REPRESENTATIVITY STUDY OF THE FRENCH HTC AND FP EXPERIMENTS FOR BURNUP CREDIT APPLICATION TO THE TN® 24 E TRANSPORT AND STORAGE CASK

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Abstract

The criticality calculations for a transport and storage cask containing irradiated fuel assemblies associated with the burnup credit practice needs the validation of the criticality codes and the associated cross-section libraries. One of the requirements for the criticality code validation is to demonstrate the similarity between the selected set of critical experiments and the cask configuration.

A set of "Haut Taux de Combustion" (HTC) and Fission Products (FP) experiments, co-funded by the AREVA Group and IRSN, was selected for the validation of the criticality code to be applied on the TN® 24 E cask loaded with 21 irradiated UO_2 fuel assemblies (12 GWd/t_{HM}).

Similarity demonstrations require identifying the neutron-physical parameters of most influence for the cask and the selected critical experiments. The traditional method for assessing the similarity between experiments and an industrial application is to compare global parameters (EALF, H/X, V_m/V_f, etc.) or reaction rates for uranium, plutonium, and fission products. This approach is employed here, with the criticality safety code package CRISTAL V1.0, for the comparison between HTC and FP experiments, on the one hand, and the TN® 24 E cask configuration, on the other hand. It is highlighted that the TN® 24 E configuration is surrounded in terms of spectral parameters and reaction rates by the selected HTC and FP experiments.

An alternative way to study the similarity is to use sensitivity/uncertainty (S/U) analysis methods. As a further assessment for the TN® 24 E cask application, its similarity with the selected set of HTC and FP experiments is analysed using the TSUNAMI tools of the SCALE 5.1 package. The TN® 24 E cask sensitivity profiles obtained with the TSUNAMI-3D module are compared to the selected FP and HTC profiles. It is shown that the profiles of the experiments match well those of TN® 24 E cask configuration in terms of magnitude and shape. Computation of the correlation coefficients (c_k) with the TSUNAMI-IP module further demonstrate a close similarity between the selected set of HTC and FP experiments and the TN® 24 E cask configuration with irradiated UO_2 fuel assemblies.

1 INTRODUCTION

One of the requirements for criticality calculations with irradiated fuel assemblies in a transport and storage cask is to perform the validation of the criticality code used for burnup credit (BUC) calculations and associated nuclear data.

The usual approach for the criticality code validation is the calculation of adequate critical experiments and bias determination for the same calculation scheme. The demonstration of similarity between selected experiments and the application case can be done in various ways. It should mainly provide insights into the neutron physical similarities that must exist between the application case and the selected experiments used for the validation.

Two series of critical experiments referred to as "Haut Taux de Combustion" (HTC) [1] and Fission Products (FP) [2] experimental programs were performed by Institut de Protection et de Sûreté Nucléaire (IPSN, now IRSN) at the Valduc research facility, with the financial support of COGEMA (now AREVA NC), within the French program supporting development of a technical basis for burnup credit validation.

A set of 111 experiments from HTC and FP series was selected for the validation of the criticality code package CRISTAL V1.0 [3] to be applied on the AREVA TN International transport and storage cask TN® 24 E loaded with 21 irradiated UO_2 fuel assemblies (minimum required average fuel assembly burnup of 12 GWd/t_{HM}).

The legacy method used to analyse the similarity between experiments and an industrial application is mainly based on comparison of global spectral parameters (e.g. energy of average neutron lethargy causing fission (EALF), moderator to fuel ratio, etc.) and specific parameters (e.g. reaction rates). For the TN® 24 E cask, the Area Of Applicability (AOA) of the criticality code validation is defined on the basis of the values of these global spectral parameters and reaction rates for HTC and FP experiments. A similarity study then demonstrates that the values of these parameters for the TN® 24 E cask configuration are inside the AOA.

In order to verify the results of this legacy representativity study, a complementary sensitivity and uncertainty (S/U) methodology, developed in the last years at Oak Ride National Laboratory (ORNL) [4] and included in SCALE 5.1 code package [5], was applied to TN® 24 E design applications.

In this framework, IRSN was involved in the modelling and calculation of FP and HTC experiments.

2 TN® 24 E CASK MODEL AND BUC CALCULATION

Burnup credit is implemented in the criticality analysis of the TN® 24 E. The cask is loaded with 21 PWR 18×18 UO_2 spent fuel assemblies. The assemblies are contained in a 25-cm thick steel shell. The fuel assemblies are separated by profiles composed of two aluminium borated plates separated by a water gap. The fuel has a maximum initial enrichment of 4.65 wt % ^{235}U with a minimum average burnup requirement of 12 GWd/t_{HM}.

The criticality of the irradiated fuel assemblies is affected by their axial burnup. A bounding axial burnup profile for the 18×18 FA was generated by AREVA NP for the TN® 24 E BUC application. The method to generate a bounding axial profile on the basis of representative axial fuel assembly burnup shapes of German NPPs derived from in-core 3D power density distribution measurements is described in [6]. Based on this bounding profile, 21 different axial burnup zones are used in order to take into account the control rod effect on the irradiated fuel composition and the lattice expansion of the fuel assembly in accidental conditions of transport (IAEA 1996 requirements [7]). The calculation scheme is based on the connection of the depletion code APOLLO2/DARWIN ([8] and [9]) and the French Criticality Safety Package CRISTAL V1.0. Figure 1 shows the 45° cross section of the TN® 24 E criticality calculation model resulting from the CRISTAL V1.0 package and Figure 2 shows the different axial burn up levels in the model that correspond to the axial burnup profile of the fuel assembly.

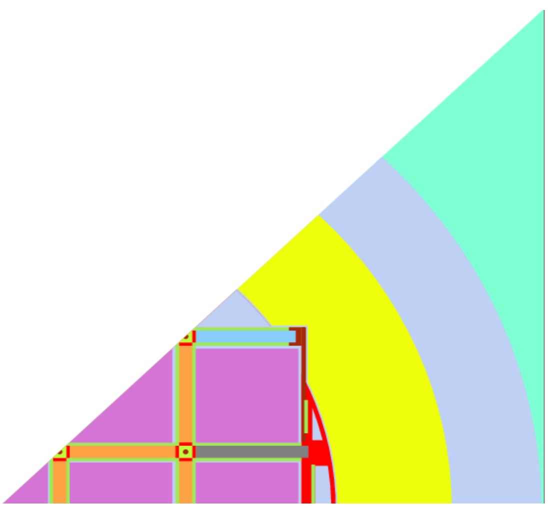

Figure 1: *Sectional view of UOX assemblies in the TN 24 E cask*

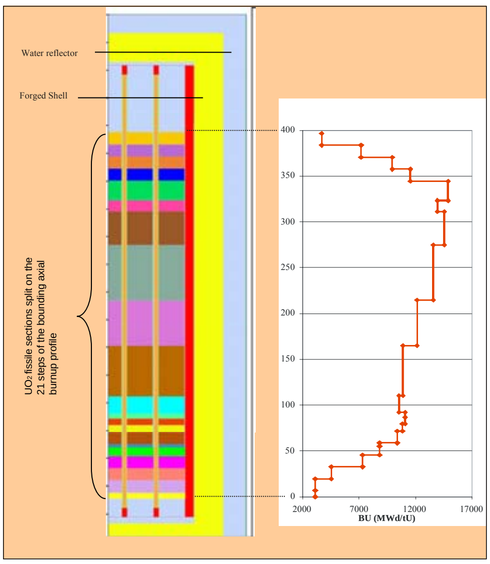

Figure 2: *Sectional view of UOX assemblies in the TN 24 E cask and the burnup profile*

From the 12 actinides and 15 fission products recommended by the OECD [10], the following actinides and fission products are considered in the criticality calculations:

− 9 actinides: ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am,
− 6 fission products: ^{103}Rh, ^{133}Cs, ^{143}Nd, ^{149}Sm, ^{152}Sm, ^{155}Gd.

The limitation to 9 actinides and 6 fission products used in the BUC methodology implemented in the TN® 24 E criticality calculation is conservative compared to the OECD recommendation and represents, as far as FPs are concerned, approximately 50% of the total worth of all fission products.

3 INTEGRAL EXPERIMENTS DEVOTED TO BURNUP CREDIT APPLICATION

The HTC experiments [1] were conducted in order to validate the cross sections of major actinides for a representative range of fuel cycle's configurations. These experiments were performed with rods having uranium and plutonium isotopic compositions simulating a $U(4.5)O_2$ fuel irradiated to a burnup of 37.5 GWd/t_{HM} but without FPs. About 200 configurations were examined, which are categorized into four groups as illustrated in Figure 3.

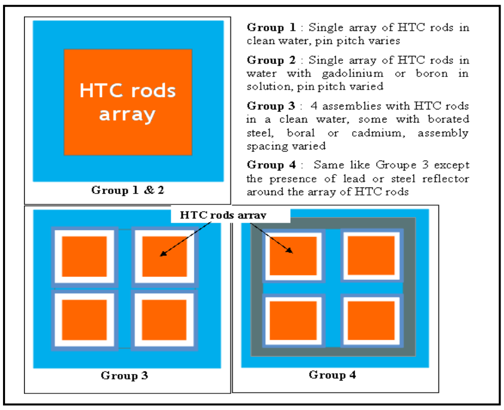

Figure 3: *HTC critical experiments configurations*

The FP experiments [2] (145 configurations) were performed including six fission products: ^{103}Rh, ^{133}Cs, ^{nat}Nd, ^{149}Sm, ^{152}Sm, ^{155}Gd. The experiments were carried out in three phases, testing different interaction conditions between the fission products and the UO_2 or the HTC rods (see Figure 4):

- "**Physical type**" experiments dealt with the FPs presented individually or as mixture in low acidic aqueous solutions contained in a tank surrounded by a driver array of UO_2 rods arranged in a 1.3-cm pitch square lattice,
- "**Elementary Dissolution type**" experiments dealt with the FPs presented individually or as mixtures in low acidic or depleted uranyl nitrate solutions, interacting with the UO_2 or the HTC rod lattice in a tank surrounded by a driver array of UO_2 rods arranged in a 1.3-cm pitch square lattice,
- "**Global Dissolution type**" experiments dealt with the mixture of FPs in depleted uranyl nitrate solutions, interacting with the array of UO_2 or HTC rods arranged in a 1.6-cm pitch square lattice.

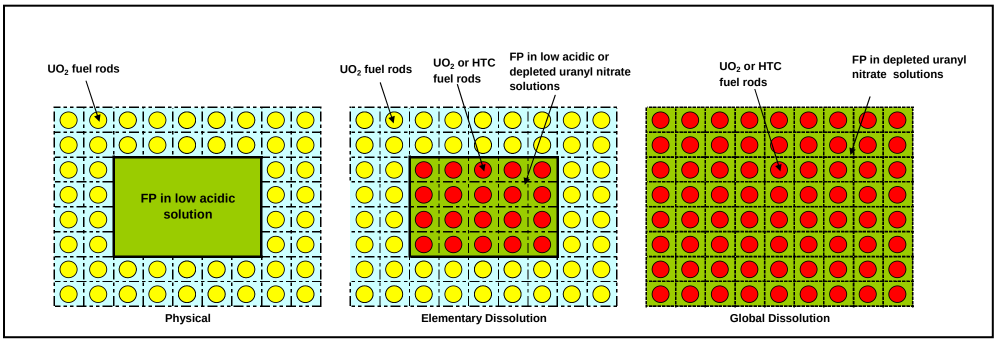

Figure 4: *FP critical experiments configurations*

4 SIMILARITY ANALYSIS BASED ON GLOBAL PHYSICAL PARAMETERS

The similarity of the selected integral experiments and the cask application is analysed using the following criteria:

- Global parameters: main neutron spectrum indicators for the TN® 24 E cask and experiments.
- Specific parameters: isotopic reaction rates for relevant isotopes in energy groups and media.

The first step of the similarity analysis consists in the selection of adequate cases of HTC and FP experiments. Series that contained soluble boron or gadolinium or used cadmium absorbers were discarded. Finally a set of 111 experiments from HTC and FP series was selected for the validation of the criticality code used for BUC.

4.1. Analysis of main spectral parameters

The global parameters calculated for the TN® 24 E configuration and for selected experimental cases are compared in Table 1. It can be pointed out that many of the global spectral parameter values (moderator to fuel ratio (V_m/V_f), slowing down parameter (q_{4eV})) of the selected cases are quite close to the TN® 24 E cask configuration. The EALF values for the selected experiments are a little lower than the one for the application case, mainly due to the reflectors being different (thick stainless steel for the TN® 24 E cask, water, lead and steel for the experiments). However, it should be noticed that the variation range of these parameters is not really large.

TN® 24 E	**Lattice type**	**Pu/(U+Pu)**	**q_{4eV}**	**EALF**	**V_m/V_f**
UOX 18×18 (4.65 wt. %). av. BU 12 GWd/t_{HM})	nominal expanded	0.54	0.7189	0.35	2.034 2.258
Experiment	**Number of selected cases**	**Pu/(U+Pu)**	**q_{4eV}**	**EALF**	**V_m/V_f**
MCT-HTC001	18	1.104	0.772 – 0.921	0.067 – 0.26	1.98 – 4.41
MCT-HTC003	6	1.104	0.80 – 0.82	0.14 – 0.15	3.74
MCT-HTC004	29	1.104	0.78 – 0.83	0.13 – 0.16	3.74
MCT-HTC005	7	1.104	0.80	0.23	3.74
LCT-PF002	28	0	0.78 – 0.81	0.23 – 0.25	2.01
MCT-PF003	14	0.183	0.78-0.80	0.23 – 0.24	2.01/1.83
MCT-PF005	5	0.183	0.79	0.23 – 0.24	2.01/1.83
MCT-PF007	4	1.104	0.82	0.14	3.74

***Table 1**: Fuel characteristics and global spectral parameters of TN® 24E application and experiments*

4.2. Reaction rates analysis for relevant isotopes

As the comparison of global spectral parameters over the whole core is not sufficient to demonstrate similarity, a comparison of fission and capture rates was performed for the main isotopes in the TN® 24 E configuration with respect to the selected experimental cases. The isotopes of main interest regarding production and absorption rates are ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and the relevant fission products in the TN® 24 E application (^{149}Sm, ^{143}Nd and ^{103}Rh).

The production rate balance for the main actinides (mainly ^{235}U and secondarily ^{239}Pu, see Figure 5) in the TN® 24 E cask is comprised between the experiments MCT-PF003 and MCT-PF005 (experiments with low plutonium content due to fresh UOX and HTC rods) and MCT-PF007 (more plutonium compared to the TN® 24 E due to the presence of only HTC rods corresponding to a burn up of 37.5 GWd/t_{HM}). For HTC experiments, the productions in ^{241}Pu are about 10%, whereas they are negligible in the TN® 24 E cask as well as in MCT-PF003 and MCT-PF005 experiments (which involve also HTC rods).

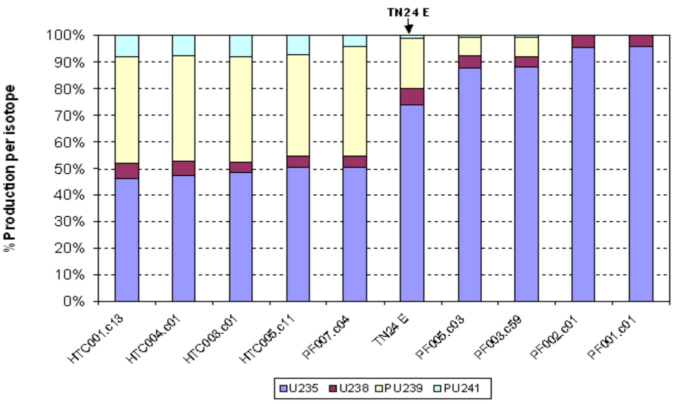

Figure 5: *Balance of production versus isotope in fissile media*

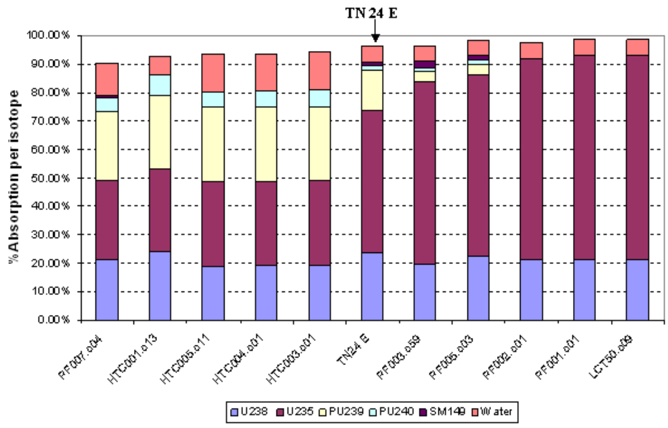

Figure 6: *Balance of absorption versus isotope in fissile media*

Concerning the absorption rate per isotope compared to the total absorption rate in fissile medium, the absorption in ^{235}U is dominant (due to fissions) (see Figure 6) for all of the tested configurations. The absorption in fission products such as ^{149}Sm is weak compared to other isotopes. The absorption balance in the TN® 24 E cask is quite similar to the experiments MCT-PF003 and MCT-PF005. Concerning the absorption rate in ^{239}Pu, the TN® 24 E is closer to MCT-PF007 and HTC experiments. Thus, it can be concluded that the TN® 24 E configuration is comprised between FP experiments involving HTC and UO_2 rods and the experiments with only HTC rods, including MCT-PF007 experiment.

A five energy-group structure [11] was chosen to analyse spectral effects. This energy group mesh (see Table 2) particularly fits the uranium, plutonium and main fission products resonances in the thermal and epithermal energy range.

Group 1	111 keV<E<19.6 MeV
Group 2	11.14 keV<E<111 keV
Group 3	9.906 eV<E<11.14 keV
Group 4	0.1 eV<E<9.906 eV
Group 5	E<0.1 eV

Table 2*: Five energy-group structure mesh*

The total production rate and total absorption rate per isotope in the fissile medium were plotted versus energy group (in the five energy-group structure) according the following formula:

$$\%\text{Production} = \frac{(\nu\Sigma_f\Phi)_i^{\text{isotope}}}{(\nu\Sigma_f\Phi)_i^{\text{total}}} \qquad \%\text{Absorption} = \frac{(\Sigma_a\Phi)_i^{\text{isotope}}}{(\Sigma_a\Phi)_i^{\text{total}}} \qquad (i= 1, 2,\ldots,5)$$

The spectral ratio of production rate in ^{235}U is shown in Figure 7. The total ratio of production in ^{235}U in the TN® 24 E lies between MCT-PF003, MCT-PF005 and experiments with only HTC rods, including MCT-PF007.

Although the balance of absorption is small in ^{149}Sm (Figure 6), it can be pointed out that absorption for this isotope in the TN® 24 E configuration is of the same order of magnitude as in MCT-PF005 and MCT-PF007 experiments with quite similar spectral ratio (Figure 8).

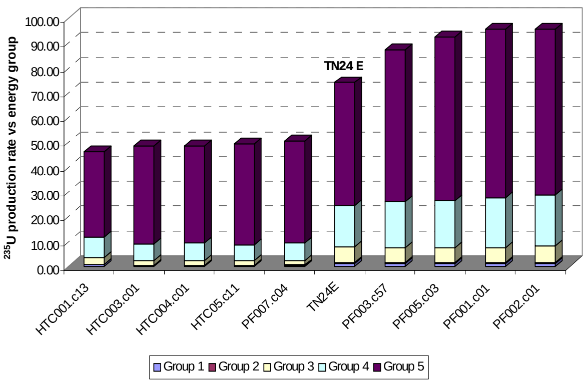

Figure 7: *^{235}U production rates in 5 energy groups*

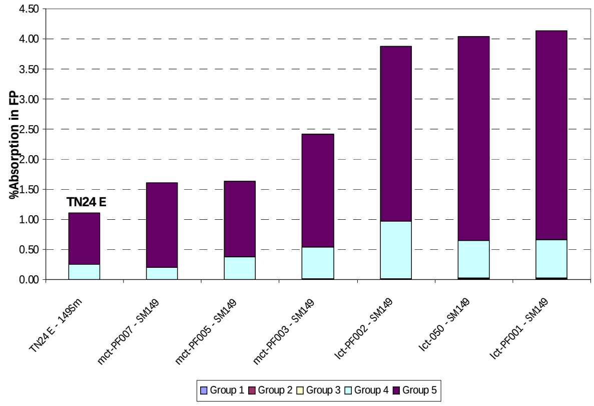

Figure 8: *^{149}Sm absorption rates in 5 energy groups*

As an intermediate conclusion, for the parameters being considered hereinbefore (global parameters and reaction rates), the TN® 24 E cask lies between the experiments MCT-PF003 and MCT-PF005 on one side, and MCT-PF007 on the other side.

5 SENSITIVITY/ UNCERTAINTY (S/U) ANALYSIS

S/U analysis is used to consolidate the results obtained by the analysis of the global spectral parameters and reaction rates.

5.1 Calculation tool and methods

The TSUNAMI-3D [12] code was used to compute sensitivities and the TSUNAMI-IP [13] code was used to compute correlations (c_k) between systems. The 238GROUPENDF/B-V cross section library was used. For the covariance data the recommended 44GROUPV5REC set was selected.
The approach consisted in building the KENO Va models for the cask and the experiments under SCALE 5.1 and verifying them thanks to the following verification tests:

- Numerical parameter verification.
- Convergence test for direct and adjoint k_{eff} calculations.
- Comparison between the computed integral sensitivities from TSUNAMI-3D and two KENO-V.a direct perturbation calculations.

5.2 Sensitivities analysis

In a first step, a comparison of sensitivity coefficients for the TN® 24 E cask demonstrates that the main contributions come from the most important actinides (^{235}U, ^{238}U, ^{239}Pu) and hydrogen scattering. It can also be noticed that sensitivities to FPs are a magnitude smaller than sensitivities to major actinides and hydrogen. For example, sensitivity to ^{149}Sm (the biggest contributor among FPs in the TN® 24 E, see Figure 9) is one order of magnitude lower than sensitivities to actinides and hydrogen. This is typical of fuel assemblies irradiated to a small burnup (see Figure 10).

It can be seen in Figure 10 that the TN® 24 E sensitivities are close to those of the FP experiments MCT-PF003 and MCT-PF005 (containing both UO_2 and HTC fuel rods, with an average Pu/(U+Pu) ratio similar to what is observed in low irradiated fuel assemblies).

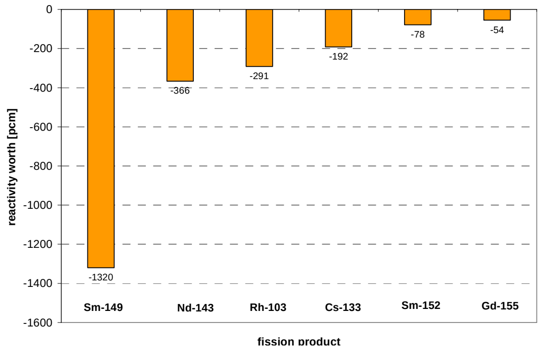

Figure 9: *FPs reactivity worth for the TN® 24 E nominal configuration*

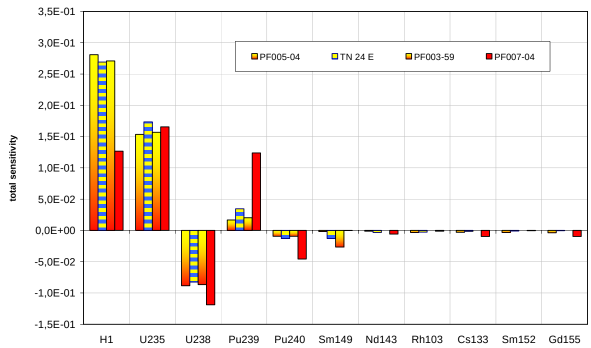

Figure 10: *Integrated total sensitivity by isotope for some FP experiments and the TN® 24 E nominal configuration*

In a second step, sensitivity profiles to relevant isotopes for the TN® 24 E configuration are compared to those for the FP and HTC experimental configurations. As an example, a comparison between the TN® 24 E and MCT-HTC series of sensitivity profiles to ^{235}U fission and ^{1}H capture are illustrated in Figure 11 and Figure 12. The sensitivity profiles for the TN® 24 E cask model and for the selected cases of the HTC series match very well (same sensitivity in thermal energy range and similar profile shape). In addition, Figure 11 and Figure 12 show that sensitivities for MCT-HTC001 cases are different and depend mainly on the pitch, while no trend is observed for configurations of series MCT-HTC003, MCT-HTC004 and MCT-HTC005, that have the same pitch.

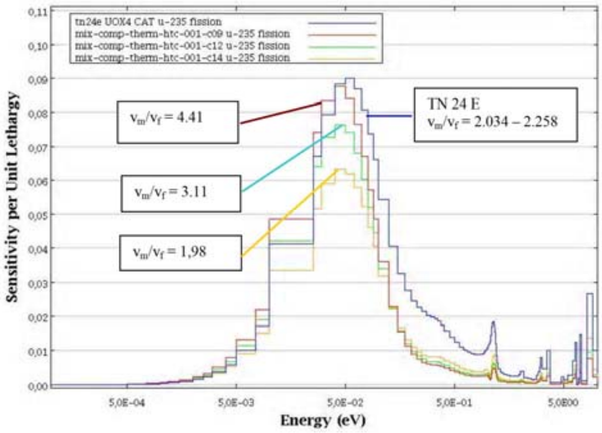

Figure 11: *^{235}U fission sensitivity profiles for TN 24 E and HTC001 series*

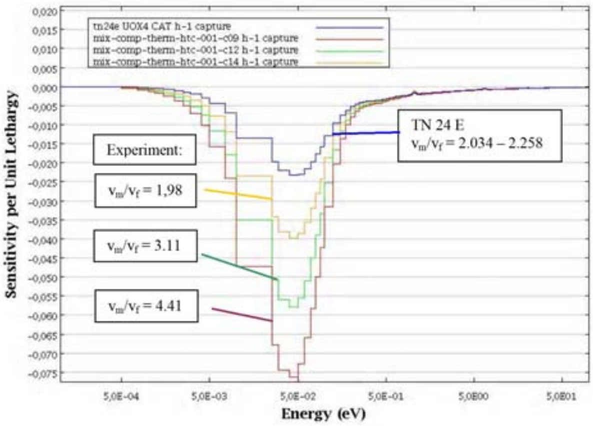

Figure 12 *^{1}H capture sensitivity profiles for TN 24 E and HTC001 series*

The selected experiments are water, lead and steel reflected. An analysis has been performed to ensure applicability of the benchmark configurations to safety analysis of the TN® 24 E application, which has a thick stainless steel shell. Comparison of the sensitivity profiles shows that the type of reflector does not impact significantly the sensitivities to major actinides, as demonstrated in Figure 13 for ^{235}U total

Figure 14 compares the ^{239}Pu fission sensitivity profiles between the TN® 24 E application and the experiments composed of only HTC rods or HTC and fresh UO_2 rods with different Pu/(U+Pu) ratios. The profile for TN® 24 E is located between those for the benchmark experiments. The profiles magnitudes are correlated with the Pu/(U+Pu) ratios.

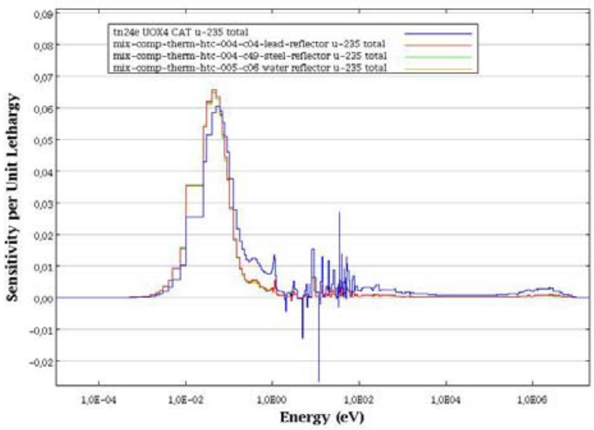

Figure 13: *^{235}U total sensitivity profiles for TN 24E and HTC004 series with different reflectors*

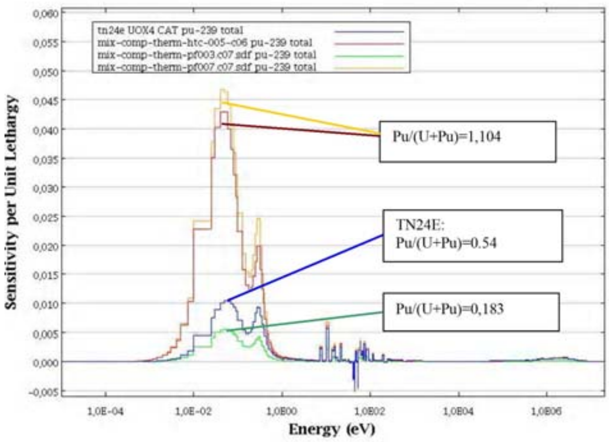

Figure 14: *^{239}Pu fission sensitivity profiles for TN 24 E and experiments with different Pu content*

Figures 15 and 16 compare the sensitivity profiles to ^{149}Sm and ^{143}Nd in the thermal energy range. It can be observed that the shapes of the sensitivity profiles are similar but their magnitude depends on the concentrations of the fission products in the experimental configurations.

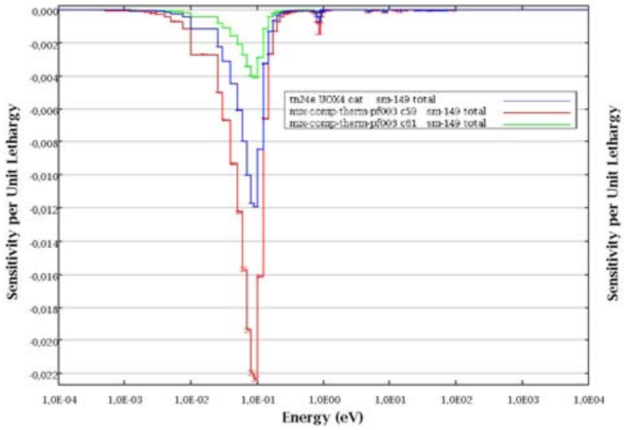

Figure 15: *Sensitivity profiles of ^{149}Sm total cross section*

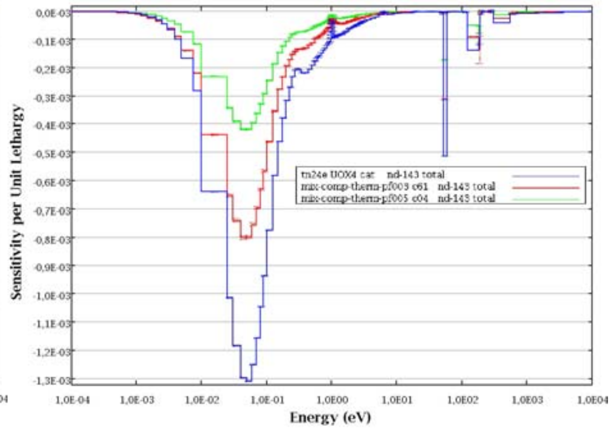

Figure 16: *Sensitivity profiles for ^{143}Nd total cross section*

5.3 Correlation between systems

The c_k correlation coefficients are calculated using TSUNAMI-IP for the HTC and FP experimental cases against the TN® 24 E application. Some of them are shown in Table 3. All the calculated correlation coefficients have values above 0.85, with the exception of the experiment MCT-HTC001 case 9, with a value of 0.8382 ± 0.0029. The strong (c_k above 0.90) correlation between the MCT-PF003 and MCT-PF005 cases and the TN® 24 E cask is due to the combination of UO_2 and HTC fuel rods in these experiments, which leads to a decrease of the average Pu content to a value closer to that of the TN® 24 E cask, whereas the presence of the fission products in the FP experiments does not significantly contribute to the c_k values due to small k_{eff} sensitivities to fission products' cross sections.

Series	Description	Case	c_k value
TN® 24 E	18x18 FA (4,65%, 12 GWd/t_{HM}) in RCT	nominal lattice	1.0000±0.0006
	18x18 FA (4,65%, 12 GWd/t_{HM}) in ACT	expanded lattice	0.9981±0.0006
MCT-HTC-001	mix-comp-therm-htc-001-c09	Case 09	0.8382±0.0029
	mix-comp-therm-htc-001-c12	Case 12	0.8639±0.0029
	mix-comp-therm-htc-001-c14	Case 14	0.8891±0.0029
MCT-HTC003	mix-comp-therm-htc-003-c04	Case 4	0.8676±0.0018
MCT-HTC004	mix-comp-therm-htc-004-c04	Case 4	0.8716±0.0019
MCT-HTC005	mix-comp-therm-htc-005-c11	Case 11	0.8622±0.0030
MCT-PF003	mix-comp-therm-pf003.c05	Case 5	0.9134±0.0032
MCT-PF005	mix-comp-therm-pf005.c04	Case 4	0.9158±0.0032
MCT-PF007	mix-comp-therm-pf007.c07	Case 7	0.8885±0.0018
LCT-PF-002	leu-comp-therm-pf002.c18	Case 18	0.8667±0.0031

Table 3: *Correlation coefficients C_k for TN® 24 E applications and representative HTC and FP experiments*

6 CONCLUSION

The results of the similarity analysis based on global spectral and reaction rate comparisons are consistent with those of the S/U analysis.

The correlation coefficients and sensitivity profiles calculated with the SCALE5.1 TSUNAMI tools on the basis of models for a representative TN® 24 E cask application and for a representative set of HTC and FP experiments show strong correlation between these configurations.

It can be pointed out that both methods, reaction rates and sensitivity comparison demonstrate that the actinides fuel composition along with the neutron moderation ratio in the fuel pin lattice are the dominant characteristics that determine the similarity between spent fuel systems.

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