Calculation of radiation exposure of the environment of interim storage facilities for the dry storage of spent fuel in dual-purpose casks

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1 Introduction

Acceptance problems in the public concerning the transport of spent nuclear fuel elements and a new political objective of the Federal Government have forced the German utilities to embark on on-site interim storage projects for the temporary storage of spent nuclear fuel elements. STEAG encotec GmbH, Essen, Germany, was awarded contracts for the conceptual planning including necessary shielding calculations for the majority of the 13 nuclear sites which opted for the dry storage concept. The capacity of the storage facilities ranges from 80 to 100 casks, according to the storage needs of the plants. The average dose rate at the surface of each cask was limited to 0.5 mSv/h, independent of the type of radiation.

These new buildings should not significantly increase the exposure of the public to radiation already originating from the existing nuclear power plant. The layout of the storage building therefore has to ensure that additional target values of 10-20 µSv/y are not exceeded. These very low target values as well as the requirement to avoid high mechanical impacts to the casks in case of external events led to a thickness of walls and ceilings of between 1.2 m and 1.3 m. The layout of the storage building is shown in **Fig. 1**.

To remove the decay heat from the casks by natural convection sufficient cross sections of the air inlet and outlet ducts are required.

Taking into account the thickness of the walls and the ceiling it is obvious that the radiation in the environment is mainly determined by the radiation that is scattered through the openings of the building. Therefore a detailed geometry model had to be set up. Due to the size and the complexity of geometry, the Monte Carlo program MCNP [1] was used. Because of the high number of identical casks and in order to obtain reasonable computer runtimes, the calculations were executed in two steps. During the first step the energy distribution and the fluxes of neutrons and photons at the surface of the casks were calculated. The fluxes were normalized to the maximum value of the average surface dose rate (0.5mSv/h). In the second step dose rates at specific receiving points outside the building were calculated, using the source from the first calculation repeatedly at all cask positions in the storage building.

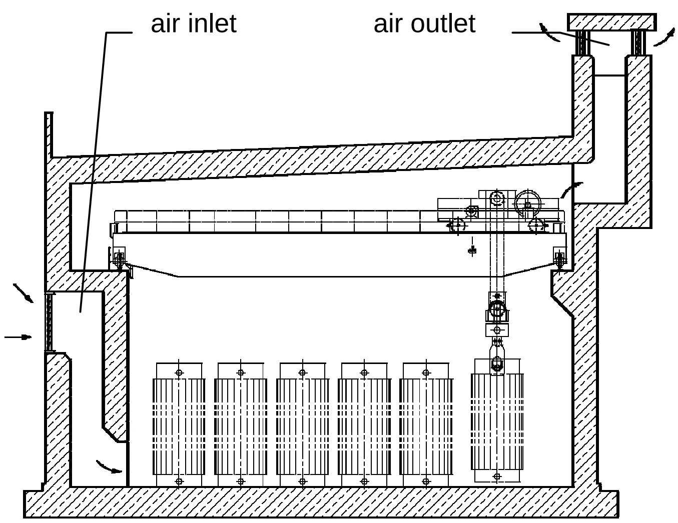


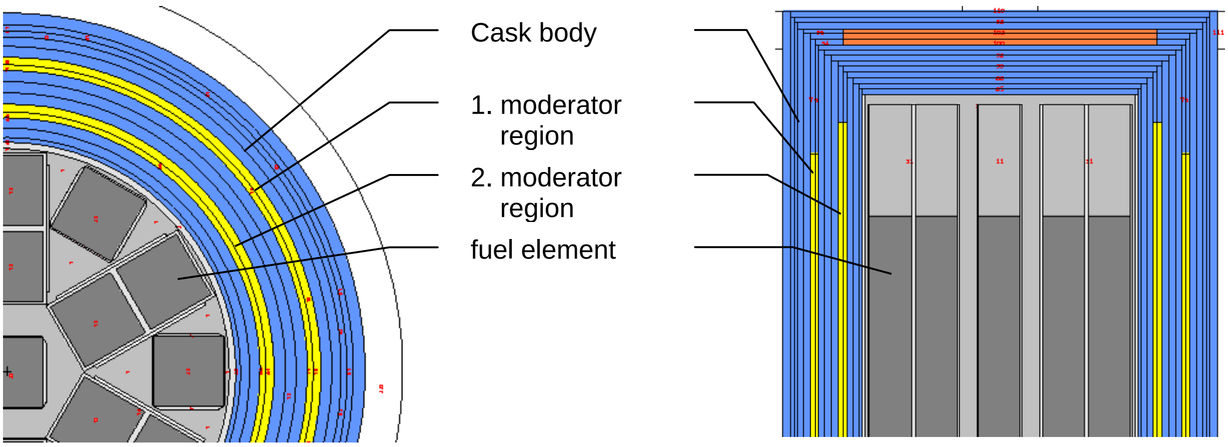
Fig. 1 Sectional view of the storage building

2 Setup of calculation model

The complete calculation model comprises the exact modeling of the source and the detailed geometry input for the storage building.

Calculation of Energy Spectrum and Source

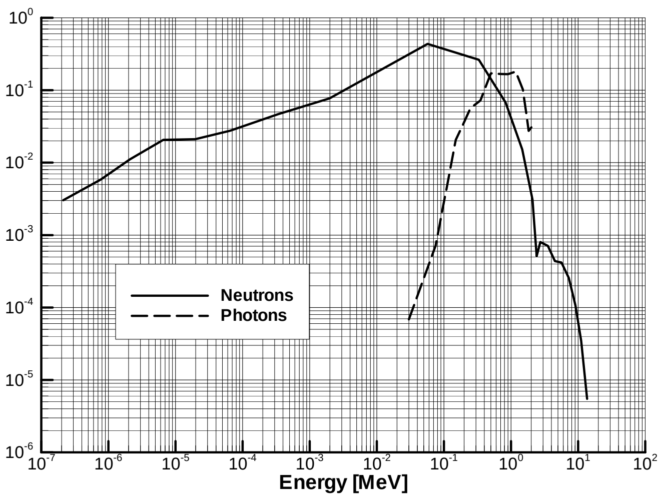
First the energy distribution and the fluxes of neutrons and photons at the surface of the casks had to be calculated. Therefore we had to set up a detailed cask model. From the various types of casks we chose a cask with an inner neutron-moderating region. Compared to the cask types with an outer neutron moderator region, this cask shows a harder neutron energy spectrum at the surface. The detailed cask model is shown in **Fig. 2**. The energy spectra of the primary neutron and photon sources were assumed to reflect a mixed load of uranium and MOX fuel elements with a burn up of 70 GWd/MTHM and a decay time of 5 years. The resulting energy spectra of photons and neutrons at the surface of the cask are shown in **Fig. 3**.



(a) Sectional top view (b) Sectional front view

Fig. 2 Detailed MCNP model of the cask

In order to satisfy the boundary condition of an average dose rate of 0.5 mSv/h at the cask surface, the primary neutron and photon source was normalized. To prevent future restrictions regarding the use of various types of casks, the shielding layout of the storage building had to take into account the full range of possibilities of the type and intensity of the radiation at the surface of the casks. So we performed all the calculations for two variants: 1) 100 % photon radiation; and 2) 100% neutron radiation at the surface of the casks, with each radiation type resulting in a dose rate of 0.5 mSv/h.



To obtain the normalization factors for the MCNP results we calculated the total fluxes at the surfaces of a single cask.

When using the Surface Source Read Card option of MCNP the particles that crossed the surface of the cask were recorded.

Fig. 3 Energy spectra of Photons and Neutrons at the Cask Surface

Modeling of the Storage Building

The particles reach the environment of the storage building mainly on three paths. The major part of the particles is scattered through the air inlets and outlets of the building. A smaller part scatters through the walls, as direct radiation to the receiving point. The minor part of exposure is caused by the skyshine effect. In order to avoid difficulties with the use of variance reduction techniques with these different paths we made up two different geometry models: 1) a simple model; and 2) a detailed model. Both geometry models were surrounded by air up to a height of 500 m. The ground was modeled as concrete with a density of 2 g/cm³.

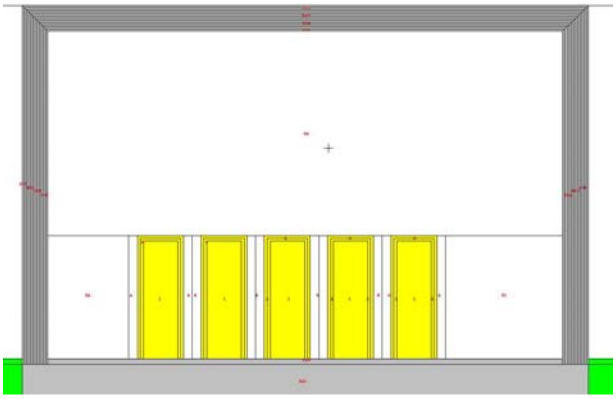


Fig. 4 Simple MCNP-model

Fig. 5 Detailed MCNP-model

1. Simple model. With the simple model shown in **Fig. 4** we calculated the effects of radiation going directly through the walls (including the scattering in the walls) as well as the effect of skyshine.

2. Detailed model. To enable the calculation of the radiation that is scattered through the openings of the building we set up the detailed model shown in **Fig. 5**. In the detailed model we artificially suppressed the particle transport through the walls by setting the program parameter "importance" to zero. To consider the radiation that is reflected at the walls, 25-cm thick concrete layers were defined at both sides of the walls and the ceiling. **Fig. 6** shows a 3-dimensional plot created by SABRINA [2] for checking the complex geometry of the MCNP-model.

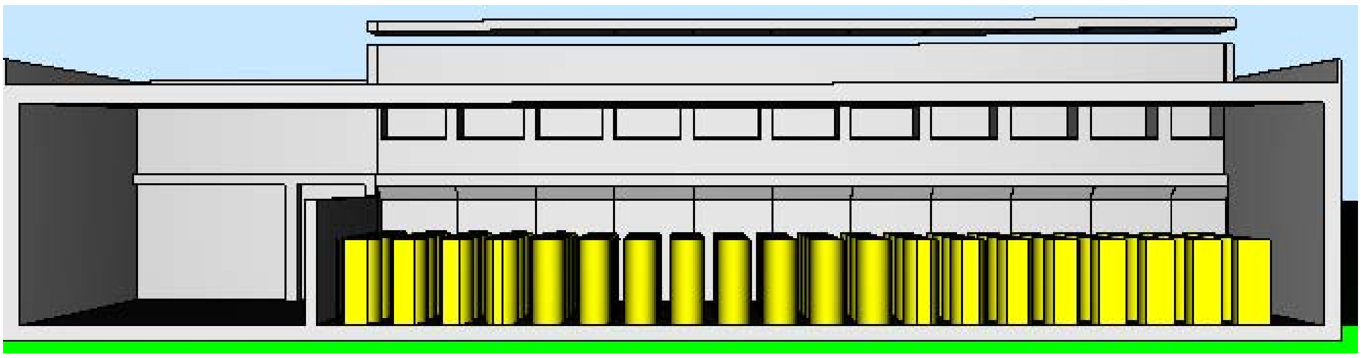


Fig. 6 SABRINA Plot from detailed MCNP-model

Modeling of the Casks within the Building

Within the building we used a simplified cask model with a surface source defined by two different ways in MCNP: 1) via the Surface Source Read Card; and 2) via the Source Definition Card. The simplified cask is a simple cast iron cylinder with two 12.5 cm outer layers to take into account reflections at the surface. Inside the cylinder we set the parameter "importance" equal to zero in order to avoid tedious particle tracking in these regions.

3 Results

To investigate the behavior of the radiation, a grid of 99 point detectors (**Fig. 7**) was defined in the surrounding area of the storage building. For each point detector, contributions from each individual geometry cell had to be defined. For simplification 12 different zones were determined, so that each detector of one zone had the same conservative contribution card. The weight-window generator was used to generate weights that were manually adjusted.

The following tables give the results of some representative receiving points outside the storage (1.5 m above ground) for the two calculated variants. The tally values give the dose rate per source particle

Point 1 lies in the longitudinal centerline at a distance of about 120 m from the outer wall of the facility. Points 2 and 3 lie on the centerline perpendicular to the main storage axis, at a distance of about 110 m in opposite directions. The results are shown by paths of the radiation.

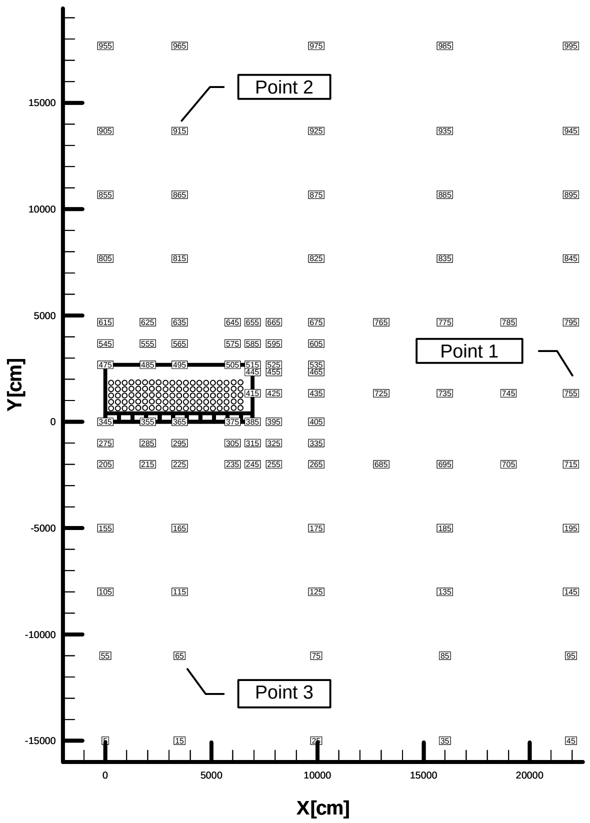


Fig. 7 Grid of 99 point detectors

Surface Source with 100% Photons

In this case the surface source consisted of photons with a spectrum as shown in **Fig. 3**.

Point	Path	Tally value mSv/h/particle	Dose µSv/y	Error
1	Scattered radiation	8.52E-22	7.05E-03	0.03
	Direct radiation and skyshine	1.70E-22	1.41E-03	0.04
	Total	1.02E-21	8.45E-03	
2	Scattered radiation	7.68E-21	6.36E-02	0.02
	Direct radiation and skyshine	5.15E-22	4.26E-03	0.04
	Total	8.19E-21	6.78E-02	
3	Scattered radiation	2.16E-21	1.79E-02	0.04
	Direct radiation and skyshine	5.64E-22	4.67E-03	0.05
	Total	2.72E-21	2.25E-02	

From the above values it can be seen that the photons scattering through the openings of the storage facility account for the major part of the total primary photon radiation.

Surface Source with 100% Neutrons

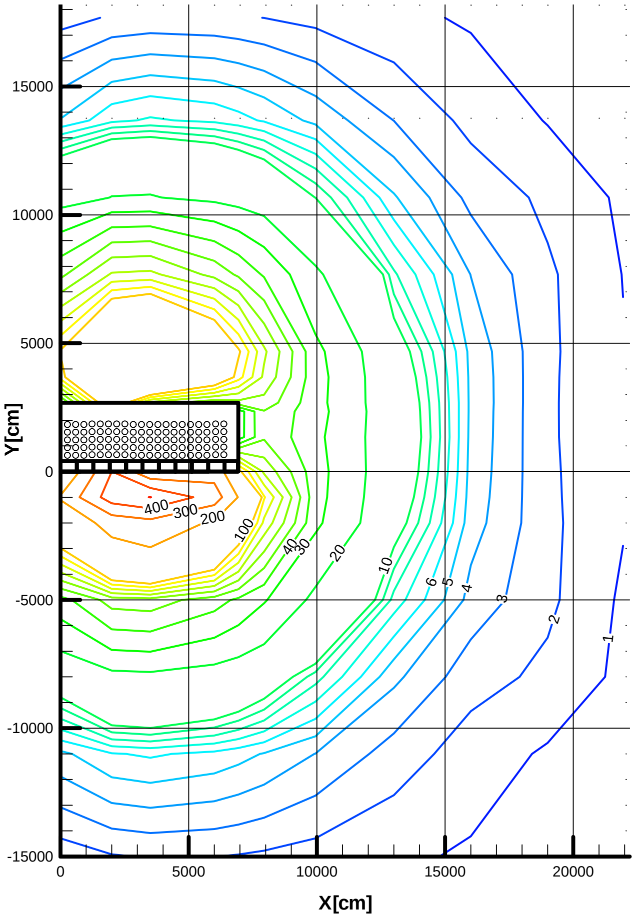
In this case the surface source consisted of neutrons only, the secondary photons from interactions of neutrons with the cask body were taken into account in the 100% photon source. The following table gives the results of the neutron calculation.

Point	Path	Tally value mSv/h/particle	Dose µSv/y	Error
1	Scattered radiation	4.78E-18	9.39E-01	0.02
	Direct radiation and skyshine	1.12E-19	2.20E-02	0.05
	Total	4.89E-18	9.61E-01	
2	Scattered radiation	3.24E-17	6.37E+00	0.01
	Direct radiation and skyshine	6.05E-19	1.19E-01	0.04
	Total	3.30E-17	6.49E+00	
3	Scattered radiation	2.58E-17	5.07E+00	0.02
	Direct radiation and skyshine	6.76E-19	1.33E-01	0.05
	Total	2.65E-17	5.21E+00	

As in the case with 100% photons, the neutrons that are scattered through the openings account for the major part of the total dose. The results of the calculation of the secondary photons from interactions with the building are as follows.

Point	Path	Tally value mSv/h/particle	Dose µSv/y	Error
1	Scattered radiation	7.37E-19	1.45E-01	0.01
	Direct radiation and skyshine	5.21E-19	1.02E-01	0.04
	Total	1.26E-18	2.48E-01	
2	Scattered radiation	5.11E-18	1.00E+00	0.02
	Direct radiation and skyshine	2.74E-18	5.39E-01	0.02
	Total	7.85E-18	1.54E+00	
3	Scattered radiation	4.37E-18	8.59E-01	0.02
	Direct radiation and skyshine	2.89E-18	5.68E-01	0.01
	Total	7.26E-18	1.43E+00	

For scattered radiation the dose rate contributions of the secondary photons are small compared to those of the neutrons. With increasing distance the contributions of the secondary photons become more important. At distances of more than some hundred meters the exposure due to photons will dominate. For direct radiation and skyshine the secondary photons contribute most to the total dose rate.



From the results it is obvious that the variant with a surface source of 100% neutrons produces the highest dose rates in the environment of the storage facility. For this case the results of a calculation of the dominating scattered radiation are shown as contour plots in **Fig. 8 and Fig. 9**.

The contour lines in **Fig. 9** show a reasonable behavior although a part of the tallies did not pass all of the 10 statistical checks. As can be seen in the plot, the annual dose shows a clear maximum on both sides of the storage building, resulting from the air inlets and outlets respectively.

At the small side of the building it is interesting to see that the neutrons disperse in a diffusional behavior. At a distance greater than about 80 m the dose rate is completely homogeneous with respect to the angle.

Fig. 8. Contour plot of the annual dose rate [µSv/y] due to the scattered radiation of neutrons

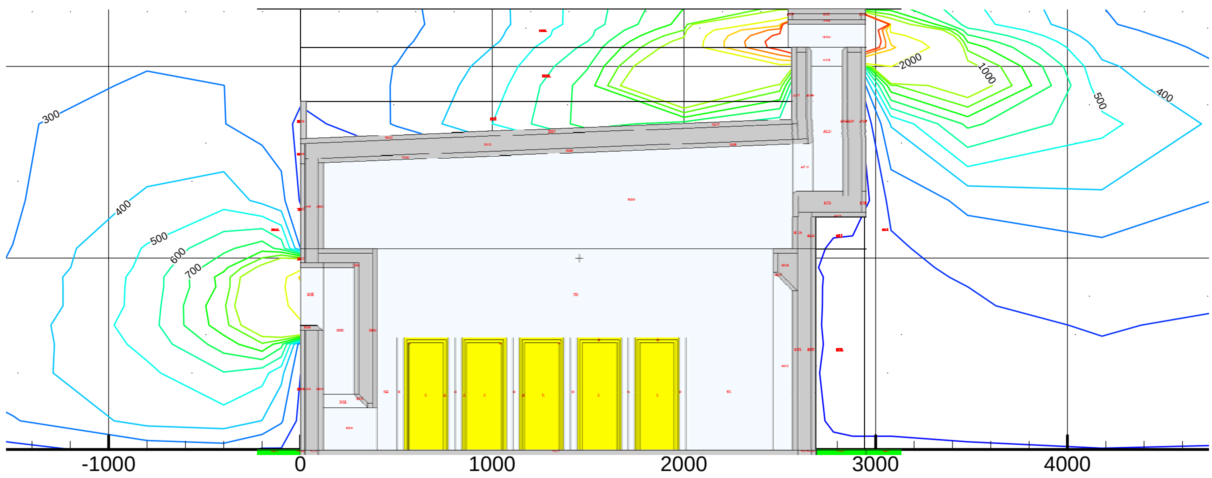


Fig. 9. Contour plot of the annual dose rate [µSv/y] due to the scattered radiation of neutrons; side view

The energy spectrum of the neutrons outside the storage facility is clearly shifted to lower energies as can be seen in **Fig. 10**. This means that low-energy neutrons resulting in the described behavior mainly determine the dispersion of neutrons outside the building.

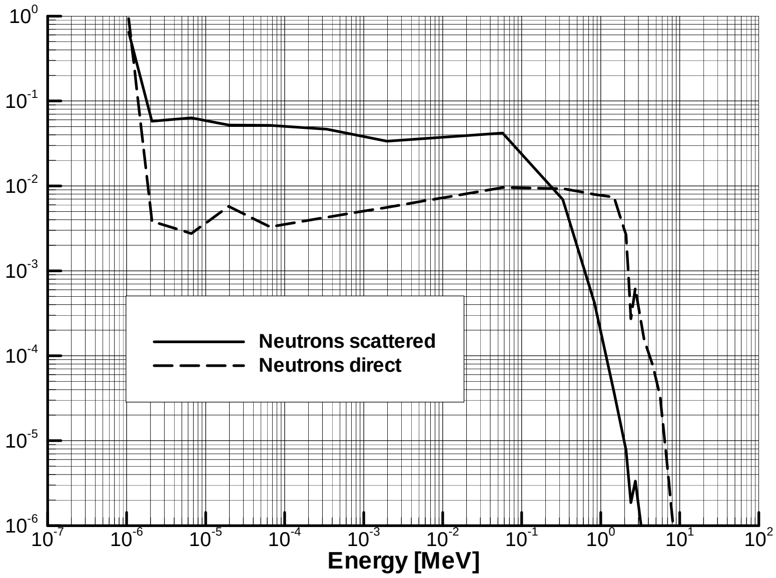


Fig. 10. Energy spectrum of neutrons outside the storage facility

4 Summary

The calculation of the radiation exposure of the environment included both the particle transports through the shielding of the casks and the particle transport through the walls and the ceiling as well as the scattering through the openings of the building. MCNP turned out to be the only applicable tool for calculating dose rates for our complicated geometries and extended sources. Splitting the problem in two steps was necessary to obtain reasonable results within acceptable computer runtimes. The calculation of a 99-point grid of point detectors and the visualization of the obtained results in a contour plot provides additional information to evaluate the quality of the calculated tallies and proved to be helpful to get an overview of the local distribution of the dose rate.

References

[1] Judith F. Briesmeister, *"A General Monte Carlo N-Particle Transport Code"*, Version 4B, LA-12625-M, Los Alamos National Laboratory, March 1997

[2] SABRINA Version 4.13
White Rock Science and The University of California