

RECOMMENDED BOUNDING AXIAL PROFILES IN BUC APPLICATIONS FROM ACTUAL BURNUP MEASUREMENT OF FRENCH PWR ASSEMBLIES

C. Riffard^a, A. Santamarina^a, J.-F. Thro^b, F. Lavaud^c

^a CEA, DEN, DER, SPRC, CEA-Cadarache, F-13108 Saint Paul lez Durance, France.

^b AREVA-NC, F-92084 Paris La défense, France.

^c EDF R&D, F-92141 Clamart, France.

Abstract

The definition of a bounding profile to be recommended for criticality studies of PWR-UOx spent fuel assemblies has been studied on the basis of a representative set of axial traces obtained from gamma spectrometry measurement in La Hague facilities. More than 200 measurements were studied here, extracted from the extensive database obtained by AREVA-NC on French 17x17 PWR-UOx FAs. This important database gives a reliable and representative range of axial shapes of burnup profiles. The study shows that a simplified description of the axial profile using 11 zones is a good compromise between time / precision of BUC calculations. The criticality calculation carried out with the BUC calculation route DARWIN-CRISTAL show a limited variability for the keff of a pool storage (1000 pcm) at 30 GWd/t using successively the various measured profiles. It justifies the use of a realistic and physical bounding profile, selected in the database, to be recommended for French FAs with a mean BU > 30 GWd/t. The conservativeness of this bounding profile is of around 1000 pcm compared with the use of an average profile at the same BU.

1. INTRODUCTION

The concept of taking credit for the reduction of the reactivity of nuclear spent fuel due to their burnup is referred as “Burnup Credit” (BUC). Allowing reactivity credit for spent nuclear fuels (SNF) offers many economic incentives. The increasing ²³⁵U enrichment and need for fuel transport and storage point out the interest for BUC methods. A recent and rigorous methodology^{1/} was developed by the CEA and AREVA-NC, carrying out the French BUC calculation route based on the code systems DARWIN^{2/} and CRISTAL^{3/}. It is accounting of:

- 15 poisoning FPs, stable and non-gaseous, in addition to the actinides;
- Conservative hypotheses for the depletion calculations;
- The qualification of the spent fuel inventory obtained with DARWIN and of the reactivity worth of BUC nuclides calculated with CRISTAL^{4/};
- A bounding axial profile of assembly BU^{5/}. The previous method using a uniform mean BU gives a non realistic cosines axial flux and is therefore not conservative for BU > 30 GWd/t^{6/}.

As a consequence, because of the so-called “end-effect” (low irradiation of the extremities of the irradiated assembly) the use of a burnup profile becomes necessary in criticality studies. The need of the definition of a conservative axial burnup profile associated to the French BUC calculation route has already been pointed out^{6, 7/}.

Previous studies carried out in CEA concerning the effect of the shape of the burnup profile on the end-effect were based on domestic and foreigners data, within the context of the benchmarks (Phases IIA-B-C) proposed to the community by the BUC Expert Group of the OECD Working Party in Criticality Studies^{7,8,9/}. Important results were obtained, showing that:

- the end-effect is maximized by the pronounced shape (II A-B) or asymmetry (II-C) of the profile,
- the use of an average shape should be convenient for criticality studies, considering the limited range of keff values obtained within the important burnup profile database.

However, some of these data, obtained with 3-D calculations on the basis of flux measurement, give more asymmetric profiles than the measured ones obtained on hundreds of PWR French assemblies in La Hague Reprocessing plant^{10/}. This French database, resulting from the cooperative effort between EDF and AREVA-NC, is obtained from actual measurements by gamma spectrometry techniques on irradiated fuel assemblies, guaranteeing the physical representativeness of the profile shapes.

The aim of this paper is the definition of a recommended axial profile for safety-criticality studies of PWR-UO_x fuels, which should be representative of actual shapes in order to be realistically conservative. For that purpose, the analysis of experimental data obtained at La Hague facility for French 900 MWe Fuel assemblies was performed. Then, the variability of the end-effect and the conservativeness of the selected profiles towards an average profile were studied, by the mean of BUC calculations with the DARWIN-CRISTAL route.

2. DATABASE ANALYSIS

2.1 OVERVIEW OF THE MEASUREMENT DATABASE

For this study, more than 200 spent fuel assemblies (SFA), measured before the dissolution process in La Hague plant, are examined. The measurements are obtained with HP-Ge gamma spectrometry on ¹³⁷Cs rays, which concentration is linearly dependant of the burnup. Two opposite faces of each assembly are systematically measured with a 1 cm axial pitch, from the bottom to the head of the assembly. Each measurement curve is constituted of 512 values along the z-axis.

From each measurement, after application of a threshold in order to avoid perturbed background signal at the extremities of the assembly, the data along the 366 cm fissile height are selected and the resulting curve is normalized to 1. More than 400 axial profiles are therefore obtained.

The profile shapes (Fig.1a, 1b, 1c) are flat in the middle area [50 cm – H-60 cm] (H : fissile column height). There are slightly dissymmetric with minimum burnup at the top of the assembly [H-60 cm – H]. This aspect is amplified for low burnup assemblies (Fig.1a, BU < 30 GWd/t). Fig.1b and Fig.1c point out that burnup profile are very similar for PWR assemblies ranging from 20 to 40 GWd/t and for assemblies in the 40-50 GWd/t burnup range. Furthermore, these two figures show that the same profile (assembly irradiated in Chinon-B3 NPP with a mean BU of 36.5 GWd/t) is bounding for any assembly measured in the 30-50 GWd/t range. The mean value of the BU plateau is less than 1.1 for SFA with a mean BU over 30 GWd/t.

On the contrary, Fig.1a points out that this profile is not conservative at low burnup, and the bounding profile corresponds to an assembly irradiated in Chinon-B1 NPP at the mean BU of 20.1 GWd/t.

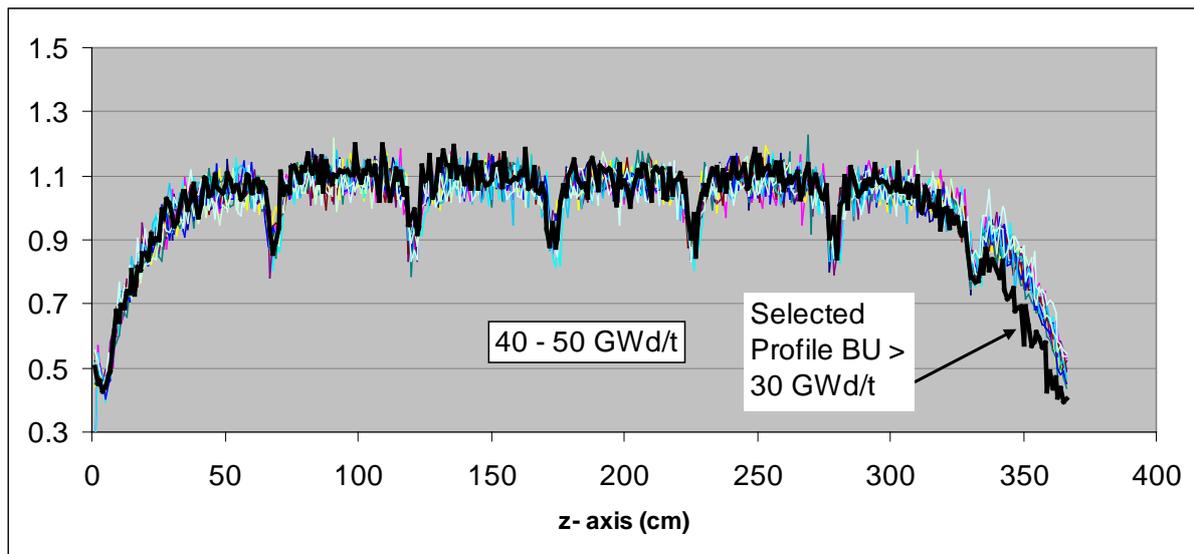
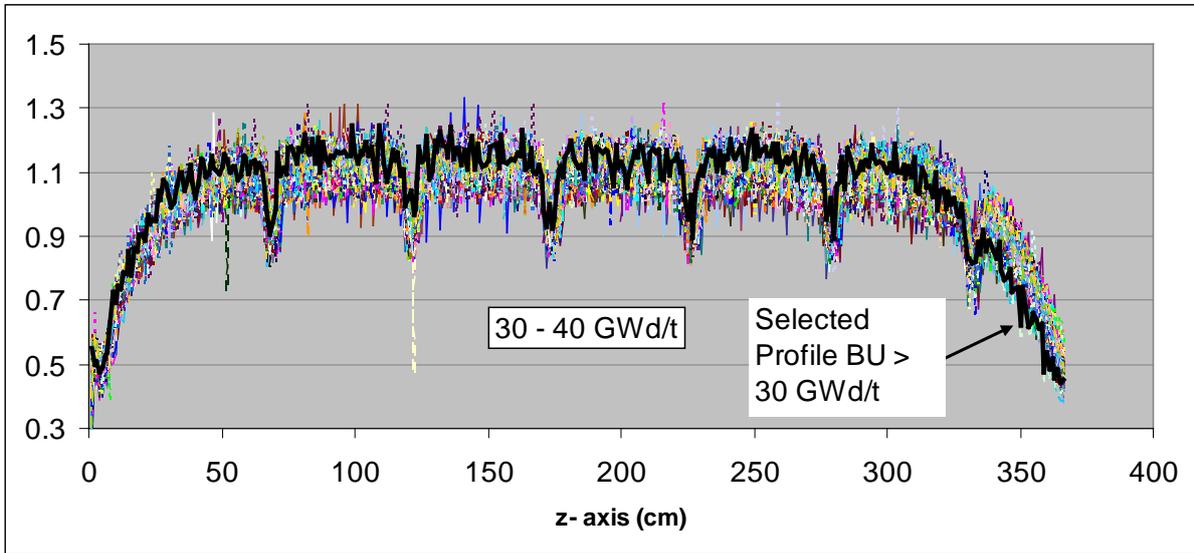
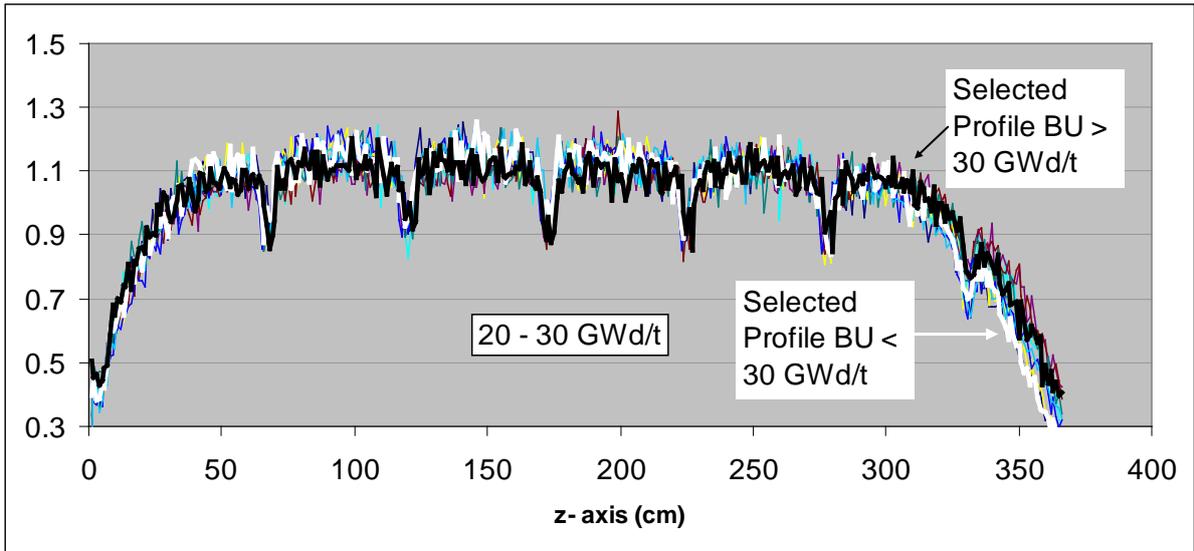


Fig.1a, 1b, 1c. PWR-UOx assembly profiles at burnup of [20 – 50 GWd/t]

The normalized average curve \hat{BU} obtained from SFA at mean $BU > 30$ GWd/t is calculated, each point of the curve at the z position along the axis being equal to the average of all N values (N being of the order of 400) at that point.

$$\hat{BU}(z) = \frac{\sum_{n=1}^N BU_n(z)}{N}, \quad z = 0 \text{ to } 366 \text{ cm} \quad (1)$$

The end-effect is sensitive to the level of irradiation at the top of the assembly. In Fig.2 are partly drawn selected normalized curves which present lowest and highest levels of irradiation, as well as the average normalized curve. This illustrates the variability of the end-effect on both sides of the average profile in the database, which must be quantified by the mean of BUC calculations.

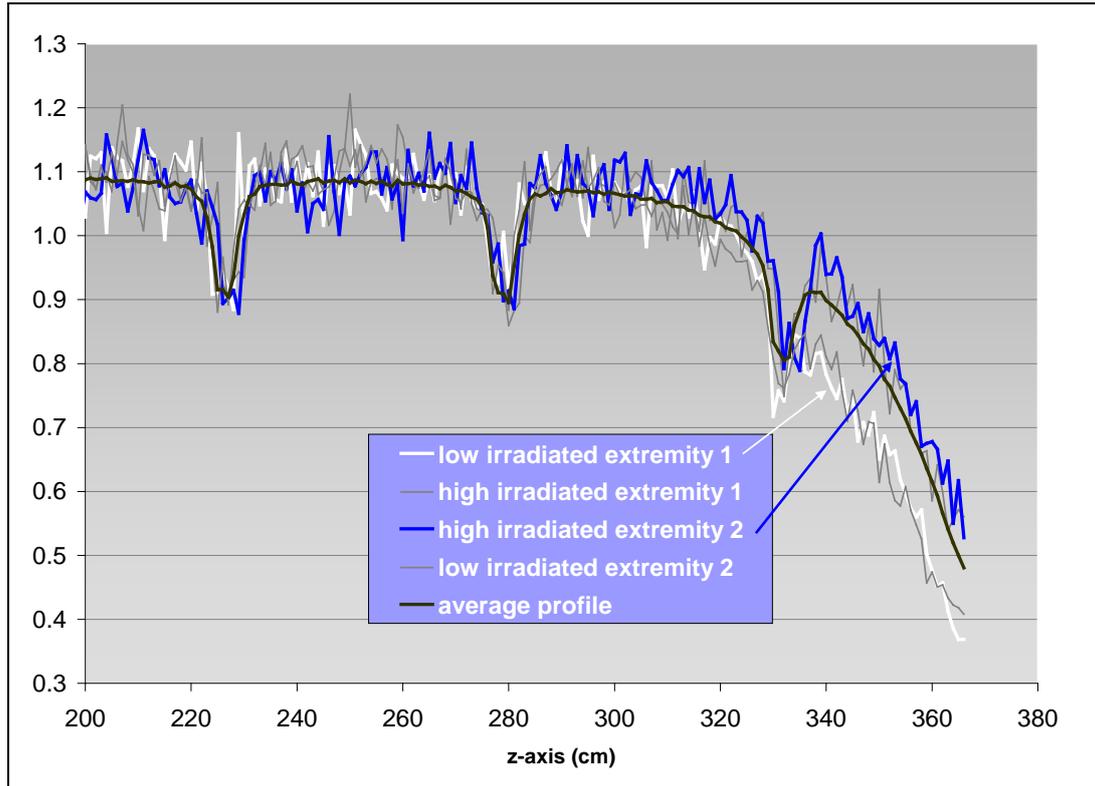


Fig.2. End-effect variability illustrated by experimental profiles

2.2 AXIAL ZONING

The modelization of the profiles, i.e. the number of axial zones used for their description, must be optimized to obtain a good computing time / precision compromise for BUC calculations. A preliminary study on the basis of an average profile obtained from the experimental data at $BU > 30$ GWd/t showed that 11 zones seems to be sufficient compared with a more detailed one (21 zones), the difference between the two cases being of only 20 pcm for the keff calculation (§3.3).

The fissile column H is divided as follows from the bottom to the top of the assembly (z in cm):

11 axial zones : $z = 0 - 11 - 22 - 33 - 45 - 73 - 268 - 303 - 324 - 343 - 354 - 366$.

For each normalized curve, a 11-zone profile $BUP(i=1,11)$ is then calculated, which is also normalized to 1, i.e. the following relation is verified:

$$\frac{\sum_{i=1}^{11} BUP(i)\Delta z(i)}{H} = 1.0 \quad (2)$$

where $\Delta z(i) = z(i+1) - z(i)$.

By comparing the BU(i) values ($i = 9, 10, 11$), the least irradiated profiles in the top zone (60 cm) are selected. One of them selected in the range of BU [30 – 40 GWd/t] is compared with the others in Fig.1a, 1b and 1c (black bold line). This profile is the bounding one for all curves obtained at BU > 30 GWd/t; on the other hand, it is not the case compared with lower burnt fuels presenting more distorted curves (Fig.1a). The bounding profile selected for BU < 30 GWd/t is drawn in Fig.1a (white line).

The simplified 11-zones axial profiles are superimposed to the detailed ones (full data) in Fig.3. The bounding profile (corresponding to the selected one shown in Fig.1b) appears again conservatively distorted at the top end in comparison with the average profile.

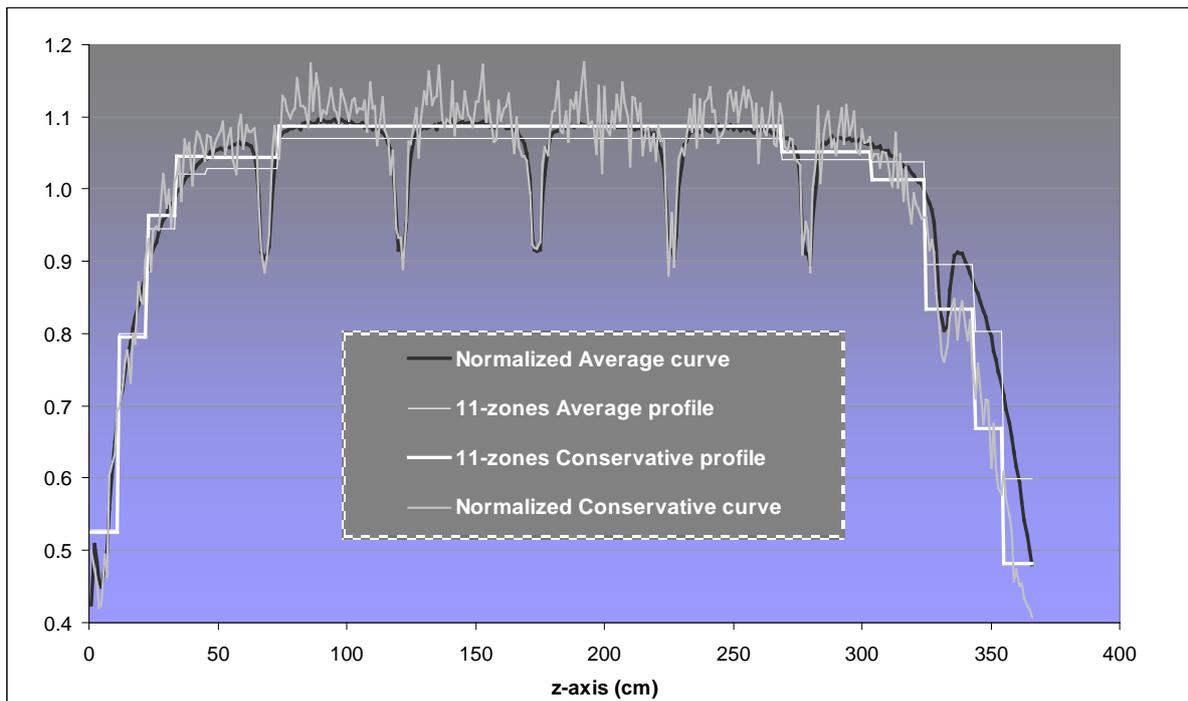


Fig.3. Simplified 11-zones profiles obtained from the average and the conservative normalized curves

3. PRESENTATION OF THE BUC CALCULATION ROUTE

The BUC calculation route “CIRACUSE” is based on the connection of the French depletion code DARWIN and the French Criticality-Safety Package CRISTAL.

The DARWIN depletion code calculates the concentrations of isotopes at the end of irradiation or after cooling time. Then, these concentrations, to which a correction factor can be applied^{11/}, are used as input data in the Criticality-Safety Package CRISTAL, which provides the effective multiplication factor associated to the calculated situation. This BUC methodology was recently implemented in the criticality-safety analysis of the TN-24 transport cask^{12/}. The sequence of the codes is presented below.

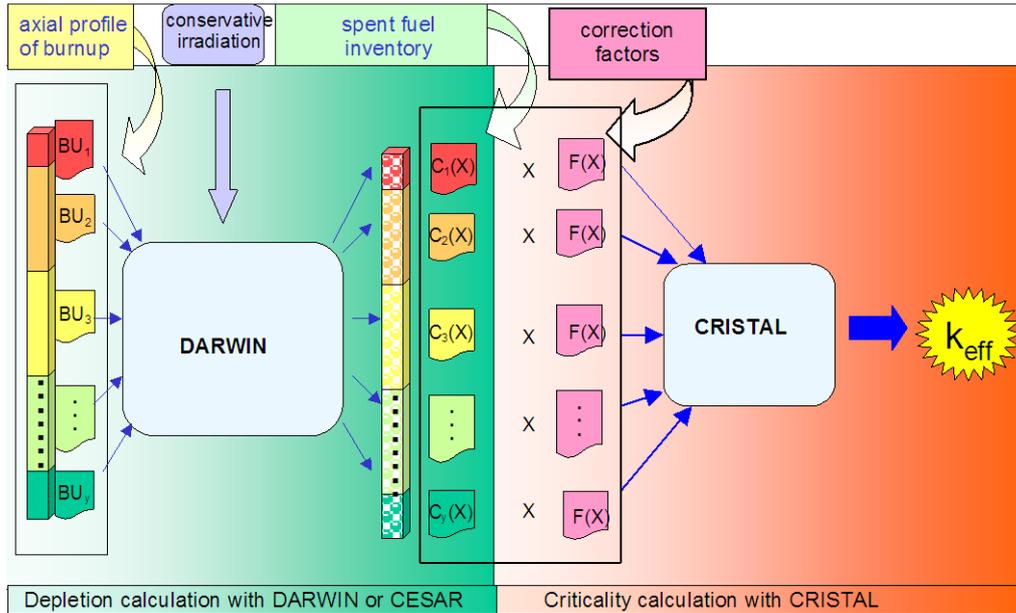


Fig.4. Presentation of the BUC calculation route DARWIN-CRISTAL

3.1 PRESENTATION OF THE DARWIN PACKAGE

DARWIN is the French reference calculation package for the fuel cycle studies. It was developed by the CEA with the support of its French partners (AREVA-NC, AREVA-NP and EDF) to estimate the physical quantities characterizing the burnup fuels from reactors: material balance, decay heat, activity, neutron, α , β , γ sources and spectrum, radiotoxicity. The simplified DARWIN structure is described in Fig.5.

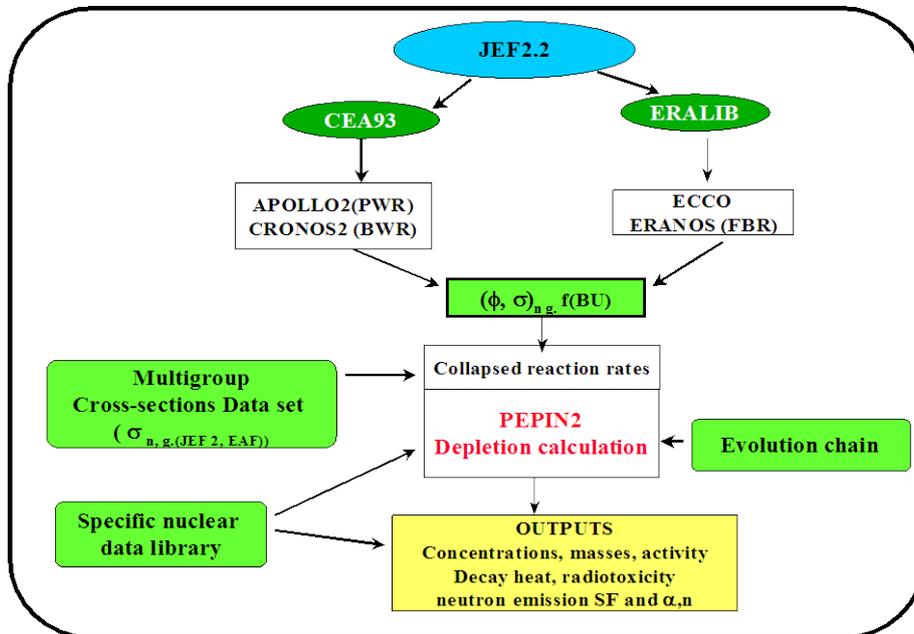


Fig.5. The DARWIN package

3.2 PRESENTATION OF THE CRISTAL PACKAGE

The CRISTAL package is composed of libraries containing basic information common to all the calculations, procedures based on recommended calculation schemes, specific calculation codes and interface software. It has been developed by IRSN and CEA with the support of AREVA-NC. Two calculation routes are available (see Fig.6):

- a design route with the CEA93 multigroup cross-sections and the APOLLO2/MORET4 codes,
- a reference route using the continuous Monte-Carlo code TRIPOLI4.

Both routes are based on the JEF2.2 version of the Joint European nuclear data file.

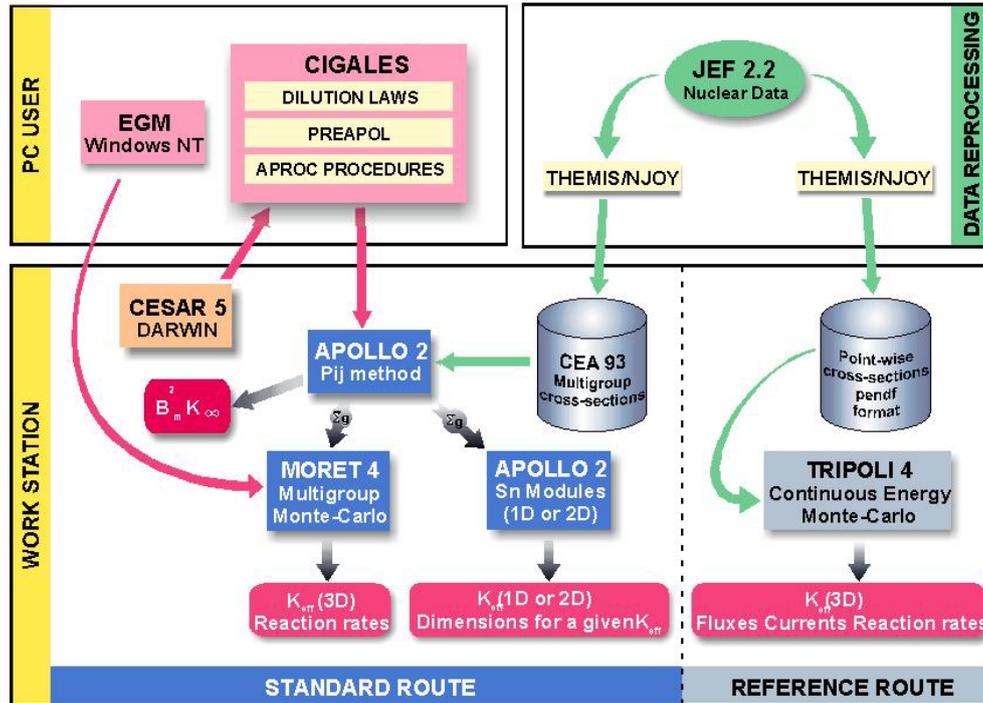


Fig.6. The CRISTAL V1 package

3.3 DESCRIPTION OF BUC CALCULATIONS

3.3.1 Depletion calculations

The assembly code APOLLO2.5^{/13/} provides the multigroup flux and self-shielded cross sections using the industrial scheme 'CEA-97' recommended for PWR-UOx fuel calculations^{/14/} and the associated 172-G library CEA93V6 based on JEF2.2^{/15/}. This standard route provides neutronic data for the equivalent assembly fuel matter in function of the burnup, by mean of a continuous depletion calculation. Besides the standard APOLLO2.5 scheme, specific options were recommended for the BUC calculation route DARWIN-CRISTAL in order to guarantee the conservativeness of spent fuel inventories used in criticality calculations, especially the use of envelope values for the thermo-mechanical parameters and of conservative in-core loading options of the assembly^{/11, 16/}. In this study, the standard CEA-97 scheme was used to independently highlight the effect of the profile shapes, in a first step. Calculations with the conservative scheme were, in addition, carried out in order to evaluate the whole resulting BUC.

The case considered here is a 17x17 PWR UOx fuel with an initial enrichment of 3.2% , irradiated at a mean burnup of 30 and 45 GWd/t, with a cooling time of 0 and 5 years. The depletion calculations carried out with the PEPIN2 module (Fig.5) are continuous at the power of 40 W/g_{HM} for the conservative route and adjusted to the local burnup for the standard route. One profile is described by the mean of 11 depletion calculations followed by decay calculations, at the BU(i) values given by:

$$BU(i) = BUP(i) * \hat{BU}, i=1 \text{ to } 11 \quad (3)$$

with BUP(i) : burnup profile value (eq.2) and $\hat{B}\hat{U}$: mean burnup of the assembly.

3.3.2 Criticality calculations

The criticality calculations are modelling a pool storage of SFA in pure water at room temperature, with an inter-assembly gap of 4 cm. The description of the spent fuel inventory in each axial zone of the assembly is limited to the BUC isotopes (and ^{16}O) : ^{234}U , ^{235}U , ^{236}U , ^{238}U , ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{237}Np , ^{241}Am , ^{243}Am , ^{103}Rh , ^{133}Cs , ^{143}Nd , ^{149}Sm , ^{152}Sm , ^{155}Gd , ^{95}Mo , ^{99}Tc , ^{101}Ru , ^{109}Ag , ^{145}Nd , ^{150}Sm , ^{151}Sm , ^{153}Eu .

The effect of the burnup profile is studied with the standard 2-D route (Pij-Sn) of the CRISTAL package. The APOLLO2-Pij calculation gives the multigroup flux and self-shielded cross-sections, which are after that collapsed in a 20-G energy structure and homogenised. The multiplication factor keff of the pool storage is then calculated using the discrete ordinates method.

4. CALCULATION RESULTS

All criticality calculation results described here are obtained for normalized 11-zones profiles.

Criticality calculations performed with the standard route show that the total variability of the keff amounts to about 1000 pcm at the burnup of 30 GWd/t, considering all profile shapes of the database as illustrated in Fig.2. Then a disparity of ± 500 pcm around a median value can be accounted for. This disparity is higher (± 2000 pcm) at the burnup of 45 GWd/t. As an illustration, in Table 1 are given the deviation of the keff values of the bounding profile selected for BU > 30 GWd/t, compared with the keff values obtained with the average profile (eq.1). This deviation varies from +850 to +2900 pcm depending on the burnup (BU) and the cooling time (CT). Therefore, this deviation between average and bounding profiles represents 1000 pcm at 30 GWd/t, to be compared with a burnup credit value (BUC) of about 24000 pcm, increasing up to around 40000 pcm at highest burnup (45 GWd/t and 5 years CT).

This is a fairly limited disparity, which confirms that 17x17 PWR-UOx fuels have in general similar burnup profiles, close to the average one.

Type of Profile	BUC (pcm)	Comparison with the average profile $\text{Ln}[k_{\text{eff}}^{\text{bounding}} / k_{\text{eff}}^{\text{av}}]$ (pcm)			
		BU 30 GWd/t		BU 45 GWd/t	
	CT 0 y	CT 5 y	CT 0 y	CT 5 y	
Average profile (BU > 30 GWd/t)	-24030	-	-	-	-
Bounding profile BU > 30GWd/t	-23180	+850	+1420	+1930	+2900

Tab.1. BUC calculation results with the standard route

The end-effect is defined as the difference in reactivity $\text{Ln}(k_{\text{eff}}^{\text{prof}} / k_{\text{eff}}^{\text{flat}})$ between the multiplication factor of the storage using either the burnup profile or the mean flat burnup.

The end-effect of the bounding profile is less than +650 pcm at the BU of 30 GWd/t (see Tab.2). Below this burnup, we can notice that the flat burnup assumption is a conservative model compared to the realistic calculation using the measured average profile.

Type of Profile	End-effect $\text{Ln}[k_{\text{eff}}^{\text{prof}} / k_{\text{eff}}^{\text{flat}}]$ (pcm)			
	BU 30 GWd/t		BU 45 GWd/t	
	CT 0 y	CT 5 y	CT 0 y	CT 5 y
Average profile (BU > 30 GWd/t)	-920	-780	-550	+30
Bounding profile BU > 30 GWd/t	-70	+640	+1380	+2940

Tab.2. End-effect results with the standard route

From these results, the recommendation concerning PWR-UOx FAs with a BU > 30 GWd/t is the use of the most conservative, normalized profile issued from the studied database: it is physically representative and realistically conservative.

Calculation results obtained with the conservative depletion route are given in Table 3. The impact of isotopic penalty factors^{/11/}, not shown in this table, amounts to about 1000 pcm. The BUC is reduced to 16000 pcm, due to the highly conservative options accounted for in the APOLLO2 calculation, which also reduce the variability of the keff compared with the average profile (<1000 pcm).

Type of Profile	BUC (pcm)	Comparison with the average profile $\text{Ln}[k_{\text{eff}}^{\text{bounding}} / k_{\text{eff}}^{\text{av}}]$ (pcm)			
		BU 30 GWd/t		BU 45 GWd/t	
	CT 0 y	CT 5 y	CT 0 y	CT 5 y	
Average profile (FAs BU > 30 GWd/t)	-16410	-	-	-	-
Bounding profile BU > 30GWd/t	-16400	+10	+270	+210	+780

Tab.3. BUC results with the conservative route

For lower burnt fuel assemblies (mean BU < 30 GWd/t), the end-effect is reduced and has a limited impact on the keff of pool storage or transport cask. Nevertheless, the bounding profile selected in the BU range [20-30 GWd/t] and shown in Fig.1a (full data) can be recommended for such cases. The conservativeness of this profile is nearly of +500 pcm (maximum value at the end of irradiation for a BU of 30 GWd/t), because of its higher distorted shape representative of earlier discharged FAs.

5. CONCLUSION - RECOMMENDED BOUNDING PROFILES

The use a burnup profile in modern criticality-safety studies allows a rigorous taking into account of the reactivity loss of SFA, on one part because of the non-conservativeness use of a mean uniform burnup profile for BU > 30 GWd/t, on the other part because of its necessity in accidental situations studies. Then the use of a bounding axial profile for PWR-UOx fuels studies is recommended, as part of the French BUC methodology.

The study presented in this paper is based on the important experimental database issued from the French industry. The definition of a bounding profile is studied on the basis of γ -spectrometry measurements on French PWR-UOx fuels processed by AREVA-NC, which were analysed by EDF and CEA laboratories. A simplified 11-zones modelization of the normalized burnup curves is adopted. The limited variability of the keff of a pool storage (1000 pcm) obtained at the burnup of 30 GWd/t from more than 200 measurements justifies the use of a realistic and physical bounding profile, selected in the database. The use of this bounding normalized profile is recommended for BU > 30 GWd/t. For lower burnup, although the end-effect becomes less sensitive, we recommend the use of a bounding profile representative of FAs in the burnup range of [20-30 GWd/t].

In conclusion, the following table describes the recommended axial zoning of the fissile height H and the corresponding values of the recommended bounding profiles, depending on the mean BU of the PWR UOx assembly, over (second column) or lower than 30 GWd/t (third column). The intrinsic conservativeness of the bounding profile at BU = 30 GWd/t (CT = 5 years) amounts to +1420 pcm and +640 pcm compared with the use of an average profile and a flat profile respectively. The remaining BUC is nearly of 23000 pcm, which is important compared with a zero BUC approach.

Axial z value (cm)	Mean BU \geq 30 GWj/t	Mean BU < 30 GWj/t
11	0.52	0.49
22	0.79	0.79
33	0.96	0.95
45	1.04	1.07
73	1.05	1.08
H-98	1.089	1.116
H-63	1.05	1.03
H-42	1.01	0.98
H-23	0.83	0.74
H-12	0.66	0.55
H	0.48	0.33

Tab.4. Recommended bounding profiles in criticality studies for French PWR assemblies

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