Nuclear Science and Technology Symposium - SYP2019
Helsinki, Finland, 30-31 October 2019

Comparison of Calculation Codes in Radiation Detector Placement and Performance Analysis

Daniel Kaartinen
Fortum Power and Heat Oy
Keilalahdentie 2-4, 02150 Espoo
daniel.kaartinen@fortum.com

ABSTRACT

A comparison between Serpent and MCNP was made using a case in which radiation detector location and its shielding were optimized. An assessment of Serpent's suitability for use in radiation safety work was done on basis of the comparison. The calculation case was a placement and performance analysis of a gamma detector used for monitoring radioactive releases during a severe reactor accident.

The most optimal placement for the detector and radiation shielding was determined by performing radiation dose rate calculations in candidate places using both codes. Also a separate computational performance comparison was done for the calculation codes in a computationally challenging case using both analogue simulations and variance reduction techniques.

In similar calculation geometries calculations Serpent's performance was on a par with that of MCNP's. Even though the photon radiation calculation module of Serpent is still under development, it was successfully used to perform all the desired radiation dose rate calculations, which were challenging even with MCNP. Variance reduction was determined to be biggest development area for Serpent. Overall, Serpent was found to be generally useful in modelling gamma radiation.

1 INTRODUCTION

Photon physics model [1] for Serpent [2] is a relatively new feature allowing the simulation of photons in various applications including reactor physics and radiation safety. In radiation safety calculations photon physics alone are often not enough; in difficult transport cases the use of variance reduction techniques is also required.

Along with new photon physics model, Serpent has introduced some new methods in variance reduction schemes like weight-window generation with response matrix [3] and self-adaptive weight-window mesh [4]. Serpent also supports the use of weight-windows meshes produced by MCNP and has a module for generating weight-window meshes based on the importance function.

The capabilities of Serpent in challenging radiation safety geometry was tested. The problem was a placement and performance analysis of an accident-condition gamma detector [5] for measuring radioactive releases in Loviisa NPP. The problem was especially challenging due to skyshine scattering in low density material like air [6].

The results from Serpent were compared to results from MCNP6.2, which was used for verification purposes.

2 DOSE RATE CALCULATIONS

Most calculations performed were dose rate calculations which were used to identify the most optimal placement for the detector. A few places were chosen beforehand as candidate places which were then studied more thoroughly.

2.1 Radiation source

A large-break loss-of-coolant (LLOCA) 220 cm^2 accident combined with station blackout leading to a severe accident was chosen because it leads quickly to a strong skyshine radiation. MELCOR analyses were done for this accident scenario to provide estimations for the amounts of radionuclides in different parts of the containment building. A gamma radiation spectrum based on the nuclide concentrations was determined and used for dose rate calculations.

2.2 Calculation geometry

MCNP geometry model of Loviisa NPP (Fig. 1 and 2) was used. It describes the whole plant area along with a more detailed layout of the reactor buildings and auxiliary buildings in some detail. The main focus on the geometry however is on the ventilation stack and ventilation channels leading to it.

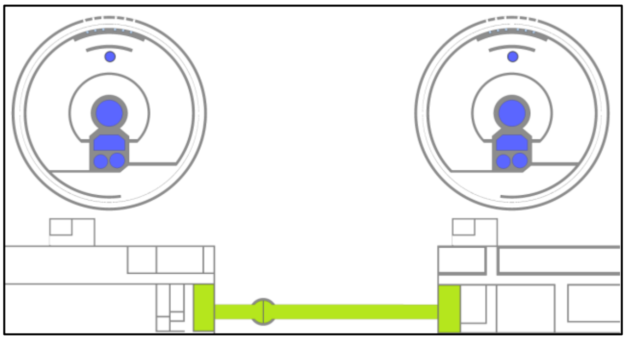

Figure 1: Part of the XY (horizontal) cross-section of the MCNP geometry model of Loviisa NPP from level +17.00 m. Concrete structures are coloured grey and suitable candidate areas for detector are coloured green. Auxiliary buildings are shown in the bottom part of the picture.

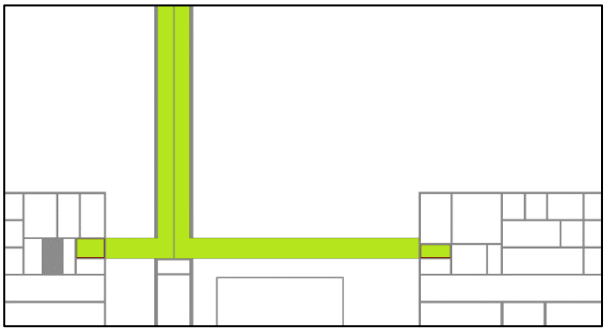

Figure 2: Part of the YZ cross-section of the MCNP geometry model of Loviisa NPP in the location of the ventilation stack.

2.3 Variance reduction

Skyshine radiation was especially difficult in terms on variance reduction. There is not one clear path for radiation meaning that vast areas of the calculation geometry contribute to the same detector. This leads to comparably long calculation times to obtain tallies with low relative errors.

Skyshine radiation, because of its properties, was also a challenge for Serpent's response matrix based importance solver which is why the weight-window generator, based on estimating adjoint function by MC-simulation, was used. This approach worked well for the skyshine problem.

For other cases where scattering in low density material does not play such a big role Serpent's response matrix method coupled with the self-adaptive mesh worked very well.

2.4 Results

Dose rates in the vertical ventilation stack and the horizontal duct leading to the stack were calculated with both Serpent and MCNP. In all cases iterative use of weight-window generators was required.

The results were calculated from two different sources. First source is the dome of the reactor building which is dominated by noble gases. The second source consists of all the other source volumes in lower parts of the containment. The dome dominates production of the skyshine radiation and the other sources that are named "segment" dominate on lower parts of the ventilation stack due to structural reasons.

Results from LLOCA in LO2 unit (on the right in Fig. 1) are presented in Fig. 3 and 4. The dose rate calculation results match very well from both codes. The biggest differences in results are due to fluctuations resulting from random sampling. Serpent calculations for the ventilation stack (Fig. 3) were done with a HPC-cluster and MCNP calculations with a computing laptop. Due to limited calculation time, MCNP results for the vertical stack show bigger fluctuations in those sections of the stack where dose rates are the lowest.

Serpent calculations for horizontal duct (Fig. 4) were done with an eight core calculation server with minimal calculation time which explains the fluctuations in the results. Overall the results of both calculation codes in all dose rate calculations matched with acceptable relative differences.

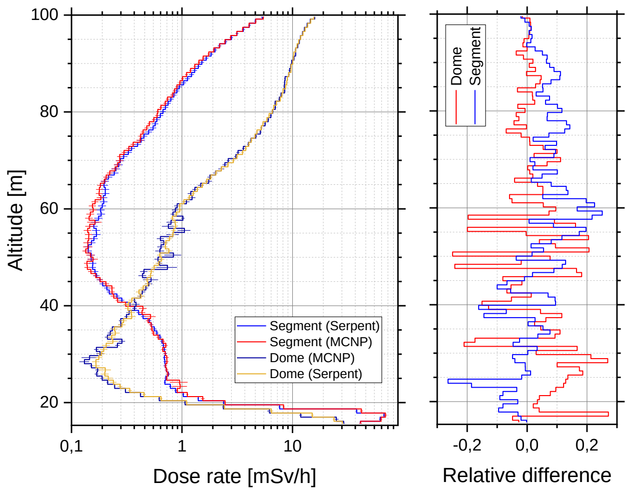

Figure 3: Dose rates inside the ventilation stack in relation to altitude inside the stack in LO2 LLOCA. Relative difference between Serpent and MCNP results are shown on the right.

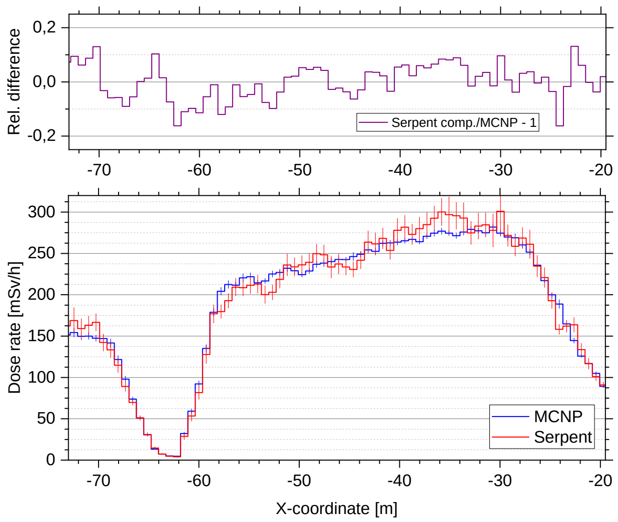

Figure 4: Dose rates in the horizontal duct in LO2 LLOCA, both sourced combined.

3 COMPARISON OF CALCULATION EFFICIENCIES

In addition to dose rate calculations, a comparison of calculation times were performed for a case very similar to the dose rate calculations of the horizontal duct. A simplified model of LO1 unit reactor building was made along with the ventilation ducts. Skyshine induced dose rates in horizontal mesh tally were calculated first without variance reduction techniques and then with weight-windows.

MCNP calculations were done with a Windows laptop and Serpent calculations were done with a Linux server. The differences in processors were taken into account by using benchmarks. This comparison does not take into account other differences in hardware and software, thus the results presented here are only indicative.

Dose rate results, relative differences in dose rates and figures of merit for calculation without variance reduction are shown in Fig. 5. Figure of Merit is defined as:

$$FOM = \frac{1}{\sigma^2 T}, \quad (1)$$

Where σ is deviation of the mean and T is the calculation time. Calculation time used for the first case was short and was merely used for generating weight-windows. Still the dose rate results agree very well and differences fit inside relative error margins. In analogue calculations FOM between the two codes doesn't differ significantly. The drop in dose rates in the calculations concerning the horizontal duct in coordinate area [-65, -55] m is the vertical concrete ventilation stack that attenuates radiation efficiently.

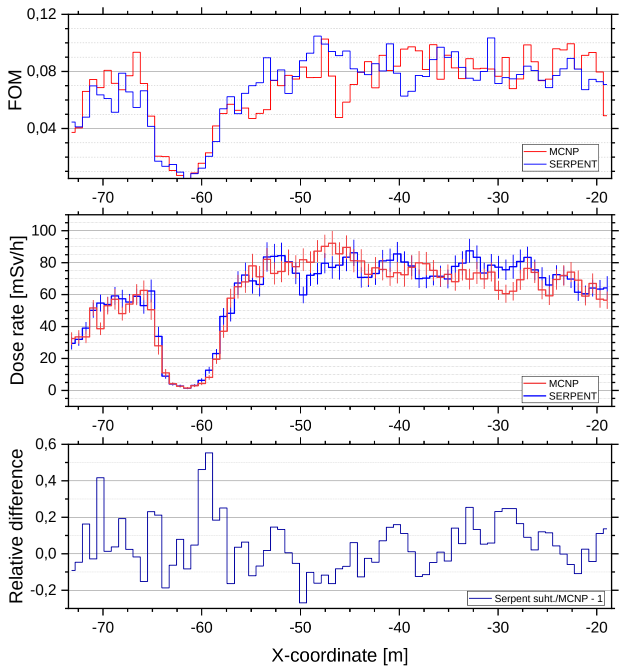

Figure 5: LO1 LLOCA skyshine induced dose rates in the horizontal duct, FOMs of the different tallies in the mesh and relative differences of dose rates.

In case where weight-windows were used, both codes, as expected, performed faster than without variance reduction. Now the dose rate results shown in Fig. 6 agree much better. Big difference however is in the FOMs. MCNP seems to work faster using weight-windows in a skyshine calculation. It is to be noted that variance reduction is a fairly new feature in Serpent and it has shown very promising results in other applications [4].

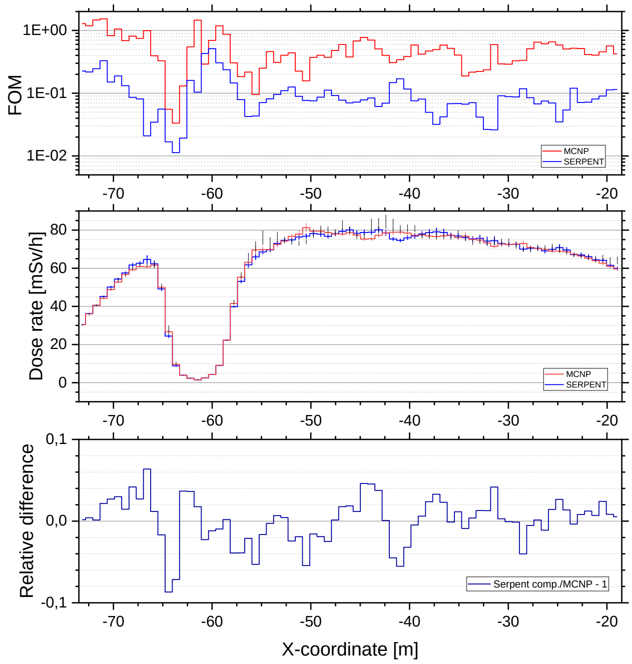

Figure 6: Results from the calculation using weight-windows.

4 CONCLUSIONS

Serpent was determined to be generally useful in modelling gamma radiation. The code performs as well as MCNP in most cases and further demonstrates new ways to construct weight-window meshes for variance reduction. The code was found to be very user friendly input-wise and provides insightful on the fly visual feedback to the user in the form of mesh plots, unlike MCNP. Even in extremely challenging and time consuming calculation cases like skyshine radiation Serpent is able to provide reliable data and increase its efficiency through variance reduction.

The development of Serpent's variance reduction during the comparison work presented in this report was rapid, with new features being added frequently. It is easy for user to contact the developer team for new features to the code and users can also make minor modifications to the code.

Further studies of Serpent's capabilities in radiation safety should be done with focus on Serpent's capability to read CAD input and also with the adaptive mesh technique that has proved itself as a very interesting and promising feature.

ACKNOWLEDGEMENTS

This short-paper was made based on a Master's thesis made in Fortum's radiation safety and environment group in spring 2019.

REFERENCES

[1] T. Kaltiaisenaho, “Implementing a photon physics model in Serpent 2”, Master's thesis, Aalto University, 2016

[2] J. Leppänen et al., "The Serpent Monte Carlo code: Status, development and applications in 2013", Ann. Nucl. Energy, 82 (2015) 142-150, 2015

[3] J. Leppänen, "Response matrix based importance solver and variance reduction scheme in the Serpent 2 Monte Carlo code", 2019

[4] J. Leppänen, "Global variance reduction scheme with self-adaptive weight window mesh in the Serpent 2 Monte Carlo code", 2019

[5] D. Kaartinen, "Laskentakoodien vertailu säteilymittarien sijoitus- ja suoritusanalyysissä", Master's thesis, LUT University, 2019

[6] I. Lagutina et al., "Skyshine from photon radiation", 1989