McCARD Gamma Transport Analysis for RFNC Photon Spectrum Benchmark

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1. Introduction

McCARD [1], Monte Carlo (MC) Code for Advanced Reactor Design, is a Monte Carlo particle transport analysis code developed at Seoul National University. A gamma transport analysis capability is already implemented [2] in McCARD, but it has not been validated thoroughly through various benchmark problem, although it is also an important topic in various studies such as the calculation of body-equivalent photon dose for radioprotection or estimation of photon heating for thermal strength material studies. In this study, McCARD gamma transport analyses are conducted for the photon leakage spectrum benchmarks [3,4] experimented at RFNC-VNIITF, Zababakhin Russian Federal Nuclear Center. The photon transport analysis capability of McCARD is verified by comparing its results with those of MCNP5 [5]. In addition, McCARD calculation results for different neutron and photo-atomic cross-section libraries, namely ENDF/B-VII.0 [6], ENDF/B-VII.1 [7], JENDL-4.0 [8] are compared with experimental measurements.

2. Benchmark Specification

2.1 Description of Experiment

The modeling and experimental data of the RFNC photon spectrum benchmarks are available in SINBAD, Shielding Integral Benchmark Archive and Database [9]. SINBAD provides two sets of the photon leakage spectra experiments at RFNC-VNIITF:

- NEA-1517/74: Photon leakage spectra from Al, Ti, Fe, Cu, Zr, Pb, ^{238}U spheres
- NEA-1517/80: RFNC photon spectra from H_2O, SiO_2 and NaCl

In the experiments, a 14 MeV D-T neutron source, generated by accelerated deuterium ion and zirconium foil target saturated with tritium, was placed in the center of spherical samples with different materials and whose were 10 cm (inside) and 20 cm (outside). The neutron sources passing through the spherical samples generate gamma rays whose spectra were measured by a scintillation detector at 850 cm away from the source. A steel rod of Ø 3×40 cm was placed between the source and the detector to delay the direct 14 MeV neutrons, not scattered by the samples, at the detector. A 1.5 m thick concrete wall with a collimator is situated between the steel rod and detector.

The total uncertainty in the measured spectra was around 12% due to uncertainties in the detector efficiency, mathematical processing of the experimental spectra, the sphere radii, and target unit dimensions.

2.2 Benchmark Modeling

McCARD and MCNP5 benchmark calculations are conducted for a simplified model shown as Fig. 1. Extra devices such as collimator and neutron detector are not modeled in these calculations. The D-T neutron source is modeled as a point neutron source of 14 MeV mono-energy with the isotropic distribution.

For the calculation of photon leakage spectra in the McCARD and MCNP5, a virtual sphere (called the detecting surface) with a radius of 850 cm, the distance between source and the detector, is modeled to tally the photon leakage spectra. The energy range of photon detection in the calculations is set to 0.3 to 8.0 MeV as in the experiment.

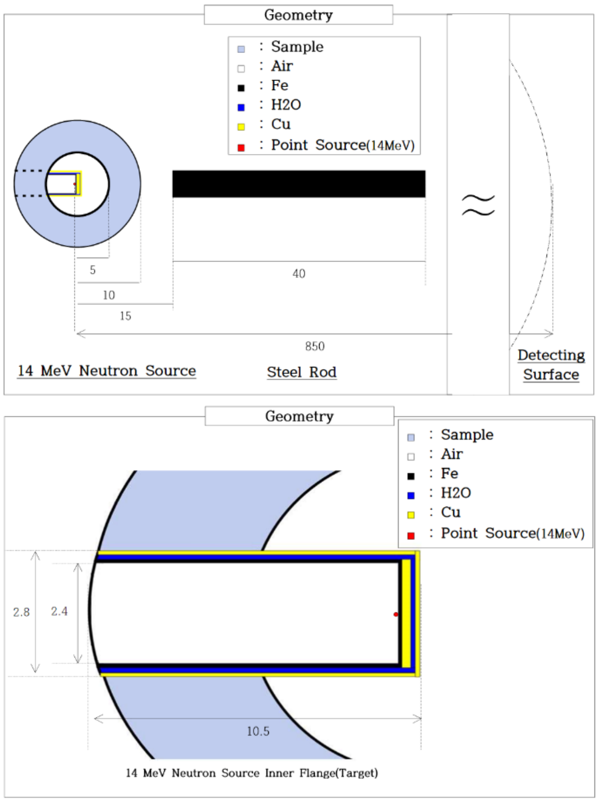

Fig. 1. Simplified model for benchmark calculation (dimensions in cm).

In this study, five sample materials in the benchmark are selected for the MC calculations as in Table I.

Table I: Material of spherical samples

Material	Weight (kg)
Al	9.86
Cu	29.92
Zr	23.66
Pb	39.11
H2O	3.6

100,000,000 neutron sources are simulated in MC calculations. Continuous-energy neutron and photon cross section libraries are produced from three different kinds of evaluated nuclear data - ENDF/B-VII.0, ENDF/B-VII.1, and JENDL-4.0 using NJOY2016 [10]. The ACE cross section libraries for neutron and photon generated by NJOY2016 are used for both McCARD and MCNP. The Gaussian energy broadening [11] which can represent well a physical radiation detector is applied in the comparisons against experiments, while not used in the comparisons between McCARD and MCNP5. The Gaussian energy broadening uses three parameters (A, B, C) in a Full Width at Half Maximum (FWHM) defined as follows,

$$FWHM = A + B\sqrt{E + CE^2}\ , \qquad (1)$$

with E the energy of the particle in MeV. Only one set of the Gaussian energy broadening parameters in Table II, defined in the SINBAD benchmark, is applied in this study.

Table II: Gaussian energy broadening parameters in all calculations

Gaussian energy broadening parameters		
A	B	C
0	0.107	0

3. Numerical Results

3.1 Comparisons between McCARD and MCNP5

Figures 2–6 show McCARD results of photon leakage spectra with ENDF/B-VII.1 for the Al, Cu, Zr, Pb, H_2O samples, respectively, compared against MCNP5. The Gaussian energy broadening option is not activated for both McCARD and MCNP5. Table III summarizes the root mean square differences (RMSDs) and the maximum relative differences of McCARD to MCNP5. The confidence interval (CI) of the RMSD given in the table is an average value of CI over all energy bins. From the table, one can see that the calculation results of McCARD agree well with MCNP5 within 95% confidence intervals in terms of the RMSD.

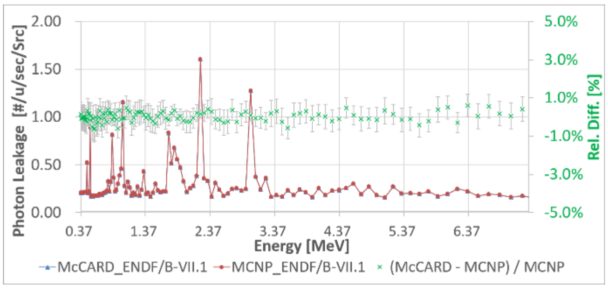

Fig. 2. McCARD calculation results of photon leakage spectra for Al sphere compared to those of MCNP5.

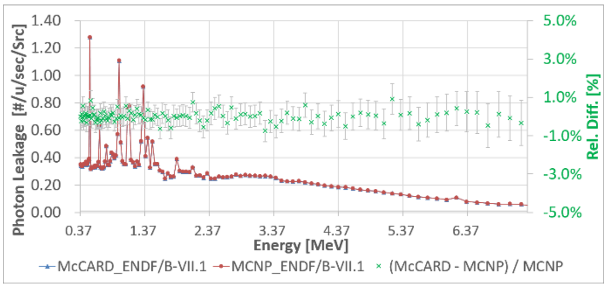

Fig. 3. McCARD calculation results of photon leakage spectra for Cu sphere compared to those of MCNP5.

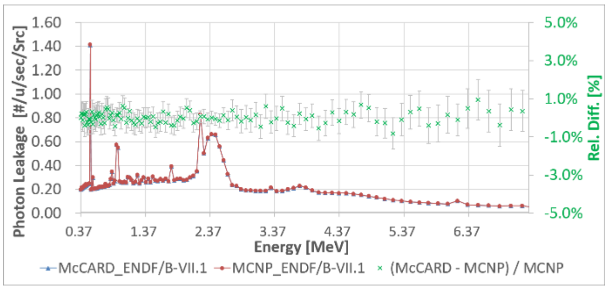

Fig. 4. McCARD calculation results of photon leakage spectra for Zr sphere compared to those of MCNP5.

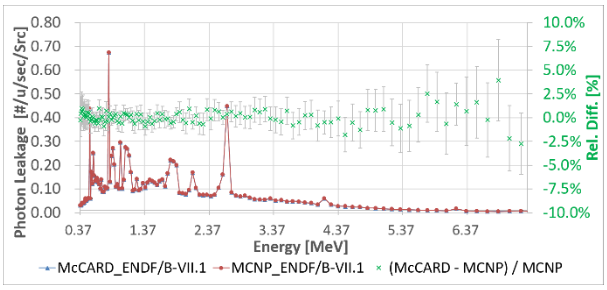

Fig. 5. McCARD calculation results of photon leakage spectra for Pb sphere compared to those of MCNP5.

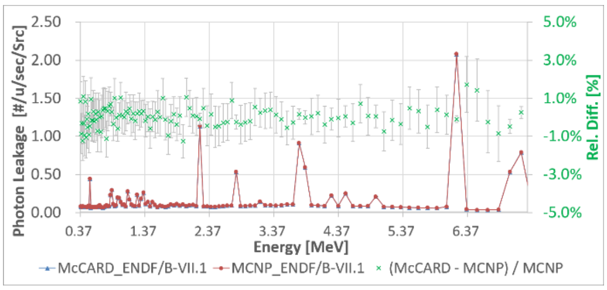

Fig. 6. McCARD calculation results of photon leakage spectra for H_2O sphere compared to those of MCNP5.

Table III: Comparison between McCARD and MCNP5 photon leakage spectra calculations

	RMSD		Rel. Diff.	
	Mean (%)	95% CI (%)	Max (%)	99% CI (%)
Al	0.26	±0.57	0.61	±0.76
Cu	0.29	±0.58	0.92	±1.05
Zr	0.31	±0.60	0.95	±1.40
Pb	0.80	±1.37	3.95	±5.65
H_2O	0.57	±0.94	1.72	±1.80

3.2 Comparisons with measurements

Figures 7–11 show the comparisons of the McCARD results calculated with varying the cross section libraries, ENDF/B-VII.0, ENDF/B-VII.1, JENDL-4.0 against experimental measurements for the five benchmark problems. The Gaussian energy broadening option is activated for these comparisons. The figures show that the gamma transport analyses for the benchmarks by McCARD are quite in accordance with experiments. Any significant effects of nuclear data libraries are not observed except for the Zr case (Fig. 9) in which ENDF/B-VII.1 shows a noticeable discrepancy compared with the others.

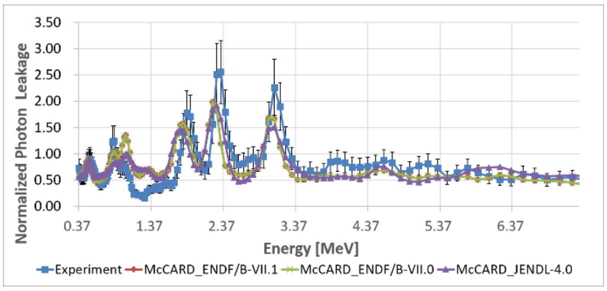

Fig. 7. McCARD calculation results of photon leakage spectra for Al sphere compared to experimental measurement data

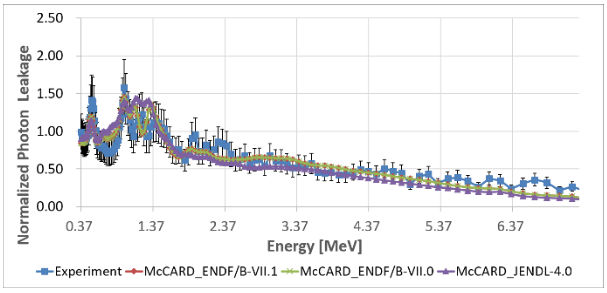

Fig. 8. McCARD calculation results of photon leakage spectra for Cu sphere compared to experimental measurement data

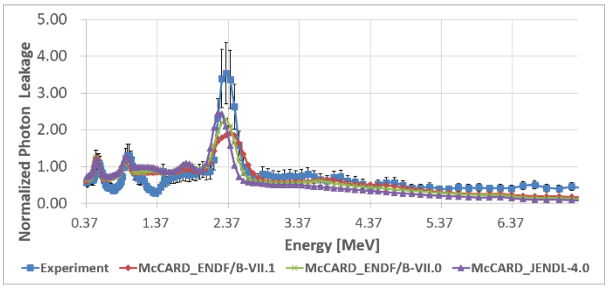

Fig. 9. McCARD calculation results of photon leakage spectra for Zr sphere compared to experimental measurement data

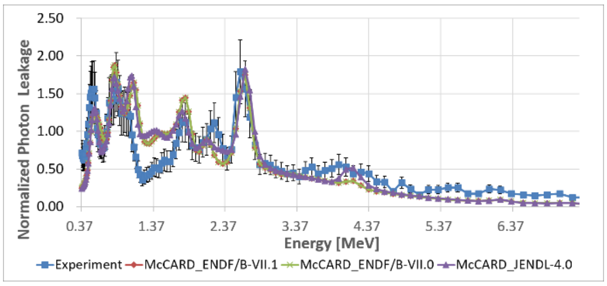

Fig. 10. McCARD calculation results of photon leakage spectra for Pb sphere compared to experimental measurement data

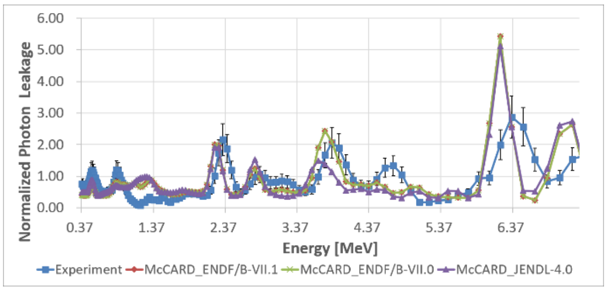

Fig. 11. McCARD calculation results of photon leakage spectra for H_2O sphere compared to experimental measurement data

4. Conclusions and Future works

McCARD gamma transport analyses are conducted for the RFNC photon leakage spectrum benchmarks in SINBAD. The benchmark calculations are performed with three different neutron cross section libraries, namely ENDF/B-VII.0, ENDF/B-VII.1, and JENDL-4.0. The calculation results of McCARD agree well with those of MCNP5 and experimental measurements. Any noticeable difference is not observed when varying evaluated nuclear data, but ENDF/B-VII.1 shows a discrepancy in the Zr case compared with the others.

For future works, McCARD analyses for other samples such as Fe, SiO_2, NaCl, and ^{238}U will be performed with additional nuclear data files of ENDF/B-VIII.0 and TENDL-15.

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