Shielding Analysis of Reinforced Concrete Container for Conditioning the Low- and Intermediate-Level Radioactive Waste from Nuclear Power Plant Krško

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ABSTRACT

This paper presents shielding analysis of the Croatian design of reinforced concrete container (RCC) using MCNP6.2 code. The structural design of the container was developed by University of Zagreb Faculty of Civil Engineering. The RCC is intended for low and intermediate-level radioactive waste storage in the new Radioactive Waste Management Center Čerkezovac. The basic RCC calculation is performed according to container design specifications. The RCC contains four metal drums with radioactive waste surrounded with grout and closed with a lid. The dose rates were tallied at multiple locations around the RCC and at the surface of the RCC to check fulfilment of regulatory requirements defined in the document IAEA SSR-6 "Regulations for the Safe Transport of Radioactive Material" Revision 1. The regulatory limits are, in terms of dose rates, 2 mSv/h at the RCC surface and 0.1 mSv/h at 2 m away from the RCC surface. The calculations were performed for three types of radioactive sources derived from characteristics of NPP Krško waste (maximum resin source, non-resin source and average radioactive source) and described in terms of source intensity and spectrum. The additional sensitivity analyses were aimed to address potential deviations in concrete and grout density, and deviations in RCC wall dimensions from the original cask design. To verify MCNP results, MAVRIC module from SCALE 6.2.4/6.3.1 was used.

Keywords: *reinforced concrete container, dose rate, shielding, MCNP, SCALE*

1 INTRODUCTION

According to IAEA safety standard, radioactive waste is classified into six categories: exempt waste, very short-lived waste, very low-, low-, intermediate- and high-level radioactive waste. Low level radioactive waste may include short lived radionuclides at higher levels of activity concentrations and long-lived radionuclides with relatively low levels of activity concentration. Such waste requires robust isolation and containment for periods up to few hundred years. Intermediate level waste may contain long lived radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred meters [1]. Generally, disposal of radioactive waste is on a long-term time scale and storage is temporary solution. Half of the low- and intermediate-level radioactive waste (LILRW) from the Nuclear Power Plant Krško will be first stored in the new radioactive waste storage center in Croatia until a suitable disposal facility is established.

The usual way of storing LILRW is by using reinforced concrete containers (RCCs). RCCs are used for storage and transport of LILRW contained within metal drums. Depending on the type, an RCC can contain four or eight drums filled with waste, which are immobilized in the RCC using a grout mixture. A review of RCC types is provided in [2].

The Croatian version of an RCC was designed by the University of Zagreb Faculty of Civil Engineering. It is designed to provide mechanical and radiation protection and will be used for LILRW storage in the new Radioactive Waste Management Center Čerkezovac. The RCC can accept up to four D6 drums, which are used in NPP Krško for storing LILRW [3].

This paper presents shielding analysis of the Croatian design of RCC using MCNP6.2 [4] code. The basic RCC calculation is performed according to container design specifications. The RCC contains four metal drums with radioactive waste surrounded with grout mixture and closed with a lid. The dose rates were tallied at multiple locations around the RCC and at the surface of the RCC to check fulfilment of regulatory requirements defined in the document IAEA SSR-6 "Regulations for the Safe Transport of Radioactive Material" Revision 1 [5]. The regulatory limits are, in terms of dose rates, 2 mSv/h at the RCC surface and 0.1 mSv/h at 2 m away from the RCC surface. The calculations were performed for three types of radioactive sources derived from characteristics of NPP Krško waste (maximum resin source, non-resin source and average radioactive source) and described in terms of source intensity and spectrum. The additional sensitivity analyses were aimed to address potential deviations in concrete and cement density, deviations in RCC wall dimensions from the original cask design. To verify MCNP results, MAVRIC module from SCALE 6.2.4/6.3.1 [6] was used.

2 METHODOLOGY

2.1 Computer codes

In this paper, the main computation tool is MCNP and MAVRIC module from SCALE code system is used for results verification. The codes main characteristics are described below.

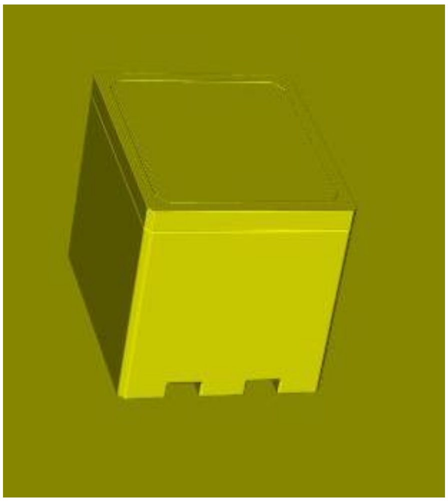
MCNP (Monte Carlo N-Particle) [4] is a general-purpose 3D transport code used for neutron, photon, electron or coupled neutron/photon/electron calculations which cover different nuclear related fields, such as radiation shielding, radiation protection, dosimetry, criticality safety, fission and fusion reactor design, activation, decontamination, decommissioning, etc. The code is based on the Monte Carlo method which is defined as a stochastic simulation. Continuous and multigroup cross sections are available. For thermal neutrons, $S(\alpha, \beta)$ scattering law and free gas treatments are also 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) [6] 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 near-uniform uncertainties for multiple tally locations. Several utility modules are also provided for data introspection and conversion.

2.2 RCC model

The basic geometrical model consists of RCC placed on a concrete ground, filled with 4 drums, poured by cement mixture, and closed with a lid as shown in Figure 1. Four D6 drums are symmetrically placed in the RCC. The interior of the drums is conservatively modelled empty (without waste).

Regarding materials used, RCC body and lid is made of concrete, filling mixture is a grout, drums are made of carbon steel and inside of drums is air. The external dimensions of the cask are 180 x 180 x 150 cm, and side wall thickness is 16 cm.



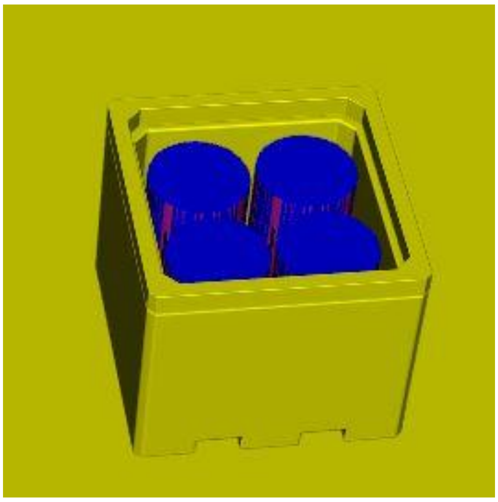


Figure 1: MCNP model of RCC cask with and without top lid

Three types of radioactive sources are considered, average source, maximum non-resin source and maximum resin source. All of them are specific for NPP Krško LILRW inventory. The average source is obtained from all radioisotope activities present in LILRW in NPP Krško. Half of the total activity is Croatian part and that activity is divided by the expected minimum number of RCC casks to obtain the average activity in RCC drums. The average source consists of Cs-137 and Co-60, with a total activity of 1.11E+10 Bq. MicroShield code (engineering point-kernel shielding code) is used to convert activity to gamma source intensity and spectra. The intensity of the average source is 1.154E+10 photon/s. The maximum non-resin source intensity is 1.688E+10 photons/s and maximum resin source intensity is 4.09E+11 photon/s. These intensities are per RCC and therefore divided into 4 drums. The source is homogeneously distributed within the drum and sampled uniformly from each drum.

In this paper, potential deviations from original design are considered. For that purpose, wall thickness is reduced by 5 mm from the original thickness and concrete and grout densities are reduced by 5 % from the original density. These cases result in higher dose rates and are therefore interesting to analyze.

We used point detectors (sphere with radius of 3 cm) to tally dose rates at the half drum height (z= 78 cm) on the symmetry line of the drum row and on the symmetry line of the RCC for distances from RCC surface as follows:

- Tally 5 – 2 cm from RCC surface, RCC symmetry line (x=0 cm, y=0 cm)
- Tally 15 – 10 cm from RCC surface, RCC symmetry line
- Tally 25 – 100 cm from RCC surface, RCC symmetry line
- Tally 35 – 200 cm from RCC surface, RCC symmetry line
- Tally 45 – 2 cm from RCC surface, D6 drum symmetry line (x=35.85 cm, y=35.85 cm)
- Tally 55 – 10 cm from RCC surface, drum symmetry line
- Tally 65 – 100 cm from RCC surface, drum symmetry line
- Tally 75 – 200 cm from RCC surface, drum symmetry line

Also, we used mesh tally over the entire model to analyze dose rate distribution around the RCC. Mesh element size (voxel) is approximately 10×10×10 cm (217 subdivisions in *x* and *y* direction and 120 subdivisions in *z* direction)

2.3 Calculation settings

In all MCNP calculations ENDF/B-VII.1 cross section library and ANSI/ANS-1977 gamma flux to dose conversion factors were used. Each calculation was performed at minimum for 100 million particles, and when necessary to obtain better statistics up to 1 billion particles.

3 RESULTS

3.1 Basic calculation

The results of basic case are shown first. Recall, basic case is RCC modeled according to design specifications, four D6 drums placed inside, poured with cement mixture and closed with a top lid. The source is defined as the maximum non-resin source. Gamma dose rates in mSv/h and associated uncertainties are given in Table 1 for point detector tally locations. All results are below the limiting 2 mSv/h. Mesh tally results are further used to identify possible outliers and give dose rate distribution over the entire model. Gamma surface dose rate distribution, limited to range between 1 and 2000 µSv/h, is shown in Figure 2. No outliers are observed at the side or at the top of the RCC. The height dependency of gamma dose rate at characteristic model points is shown in Figure 3. The first point is on the RCC symmetry line, the second is between the drums, the third is in the upper right quadrant drum symmetry line, the fourth and the fifth are corresponding points at RCC surface. Zero elevation is at the ground surface (the cask is placed on 40 cm thick concrete slab) and cask top surface is at height of 150 cm. The first three curves are mentioned to show decrease of dose rate with increasing distance from the cask top. At z=350 cm, 2 m from the upper surface the dose rate is below 0.1 mSv/h. The surface dose is slightly higher at the location just above drum center, but with increased distance the maximum is located on RCC symmetry line. Two curves showing axial distribution of dose rate at cask side surface indicate dominant influence of drum position on the maximum surface dose rate. The change of gamma dose rate with x-distance for characteristic cask location is shown in Figure 4. Selected elevations are at drum mid height (z=78 cm), and at RCC height (z=150 cm). The first and the third curve are there to show limiting side dose rate decrease with distance. The same as for z-dependency close to the surface, the dose rate is determined by drum position and with increased distance it is on a symmetry line.

Table 1: Gamma dose rates [mSv/h] at point detector tally locations

Tally	Gamma dose rate [mSv/h]	Uncertainty [%]
5	1.6583E-01	0.36
15	1.7540E-01	0.08
25	7.6004E-02	0.03
35	3.1025E-02	0.04
45	3.3005E-01	0.27
55	2.5997E-01	1.08
65	6.9287E-02	0.05
75	2.9456E-02	0.05

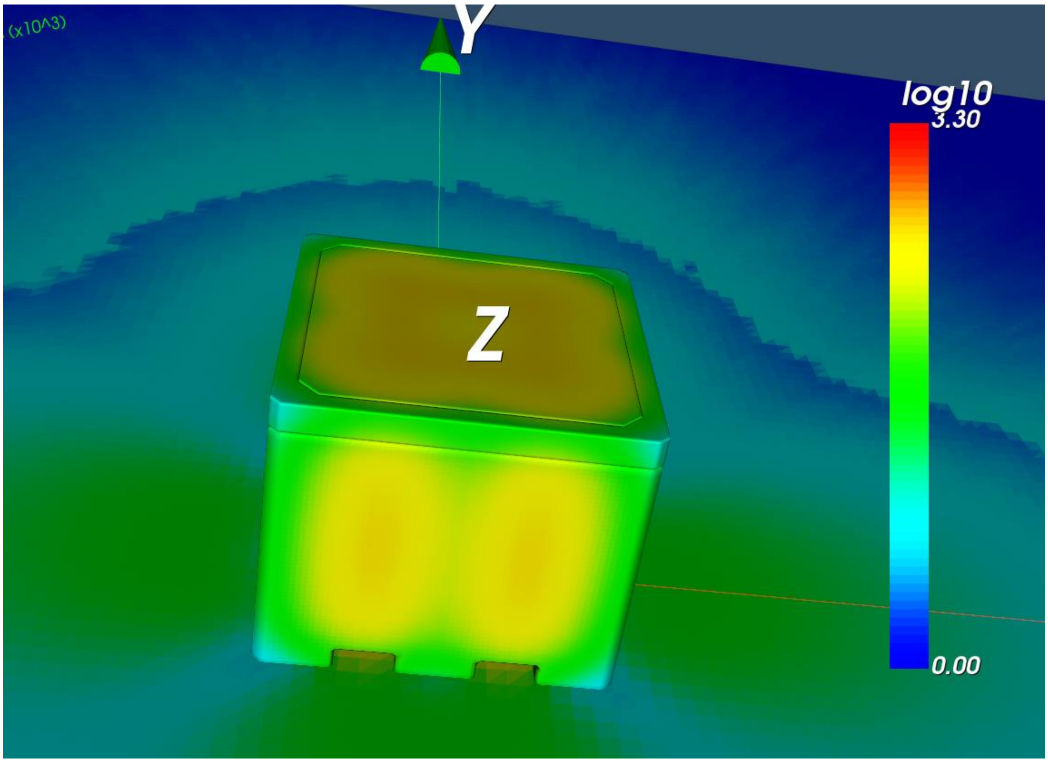


Figure 2 Surface gamma dose rates, logarithmic scale between 1 μSv/h and 2000 μSv/h

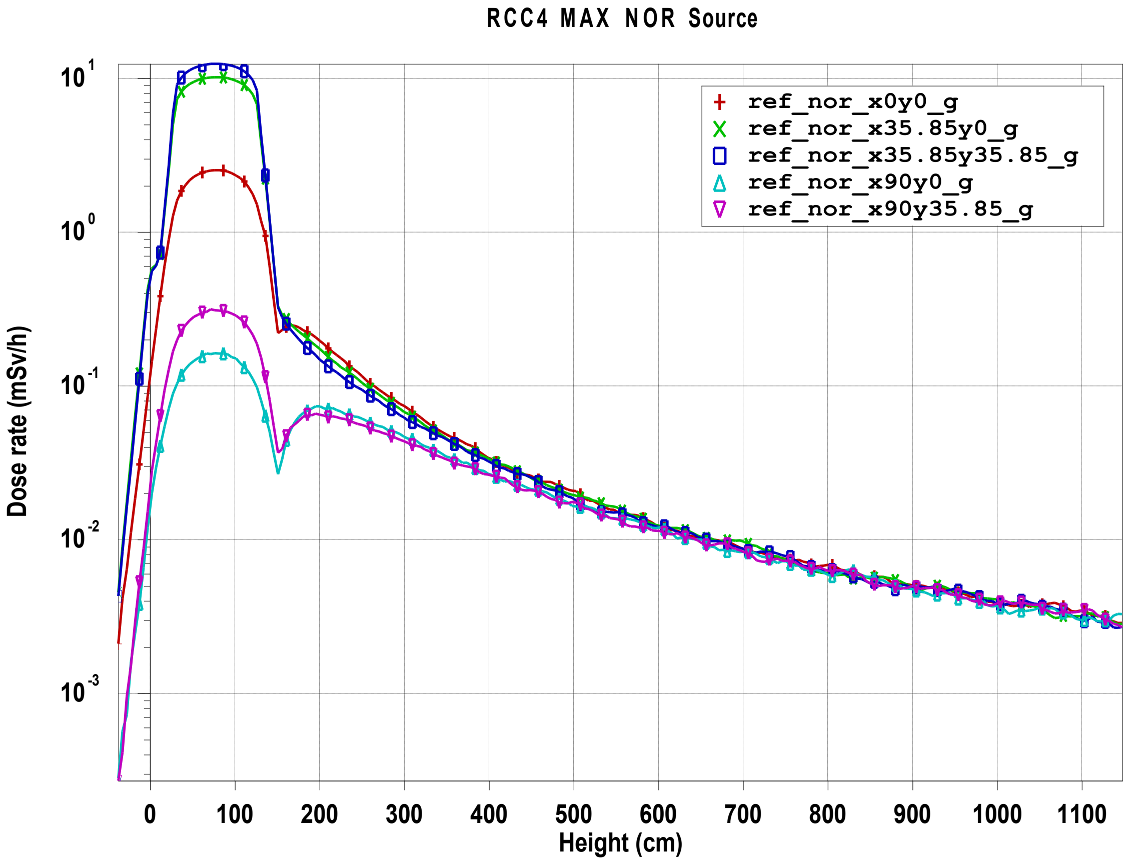


Figure 3 Gamma dose rates versus height for characteristic model points

Other curves are there to show change of dose rate along cask side and top surface. Top surface dose rate is slightly higher, and side dose rate distribution shows clear influence of drum position.

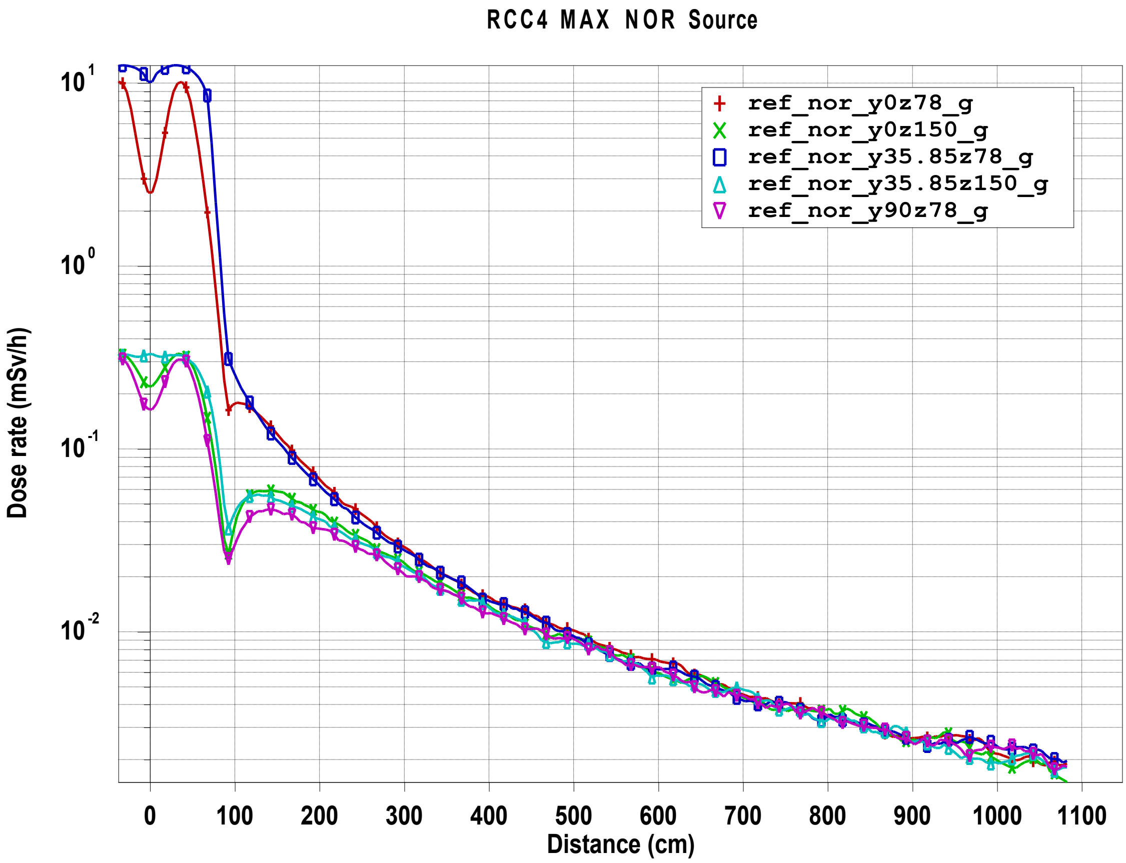


Figure 4 Gamma dose rates versus x-distance for characteristic model points

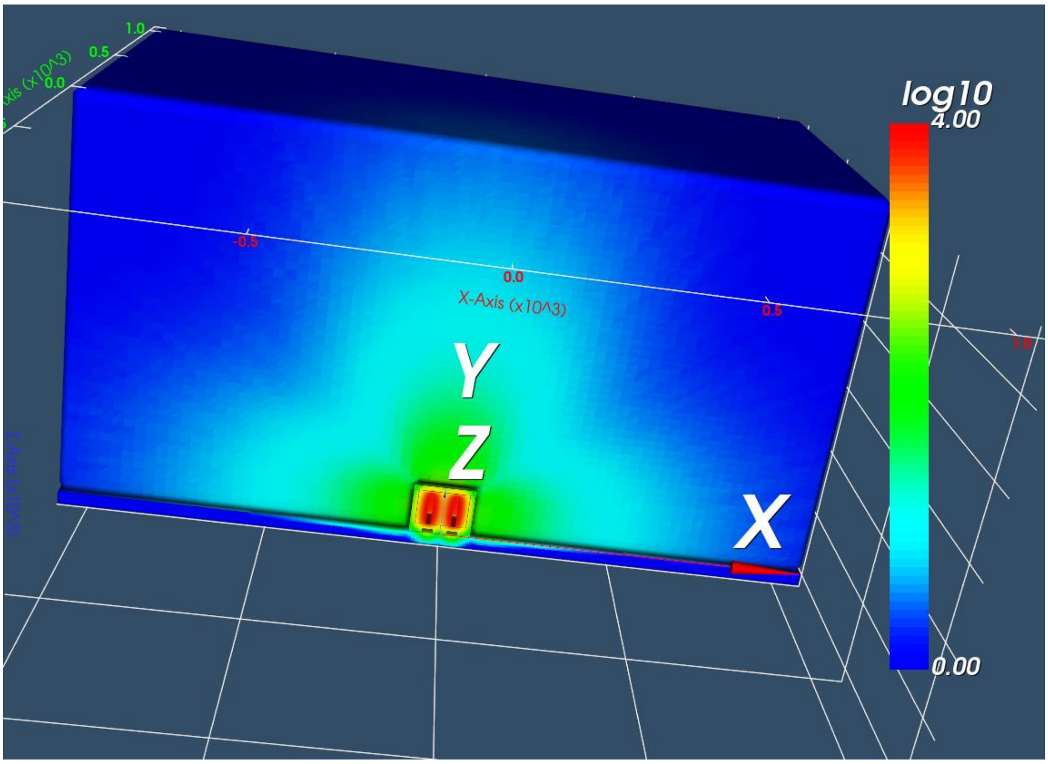


Figure 5 Gamma dose rates in model x-z plane, logarithmic scale 1 μSv/h to 10000 μSv/h

The 3D distribution of gamma dose rate in the model ZX plane is shown in Figure 5. The logarithmic scale was used, and the range is limited to 1 to 10000 μSv/h. As already shown, near the RCC side surface, the maximum dose rate is expected at the drum symmetry line, however, further from the RCC, the maximum is in the RCC symmetry line, or the difference is very small. Characteristic shape of dose rate isolines can be seen around the cask and above it. Gamma radiation is penetrating the ground surface, meaning that attention should be paid to the increased dose rates below the cask during manipulations that include cask lifting. The lowest dose rates are at the corner edges of the RCC due to larger distance that gammas pass through the cement filling and concrete body.

To address different types of sources (maximum non-resin source, maximum resin source and average source) in base geometry, Table 2 shows gamma dose rates at point detector tally locations for different sources. The maximum dose rates are obtained for the resin source due to highest activity and highest intensity, followed by maximum non-resin source and average source. The results for non-resin and average source are below regulatory requirements. However, for the resin source, gamma dose rates at the side surface are 2.78 mSv/h and 5.85 mSv/h, and at 2 m away from the side surface gamma dose rates are 0.54 mSv/h and 0.51 mSv/h. These results are higher than the regulatory limit so it is important to note that the assumed amount of activity cannot be placed in one RCC. Based on the limiting surface dose rate, only 34 % of maximum activity can be placed in RCC and based on the dose rate at 2 m distance only 18 % of maximum activity.

Table 2: Comparison of gamma dose rate [mSv/h] for maximum non-resin, resin and average source at point detector tally side locations, drum mid height elevation z=78 cm

Tally	**Gamma dose rate [mSv/h] / uncertainty [%]**		
	Non-resin source	**Resin source**	**Average source**
5	1.6583E-01 / 0.36	2.7751E+00 / 0.41	5.5494E-02 / 0.50
15	1.7540E-01 / 0.08	2.9813E+00 / 0.10	6.0789E-02 / 0.11
25	7.6004E-02 / 0.03	1.3188E+00 / 0.03	2.7710E-02 / 0.06
35	3.1025E-02 / 0.04	5.3668E-01 / 0.05	1.1214E-02 / 0.04
45	3.3005E-01 / 0.27	5.8491E+00 / 0.29	1.2622E-01 / 0.32
55	2.5997E-01 / 1.08	4.5999E+00 / 1.44	9.7320E-02 / 0.12
65	6.9287E-02 / 0.05	1.2020E+00 / 0.05	2.5225E-02 / 0.04
75	2.9464E-02 / 0.05	5.1367E-01 / 0.05	1.0626E-02 / 0.06

The change of gamma dose rate with x-distance for three types of the source, along RCC symmetry line (y=0 cm) and drum symmetry line (y=38.85 cm) at elevation of drum mid height (z= 78 cm, expected maximum of axial distribution), is shown in Figure 6. At a distance of x=290 cm (2 m from the side surface) dose rate should be lower than 0.1 mSv/h. The calculated dose rate, as shown in the previous table is above 0.5 mSv/h. In Figure 7, x-dependency relevant for maximum surface dose rate determination is shown. The focus of the assessment is on the x-distance between 0 and 90 cm (half side of the cask). The line through the point y=35.85 cm, z=150 cm (cask top surface just above drum z-symmetry line) should contain top surface maximum, and line passing through point y= 90 cm, z= 78 cm (cask side at elevation of drum mid height) should contain side surface maximum. It can be seen that for maxium resin source both maximum values are above 5 mSv/h. Side dose rate distribution shows clear maximums at the point of the smallest distance between drum surface and cask wall. For two other source types there is no problem and both regulatory requirements are fulfilled.

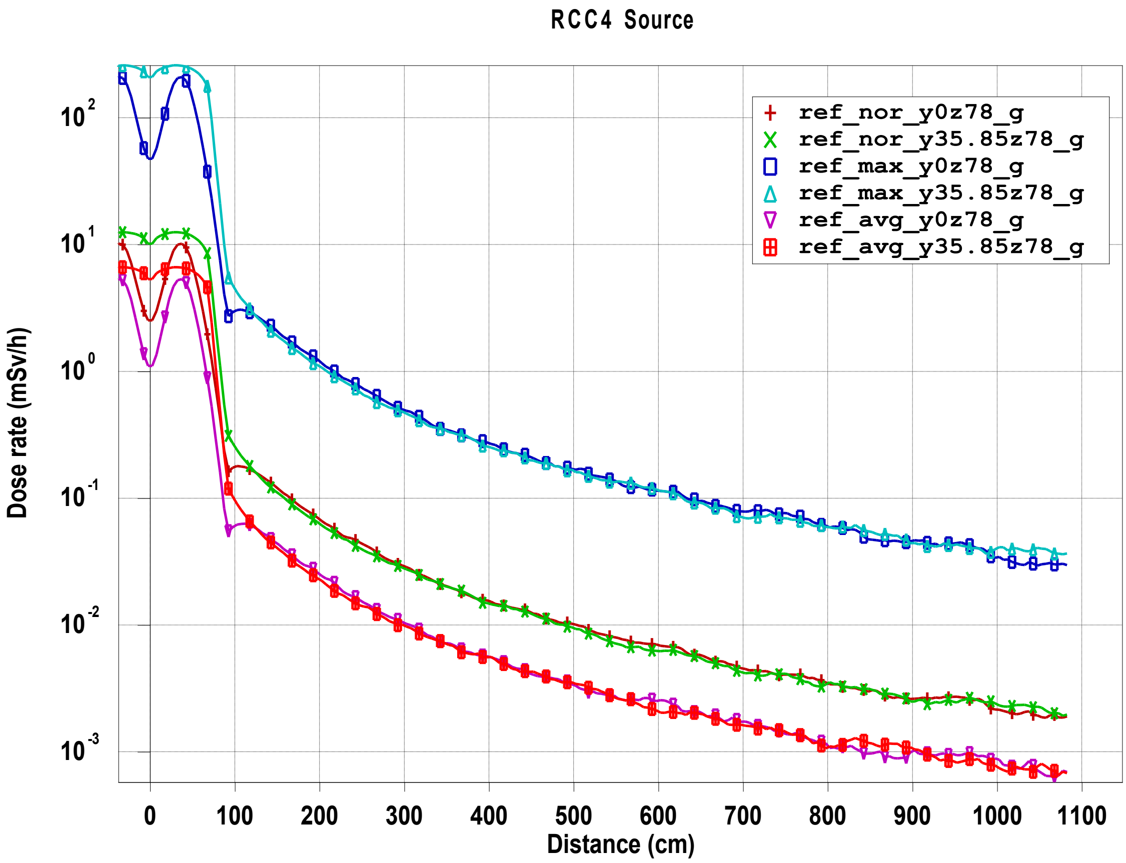


Figure 6 Gamma dose rates versus *x*-distance for characteristic model points

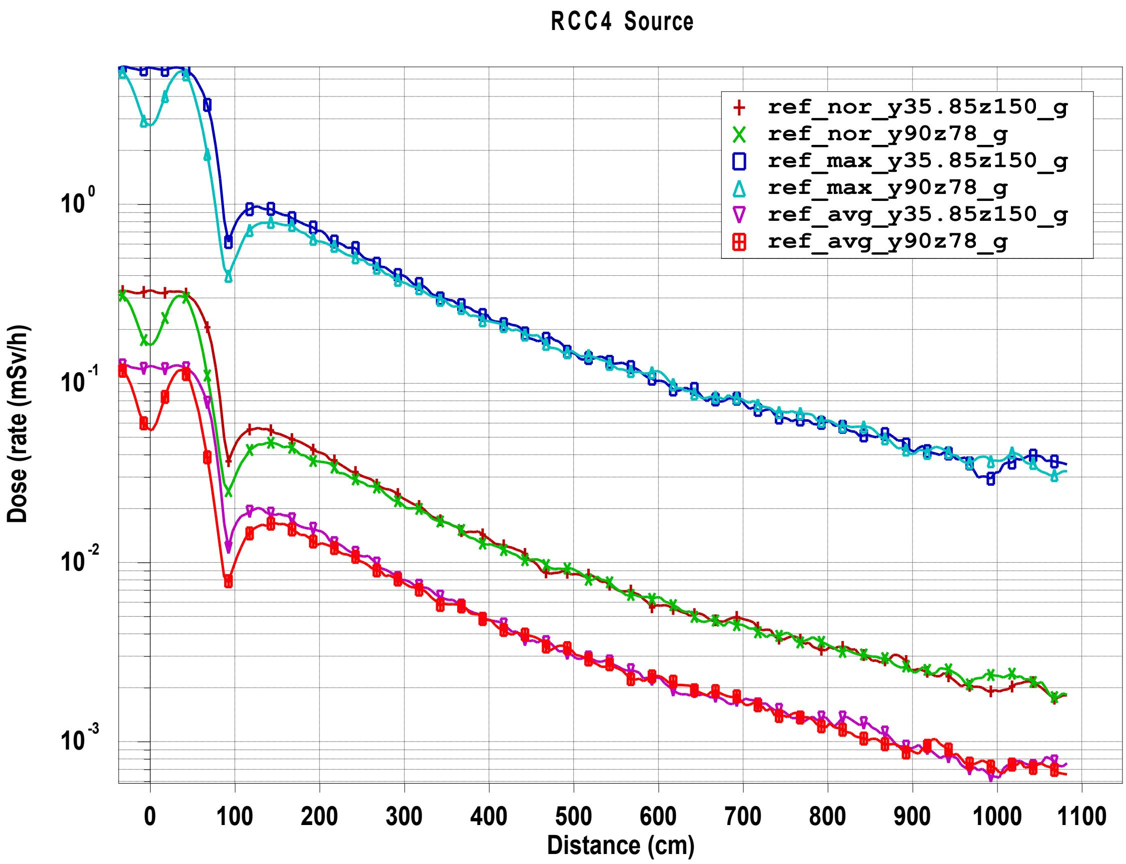


Figure 7 Gamma dose rates versus *x*-distance, RCC side and top surface

3.2 Reduced wall thickness

Furthermore, we investigated the impact of reduced RCC outer dimension (reduced wall thickness) on gamma dose rates around RCC. The comparison of gamma dose rates in reference case and reduced dimensions case is given in Table 3. The comparison was made for maximum non-resin source. Reduced RCC outer dimensions (by 5 mm, maximum assumed manufacturing tolerance) result in slightly higher gamma dose rates with the maximum relative difference of about 6.5 %. The increase is typically larger at the distance than on the RCC surface.

Table 3: Comparison of gamma dose rate [mSv/h] in reference case and in case of reduced RCC outer dimensions (reduced thickness), drum mid height elevation z=78 cm

Tally	Gamma dose rate [mSv/h] / uncertainty [%]		Relative deviation of gamma dose rate [%]
	Reference case	Reduced dimensions	
5	1.6583E-01 / 0.36	1.7278E-01 / 0.25	4.19
15	1.7540E-01 / 0.08	1.8676E-01 / 0.09	6.48
25	7.6004E-02 / 0.03	8.0226E-02 / 0.03	5.55
35	3.1025E-02 / 0.04	3.2740E-02 / 0.04	5.53
45	3.3005E-01 / 0.27	3.3868E-01 / 0.21	2.61
55	2.5997E-01 / 1.08	2.7438E-01 / 1.10	5.54
65	6.9287E-02 / 0.05	7.3146E-02 / 0.05	5.57
75	2.9464E-02 / 0.05	3.1103E-02 / 0.06	5.59

3.3 Reduced concrete and grout density

The influence of potential deviations in densities of concrete and cement mixture from original design values are addressed next. Table 4 shows comparison of gamma dose rates and associated uncertainties at point detector locations for base case and reduced density case. In reduced density case, everything is the same except densities of concrete and cement mixture which are reduced for 5 %. The comparison is again performed for maximum non-resin source. Material density reduction results in higher gamma dose rates expectedly. Relative deviations (increase) in gamma dose rates are in the range of 13 % to 19 %. In RCC symmetry plane the increase due to density reduction is larger at the surface and then it is decreasing. For drum symmetry plane the increase in dose rate is generally smaller, and it is slightly increasing with the distance. Clearly, at the larger distances the difference in dose rate increase is almost the same for both planes and it is around 14 %.

Table 4: Comparison of gamma dose rates [mSv/h] for the reference case and reduced-density of concrete and cement mixture, drum mid height elevation z=78 cm

Tally	Gamma dose rate [mSv/h] / uncertainty [%]		Relative deviation of gamma dose rate [%]
	Reference case	Reduced density	
5	1.6583E-01 / 0.36	1.9721E-01 / 0.33	18.92
15	1.7540E-01 / 0.08	2.0698E-01 / 0.57	18.00
25	7.6004E-02 / 0.03	8.6608E-02 / 0.03	13.95
35	3.1025E-02 / 0.04	3.5342E-02 / 0.03	13.91
45	3.3005E-01 / 0.27	3.7332E-01 / 0.27	13.11
55	2.5997E-01 / 1.08	2.9478E-01 / 1.20	13.39
65	6.9287E-02 / 0.05	7.8993E-02 / 0.06	14.01
75	2.9464E-02 / 0.05	3.3591E-02 / 0.05	14.04

In Figure 8 enlarged part of dose rates *x*-dependency is shown for reference case (label ref) and reduced density case (label red), at the drum mid height (*z*=78 cm). The first two curves in the figure are relevant for showing influence of material density decrease to increase of dose rates at the distance of 2 m from the cask surface (*x*=290 cm). The increase in dose rates is present for all curves. Close to the cask surface it is larger for RCC symmetry plane (*y*=0 cm) than for the drum symmetry plane (*y*=35.85 cm). The influence is rather large, at the distance, for the distributions on the side of RCC (*y*=90 cm), but these curves are mostly relevant for showing increase in the surface dose rates. The values at the distance are always lower for side curves than for the distant values on the cask and drum symmetry lines. In Figure 9 enlarged part of dose rates *z*-dependency is shown for reference case (label ref) and reduced density case (label red). The first two curves for both cases are to show influence at the distance from top surface (*z*=350 cm is 2 m from the top of the cask). The third curve for both cases is there to show increase in axial dose rate distribution on RCC side surface (*x*=90 cm). The influence of density reduction is larger at the distance than at the surface of the cask. The increase is combined influence of both grout and concrete density decrease. The combined thickness of the materials is the same for the whole top surface of the cask. For the side of the cask the influence of the reduction is smaller at the drum symmetry line where grout thickness is small.

3.4 Results verification using SCALE/MAVRIC

To verify obtained MCNP results, we also performed calculations using MAVRIC module from SCALE6.2.4. The comparison is made for the reference case with D6 drums and maximum non-resin source. For all detector locations, relative deviations of dose rates are within 5 %, what is expected difference for this type of calculation and demonstrates that MCNP results are valid. The increase of the difference with the distance is expected. It is not completely clear why we have increased difference in the predictions at the distance of 10 cm from the surface.

Table 5: Comparison of gamma dose rate [mSv/h] obtained using MCNP6 and SCALE for the reference case with D6 drums and maximum non-resin source, z= 78 cm

Tally	**Gamma dose rate [mSv/h] / uncertainty [%]**		**Relative deviation of gamma dose rate [%]**
	MCNP6	**SCALE**	
5	1.6583E-01 / 0.36	1.68570E-01 / 0.89	1.65
15	1.7540E-01 / 0.08	1.83305E-01 / 0.32	4.51
25	7.6004E-02 / 0.03	7.86491E-02 / 0.09	3.48
35	3.1025E-02 / 0.04	3.20041E-02 / 0.08	3.16
45	3.3005E-01 / 0.27	3.30368E-01 / 0.68	0.10
55	2.5997E-01 / 1.08	2.67952E-01 / 0.29	3.07
65	6.9287E-02 / 0.05	7.17343E-02 / 0.10	3.53
75	2.9456E-02 / 0.05	3.04074E-02 / 0.08	3.23

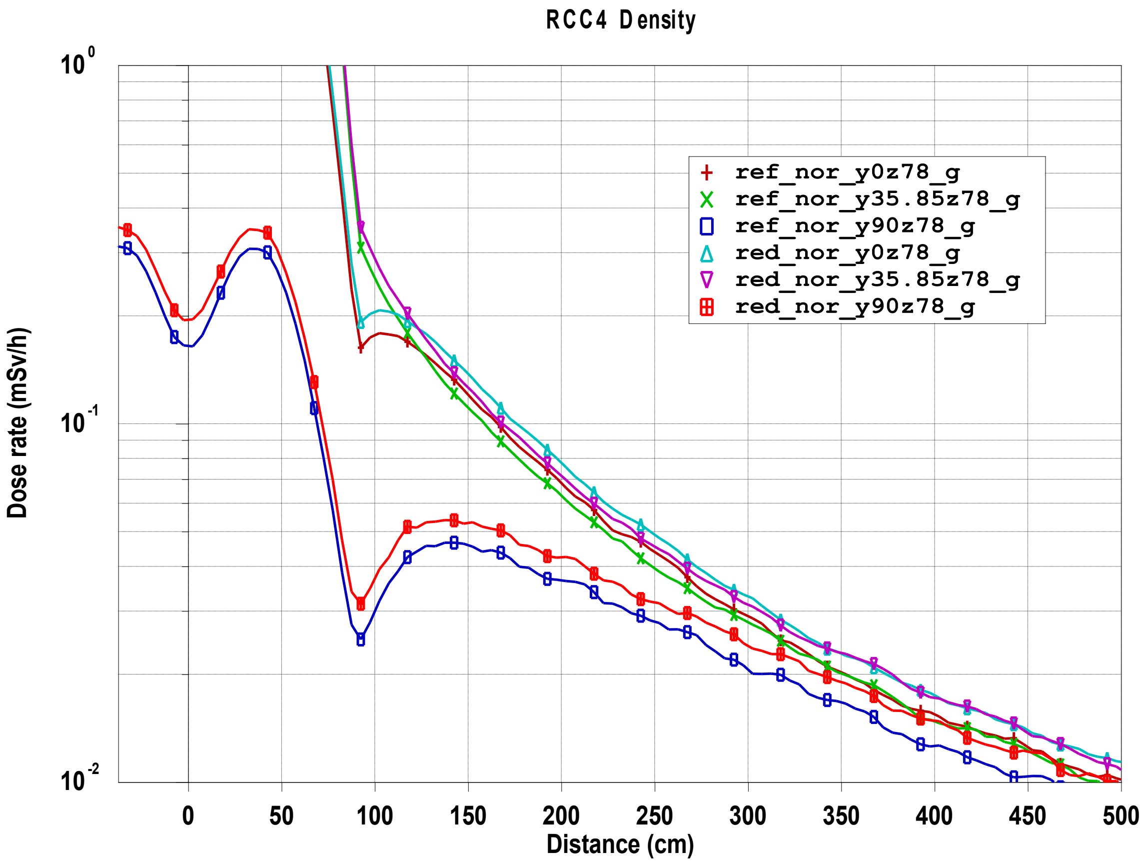


Figure 8 Gamma dose rates versus x-distance, reference and reduced density cases

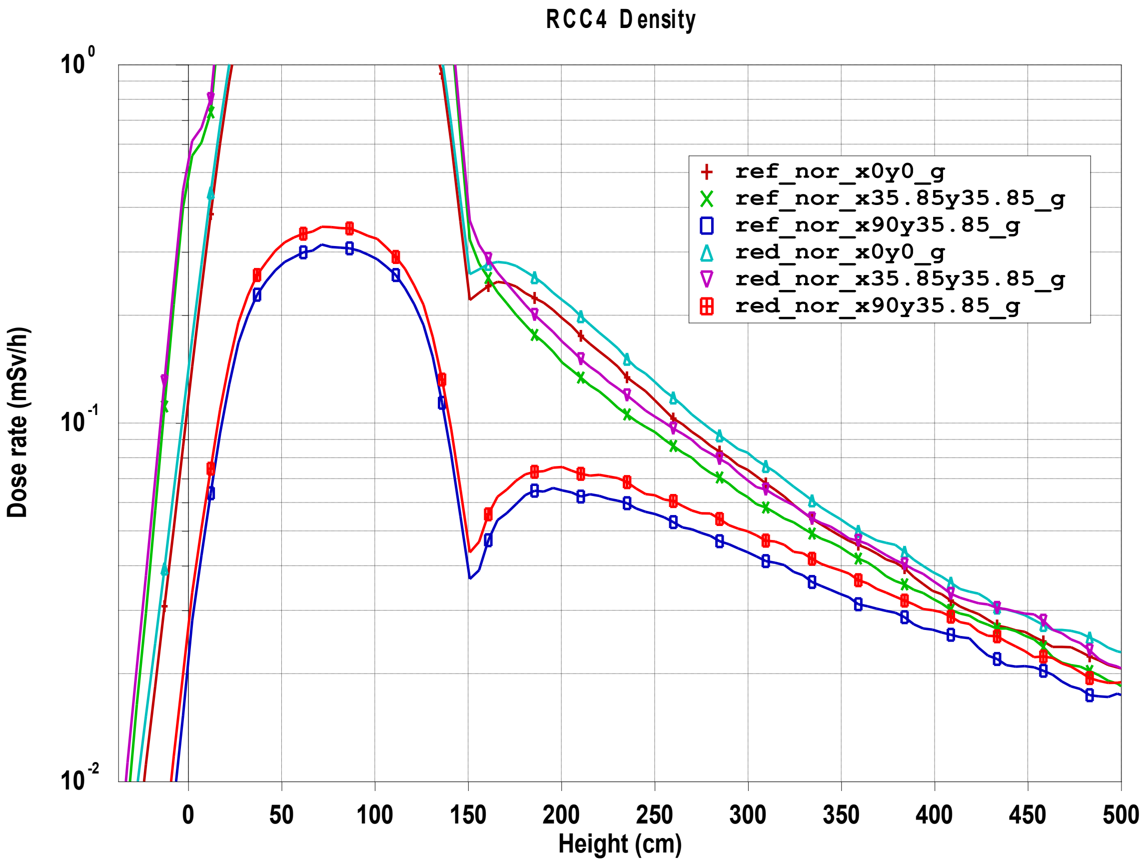


Figure 9 Gamma dose rates versus z-distance for characteristic model points

4 CONCLUSION

In this paper, RCC shielding capabilities are analyzed using MCNP code. Basic case according to design specifications and maximum non-resin source was considered first. The obtained dose rates for all detector locations were within the regulatory limit, and there were no outliers present at the side and at the top of the RCC. Three types of sources were compared (average source, maximum non-resin and maximum resin source). The results show that in case of the maximum resin source, dose rates surpass the regulatory limits and that that amount of activity cannot be placed in RCC. Only around 18 % of original D6 activity can be placed in single RCC. Potential deviations from the original design included reduced RCC wall thickness and reduced concrete and grout density. In case of reduced wall thickness, the relative deviation from the reference case is about 5 % and in case of reduced material density relative increase in dose rates are in the range of 13 % to 19 %. The increase in maximum dose rate is larger at the top than at the side of the cask. The maximum dose rates stay within regulatory limits for maximum non-resin and for average radioactive sources. Finally, to verify the obtained results, MAVRIC module from SCALE package was used to calculate dose rates for the reference case. The relative deviations between MCNP and SCALE gamma dose rates are within 5 %, what is acceptable for this type of the shielding calculation.

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