17th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 May 2016, Budapest, Hungary

VALIDATION OF THE GAMMA SUBMERSION CALCULATION OF THE REMOTE POWER PLANT MONITORING SYSTEM OF THE FEDERAL STATE OF BADEN-WÜRTTEMBERG

Janis Lapins[1], Wolfgang Bernnat[2], Walter Scheuermann[2]

[1]Institute of Nuclear Technology and Energy Systems, Pfaffenwaldring 31, University of Stuttgart, Stuttgart, Germany
[2]KE-Technologie GmbH, Stuttgart, Germany

Abstract: The radioactive dispersion model used in the framework of the remote nuclear power plant monitoring system of the federal state of Baden-Württemberg applies the method of adjoint fluxes to calculate the sky shine from gamma rays with a regarded gamma energy spectrum for nuclides released. The spectrum is represented by 30 energy groups of the released nuclides. A procedure has been developed to calculate the dose distribution on the ground in case of an accident with a release of radioactivity. For validation purposes, the results produced with the adjoint method in the dispersion code ABR are compared to results produced by forward calculations with Monte Carlo methods using the Los Alamos Code MCNP6.

Key words: *adjoint method, MCNP, validation, gamma submersion*

THE MODULAR DISPERSION TOOL "ABR"

The federal state of Baden-Württemberg, Germany, operates a remote power plant monitoring system that has an online access to the main safety relevant parameter of the power plant as well as the meteorological data provided by the German weather forecast service (DWD). The data are sent to a server system that is operated for the Ministry of Environment of the federal state. The radioactive dispersion tool "ABR" is an integral part of this system and is used for calculation of radiological consequences in case of an accident, or to prepare and to perform emergency exercises for the civil protection. For a dispersion calculation, the ABR has to account for the following:

- Interpolation of forecasted or measured precipitation to grid (precipitation module)
- Calculation of the wind field from forecast or measurement on grid (terrain-following wind field module)
- Release of the amount of radioactivity to the environment accounting for decay time of nuclides between shutdown of the reactor and the time of emission (release module)
- Transport of radioactivity with wind, also washout and fallout due to deposition or rain, respectively (Lagrange particle transport module)
- Sky shine to a detector 1 m above the ground (sky shine module)
- Calculation of the doses from various exposure paths (gamma submersion, beta submersion, inhalation and ground shine) and for 25 organs and one effective dose (dose module)

All of this is performed by the different modules of the programme system mentioned above. However, this paper will focus on the validation of the sky shine module in conjunction with the dose module which calculates the gamma submersion by the method of adjoint fluxes [1]. For validation, the reference code system MCNP6 [2] is used. Results produced with ABR are benchmarked against it.

METHOD OF CALCULATION

The dose calculation is performed applying the method of adjoint fluxes to calculate the gamma cloud radiation with a regarded gamma ray energy spectrum for nuclides released comprising 30 energy groups. This procedure enables an efficient algorithm to calculate the dose rates or integrated doses in case of an accident with a release of radioactivity. The system is part of the emergency preparedness and response and is in online operational service. The adjoint fluxes were produced by results from MCNP6 [2].
For validation purposes, the results produced with the adjoint method in the dispersion code ABR are compared to results produced by forward calculations with Monte Carlo methods using MCNP6. The

computational procedure comprises the following steps: From a point or a volume source, respectively, photons are started isotropically for average energies of the 30 energy groups or distinctive gamma spectrum for single nuclides. Travelling through space, these photons collide with nuclides present in air or the ground and are scattered until they reach the detector. With the help of point detectors, the flux density spectrum can be estimated, and, by making use of a dose-flux-relation, the resulting gamma submersion dose on the ground can be determined.
The backward method in the ABR uses the adjoint fluxes to evaluate the influence of a certain nuclide (spectrum) in the cloud at a certain distance from a detector point on the ground. To obtain these adjoint fluxes, a large number of calculations has been performed to determine the adjoint flux for all energy groups and distances (radii). The radii for which the fluxes were produced are support points. Radii between support points are interpolated. Depending on the energy of the group under consideration there are different exponential fitting functions that account for both energy and distance. The energy deposited within human tissue is accounted for by age classes and by use dose factors from the German Radiation Protection Ordinance that provide dose factors for organs and effective dose [5].

SOLUTION OF THE TRANSPORT EQUATION
The transport equation in operator notation is

$$M\Phi = Q \tag{1}$$

with

$$M = \vec{\Omega} grad + \Sigma_T(E) + \iint_{\vec{\Omega}'E'} \Sigma_s(\overrightarrow{\Omega'} \to \vec{\Omega}, E' \longrightarrow E) dE'\, d\Omega' \tag{2}$$

In equation (1) above $Q(\vec{r},\ \vec{\Omega}, E)$ represents the source vector and $\Phi(\vec{r},\ \vec{\Omega}, E)$ represents the flux density vector which both depend on the location $\vec{r}$, the direction $\vec{\Omega}$, and the Energy E. In equation (2) the first term represents the leakage term, $\Sigma_T(E)$ represents the collision, and the integral represents the scattering from any direction $\overrightarrow{\Omega'}$ and energy E' into the direction $\vec{\Omega}$ and energy E of interest.
After solution of the transport equation reaction rates, e.g. dose rates $\overline{D}$ can be calculated with the help of a response function $R(\vec{r}, E)$ such that the condition

$$\overline{D} = \langle \Phi R \rangle = \int_V \int_E \Phi(\vec{r}, E)\, R(\vec{r}, E) dr dE \tag{3}$$

is valid. The adjoint equation to the equation (1) is

$$M^+\Phi^+ = R \tag{4}$$

The adjoint equation has to be defined in a way that the condition

$$\langle \Phi^+ M \Phi \rangle = \langle \Phi M^+ \Phi^+ \rangle \tag{5}$$

holds. If this is the case, the following is also valid:

$$\overline{D} = \langle \Phi^+ M \Phi \rangle = \langle \Phi^+ Q \rangle = \langle \Phi M^+ \Phi^+ \rangle = \langle \Phi R \rangle = \overline{D} \tag{6}$$

I.e. instead of eq. (1), the adjoint function eq. (4) can be solved and the reaction rates are determined by eq. (3). The solution of the adjoint transport equation provides a relation between photon emission of a certain energy/energy range of a point/volume regarded and the dose at a computational point.

CALCULATION OF ADJOINT FLUXES WITH MCNP
The calculation of the gamma submersion as a consequence of radioactive nuclides in the radioactive cloud can be achieved if the spatial and energy distribution of the gamma sources in relation to certain computational points at the ground are known, together with the composition of air and soil. The computation necessitates the solution of the photon transport equation with respect to the energy dependence of the possible reactions of photons with atoms in air or soil (photo-electrical effect, Compton effect, pair production effect etc.). The solution of the transport equation yields photon spectra for computational points that enable dose calculations. Relevant dose/flux relations are defined by ICRP, [3]. For photons ICRP 74 can be applied. The dose/flux relation is presented in **Figure 2**. With Monte Carlo codes with their continuous energy dependence of the cross sections, a direct solution of the adjoint transport equation is not possible. Nevertheless, these codes can be used to estimate the contribution of a source point/volume to the dose at a computational point, see **Figure 1**. To do this, the source

point/volume a sufficiently great number of photon trajectories have to be simulated and their contribution to the dose is calculated. Computing the dose rates at a computational point of interest, the relevant contributions from all source points/volumes of the whole emission field have to be summed up such that the dose at the computational point (x, y, z) can be estimated with

$$D(x,y,z) = \sum_q \sum_g \Phi_g^+ \left(r_q, z_q - z\right) \cdot Q(x_q, y_q, z_q) \cdot V_q \tag{7}$$

with

$$r_q = \sqrt{\left(x_q - x\right)^2 + (y_q - y)^2} \tag{8}$$

Φ_g^+ as the adjoint flux depending on the radius and the height, Q_g as specific source concentration and V_q as the volume that contains the concentration.

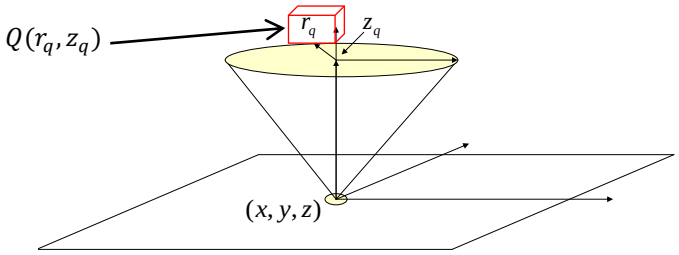

Figure 1. Source point/volume $Q(r_q, z_q)$ and computational point of interest $P(x, y, z)$ in dose calculations

The index q corresponds to the source; the index g corresponds to the energy group or the gamma line of the source of the photon emission energy. The coordinates x, y, z correspond to the computational point of interest. The coordinates x_q, y_q (resp. r_q), z_q correspond to the centre point of the source volume V_q, see Figure 1.

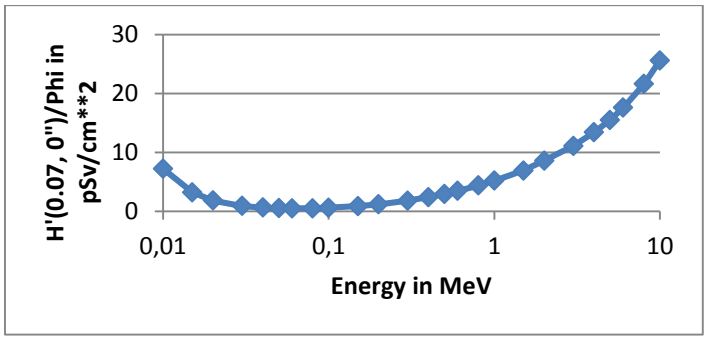

Figure 2. Dose/flux relation for gamma energies from 0.01 – 10 MeV in 0.07 cm depth of the body according to ICRP 74 [3]

2 SCENARIOS FOR DOSE COMPARISONS: A HOMOGENEOUS AND A NON-HOMOGENEOUS RADIOACTIVE CLOUD OF REFERENCE NUCLIDES

For comparison of the results of the gamma submersion dose rates, two scenarios have been defined. The base scenario assumes a homogeneous concentration distribution of three reference nuclides Xe-133, Cs-137 and I-131 with a flat topography both for the ABR and MCNP, respectively. There is no use of the dispersion module of the ABR, but the concentrations are artificially input into the sky shine and dose modules of the ABR. The computational domain and the boundary conditions for this scenario are presented in Table 1. A sketch of the scenario is shown in Figure 5.

An advanced scenario with a 3-D cloud is also presented. For this scenario, a realistic concentration distribution has been generated with the ABR, i.e. the release height of 150 metres with a wind speed of 4 m/s at 10 m height and increasing wind speed with the height for diffusion category D (neutral conditions). The released activity is transported with the wind. After one time step the doses are compared. Since the MCNP cannot simulate the transport of radioactive particles with the wind, the distribution of concentration of the isotope regarded is imported to MCNP via an interface. The results for the dose calculation are also compared. The radioactive cloud together with the wind speed is presented in

Figure 6. For this paper, the shape of the cloud is regarded as given as the dose rates are subject to comparison and not the cloud shape. The boundary conditions and general assumptions for this case is given in Table 2

The gamma lines of the reference nuclides are shown in **Figure 3** and **Figure 4**, [4]. These gamma emissions are accounted for in the 30 group spectrum of the ABR with their respective intensity. For the MCNP calculation, the gamma energies and their respective intensity are directly input.

Table 1.Simulation set-up for homogeneous cloud from 120 – 160 m

Constant source	ABR	MCNP6
Computational area (x, y, z)	20 km x 20 km x 1 km	20 km x 20 km x 1 km
Mesh number (x, y,z)	100 x 100 x 25	-
Mesh size in x, y, z - direction	200 m , 200 m, 40 m	-
Cloud height	120 – 160 m	120 – 160 m
Activity in cloud [Bqm^{-3}]		
Cs-137	6.0E+04	6.0E+04
Xe-133	2.0E+10	2.0E+10
I-131	1.0E+06	1.0E+06

Table 2. Simulation set-up for a non-homogeneous cloud

Realistic source	ABR	MCNP6
Computational area (x, y, z)	20 km x 20 km x 1 km	20 km x 20 km x 1 km
Mesh number (x, y,z)	100 x 100 x 25	100 x 100 x 25
Mesh size in x, y, z - direction	200 m , 200 m, 40 m	200 m , 200 m, 40 m
Emission height	150 m	150 m
Total activity released [Bq]		Activity imported via interface
Cs-137	6.0E+09	6.0E+09
Xe-133	2.0E+17	2.0E+17
I-131	1.0E+10	1.0E+10
Wind speed in 10 m height	4 m/s	-
Diffusion category	D	-
Emission duration	1 hour	-

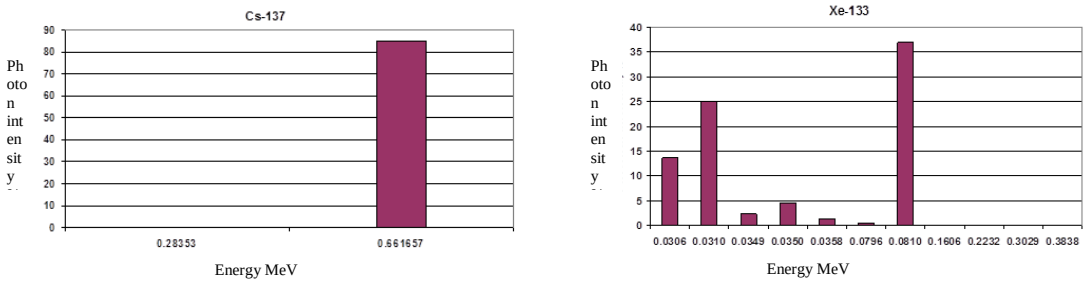

Figure 3. Gamma lines and intensities of Cs-137 and Xe-133 (NUDAT 2.6) [4]

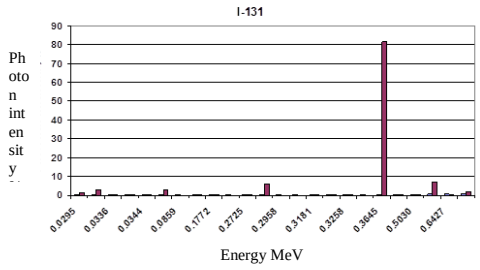

Figure 4. Gamma lines of I-131 (NUDAT 2.6) [4]

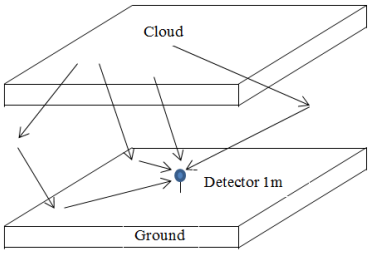

Figure 5. Sketch of the scenario with homogeneous emission layer and exemplary paths from the cloud to the detector (direct, indirect via air and ground reflection, or both)

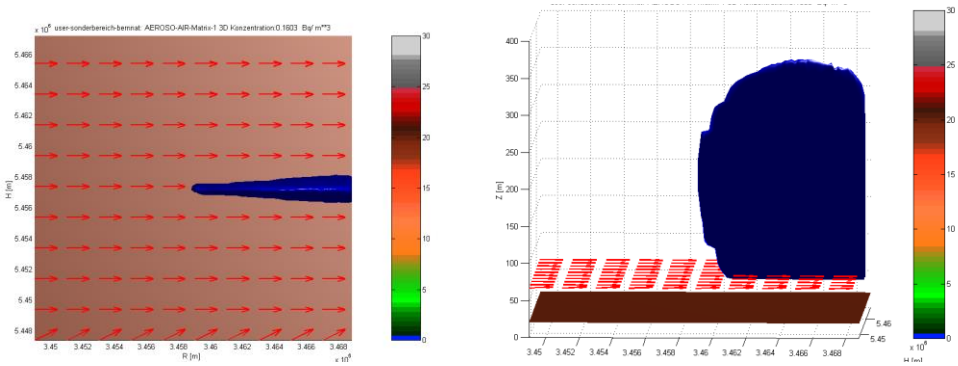

Figure 6. Non-homogeneous distribution of aerosoles after 1 hour with a wind speed of 4 m/s at a height of 10 m simulated with the ABR. The concentration is exported to MCNP

RESULTS OF COMPARISON

The results of the comparison are presented in the tables below. One can see that the results are in good agreement for the three reference nuclides.

Table 3. Results for the base case with homogeneous cloud

Nuclide	MCNP6 [Sv/h]	ABR [Sv/h]	Ratio ABR/MCNP6
Cs-137	9.31E-07	8.33E-07	0.89
Xe-133	1.36E-02	1.30E-02	0.96
I-131	1.01E-05	1.03E-05	1.02

Table 4. Results for the advanced case with non-homogenous cloud

Nuclide	MCNP6 [Sv/h]	ABR [Sv/h]	Ratio ABR/MCNP6
Cs-137	1.42E-10	1.36E-10	0.96
Xe-133	4.49E-04	4.9E-04	1.09
I-131	1.49E-10	1.57E-10	1.05

CONCLUSION

The results for the comparison of gamma submersion dose rates show that there is good agreement between the ABR and MCNP6 for the cases analysed. It could be shown that for all three reference nuclides the maximum deviation for the dose rate of Cs-137 is -11% for the base case.

For the non-homogenous distribution of the concentration for the reference nuclides the agreement is better than 10%. Keeping in mind that for a real dispersion calculation there are a multitude of uncertainties, e.g. emitted nuclide vector, meteorological prediction, transport of cloud, this agreement presented for the comparison of the dose rates for the reference nuclide each can be regarded as excellent.

REFERENCES

[1] Sohn, G. Pfister, W. Bernnat, G. Hehn: Dose, ein neuer Dosismodul zur Berechnung der effektiven Dosis von 21 Organdosen für die Dosispfade Submersion, Inhalation und Bodenstrahlung, IKE 6 UM 3, Nov. 1994.

[2] D. B. Pelowitz: MCNP6™ User's Manual Version 1.0 LA-CP-13-00634, Rev. 0 (2013)

[3] ICRP, 1996: Conversion Coefficients for use in Radiological Protection against External Radiation. ICRP Publication 74, Ann. ICRP 26 (3-4).

[4] NUDAT 2.6, National Nuclear Data Centre, Brookhaven National Laboratory.

[5] Entwurf zur AVV zu §47 Strahlenschutzverordnung, Anhang 3 (German: General Administrative Regulation for §47 of the German Radiation Protection Ordinance, Appendix 3), (2005).