Gamma Dose Rate Calculations for RCC4 and RCC8 Containers using Monte Carlo Codes

Paulina Družijanić, Davor Grgić, Radomir Ječmenica, Siniša Šadek
University of Zagreb Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb, Croatia
Paulina.Druzijanic@fer.hr, Davor.Grgić@fer.hr, Radomir.Jecmenica@fer.hr, Sinisa.Sadek@fer.hr

ABSTRACT

In this paper, Monte Carlo codes are used for gamma dose rate calculations of the Reinforced Concrete Container with 4 and 8 positions for radioactive waste drums (RCC4 and RCC8). Generic designs of the RCC4 and RCC8 are used in the model. Similar containers are foreseen for use in Croatian temporary storage in Čerkezovac. The drums are standard 210 l drums for radioactive waste as used in the Nuclear Power Plant Krško. The source is homogenous volume source based on equivalent Cs-137 and Co-60 isotopes activity. The dose rates are tallied at the surface of the RCC4 and RCC8, as well as at the distances in the direction perpendicular to the container surface to show spatial dependence of dose rates. Additionally, a mesh tally is used to cover the entire model. Three cases are analysed. One covers the transport of the container (on the truck), one container on the ground, and one container within the concrete building. The results of gamma dose rates obtained with different Monte Carlo codes are compared. Finally, the skyshine effect and backscattering **influence** of the walls are assessed using the developed models.

Keywords: *LILRW radioactive waste, RCC container, dose rate, Monte Carlo, MCNP, SCALE MAVRIC*

1 INTRODUCTION

Reinforced concrete containers (RCC) can be used for conditioning, transport and storage of low- and intermediate-level radioactive waste. Radioactive waste is contained within metal drums which are placed in RCCs and poured with a bituminous or concrete mass. RCC can contain several drums which are immobilized to make handling, transport, storage and disposal easier.

A common way to calculate dose rates emanating from radiation sources is to use Monte Carlo codes such as MCNP [1] or MAVRIC module from the SCALE Code System [2]. The results they provide are based on a large number of simulated histories and are statistically presented. The codes deal with detailed 3D geometry, may handle multiple volumetric sources, have a rich collection of variance reduction techniques, a wide range of tallies and an extensive collection of cross-section data.

Only several research paper on the dose rates around RCC are available. Spatial interpolation of gamma dose in radioactive waste storage facility based on the measurements was done by Harun el al. [3]. Shin et at. performed radiological analysis of transport and storage container for very low level liquid waste [4]. Skyshine gamma dose rates around a future silo type LILRW (Low and Intermediate Level Radioactive Waste) repository in Slovenia were calculated by Kotnik et al. using the MCNP and ADVANTG codes [5].

In our previous work we developed methodology to calculate the dose rates emanating from spent fuel dry storage casks. First, we performed calculations for a benchmark case [6], followed by a standalone storage cask [7], transfer cask [8], and finally for the dry storage building [9] and during loading activities [10].

In this paper, Monte Carlo codes are used for gamma dose rate calculations around the Reinforced Concrete Container with 4 and 8 positions for radioactive waste drums (RCC4 and RCC8). Generic designs of the RCC4 and RCC8 are used in the model. Similar containers are foreseen for use in Croatian temporary storage in Čerkezovac. The drums are standard 210 l drums for radioactive waste as used in the Nuclear Power Plant Krško. The source is homogenous volume source based on equivalent Cs-137 and Co-60 isotopes activity. Three cases are considered. One covers the transport of the container (on the truck), one container on the ground, and one container within the concrete building. The main calculation tool is MCNP and SCALE/MAVRIC is used to verify the results. The developed models are used to investigate the influence of skyshine effect and backscattering from the walls on calculated dose rates.

2 METHODOLOGY

2.1 Monte Carlo codes

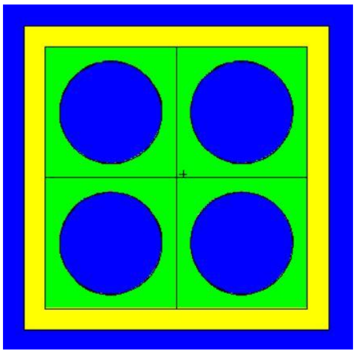
MCNP (Monte Carlo N-Particle) [1] is a general purpose 3D transport code used for neutron, photon, electron or coupled neutron/photon/electron calculations which cover different nuclear related fields, such as radiation shielding, radiation protection, dosimetry, criticality safety, fission and fusion reactor design, activation, decontamination, decommissioning, etc. The code is based on the Monte Carlo method which is defined as a stochastic simulation. Continuous, as well as multigroup, cross sections are available and for thermal neutrons, S(a, b) and free gas treatments are available. MCNP is versatile due to its features (definition of powerful general source, criticality source, and surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data).

SCALE/MAVRIC (Monaco with Automated Variance Reduction using Importance Calculations) [2] is a radiation transport module designed to apply the multigroup and continuous-energy fixed source Monte Carlo code, Monaco, to solve problems too challenging for standard, unbiased Monte Carlo methods. MAVRIC is based on the Consistent Adjoint Driven Importance Sampling (CADIS) methodology, which uses an importance map and a biased source that are derived to work together. In the Forwarded-Weighted CADIS (FW-CADIS) methodology, an additional Denovo calculation is performed to further optimize the Monaco model to obtain uniform uncertainties for multiple tally locations. Several utility modules are also provided for data introspection and conversion.

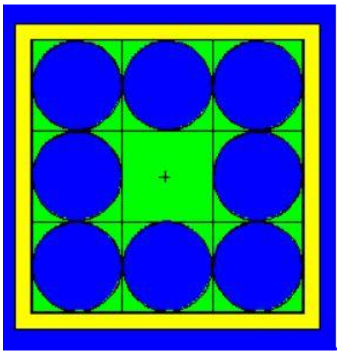
2.2 MCNP modelling

MCNP models of the RCC4 and RCC8 are shown in Figure 1. The drums are 210 l cylindrical vessels made of carbon steel. Such drums are used in the NPP Krško for intermediate- and low-level radioactive waste storage. Since the content of the drums may vary, in this model they are conservatively left empty, ie. filled with air as a source material. The drums are symmetrically placed in the RCCs. RCCs are empty boxes with the wall thickness of 12 cm, poured with a bituminous or concrete mass after placement of drums. In this model we used Magnus concrete mixture as a pouring material. Four cases have been considered as shown in Figure 2: RCC on the ground; RCC in a simple building; RCC in a small building, and RCC on a truck. These cases are expected configurations during transport and storage of the packages. Both RCC4 and RCC8 are analysed. A small building case is considered to investigate the dose rate increase due to backscattering from the walls.

The source is modelled in the MCNP as homogeneous volumetric source present in each drum. Equivalent source consists of Cs-137 and Co-60 with the respective activities of 1.0E+10 and 1.12E+9 Bq. MicroShield code is used to convert the source activity into intensity and spectrum. The total intensity of the source is 1.1539E+10 photons/s. Cs-137 decay energy of 0.6617 MeV and Co-60 decay energies of 1.1732 MeV and 1.3325 MeV dominate the energy spectrum.

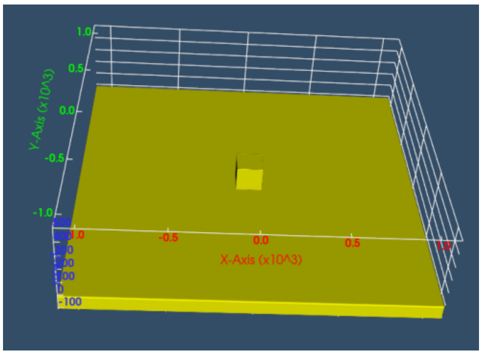


a) RCC4 model

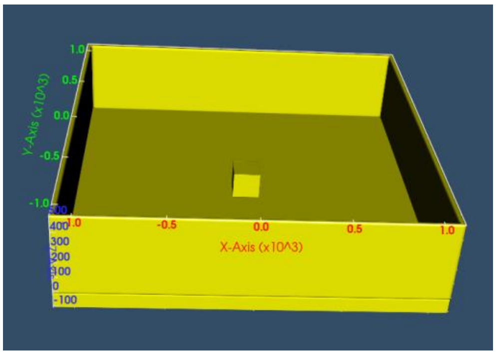


b) RCC8 model

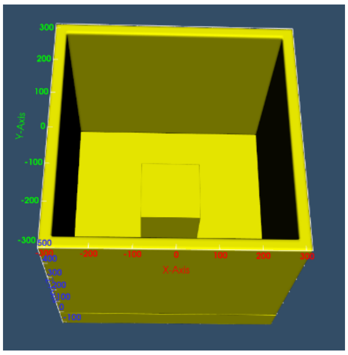
Figure 1: MCNP model of a) RCC4 and b) RCC8 (not to scale)



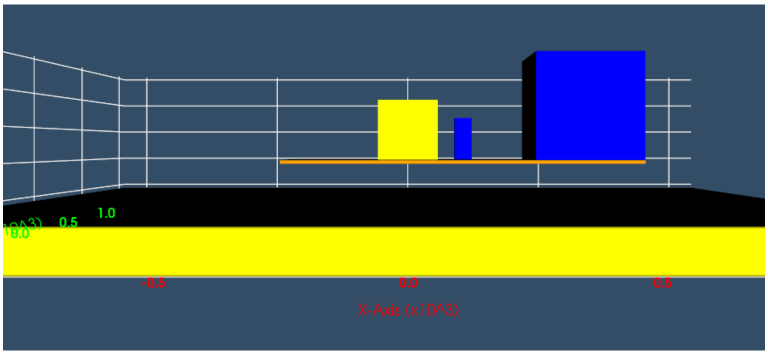
a)



b)



c)



d)

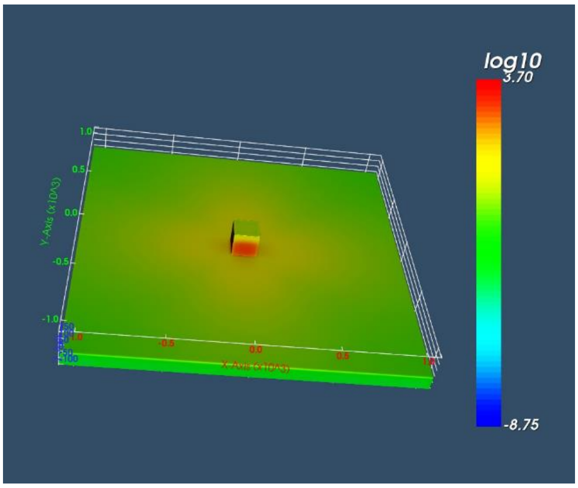
Figure 2: MCNP model of an RCC4 a) on the ground b) on a truck c) in a simple building and d) in a small building

Tallies are placed at the surface of the RCC, as well as at 1 m, 2 m, 3 m, 4 m, and 5 m from the RCC surface. Both point detectors and wall detectors are used.

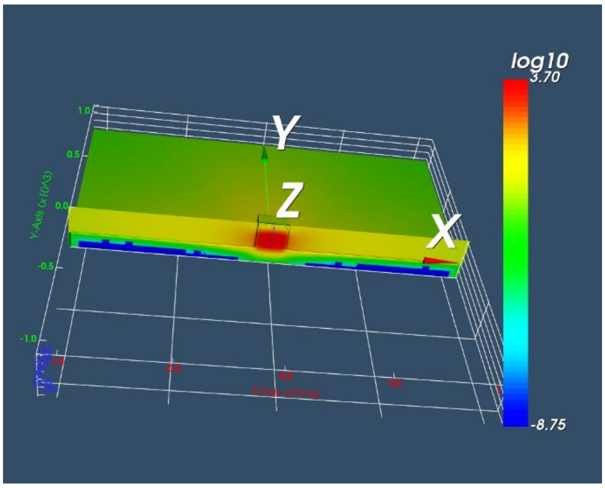
The ANSI/ANS 1977 Gamma flux to dose conversion factors [11], and ENDF/B-VII.1 cross section continuous energy libraries are used.

3 RESULTS

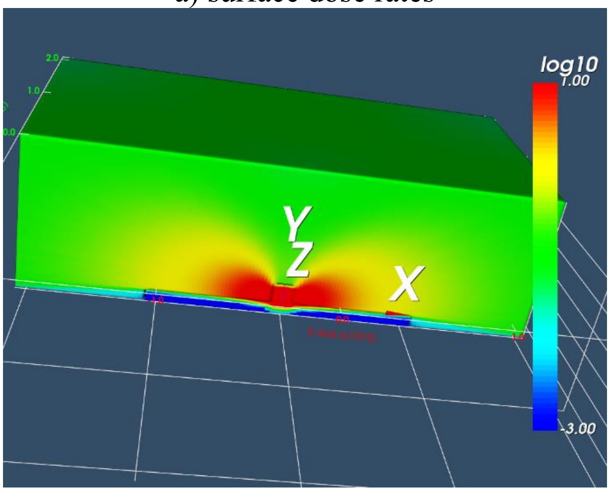
The dose rate distribution around the RCC4 placed on the ground for different views is shown in Figure 3, while Figure 4 shows dose rate distribution for RCC4 in the building (wall height 5 m, without roof). In Figure 3 a) surface dose rates and b) volume dose rates, it can be seen that the highest dose rates are within the RCC due to a source present in the drums. From Figure 3 c) it can be seen that air dose rates are significantly lower above the RCC lid than at the RCC sides. The reason for this lies in the fact that the drums are placed on the floor of the RCC and about 58 cm free space above the drums is filled with magnus concrete, which, together with top lid, presents a significant shielding above the RCC4. Since there are four symmetrically placed drums in the RCC4, the dose rate distribution around the RCC4 (at elevation 1.2 m above ground) has specific shape as shown in Figure 3 d). The reduction of the dose rate due to building walls can be seen in Figure 4. When compared to Figure 3 d), it can be seen that the dose rates are significantly lower behind the building walls since the walls are 40 cm thick and made of concrete, therefore present a good shielding.



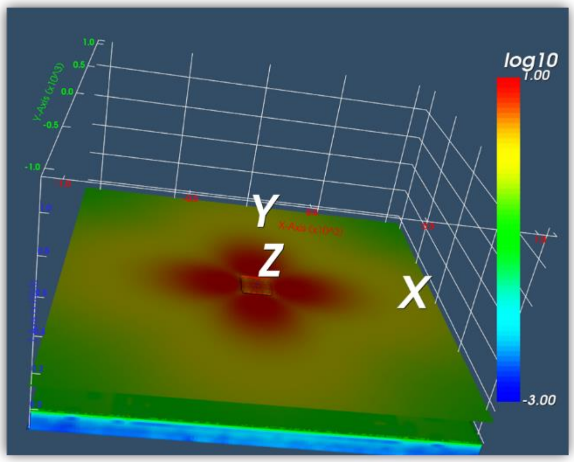
a) surface dose rates



b) volume dose rates



c) vertical distribution of dose rate



d) horizontal distribution of dose rate at 1.2 m

Figure 3: Dose rates [μSv/h] for RCC4 on the ground

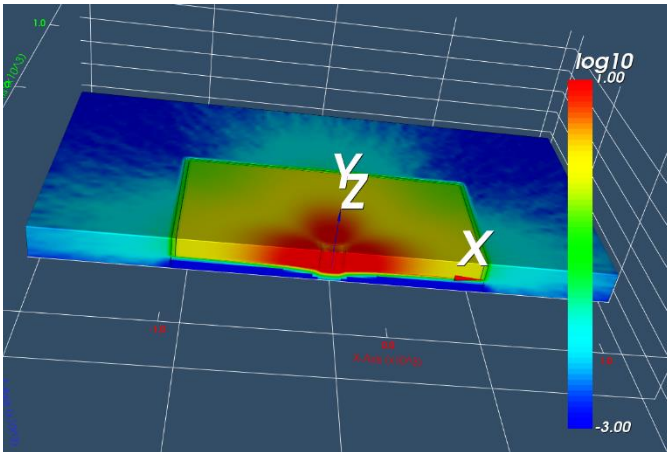
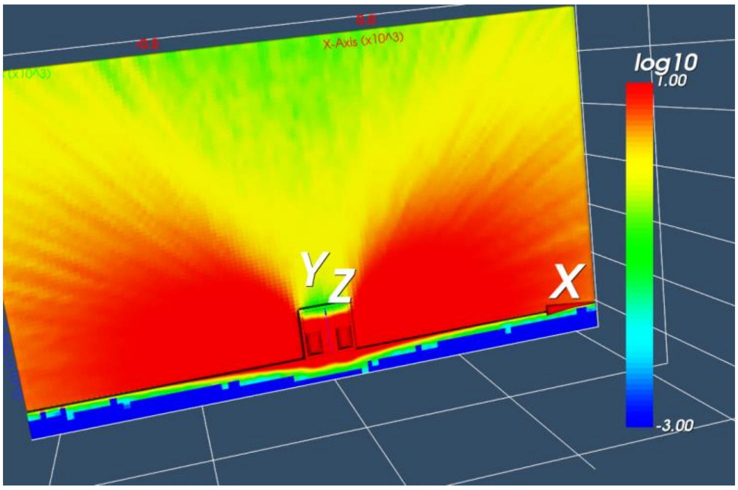
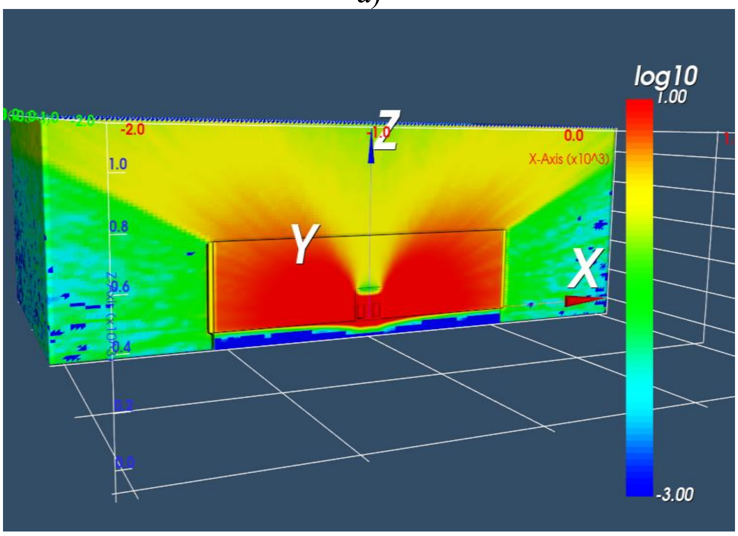


Figure 4: Dose rates [µSv/h] for RCC4 in the simple building

The dose rate distribution (logarithm of values) around the RCC8 on the ground and in the building without roof is shown in Figure 5. RCC8 has a source twice as large as RCC4. The position of the drums within the RCC plays an important role in dose rate assessment. We assumed that all drums are placed close to the RCC8 walls, so the dose rates obtained this way are conservative since there is the least shielding involved.



a)



b)

Figure 5: Dose rates [µSv/h] for RCC8 a) on the ground, b) in the building

The comparison of dose rates for RCC4 and RCC8 at different elevations, at the central plane of RCC, is shown in Figure 6. At different elevations, dose rate distributions have different shapes. A 50 cm elevation is between the drum top and bottom elevations, 120 cm is in the magnus concrete filling, while 150 cm is in the top lid concrete. The highest dose rates in the center are at 50 cm elevation, expectedly, and they fall rapidly due to attenuation in the RCC concrete body, after which they exponentially decrease with the distance from the RCC. When comparing the results of RCC4 and RCC8, at one meter from the RCC surface and height 50 cm, the dose rate for RCC4 is 33 μSv/h and for RCC8 it is 151 μSv/h. The latter are higher for two reasons, there is twice as large source and more drums are located on the periphery of the RCC. At the elevations above drums, the outside air dose rates first increase with the distance (influence of lower part of the cask), and then decrease, being independent of the elevation for larger distances (at about distance of 5 m for RCC4 and at distance of about 7 m from container center).

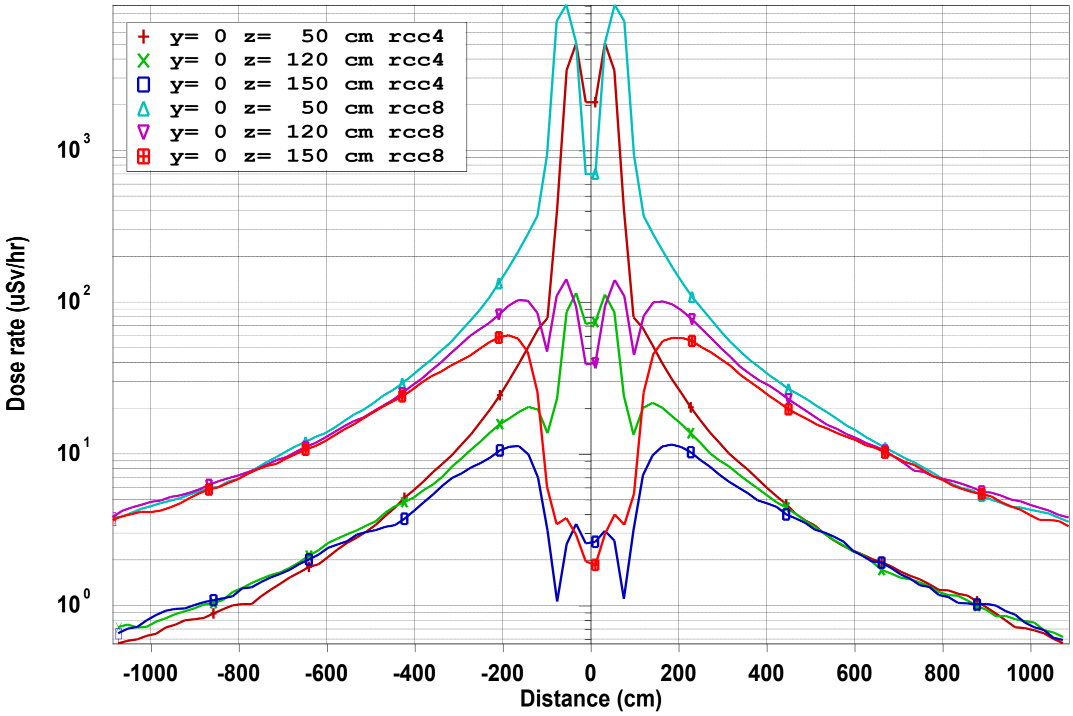


Figure 6: Comparison of dose rates for RCC4 and RCC8 at different elevations

The effect of the backscattering from the walls is seen in Figure 7. The red curve presents dose rates for RCC4 placed on the ground and the green curve presents dose rates for RCC4 in the building. Both curves decrease exponentially with the distance from the RCC surface, but when close to the building walls, the green curve is slightly above the red one due to backscattering from the walls. Behind the building walls there is a significant decrease of dose rates due to the attenuation within the building walls. The height of the concrete walls in simple building is 5 m and thickness is 40 cm. The distance from the RCC outer surface to the wall inner surface is 10 m. The building has no roof (usually LILRW storage buildings have light metal roof and solid concrete walls). Whole calculation domain is 40 x 40 x 12.6 m. RCC4 is in the center of the domain placed on 100 cm concrete foundation (height of the air above is 11.6 m). The blue curve represents dose rate as calculated by 16 point detectors (first is 3 cm from the surface and then the distance is increasing in steps of 1 m). The red and green curves were plotted using mesh tally dose rate values. The voxel size is approximately 20x20x20 cm. The calculation is analog MC calculation with 1E9 particles. The results obtained from mesh tallies and from point detectors are very similar, but the relative uncertainties at point detectors are usually smaller.

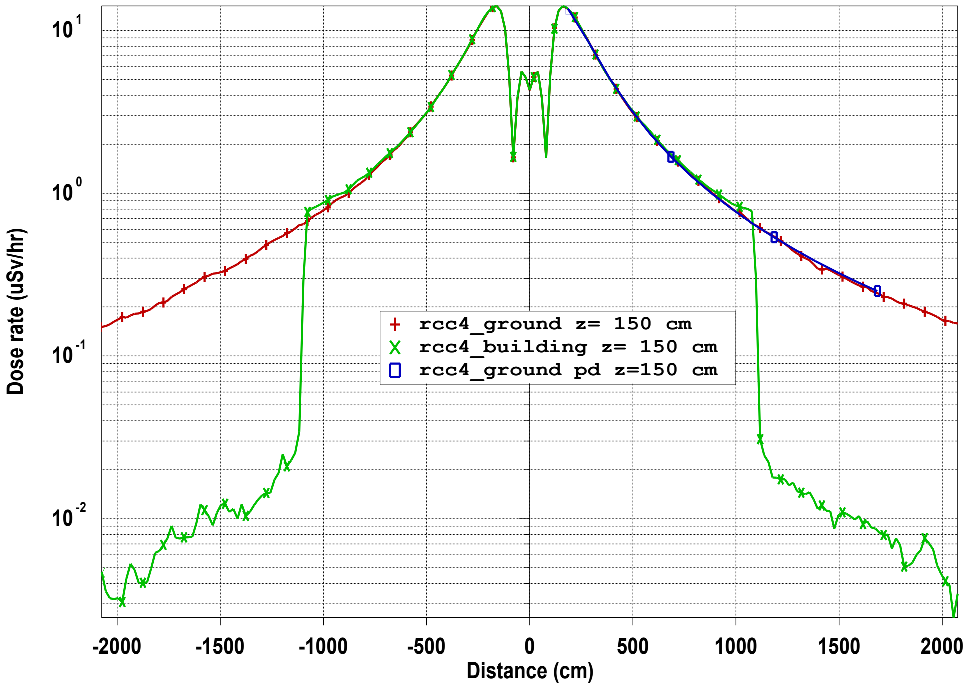


Figure 7: RCC4 on the ground and in the building – backscattering from the walls

The backscattering effect can also be observed for the RCC8 case. The comparison of dose rates of RCC8 on the ground and in the building is shown in Figure 8. Similar behavior may be seen as in the case of RCC4. The only difference is the elevation, in the case of RCC4 the elevation is 150 cm, and in case of RCC8 120 cm. Recall, the plane 120 cm passes through the magnus concrete filling and 150 cm passes through the top lid, therefore lower dose rates in the center are observable at higher elevation.

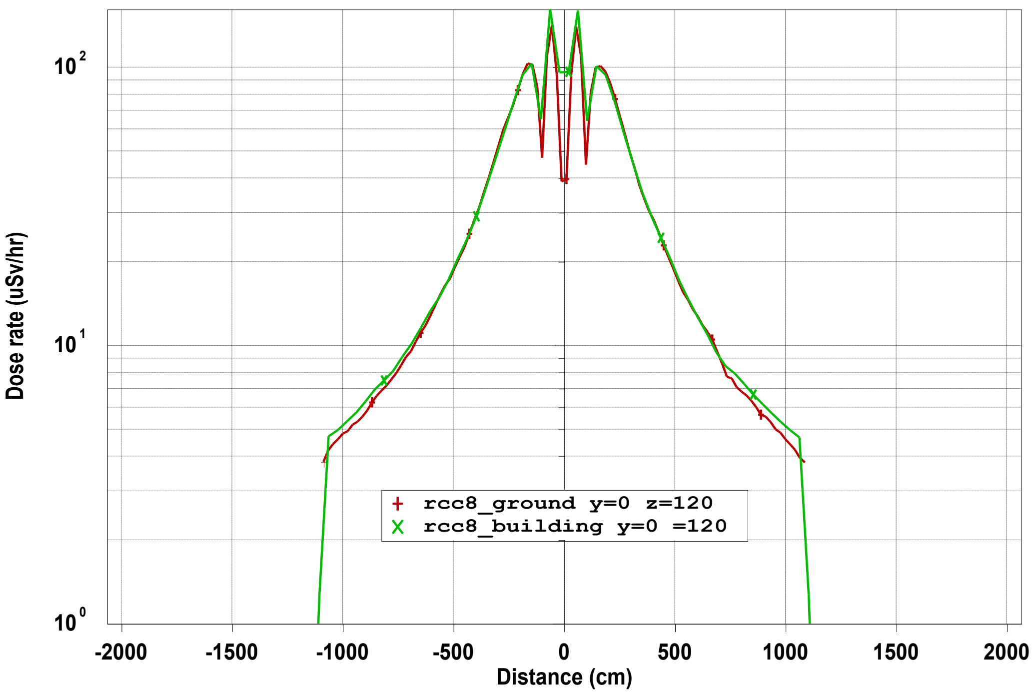


Figure 8: RCC8 on the ground and in the building

The skyshine effect can be present outside of LILRW storage building with light metal roof and thick concrete walls. It depends on geometry of the source and its relative position within the building (cross section of the building and height of the walls), and thickness of the building walls. Figure 9 shows dose rate change at 1.5 m above ground outside the small building without roof. The distance from RCC4 outer surface to wall inner surface (height of the wall is 5 m) is 2 m. The initial thickness of the wall is 40 cm and additional calculations use thickness of 30 cm. The label air means default thickness of the air above RCC4 (10 m) and label air ex means increase of air thickness for 50 m. The letter h means that hybrid calculation (ADVANTG/MCNP6) was used in that case. Both analog and hybrid calculations use statistics based on 1.0E9 particles. Point detector data were used for graphs preparation. First, we can see influence of wall thickness in dose rate reduction. Second, the thickness of air above building generally has small influence (spatial angle formed by RCC4 upper surface and building opening), but it is increasing with the thickness of the wall (and distance from the wall) due to the skyshine. The label imp 0 means wall with zero importance (there is no transport of radiation through it). In that case (absence of direct shine) the dose rate increase due to skyshine with the distance from the wall can be seen, as well as the influence of the air thickness above the building to relative importance of skyshine, which increases with more air above. Estimated dose rate increase due to skyshine for this configuration is about 3.0E-4 μSv/hr and that is in accordance with results shown for real 40 cm thick wall when the influence of the skyshine effect can be seen for distances larger than 8 m.

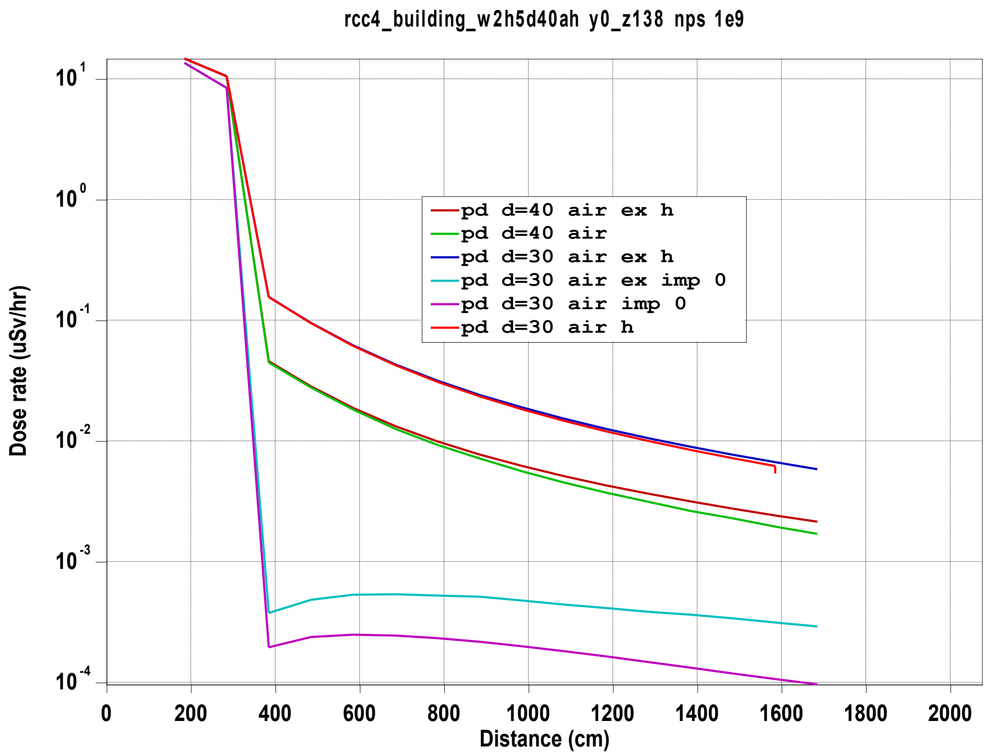
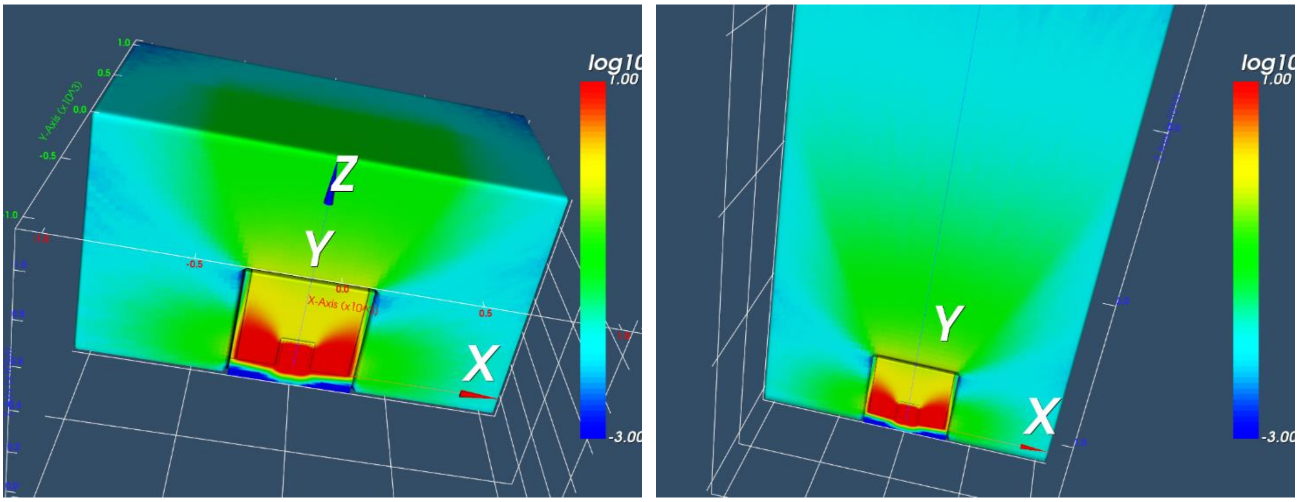


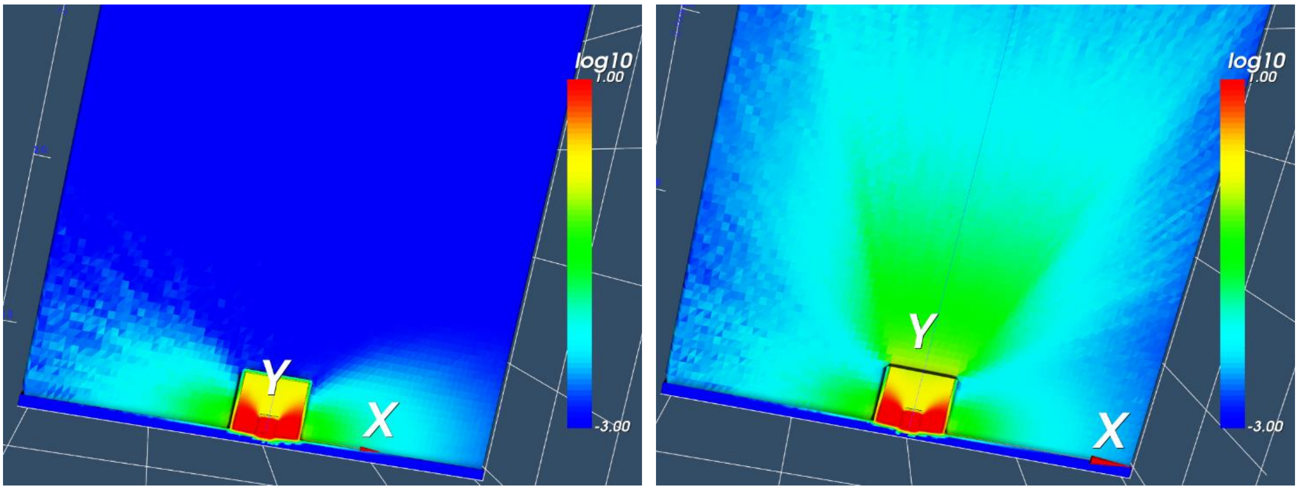
Figure 9: Skyshine effect in small building

3D distributions of dose rate around small building without roof are shown in Figure 10. The thickness of the concrete walls is 30 cm and height is 5 m. The distance from the RCC4 outer surface to the wall inner surface is 2 m and the distance from the wall to the domain boundary is 10 m. The height of air above RCC4 is 10 m in case of the model on the left and 60 m in the case of the model on the right of the figure. The gamma radiation is streaming through roof opening. Due to increased path through the wall upper part, there is low dose rate region just below the top of the wall. To consider the impact of skyshine around the building, the thickness of air layer above the building should be at least 50 to 100 m. In this case the combination of source and wall geometry and thickness of the wall caused direct shine to be more important than the skyshine, and thickness of the air above the building has small influence on dose rate around the building. Clearly, if we want to see decrease in dose rate above the building, the domain should be at least 50 m high. We also wanted to check the influence of the small building roof presence on dose rates around the building and we performed additional set of calculations with and without the roof. The results are presented in Figure 11. The model is the same as before, but the concrete foundation is extended cross the entire domain and external boundary is at 20 m from the RCC4 surface (increased calculation domain). The roof is 30 cm thick concrete slab, so it plays an important role in decreasing the dose rates above the building and to some extent around the building compared to the case when there is no roof. The top boundary of the domain of both models is 60 m above RCC4 top lid. The hybrid calculation was used with 1E9 particles generated. That was necessary to get better statistics for the case with a roof and for consistency the same approach was used for case without a roof. Dose rates are shown in the range between 1.0E-3 and 10 μSv/h. Mesh voxel size was 20x20x20 cm.



a) domain height 11 m b) domain height 61 m

Figure 10: Dose rates [μSv/h] for RCC4 in a small building



a) with the roof b) without the roof

Figure 11: Dose rates [μSv/h] for small building a) with the roof and b) without the roof

A better insight into the backscattering and skyshine effects can be seen in Figure 12. The thickness of the wall (30 cm) and its height (5 m) are constant, but the distance from the RCC4 surface to the wall surface is increasing from 2 m (w2h5, small building) to 10 m (w10h5, simple building). With increased distance between the container and the wall, backscattering influence inside building is decreasing and skyshine influence outside of the building is increasing due to increased view angle between RCC4 top and atmosphere above building. The values are based on point detector readings. The dose rate distribution at the inner walls of the small building is shown in Figure 13. The dose rates are limited to range from 1E-3 to 1E+1 μSv/h.

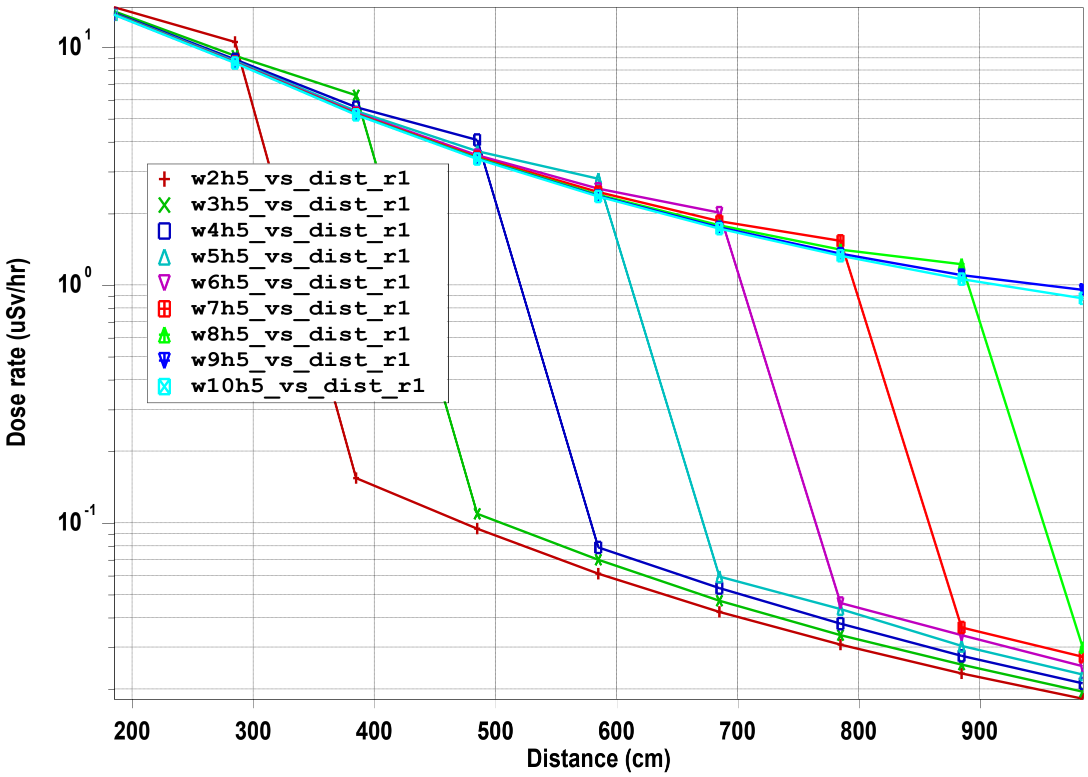


Figure 12: Backscattering and skyshine effect

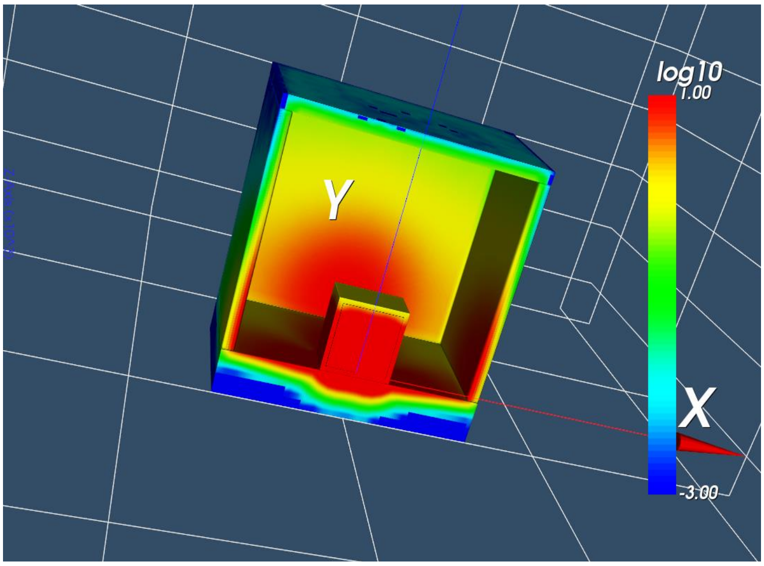
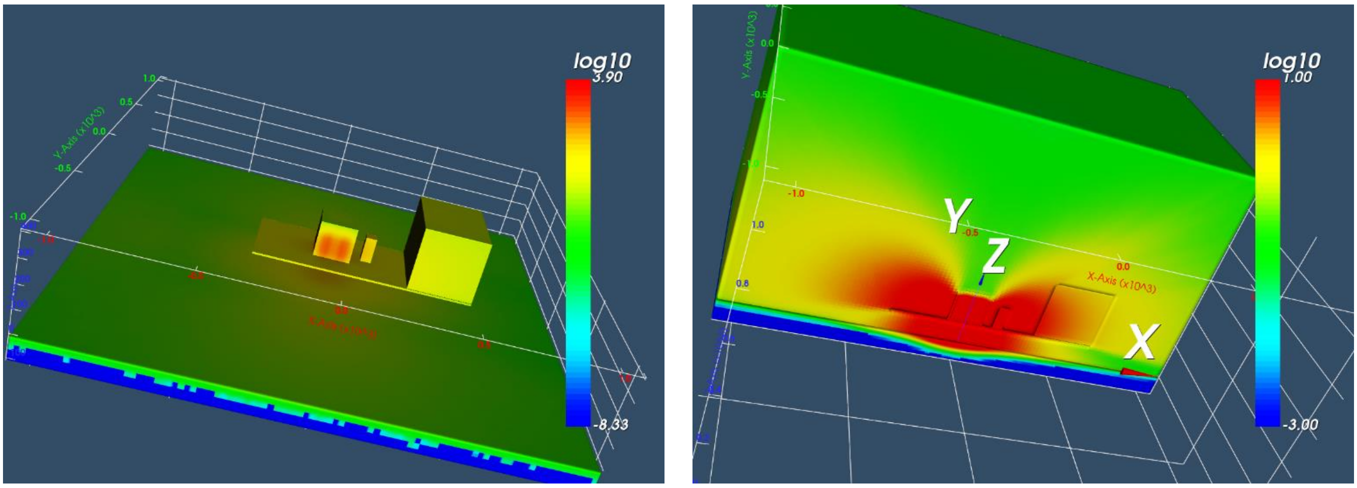


Figure 13: Dose rates [μSv/h] on the inner walls of a small building

Finally, while transporting the RCC from the power plant to the storage, the driver will spend certain time in the truck's cab, so it is important to have an insight into the dose rate distribution around and within the truck. The results in case of RCC4 placed on a truck are shown in Figure 14, case a) all results shown, and case b) only dose rates below 10 μSv/h to show the distribution within the truck's cab.



a) b)

Figure 14: Dose rates [µSv/h] for RCC4 on a truck a) all results, b) dose rates below 10 µSv/h

To validate the MCNP results, SCALE models of RCC4 placed on the ground and in the building were developed and the calculations were performed. The comparison of the results is given in Table 1 for the height of 1.2 m above ground and distance 1 m from the cask surface. In both cases differences between the code results are less than 6%. This means that the results of the two codes agree very well.

Table 2 shows the comparison of MCNP and SCALE results for the case of RCC4 in the building for five point detectors placed at selected distances from the RCC4 surface (elevation is 1.2 m above ground). Small differences in the dose rates are observable because they are tallied using point detectors.

Table 1: MCNP and SCALE dose rate comparison at 1 m from the RCC4 surface

Code	RCC4 on the ground		RCC4 in the building	
	Gamma dose rate [µSv/h]	Relative uncertainty [%]	Gamma flux [µSv/h]	Relative uncertainty [%]
MCNP	13.64	0.05	13.67	0.14
SCALE	14.44	0.14	14.53	0.19

Table 2: MCNP and SCALE point detector dose rate comparison for the RCC4 in the building

Point detector distance from the RCC4 surface	MCNP		SCALE	
	Gamma dose rate [µSv/h]	Relative uncertainty [%]	Gamma flux [µSv/h]	Relative uncertainty [%]
1 m	1.3670E+01	0.05	1.45321E+01	0.19
2 m	8.5559E+00	0.04	9.02097E-00	0.11
3 m	5.1844E+00	0.05	5.45051E-00	0.11
4 m	3.3785E+00	0.06	3.54734E-00	0.11
5 m	2.3531E+00	0.21	2.46792E-00	0.12

4 CONCLUSION

Shielding calculations were performed to determine dose rates at different stages of transport and storage of LILRW within four or eight drums in the RCC container. The obtained dose rate distribution shows specific shape around the RCC due to a symmetrical position of the drums. Dose rates are much lower at the top of the RCC than at the sides due to more shielding material above the drums. The dose rates around RCC8 are higher than around RCC4 configuration due to doubled source intensity and larger volume of the container.

Additionally, the model was extended to study the influence of skyshine and backscattering from the walls to dose rates around containers. The influence of skyshine is seen outside a building depending on wall thickness and view angle between RCC top lid and atmosphere above the building. The influence of the backscattering from the walls is better observed when considering RCC4 in a small building since in that case the walls are closer to the RCC4.

Finally, the obtained MCNP results were validate using the MAVRIC module of the SCALE Code System. The results of the two codes agree very well.

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