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Impact of the New IAEA Shielding Recommendations on Spent Fuel Storage and Transport Cask Performance

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Abstract

According to the latest IAEA recommendations (2012, SSR-6[1]), shielding analyses under routine transport conditions have to be performed considering loading plans with the maximum allowed radioactive contents. In parallel, regulators of storage now request the definition of generic loading plans.

Thus, cask designers are facing the challenge of implementing a method to define maximum generic loading plans and to avoid a performance decrease on new cask design or cask license renewal.

Introduction

Fuel assembly characteristics are evolving in order to improve performance of reactor operations. As a result enrichment is slightly increasing as well as burnup. In addition, in some cases there is a need to unload the reactor as soon as possible implying shorter cooling time.

To improve cask performance with the largest possible loading capacity of spent fuel assemblies, the largest practicable burnup and shortest cooling time while conforming to all safety requirements, AREVA TN has adapted its design process and has developed a more elaborated shielding analysis method to meet the latest regulatory recommendations.

This new method avoids to develop a safety demonstration based on a loading plan matrix with a limited number of homogeneous and non homogeneous loading options.

Regulatory Practice and Consequences

The 2009 IAEA recommendations (TS-R-1[2]) required that the maximum radioactive contents only be considered for shielding analyses under accident conditions of transport. Typical contents were used in order to demonstrate the compliance of the shielding thresholds under routine conditions of transport.

With the 2012 IAEA recommendations (SSR-6[1]), the maximum radioactive contents must now be considered under both conditions of transport and for all package types. As maximum radiation levels have not changed, routine conditions of transport are now the shielding relevant conditions in the licensing process. In parallel, in some countries, storage authorities have strengthened their recommendations and require to the definition of generic loading plans.

Thus, cask designers are facing the challenge of implementing a method to define maximum generic loading plans without restrictions on new cask design or cask license renewal.

Indeed, following the standard shielding analysis method leads to define a matrix of bounding loading plans based on limited heterogeneities from the maximum burnup and the minimum cooling time authorized in the case of a homogeneous loading plan. It allows a standard licensing process but this reaches a limited loading capacity and flexibility.

The new shielding analysis method developed by AREVA TN reconsiders the standard definition of the content in order to take advantage of potential heterogeneities between sources of the loaded fuel assemblies and of the self-shielding between the loaded fuel assemblies. The maximum authorized radioactive content is defined with only maximum neutron and gamma sources authorized in each basket lodgement.

AREVA TN New Shielding Analysis Method

Shielding relevant cask area

The key step of this method is based on a detailed shielding analysis in order to identify the shielding relevant cask areas. These areas are defined by the variations of shielding material thickness, by the specific basket geometry associated to the burnup, cooling time heterogeneities of loading plans, and by the radiation level thresholds. They correspond to zones on the cask surface or in the cask vicinity where the relative maximum radiation levels occur.

In this way, based on a 3D detailed geometry model[3,4] (Fig. 1), the geometric scope in which the radiation levels must be verified can be reduced.

Application to the TN®9-4 transport cask

The TN®9-4 cask is a transfer cask for the transport of 7 BWR UO_2 spent fuel assemblies (Fig. 2) from the Mühleberg NPP (KKM) to the Zwilag facility (Swiss centralized interim storage facility). These fuel assemblies are then loaded into the TN®24 BH which is designed for the transport and the interim storage of 69 BWR UO_2 spent fuel assemblies.

Regarding the maximum radiation levels generated at the contact of the TN®9-4 cask external surface, in the different axial and radial areas defined with an adapted external surface map (Fig. 1), the detailed shielding analysis performed allows reducing the fulfilment of the radiation level threshold, only

- in the bottom trunnion areas (Fig. 2),
- in the bottom radial areas following the angular directions 45°, 135°, 225° and 315° (Fig. 2).

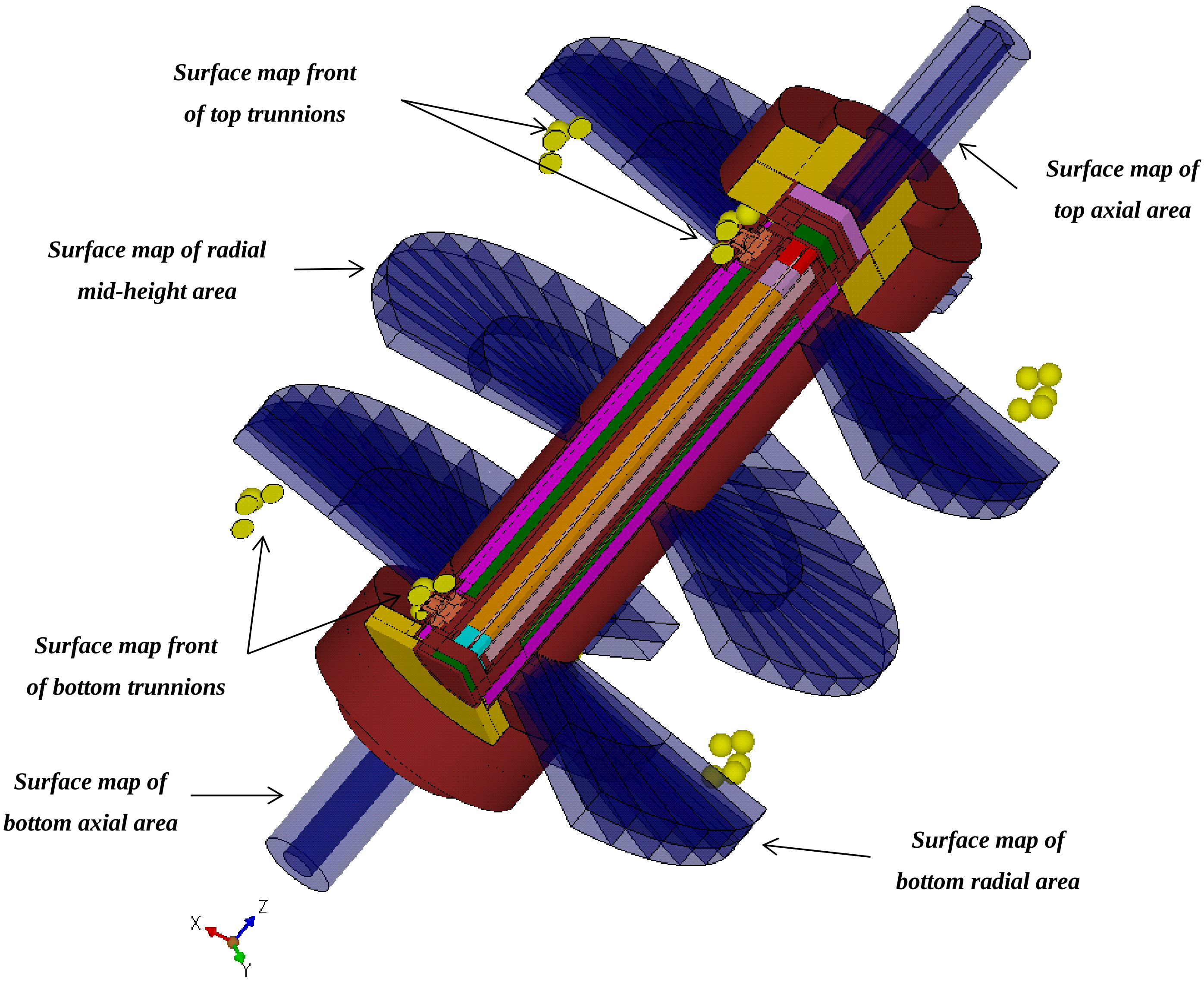

Figure 1: 3D detailed model of the TN®9-4 transport cask – External surface map

To illustrate the strength of this geometrical scope reduction, a sensitivity analysis was performed on the radiation level distribution taking into account heterogeneous loading plans. Considering up to 7 fuel assemblies with a high average burn-up (60 GWd/t_{HM}) associated with fuel assemblies with a very low average burn-up (2 GWd/t_{HM}), the radiation level distributions of the 47 possible heterogeneous loading plans were analyzed.

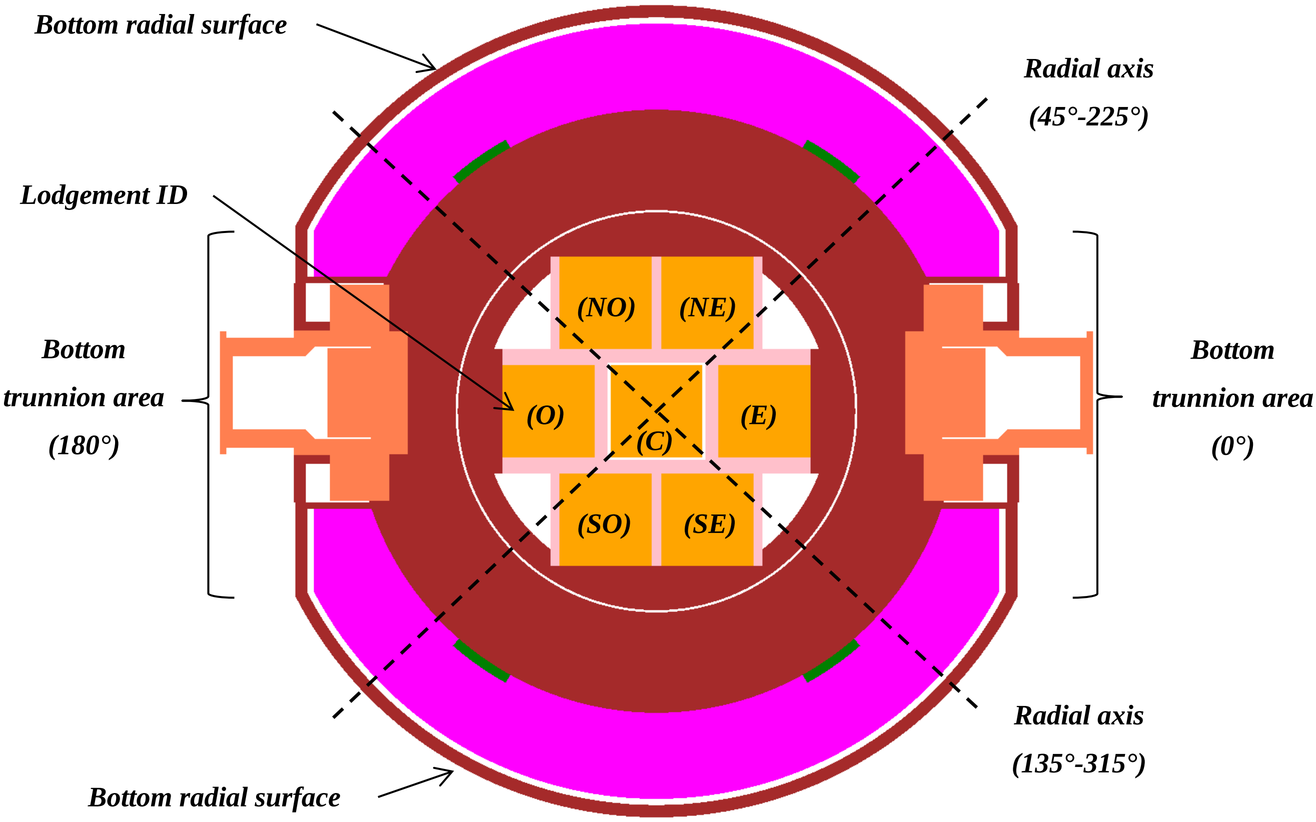

Figure 2: 3D detailed model of the TN®9-4 transport cask – Bottom trunnion section

Figure 3 presents the radiation level distribution at the contact of the TN®9-4 external surface in the bottom trunnion section for loading plans which generate the maximum radiation levels according to the considered number of fuel assemblies with a high burn-up.

Two types of loading plans (LP) can be identified according to the radiation level threshold (2 mSv/h at the contact[1,2]):

- loading plans with up to 5 fuel assemblies with a high burn-up, for which the maximum radiation levels will be always below 2 mSv/h,
- loading plans with 6 or 7 fuel assemblies with a high burn-up, for which the maximum radiation level exceed 2 mSv/h.

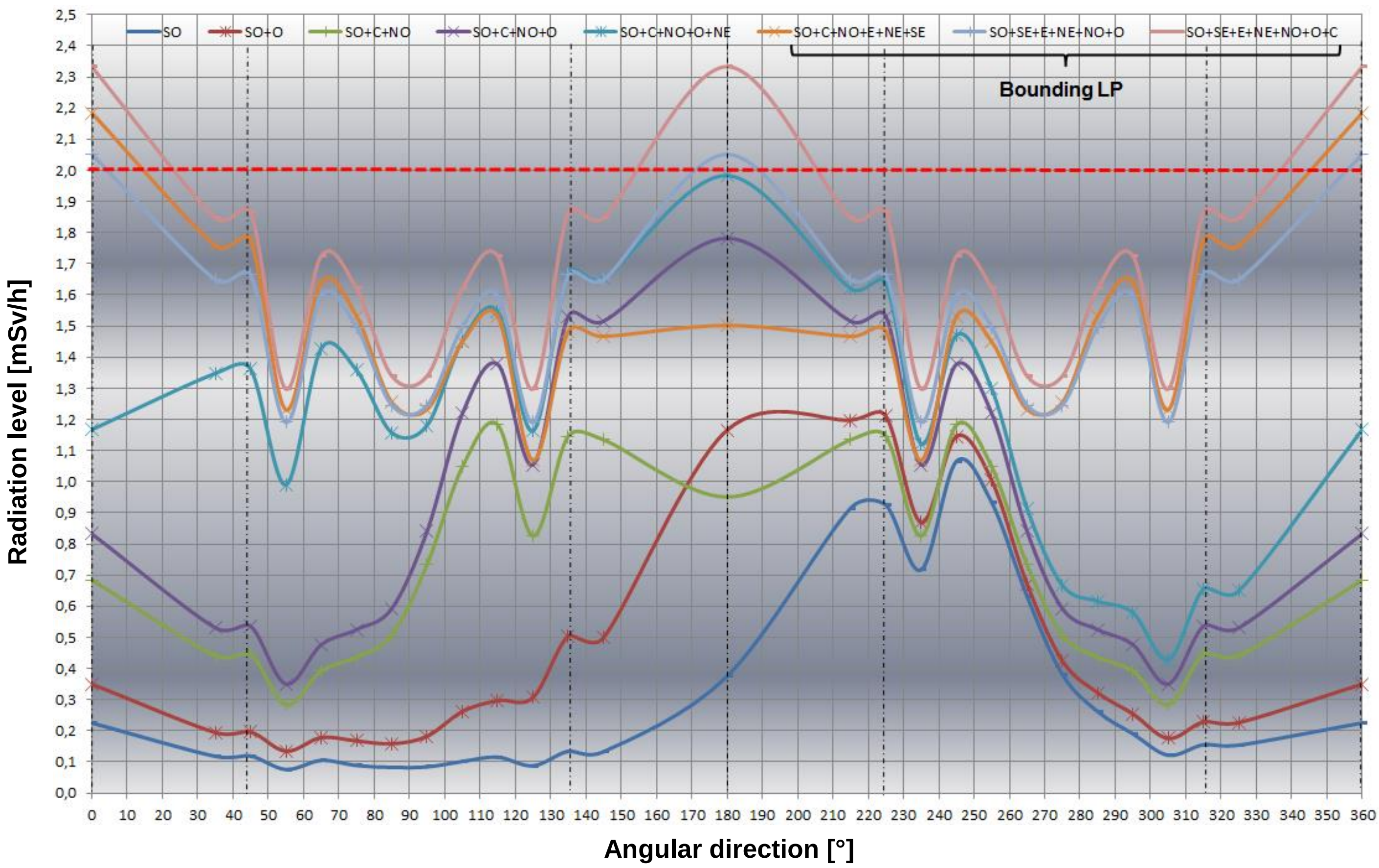

Figure 3: Radiation level distribution at contact of the TN®9-4 bottom radial surface

For these two bounding loading plans:

- the maximum radiation levels exceeding the radiation level threshold occur only in the radial directions 0° and 180°, i.e. at the contact of the bottom trunnions (Fig. 3),
- secondary maximum radiation levels always occur following the symmetrical radial directions 45°, 135°, 225° and 315° (Fig. 3),
- secondary minimum radiation levels always occur following the symmetrical radial directions 90° and 270° (Fig. 3).

Thus, following the detailed shielding analysis performed, the reduction of the geometrical scope, in which the radiation levels must be calculated, is fully adapted to highly heterogeneous loading plans.

<u>Linear inequalities system</u>

The new shielding analysis method followed by AREVA TN reconsiders the homogeneous model of the content in order to establish the maximal loading capacity of a cask. The result of this method is expressed under the shape of a linear inequalities system.

This method takes advantage of potential heterogeneities between sources of the fuel assemblies to be loaded through the comparison of the real fuel assemblies sources with cask specific reference source terms associated with the cask design. Futhermore the self-shielding of fuel assemblies loaded at the basket center by the fuel assemblies loaded at the basket periphery is integrated by the definition of the individual contribution of each source loaded in each basket lodgement to the radiation level generated in each shielding relevant cask area.

To optimize the cask capacity and to efficiently adapt the conservatism strength required, a normalization of the inequality results considering reference loading plans has been conducted.

Thus, for each shielding relevant cask area, a linear inequality is defined as follow:

$$\sum_{lodg}\left(\sum_{j=1}^{2}\frac{f_j^{lodg}(n)\times S_j^{lodg}(n)}{\eta(n)\times RST_j\ (n)}+\sum_i\frac{f_i^{lodg}(\gamma)\times S_i^{lodg}(\gamma)}{\eta(\gamma)\times RST_i\ (\gamma)}+\sum_c\frac{f_c^{lodg}(\gamma_{act})\times S_c^{lodg}(\gamma_{act})}{\eta(\gamma_{act})\times RST_c\ (\gamma_{act})}\right)\leq 1$$

where

- *j*: neutron source index, “j” = [1, 2] = [(α, n) reaction; spontaneous fissions],
- *i*: gamma energy group index,
- γ_{act}: activation gamma source,
- *c*: fuel axial zone index for activation gamma,
- *lodg*: basket lodgement ID,
- $S_j^{lodg}(n)$, $S_i^{lodg}(\gamma)$, $S_c^{lodg}(\gamma_{act})$: neutron, gamma and activation gamma source strengths of the fuel assembly loaded in the basket lodgement “lodg”,
- $f_j^{lodg}(n)$, $f_i^{lodg}(\gamma)$, $f_c^{lodg}(\gamma_{act})$: contribution factors of neutron, gamma and activation gamma sources of the fuel assembly loaded in the basket lodgement “lodg”,
- $RST_j\ (n)$, $RST_i\ (\gamma)$, $RST_c\ (\gamma_{act})$: reference source terms for neutron, gamma and activation gamma sources,
- $\eta(n)$, $\eta(\gamma)$, $\eta(\gamma_{act})$: neutron, gamma and activation gamma effective normalization factors in the shielding relevant cask area considered.

Cask Loading Management

Using the linear inequalities system, the cask owner is able to directly assess the relevant radiation level of any loading plan. The major advantage of this approach is to allow the cask owner to take into account the real source strength heterogeneities of a real loading with a simple and efficient tool.

Indeed, through a simple spreadsheet (Fig. 4), the use of the linear inequalities system only involves calculating the real sources of fuel assemblies to be loaded using a validated depletion code. In comparison to the time needed to perform a complete shielding calculation using a 3D Monte-Carlo code, using this method is decisive to give the cask user the maximum flexibility for loading management.

Source loaded							
TN 9/4 transport cask	NO	NE	O	C	E	SO	SE
FS source (n/s/t_{ML})							
(α, n) source (n/s/t_{ML})							
γ source (γ/s/t_{ML})							
^{60}Co activity - FA top (Bq/zone)							
60Co activity - FA plenum (Bq/zone)							
60Co activity - FA bottom (Bq/zone)							

Figure 4: Spreadsheet example

Furthermore, in the typical long-term situation in which the fuel burnup increases and the fuel cooling time decreases, the use of the linear inequalities system makes it easy to define an adapted long-term pool unloading strategy based on an optimized management of cold and hot fuel assemblies. Thus, the time during which a cask can be used only with a reduced loading capacity, because of remaining spent fuel assembles with high burnup and low cooling times is reduced and the cask availability and performance are strengthened (Ref. 5).

This directly contributes to a decrease in the total number of required cask loadings and shipments and a significant decrease of all radiation exposure in accordance with ALARA objectives.

Conclusions

In order to avoid unnecessary restrictions of the authorized content characteristics while still meeting the new requirements, AREVA TN has adapted its design process and developed a more elaborated shielding analysis method.

The linear inequalities system, resulting from the AREVA TN new shielding analysis method, presents a high implementation flexibility and allows taking advantage of the explicit characteristics of the fuel assembly inventory.

Associated with an appropriate cask loading strategy, this innovative shielding analysis method provides a cask with the largest possible loading capacity of spent fuel assemblies with the largest practicable burnup and shortest cooling time within all safety requirements.

The relevant technical advantages of this approach are the following:

- It avoids the necessity of defining in the license a maximal burnup and a minimum cooling time authorized in order to respect the radiation level thresholds.
- It avoids the necessity of defining a matrix of bounding loading plans in order to allow heterogeneous loading plans.
- It does not require any dose rate calculation for each loading.
- It provides a simple and efficient tool in the form of linear inequalities to verify that the radiation level thresholds are met.

This method has been validated by the German authorities (BfS, TÜV) for the design approval of the dual purpose TN®24 E package. Furthermore, this method has been implemented for the design approval of the transport casks TN®G3 and TN®17 MAX, and for the license renewals of the TN®24 BH, TN®24 SH, TN®24 GB and TN®9-4 package.

The determined linear inequalities system ensures the acceptance of the transport of any radioactive content in conformity with the regulations and allows the use of highly heterogeneous loading plans. The use of this validated method is decisive in giving the cask user the maximum flexibility for an optimized management of cask loading plans in the long term.

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