Shielding Analysis of a Transport and Storage Cask for Spent BWR Fuel Applicability of the Code SAS4 and Discussion of Results

Franz Hilbert (1), Makoto Morishima (2), Hiroki Tamaki (2)

(1) Nuclear Cargo + Service GmbH, Hanau
(2) Mitsubishi Heavy Industries, Kobe

1. Introduction

For the shielding analysis of transport and storage casks for spent fuel the use of computer codes is state of the art. However, in most applications the computer models used for the analysis are simplified to circular geometries to save modelling effort and calculation time. Furthermore, the active zone of the fuel is modelled as homogeneous zone with a uniform average burn-up. In the first part of the present paper it is shown that an exact model is feasible and the effect of the geometrical shape on the dose rates is illustrated. The second part of the paper shows the comparison of the dose rates calculated with 5 different fuel models. Finally, the accuracy of the calculations is discussed.

2. Design of the Transport and Storage Cask

The transport and storage cask consists of a cask body and primary and secondary lids made of forged steel. For shielding purposes a layer of neutron shielding covered by a steel sheet is present around the cask body. During transport the bottom and the lid side are covered by shock absorbers made of wood in a steel casing. The BWR fuel assemblies are positioned inside the cask cavity in aluminium tubes. Fig. 1 shows the basic design of the transport and storage cask.

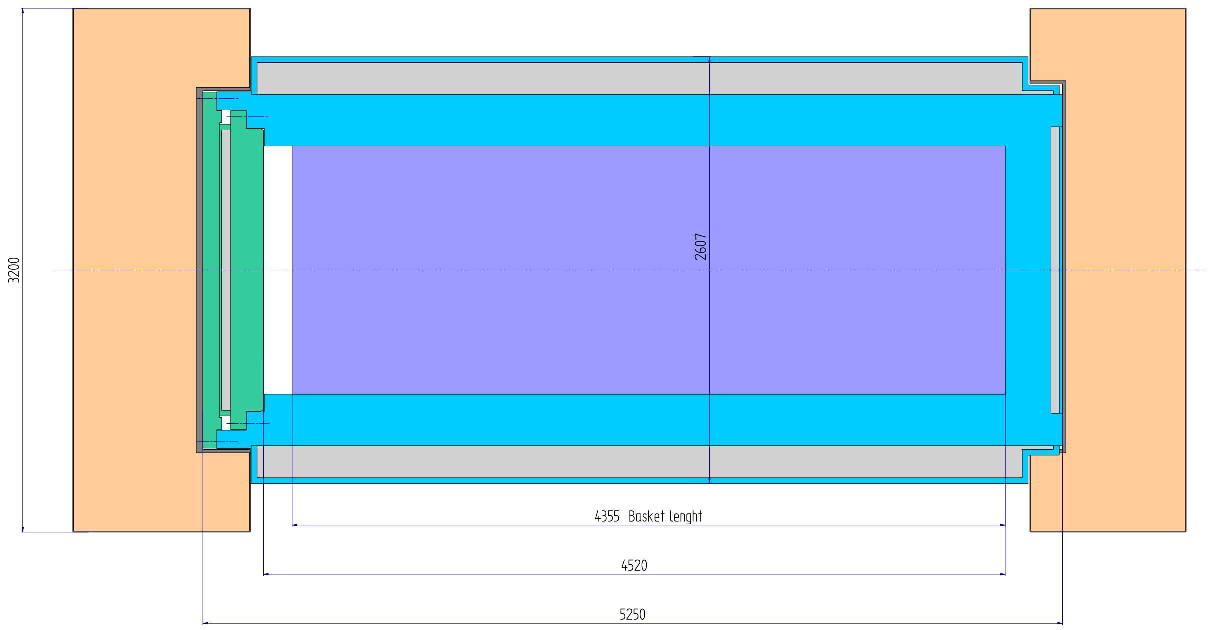


Fig. 1. The transport and storage cask

3. Model for Shielding Analysis

The most important design features of the transport and storage cask with respect to shielding analysis are:

- Non circular cross section
- Shape of cavity machined to fit the basket
- External layer of neutron shielding

- Flats at trunnions

For the analysis the calculation sequence SAS4 of the SCALE4.4A package [1] was used. For the model the option to build a full MARS geometry was chosen because the standardized models were not applicable. Although rather complicated a model could be set up which represented all important design features:

- The non circular cross section of the cask body, the neutron shielding and the outer shell were modelled in full compliance with the original, only the geometrically complicated transition area between the non-circular section and the round shape at the lid area was simplified in a conservative manner.
- The internal shape of the cask cavity was modelled in full compliance with the original.
- The trunnion areas were modelled as close as possible to the original. Only the trunnions were truncated in the model to the outer dimensions of the flats.

The calculation model is shown in Fig. 3. Fig. 3A shows the longitudinal section of the model. The steel of the body and the lids is blue, the neutron shielding green and the outer shell light blue. The basket is shown in yellow. The active fuel zone is shown in red. Fig. 3B shows cross sections of the calculation model. The upper cross section is at the upper trunnions, the lower cross section at half height of the calculation model.

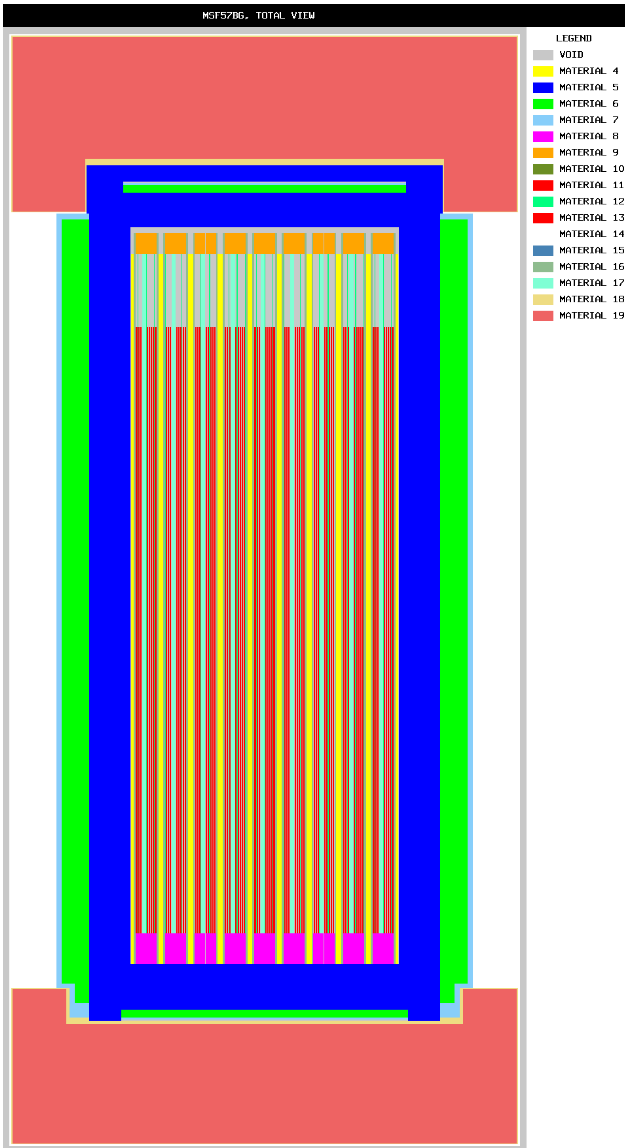


Fig.3A. SAS4 Calculation model, longitudinal section

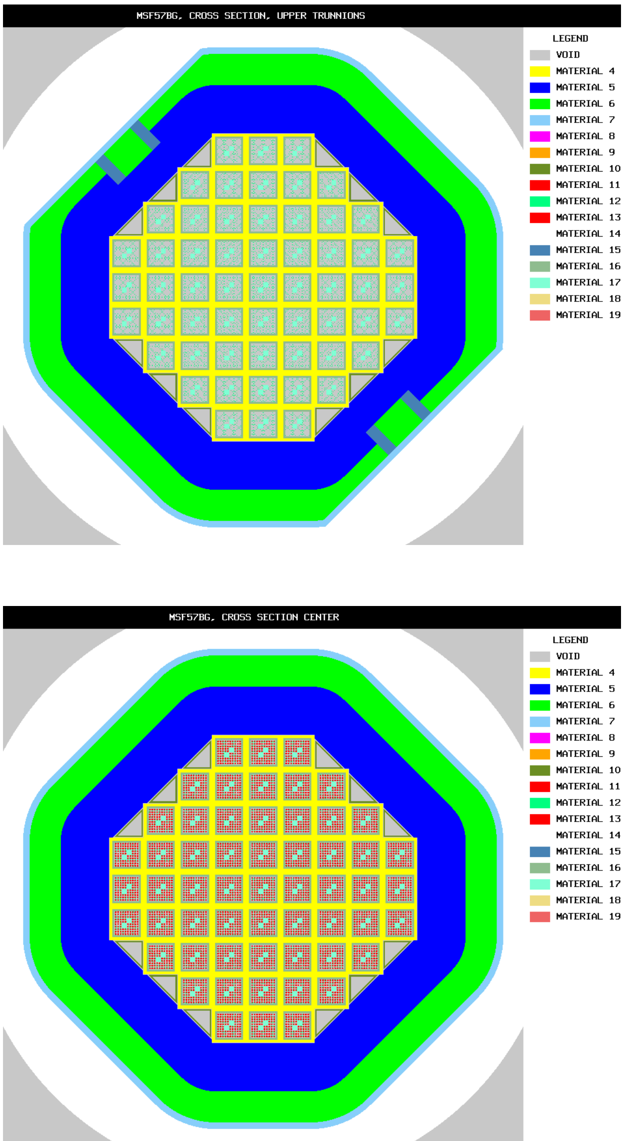


Fig. 3B. SAS4 calculation model, cross sections

The 57 fuel assemblies were modelled individually within the basket tubes. The hardware zones at the top and bottom side were modelled separately from the active fuel zone. For the fuel zone 5 different models were taken into account. The models 1, 3 and 4 described below were a close approximation of the fuel assembly with individual fuel rods and water channel; in the models 2 and 5 the source zones were homogenized.

1. Subdivision of the active zone in 24 separate burn-up zones with individually calculated source strengths and spectra.
2. Same as model 1, but homogenized source zones.
3. Use of the SAS4 option for a burn-up profile using the source spectrum of fuel model 4 and the profile given by the ratio of the source strengths of model 1 and model 4.
4. Uniform burn-up over the complete length of the active zone with source strength and spectrum calculated for the average burn-up equivalent to the 24 burn-up zones.
5. Same as model 4, but homogenized source zone.

For the calculation of the dose rates the option to define surface detectors was used. For the radial and axial calculations 30 angle intervals and 30 height respective radius intervals were specified resulting in a total number of 900 individual surface detectors for each distance. These surface detectors were specified for 8 distances in radial and for 6 distances in axial direction from the surface of the cask to a distance of 2 m from the surface of a rail wagon.

4. Burn-up profile

The burn-up profiles for the analyzed BWR fuel assemblies consist of 24 burn-up zones plus the two zones for the structural parts of the head and the foot of the assemblies. A typical burn-up profile is shown in Fig. 4.

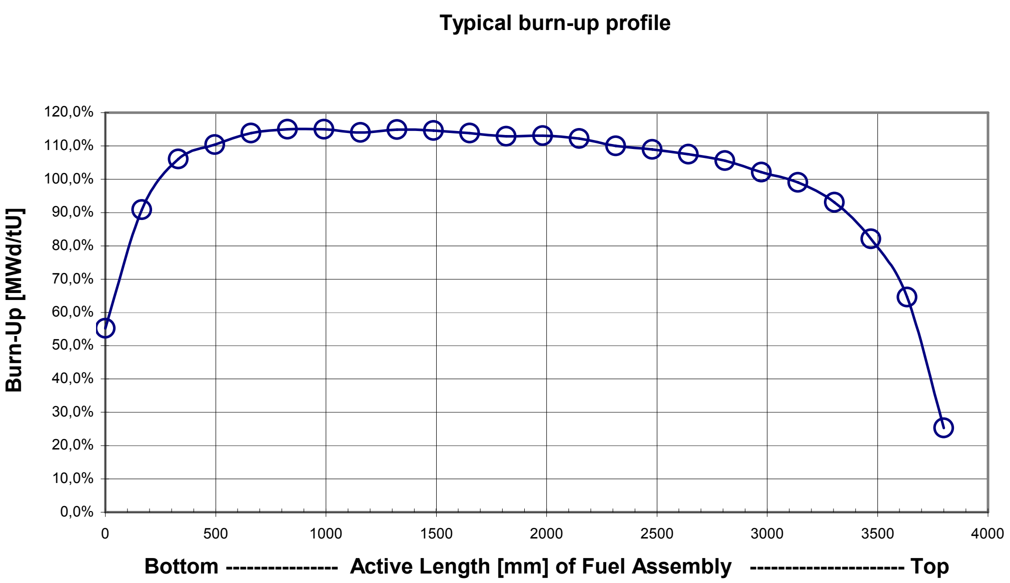


Fig. 4. Typical burn-up profile of a BWR fuel assembly

5. Dose rates calculated with burn-up zones

The results of the calculation with the burn-up zones given in Fig. 4 are shown in Fig. 5 for radial dose rates and in Fig. 6 for axial dose rates. For these results the single burn-up zones were analyzed separately and the results combined. Two separate runs of SAS4 are required for neutron sources and gamma sources. Hence for both radial and axial dose rates in total 48 SAS4 calculations had to be carried out for the active fuel zone and two additional calculations for the gamma dose rates of the structural parts of the assembly foot and head. All results shown are normalized relative to the lowest value of all surface detectors in the plot area.

Fig. 5A to D show the surface of the cask developed in a plane. The unit of the x-axis is the angle at the circumference of the cask, the unit of the y-axis is the height from the centre of the package. The mesh shows the centres of the 900 surface detectors. In all 4 figures the position of the trunnions can be clearly spotted as red spot. In Fig. 5C and D the influence of the noncircular shape of the cask body can be easily seen.

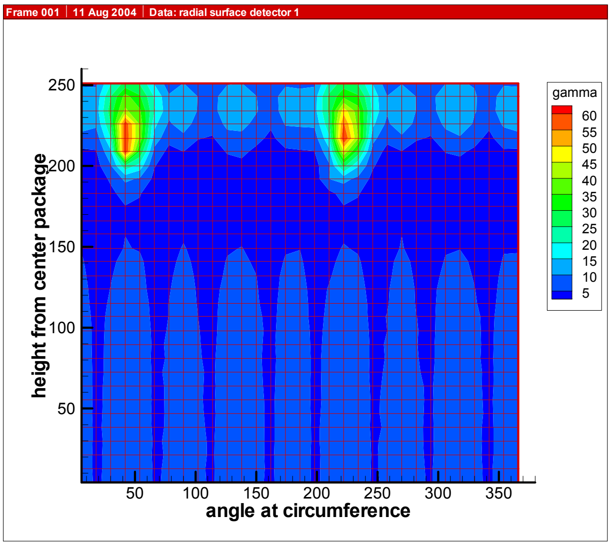


Fig. 5A. Normalized radial gamma surface dose rates calculated with burn-up zones according to Fig. 4

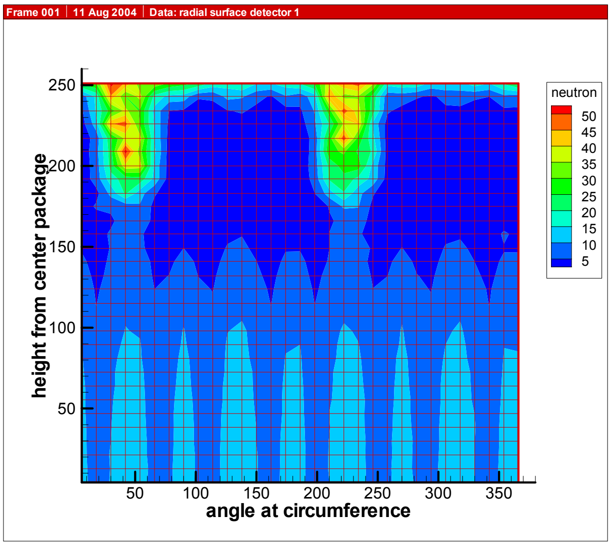


Fig. 5B. Normalized radial neutron surface dose rates calculated with burn-up zones according to Fig. 4

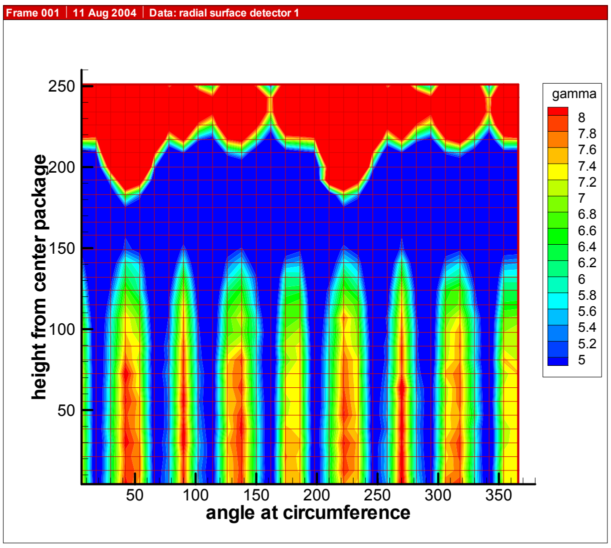


Fig. 5C. Normalized radial gamma surface dose rates calculated with burn-up zones according to Fig. 4, range 5 to 8

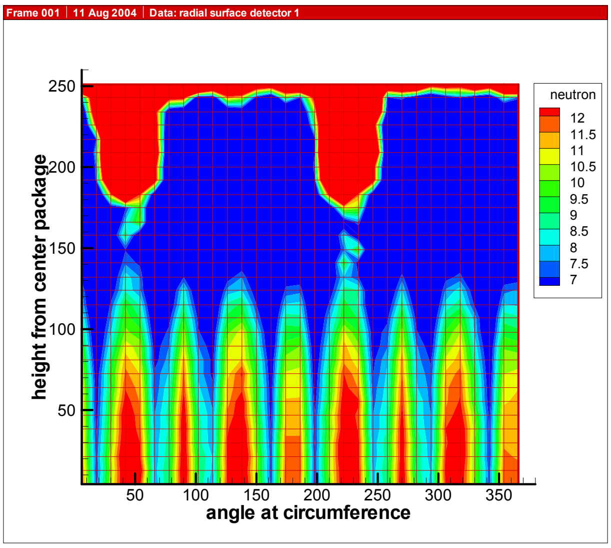
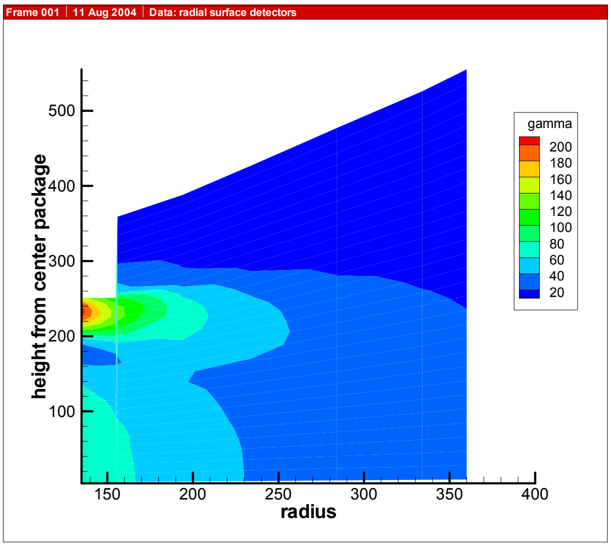


Fig. 5D. Normalized radial neutron surface dose rates calculated with burn-up zones according to Fig. 4, range 7 to 12

In Fig. 5E and F the longitudinal section of the dose rates is shown. The calculation model of the cask with the shock absorber is located on the left side of each figure. The x-axis starts at the surface of the cask and ends at 2 m distance from the rail wagon. The y-axis is the height of the cask measured from the centre. Fig. 5E shows that the gamma dose rate has a high peak at the trunnion flats and a second, lower peak at half height of the cask. Fig. 5F shows that the neutron dose rate has a high peak at the end of the neutron shielding as well as a smaller peak at half height of the cask.



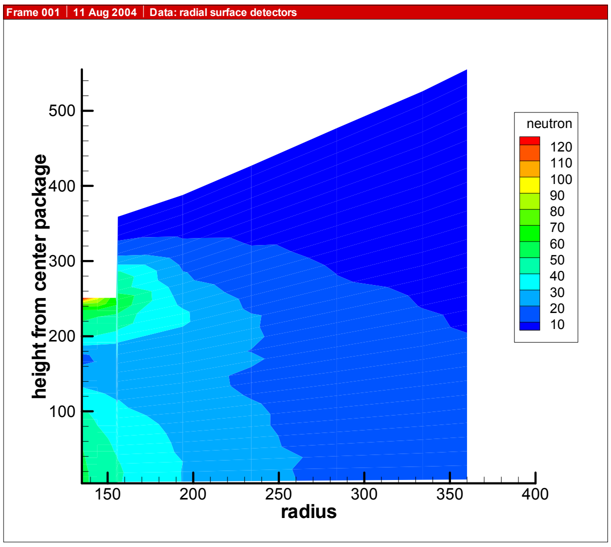
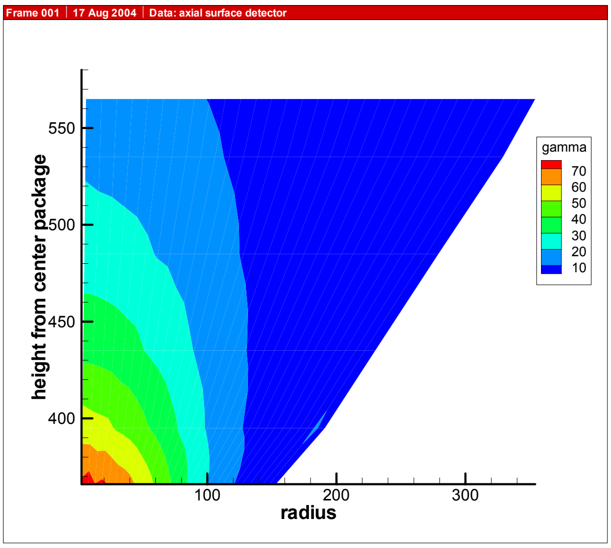


Fig. 5E. Normalized radial gamma dose rate calculated with burn-up zones according to Fig. 4

Fig. 5F. Normalized radial neutron dose rate calculated with burn-up zones according to Fig. 4

Fig. 6A shows the axial gamma dose rates and Fig. 6B the axial neutron dose rates at the upper shock absorber of the cask. The major amount of the gamma dose rate results from the activation of the structural parts of the head and foot of the fuel assembly. For both the gamma and neutron dose rate the value reaches a maximum in the axis of the cask. The ratio between the neutron dose rate at larger radii and the neutron dose rate at the cask axis is higher than for the gamma dose rates. The reason for this is the disturbed neutron shielding in the area of the lid flanges.



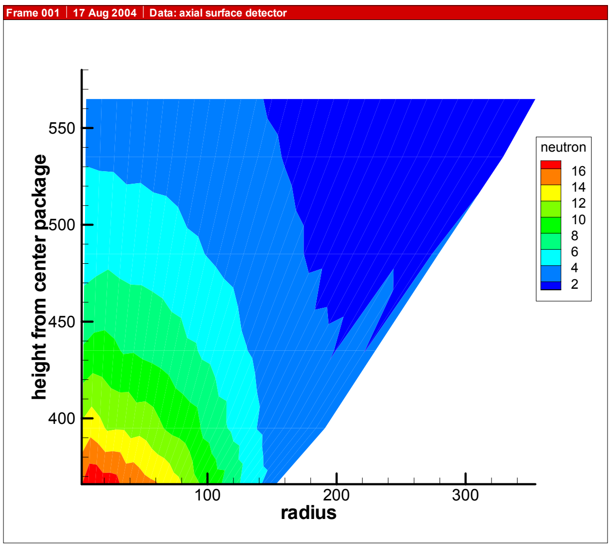


Fig. 6A. Normalized axial gamma dose rate calculated with burn-up zones according to Fig. 4

Fig. 6B. Normalized axial neutron dose rate calculated with burn-up zones according to Fig. 4

6. Comparison of results calculated with the different fuel models

Fig. 7 shows the comparison of the dose rates calculated with the different fuel models described in section 3. All values are normalized to the dose rates calculated for the explicit burn-up zones at half height of the package.

Fig. 7A and 7B show the comparison of the radial surface dose rates. The dose rates calculated with the burn-up zones (“burn-up gamma”, “burn-up neutron”) are at the centre of the package always higher than those calculated with the other fuel models. In the area of the flats and trunnions the dose rates calculated with the burn-up zones are always lower than those calculated with the other models. This behaviour is very striking for the neutron dose rate, where the value calculated with a uniform source is approx. 10 times the value calculated with the burn-up zones. Even the SAS4 option to use a burn-up profile leads to an overestimate of the neutron dose rate.

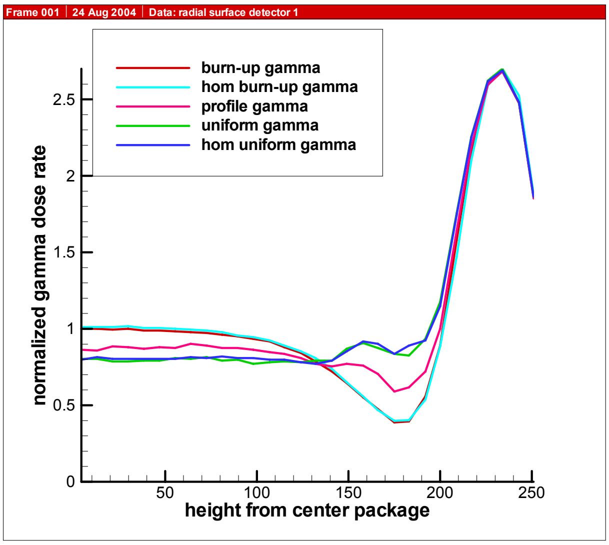


Fig. 7A. Normalized radial surface gamma dose rates calculated with the different fuel models

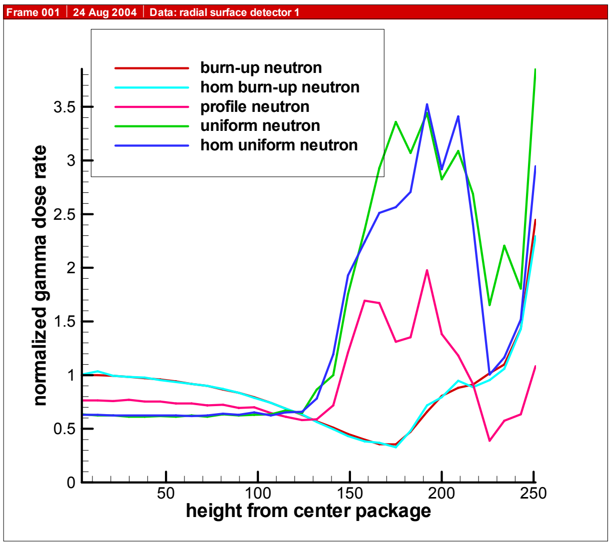


Fig. 7B. Normalized radial surface neutron dose rates calculated with the different fuel models

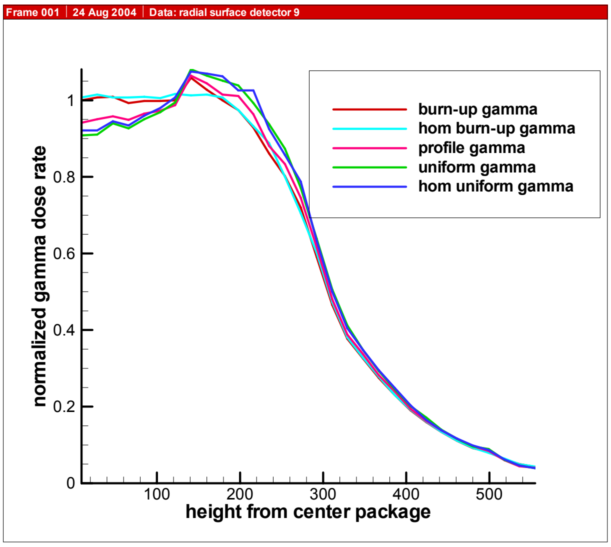


Fig. 7C. Normalized radial gamma dose rates at 2 m distance from the vehicle calculated with the different fuel models

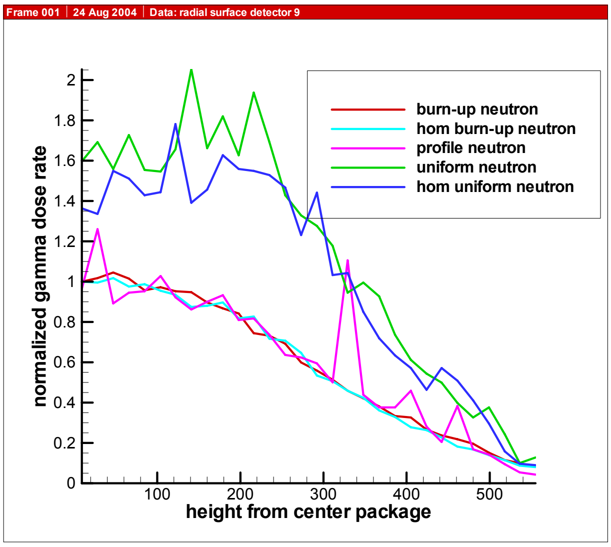


Fig. 7D. Normalized radial neutron dose rates at 2 m distance from the vehicle calculated with the different fuel models

Fig. 7C and 7D show the comparison of the radial dose rates in 2 m distance from the vehicle. For the gamma dose rates the differences between the values calculated with the 5 fuel models are negligible. The fuel models with uniform burn-up leads to an overestimate of the neutron dose rates of approx. 50%. The SAS4 fuel modelling option with burn-up profile is equivalent to the model with explicit burn-up zones.

In all cases the figures show that the results calculated with the fuel assembly model with individual fuel rods are within statistical uncertainties identical to the results calculated with the homogenized source zones.

Fig. 8 shows the comparison of the axial surface dose rates. The x-axis is the radius from the centre of the cask. Fig. 8A shows that the gamma dose rate calculated with the different fuel models are identical. The reason for this is that the major part of the gamma dose rate results from the structural parts of the fuel assembly. The neutron dose rate shows significant differences for the 3 investigated fuel models.

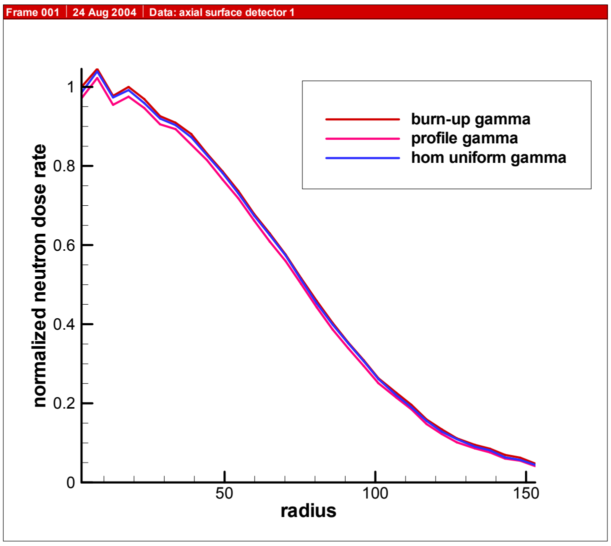


Fig. 8A. Normalized axial surface gamma dose rates calculated with the different fuel models

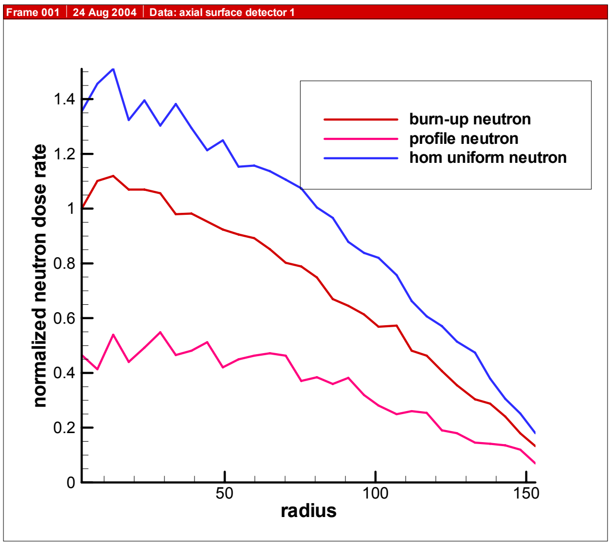


Fig. 8B. Normalized axial surface neutron dose rates calculated with the different fuel models

In all cases the figures show that the fuel models with explicit burn-up zones lead to the smoothest appearance of the dose rate profiles. The reason for this is certainly the reduction of the statistical errors by the combination of 12 (for the neutron dose) respectively 13 (for the gamma dose) SAS4 runs.

7. Accuracy of the Monte Carlo Analysis

The accuracy of the results of the Monte Carlo calculations depends on the parameters “number of particles per generation” and “number of generations” as well as on the biasing method used in SAS4. For the previously described calculations the parameters listed in Tab. 1 were used.

	Gamma dose rate	Neutron dose rate
Number of particles per generation	1000 – 2000 (2000)	1000
Number of generations	2000 – 8000 (2000)	2000 – 4000 (2000)

Tab. 1. Parameters used for the SAS4 calculations, standard values in brackets

For all calculations the results were considered acceptable if the standard deviation of the average dose rate was less or equal than 0.05 for all surface detector distances. For some cases the calculations did not converge as requested. In these cases the number of particles per generations was modified and the number of generations increased. Finally, the random number used to start the calculations was modified to reach the required standard deviations. Fig. 9 shows the standard deviations of the calculation results shown in Fig. 5.

For gamma dose rate calculations the standard deviations are for almost all individual surface detectors in the range of 0.05. Only a slight increase of the standard deviation in the area of the trunnions can be observed. The standard deviations for the neutron dose rate are in the range of 0.05 in the areas of the neutron shielding where the biasing of SAS4 is near optimal. In the trunnion areas the thickness of the neutron shielding is reduced and disturbed by the trunnion and the biasing procedure becomes suboptimal. Furthermore, for shielding areas above the top of the active zone the distances a neutron has to travel through steel and neutron shielding increase, thus leading again to a suboptimal biasing. In these areas with suboptimal biasing the standard deviation is in the range of 0.2 to 0.3. Both for gamma and neutron calculations there remain a few scattered spots where the standard deviation remains high. This behaviour was experienced as well for other calculation models and is typical for this kind of calculations.

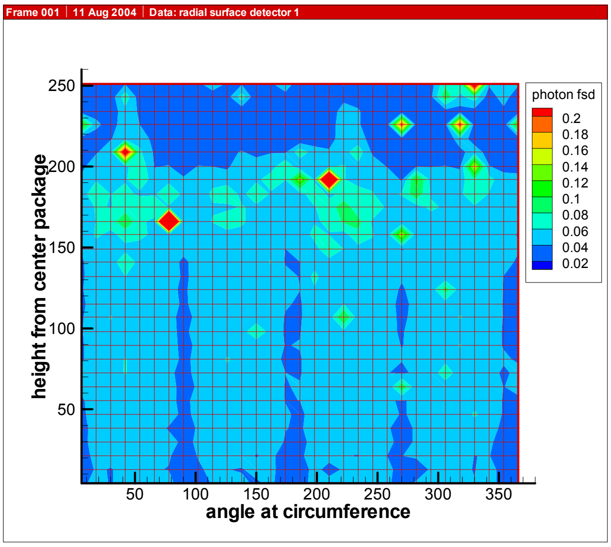


Fig. 9A. Standard deviations of the surface gamma dose rate shown in Fig. 5A and 5C

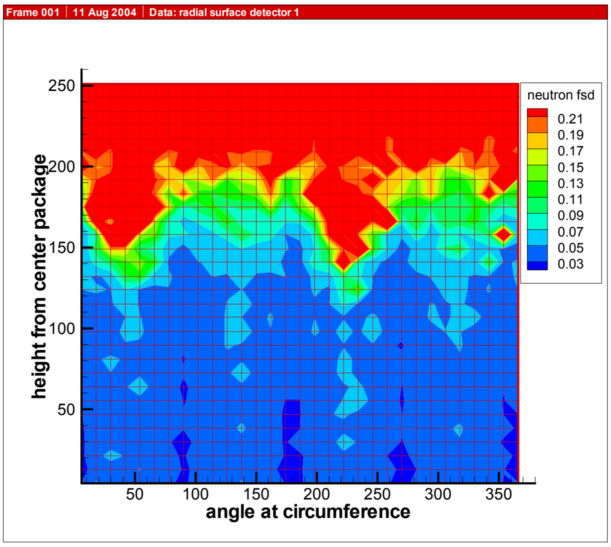


Fig. 9B. Standard deviations of the neutron dose rate shown in Fig. 5B and 5D

8. Conclusions

The paper shows that the calculation sequence SAS4 of the SCALE code package can be used for the shielding analysis of rather complicated cask geometries. Fig. 5 shows that the influence of all relevant design features of the cask on the dose rates can be evaluated with SAS4.

The model used for the representation of the fuel assembly has a large influence on the calculated dose rates. The radial results calculated with the models using burn-up zones and the SAS4 profile option are in almost all cases nearly identical. Only the surface neutron dose rate in the area of the trunnion flats is for the model using the SAS4 profile option much higher. The uniform source models underestimate the surface dose rates in the centre of the cask and overestimate them at the ends of the active zone considerably. The gamma dose rates at 2 m distance from the vehicle are for all fuel models identical. The neutron dose rates at 2 m distance from the vehicle however are for the models using a uniform source approx. 50 to 100% higher.

The axial gamma dose rates are for all fuel models identical. This can be explained by the predominant influence of the activation of the structural parts of the head and foot of the fuel assembly. The axial neutron dose rates are for all models different. The fuel model using a uniform source overestimates the dose rate by 40 % and the fuel model using the SAS4 profile option underestimates the dose rates by 50%.

The typical cpu times required for the analysis depend largely on the fuel model, on the number of particles per generation and the number of generations per run. For the models with individual fuel rods and the standard parameter values given in Tab. 1 the typical cpu time is approx. 12 hours on a modern fast PC (Xeon(TM) processor 3.06 GHz). For the homogenized fuel assembly model the typical cpu time is approx. 4 hours. A full analysis with the fuel model using individual fuel rods and burn-up zones would require approx. 6 weeks. A full analysis with the fuel model using homogeneous burn-up zones would provide the same accuracy but require only approx. 2 weeks cpu time.

Literature

[1] SCALE4.4A, A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation, NUREG/CR-0200, Rev. 6, ORNL/NUREG/CSD-2/R6