RAPPORT

OECD / NEA

BURNUP CREDIT CRITICALITY BENCHMARK

ANALYSIS OF PHASE II-B RESULTS: CONCEPTUAL PWR SPENT FUEL TRANSPORTATION CASK

A. NOURI

IPSN / Département de Prévention et d'Etude des Accidents / Service d'Etudes de Criticité

Rapport IPSN/98-05

NEA/NSC/DOC(98)1

INSTITUT DE PROTECTION ET DE SURETE NUCLEAIRE

RÉPUBLIQUE FRANÇAISE

INSTITUT DE PROTECTION ET DE SÛRETÉ NUCLÉAIRE

DÉPARTEMENT DE PRÉVENTION ET D'ÉTUDE DES ACCIDENTS

Service d'Études de Criticité

BP 6, 92265 FONTENAY-AUX-ROSES CEDEX, France - Télecopie : (1) 46.57.29.98 - Téléphone : (1) 46.54.74.21

Demandeur	OCDE
Référence de la demande	
Numéro de la fiche d'action	
Référence de la note	**Rapport IPSN / 98-05, SEC/T/98.197, NEA/NSC/DOC(98)1**

TITRE : OECD / NEA BURNUP CREDIT CRITICALITY BENCHMARK ANALYSIS OF PHASE II-B RESULTS: CONCEPTUAL PWR SPENT FUEL TRANSPORTATION CASK

RESUME : Le groupe de travail « Burnup Credit Criticality Benchmark » de l'OCDE/AEN a étudié l'effet du profil axial du taux de combustion sur la criticité d'un emballage de transport d'assemblages REP irradiés (Phase II-B). Les résultats finaux de ce benchmark sont présentés et analysés dans le présent rapport. Neuf cas de base et deux configurations accidentelles complémentaires ont été considérés. Les paramètres étudiés sont : le taux de combustion (0 GWj/t dans le cas du combustible neuf, 30 et 50 GWj/t dans le cas du combustible irradié), la composition du combustible (selon que celle-ci comprend les actinides et les produits de fissions ou les actinides uniquement), la description du profil axial du taux de combustion (une ou neuf zones homogènes). Au total, quatorze participants appartenant à sept pays différents ont soumis des résultats partiels ou complets (keff et taux de fission).

De bons accords ont été obtenus entre les k_{eff} calculés par les participants. La dispersion des résultats, caractérisée par 2 σ_r (où σ_r est l'écart-type divisé par la valeur moyenne) variait entre 0,5 % et 1,1 % pour les cas avec un combustible irradié et valait 1,3 % pour le cas avec un combustible neuf. L'effet en réactivité du profil axial de taux de combustion dans les cas de base était similaire à celui obtenu dans la phase II-A : moins de 1000 pcm en valeur absolue pour les cas où le taux de combustion est inférieur ou égal à 30 GWj/t ou pour les cas sans produits de fission et de l'ordre de -4000 pcm pour le cas à 50 GWj/t avec les produits de fission. Ceci étant, l'étude des deux configurations accidentelles a mis en évidence que l'effet en réactivité de la discrétisation axiale du taux combustion dépendait de la configuration géométrique étudiée. En effet pour ces configurations accidentelles, l'approximation du taux de combustion axialement uniforme a été trouvée non conservatoire même pour de faibles valeurs du taux de combustion (10 GWj/t) et sans les produits de fission ; l'effet en réactivité du profil axial du taux de combustion atteignait -14000 pcm dans le cas où le taux de combustion est de 50 GWj/t et où la composition inclut les produits de fission.

Le calcul des fractions et des densités de fission a également été considéré. L'analyse a mis en évidence des problèmes de convergence des sources dans les cas où le profil axial du taux de combustion est décrit.

S.E.C.
VU DE CA Q
DATE : 12 Mai 1998
VISA
NOM : LEJANG

A	30/03/98	
IND.	DATE	OBJET

	Réservé à l'unité		Autorisation de diffusion		
	Auteur(s)	Vérificateur *	Chef d'Unité	Chef du DPEA	Directeur de l'IPSN
Noms	A. NOURI	GT OCDE Burnup Credit	P. COUSINOU	p.o J. DUCO	M. LIVOLANT
Dates	30/03/98	Décembre 97	23/04/98	05 mai 1998	11 mai 98
Signatures		N. T. GULLIFORD (AEA-Technology)			

* rapport sous assurance de la qualité

RÉSUMÉ

Le groupe de travail « Burn-up Credit Criticality Benchmark » de l'OCDE/AEN a étudié l'effet du profil axial du taux de combustion sur la criticité d'un emballage de transport d'assemblages REP irradiés (Phase II-B). Les résultats finaux de ce benchmark sont présentés et analysés dans le présent rapport.

Neuf cas de base et deux configurations accidentelles complémentaires ont été considérés. Les paramètres étudiés sont : le taux de combustion (0 GWj/t dans le cas du combustible neuf, 30 et 50 GWj/t dans le cas du combustible irradié), la composition du combustible (selon que celle-ci comprend les actinides et les produits de fissions ou les actinides uniquement), la description du profil axial du taux de combustion (une ou neuf zones homogènes). Au total, quatorze participants appartenant à sept pays différents ont soumis des résultats partiels ou complets (k_{eff} et taux de fission).

De bons accords ont été obtenus entre les k_{eff} calculés par les participants. La dispersion des résultats, caractérisée par 2 σ_r (où σ_r est l'écart-type divisé par la valeur moyenne) variait entre 0,5 % et 1,1 % pour les cas avec un combustible irradié et valait 1,3 % pour le cas avec un combustible neuf. L'effet en réactivité du profil axial de taux de combustion dans les cas de base était similaire à celui obtenu dans la phase II-A : moins de 1000 pcm en valeur absolue pour les cas où le taux de combustion est inférieur ou égal à 30 GWj/t ou pour les cas sans produits de fission et de l'ordre de -4000 pcm pour le cas à 50 GWj/t avec les produits de fission. Ceci étant, l'étude des deux configurations accidentelles a mis en évidence que l'effet en réactivité de la discrétisation axiale du taux combustion dépendait de la configuration géométrique étudiée. En effet pour ces configurations accidentelles, l'approximation du taux de combustion axialement uniforme a été trouvée non conservatoire même pour de faibles valeurs du taux de combustion (10 GWj/t) et sans les produits de fission ; l'effet en réactivité du profil axial du taux de combustion atteignait -14000 pcm dans le cas où le taux de combustion est 50 GWj/t et où la composition inclut les produits de fission.

Le calcul des fractions et des densités de fission a également été considéré. L'analyse a mis en évidence des problèmes de convergence des sources dans les cas où le profil axial du taux de combustion est décrit.

Mots-clé : Criticité, Taux de combustion, Assemblages REP, Emballage de transport, Profil axial du taux de combustion, Convergence des sources

SUMMARY

The OECD/NEA "Burn-up Credit Criticality Benchmark" working group has studied the effect of axial burn-up profile on the criticality of a realistic PWR spent fuel transport cask (Phase II-B). The final results of this benchmark are presented and analysed in this report.

Nine basic cases and two additional accident configurations were considered with the following varying parameters: burn-up (0 GWd/t for fresh fuel, 30 and 50 GWd/t), fuel composition (actinides only and actinides with fifteen fission products), axial burn-up discretisation (1 or 9 zones). In all, fourteen participants from seven different countries submitted partial or complete results (multiplication factors, fission reaction rates).

Good agreement was found between participants for calculated k_{eff}. The dispersion of results, characterised by 2 σ_r (where σ_r is the ratio between the standard deviation and the average value) ranged from 0.5% to 1.1% for irradiated fuels and was equal to 1.3% for fresh fuel. The reactivity effect of axial burn-up profile for basic cases was similar to that obtained in Phase II-A: less than 1000 pcm for cases with burn-up less than or equal to 30 GWd/t or for cases without fission products and about -4000 pcm for 50 GWd/t burn-up and composition including fission products. However, two accident cases highlighted that the reactivity effect of axial burn-up discretisation depends on the configuration studied. For the accident conditions defined for this benchmark, the axially averaged flat distribution was found to be a non-conservative approximation even for low burn-ups (10 GWd/t) and without fission products; the reactivity effect of burn-up profile reached -14000 pcm for 50 GWd/t burn-up and composition including fission products.

The calculation of fission fractions and densities was also investigated. The analysis identified problems of source convergence when the axial burn-up profile is modelled.

Keywords: criticality, burn-up, PWR fuel, transport cask, axial burn-up profile, end effect, source convergence

TABLE OF CONTENTS

List of tables

List of figures

GLOSSARY OF TERMS AND ABBREVIATIONS

ID:	Inner diameter
OD:	Outer diameter
σ:	Standard deviation
σ_r:	Reduced standard deviation defined as σ divided by the average value
pcm:	10^{-5}
FP:	Fission product
BU:	Burn-up
$\Delta\rho$:	Reactivity effect
Fission density:	Volume-averaged fission reaction rate in a given region (see § 4)
Fission fraction:	Proportion of fissions in a given region (see § 4)

For the two last quantities the normalisation used is such that the sum over all regions is equal to 1.

I. INTRODUCTION

The aim of Phase II of the OECD/NEA Burn-up Credit working group was to study the effect of axial burn-up profile on the criticality of configurations containing PWR fuel assemblies. This phase was divided into two benchmark exercises, namely Phase II-A and Phase II-B. A description of these benchmarks is given below. This report presents the results and analysis of Phase II-B.

Phase II-A

The configuration considered was a laterally infinite array of PWR fuel with the following characteristics:

- initial enrichment equal to 3.6 wt% or 4.5 wt%;
- fuel diameter equal to 0.824 cm and array pitch equal to 1.33 cm which lead to a moderation ration Vmod/Vox = 2.0;
- different burn-ups: 0, 10, 30 or 50 GWd/t, and two cooling times: 1 or 5 years;
- axially, a symmetrical configuration was adopted comprising 9 fuel regions (total height = 365.7 cm), an upper and lower plug and water reflector (30 cm).

In total 26 configurations were calculated by 18 different participants from 10 different countries.

Phase II-B

A realistic configuration of 21 PWR spent fuel assemblies in a stainless steel transport flask was evaluated (see Appendix 1 and Figures 1, 2 and 3). A borated stainless steel basket centred in the flask separates the assemblies. The basket (5×5 array with the four corner positions removed) was fully flooded with water. The main characteristics of the fuel assembly are:

- 17×17 array (289 rods, no guide tubes), water moderated cells with pitch equal to 1.2598 cm;
- initial fuel enrichment equal to 4.5 wt%;
- fuel diameter equal to 0.8192 cm, rod ID = 0.8357 cm and OD = 0.9500 cm which lead to a moderation ratio Vmod / Vox = 1.67.

Nine different specified cases were studied (which are a subset of the total 26 cases studied in Phase II-A). The following parameters were considered:

- Burn-up: 0 (fresh fuel), 30 GWd/t or 50 GWd/t.

- Cooling time: 5 years.

- Fuel composition: the composition used was specified in Phase II-A (see Appendix 1). For irradiated fuels, two types of representation were studied, one where the composition included both actinides and fission products and a second where only actinides were present.

- Axial burn-up modelling: as in Phase II-A, the effect of burn-up profile modelling was studied. Two approximations were compared: one uniform burn-up zone (equal to the axial average burn-up) and an axially symmetrical distributed burn-up represented by nine uniform zones as shown in Figure 3; the burn-up in each zone is given in the following table.

	Zone dimension (in cm) and burn-up (in GWd/t)				
Zone number	1 and 9	2 and 8	3 and 7	4 and 6	5
Dimension (cm)	5	5	10	20	285.7
Burn-up (GWd/t) Av. = 30 GWd/t	12.33	14.04	18.01	24.01	32.86
Burn-up (GWd/t) Av. = 50 GWd/t	21.57	24.02	30.58	40.42	54.61

These cases are summarised in Table 1.

D. Mennerdahl made a proposal for two additional benchmarks (X1 and X2) in order to accentuate the effect of axial burn-up profile discretisation in accident conditions (Appendix 2). The specifications of these benchmarks are close to those of Cases A and B: burn-up equal to 30 GWd/t, fission products included, with or without burn-up profile. The only change consists of reducing the borated steel basket height. Thus, while the top of this basket is at the same level as water in the basic cases (A and B), it becomes 20 cm lower than the top of fuel assemblies in the modified cases (X1 and X2). This introduces a strong axial heterogeneity to the problem which has an important impact on modelling effects associated with representations of the axial burn-up profile.

Fourteen participants from seven different countries submitted partial or complete results (k_{eff} and fission densities). Table 2 gives a brief description of the participants, of the system of codes and of cross-sections libraries used. A more detailed description is reported in Appendix 3.

II. SOME STATISTICAL CONSIDERATIONS

The statistical analysis presented in this report is slightly different from the one considered in Phase II-A. Some definitions are first introduced before the analysis of results.

An estimate of the average value of a sample of n data x_i is given by:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

When n is the full size of the sample, the standard deviation, which characterises the spread of the sample, is defined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n}}$$

When n is not the full size of the sample, an unbiased estimate of the standard deviation is given by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n-1}}$$

Using these definitions, it is clear that the value of σ depends on the magnitude of x_i. As an example, let us consider two series of results: $\left(x_1 = 0.90,\ x_2 = 1.00,\ x_3 = 1.10\right)$ and $\left(y_1 = 9.00,\ y_2 = 10.00,\ y_3 = 11.00\right)$, we find:

$\bar{x}$ = 1.00 and the corresponding σ = 0.10; $\bar{y}$ = 10.00 and the corresponding σ = 1.00.

At first sight we might conclude that the spread in the y_i series is higher than the x_i series, which would be misleading since the two series are similarly distributed. In this case the parameter chosen to characterise the spread of the samples is not adequate for comparison purposes. It is more convenient to use the relative standard deviation defined as:

$$\sigma_r = {}^{\sigma}\!\big/_{\left|\bar{x}\right|}$$

that gives the same spread for the two series, i.e. $\sigma_r = 10\%$.

In this study, the x_i are parameters (k_{eff}, reaction rates) calculated by different participants. Because of the complexity of the configuration investigated, all calculations, except those carried out by CSN, were based on the Monte Carlo method. Thus, for each x_i value, as well as for the average, there is an associated statistical uncertainty. The statistical uncertainty in $\overline{x}$ is the square root of the quadratic sum of the individual statistical uncertainties divided by n. A typical value of the statistical uncertainty on individual k_{eff} is 0.02%. Thus, the average k_{eff} values are statistically very accurate and the associated relative standard deviation reflects the real spread of results. On the other hand, statistically accurate results are more difficult to obtain for reactions rates, particularly in regions where the flux is very small. It is not unusual to find individual statistical uncertainties of the order of the x_i value. Thus, the average value $\overline{x}$ has a large statistical uncertainty that strongly contributes to the relative standard deviation.

III. RESULTS AND DISCUSSION

1. *Multiplication factors and standard deviation*

Table 3 lists the multiplication factors obtained by all participants. It also provides the average multiplication factor and the value of the quantity 2 * σ_r.

Table 4 shows the discrepancies in the calculated k_{eff} of each participant from the average value. These discrepancies, expressed in pcm (1 pcm = 10^{-5}), were calculated as:

$$\ln\left(\frac{k_i}{\bar{k}}\right)$$

k_i is the individual multiplication factor and $\bar{k}$ is the average k_{eff}.

This table also shows the minimum and maximum values of the discrepancies for each case. We notice that BfS-IKE results are the lowest ones for cases with flat burn-up distribution and that CSN results are the highest ones for cases including fission products. This last observation can be explained by the absence of three FPs (^{95}Mo, ^{99}Tc and ^{101}Ru) in the CSN calculations (see CSN comments in Appendix 3). If BfS-IKE results for uniform burn-up cases (A, A', C and C') and CSN results for cases including FPs (A, B, C and D) are not taken into account in the analysis, the dispersions of k_{eff} values are found to be smaller (sometimes by a factor of 4) for all cases (see Table 3). The results can be grouped into three main categories:

- participants with results significantly greater than the average: ABB, BNFL, IPSN, JINS-1 and UKDOT;
- participants with results significantly lower than the average: EMS, GRS, JINS-2, ORNL and PNC; all these participants use codes and cross-section libraries derived from the SCALE system;
- participants with results close to the average values: CEA and JAERI.

From Table 3 we can make the following remarks:

- the relative standard deviation is higher for fresh fuel ($2\sigma_r$ = 1.3%) than for cases with other major and minor actinides (from 0.5% to 1.1%);
- when fission products are included, the relative standard deviation of the calculated k_{eff} values is decreased;
- when the axial burn-up profile is modelled, the relative standard deviation of the calculated k_{eff} values is increased.

The lowest $2\sigma_r$ value was obtained for 50 GWd/t burn-up, a flat burn-up profile and with composition including fission products. The first two remarks suggest the existence of compensating effects between, on the one hand, the differences of uranium cross-sections and on the other hand, the differences of other actinides and fission products cross-sections. The third remark suggests that a precise description of axial burn-up profile introduces a difficulty of computation.

The multiplication factors are rather different from those obtained in the previous benchmark exercise (Phase II-A). The differences may be attributed to:

- differences in the configurations: in Phase II-A, laterally infinite array was studied while in Phase II-B a radially finite cask containing 21 assemblies separated by borated stainless steel and reflected by stainless steel was considered; also, axial differences exist between the two configurations;

- differences in the moderation ratio.

For instance, the following table gives some comparisons:

Case # in Phase II-A	14	23	24	25	26
Case # in Phase II-B	E	D	C	D’	C’
Burn-up (GWd/t)	0 (fresh fuel)	50	50	50	50
FP included ?	–	Y	Y	N	N
BU profile ?	–	Y	N	Y	N
(Phase II-A) Average k_{eff} $2 * \sigma_r$	 1.4783 1.6%	 1.0543 1.5%	 1.0123 1.3%	 1.1800 0.9%	 1.1734 0.8%
(Phase II-B) Average k_{eff} $2 * \sigma_r$	 1.1257 1.3%	 0.7933 0.8%	 0.7641 0.5%	 0.8791 1.0%	 0.8737 0.7%

Since the participation in the benchmarks has changed between the two phases it is not completely valid to compare the dispersion of results. Also, this dispersions depends, as shown in Table 3, on the data discarded from the analysis due to specific approximations used.

2. *Effect of axial burn-up distribution*

In Table 5, the reactivity effect of the axial burn-up distribution (also called the end effect) is measured (in pcm) using the following expression:

$$\Delta\rho = \ln\left(\frac{k(\text{uniform axial burnup})}{k(\text{nine axial burnup zones})}\right)$$

When this value is negative, it means that a precise modelisation of the axial profile makes the multiplication factor higher and that the uniform axial burn-up hypothesis is not conservative. Table 5 also gives, for each case, the average effect of the axial burn-up and a measure of the spread of the results ($2 * \sigma_r$). It is important to note that due to statistical uncertainties in k_{eff} the dispersion of the small end effects is consequently high.

From this table one can make the following remarks:

- the end effects found by BfS-IKE are very different from the other participants (this was not observed in the previous phase); indeed, as we have already noticed, BfS-IKE results for cases with flat burn-up distribution are too low, which leads to negative end effects for all cases;

- if BfS-IKE results are not considered, very good agreements are obtained between the remaining participants with a relative small spread of results (appended to Table 5 are the averages and dispersions without BfS-IKE results);

- for cases without fission products, the absolute value of the end effect is less than 1000 pcm even for 50 GWd/t burn-up;

- for the 30 GWd/t burn-up, the absolute value of the end effect is still lower than 1000 pcm, even with fission products;

- for high burn-ups the uniform distribution hypothesis is not conservative;

- the end effect increases when the fission products are included, which leads the uniform distribution to under-predict the k_{eff} by about -4000 pcm for burn-up equal to 50 GWd/t.

All these remarks are consistent with those found in the previous benchmark exercise. The following table gives a direct comparison of the end effect in both phases (BfS-IKE results of Phase II-B were not taken into account). The end effects reported in Phase II-A were normalised by the corresponding k_{eff} values in order compare similar quantities.

Burn-up (GWd/t)	50	50
FP included ?	Y	N
(Phase II-A) Average end effect (pcm) 2 * σ_r	 -3994 22%	 -559 116%
(Phase II-B) Average end effect (pcm) 2 * σ_r	 -3722 12%	 -567 83%

A good agreement is found between the results of the two phases.

3. *Additional cases*

The calculation results submitted by the participants to this extra exercise are reported in Table 6. As expected, these results clearly indicate that the end effect depends on the configuration studied. While the flat burn-up distribution approximation can be acceptable for configurations studied in Phase II-A and in basic Phase II-B cases, for burn-ups lower than or equal to 30 GWd/t, the additional cases show large (and thus non acceptable) under-predictions (about -8000 pcm) due to this approximation. Additional cases, calculated by D. Mennerdahl and G. Poullot show that even for a 10 GWd/t burn-up, one year cooling time and without considering FPs, the flat distribution approximation under-predicts the k_{eff} by about -2000 pcm and that this under-prediction exceeds -14000 pcm for a 50 GWd/t burn-up when FPs are included. Clearly, axially homogeneous fuel burn-up models are not suitable for cases where other strong axial heterogeneities are present.

4. Fission fractions and densities

The end effect discussed in the previous section is related to axial fission distribution. In Phase II-A, fission densities in nine zones, as defined in the following formula, were investigated:

$$X_i = \frac{\dfrac{\int_{V_i} \Sigma_f(\vec{r},E)\Phi(\vec{r},E)d\vec{r}dE}{V_i}}{\sum_i \left(\dfrac{\int_{V_i} \Sigma_f(\vec{r},E)\Phi(\vec{r},E)d\vec{r}dE}{V_i} \right)} \quad (1)$$

where V_i is the volume of zone i, Φ is the scalar flux and Σ_f the fission macroscopic cross-section. X_i is then the number of fissions by unit volume in region i normalised to one fission by unit volume in the whole system. In Phase II-B, contributors were asked to calculate fission fractions, defined as:

$$F_i = \frac{\int_{V_i} \Sigma_f(\vec{r},E)\Phi(\vec{r},E)d\vec{r}dE}{\sum_i \int_{V_i} \Sigma_f(\vec{r},E)\Phi(\vec{r},E)d\vec{r}dE} \quad (2)$$

F_i is then the number of fissions in region i normalised to one fission in the whole system. The data submitted by participants are collected in Table 7. One can easily see that different definitions and normalisation assumptions were used. The data submitted by BNFL was a five-zone fission profile were regions 1+9, 2+8, 3+7and 4+6 were summed, which assumes that the fission profile may be treated as being symmetric. Since the asymmetry of fission distribution will be investigated, BNFL data was not considered in this section. The data in Table 7 was first normalised to unity by dividing each value by the sum over all regions (Table 8). From this table we clearly see that BfS-IKE, BNFL, CSN, EMS, JAERI, ORNL and UKDOT calculated fission densities while IPSN, JINS-1, JINS-2 and PNC calculated fission fractions. Table 9 gives the modified results of all participants in terms of fission fractions and Table 10 gives fission densities. To transform fission fractions into fission densities each value F_i is divided by the volume of the corresponding zone and the resulting values are normalised to unity. Multiplying X_i values by the corresponding volume and normalising the resulting values to unity is required to transform fission densities to fission fractions. In Tables 9 and 10, average values and dispersions among participants are also reported. Here again, it is important to note that due to Monte Carlo statistical uncertainties, regions where reaction rates are small are not adequately sampled. The dispersion of these results is strongly influenced by statistical uncertainties.

Fission fractions and densities (average values in Tables 9 and 10) for flat burn-up cases (A, C and E) and for distributed burn-up cases (B and D) are presented in Figures 4, 4bis, 5 and 5bis.

While about 90% of fissions occur in the central region for flat burn-up cases, this proportion decreases with increasing burn-up for distributed burn-up cases: about 50% for 30 GWd/t and 28% for 50 GWd/t. Fission in peripheral regions shows corresponding increases which helps explain changes in the end effect with burn-up. This effect is perhaps shown more clearly in the fission densities (Figures 4bis and 5bis). For flat axial burn-up cases, the fission density is close to a cosine while in distributed axial burn-up cases the fission density is minimal in the central region. This phenomenon is accentuated with increasing burn-up. Note that for cases with burn-up profile it is unclear whether the fission distribution is symmetrical or not. In fact, the configuration is slightly asymmetrical due to additional hardware at the top of the cask. So, despite the symmetrical burn-up profile, the resulting fission density may show strong asymmetry. For instance, at a first sight, Case D (50 GWd/t with fission products) seems to present a symmetrical profile (Figure 5 or 5bis), but this results from compensations since there are three classes of results of equal importance:

- strongly asymmetrical distribution toward the top of the cask;
- strongly asymmetrical distribution toward the bottom of the cask;
- symmetrical distribution.

A more accurate representation of fission or flux distribution was investigated by J. Conde and J. Stewart. Figure 6 gives fission density distribution obtained by Stewart for Cases D, D’ and E and Figures 7 and 8 give neutron fluxes calculated by Conde for Cases A through E.

Figures 9 through 13 (respectively 9bis through 13bis) give the fission fractions (respectively fission densities) obtained by participants for Cases A, B, C, D and E. It is not surprising that the agreement between participants are fairly good for cases with flat burn-up distribution. In contrast, Cases B and D where a burn-up profile was modelled exhibit large discrepancies. The shapes obtained for fission fractions do not show the same asymmetry properties. For some participants, strong asymmetry is observed, favouring regions at the top of the fuel assembly (BfS-IKE, IPSN, JAERI) or at the bottom (CSN, ORNL and UKDOT), while some fission profiles are quite symmetrical (JINS-1, JINS-2, PNC). The fission profile is related to the eigenfunction convergence in the calculation which was not achieved in the same way in different codes. The discussion of this phenomenon cannot be carried out in detail in this report since it requires more information about calculation parameters (number of neutrons per generation, neutron source distribution in the first generation...) and the strategy of each code to control and to achieve the convergence (number of generation skipped and source powering algorithms). Some participants consider that this is a secondary problem since only eigenvalue convergence is required and others believe that eigenfunction convergence is also of importance. Some tests were made by S. Mitake and O. Sato in order to study the effect of calculation parameters on the convergence (see Appendix 5). In particular, the number of generations was varied from 103 to 3203 with fixed number of neutrons by generation equal to 300. The results show that the convergence is not achieved even with increased generations and that the deviation of multiplication factors are about 0.5% $\Delta k/k$. The effect of the number of neutrons by generation (with fixed number of generations) was also investigated and the results show that eigenfunction convergence was achieved with about 2400 neutrons by generation. Other tests were made by G. Poullot and A. Nouri on the effect of initial source distribution on the convergence. The results clearly show that this distribution is of importance for cases with burn-up profile and that its effect on the eigenvalue may be important.

In conclusion, this section showed that the eigenfunction convergence aspects (calculation parameters and powering strategy) become important for configurations with distributed burn-up profile. More detailed discussions require specific calculations and code comparisons and it may be of interest to be investigated in a separate phase.

5. Safety margins

As far as the end effect is concerned, the results of this phase can be summarised by considering the safety margins available in different calculation hypotheses. To this end, the reference calculation is taken for irradiated fuel where the composition includes actinides and the fifteen selected fission products and with axial burn-up described by nine uniform zones. The progressive hypotheses that were considered in this study are:

1) fresh fuel;

2) irradiated fuel where the composition includes only actinides (without FPs) and axially average flat burn-up distribution;

3) irradiated fuel including actinides and FPs and with axially average flat burn-up distribution.

The safety margins are then evaluated as:

$$\Delta\rho = \ln\left(\frac{k_{eff}\,(\text{hypothesis})}{k_{eff}\,(\text{reference})}\right) \text{ (in pcm)}$$

The following tables give these margins for the two kinds of configurations studied, namely: basic cases and accidental situations (in accidental situations, additional results for burn-up equal to 50 GWd/t were submitted by D. Mennerdhal and G. Poullot). We see that average flat burn-up approximation should be used with care since it can lead to non-conservative results, even for irradiated fuel composition without FPs. The reactivity effect resulting from axial burn-up approximations should be evaluated for each practical application.

Safety margins for basic cases (in pcm)

	Modelling approximations		
Burn-up (GWd/t)	Fresh fuel	Irradiated fuel No FPs – Flat burn-up	Irradiated fuel FPs included – Flat burn-up
30	22820	8010	-350
50	34870	9370	-3990

Safety margins for accidental situations (in pcm)

	Modelling approximations		
Burn-up (GWd/t)	Fresh fuel	Irradiated fuel No FPs – Flat burn-up	Irradiated fuel FPs included – Flat burn-up
30	14530	700	-8120
50	23870	10	-14480

IV. CONCLUSIONS

In the Phase II-B benchmark, a realistic configuration describing 21 PWR spent fuel assemblies in a stainless steel transport cask was studied to analyse the effect of the axial burn-up distribution on the multiplication factor. Additional cases addressing an accidental upward shift of the fuel assemblies were also studied. If we restrict ourselves to the basic cases (A through E and A' through D'), the conclusions of this study can be presented as follows:

- If one discards CSN results for cases which include FPs and BfS-IKE results for cases with flat burn-up distribution, good agreements were found between the results submitted by the twelve other participants. The difference of individual results from the average multiplication factor varies from -700 pcm to +700 pcm, except for fresh fuel where the discrepancies vary from -1000 pcm to +1000 pcm.

- The end effect is small for burn-ups less than or equal to 30 GWd/t or for cases without fission products (less than 1000 pcm).

- When the burn-up exceeds 30 GWd/t and when fission products are included in the fuel composition, the end effect becomes important and the uniform axial distribution underpredicts the multiplication factor by about -4000 pcm.

These results are fairly consistent with those obtained in the Phase II-A.

However, results for the accident configurations illustrate the limitations of the last two conclusions. The axially average flat burn-up distribution is found to be a non-conservative approximation, even for very low burn-ups and without including FPs. Clearly, the use of axially homogeneous fuel compositions may be unsuitable for cases where there are significant axial heterogeneities.

The comparison of fission distributions indicates problems of eigenfunction convergence for cases with burn-up profile. This problem involves code algorithms and calculation parameters that are not all known for this study. Complementary studies are needed to investigate this particular problem of convergence in more detail.

Acknowledgements

The author is indebted to all participants for their contribution to this benchmark and for valuable discussions during the sessions. Special thanks to M. Brady (Mikey) for her enthusiastic chairing of the working group, to E. Sartori for his constant support and help during the preparation of the manuscript and to N.T. Gulliford (Jim) for reviewing the text. Thanks go to A. McWhorter for her dedication in editing this report and for her efforts to improve the layout of the text.

REFERENCES

[1] M. Takano, “OECD/NEA Burn-up Credit Criticality Benchmark-Results of Phase-IA. Simple PWR Spent Fuel Cell”, JAERI-M 94-003, NEA/NSC/DOC(93)22, January 94.

[2] M.D. Dehart, M.C. Brady and C.V. Parks, “OECD/NEA Burn-up Credit Criticality Benchmark: Phase I-B Results”, ORNL-6901, NEA/NSC/DOC(96)06, June 96.

[3] M. Takano and H. Okuno, “OECD/NEA Burn-up Credit Criticality Benchmark: Results of Phase II-A”, Report JAERI-Research 96-003, NEA/NSC/DOC(96)01 (February 96).

[4] “Proposed Spent Fuel Cask Geometry: OECD Phase II-B Benchmark”, NEA/NSC/DOC(94)25, May 1994.

[5] D. Mennerdhal, “Burn-up Credit Benchmark Problems: Flat or Realistic Axial Profiles?”, EMS/FO/94.04 and EMS/FO/95.07, October 95.

Table 1. Cases identification (nine basic cases)

Case #	Burn-up (GWd/t)	Axial profile modelled?	Fission product included?
A	30	No	Yes
A’	30	No	No
B	30	Yes	Yes
B’	30	Yes	No
C	50	No	Yes
C’	50	No	No
D	50	Yes	Yes
D’	50	Yes	No
E	0 (fresh fuel)	–	–

For all irradiated fuels the cooling time is equal to five years.

Table 2. List of participants

#	Participant	Country	Code used	Library used	Groups	Comments
1	ABB	Sweden	PHOENIX4 (2-D lattice code) + KENO-V.a (MC)	PHOENIX4 library (ENDF/B6)	89	MC calculation performed using 99 groups
2	BfS-IKE	Germany	CHM / MORSE-K	242-group library (JEF-1) 60-group for MORSE	242/60	Cr and Fe were omitted in the fuel cladding material
3	BNFL	UK	MONK (MC)	8220 group UKNDL + JEF2.2 for FP	Pointwise	
4	CEA	France	APOLLO-2 (assembly code) + TRIMARAN-2 (MC)	CEA93 (JEF2.2)	99	MC calculation performed using 16 groups
5	CSN	Spain	CASMO-3/SIMULATE-3P	70-group E4LTJB7 (ENDF/B4-B5 anf JEF2)	70	^{95}Mo, ^{99}Tc and ^{101}Ru were omitted
6	EMS	Sweden	SCALE-4.1	27 group burn-up library	27	
7	GRS	Germany	SCALE-4	27 group depletion library	27	
8	IPSN	France	APOLLO-1 (assembly code) + MORET-3 (MC)	CEA86 (JEF1 + ENDF/B4 and B5)	99	
9	JAERI	Japan	MCNP-4A (MC)	JENDL3.2	Pointwise	
10	JINS-1	Japan	KENO-V.a (MC)	MGCL-JINS (JENDL3.2 for FP and ENDF/B4 for the others)	137	Fuel pellets, clads and moderators are modelled individually. No smeared technique applied.
11	JINS-2	Japan	KENO-V.a (MC)	Scale 27 group library	27	
12	ORNL	USA	SCALE-4.3	Scale 44Groupndf5	44	CSAS25 sequence for no axial distribution. CSASN sequence + stand-alone KENO-V.a for cases with axial distribution.
13	PNC	Japan	SCALE-4.2	27 group burn-up library	27	
14	UKDOT	UK	MONK-6.B (MC)	8220 group UKNDL + JEF2.2 for FP	Pointwise	

Table 3. Multiplication factors k_{eff} from participants (nine basic cases)

Case #	A	A'	B	B'	C	C'	D	D'	E
Burn-up (GWd/t)	30	30	30	30	50	50	50	50	0 (fresh fuel)
Fission product included?	Y	N	Y	N	Y	N	Y	N	–
Burn-up profile modelled?	N	N	Y	Y	N	N	Y	Y	–

#	Institute	Country	Code used	A	A'	B	B'	C	C'	D	D'	E
1	ABB	Sweden	PHOENIX4/KENO-V.a	0.8953		0.8968		0.7665		0.7950		1.1309
2	BfS-IKE	Germany	CGM/MORSE-K	0.8762	0.9595	0.9003	0.9693	0.7407	0.8553	0.7977	0.8839	1.1272
3	BNFL	UK	MONK	0.8958	0.9780	0.9008	0.9689	0.7640	0.8765	0.7967	0.8811	1.1345
4	CSN	Spain	CASMO-3/SIMULATE-3P	0.9034	0.9742	0.9058	0.9676	0.7755	0.8753	0.8073	0.8847	1.1246
5	CEA	France	APOLLO-2 + TRIMARAN-2	0.8932	0.9714	0.8916	0.9636	0.7613	0.8749	0.7906	0.8791	1.1297
6	EMS	Sweden	SCALE-4.1	0.8900	0.9683	0.8900	0.9594	0.7630	0.8720	0.7923	0.8751	1.1155
7	GRS	Germany	SCALE-4	0.8917	0.9652	0.8906	0.9588	0.7625	0.8706	0.7915	0.8754	1.1172
8	IPSN	France	APOLLO-1 + MORET-3	0.8976	0.9776	0.8978	0.9709	0.7651	0.8770	0.7944	0.8846	1.1337
9	JAERI	Japan	MCNP-4A	0.8923	0.9718	0.8919	0.9629	0.7650	0.8733	0.7923	0.8771	1.1291
10	JINS-1	Japan	KENO-V.a	0.8997	0.9773	0.8997	0.9711	0.7690	0.8792	0.7988	0.8831	1.1270
11	JINS-2	Japan	KENO-V.a	0.8883	0.9641	0.8908	0.9573	0.7614	0.8683	0.7885	0.8742	1.1122
12	ORNL	USA	SCALE-4.3	0.8912	0.9684	0.8944	0.9594	0.7642	0.8711	0.7921	0.8721	1.1214
13	PNC	Japan	SCALE-4.2	0.8904	0.9670	0.8913	0.9602	0.7628	0.8703	0.7890	0.8756	1.1202
14	UKDOT	UK	MONK-6.B	0.8956	0.9763	0.9028	0.9716	0.7644	0.8757	0.7940	0.8817	1.1363
			Case #	A	A'	B	B'	C	C'	D	D'	E
			Average k_{eff}	0.8929	0.9707	0.8960	0.9647	0.7632	0.8723	0.7943	0.8791	1.1257
			$2\ \sigma_r$	1.4%	1.2%	1.1%	1.1%	1.9%	1.3%	1.2%	1.0%	1.3%
			Average*	0.8934	0.9716	0.8953	0.9647	0.7641	0.8737	0.7933	0.8791	1.1257
			$2\ \sigma^*_r$	0.7%	1.0%	1.0%	1.1%	0.5%	0.7%	0.8%	1.0%	1.3%

* Average value and relative standard deviation were calculated without taking into account BfS-IKE results for cases A, A’ C and C’ and CSN results for cases A, B, C and D.

Table 4. Relative difference from average k_{eff} value (nine basic cases)

$$\ln\left(\frac{k_{eff,i}}{\bar{k}_{eff}}\right) \text{ expressed in pcm}$$

Case #	A	A'	B	B'	C	C'	D	D'	E
Burn-up (GWd/t)	30	30	30	30	50	50	50	50	0 (fresh fuel)
Fission product included?	Y	N	Y	N	Y	N	Y	N	–
Burn-up profile modelled?	N	N	Y	Y	N	N	Y	Y	–

#	Institute	Country	Code used	A	A'	B	B'	C	C'	D	D'	E
1	ABB	Sweden	PHOENIX4/KENO-V.a	268		84		426		88		463
2	BfS-IKE	Germany	CGM/MORSE-K	-1889	-1161	474	476	-2998	-1965	427	550	135
3	BNFL	UK	MONK	324	749	529	435	99	484	301	232	781
4	CSN	Spain	CASMO-3/SIMULATE-3P	1168	359	1083	300	1593	347	1624	640	-98
5	CEA	France	APOLLO-2 + TRIMARAN-2	33	71	-497	-114	-255	301	-467	5	357
6	EMS	Sweden	SCALE-4.1	-326	-248	-677	-551	-32	-31	-252	-451	-908
7	GRS	Germany	SCALE-4	-135	-569	-610	-613	-97	-192	-353	-417	-756
8	IPSN	France	APOLLO-1 + MORET-3	524	708	196	641	243	541	12	629	710
9	JAERI	Japan	MCNP-4A	-71	116	-461	-183	234	117	-254	-222	306
10	JINS-1	Japan	KENO-V.a	761	681	407	665	754	796	566	459	116
11	JINS-2	Japan	KENO-V.a	-519	-682	-586	-769	-247	-460	-729	-553	-1204
12	ORNL	USA	SCALE-4.3	-191	-238	-184	-551	125	-134	-278	-794	-381
13	PNC	Japan	SCALE-4.2	-281	-383	-531	-467	-58	-226	-670	-394	-488
14	UKDOT	UK	MONK-6.B	301	575	751	713	151	393	-38	300	939
			Minimum relative difference	-1889	-1161	-677	-769	-2998	-1965	-729	-794	-1204
			Maximum relative difference	1168	749	1083	713	1593	796	1624	640	939

Table 5. Reactivity effect of burn-up profile (basic cases)

$$\Delta\rho = \ln\left(\frac{k_{eff}(\text{uniform axial burn - up})}{k_{eff}(\text{nine axial burn - up zones}}\right) \text{ expressed in pcm}$$

Case #	1	2	3	4
Burn-up (GWd/t)	30	30	50	50
Fission product included?	Y	N	Y	N

#	Institute	Country	Code used	1	2	3	4
1	ABB	Sweden	PHOENIX4/KENO-V.a	-167		-3651	
2	BfS-IKE	Germany	CGM/MORSE-K	-2713	-1016	-7414	-3289
3	BNFL	UK	MONK	-557	935	-4191	-523
4	CSN	Spain	CASMO-3/SIMULATE-3P	-265	680	-4020	-1068
5	CEA	France	APOLLO-2 + TRIMARAN-2	179	806	-3776	-479
6	EMS	Sweden	SCALE-4.1	0	923	-3768	-355
7	GRS	Germany	SCALE-4	123	665	-3733	-550
8	IPSN	France	APOLLO-1 + MORET-3	-22	688	-3758	-863
9	JAERI	Japan	MCNP-4A	39	919	-3501	-436
10	JINS-1	Japan	KENO-V.a	3	636	-3801	-438
11	JINS-2	Japan	KENO-V.a	-284	708	-3506	-682
12	ORNL	USA	SCALE-4.3	-358	934	-3586	-115
13	PNC	Japan	SCALE-4.2	-101	706	-3377	-607
14	UKDOT	UK	MONK-6.B	-801	483	-3799	-683
			Average	-352	620	-4006	-776
			2* σ_r	401%	158%	50%	196%
			Average (without BfS-IKE)	-170	757	-3722	-567
			2 * σ_r (without BfS-IKE)	317%	37%	12%	83%

A negative value of $\Delta\rho$ means that the uniform axial burn-up hypothesis is not conservative.

Table 6. k_{eff} and reactivity effect of burn-up profile for additional benchmarks (accidental situations cf. Appendix 4)

$$\Delta\rho(\text{pcm}) = \ln\left(\frac{k_{eff}\,(\text{without profile})}{k_{eff}\,(\text{with profile})}\right)$$

Case #	X1	X2
Burn-up (GWd/t)	30	30
Fission product included?	Y	Y
Burn-up profile modelled?	N	Y

#	Institute	Country	Code used	k_{eff}	k_{eff}	End effect Δρ (pcm)
3	BNFL	UK	MONK	0.9236	1.0003	-7978
5	CEA	France	APOLLO-2 + TRIMARAN-2	0.9216	1.0026	-8424
6	EMS	Sweden	SCALE-4.1	0.9291	1.0035	-7703
8	IPSN	France	APOLLO-1 + MORET-3	0.9295	1.0081	-8118
10	JINS-1	Japan	KENO-V.a	0.9328	1.0094	-7892
11	JINS-2	Japan	KENO-V.a	0.9222	0.9998	-8079
14	UKDOT	UK	MONK-6.B	0.9219	1.0003	-8162
			Average	0.9258	1.0034	-8051
			2* σ_r	0.9%	0.7%	5.2%

Table 7. Fission densities/fractions as submitted by participants

			CASE A Burn-up = 30 GWd/t – FP included – No BU profile									**CASE A'** Burn-up = 30 GWd/t – No FP included – No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	6.52	7.944	11.2	16.52	27.36	12.41	8.767	5.179	4.102	1.835	3.946	3.83	6.924	39.09	19.46	11.1	7.707	6.107
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.135	0.19	0.282	0.462	1.184	0.466	0.286	0.194	0.142	0.134	0.189	0.281	0.462	1.184	0.466	0.3	0.194	0.141
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.05	0.06	0.09	0.14	0.28	0.15	0.11	0.08	0.06	0.05	0.06	0.09	0.15	0.27	0.15	0.1	0.07	0.05
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	6E-04	8E-04	0.002	0.009	0.932	0.039	0.011	0.003	0.002	0.001	0.002	0.005	0.024	0.942	0.017	0.006	0.002	0.001
9	JAERI	Japan	0.041	0.06	0.084	0.124	0.361	0.138	0.085	0.062	0.045	0.037	0.051	0.079	0.136	0.483	0.099	0.057	0.034	0.023
10	JINS-1	Japan	0.002	0.003	0.007	0.022	0.898	0.045	0.014	0.005	0.004	0.002	0.003	0.01	0.033	0.912	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.003	0.01	0.03	0.918	0.024	0.007	0.003	0.002	0.002	0.003	0.008	0.027	0.92	0.026	0.008	0.003	0.002
12	ORNL	USA	2E-07	2E-07	3E-07	5E-07	9E-07	2E-07	1E-07	1E-07	8E-08	2E-07	2E-07	3E-07	5E-07	1E-06	3E-07	2E-07	1E-07	7E-08
13	PNC	Japan	0.003	0.004	0.011	0.034	0.906	0.029	0.009	0.003	0.002	0.002	0.003	0.009	0.027	0.909	0.034	0.01	0.003	0.002
14	UKDOT	UK	0.012	0.015	0.023	0.038	0.34	0.243	0.149	0.099	0.081	0.048	0.062	0.091	0.15	0.365	0.124	0.076	0.049	0.035

			CASE B Burn-up = 30 GWd/t – FP included – Nine-zone profile									**CASE B'** Burn-up = 30 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.751	0.862	1.104	1.233	3.969	26.22	26.46	21.75	17.65	7.403	9.055	12.22	14.93	11.46	15.22	12.46	9.676	7.58
3	BNFL	UK	0.086	0.111	0.135	0.135	0.066	0.135	0.135	0.111	0.086	0.074	0.095	0.12	0.138	0.146	0.138	0.12	0.095	0.074
4	CSN	Spain	0.118	0.153	0.186	0.183	0.597	4.943	5.105	4.249	3.365	0.679	0.901	1.149	1.279	0.847	2.216	2.015	1.596	1.236
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.02	0.02	0.03	0.03	0.03	0.25	0.25	0.2	0.17	0.13	0.16	0.21	0.24	0.08	0.06	0.05	0.04	0.03
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.038	0.047	0.117	0.243	0.521	0.018	0.009	0.004	0.003	0.004	0.005	0.013	0.029	0.757	0.117	0.046	0.017	0.013
9	JAERI	Japan	0.121	0.15	0.187	0.185	0.053	0.092	0.087	0.07	0.054	0.071	0.09	0.119	0.133	0.096	0.156	0.14	0.108	0.087
10	JINS-1	Japan	0.037	0.046	0.113	0.223	0.505	0.04	0.021	0.008	0.007	0.01	0.013	0.034	0.079	0.73	0.077	0.034	0.013	0.01
11	JINS-2	Japan	0.032	0.04	0.097	0.194	0.48	0.083	0.042	0.017	0.014	0.016	0.02	0.054	0.126	0.688	0.057	0.023	0.009	0.007
12	ORNL	USA	2E-06	2E-06	3E-06	3E-06	5E-07	6E-07	6E-07	5E-07	4E-07	7E-07	9E-07	1E-06	1E-06	8E-07	6E-07	6E-07	4E-07	3E-07
13	PNC	Japan	0.017	0.022	0.054	0.104	0.573	0.122	0.063	0.025	0.02	0.009	0.012	0.031	0.072	0.747	0.075	0.032	0.012	0.009
14	UKDOT	UK	0.045	0.054	0.069	0.07	0.029	0.213	0.211	0.167	0.142	0.066	0.084	0.112	0.131	0.095	0.165	0.146	0.11	0.09

This table gives the data as submitted by participants. Note that this data is not homogeneous since on the one hand two different definitions of fission distribution were used (fission density as defined in Eq. 1 or fission fraction as defined in Eq. 2), and on the other hand different normalisations were assumed. In Tables 9 and 10 the data is made homogeneous as discussed in Paragraph 4.

Table 7. Fission densities/fractions as submitted by participants (cont.)

			CASE C Burn-up = 50 GWd/t - FP included - No BU profile									**CASE C'** Burn-up = 50 GWd/t - No FP included - No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden																		
2	BfS-IKE	Germany	2.979	4.1	6.495	11.04	35.45	15.28	11.17	7.7	5.789	2.126	2.838	4.13	7.343	29.2	23.52	14.43	9.142	7.262
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.135	0.19	0.282	0.462	1.184	0.466	0.286	0.195	0.142	0.133	0.189	0.281	0.461	1.184	0.465	0.285	0.193	0.14
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.03	0.04	0.07	0.1	0.23	0.23	0.14	0.09	0.07	0.05	0.07	0.11	0.2	0.34	0.1	0.05	0.04	0.03
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	3E-04	4E-04	0.001	0.005	0.97	0.017	0.004	0.001	8E-04	4E-04	7E-04	0.003	0.01	0.904	0.057	0.016	0.005	0.004
9	JAERI	Japan	0.03	0.046	0.07	0.118	0.444	0.14	0.076	0.048	0.029	0.029	0.04	0.057	0.103	0.425	0.155	0.089	0.06	0.042
10	JINS-1	Japan	0.002	0.003	0.009	0.028	0.914	0.029	0.009	0.003	0.002	0.003	0.003	0.01	0.03	0.913	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.003	0.003	0.01	0.032	0.921	0.021	0.007	0.002	0.002	0.002	0.003	0.009	0.029	0.913	0.029	0.01	0.003	0.002
12	ORNL	USA	7E-08	1E-07	1E-07	2E-07	8E-07	4E-07	2E-07	1E-07	1E-07	1E-07	2E-07	3E-07	5E-07	9E-07	3E-07	2E-07	1E-07	1E-07
13	PNC	Japan	0.002	0.003	0.01	0.03	0.907	0.031	0.011	0.004	0.003	0.003	0.003	0.011	0.035	0.89	0.038	0.012	0.004	0.003
14	UKDOT	UK	0.042	0.057	0.087	0.163	0.339	0.135	0.083	0.056	0.039	0.042	0.056	0.089	0.159	0.377	0.123	0.07	0.047	0.036

			CASE D Burn-up = 50 GWd/t – FP included – Nine-zone profile									**CASE D'** Burn-up = 50 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	13.97	16.58	18.44	14.56	1.291	8.589	10.22	8.94	7.415	8.452	10.58	12.84	12.26	3.254	13.94	15.14	12.77	10.76
3	BNFL	UK	0.104	0.131	0.143	0.11	0.024	0.11	0.143	0.131	0.104	0.09	0.115	0.136	0.128	0.061	0.128	0.136	0.115	0.09
4	CSN	Spain	0.009	0.011	0.012	0.01	0.324	6.198	8.068	7.419	6.1	0.037	0.047	0.055	0.051	0.502	5.542	6.159	5.299	4.225
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.14	0.16	0.18	0.14	0.01	0.09	0.11	0.1	0.08	0.18	0.22	0.26	0.25	0.03	0.02	0.02	0.02	0.01
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.081	0.095	0.214	0.336	0.253	0.009	0.007	0.003	0.002	0.032	0.041	0.102	0.19	0.439	0.101	0.055	0.022	0.017
9	JAERI	Japan	0.14	0.165	0.183	0.142	0.012	0.08	0.103	0.094	0.081	0.053	0.065	0.078	0.073	0.026	0.188	0.204	0.172	0.141
10	JINS-1	Japan	0.041	0.048	0.109	0.174	0.285	0.161	0.1	0.044	0.037	0.018	0.021	0.052	0.099	0.471	0.177	0.091	0.039	0.032
11	JINS-2	Japan	0.036	0.041	0.093	0.15	0.292	0.183	0.112	0.05	0.043	0.018	0.022	0.051	0.095	0.464	0.186	0.095	0.038	0.032
12	ORNL	USA	8E-07	1E-06	1E-06	9E-07	2E-07	3E-06	4E-06	4E-06	3E-06	9E-07	1E-06	1E-06	1E-06	4E-07	3E-06	3E-06	3E-06	2E-06
13	PNC	Japan	0.04	0.048	0.106	0.173	0.316	0.147	0.093	0.042	0.035	0.021	0.026	0.063	0.121	0.525	0.131	0.065	0.026	0.022
14	UKDOT	UK	0.052	0.062	0.069	0.053	0.011	0.167	0.217	0.199	0.17	0.045	0.054	0.066	0.063	0.027	0.197	0.218	0.181	0.148

This table gives the data as submitted by participants. Note that this data is not homogeneous since on the one hand two different definitions of fission distribution were used (fission density as defined in Eq. 1 or fission fraction as defined in Eq. 2), and on the other hand different normalisations were assumed. In Tables 9 and 10 the data is made homogeneous as discussed in Paragraph 4.

Table 7. Fission densities/fractions as submitted by participants (cont.)

CASE E											
			Fresh fuel								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	4.339	5.726	9.22	14.17	28.8	15.91	9.604	6.692	5.536
3	BNFL	UK	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.133	0.189	0.286	0.461	1.184	0.465	0.285	0.193	0.139
5	CEA	France	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.06	0.08	0.12	0.18	0.26	0.13	0.08	0.06	0.04
7	GRS	Germany	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.001	0.002	0.006	0.024	0.935	0.022	0.006	0.002	0.001
9	JAERI	Japan	0.029	0.042	0.066	0.121	0.454	0.127	0.076	0.048	0.037
10	JINS-1	Japan	0.002	0.003	0.008	0.026	0.923	0.025	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.002	0.007	0.023	0.925	0.027	0.009	0.003	0.002
12	ORNL	USA	2E-07	2E-07	3E-07	4E-07	1E-06	8E-07	5E-07	4E-07	3E-07
13	PNC	Japan	0.002	0.003	0.008	0.026	0.91	0.035	0.011	0.004	0.002
14	UKDOT	UK	0.042	0.059	0.086	0.139	0.364	0.126	0.085	0.057	0.042

This table gives the data as submitted by participants. Note that this data is not homogeneous since on the one hand two different definitions of fission distribution were used (fission density as defined in Eq. 1 or fission fraction as defined in Eq. 2), and on the other hand different normalisations were assumed. In Tables 9 and 10 the data is made homogeneous as discussed in Paragraph 4.

Table 8. Normalised fission densities/fractions

			CASE A Burn-up = 30 GWd/t – FP included – No BU profiles									**CASE A'** Burn-up = 30 GWd/t – No FP included – No BU profiles								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.065	0.079	0.112	0.165	0.274	0.124	0.088	0.052	0.041	0.018	0.039	0.038	0.069	0.391	0.195	0.111	0.077	0.061
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.084	0.138	0.354	0.139	0.086	0.058	0.043	0.040	0.056	0.084	0.138	0.353	0.139	0.090	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.049	0.059	0.088	0.137	0.275	0.147	0.108	0.078	0.059	0.051	0.061	0.091	0.152	0.273	0.152	0.101	0.071	0.051
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.001	0.001	0.002	0.009	0.932	0.039	0.011	0.003	0.002	0.001	0.002	0.005	0.024	0.942	0.017	0.006	0.002	0.001
9	JAERI	Japan	0.041	0.060	0.084	0.124	0.361	0.138	0.085	0.062	0.045	0.037	0.051	0.079	0.136	0.483	0.099	0.057	0.034	0.023
10	JINS-1	Japan	0.002	0.003	0.007	0.022	0.898	0.045	0.014	0.005	0.004	0.002	0.003	0.010	0.033	0.912	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.003	0.010	0.030	0.918	0.024	0.007	0.003	0.002	0.002	0.003	0.008	0.027	0.920	0.026	0.008	0.003	0.002
12	ORNL	USA	0.059	0.072	0.112	0.182	0.352	0.092	0.057	0.041	0.032	0.056	0.078	0.118	0.187	0.352	0.090	0.055	0.039	0.025
13	PNC	Japan	0.003	0.004	0.011	0.034	0.905	0.029	0.009	0.003	0.002	0.002	0.003	0.009	0.027	0.910	0.034	0.010	0.003	0.002
14	UKDOT	UK	0.012	0.015	0.023	0.038	0.340	0.243	0.149	0.099	0.081	0.048	0.062	0.091	0.150	0.365	0.124	0.076	0.049	0.035

			CASE B Burn-up = 30 GWd/t – FP included – Nine-zone profile									**CASE B'** Burn-up = 30 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.008	0.009	0.011	0.012	0.040	0.262	0.265	0.217	0.177	0.074	0.091	0.122	0.149	0.115	0.152	0.125	0.097	0.076
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.006	0.008	0.010	0.010	0.032	0.262	0.270	0.225	0.178	0.057	0.076	0.096	0.107	0.071	0.186	0.169	0.134	0.104
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.020	0.020	0.030	0.030	0.030	0.250	0.250	0.200	0.170	0.130	0.160	0.210	0.240	0.080	0.060	0.050	0.040	0.030
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.038	0.047	0.117	0.243	0.521	0.018	0.009	0.004	0.003	0.004	0.005	0.013	0.029	0.757	0.117	0.046	0.017	0.013
9	JAERI	Japan	0.121	0.150	0.187	0.185	0.053	0.092	0.087	0.070	0.054	0.071	0.090	0.119	0.133	0.096	0.156	0.140	0.108	0.087
10	JINS-1	Japan	0.037	0.046	0.113	0.223	0.505	0.040	0.021	0.008	0.007	0.010	0.013	0.034	0.079	0.730	0.077	0.034	0.013	0.010
11	JINS-2	Japan	0.032	0.040	0.097	0.194	0.480	0.083	0.042	0.017	0.014	0.016	0.020	0.054	0.126	0.688	0.057	0.023	0.009	0.007
12	ORNL	USA	0.154	0.189	0.229	0.231	0.040	0.046	0.045	0.036	0.030	0.102	0.128	0.168	0.192	0.121	0.093	0.082	0.064	0.051
13	PNC	Japan	0.017	0.022	0.054	0.104	0.573	0.122	0.063	0.025	0.020	0.009	0.012	0.031	0.072	0.748	0.075	0.032	0.012	0.009
14	UKDOT	UK	0.045	0.054	0.069	0.070	0.029	0.213	0.211	0.167	0.142	0.066	0.084	0.112	0.131	0.095	0.165	0.146	0.110	0.090

Normalised fission distributions are reported in this table. The results of each participant and for each case are normalised to unity. Note that this data is still heterogeneous since BfS-IKE, CSN, EMS, JAERI, ORNL and UKDOT results are fission densities (see Eq. 1) while IPSN, JINS-1, JINS-2 and PNC results are fission fractions (see Eq. 2).

Table 8. Normalised fission densities/fractions (cont.)

			CASE C Burn-up = 50 GWd/t – FP included – No BU profile									**CASE C'** Burn-up = 50 GWd/t – No FP included – No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.030	0.041	0.065	0.110	0.355	0.153	0.112	0.077	0.058	0.021	0.028	0.041	0.073	0.292	0.235	0.144	0.091	0.073
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.084	0.138	0.354	0.140	0.086	0.058	0.043	0.040	0.057	0.084	0.138	0.355	0.140	0.086	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.030	0.040	0.070	0.100	0.230	0.230	0.140	0.090	0.070	0.051	0.071	0.111	0.202	0.343	0.101	0.051	0.040	0.030
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.000	0.000	0.001	0.005	0.970	0.017	0.004	0.001	0.001	0.000	0.001	0.003	0.010	0.904	0.057	0.016	0.005	0.004
9	JAERI	Japan	0.030	0.046	0.070	0.118	0.444	0.140	0.076	0.048	0.029	0.029	0.040	0.057	0.103	0.425	0.155	0.089	0.060	0.042
10	JINS-1	Japan	0.002	0.003	0.009	0.028	0.914	0.029	0.009	0.003	0.002	0.003	0.003	0.010	0.030	0.913	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.003	0.003	0.010	0.032	0.921	0.021	0.007	0.002	0.002	0.002	0.003	0.009	0.029	0.913	0.029	0.010	0.003	0.002
12	ORNL	USA	0.032	0.046	0.067	0.108	0.360	0.167	0.100	0.067	0.054	0.052	0.068	0.106	0.165	0.318	0.118	0.076	0.054	0.043
13	PNC	Japan	0.002	0.003	0.010	0.030	0.906	0.031	0.011	0.004	0.003	0.003	0.003	0.011	0.035	0.891	0.038	0.012	0.004	0.003
14	UKDOT	UK	0.042	0.057	0.087	0.163	0.339	0.135	0.083	0.056	0.039	0.042	0.056	0.089	0.159	0.377	0.123	0.070	0.047	0.036

			CASE D Burn-up = 50 GWd/t – FP included – Nine-zone profile									CASE D' Burn-up = 50 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.140	0.166	0.184	0.146	0.013	0.086	0.102	0.089	0.074	0.085	0.106	0.128	0.123	0.033	0.139	0.151	0.128	0.108
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.000	0.000	0.000	0.000	0.012	0.220	0.287	0.264	0.217	0.002	0.002	0.003	0.002	0.023	0.253	0.281	0.242	0.193
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.139	0.158	0.178	0.139	0.010	0.089	0.109	0.099	0.079	0.178	0.218	0.257	0.248	0.030	0.020	0.020	0.020	0.010
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.081	0.095	0.214	0.336	0.254	0.009	0.007	0.003	0.002	0.032	0.041	0.102	0.190	0.439	0.101	0.055	0.022	0.017
9	JAERI	Japan	0.140	0.165	0.183	0.142	0.012	0.080	0.103	0.094	0.081	0.053	0.065	0.078	0.073	0.026	0.188	0.203	0.172	0.141
10	JINS-1	Japan	0.041	0.048	0.109	0.174	0.285	0.161	0.100	0.044	0.037	0.018	0.021	0.052	0.099	0.471	0.177	0.091	0.039	0.032
11	JINS-2	Japan	0.036	0.041	0.093	0.150	0.292	0.183	0.112	0.050	0.043	0.018	0.022	0.051	0.095	0.464	0.186	0.094	0.038	0.032
12	ORNL	USA	0.044	0.053	0.061	0.049	0.013	0.177	0.223	0.204	0.176	0.057	0.067	0.080	0.074	0.027	0.187	0.199	0.167	0.141
13	PNC	Japan	0.040	0.048	0.106	0.173	0.316	0.147	0.093	0.042	0.035	0.021	0.026	0.063	0.121	0.525	0.131	0.065	0.026	0.022
14	UKDOT	UK	0.052	0.062	0.069	0.053	0.011	0.167	0.217	0.199	0.170	0.045	0.054	0.066	0.063	0.027	0.197	0.218	0.181	0.148

Normalised fission distributions are reported in this table. The results of each participant and for each case are normalised to unity. Note that this data is still heterogeneous since BfS-IKE, CSN, EMS, JAERI, ORNL and UKDOT results are fission densities (see Eq. 1) while IPSN, JINS-1, JINS-2 and PNC results are fission fractions (see Eq. 2).

Table 8. Normalised fission densities/fractions (cont.)

CASE E											
		Fresh fuel									
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.043	0.057	0.092	0.142	0.288	0.159	0.096	0.067	0.055
3	BNFL	UK	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.086	0.138	0.355	0.139	0.085	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.059	0.079	0.119	0.178	0.257	0.129	0.079	0.059	0.040
7	GRS	Germany	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.001	0.002	0.006	0.024	0.935	0.022	0.006	0.002	0.001
9	JAERI	Japan	0.029	0.042	0.066	0.121	0.454	0.127	0.076	0.048	0.037
10	JINS-1	Japan	0.002	0.003	0.008	0.026	0.923	0.025	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.002	0.007	0.022	0.925	0.027	0.009	0.003	0.002
12	ORNL	USA	0.038	0.047	0.067	0.106	0.264	0.196	0.129	0.086	0.068
13	PNC	Japan	0.002	0.003	0.008	0.026	0.909	0.035	0.011	0.004	0.002
14	UKDOT	UK	0.042	0.059	0.086	0.139	0.364	0.126	0.085	0.057	0.042

Normalised fission distributions are reported in this table. The results of each participant and for each case are normalised to unity. Note that this data is still heterogeneous since BfS-IKE, CSN, EMS, JAERI, ORNL and UKDOT results are fission densities (see Eq. 1) while IPSN, JINS-1, JINS-2 and PNC results are fission fractions (see Eq. 2).

Table 9. Normalised fission fractions

			CASE A Burn-up = 30 GWd/t – FP included – No BU profile									**CASE A'** Burn-up = 30 GWd/t – No FP included – No BU profiles								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.004	0.005	0.013	0.038	0.897	0.028	0.010	0.003	0.002	0.001	0.002	0.003	0.012	0.935	0.033	0.009	0.003	0.003
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.002	0.003	0.008	0.025	0.925	0.025	0.008	0.003	0.002	0.002	0.003	0.008	0.025	0.924	0.025	0.008	0.003	0.002
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.003	0.003	0.010	0.031	0.898	0.034	0.012	0.004	0.003	0.003	0.003	0.010	0.035	0.895	0.035	0.012	0.004	0.003
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.001	0.001	0.002	0.009	0.932	0.039	0.011	0.003	0.002	0.001	0.002	0.005	0.024	0.942	0.017	0.006	0.002	0.001
9	JAERI	Japan	0.002	0.003	0.008	0.022	0.928	0.025	0.008	0.003	0.002	0.001	0.002	0.005	0.019	0.953	0.014	0.004	0.001	0.001
10	JINS-1	Japan	0.002	0.003	0.007	0.022	0.898	0.045	0.014	0.005	0.004	0.002	0.003	0.010	0.033	0.912	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.003	0.010	0.030	0.918	0.024	0.007	0.003	0.002	0.002	0.003	0.008	0.027	0.920	0.026	0.008	0.003	0.002
12	ORNL	USA	0.003	0.003	0.010	0.033	0.925	0.017	0.005	0.002	0.001	0.003	0.004	0.011	0.034	0.924	0.017	0.005	0.002	0.001
13	PNC	Japan	0.003	0.004	0.011	0.034	0.905	0.029	0.009	0.003	0.002	0.002	0.003	0.009	0.027	0.910	0.034	0.010	0.003	0.002
14	UKDOT	UK	0.001	0.001	0.002	0.007	0.921	0.046	0.014	0.005	0.004	0.002	0.003	0.008	0.027	0.928	0.022	0.007	0.002	0.002
		Average	0.002	0.003	0.008	0.025	0.915	0.031	0.010	0.003	0.002	0.002	0.003	0.008	0.026	0.924	0.025	0.008	0.003	0.002
		2 * σ_r	86%	80%	78%	74%	3%	55%	54%	55%	61%	63%	51%	58%	49%	3%	54%	54%	62%	66%

			CASE B Burn-up = 30 GWd/t – FP included – Nine-zone profile									**CASE B'** Burn-up = 30 GWd/t – No FP included – None-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.002	0.002	0.005	0.011	0.524	0.242	0.122	0.050	0.041	0.009	0.011	0.028	0.070	0.763	0.071	0.029	0.011	0.009
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.002	0.002	0.005	0.010	0.467	0.271	0.140	0.058	0.046	0.009	0.012	0.031	0.070	0.662	0.121	0.055	0.022	0.017
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.005	0.005	0.016	0.032	0.451	0.263	0.131	0.053	0.045	0.020	0.024	0.063	0.144	0.687	0.036	0.015	0.006	0.005
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.038	0.047	0.117	0.243	0.521	0.018	0.009	0.004	0.003	0.004	0.005	0.013	0.029	0.757	0.117	0.046	0.017	0.013
9	JAERI	Japan	0.024	0.029	0.073	0.145	0.598	0.072	0.034	0.014	0.011	0.009	0.012	0.031	0.070	0.731	0.083	0.037	0.014	0.012
10	JINS-1	Japan	0.037	0.046	0.113	0.223	0.505	0.040	0.021	0.008	0.007	0.010	0.013	0.034	0.079	0.730	0.077	0.034	0.013	0.010
11	JINS-2	Japan	0.032	0.040	0.097	0.194	0.480	0.083	0.042	0.017	0.014	0.016	0.020	0.054	0.126	0.688	0.057	0.023	0.009	0.007
12	ORNL	USA	0.036	0.043	0.106	0.213	0.524	0.042	0.021	0.008	0.007	0.011	0.014	0.038	0.086	0.777	0.042	0.018	0.007	0.006
13	PNC	Japan	0.017	0.022	0.054	0.104	0.573	0.122	0.063	0.025	0.020	0.009	0.012	0.031	0.072	0.748	0.075	0.032	0.012	0.009
14	UKDOT	UK	0.012	0.014	0.036	0.075	0.443	0.226	0.112	0.044	0.038	0.009	0.011	0.030	0.070	0.725	0.089	0.039	0.015	0.012
		Average	0.020	0.025	0.062	0.125	0.508	0.138	0.070	0.028	0.023	0.011	0.013	0.035	0.082	0.727	0.077	0.033	0.013	0.010
		2 * σ_r	132%	133%	131%	132%	18%	133%	134%	135%	134%	73%	70%	72%	71%	9%	66%	68%	68%	67%

Table 9. Normalised fission fractions (cont.)

			CASE C Burn-up = 50 GWd/t – FP included – No BU profile									**CASE C'** Burn-up = 50 GWd/t – No FP included – No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.001	0.002	0.006	0.020	0.926	0.028	0.010	0.004	0.003	0.001	0.002	0.004	0.016	0.902	0.051	0.016	0.005	0.004
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.002	0.003	0.008	0.025	0.925	0.025	0.008	0.003	0.002	0.002	0.003	0.008	0.025	0.925	0.025	0.008	0.003	0.002
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.002	0.003	0.009	0.026	0.870	0.061	0.019	0.006	0.005	0.002	0.003	0.010	0.038	0.919	0.019	0.005	0.002	0.001
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.000	0.000	0.001	0.005	0.970	0.017	0.004	0.001	0.001	0.000	0.001	0.003	0.010	0.904	0.057	0.016	0.005	0.004
9	JAERI	Japan	0.001	0.002	0.005	0.018	0.945	0.021	0.006	0.002	0.001	0.001	0.002	0.004	0.016	0.942	0.024	0.007	0.002	0.002
10	JINS-1	Japan	0.002	0.003	0.009	0.028	0.914	0.029	0.009	0.003	0.002	0.003	0.003	0.010	0.030	0.913	0.027	0.008	0.003	0.002
11	JINS-2	Japan	0.003	0.003	0.010	0.032	0.921	0.021	0.007	0.002	0.002	0.002	0.003	0.009	0.029	0.913	0.029	0.010	0.003	0.002
12	ORNL	USA	0.001	0.002	0.006	0.020	0.926	0.030	0.009	0.003	0.002	0.003	0.003	0.011	0.033	0.914	0.024	0.008	0.003	0.002
13	PNC	Japan	0.002	0.003	0.010	0.030	0.906	0.031	0.011	0.004	0.003	0.003	0.003	0.011	0.035	0.891	0.038	0.012	0.004	0.003
14	UKDOT	UK	0.002	0.003	0.008	0.031	0.918	0.026	0.008	0.003	0.002	0.002	0.002	0.008	0.027	0.930	0.021	0.006	0.002	0.002
		Average	0.002	0.002	0.007	0.023	0.922	0.029	0.009	0.003	0.002	0.002	0.002	0.008	0.026	0.915	0.032	0.010	0.003	0.002
		2 * σ_r	72%	67%	68%	64%	5%	76%	78%	76%	87%	75%	68%	69%	64%	3%	74%	75%	66%	67%

			CASE D Burn-up = 50 GWd/t – FP included – Nine-zone profile									**CASE D'** Burn-up = 50 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.052	0.061	0.136	0.215	0.273	0.127	0.076	0.033	0.027	0.022	0.027	0.066	0.126	0.478	0.143	0.078	0.033	0.028
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.000	0.000	0.000	0.001	0.253	0.339	0.221	0.102	0.084	0.001	0.001	0.002	0.003	0.392	0.303	0.169	0.073	0.058
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.055	0.063	0.141	0.219	0.224	0.141	0.086	0.039	0.031	0.048	0.058	0.137	0.264	0.453	0.021	0.011	0.005	0.003
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.081	0.095	0.214	0.336	0.254	0.009	0.007	0.003	0.002	0.032	0.041	0.102	0.190	0.439	0.101	0.055	0.022	0.017
9	JAERI	Japan	0.053	0.063	0.139	0.216	0.263	0.121	0.079	0.036	0.031	0.015	0.018	0.044	0.082	0.426	0.212	0.115	0.048	0.040
10	JINS-1	Japan	0.041	0.048	0.109	0.174	0.285	0.161	0.100	0.044	0.037	0.018	0.021	0.052	0.099	0.471	0.177	0.091	0.039	0.032
11	JINS-2	Japan	0.036	0.041	0.093	0.150	0.292	0.183	0.112	0.050	0.043	0.018	0.022	0.051	0.095	0.464	0.186	0.094	0.038	0.032
12	ORNL	USA	0.016	0.020	0.045	0.073	0.280	0.261	0.165	0.075	0.065	0.016	0.019	0.045	0.082	0.431	0.209	0.111	0.047	0.039
13	PNC	Japan	0.040	0.048	0.106	0.173	0.316	0.147	0.093	0.042	0.035	0.021	0.026	0.063	0.121	0.525	0.131	0.065	0.026	0.022
14	UKDOT	UK	0.020	0.024	0.053	0.082	0.253	0.257	0.167	0.077	0.065	0.012	0.015	0.037	0.070	0.434	0.219	0.121	0.050	0.041
		Average	0.039	0.046	0.104	0.164	0.269	0.175	0.111	0.050	0.042	0.020	0.025	0.060	0.113	0.451	0.170	0.091	0.038	0.031
		2 * σ_r	106%	105%	105%	104%	17%	95%	98%	100%	100%	112%	113%	112%	114%	14%	82%	85%	87%	88%

Table 9. Normalised fission fractions (cont.)

CASE E											
		Fresh fuel									
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.002	0.003	0.010	0.031	0.901	0.035	0.011	0.004	0.003
3	BNFL	UK	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.002	0.003	0.008	0.025	0.925	0.025	0.008	0.003	0.002
5	CEA	France	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.004	0.005	0.014	0.043	0.888	0.031	0.010	0.004	0.002
7	GRS	Germany	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.001	0.002	0.006	0.024	0.935	0.022	0.006	0.002	0.001
9	JAERI	Japan	0.001	0.002	0.005	0.018	0.948	0.019	0.006	0.002	0.001
10	JINS-1	Japan	0.002	0.003	0.008	0.026	0.923	0.025	0.008	0.003	0.002
11	JINS-2	Japan	0.002	0.002	0.007	0.022	0.925	0.027	0.009	0.003	0.002
12	ORNL	USA	0.002	0.003	0.008	0.025	0.891	0.046	0.015	0.005	0.004
13	PNC	Japan	0.002	0.003	0.008	0.026	0.909	0.035	0.011	0.004	0.002
14	UKDOT	UK	0.002	0.003	0.008	0.025	0.928	0.023	0.008	0.003	0.002
		Average	0.002	0.003	0.008	0.027	0.917	0.029	0.009	0.003	0.002
		$2 * \sigma_r$	62%	57%	57%	45%	4%	51%	56%	61%	66%

Table 10. Normalised fission densities

			CASE A Burn-up = 30 GWd/t – FP included – No BU profile									**CASE A'** Burn-up = 30 GWd/t – No FP included – No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.065	0.079	0.112	0.165	0.274	0.124	0.088	0.052	0.041	0.018	0.039	0.038	0.069	0.391	0.195	0.111	0.077	0.061
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.084	0.138	0.354	0.139	0.086	0.058	0.043	0.040	0.056	0.084	0.138	0.353	0.139	0.090	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.049	0.059	0.088	0.137	0.275	0.147	0.108	0.078	0.059	0.051	0.061	0.091	0.152	0.273	0.152	0.101	0.071	0.051
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.013	0.020	0.029	0.056	0.389	0.233	0.128	0.081	0.051	0.031	0.043	0.069	0.156	0.435	0.114	0.080	0.041	0.031
9	JAERI	Japan	0.041	0.060	0.084	0.124	0.361	0.138	0.085	0.062	0.045	0.037	0.051	0.079	0.136	0.483	0.099	0.057	0.034	0.023
10	JINS-1	Japan	0.036	0.045	0.066	0.099	0.279	0.202	0.123	0.086	0.065	0.049	0.067	0.100	0.162	0.315	0.132	0.082	0.055	0.039
11	JINS-2	Japan	0.050	0.066	0.102	0.157	0.332	0.126	0.076	0.052	0.038	0.045	0.060	0.084	0.140	0.336	0.136	0.088	0.062	0.049
12	ORNL	USA	0.059	0.072	0.112	0.182	0.352	0.092	0.057	0.041	0.032	0.056	0.078	0.118	0.187	0.352	0.090	0.055	0.039	0.025
13	PNC	Japan	0.056	0.075	0.103	0.159	0.296	0.135	0.084	0.056	0.037	0.039	0.059	0.089	0.133	0.314	0.168	0.099	0.059	0.039
14	UKDOT	UK	0.012	0.015	0.023	0.038	0.340	0.243	0.149	0.099	0.081	0.048	0.062	0.091	0.150	0.365	0.124	0.076	0.049	0.035
		Average	0.042	0.055	0.080	0.126	0.325	0.158	0.098	0.067	0.049	0.041	0.058	0.084	0.142	0.362	0.135	0.084	0.055	0.039
		$2 * \sigma_r$	78%	72%	72%	68%	23%	57%	51%	50%	55%	47%	35%	44%	38%	31%	42%	39%	46%	54%

			CASE B Burn-up = 30 GWd/t – FP included – Nine-zone profile									**CASE B'** Burn-up = 30 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.008	0.009	0.011	0.012	0.040	0.262	0.265	0.217	0.177	0.074	0.091	0.122	0.149	0.115	0.152	0.125	0.097	0.076
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.006	0.008	0.010	0.010	0.032	0.262	0.270	0.225	0.178	0.057	0.076	0.096	0.107	0.071	0.186	0.169	0.134	0.104
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.020	0.020	0.030	0.030	0.030	0.250	0.250	0.200	0.170	0.130	0.160	0.210	0.240	0.080	0.060	0.050	0.040	0.030
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.167	0.203	0.255	0.264	0.040	0.019	0.020	0.017	0.015	0.033	0.044	0.053	0.062	0.113	0.249	0.195	0.143	0.107
9	JAERI	Japan	0.121	0.150	0.187	0.185	0.053	0.092	0.087	0.070	0.054	0.071	0.090	0.119	0.133	0.096	0.156	0.140	0.108	0.087
10	JINS-1	Japan	0.156	0.190	0.235	0.232	0.037	0.042	0.043	0.035	0.030	0.079	0.098	0.129	0.150	0.097	0.147	0.128	0.096	0.076
11	JINS-2	Japan	0.129	0.158	0.194	0.193	0.034	0.083	0.084	0.068	0.057	0.107	0.136	0.182	0.212	0.081	0.096	0.077	0.060	0.048
12	ORNL	USA	0.154	0.189	0.229	0.231	0.040	0.046	0.045	0.036	0.030	0.102	0.128	0.168	0.192	0.121	0.093	0.082	0.064	0.051
13	PNC	Japan	0.081	0.105	0.129	0.124	0.048	0.146	0.151	0.120	0.096	0.073	0.097	0.126	0.146	0.106	0.152	0.130	0.097	0.073
14	UKDOT	UK	0.045	0.054	0.069	0.070	0.029	0.213	0.211	0.167	0.142	0.066	0.084	0.112	0.131	0.095	0.165	0.146	0.110	0.090
		Average	0.089	0.109	0.135	0.135	0.038	0.141	0.143	0.116	0.095	0.079	0.100	0.132	0.152	0.097	0.146	0.124	0.095	0.074
		$2 * \sigma_r$	132%	133%	131%	132%	37%	125%	126%	127%	126%	63%	60%	61%	61%	31%	66%	64%	62%	60%

Table 10. Normalised fission densities (cont.)

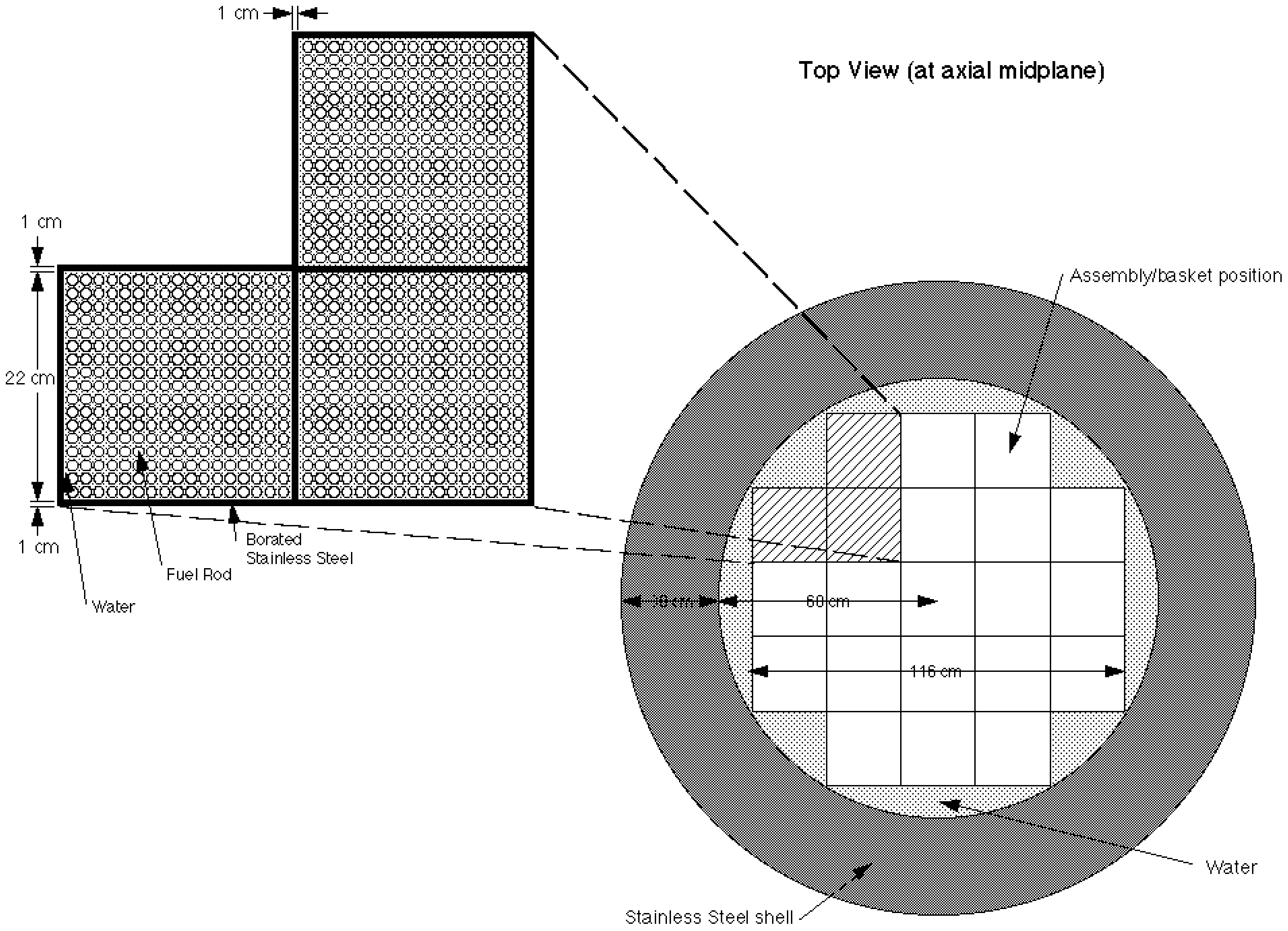
			CASE C Burn-up = 50 GWd/t – FP included – No BU profile									**CASE C'** Burn-up = 50 GWd/t – No FP included – No BU profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.030	0.041	0.065	0.110	0.355	0.153	0.112	0.077	0.058	0.021	0.028	0.041	0.073	0.292	0.235	0.144	0.091	0.073
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.084	0.138	0.354	0.140	0.086	0.058	0.043	0.040	0.057	0.084	0.138	0.355	0.140	0.086	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.030	0.040	0.070	0.100	0.230	0.230	0.140	0.090	0.070	0.050	0.070	0.110	0.200	0.340	0.100	0.050	0.040	0.030
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.009	0.014	0.022	0.043	0.604	0.150	0.079	0.050	0.028	0.009	0.014	0.026	0.047	0.304	0.274	0.157	0.100	0.070
9	JAERI	Japan	0.030	0.046	0.070	0.118	0.444	0.140	0.076	0.048	0.029	0.029	0.040	0.057	0.103	0.425	0.155	0.089	0.060	0.042
10	JINS-1	Japan	0.047	0.063	0.093	0.139	0.317	0.142	0.090	0.063	0.047	0.050	0.068	0.099	0.150	0.317	0.136	0.083	0.056	0.040
11	JINS-2	Japan	0.053	0.070	0.105	0.168	0.339	0.111	0.070	0.049	0.036	0.043	0.059	0.088	0.144	0.317	0.143	0.095	0.063	0.048
12	ORNL	USA	0.032	0.046	0.067	0.108	0.360	0.167	0.100	0.067	0.054	0.052	0.068	0.106	0.165	0.318	0.118	0.076	0.054	0.043
13	PNC	Japan	0.037	0.056	0.093	0.140	0.296	0.145	0.103	0.075	0.056	0.051	0.051	0.094	0.150	0.267	0.163	0.103	0.069	0.051
14	UKDOT	UK	0.042	0.057	0.087	0.163	0.339	0.135	0.083	0.056	0.039	0.042	0.056	0.089	0.159	0.377	0.123	0.070	0.047	0.036
		Average	0.035	0.049	0.075	0.123	0.364	0.151	0.094	0.063	0.046	0.039	0.051	0.079	0.133	0.331	0.159	0.095	0.064	0.048
		2 * σ_r	62%	57%	55%	53%	50%	37%	40%	40%	54%	68%	65%	65%	62%	25%	62%	62%	53%	52%

			CASE D Burn-up = 50 GWd/t – FP included – Nine-zone profile									**CASE D'** Burn-up = 50 GWd/t – No FP included – Nine-zone profile								
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.140	0.166	0.184	0.146	0.013	0.086	0.102	0.089	0.074	0.085	0.106	0.128	0.123	0.033	0.139	0.151	0.128	0.108
3	BNFL	UK	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.000	0.000	0.000	0.000	0.012	0.220	0.287	0.264	0.217	0.002	0.002	0.003	0.002	0.023	0.253	0.281	0.242	0.193
5	CEA	France	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.139	0.158	0.178	0.139	0.010	0.089	0.109	0.099	0.079	0.178	0.218	0.257	0.248	0.030	0.020	0.020	0.020	0.010
7	GRS	Germany	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.211	0.248	0.280	0.220	0.012	0.006	0.009	0.008	0.006	0.119	0.151	0.187	0.175	0.028	0.092	0.102	0.082	0.064
9	JAERI	Japan	0.140	0.165	0.183	0.142	0.012	0.080	0.103	0.094	0.081	0.053	0.065	0.078	0.073	0.026	0.188	0.203	0.172	0.141
10	JINS-1	Japan	0.113	0.132	0.150	0.119	0.014	0.110	0.137	0.122	0.102	0.068	0.082	0.100	0.096	0.032	0.171	0.177	0.151	0.123
11	JINS-2	Japan	0.099	0.115	0.129	0.104	0.014	0.127	0.155	0.138	0.118	0.068	0.083	0.098	0.091	0.031	0.178	0.181	0.147	0.122
12	ORNL	USA	0.044	0.053	0.061	0.049	0.013	0.177	0.223	0.204	0.176	0.057	0.067	0.080	0.074	0.027	0.187	0.199	0.167	0.141
13	PNC	Japan	0.114	0.137	0.151	0.124	0.016	0.105	0.133	0.120	0.100	0.091	0.112	0.136	0.131	0.040	0.142	0.141	0.112	0.095
14	UKDOT	UK	0.052	0.062	0.069	0.053	0.011	0.167	0.217	0.199	0.170	0.045	0.054	0.066	0.063	0.027	0.197	0.218	0.181	0.148
		Average	0.105	0.124	0.139	0.110	0.013	0.117	0.148	0.134	0.112	0.077	0.094	0.113	0.107	0.030	0.157	0.167	0.140	0.114
		2 * σ_r	103%	103%	103%	102%	24%	93%	96%	98%	98%	112%	112%	112%	113%	28%	74%	77%	78%	79%

Table 10. Normalised fission densities (cont.)

CASE E											
		Fresh fuel									
#	Institute	Country	Reg-1	Reg-2	Reg-3	Reg-4	Reg-5	Reg-6	Reg-7	Reg-8	Reg-9
1	ABB	Sweden	/	/	/	/	/	/	/	/	/
2	BfS-IKE	Germany	0.043	0.057	0.092	0.142	0.288	0.159	0.096	0.067	0.055
3	BNFL	UK	/	/	/	/	/	/	/	/	/
4	CSN	Spain	0.040	0.057	0.086	0.138	0.355	0.139	0.085	0.058	0.042
5	CEA	France	/	/	/	/	/	/	/	/	/
6	EMS	Sweden	0.059	0.079	0.119	0.178	0.257	0.129	0.079	0.059	0.040
7	GRS	Germany	/	/	/	/	/	/	/	/	/
8	IPSN	France	0.032	0.045	0.072	0.151	0.407	0.139	0.078	0.045	0.032
9	JAERI	Japan	0.029	0.042	0.066	0.121	0.454	0.127	0.076	0.048	0.037
10	JINS-1	Japan	0.045	0.060	0.090	0.141	0.347	0.135	0.083	0.056	0.044
11	JINS-2	Japan	0.040	0.054	0.079	0.122	0.351	0.147	0.094	0.065	0.048
12	ORNL	USA	0.038	0.047	0.067	0.106	0.264	0.196	0.129	0.086	0.068
13	PNC	Japan	0.039	0.058	0.077	0.126	0.308	0.169	0.106	0.077	0.039
14	UKDOT	UK	0.042	0.059	0.086	0.139	0.364	0.126	0.085	0.057	0.042
		Average	0.041	0.056	0.083	0.136	0.340	0.147	0.091	0.062	0.045
		$2 * \sigma_r$	37%	34%	34%	26%	33%	27%	32%	37%	42%

Figure 1



1 cm
Top View (at axial midplane)
1 cm
22 cm
1 cm
Borated Stainless Steel
Fuel Rod
Water
Assembly/basket position
30 cm
60 cm
116 cm
Water
Stainless Steel shell

Figure 2

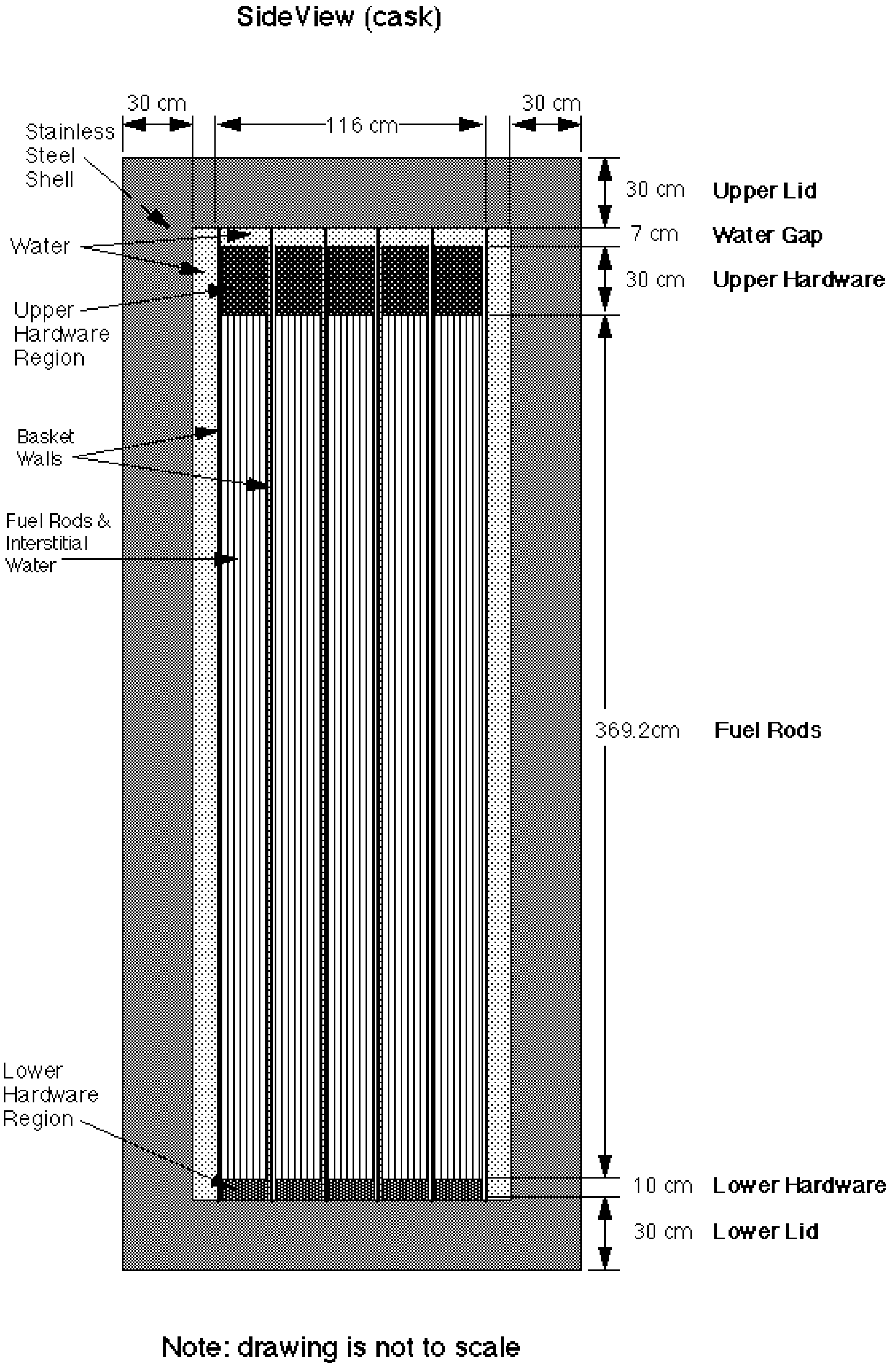

SideView (cask)
30 cm
116 cm
30 cm
Stainless Steel Shell
Water
Upper Hardware Region
Basket Walls
Fuel Rods & Interstitial Water
Lower Hardware Region
30 cm
Upper Lid
7 cm
Water Gap
30 cm
Upper Hardware
369.2cm
Fuel Rods
10 cm
Lower Hardware
30 cm
Lower Lid
Note: drawing is not to scale

Figure 3

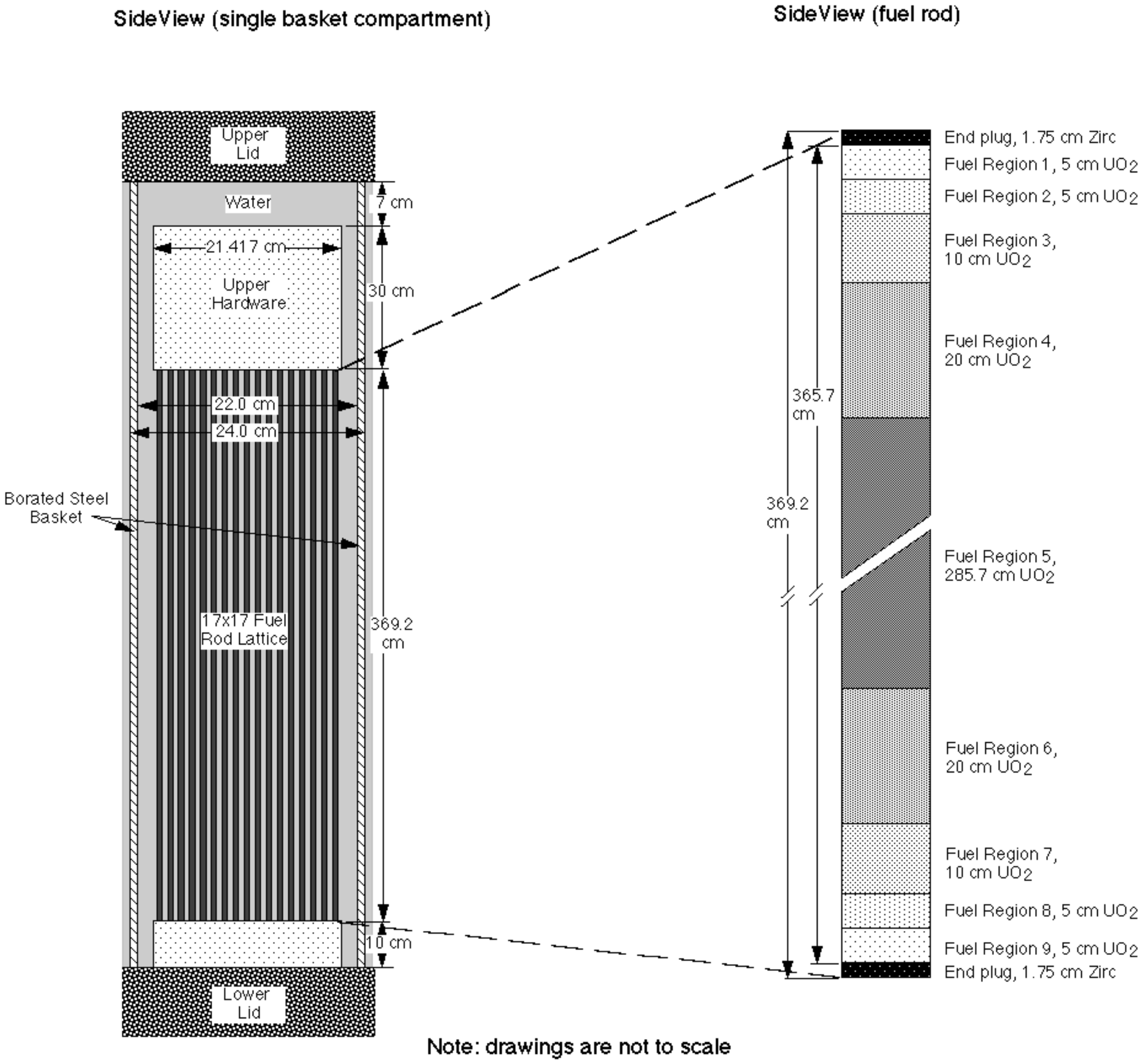

SideView (single basket compartment)
SideView (fuel rod)
Upper Lid
Water
7 cm
21.417 cm
Upper Hardware
30 cm
22.0 cm
24.0 cm
Borated Steel Basket
17x17 Fuel Rod Lattice
369.2 cm
10 cm
Lower Lid
End plug, 1.75 cm Zirc
Fuel Region 1, 5 cm UO2
Fuel Region 2, 5 cm UO2
Fuel Region 3, 10 cm UO2
Fuel Region 4, 20 cm UO2
365.7 cm
369.2 cm
Fuel Region 5, 285.7 cm UO2
Fuel Region 6, 20 cm UO2
Fuel Region 7, 10 cm UO2
Fuel Region 8, 5 cm UO2
Fuel Region 9, 5 cm UO2
End plug, 1.75 cm Zirc
Note: drawings are not to scale

Figure 4

Fission fractions - Flat burnup profile

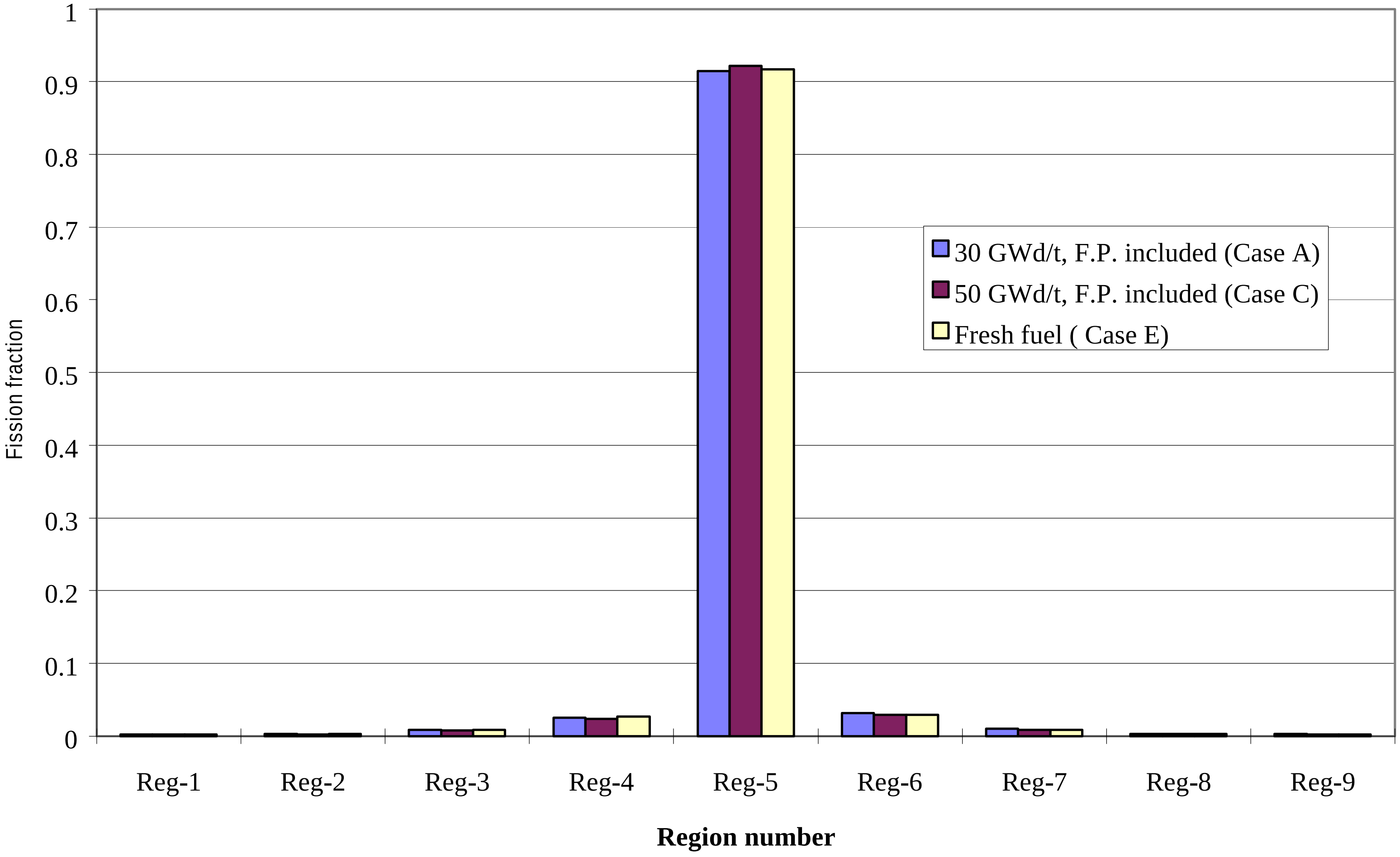


Figure 4bis

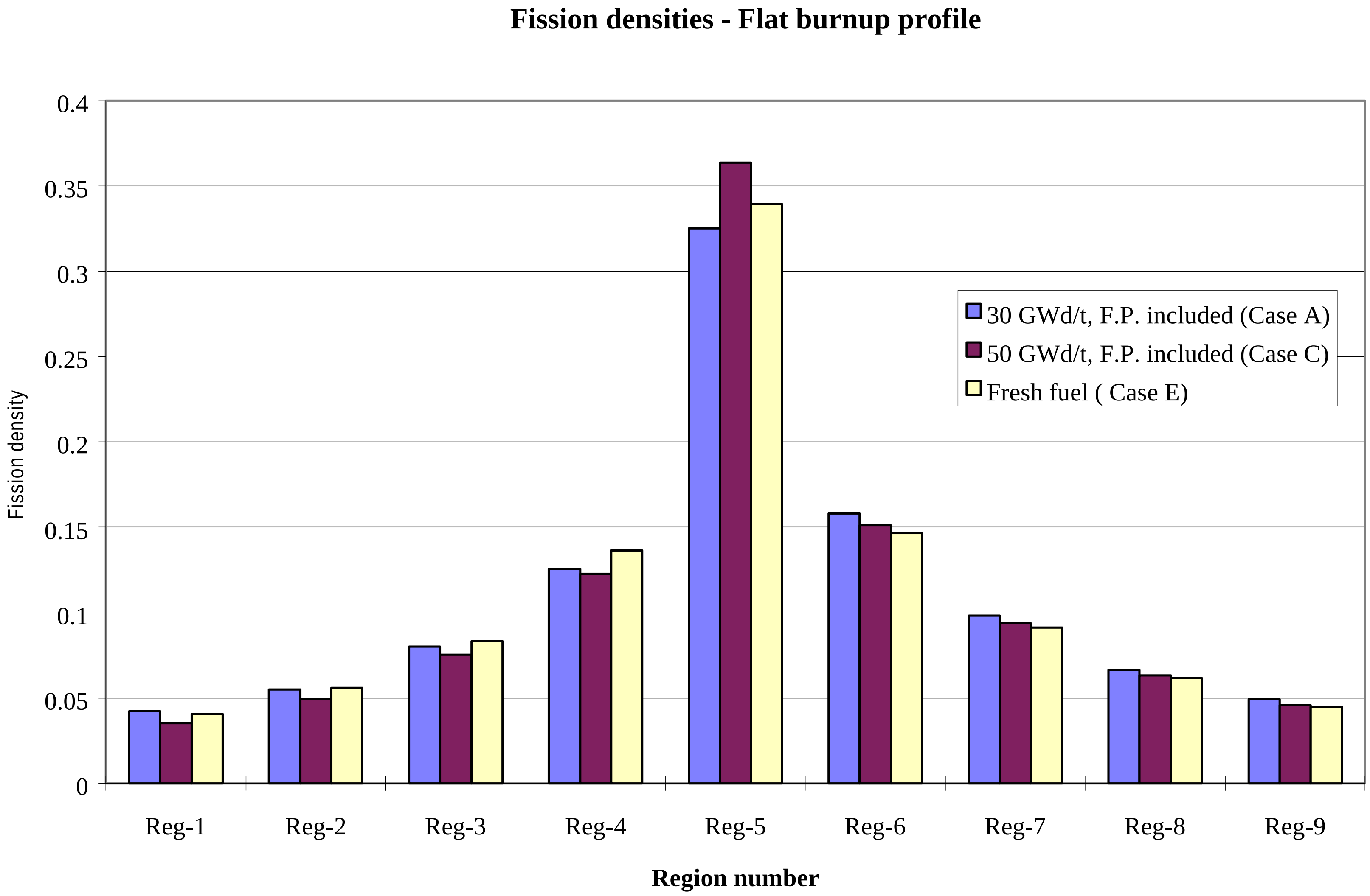

Fission densities - Flat burnup profile
Fission density
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Reg-1
Reg-2
Reg-3
Reg-4
Reg-5
Reg-6
Reg-7
Reg-8
Reg-9
Region number
30 GWd/t, F.P. included (Case A)
50 GWd/t, F.P. included (Case C)
Fresh fuel (Case E)

Figure 5

Fission fractions - Nine-zone profile

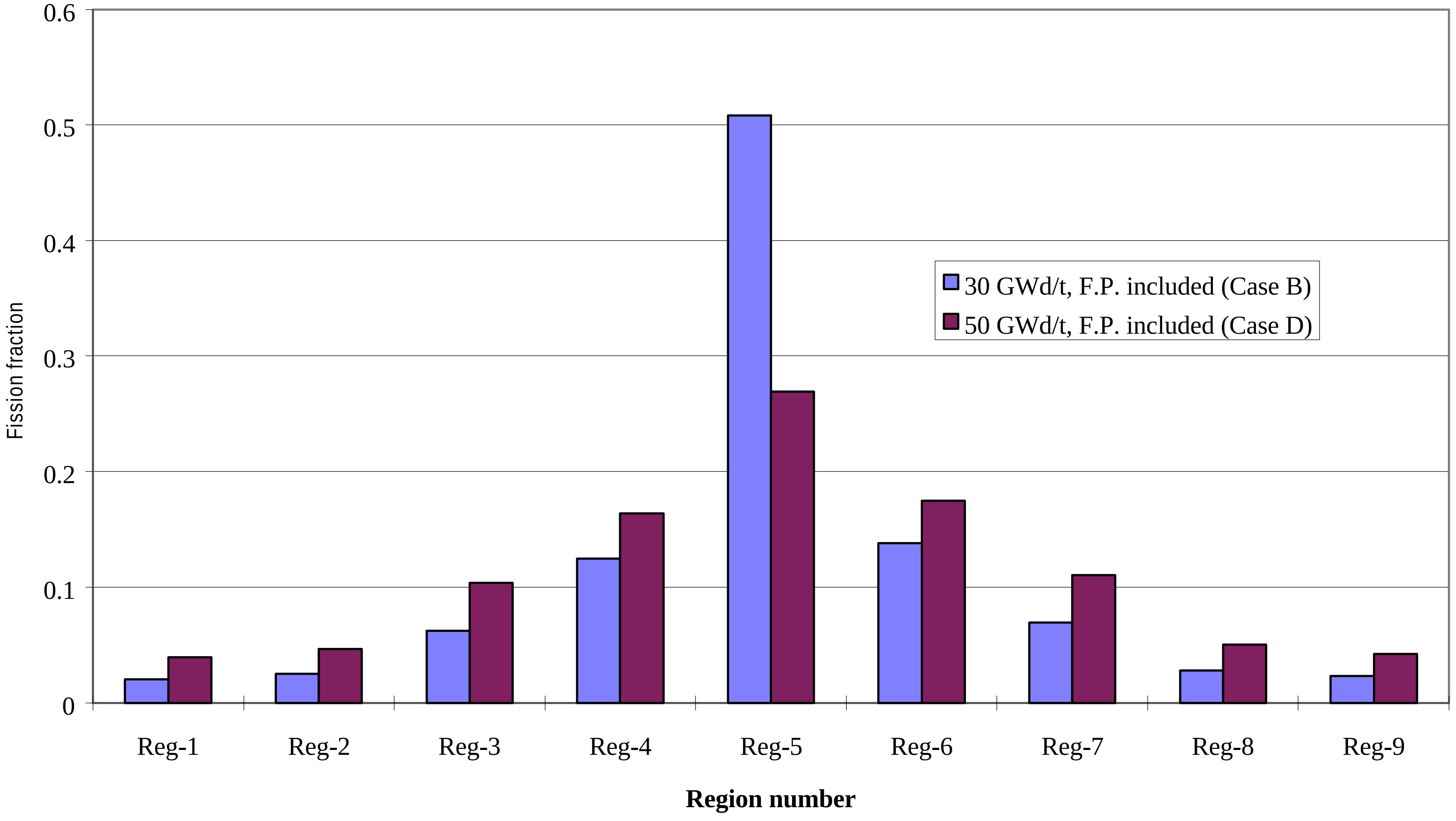


Figure 5bis

Fission densities - Nine-zone profile

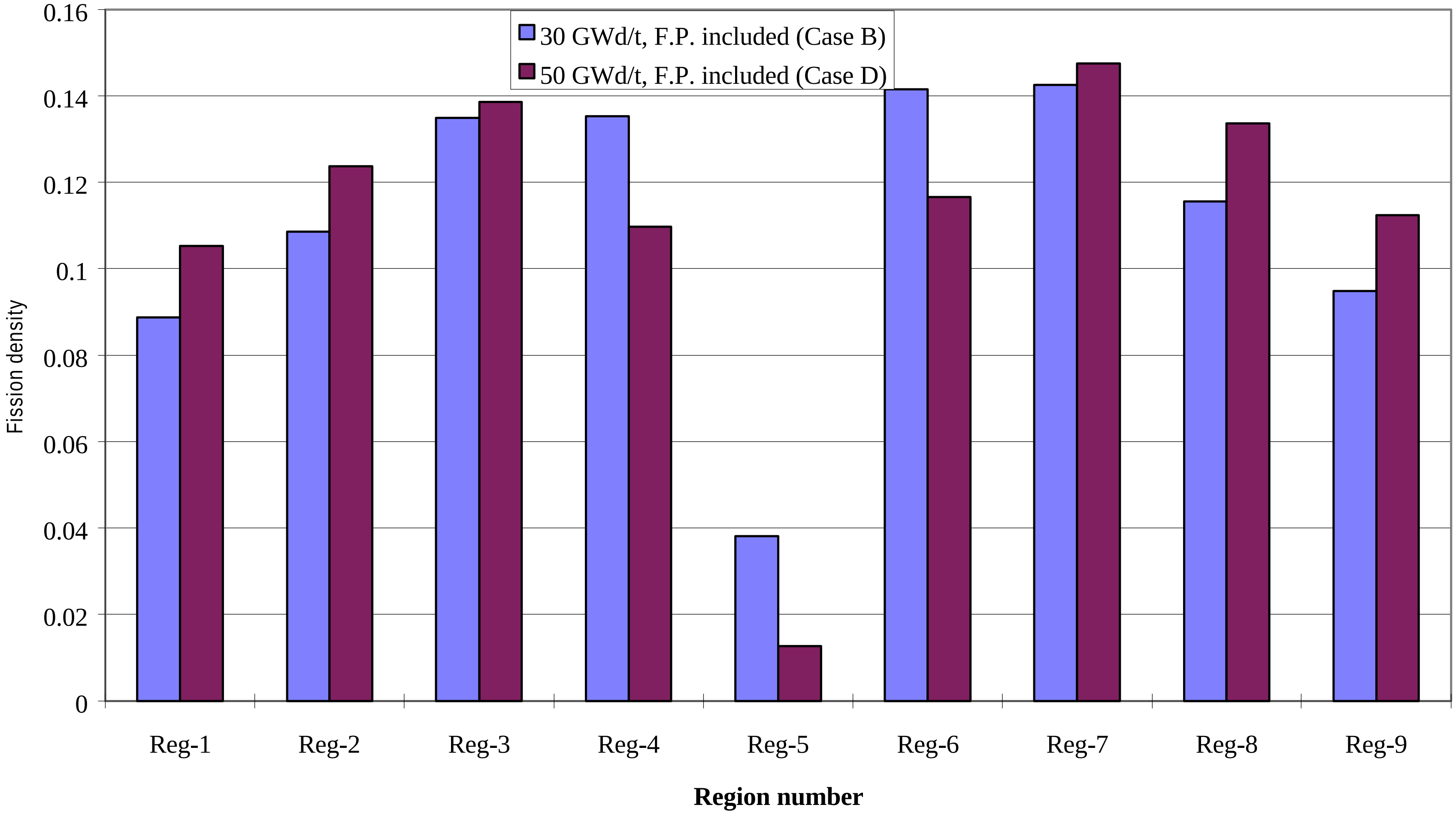


Figure 6

Precise representation of Fission Density calculated by J. Stewart

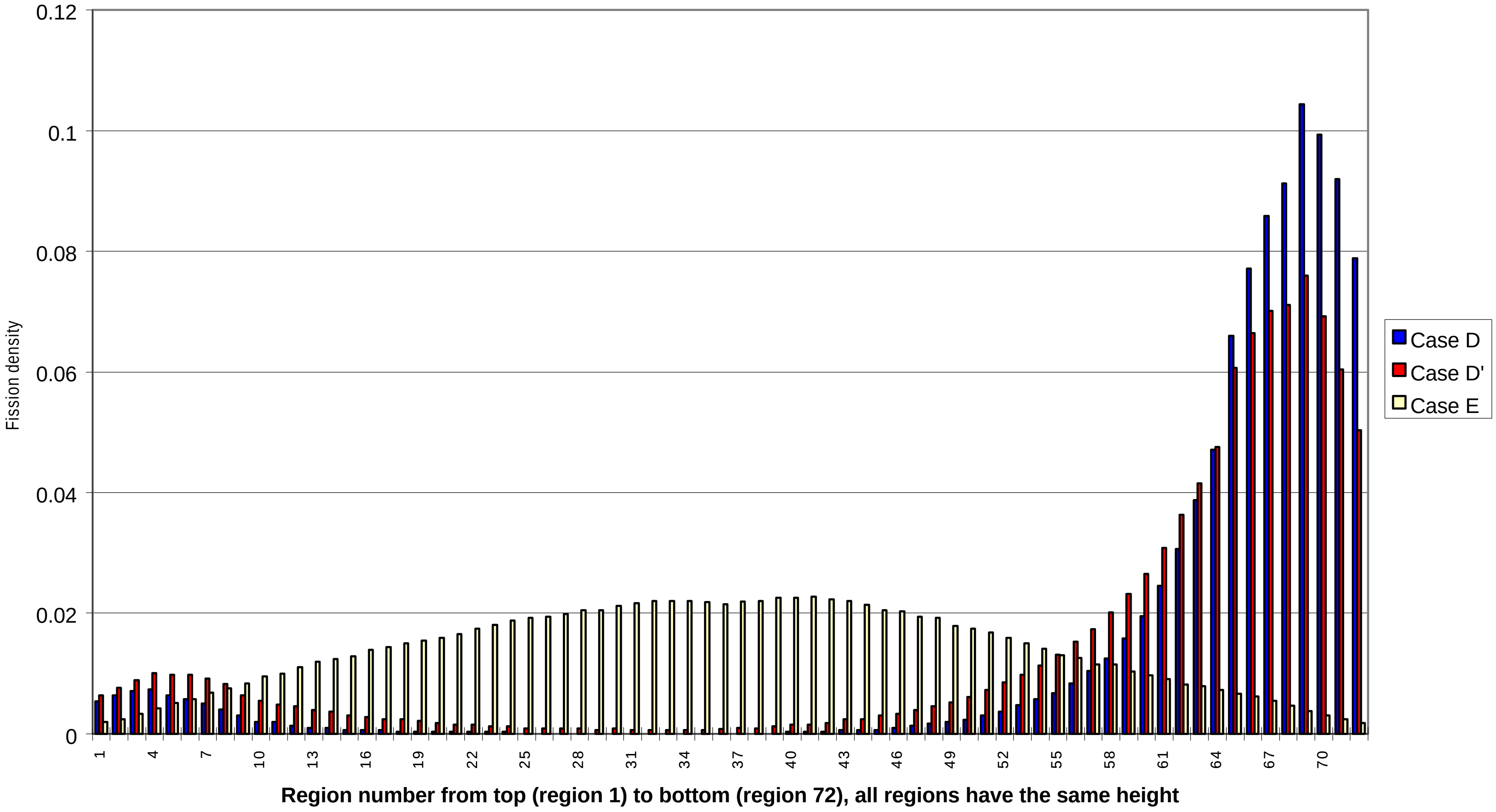


Figure 7

Precise representation of Neutron Flux Distribution calculated by J. Conde

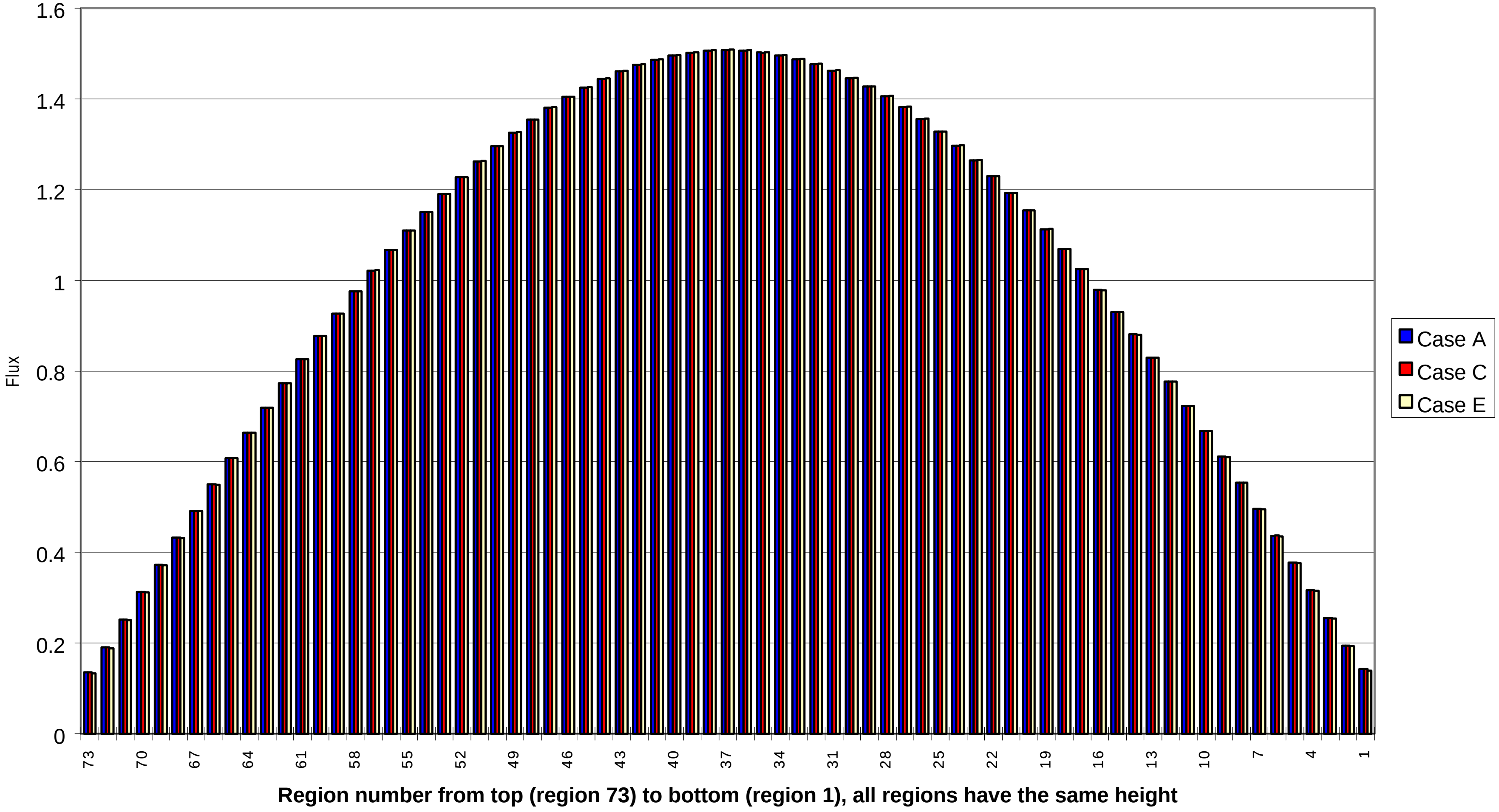


Figure 8

Precise representation of Neutron Flux Distribution calculated by J. Conde

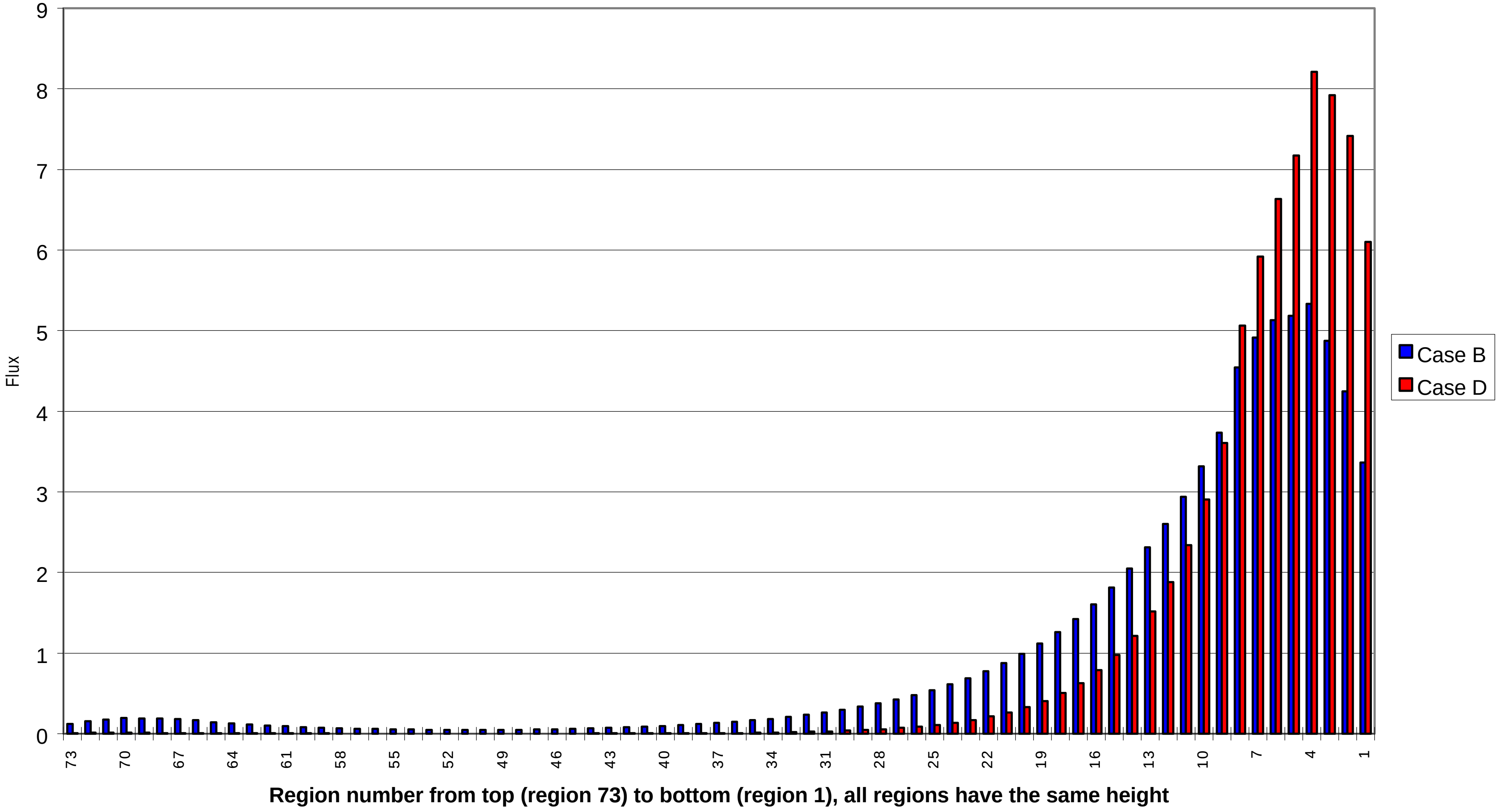


Figure 9

Case A - Fission fractions

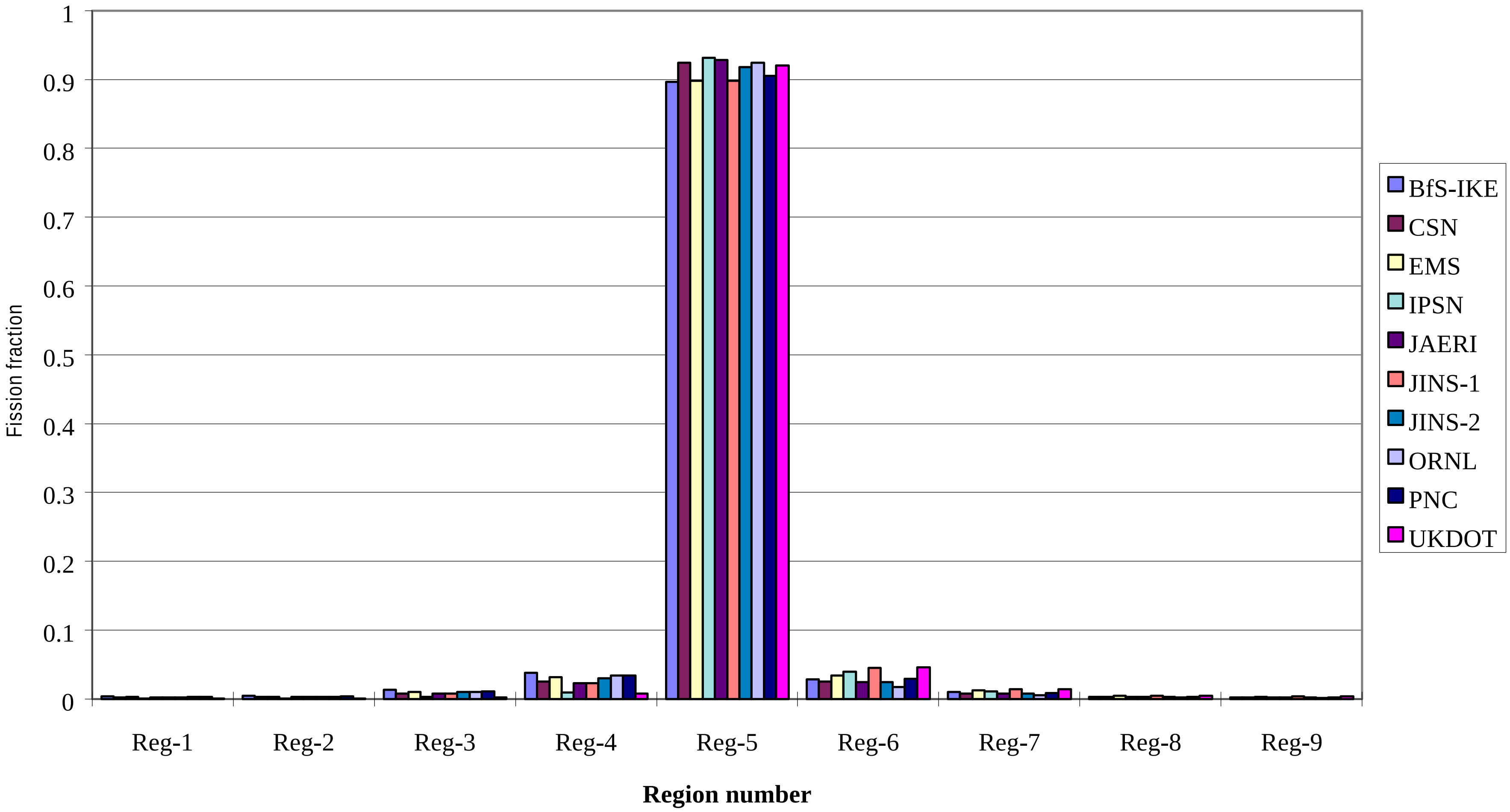


Figure 9bis

Case A - Fission densities

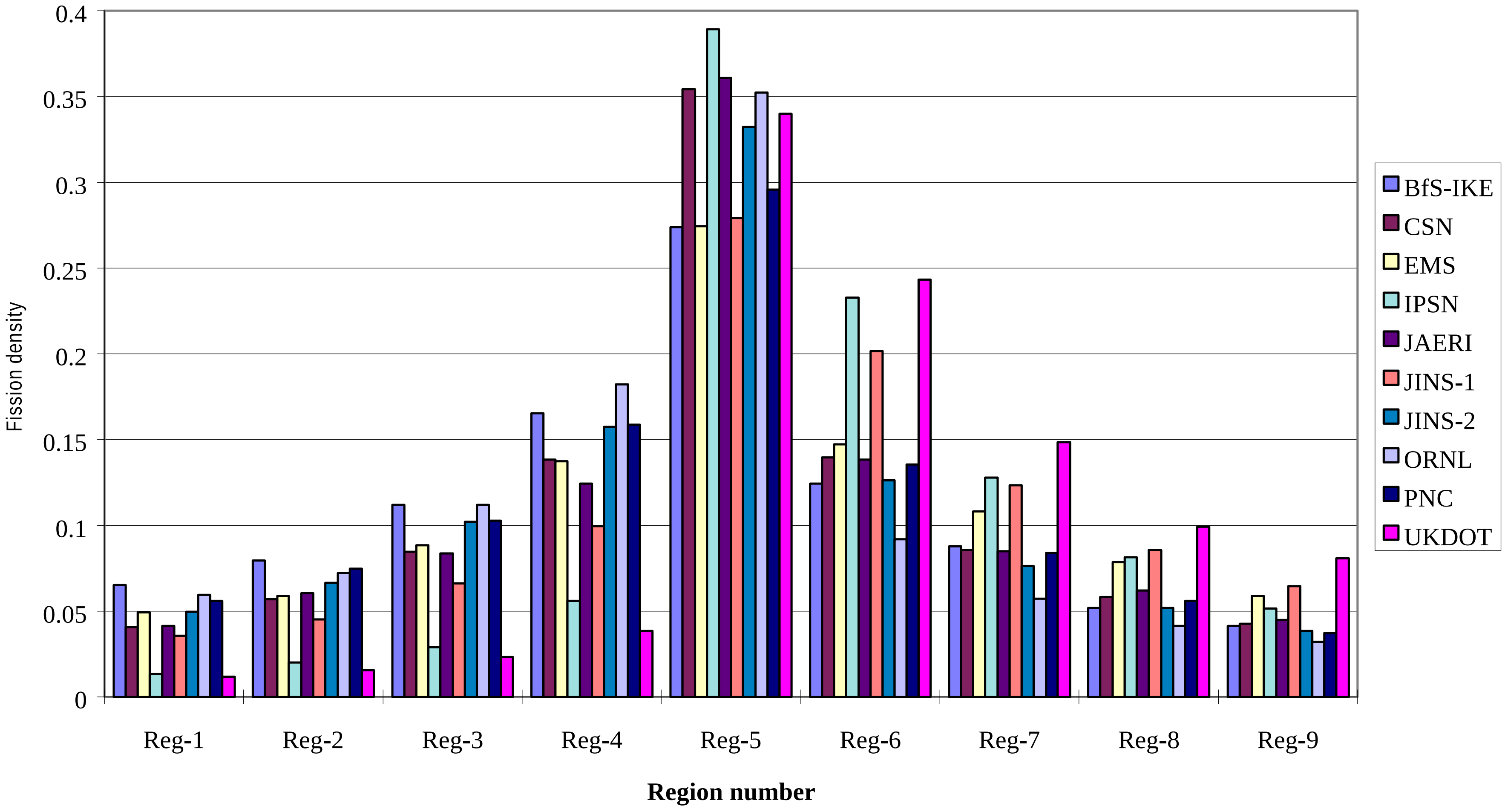


Figure 10

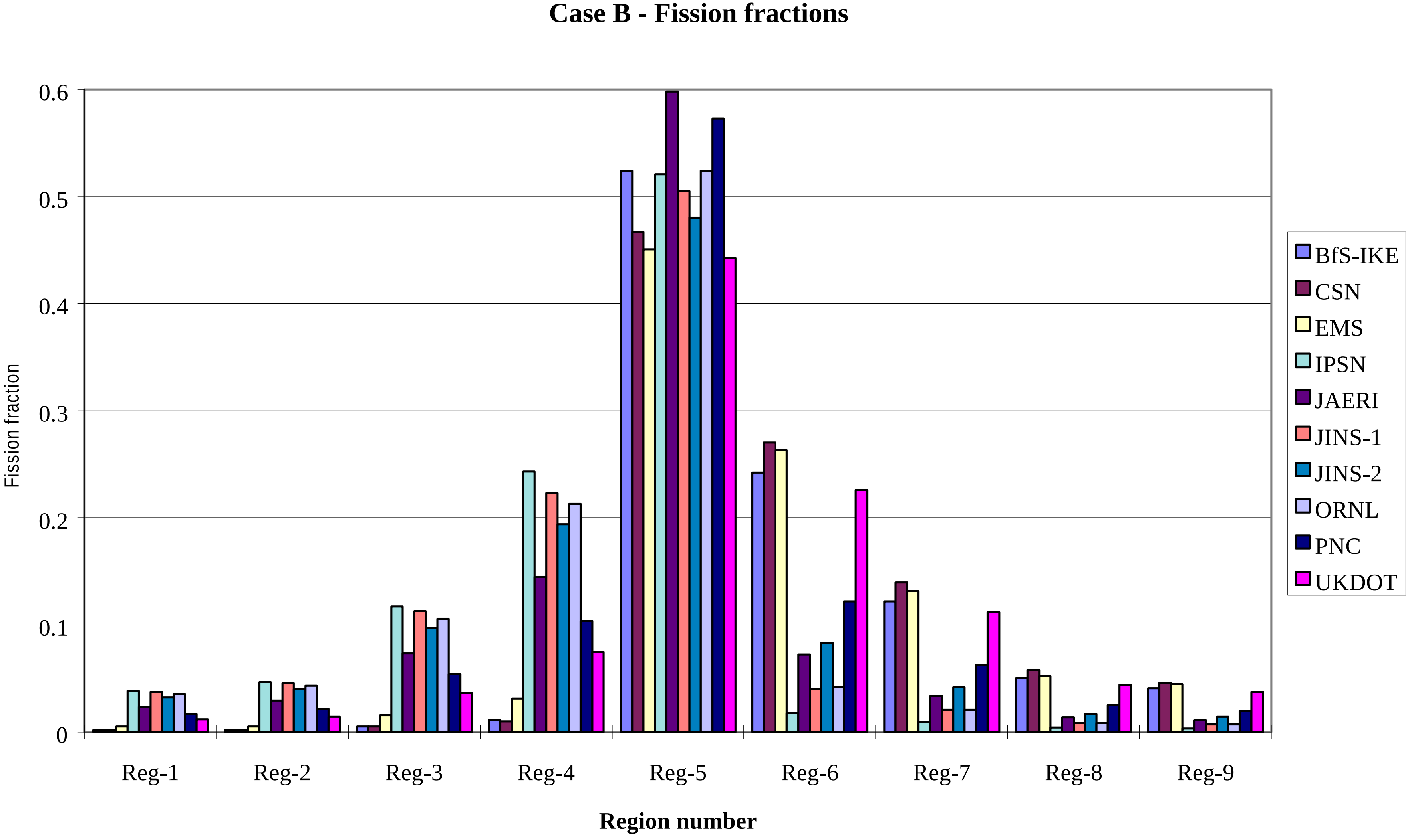

Case B - Fission fractions
0.6
0.5
0.4
0.3
0.2
0.1
0
Fission fraction
Reg-1
Reg-2
Reg-3
Reg-4
Reg-5
Reg-6
Reg-7
Reg-8
Reg-9
Region number
BfS-IKE
CSN
EMS
IPSN
JAERI
JINS-1
JINS-2
ORNL
PNC
UKDOT

Figure 10bis

Case B - Fission densities

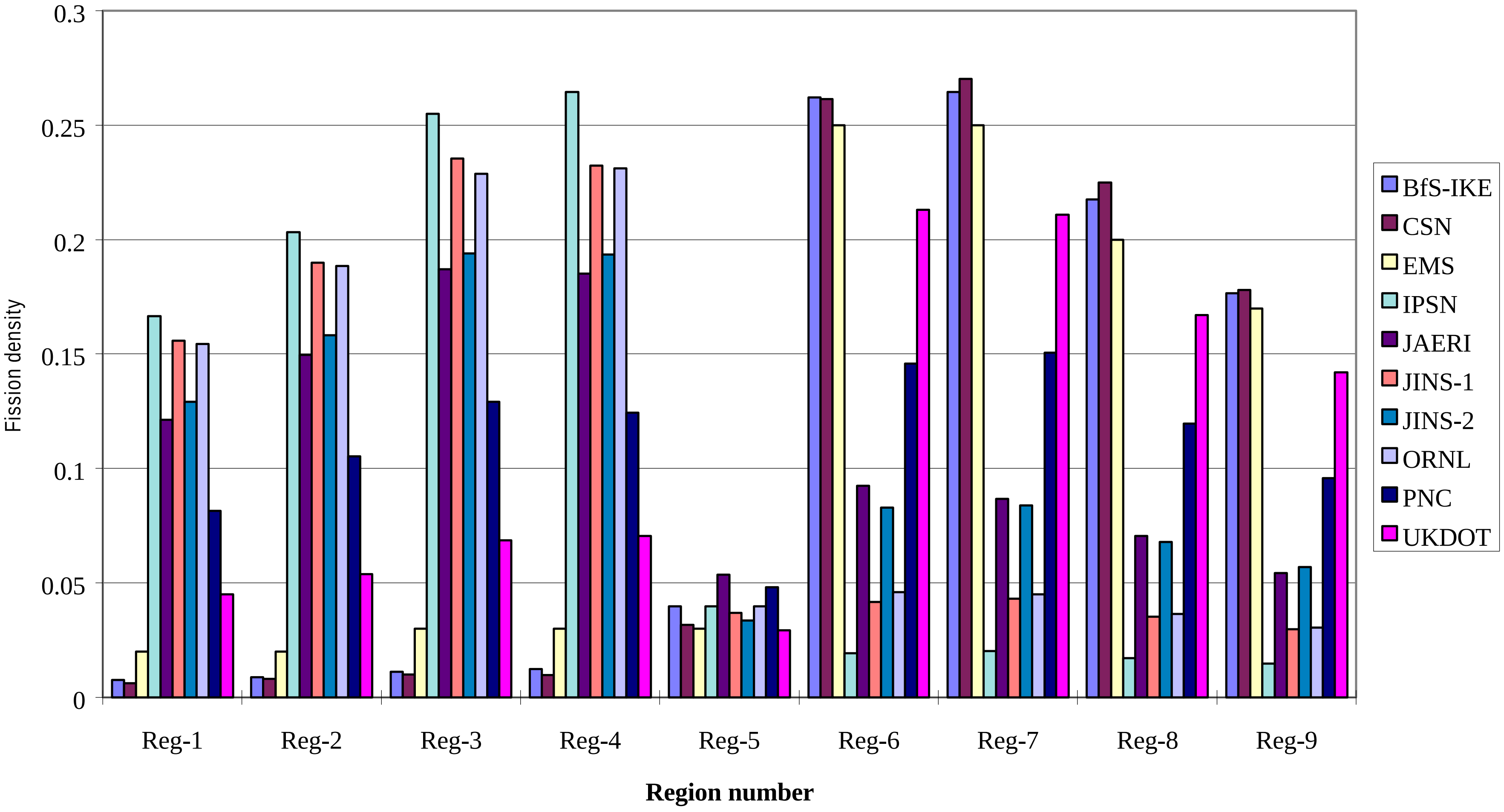


Figure 11

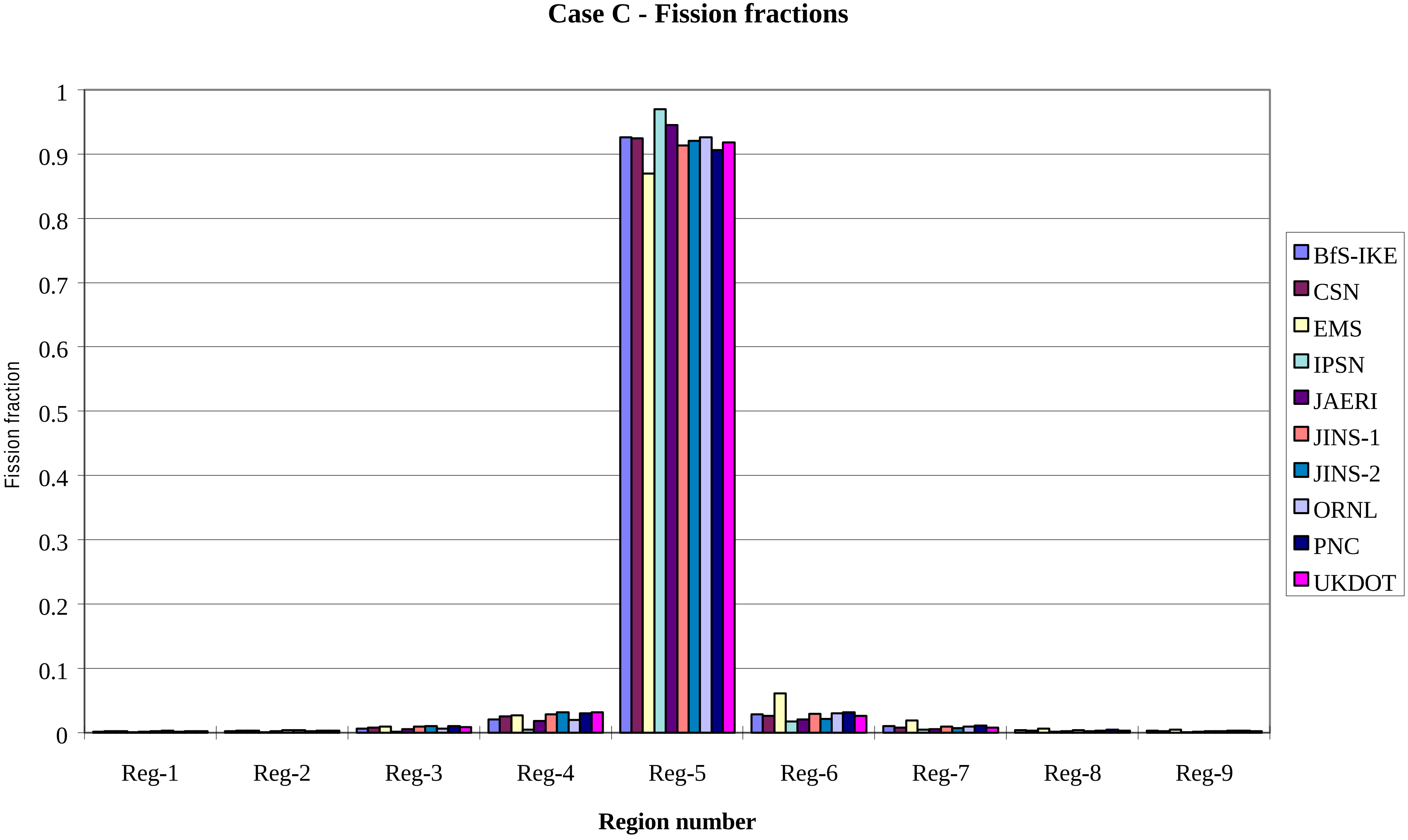

Case C - Fission fractions
Fission fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reg-1
Reg-2
Reg-3
Reg-4
Reg-5
Reg-6
Reg-7
Reg-8
Reg-9
Region number
BfS-IKE
CSN
EMS
IPSN
JAERI
JINS-1
JINS-2
ORNL
PNC
UKDOT

Figure 11bis

Case C - Fission densities

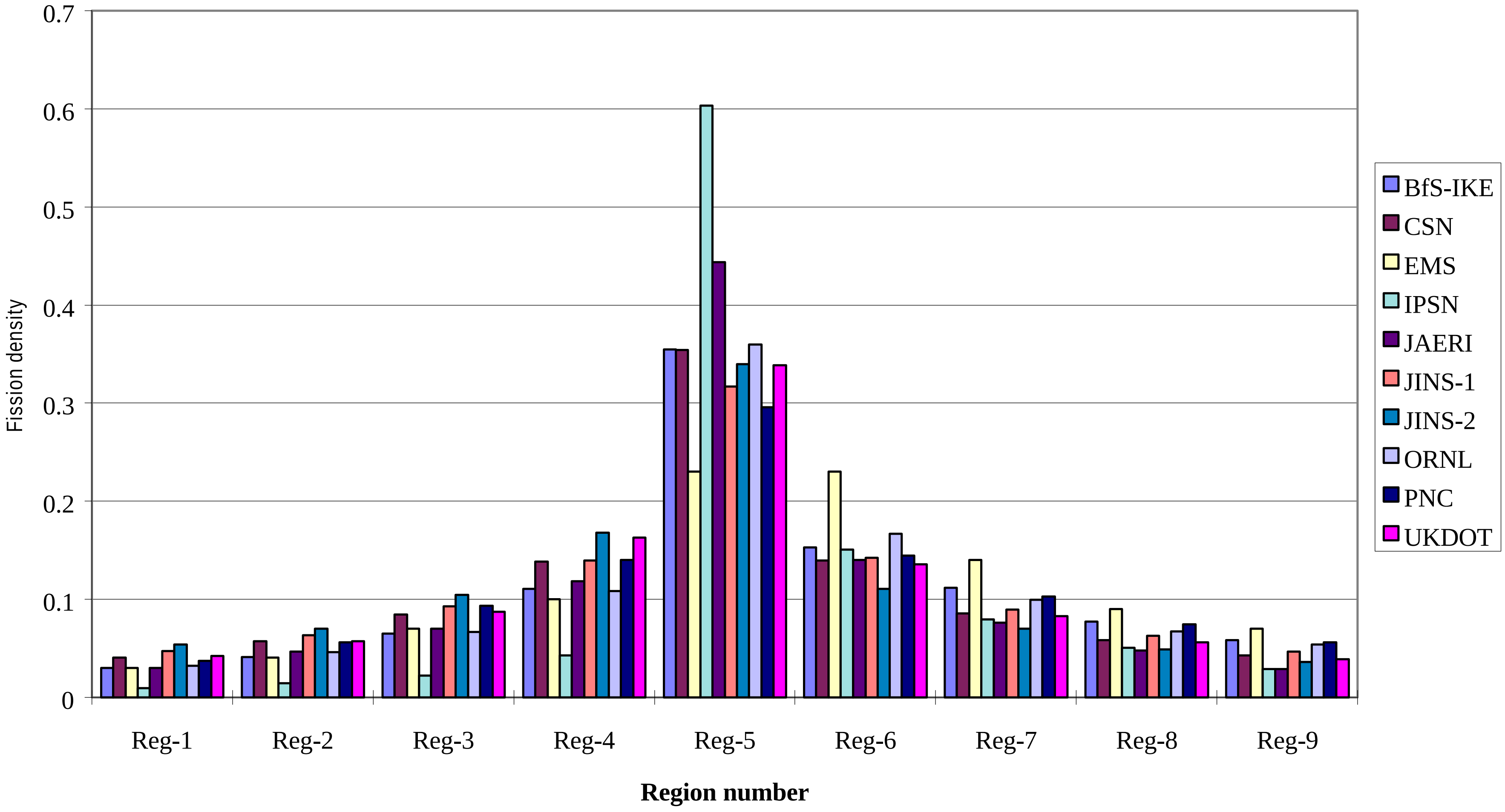


Figure 12

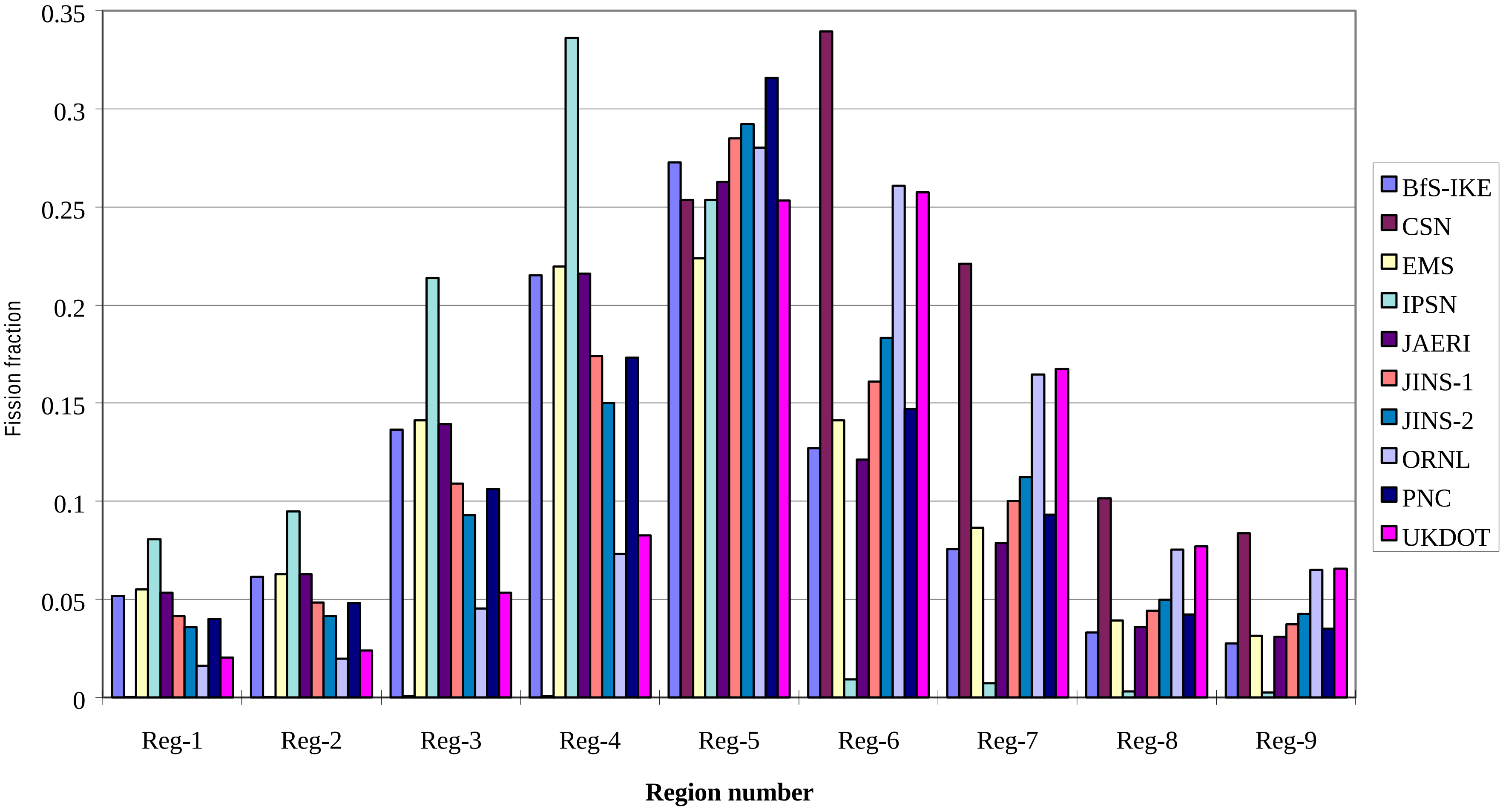

Case D - Fission fractions
Fission fraction
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Reg-1
Reg-2
Reg-3
Reg-4
Reg-5
Reg-6
Reg-7
Reg-8
Reg-9
Region number
BfS-IKE
CSN
EMS
IPSN
JAERI
JINS-1
JINS-2
ORNL
PNC
UKDOT

Figure 12bis

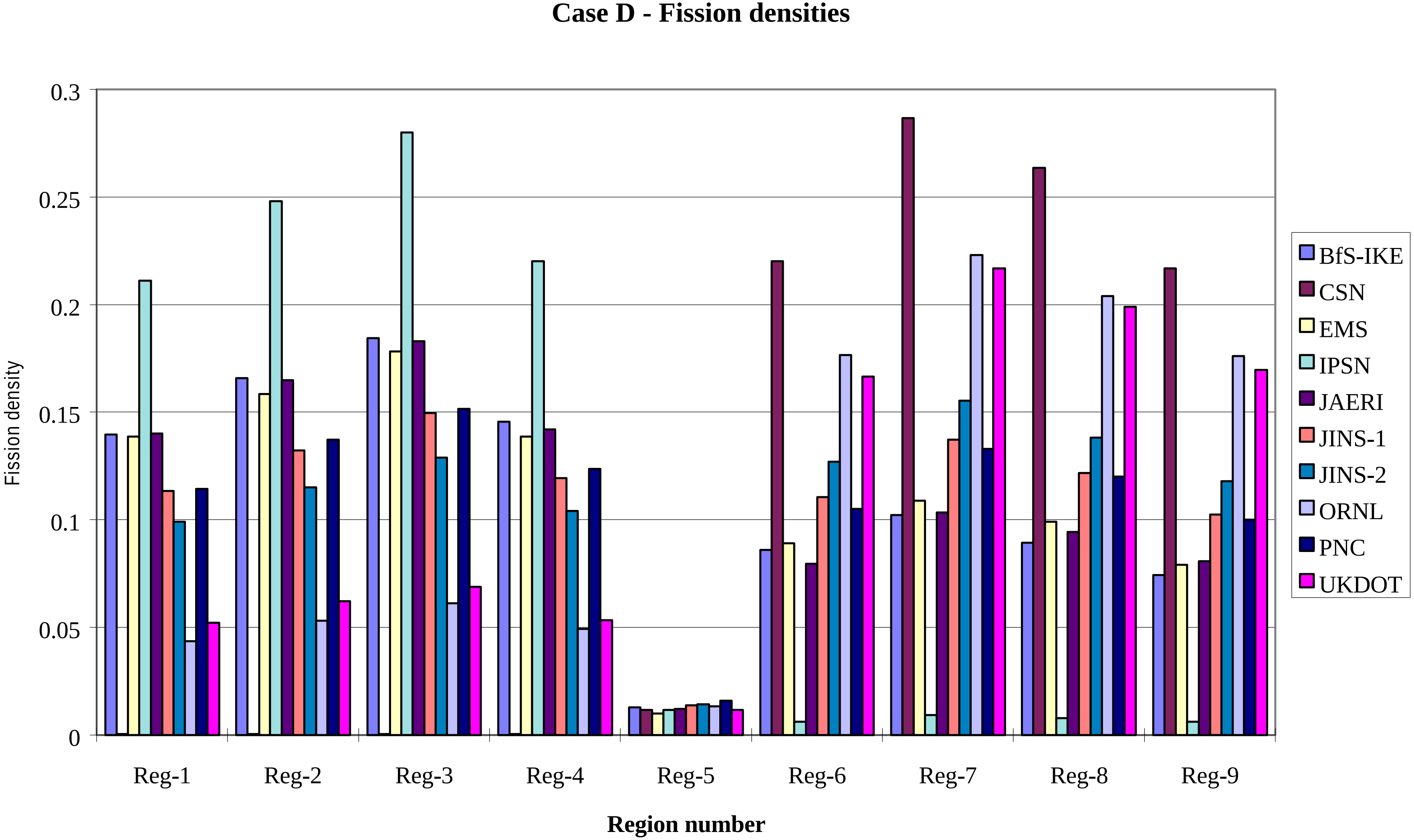


Figure 13

Case E - Fission fractions

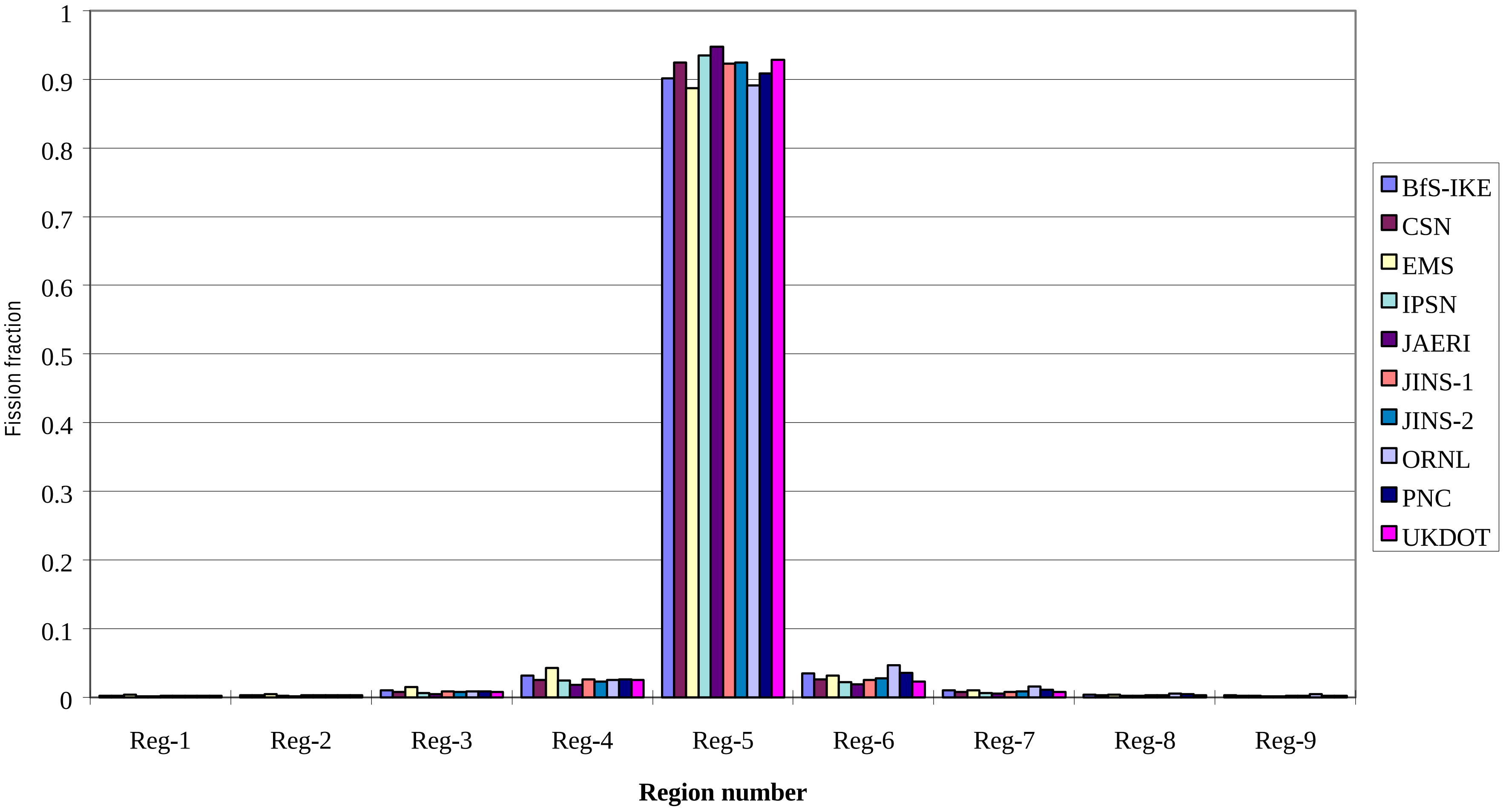
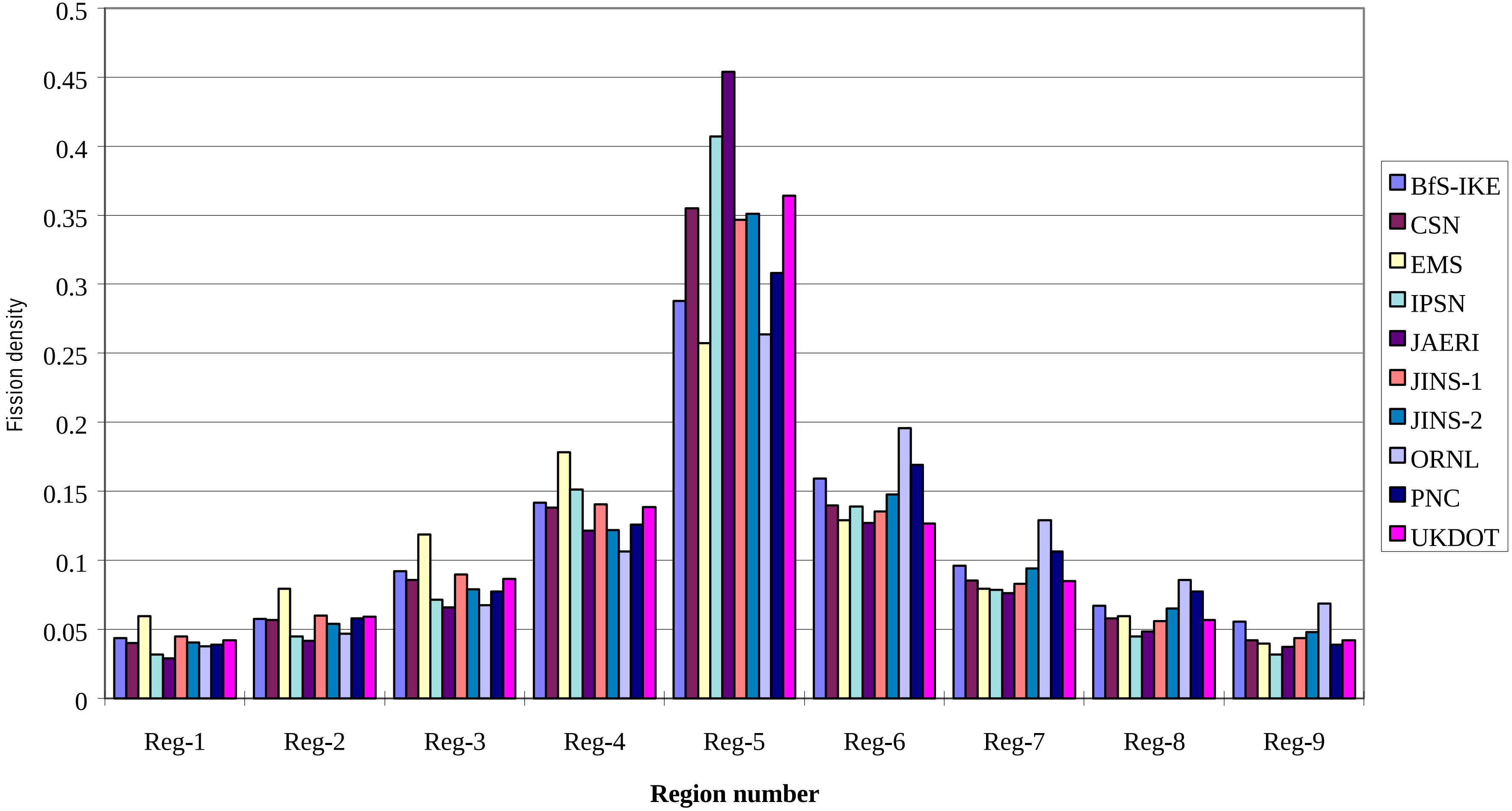


Figure 13bis

Case E - Fission densities



APPENDIX 1

Material and geometrical description

Fuel assembly (based on Westinghouse 17×17 design)

Fuel rod data

Fuel diameter	0.8192 cm
Rod ID	0.8357 cm
Rod OD	0.9500 cm
Fuel length	365.7 cm
Fuel material	UO_2 (assumed isotopic composition from Phase II-A 4.5 wt% 30 GWd/t fuel, 5 y cooling time)
Clad material	Zircaloy
Gas gap	Void
Endplug material	Zircaloy
Endplug height	1.75 cm
Full rod length	369.2 cm (fuel + 2 endplug)
Upper hardware	30.0 cm
Lower hardware	10.0 cm
Upper water region	7.0 cm
Lower water region	0.0 cm

Axial fuel division (9 axial regions)

Region 1 (fuel top)	5 cm
Region 2	5 cm
Region 3	10 cm
Region 4	20 cm
Region 5	285.7 cm
Region 6	20 cm
Region 7	10 cm
Region 8	5 cm
Region 9	5 cm

Assembly data

Lattice	17×17 (289 fuel rods, no guide tubes)
Dimensions	$21.41728 \times 21.41728 \times 409.2\ cm^3$
Pitch	1.25984 cm
Moderator	Water
Upper and lower end Hardware	50% stainless steel, 50% H_2O (by volume) (Note: rather than attempt to model the detail of the assembly end hardware, it has been chosen to mock up the hardware as a region of smeared water and stainless steel. Other hardware (e.g., grid spacers) is ignored.

Cask

Cask shell

ID	136.0 cm
OD	196.0 cm
Material	Stainless steel (SS304)
Height (outside)	476.2 cm
Height (inner cavity)	416.2 cm

Assembly basket

Inner basket compartment dimensions	22 cm×22 cm×416.2 cm (per assembly's position)
Material	Borated stainless steel (1 wt % boron)
Basket wall thickness	1 cm

Configuration

21 assembly positions in a 5×5 array (no corner positions)
Fuel assemblies are centred within basket region
Cask is completely flooded with water

Material compositions (densities in atom/barn-cm)

Zircaloy	Cr	7.589^{E}-05
	Fe	1.484^{E}-04
	Zr	4.298^{E}-02
Water	H	6.662^{E}-04
	O	3.331^{E}-02
Stainless steel	Cr	1.743^{E}-02
	Mn	1.736^{E}-03
	Fe	5.936^{E}-02
	Ni	7.721^{E}-03
Borated (1 wt %) stainless steel	Cr	1.691^{E}-02
	Mn	1.684^{E}-03
	Fe	5.758^{E}-02
	Ni	7.489^{E}-03
	^{10}B	7.836^{E}-04
	^{11}B	3.181^{E}-03
50/50 stainless steel/ water mixture	Cr	8.714^{E}-02
	Mn	8.682^{E}-04
	Fe	2.968^{E}-02
	Ni	3.860^{E}-03
	H	3.338^{E}-02
	O	1.669^{E}-02

APPENDIX 2

Spent fuel composition

Axially averaged burn-up cases (A and C)

Average BU = 30 GWd/t 5 years cooling time	
^{234}U	5.83E-06
^{235}U	4.33E-04
^{236}U	1.16E-04
^{238}U	2.16E-02
^{238}Pu	2.60E-06
^{239}Pu	1.42E-04
^{240}Pu	3.84E-05
^{241}Pu	2.14E-05
^{242}Pu	5.39E-06
^{241}Am	6.50E-06
^{243}Am	9.10E-07
^{237}Np	1.07E-05
^{95}Mo	4.24E-05
^{99}Tc	4.08E-05
^{101}Ru	3.80E-05
^{103}Rh	2.30E-05
^{109}Ag	3.09E-06
^{133}Cs	4.45E-05
^{147}Sm	7.95E-06
^{149}Sm	1.99E-07
^{150}Sm	1.03E-05
^{151}Sm	6.57E-07
^{152}Sm	4.11E-06
^{143}Nd	3.31E-05
^{145}Nd	2.49E-05
^{153}Eu	3.17E-06
^{155}Gd	2.14E-07
^{16}O	4.62E-02

Average BU = 50 GWd/t 5 years cooling time	
^{234}U	4.56E-06
^{235}U	2.07E-04
^{236}U	1.46E-04
^{238}U	2.12E-02
^{238}Pu	8.69E-06
^{239}Pu	1.53E-04
^{240}Pu	6.15E-05
^{241}Pu	3.43E-05
^{242}Pu	1.71E-05
^{241}Am	1.08E-05
^{243}Am	4.81E-06
^{237}Np	1.99E-05
^{95}Mo	6.52E-05
^{99}Tc	6.26E-05
^{101}Ru	6.24E-05
^{103}Rh	3.36E-05
^{109}Ag	6.25E-06
^{133}Cs	6.77E-05
^{147}Sm	9.90E-06
^{149}Sm	1.96E-07
^{150}Sm	1.72E-05
^{151}Sm	7.95E-07
^{152}Sm	6.33E-06
^{143}Nd	4.45E-05
^{145}Nd	3.74E-05
^{153}Eu	5.99E-06
^{155}Gd	5.31E-07
^{16}O	4.62E-02

Axially distributed burn-up cases (Case B)

Average BU = 30 GWd/t 5 years cooling time Locations 1 & 9 (12.33 GWd/t)	
^{234}U	7.27E-06
^{235}U	7.47E-04
^{236}U	6.32E-05
^{238}U	2.19E-02
^{238}Pu	2.79E-07
^{239}Pu	9.32E-05
^{240}Pu	1.29E-05
^{241}Pu	5.14E-06
^{242}Pu	4.29E-07
^{241}Am	1.46E-06
^{243}Am	2.91E-08
^{237}Np	3.11E-06
^{95}Mo	1.87E-05
^{99}Tc	1.79E-05
^{101}Ru	1.57E-05
^{103}Rh	1.02E-05
^{109}Ag	7.91E-07
^{133}Cs	1.97E-05
^{147}Sm	4.22E-06
^{149}Sm	1.74E-07
^{150}Sm	3.73E-06
^{151}Sm	4.62E-07
^{152}Sm	1.69E-06
^{143}Nd	1.61E-05
^{145}Nd	1.12E-05
^{153}Eu	9.01E-07
^{155}Gd	5.43E-08
^{16}O	4.62E-02

Average BU = 30 GWd/t 5 years cooling time Locations 2 & 8 (14.04 GWd/t)	
^{234}U	7.12E-06
^{235}U	7.11E-04
^{236}U	6.97E-05
^{238}U	2.18E-02
^{238}Pu	3.85E-07
^{239}Pu	1.01E-04
^{240}Pu	1.53E-05
^{241}Pu	6.59E-06
^{242}Pu	6.43E-07
^{241}Am	1.89E-06
^{243}Am	4.86E-08
^{237}Np	3.73E-06
^{95}Mo	2.12E-05
^{99}Tc	2.03E-05
^{101}Ru	1.79E-05
^{103}Rh	1.16E-05
^{109}Ag	9.71E-07
^{133}Cs	2.22E-05
^{147}Sm	4.68E-06
^{149}Sm	1.80E-07
^{150}Sm	4.33E-06
^{151}Sm	4.86E-07
^{152}Sm	1.95E-06
^{143}Nd	1.80E-05
^{145}Nd	1.26E-05
^{153}Eu	1.08E-06
^{155}Gd	6.38E-08
^{16}O	4.62E-02

Average BU = 30 GWd/t 5 years cooling time Locations 3 & 7 (18.01 GWd/t)	
^{234}U	6.78E-06
^{235}U	6.33E-04
^{236}U	8.35E-05
^{238}U	2.18E-02
^{238}Pu	7.18E-07
^{239}Pu	1.16E-04
^{240}Pu	2.12E-05
^{241}Pu	1.02E-05
^{242}Pu	1.36E-06
^{241}Am	2.98E-06
^{243}Am	1.29E-07
^{237}Np	5.29E-06
^{95}Mo	2.67E-05
^{99}Tc	2.57E-05
^{101}Ru	2.30E-05
^{103}Rh	1.46E-05
^{109}Ag	1.43E-06
^{133}Cs	2.81E-05
^{147}Sm	5.67E-06
^{149}Sm	1.89E-07
^{150}Sm	5.78E-06
^{151}Sm	5.36E-07
^{152}Sm	2.52E-06
^{143}Nd	2.23E-05
^{145}Nd	1.58E-05
^{153}Eu	1.55E-06
^{155}Gd	9.02E-08
^{16}O	4.62E-02

Axially distributed burn-ups (Case B)

Average BU = 30 GWd/t 5 years cooling time Locations 4 & 6 (24.01 GWd/t)	
^{234}U	6.29E-06
^{235}U	5.26E-04
^{236}U	1.02E-04
^{238}U	2.17E-02
^{238}Pu	1.49E-06
^{239}Pu	1.32E-04
^{240}Pu	2.99E-05
^{241}Pu	1.59E-05
^{242}Pu	3.03E-06
^{241}Am	4.76E-06
^{243}Am	3.97E-07
^{237}Np	7.90E-06
^{95}Mo	3.48E-05
^{99}Tc	3.34E-05
^{101}Ru	3.05E-05
^{103}Rh	1.90E-05
^{109}Ag	2.22E-06
^{133}Cs	3.65E-05
^{147}Sm	6.93E-06
^{149}Sm	1.96E-07
^{150}Sm	8.04E-06
^{151}Sm	6.01E-07
^{152}Sm	3.35E-06
^{143}Nd	2.81E-05
^{145}Nd	2.05E-05
^{153}Eu	2.33E-06
^{155}Gd	1.44E-07
^{16}O	4.62E-02

Average BU = 30 GWd/t 5 years cooling time Location 5 (32.86 GWd/t)	
^{234}U	5.62E-06
^{235}U	3.93E-04
^{236}U	1.22E-04
^{238}U	2.15E-02
^{238}Pu	3.26E-06
^{239}Pu	1.45E-04
^{240}Pu	4.22E-05
^{241}Pu	2.37E-05
^{242}Pu	6.73E-06
^{241}Am	7.27E-06
^{243}Am	1.25E-06
^{237}Np	1.20E-05
^{95}Mo	4.59E-05
^{99}Tc	4.42E-05
^{101}Ru	4.16E-05
^{103}Rh	2.48E-05
^{109}Ag	3.52E-06
^{133}Cs	4.81E-05
^{147}Sm	8.35E-06
^{149}Sm	2.00E-07
^{150}Sm	1.13E-05
^{151}Sm	6.81E-07
^{152}Sm	4.46E-06
^{143}Nd	3.52E-05
^{145}Nd	2.68E-05
^{153}Eu	3.58E-06
^{155}Gd	2.53E-07
^{16}O	4.62E-02

Axially distributed burn-up cases (Case D)

Average BU = 50 GWd/t 5 years cooling time Locations 1 & 9 (21.56 GWd/t)	
^{234}U	6.49E-06
^{235}U	5.68E-04
^{236}U	9.46E-05
^{238}U	2.17E-02
^{238}Pu	1.13E-06
^{239}Pu	1.26E-04
^{240}Pu	2.64E-05
^{241}Pu	1.36E-05
^{242}Pu	2.26E-06
^{241}Am	4.03E-06
^{243}Am	2.62E-07
^{237}Np	6.81E-06
^{95}Mo	3.15E-05
^{99}Tc	3.03E-05
^{101}Ru	2.75E-05
^{103}Rh	1.73E-05
^{109}Ag	1.89E-06
^{133}Cs	3.31E-05
^{147}Sm	6.45E-06
^{149}Sm	1.94E-07
^{150}Sm	7.12E-06
^{151}Sm	5.75E-07
^{152}Sm	3.02E-06
^{143}Nd	2.58E-05
^{145}Nd	1.86E-05
^{153}Eu	2.00E-06
^{155}Gd	1.20E-07
^{16}O	4.62E-02

Average BU = 50 GWd/t 5 years cooling time Locations 2 & 8 (24.02 GWd/t)	
^{234}U	6.29E-06
^{235}U	5.26E-04
^{236}U	1.02E-04
^{238}U	2.17E-02
^{238}Pu	1.49E-06
^{239}Pu	1.32E-04
^{240}Pu	3.00E-05
^{241}Pu	1.60E-05
^{242}Pu	3.03E-06
^{241}Am	4.76E-06
^{243}Am	3.98E-07
^{237}Np	7.90E-06
^{95}Mo	3.48E-05
^{99}Tc	3.35E-05
^{101}Ru	3.05E-05
^{103}Rh	1.90E-05
^{109}Ag	2.22E-06
^{133}Cs	3.65E-05
^{147}Sm	6.93E-06
^{149}Sm	1.96E-07
^{150}Sm	8.05E-06
^{151}Sm	6.01E-07
^{152}Sm	3.35E-06
^{143}Nd	2.81E-05
^{145}Nd	2.05E-05
^{153}Eu	2.33E-06
^{155}Gd	1.44E-07
^{16}O	4.62E-02

Average BU = 50 GWd/t 5 years cooling time Locations 3 & 7 (30.58 GWd/t)	
^{234}U	5.79E-06
^{235}U	4.25E-04
^{236}U	1.18E-04
^{238}U	2.16E-02
^{238}Pu	2.73E-06
^{239}Pu	1.42E-04
^{240}Pu	3.91E-05
^{241}Pu	2.19E-05
^{242}Pu	5.65E-06
^{241}Am	6.66E-06
^{243}Am	9.74E-07
^{237}Np	1.09E-05
^{95}Mo	4.31E-05
^{99}Tc	4.15E-05
^{101}Ru	3.88E-05
^{103}Rh	2.34E-05
^{109}Ag	3.18E-06
^{133}Cs	4.53E-05
^{147}Sm	8.03E-06
^{149}Sm	1.99E-07
^{150}Sm	1.05E-05
^{151}Sm	6.62E-07
^{152}Sm	4.18E-06
^{143}Nd	3.35E-05
^{145}Nd	2.53E-05
^{153}Eu	3.25E-06
^{155}Gd	2.22E-07
^{16}O	4.62E-02

Axially distributed burn-up cases (Case D)

Average BU = 50 GWd/t 5 years cooling time Locations 4 & 6 (40.42 GWd/t)	
^{234}U	5.12E-06
^{235}U	3.00E-04
^{236}U	1.35E-04
^{238}U	2.14E-02
^{238}Pu	5.37E-06
^{239}Pu	1.51E-04
^{240}Pu	5.15E-05
^{241}Pu	2.92E-05
^{242}Pu	1.09E-05
^{241}Am	9.09E-06
^{243}Am	2.51E-06
^{237}Np	1.56E-05
^{95}Mo	5.48E-05
^{99}Tc	5.27E-05
^{101}Ru	5.09E-05
^{103}Rh	2.91E-05
^{109}Ag	4.71E-06
^{133}Cs	5.73E-05
^{147}Sm	9.21E-06
^{149}Sm	2.00E-07
^{150}Sm	1.40E-05
^{151}Sm	7.38E-07
^{152}Sm	5.33E-06
^{143}Nd	4.00E-05
^{145}Nd	3.18E-05
^{153}Eu	4.67E-06
^{155}Gd	3.69E-07
^{16}O	4.62E-02

Average BU = 50 GWd/t 5 years cooling time Location 5 (54.60 GWd/t)	
^{234}U	4.33E-06
^{235}U	1.71E-04
^{236}U	1.49E-04
^{238}U	2.11E-02
^{238}Pu	1.05E-05
^{239}Pu	1.53E-04
^{240}Pu	6.55E-05
^{241}Pu	3.60E-05
^{242}Pu	2.03E-05
^{241}Am	1.14E-05
^{243}Am	6.16E-06
^{237}Np	2.18E-05
^{95}Mo	6.99E-05
^{99}Tc	6.70E-05
^{101}Ru	6.79E-05
^{103}Rh	3.54E-05
^{109}Ag	6.98E-06
^{133}Cs	7.23E-05
^{147}Sm	1.01E-05
^{149}Sm	1.93E-07
^{150}Sm	1.86E-05
^{151}Sm	8.18E-07
^{152}Sm	6.76E-06
^{143}Nd	4.60E-05
^{145}Nd	3.99E-05
^{153}Eu	6.59E-06
^{155}Gd	6.09E-07
^{16}O	4.62E-02

APPENDIX 3

Participants and analysis methods

(1) ABB, Sweden

Institute: ABB Atom, Nuclear Fuel Division (BRM), Sweden
Participants: Peter Hoglund, Waldemar Lipiec
Computer codes: PHOENIX4/KENO-Va
Data library: PHOENIX LIBRARY: 17 May 1994 (ENDF/B-VI based)
No. of neutron energy groups: 89 neutron energy groups

Comments:

The ABB standard code system for criticality calculations has been used in the analysis. It consists of a 2-D lattice code PHOENIX (collision probability with current coupling and final treatment by the S4 method) and the 3-D Monte Carlo code KENO-V.a. The final geometry of the 3-D system has been modelled in KENO. PHOENIX was used for local calculations to homogenise fuel assemblies and condense the cross-sections to 13 groups. Two types of assemblies have been distinguished: 13 in central positions and 8 in the corners. The resulting P0 transport corrected cross-sections for these two assembly types (for Cases B and D also combined with five axial regions) were used in the KENO calculations. The number of neutron histories was more than 650 000 for each case. Cases D and E converged slower and have a bit larger standard deviation.

(2) BfS-IKE, Germany

Institute: Bundesamt für Strahlenschutz (BfS), Salzgittzer, and Institut für Kernenergetik und Energiesysteme (IKE), Stuttgart, Germany
Participants: H.-H. Schweer (BfS), W. Bernnat (IKE)
Computer codes: CGM Code, developed at IKE and Monte Carlo Code MORSE-K
Data library: Based on JEF-1 data
No. of neutron energy groups: 242 for CGM and 60 for MORSE-K

Additional assumptions:

For the cladding material in the fuel region Cr and Fe were omitted.

(3) BNFL, UK

Company: British Nuclear Fuels plc, Risley, Warrington, England
Participants: Peter Rex Thorne and Russel Bowden
Computer codes: MONK6B Monte Carlo method, using Superhistory powering
Data library: MONK6B 8220 Point Energy Library, derived from UKNDL and JEF-2
No. of neutron energy groups: Continuous energy

Comments:

MONK6B on Research Machines 486/20 SystemBase 25, operating under SCO UNIX System 5 Release 3.2.2.

3-D modelling of requested system.

No nuclides omitted from requested calculations. No convergence limit set on eigenvalue. Calculations performed using 20 stages of 1000 source neutrons per stage. Typical eigenvalue uncertainty on individual calculations of the order of 0.0018. Combined results show mean uncertainty of the order of 0.0010. It should be noted that the fission density distributions presented above combine the relative fission densities of the corresponding axial regions at each end of the fuel, due to limitations in running MONK6B calculations on the current computer system with the extended UKNDL/JEF-2 nuclear data library and the large number of materials, each containing a large number of nuclides. Analysis of the fission density results in nine axial zones should therefore, as a first approximation, assume symmetry of the fission density distribution about the central axial region.

(4) CEA, France

Institute:	CEA-SACLAY DMT/SERMA/LEPP, France
Participants:	Y.K. Lee, C. Diop
Computer codes:	APOLLO2 + TRIMARAN2 (cf: ICNC'95, pp. 3.12)
Data library:	CEA93 (derived from JEF2.2)

No. of neutron energy groups: 99

(5) CSN, Spain

Institute:	Consejo de Seguridad Nuclear (CSN), Spain
Participants:	Jose M. Conde, Manuel Recio
Computer codes:	CASMO-3 v. 4.7 and SIMULATE-3P v. 4.02
Data library:	E4LTJB7, based primarily on ENDF/B-4, although some data come from ENDF/B-5 and JEF-2, processed with NJOY

No. of neutron energy groups: 70; the group structure is similar to that of WIMS with the addition of one boundary at 1.855 eV

Additional assumptions:

The absorber nuclides ^{95}Mo, ^{99}Tc and ^{101}Ru are not included in the data library. Cross-sections for each fuel segment under storage conditions have been calculated using the CASMO storage rack option. Cross-sections for both the axial and radial reflectors have been obtained using the CASMO reflector model. A model has been set up for SIMULATE including 73 axial nodes, 5 cm high. Each fuel element has been modelled using 2×2 radial nodes. Three different radial reflectors have been used, depending on the water thickness between the storage position and the cask wall. The axial reflectors in the model are shorter than in the Benchmark specification. It has been verified that both this difference and the active length difference (365 cm instead of 365.7 cm) have a negligible impact on the results.

(6) EMS, Sweden

Company:	E Mennerdahl Systems (EMS)
Participants:	Dennis Mennerdahl
Computer codes:	SCALE 4.1
Data library:	Burn-up library 27BURN-UPLIB

No. of neutron energy groups: 27

Comments:

The number of neutron histories used for fresh fuel and flat axial burn-up profile was 100 000; the number of neutron histories for realistic axial burn-up profile was 700 000. Fission densities are not calculated accurately and should not be trusted, as they are useful only to the person making the calculation (the code system has not been designed and validated for calculation of fission densities). Neutrons started in all fissile material for all problems. Fission densities are calculated as double integral (volume and energy) of fissions in one zone divided by the volume of that zone. The normalised data is the fission density of one zone divided by the sum of the fission densities of all zones. The formula given in the hand written specifications seems to concern fissions per region.

(7) GRS, Germany

Institute: Gesellschaft für Anlagen und Reaktorsicherheit (GRS) 85748 Garching, Germany
Participants: B. Gmal, E.F. Moser, W. Weber
Computer codes: SCALE-4
Data library: Depletion library 27BURNUPLIB
No. of neutron energy groups: 27

Comments:

Number of neutron histories: 300 000 (500 batches a 600 neutrons). Code sequences: CSAS2X, KENO-V.a for flat burn-up distribution, CSASIX, WAX, KENO-V.a for burn-up profile.

(8) IPSN, France

Institute: Institut de Protection et de Sûreté Nucléaire (France)
Participants: G. Poullot, A. Nouri
Computer codes: APOLLO-1 (collision probability method, self-shielding)
MORET-3 (Monte Carlo)
Data library: CEA86 (based on JEF-1, ENDF/B4 ENDF/B5 and internal evaluations)
No. of neutron energy groups: 99 for APOLLO-1 and 16 for MORET-3

(9) JAERI, Japan

Institute: Fuel Cycle Safety Evaluation Laboratory, JAERI Japan
Participants: Kenya Suyama
Computer codes: MCNP4A
Data library: JENDL-3.2 library (FSXLIB-J3R2) at 300 K
No. of neutron energy groups: Continuous

(10) JINS-1, Japan

Institute: Institute of Nuclear Safety, NUPEC
Participants: Susumu Mitake (INS) and Osamu Sato (MRI)
Computer codes: MGCL-JINS; resonance self-shielding correction: Bondarenko
Data library: ENDF/B-IV (JENDL-3.2 for FP nuclides)
No. of neutron energy groups: 137

(11) JINS-2, Japan

Institute: Institute of Nuclear Safety, NUPEC
Participants: Susumu Mitake (INS) and Osamu Sato (MRI)
Computer codes: SCALE; resonance self-shielding correction: Nordheim
Data library: ENDF/B4
No. of neutron energy groups: 27

Comments for (10) and (11):

Code for k-effective calculation: KENO-V.a. Geometry modelling: Fuel pellets, clads and moderators are modelled individually based on their configurations and dimensions described in NEA/NSC/DOC(94)25 (19 May 1994). No smeared technique is applied. Also referred is EMS/FO/95-07 prepared by D. Mennerdahl (13 Oct 95). Monte Carlo parameters (for all cases): No. of generations: 403, No. of initially skipped generations: 3, No. of histories/generation: 2400, Total no. of histories: 960 000.

(12) ORNL, USA

Institute: Oak Ridge National Laboratory
Participants: M.D. DeHart, C.V. Parks
Codes used: SCALE-4.3 CSAS25 sequence for no axial distributions; Multiple CSASN sequences + standalone KENO-V.a calculation for cases with axial distributions
Data library: SCALE 44GROUPNDF5 (44-group, ENDF/B-V) library

Additional assumptions:

Resonance corrected cross-sections for all but seven actinides were calculated based on Region 5 (centre) conditions. ORNL's experience has shown that resonance processing is sensitive to burn-up only for ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, and ^{241}Pu. Other nuclides have too little net worth or are too diluted to be sensitive to burn-up. Resonance corrections were calculated as a function of axial location (i.e. burn-up) only for these seven nuclides.

(13) PNC, Japan

Institute: PNC Tokai Works
Participants: Ichiro Nojiri
Computer codes: SCALE-4.2 (CSASIX – WAX – KENO V.a)
Data library: BURNUP library for SCALE-4.2: 27BURNUPLIB (ENDF-B/IV and V)
No. of neutron energy groups: 27
Neutron data processing code or method: BONAMI-S , NITAWL-II
Geometry modelling: 3-D
Employed convergence limit or statistical errors for eigenvalues: 0.0010

(14) UKDOT, UK

No. of neutron energy groups:
Institute: United Kingdom Department of Transport
Participant: Jim Stewart
Computer code: MONK6B (SCO UNIX PC VERSION - SCO7)
Data library: MONK- 8220 point energy library (MONK6 library with added fission products)
No. of groups: Continuous
Geometry: 3-D model
Convergence: Typical standard deviation on k_{eff} about 0.0008

APPENDIX 4

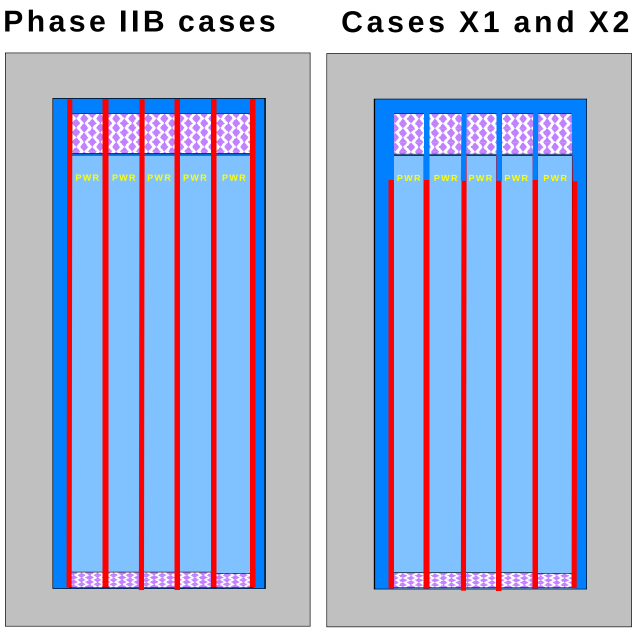
Additional accident configurations

E. Mennerdahl Systems
Starvägen 12
S-183 51 TÄBY

EMS/FO/95-07

BURN-UP CREDIT BENCHMARK PROBLEMS: FLAT OR REALISTIC AXIAL PROFILES?

Dennis Mennerdahl
October 13, 1995



Contribution to Phase II-B of a study by the
OECD/NEA Working Group on Burn-up Credit in Criticality Safety

Sponsored by the Swedish Nuclear Power Inspectorate

Tel: (+46) 8 -756 58 12 ◆ Fax: (+46) 8 -756 58 72 ◆ Internet: dennis.mennerdahl@ems.se

BURN-UP CREDIT BENCHMARK PROBLEMS:
FLAT OR REALISTIC AXIAL PROFILES?

1. Introduction

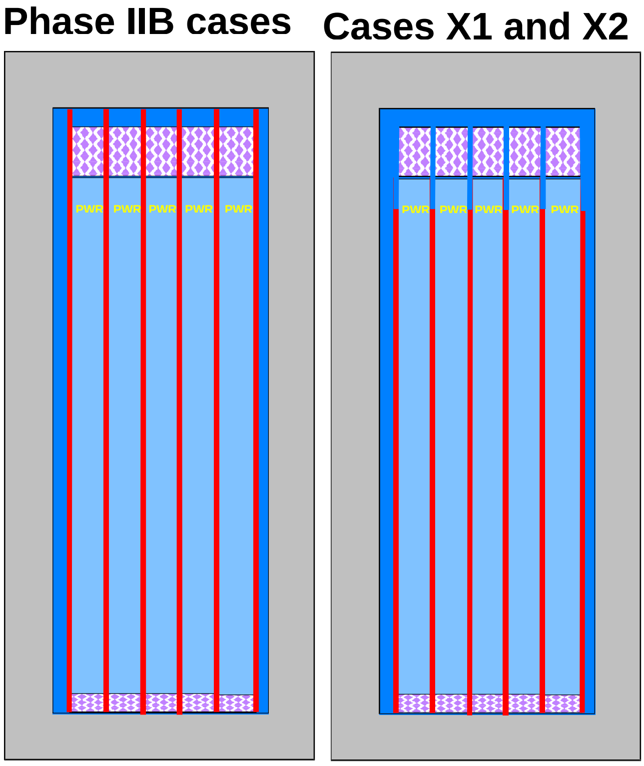
This paper contains specifications for two benchmark problems, in addition to the nine benchmark problems selected for Phase II-B by the OECD/NEA Working Group on Burn-up Credit. Comments to the additional proposals are also given.

2. Benchmark problem specifications

The isotopics and geometry of Problems A and B of Phase II-B are used. The only change is that the boron steel of the top 20 cm of fuel and above is replaced with water (see figure). This is a slight modification to the previous (incomplete) proposal.

- *Requested information:* K_{eff} and standard deviation (for Monte Carlo methods).

- *Optional:* Neutron source distribution, normalised fission densities, results without fission products.



20 cm from top of fuel region.
Boron steel (red) replaced with water.

- **Problem X1**. Flat burn-up profile as in Problem A of Phase II-B. Burn-up 30 GWd/tU and cooling time five years. Includes fission products.

- **Problem X2**. A more realistic axial burn-up profile as in Problem B of Phase II-B. Burn-up 30 GWd/tU and cooling time five years. Includes fission products.

3. Preliminary results

Problem	K_{eff}	σ
X1	0.9274	0.0012
X2	1.0040	0.0012
Δk	0.0766	0.0017

Problem	K_{eff}	σ
A	0.8900	0.0020
B	0.8900	0.0008
Δk	0.0000	0.0022

4. Problem discussion

Criticality safety is often summarised as a requirement for the neutron multiplication factor to be less than 1.00 with some margin.

$$Neutron\ multiplication\ \ factor = \frac{production\ \ factor}{absorption\ term + leakage\ term}$$

The production factor takes into account neutron physics properties of the fissile material. This material includes actinides and fission products. The absorption term as used here includes effects of the materials between the fuel rods and assemblies but not absorbing materials between the major reflector materials and the fuel assemblies. The leakage term is defined as the combined effects of leakage from the outside reflector material, of absorption in the materials surrounding the fuel array and of changes in the energy spectrum, geometry and direction of returning neutrons.

The purpose of Phase II, as I understand it, is to study the influence of axial variations and to discuss possible approximations, in particular assuming a flat axial burn-up profile. A flat burn-up profile based on fresh fuel is one extreme. A flat burn-up profile based on an average burn-up for the whole assembly is the other extreme. A correct solution must take the real axial burn-up profile into account.

Phase II-A includes two parameters that vary axially, total burn-up and cooling time. Both are related to the “production factor” in the ratio defined above. Unfortunately, Phase II-B does not add any parameters.

The two additional benchmark problems that have been proposed earlier and are specified here, add axial variations to both the “absorption term” and to the “leakage term”. The boron steel acts both as an “internal absorber” of neutrons travelling between fuel assemblies and as a “reflector absorber” to reduce the number of neutrons that are reflected.

The benchmark problems defined here may not be directly related to a realistic incident for the transport cask selected for Phase II-B. For spent fuel pools, similar effects have been identified and analysed, with credit taken for burn-up. In the USA, up to 10 cm “gaps” have been observed in absorber materials. In Sweden, 60 cm “overlaps” (no water separation as opposed to the normal 10 cm separation) between stored fuel and fuel being handled were considered possible events for PWR and BWR spent fuel.

There are other ways to let the leakage term vary axially. One way would be to let a good reflector material closely surround the fuel region at the top, while the central region is surrounded by a poor reflector. Using a cask design where leakage is more important is another option. However, the purpose of this paper is not to maximise the theoretical impact of axial variations, but to define some useful benchmark specifications and to encourage further studies.

5. Background

The benchmark problems selected in the Phases II-A and II-B are typical for simple design calculations. However, they are not representative of some of the more complicated situations that are identified and analysed in safety assessments and in incidents that were not analysed at all. An explanation could be that the majority of the Working Group either has specific interests (nothing wrong with that – it is often such interests that lead to major contributions to safety) that are covered by the existing benchmark problems or has little interest in burn-up credit.

For those of us who are interested in and feel responsible for criticality safety in general, there are reasons for concern. A flat axial burn-up profile is a very crude approximation and before we support its use, we should understand its limitations. It is also important to have adequate methods and training to handle the situations when the approximation is not adequate.

The Working Group is involved in testing and comparing calculation methods. Are these capable of solving problems related to burn-up credit correctly? So far, we don’t know. The Phase II-A and II-B results have caused some of us to believe that the flat profile approximation is acceptable for burn-ups less than 50 GWd/tU and cooling times shorter than five years. Even for that high burn-up and cooling time, the effect on k_{eff} only seems to be 3-4%. Generalised conclusions like these are dangerous. At least one paper at the ICNC'95 conference referred to such preliminary results of the Working Group.

6. Motivation for “a deeper understanding”

In Sweden, there are currently no immediate requests for burn-up credit. Several years ago, the issue was seriously studied in connection with the design of compact storage modules for PWR and BWR spent fuel at the large central facility in Sweden (CLAB). A result of the study was that burn-up credit was possible, but that the combined effect of administrative and technical controls, uncertainties and probable delays was not worth the effort. Large amounts of boron steel were used instead.

Spent fuel is shipped in Sweden, usually using package designs from other states. The authorities should be prepared for dealing with requests for burn-up credit if this is practised in other parts of the world.

However, the most important reason for evaluating burn-up credit is probably the need to be able to estimate the real safety margin. This can be very important in case of an incident.

One scenario is that the experts, based on the flat profile approximation, conclude that criticality cannot occur. Then, during recovery operations, there is a criticality accident.

Another scenario is that the experts, knowing that burn-up credit can be complicated but not being prepared for it, make a conservative (pessimistic) assumption and recommend the surrounding population to be evacuated. Such an operation could lead to very severe consequences in many ways.

Fast and proper evaluation of incidents may save lives, property and other resources, reduce stress (panic) in the population and increase the trust in the nuclear industry and authorities. Conservative assumptions (fresh fuel) in the case of an incident could lead to much more severe consequences than even a criticality accident.

7. Conclusions related to general criticality safety

In Phases II-A and II-B, we have shown that scenarios exist where the flat axial burn-up profile approximation appear acceptable for burn-ups not exceeding 30 GWd/tU and cooling times not exceeding five years. However, we have also recognised that with realistic axial burn-up profiles, the calculation problem is more complicated.

For burn-ups of about 50 GWd/tU and cooling times of up to five years, the flat axial burn-up profile approximation is non-conservative with a Δk_{eff} of about 0.03. In Monte Carlo methods, the number of neutrons that normally give "converging" statistics is no longer sufficient. The trend (bias) may be missed if the user is not aware of the problem. With deterministic methods, other complications have been noticed.

Phases II-A and II-B only deal with axial effects due to varying fissile material (neutron production factor). Axial effects due to variations in absorption and leakage are not included. Realistic applications and design basis incidents in transport, handling and storage of spent fuel often involve combinations of the three mentioned variations. Without studying such combinations, we will not know if our calculation methods are adequate.

To give some indication of the potential for a much higher Δk_{eff} than 0.03 even for the case of 30 GWd/tU, the additional problems X1 and X2 have been specified. These problems are not optimised, but chosen so that they are similar to the Phase II-B problems. The preliminary Δk_{eff} of 0.08 indicates that also for lower burn-ups than 30 GWd/tU, the flat axial burn-up profile approximation may not be adequate. The approximation has to be evaluated for each application and scenario.

APPENDIX 5

Supplementary study of convergence

Note by Susumu Mitake and Osamu Sato
Institute of Nuclear Safety, NUPEC

1. Problem specification

The following documents were used:

- Agreed Modification of Problem II-B: NEA/NSC/DOC(95)15, Annex 3
- Proposed Spent Fuel Cask Geometry, OECD Phase II-B Benchmark: NEA/NSC/DOC(94)25
- Burn-up credit – Axial effect – Criticality safety: EMS/FO/94-04

2. Analysed cases

Including the cases proposed by Mennerdahl, eleven cases (A...E, and 6...11) were analysed.

Burn-up and cooling	Axial distribution	Gap	Case ID
30 GWD/tU 5 years with fission products	No	Borated steel with 20 cm water region with 10 cm water region	A 6 8
30 GWD/tU 5 years with fission products	Specified	Borated steel with 20 cm water region with 10 cm water region	B 7 9
50 GWD/tU 5 years with fission products	No	Borated steel Steel	C 10
50 GWD/tU 5 years with fission products	Specified	Borated steel Steel	D 11
Fresh fuel (4.5 wt% ^{235}U)	No	Borated steel	E

3. Analytical method

For cases A to E, two neutron libraries, MGCL-JINS library and SCALE 27-group library, were comparatively used. And, for cases 6 to 11, only the former was used. The KENO-V.a code was used for the k-effective calculations.

1) MGCL-JINS library
   Neutron cross-section: ENDF/B-IV (JENDL-3.2 data were adopted for fission product nuclides)
   No. of energy groups: 137
   Resonance self-shielding correction: Bondarenko

2) SCALE 27-Group library
   Neutron cross-section: ENDF/B-IV
   No. of energy groups: 27
   Resonance self-shielding correction: Nordheim

4. Geometry modelling

Fuel pellets, clads and moderators were modeled individually based on their configurations and dimensions described in NEA/NSC/DOC(94)25. No smeared technique was applied, except for the End Hardware region. Volumetric fractions of steel and water were only specified for the region.

5. Monte Carlo parameters

No. of generations:	403
No. of initially skipped generations:	3
No. of histories/generation:	300
Total no. of histories:	120 000

6. Results

	With MGCL-JINS library		With SCALE 27-G library	
	k_{eff}	Statistical error (1-sigma)	k_{eff}	Statistical error (1-sigma)
A	0.83062	0.00177	0.82317	0.00164
B	0.89978	0.00185	0.88727	0.00167
C	0.76866	0.00162	0.75831	0.00149
D	0.79806	0.00165	0.78460	0.00176
E	1.13043	0.00186	1.11456	0.00194

	With MGCL-JINS library	
	k_{eff}	Statistical error (1-sigma)
6	0.9361	0.0019
7	0.9361	0.0022
8	0.8548	0.0017
9	0.9747	0.0020
10	0.8777	0.0016
11	0.9053	0.0017

7. Fission distribution

In the Monte Carlo simulation analysis, the number of fissions occurring in the top or bottom regions of fuel pins are calculated to be small, because the neutron importance of these regions are small compared to that of the central region. Therefore, large statistical deviations of fission rates result at the top or bottom regions. When it is required to evaluate the difference of the analytical results which are made with or without the axial burn-up profile, however, the accuracy of fission rates calculated in these regions may increase to play a more important role in defining the multiplication factor. So, we checked the fission rates and their statistical errors in each axial region of the fuel pins and the multiplication factors, varying the number of generations (GEN) and the number of histories per generation (NPG), as suggested by Mennerdahl. The results of these calculations for the E-compositions (fresh fuel) with the KENO-V.a code and the MGCL-JINS library are shown in Table AI.

The results with various GENs (from 103 to 3203) and a fixed NPG (300) are tabulated in the upper half of the table. The fission fraction of central region (Region 5) is as high as over 90%, and the contributions of the top and bottom regions (Regions 1, 2, 8 and 9) are only a few per cent. The fission fraction of Region 5 varies with the value of GEN, and does not converge even with increased generations. Deviation of the multiplication factors with the various GENs results to about 0.5%Dk/k.

The lower half of the table shows the results with various NPGs (from 300 to 4800) and a fixed GEN (203). The fission fractions in each axial region converge simply with increased histories, and differences of the fission fractions and the multiplication factors for the cases with NPG of 2400 and 4800 are as low as 0.001 and about 0.07% Dk/k, respectively. Thus, the NPG of 2400 is large enough for the present analysis with axial burn-up profile.

(Our results presented in § 6 had been obtained before the above discussions were made, so we had previously used an NPG of 300 and a GEN of 403.)

8. Comparison with Phase II-A

The reactivity change among these cases, which is evaluated with a formula (k-k')/kk' using k-effectives, was also analysed in the Phase II-A problem, an infinite array of fuel rods.

First, the reactivity decrease with burn-up are comparatively tabulated for the cases without axial burn-up distribution.

	30 GWd/tU		50 GWd/tU	
	MGCL-JINS	SCALE 27G	MGCL-JINS	SCALE 27G
Phase II-A (rod array)	-22.2%	-22.6%	-30.7%	-30.7%
Phase II-B (cask)	-31.9%	-31.8%	-41.6%	-42.2%

Reactivity change: [k(A)-k(E)]/k(A)k(E) or [k(C)-k(E)]/k(C)k(E)

Greater reactivity decrease are found in the cases of Phase II-B which have a larger neutron leakage. It may be not easy to explain the physical meaning of these results simply based on the neutron balance concept.

Second, the reactivity increases due to the effect of axial burn-up distribution are compared.

	30 GWd/tU		50 GWd/tU	
	MGCL-JINS	SCALE 27G	MGCL-JINS	SCALE 27G
Phase II-A (rod array)	+ 5.38%	+ 5.90%	+ 3.87%	+ 3.67%
Phase II-B (cask)	+ 9.25%	+ 8.78%	+ 4.79%	+ 4.42%

Reactivity change: [k(B)-k(A)]/k(B)k(A) or [k(D)-k(C)]/k(D)k(C)

The reactivity increases are significant for the cases of transport cask configuration in which a finite number of fuel rods are allocated.

Table AI. Axial fission distributions and multiplication factors with various NPG and GEN (Case 5: fresh fuel)

NPG	300											
GEN	103		203		403		803		1603		3203	
Ax. reg.	Fissions*	± 1σ	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ
1 (5cm)	0.0052	± 11.24%	0.0015	± 12.72%	0.0016	± 8.45%	0.0019	± 7.98%	0.0022	± 5.85%	0.0027	± 3.42%
2 (5cm)	0.0070	± 9%	0.0020	± 10.83%	0.0019	± 8.06%	0.0022	± 7.02%	0.0027	± 5.14%	0.0035	± 3.15%
3 (10cm)	0.0220	± 6.44%	0.0072	± 8.3%	0.0061	± 5.51%	0.0065	± 6.05%	0.0086	± 4.46%	0.0104	± 2.21%
4 (20cm)	0.0532	± 5.6%	0.0243	± 6%	0.0203	± 3.85%	0.0189	± 5.49%	0.0268	± 3.38%	0.0339	± 1.32%
5 (285.7cm)	0.8943	± 0.66%	0.9196	± 0.56%	0.9567	± 0.26%	0.9439	± 0.26%	0.9106	± 0.21%	0.9086	± 0.16%
6 (20cm)	0.0111	± 9.93%	0.0304	± 6.73%	0.0090	± 6.34%	0.0186	± 3.56%	0.0324	± 2.14%	0.0271	± 1.89%
7 (10cm)	0.0049	± 13%	0.0101	± 8.79%	0.0028	± 7.92%	0.0050	± 5.76%	0.0106	± 2.69%	0.0086	± 2.36%
8 (5cm)	0.0014	± 17.65%	0.0027	± 11.49%	0.0008	± 12.86%	0.0016	± 7.14%	0.0035	± 3.58%	0.0030	± 2.81%
9 (5cm)	0.0010	± 19.37%	0.0021	± 13.5%	0.0008	± 12.82%	0.0013	± 8.24%	0.0026	± 4.03%	0.0023	± 3.14%
k_{eff}	1.1300	± 0.00406	1.1287	± 0.00282	1.1283	± 0.00207	1.1249	± 0.0016	1.1244	± 0.00101	1.1249	± 0.00072

NPG	300		600		1200		2400		4800	
GEN	203									
Ax. reg.	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ	Fissions	± 1σ
1 (5cm)	0.0015	± 12.72%	0.0014	± 9.71%	0.0011	± 7.96%	0.0016	± 4.73%	0.0016	± 3.6%
2 (5cm)	0.0020	± 10.83%	0.0020	± 8.81%	0.0014	± 7.6%	0.0020	± 4.27%	0.0021	± 3.16%
3 (10cm)	0.0072	± 8.3%	0.0068	± 6.54%	0.0047	± 5.69%	0.0064	± 3.28%	0.0065	± 2.49%
4 (20cm)	0.0243	± 6%	0.0240	± 4.87%	0.0174	± 4.38%	0.0222	± 2.48%	0.0226	± 1.93%
5 (285.7cm)	0.9196	± 0.56%	0.9308	± 0.35%	0.9220	± 0.26%	0.9260	± 0.17%	0.9264	± 0.12%
6 (20cm)	0.0304	± 6.73%	0.0223	± 5.07%	0.0377	± 3.2%	0.0306	± 2.4%	0.0293	± 1.75%
7 (10cm)	0.0101	± 8.79%	0.0079	± 6.54%	0.0123	± 3.83%	0.0098	± 2.99%	0.0093	± 2.26%
8 (5cm)	0.0027	± 11.49%	0.0024	± 7.86%	0.0039	± 4.75%	0.0032	± 3.67%	0.0030	± 2.87%
9 (5cm)	0.0021	± 13.5%	0.0017	± 9.99%	0.0027	± 5.67%	0.0023	± 4.29%	0.0022	± 3.18%
k_{eff}	1.1287	± 0.00282	1.1275	± 0.00199	1.1289	± 0.00142	1.1291	± 0.00099	1.1283	± 0.0007

* Fission distributions are calculated by KENO-V.a code with MGCL-JINS library, and the total fission is normalised to unity.
NPG: Number of histories/generation
GEN: Number of generations