. Lower-Level Detector Responses

Detector	Value (rem)	Relative Uncertainty
west	6.18	1.6%
center	4.83	2.0%
east	4.07	2.1%

Table II. Upper-Level Detector Responses

Detector	Value (rem)	Relative Uncertainty
south	5.01E+03	0.9%
center	4.26E+03	1.0%
north	3.73E+03	1.1%

The FW-CADIS option in MAVRIC was used for the calculation of the dose everywhere inside and just outside the building. This option automatically did the following: First, a forward discrete ordinates calculation estimated the doses everywhere. This estimation was then used to construct a weighted adjoint source, which was defined as a volume covering the building and the areas to the north, west, and south of the building. Finally, the resulting adjoint fluxes were used to create an importance map and biased source, which were then used by Monaco. Calculation times for the MAVRIC components were 24 min for the forward Denovo, 24 min for the adjoint Denovo, and 15 h for Monaco. The final mesh tally is shown in Figure 2. The mesh tally was calculated with 86% of the voxels having less than 5% relative uncertainty. FW-CADIS helps balance the calculation so that areas of high dose and low dose are computed with more uniform relative uncertainties.
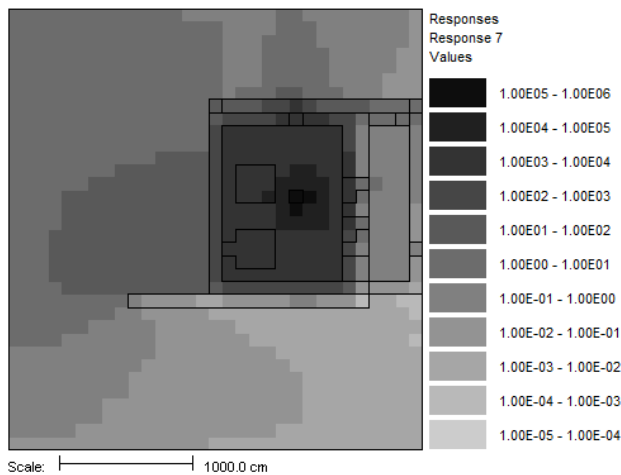

Fig. 2. Mesh tally of total dose (rem) from the excursion.

Using analog transport calculations—without any variance reduction—takes much longer. For the total dose at the upper level detectors, the figure-of-merit for the CADIS calculation was 210 times higher than analog. For the harder lower level detectors, CADIS was 2000–5000 times faster than analog. The analog mesh tally was allowed to run for 240 h, and only 19% of the voxels had less than 5% relative uncertainty (all close to the critical assembly).

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