MCNP 6.1.1 Validation for Shielding Applications

Timothy D. Jackson*
**Consolidated Nuclear Services, Y-12 National Security Complex, PO BOX 2009 MS8010, Oak Ridge, TN 37831, Timothy.Jackson@cns.doe.gov*

INTRODUCTION

Radiation transport calculations are performed at Y-12 to aid in verifying existing detector coverage and determining detector locations for new installations for the criticality accident alarm system (CAAS), criticality accident evacuation zones, dose rates near shipping containers, and for other applications. The American National Standards Institute (ANSI) and American Nuclear Society (ANS) standard for *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations* does not provide any guidance specific to performing validations for shielding applications, but the ANSI/ANS standard for *Criticality Accident Alarm System* requires that, if CAAS is needed, then CAAS coverage for operations shall be verified. This report presents the methodology for the validation of MCNP 6.1.1 for shielding applications and discusses the applicability and limitations of the benchmarks selected for the validation. Twelve sets of benchmark experiments were selected to represent a range of calculations and a range of materials that may be used in shielding calculations. C/E ratios were created for each benchmark case, and the range of C/E ratios was used to set a safety margin for shielding calculations. Due to limitations in benchmark description and documentation, assumptions had to be made on materials and dose response, which were chosen to be consistent with the process at Y- 12.

The intent and general process of validating a code system and cross section library for shielding applications is the same as that of validating for criticality safety: model benchmark experiments, calculate calculation-to-experiment ratios, and provide a value representing the required conservativism to be required in calculations. There exist a number of differences between a shielding validation and a criticality validation, including the number and quality of benchmarks and the nature of what a conservative value is. Specifically, relatively few benchmark experiments exist for shielding analyses in comparison to the hundreds of experiments available for criticality calculations. Additionally, conservatism is dependent on the shielding application, with low calculated doses being conservative for CAAS calculations, and high calculated doses conservative for evacuation zone analysis, for example. The shielding validation consists of modeling multiple benchmark experiments, running them with MCNP with appropriate variance reduction, and analyzing the results to determine a safety margin to be applied to calculated results. This is analogous to the process prescribed in *ANSI/ ANS 8.24* for validations of code systems for criticality calculations.

DISCUSSION

Benchmarks were selected to be applicable to a range of potential shielding analyses at Y-12, and include transport of primary and secondary gamma-rays, primary and secondary fission neutrons, and fusion neutrons from DT reactions. Models were either developed based on information provided by the benchmark authors or based on models provided by the benchmark authors. Tallies in the MCNP results were compared to the measured data, and C/E ratios were created for each benchmark. With only a small number of benchmark experiments used, tests for normality in results were not performed. Instead, the range of C/E ratios was calculated.. The selected benchmarks come from a variety of sources, including conference proceedings, journal articles, OECD designated benchmarks, and the Shielding Integral Benchmark Archive Database (SINBAD) set of shielding benchmarks.

Twelve sets of benchmark experiments were modeled to create a validation for shielding analysis. Five of the cases which are directly applicable to CAAS analysis are presented here. The selected benchmarks include calculations relevant to CAAS analysis, including skyshine, transport through concrete mazes, coupled transport of neutrons and gamma-rays, and calculations with significant quantities of water.

The Baikal-1 Skyshine Benchmark [1] involves calculating the dose due to primary and secondary photons and primary neutrons at distances up to 1500 m near the ground-air interface. This benchmark includes a source representative of the leakage from a critical assembly. Simplifications from the experiment include the use of a single-layer atmosphere model over a realistic model.

The Stanford Concrete Maze experiment [2] measured the neutron and gamma-ray dose due to a ^{252}Cf source in a concrete maze similar to a medical accelerator room and can be considered to be a calculation dominated by the transport of radiation through concrete. The source location within the maze was not reported, but was estimated based on figures presented by the experiment authors. The concrete composition was not reported, so four concrete compositions (Oak Ridge, Regular, SLAC, and Hanford-Wet [3]) were modeled. The Hanford-Wet concrete was modeled to represent a "wet" concrete, while the other three concretes were assumed to be dry.

A gamma-ray skyshine experiment [4] was included in order to include direct measurements of primary gamma-ray skyshine transport. All materials definitions, including atmospheric conditions, ground composition, and the composition of the concrete silo containing the ^{60}Co source had to be assumed. Dry air was assumed, as well as the ground material composition of the Baikal-1 benchmark. For simplification, the calculation source was biased so as to ignore scattering within the concrete silo containing the source.

A series of neutron activation and thermoluminescent dosimeter (TLD) measurements performed at SILENE [5] was included as a benchmark experiment. A measurement consisting of activation foils containing Co, Au, In, Fe, Mn, and Ni located within a concrete scattering box as well as Al_2O_3 TLD dose was selected for inclusion in this validation. The benchmark authors present a high-fidelity model of the fission neutron source distribution within the SILENE critical assembly, which is inconsistent with the methodology used at Y-12. Three source definitions were used for the calculation model: a low fidelity model developed consistently with the process used for the benchmark model, a line source uniform in position with an energy distribution equal to the leakage neutron energy distribution of SILENE, and using the Surface Source Read and Surface Source Write cards provided with the MCNP software.

To validate the cross section of water for use in shielding calculations, the Winfrith Water Benchmark [6] was included, which measures the disintegration rate of $^{32}S(n,p)^{32}P$, due to ^{252}Cf sources in a tank of water with varying source-detector separation distances. Some uncertainty was introduced, but not quantified, due to an inconsistent material definition for stainless steel provided by the benchmark authors, with three different stainless steel compositions provided among the supplemental documentation.

RESULTS

The ratios between the calculated and measured results for the selected benchmarks discussed are shown in Table I and Table II.

TABLE I. Neutron C/E Ratios of Selected Benchmarks

Benchmark	Neutron C/E
Baikal-1 Skyshine	0.72 - 0.93
Concrete Maze	0.86-1.05
Winfrith Water Benchmark	0.97-1.079
SILENE	0.70-1.59

TABLE II. Photon C/E Ratios of Selected Benchmarks

Benchmark	Photon C/E
Baikal-1 Skyshine	0.45 - 0.73
Concrete Maze	0.63-0.72
Gamma-Ray Skyshine	0.68 – 0.97

The Baikal-1 calculated results were consistent with the benchmark within the experimental uncertainty for the neutron results, but under-predicts the secondary photon dose rate. This is coupled to under-calculation of the neutron dose, both of which may be due to underestimation of source intensity.

All photon results are under-calculated in the SLAC concrete maze experiment, while the neutron-results range from a C/E of 0.86-1.05, dependent on concrete composition. All of the “dry” concretes underpredict the neutron dose, while the “wet” concrete overpredicts the neutron dose.

At close distances (< 200 ft) the gamma-ray skyshine calculation under-predicts the measured results (C/E < 0.77), which may be due to not including scattering within and off of the silo containing the source, but at distances up to 700 ft, the calculation is reasonably consistent with or positively biased compared to the measured results (C/E 0.9- 1.29). This benchmark is included in the validation inputs provided with MCNP, which presents results nearly identical with the measured data using an identical geometry. The MCNP authors’ results could not be replicated.

The low-fidelity source model and Surface Source Read model of the SILENE benchmark calculations were consistent with each other, and in general calculate within a C/E range of 1.18-1.97 for neutron activation results. The leakage source model has a C/E range of 1.19-1.59, which is similar to the other sources. All cases cluster around a C/E of 0.70 for the TLD results.

The Winfrith Water benchmark measured and calculated results demonstrate non-intuitive trends with respect to the total distance between the source and detector, which are attributed to effects of the experimental geometry. There is reasonably good agreement between the measured and calculated results, with C/E ratios ranging from 0.97 for the nearest case to 1.07 for the furthest cases. These are within or close to the total uncertainty reported by the benchmark authors of 6%.

These presented C/E ratios are within the range of the C/E ratios for all twelve benchmark experiments, and represent selected benchmark experiments directly applicable to CAAS analysis. All but one of the benchmarks has a C/E range within a factor of two. The notable exception is the Baikal-1 skyshine experiment, which has a photon C/E slightly below 0.5 at a large horizontal distance from the source. At this distance, almost all of the dose is due to secondary photons, which is sensitive to uncertainty in the measured source intensity. In general, a factor of two margin in calculated results is supported by the validation results.

REFERENCES

[1] NEA NUCLEAR SCIENCE COMMITTEE, "BAIKAL-1 SKYSHINE, Benchmark ALARM-REAC-AIR-SKY-001," International Handbook of Evaluated Criticality Safety Benchmark Experiments (2010).
[2] IPE, N. E., ET AL., "Shielding of Radiation Fields Generated by Cf-252 in a Concrete Maze, Part 1-Experiment", SLAC-PUB-7695, Stanford Linear Accelerator Center, (1998).
[3] R. J. MCCONN, JR., "Compendium of Material Composition Data for Radiation Transport Modeling", PNNL-15870, Pacific Northwest National Laboratory, (2011).
[4] NASON, SHULTIS, AND FAW, "A Benchmark Gamma-Ray Skyshine Experiment," Nuclear Science and Engineering 79, (1981).
[5] MILLER, THOMAS MARTIN, ET AL., "Neutron Activation and Thermoluminescent Detector Responses to a Bare Pulse of the CEA Valduc SILENE Critical Assembly", ORNL/TM-2015/462, ORNL, (2015).
[6] B. L. KIRK, "Winfrith Water Benchmark Experiment (ASPIS), SINBAD abstract NEA-1517/37", SINBAD-2007.05, Shielding Integral Benchmark Archive and Database, RSICC, ORNL, (2007).