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# Parametric Studies of the Effect of MOx Environment and Control Rods for PWR-UOx Burnup Credit Implementation

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The increase of PWR-UOX fuel initial enrichment and the extensive needs for spent fuel storage or cask capacities reinforce the interest in taking burnup credit into account in criticality calculations. However, this utilization of credit for fuel burnup requires the definition of a methodology that ensures the conservatism of calculations. In order to guarantee the conservatism of the spent fuel inventory calculation, a depletion calculation scheme for burnup credit is under development.

This paper presents the studies on the main parameters which have an effect on nuclides concentration: the presence of control rods during depletion and the fuel assembly environment, particularly the presence of MOx fuels around the $UO_2$ assembly. Reactivity effects which are relevant to these parameters are then presented, and physics phenomena are identified.

***Keywords : Credit burnup, MOx environment, control rods, DARWIN, CRISTAL***

## 1. Introduction

Criticality and safety analyses have traditionally assumed that the spent nuclear fuel is fresh. This assumption is very conservative since the negative reactivity of actinides and fission products is not taken into account.

The concept of taking credit for this reduction in the reactivity of nuclear fuel due to fuel burnup, is referred to as « Burnup Credit » (BUC). Allowing reactivity credit for spent fuel offers many economic incentives. Various design studies pointed out that a load increase in several fuel cycle devices (casks, storage pools, dissolvers) is possible when actinides and fission products are accounted for in criticality studies[1)]. However, this utilization of credit for fuel burnup requires the definition of a methodology that ensures the conservatism of calculations. A working group composed of French Nuclear industrialists and researchers was created in 1997 to discuss this methodology [2)].

In this working group, the CEA (Commissariat à l'Energie Atomique) teams are involved in the development of a conservative depletion calculation scheme for 17x17 UOX assemblies. In order to guarantee the conservatism of the spent fuel inventory calculation, we are looking in this paper at the impact on UOx assemblies reactivity of some depletion modelling parameters. This paper presents the studies on the main parameters which have an effect on nuclides concentration: the presence of control rods during depletion and the fuel assembly environment, particularly the presence of MOx fuels around the $UO_2$ assembly. Reactivity effects which are relevant to these parameters are then presented, and physics phenomena are identified.

## 2. Presentation of the calculation tools

The studies have been carried out using the DARWIN package [3),4)] to calculate isotopic concentrations in spent fuel and the criticality-safety package CRISTAL [5)] to predict the Keff of a spent nuclear fuel device. These are both based on the APOLLO2 [6)] code.

APOLLO2 is a modular code which solves the Boltzmann equation either with the integral form by using the collision probability method or with the differential form by using the Sn method. The Neutron Data Library used is the 'CEA93' library in a 172-group structure. These multigroup cross-sections and effective cross-sections were processed by NJOY from the JEF2.2 European File [7)].

DARWIN is the French reference calculation package for the fuel cycle studies. It was developed by the CEA and its French partners (COGEMA, EDF and FRAMATOME) to estimate the physical quantities characterizing the burnup fuels from reactors: material

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balance, decay heat, activity, neutron, γ, α, β sources and spectrum, radiotoxicity.
The simplified DARWIN structure, based on new codes and libraries, is described in Fig.1.

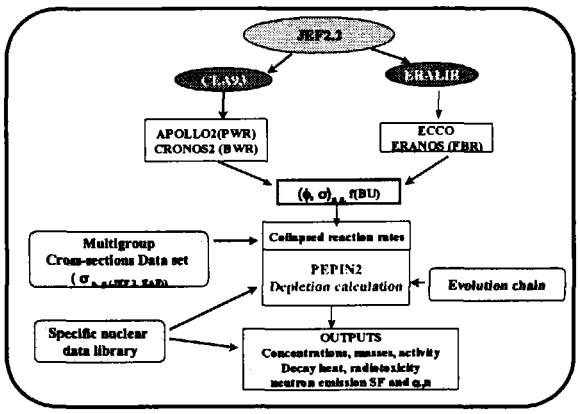


**Figure 1** : the DARWIN package

The PEPIN2 program calculates nuclide depletion. Different libraries feed this module:
- neutronic data provided by French assembly or transport codes, APOLLO2 (for PWR and BWR studies), the ECCO-ERANOS system (for FBR studies) : these data are self-shielded cross sections and neutron spectra,
- nuclear data (decay data, fission and (α,n) yields) and evolution chains,
- complementary cross-sections, missing from the transport codes libraries, especially for activation products. They are included in the 'cycle library'.

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.

Two calculation routes are available (see Fig.2):
- 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 latest version of the Joint European nuclear data file JEF2.2.

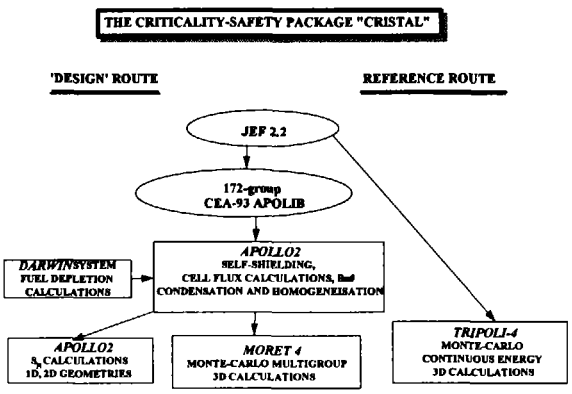


**Figure 2** : the CRISTAL package

## 3. Calculation models

### 3.1 Depletion calculations

The accuracy of the DARWIN results depends mainly on the APOLLO2 assembly calculation. This calculation solves the integral form of the Boltzmann equation through the collision probability method. The calculation options used are mainly based on the recommendations stemming from the APOLLO2 reference calculation route devoted to depletion calculation of 17x17 $UO_2$ and MOx PWR assemblies [8) 9)].

The PEPIN2 evolution module then uses the results provided by APOLLO2, self-shielded cross-sections and multigroup spectra, to make up the collapsed library with burnup dependent cross-sections, required to characterize the isotopes described in the depletion chains.

In order to study the effect of control rods (CRs) and MOx environment on UOx assemblies reactivity, five configurations were modelled in the depletion calculation. These configurations are not strictly representative of the real French PWR operating conditions, but enable us to obtain bounding values of the studied effects.

1. UOx assembly irradiated without CRs, surrounded by 8 UOx assemblies, irradiated without CRs. This configuration is used as a reference calculation,
2. UOx assembly irradiated without CRs, surrounded by 8 MOx assemblies, irradiated without CRs This configuration enables us to determine the effect of MOx environment,
3. UOx assembly irradiated without CRs, surrounded by 8 MOx assemblies irradiated with CRs in order to evaluate the effect of MOx environment irradiated with CRs,
4. UOx assembly irradiated with CRs, surrounded by 8 UOx assemblies irradiated without CRs. This configuration gives the effect of CRs,
5. UOx assembly irradiated with CRs, surrounded by 8 MOx assemblies irradiated without CRs. In this case we evaluate the effect of both CRs and MOx environment.

In all these configurations, the central UOx assembly initial fuel enrichment is of 4.5 wt% $^{235}U$, and the CR design is the 17x17 $B_4C$ design. It consists of inserting 24 $B_4C$ CRs in the 24 guide tubes, as shown in Fig.3.

Only the central UOx assembly deplete, the environment UOx or MOx is at fixed burnup.

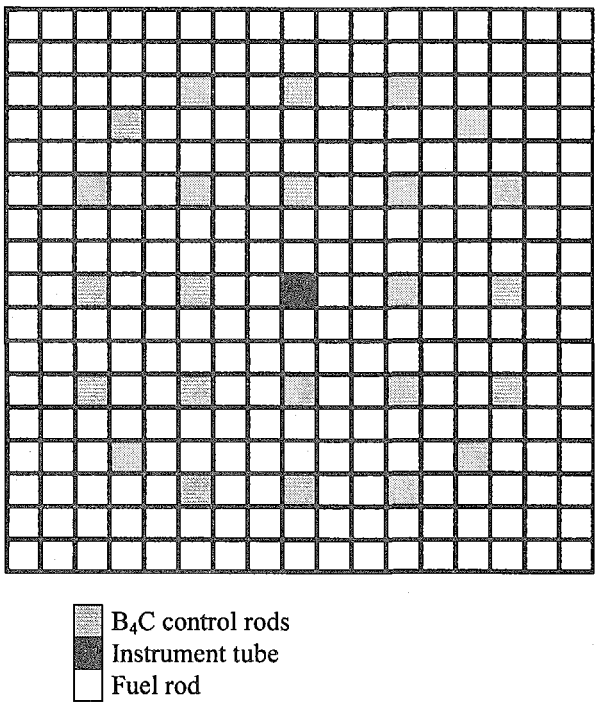


**Figure 3** : 17x17 assembly lattice with control rods location

The MOx fuel, surrounding the UOx assembly, is a 17x17 assembly with an initial Pu amount in the central zone of 5.6 wt%, irradiated at 15 GWd/t.
In the reference case, where the UOx assembly is surrounded by 8 UOx assemblies, these last ones consist of UOx with an initial enrichment of 3.5 wt% $^{235}U$ irradiated at 24 GWd/t.

The other parameters used for the depletion calculations are summarized in Table 1.

**Table 1** : Summary of parameters used for the depletion calculations

| | |
|---|---|
| Fuel température (K) | 955 |
| Clad température (K) | 673 |
| Moderator température (K) | 577 |
| Power density (MW/t) | 60 |
| Moderator boron concentration (ppm) | 1200 |

These parameters are very conservative in relation to the reactivity itself. But we have checked that the $\Delta\rho$ presented in the following paragraphs are not sensitive to variations of these parameters.

### 3.2 Criticality calculations

The CRISTAL calculations are performed with the design route, APOLLO2 Pij and Sn [10]. The configuration represents a storage pool (i.e., 20°C with no soluble bore present). We use then the reference calculation scheme that models an infinite array (XY calculation) of UOx assemblies under water.

The UOx assembly spent fuel inventory, calculated using the DARWIN package (with no cooling time), is injected as input data in the criticality calculation to predict the Keff.

In order to separate the "end effect" problem and the inventory calculation one, the calculations are performed with a flat average burnup distribution.

The spent fuel is composed of the following BUC nuclides:

- the fifteen fission products corresponding to the most absorbing, stable and non volatile elements : $^{149}Sm$, $^{103}Rh$, $^{143}Nd$, $^{133}Cs$, $^{155}Gd$, $^{151}Sm$, $^{152}Sm$, $^{99}Tc$, $^{145}Nd$, $^{153}Eu$, $^{95}Mo$, $^{147}Sm$, $^{150}Sm$, $^{109}Ag$ and $^{101}Ru$ [11],

- actinides $^{234}U$, $^{235}U$, $^{236}U$, $^{238}U$, $^{238}Pu$, $^{239}Pu$, $^{240}Pu$, $^{241}Pu$ and $^{242}Pu$ and also minor actinides $^{237}Np$, $^{241}Am$ and $^{243}Am$, whose contribution to the negative reactivity worth becomes significant for an average UOx spent fuel at about 40 GWd/t.

## 4. Effect of MOx environment and control rods

### 4.1 Physics phenomena

The presence of MOx environment or control rods during the depletion of an UOx assembly increases the reactivity of burned fuel by hardening the neutron spectrum (due to the removal of thermal neutrons by capture and the displacement of the moderator), leading for a given burnup to:

- an increase of $^{235}U$ and Pu isotopes concentrations, due to a decrease in $^{235}U$ fission and an increase in $^{238}U$ capture,
- an increase of $^{241}Am$ and $^{243}Am$ concentration, linked respectively to the $^{241}Pu$ and $^{242}Pu$ increase,
- an increase of most fission product concentration, due to the decrease of neutron capture by fission product, mainly those which are absorbing in the thermal range ($^{149}Sm$, $^{151}Sm$, $^{143}Nd$ and $^{155}Gd$).

The following paragraphs present the impact of both control rods and MOx environment on the reactivity of an infinite array of UOx assemblies under water.

### 4.2 Effect of MOX environment

In France, the plutonium from the La Hague reprocessing plant is recycled in PWRs. Currently twenty-four 900 MWe PWRs are devoted to Pu recycling in 30% mixed core loading. We are then interested by quantify the effect of MOx fuel around an UOx assembly. However, the assumption of an UOx assembly completely surrounded by MOx assemblies (4 on sides and 4 in corners) is very conservative.

Table 2 gives the impact of MOx environment on reactivity (configuration 2).

In this table $\Delta\rho$ is the reactivity defined as

$$\Delta\rho = \rho\,(\mathrm{Mox_{env}}) - \rho\,(\mathrm{Uox_{env}}) = \mathrm{Ln}\,\frac{K_{eff}\,(\mathrm{Mox\ env})}{K_{eff}\,(\mathrm{Uox\ env})}$$

and expressed in pcm ($10^{-5}$).

**Table 2**: Impact of MOx environment on an infinite array of UOx assemblies

| UOx depletion calculation BU | ρ (MOxenv) - ρ (UOxenv) |
|---|---|
| 10 GWd/t | +45 pcm |
| 20 GWd/t | +300 pcm |
| 30 GWd/t | +670 pcm |
| 40 GWd/t | +1250 pcm |

This table shows that the spectrum hardening due to the MOx environment leads to a significant increase in reactivity : 1250 pcm ($10^{-5}$) for an infinite array of UOx assemblies irradiated at 40 GWd/t and completely surrounded by MOx.

We have also evaluated the impact on reactivity of the burnup of the MOx environment. Table 3 shows that the reactivity of an UOx array irradiated with a MOX environment at 30 GWd/t is lower than the reactivity with a MOX environment at 15 GWd/t. This is due to the decrease of $^{239}$Pu concentration with increasing burnup in the MOX environment, leading to a softer neutron spectrum. Anyway, the impact of the MOx environment burnup is very slight.

**Table 3:** Impact of the MOx environment burnup

| UOx depletion calculation BU | ρ(Moxenv 10 GWd/t) - ρ(Moxenv 15 GWd/t) | ρ(Moxenv 20 GWd/t) - ρ(Moxenv 15 GWd/t) | ρ(Moxenv 30 GWd/t) - ρ(Moxenv 15 GWd/t) |
|---|---|---|---|
| 20 GWd/t | -1 pcm | -25 pcm | -50 pcm |
| 40 GWd/t | +85 pcm | -120 pcm | -260 pcm |

The last study devoted to the impact of a MOx environment on the reactivity of an array of UOx assemblies concerns the assumption that the MOx fuels surrounding the UOx assembly were irradiated at 15 GWd/t with control rods inserted. This configuration may enhance the hardening of the spectrum. However, this effect is quite small compare to the effect due to the MOx environment itself. The corresponding values are detailed in Table 4.

**Table 4: Impact of insertion of control rods in MOx environment**

| UOx depletion calculation BU | ρ (MOxenv CRs inserted) – ρ (MOxenv no CRs) |
|---|---|
| 10 GWd/t | -5 pcm |
| 20 GWd/t | +5 pcm |
| 30 GWd/t | +40 pcm |
| 40 GWd/t | +30 pcm |

### 4.3 Effect of CRs insertion

French PWR operations can involve periods of partial CRs insertion. In order to bound the reactivity effect due to this insertion, we have considered a full axial control rods insertion during the entire burnup.

The results are presented in Table 5. In this calculation the central UOx assembly, with CRs inserted, is surrounded by UOx fuels depleted without CRs.
The effects of a short insertion period corresponding approximately to one cycle of irradiation, are also given in Table 5.

**Table 5**: Impact of control rods insertion on UOx reactivity

| | ρ (UOx with CRs) - ρ (UOx without CRs), UOxenv | | | |
|---|---|---|---|---|
| UOx depletion calculation BU | UOx with CRs from 0 to 40 GWd/t | UOx with CRs from 0 to 12 GWd/t | UOx with CRs from 12 to 24 GWd/t | UOx with CRs from 24 to 40 GWd/t |
| 10 GWd/t | +270 pcm | +270 pcm | - | - |
| 20 GWd/t | +1070 pcm | +470 pcm | +420 pcm | - |
| 30 GWd/t | +2260 pcm | +440 pcm | +810 pcm | +480 pcm |
| 40 GWd/t | +4050 pcm | +520 pcm | +680 pcm | +2090 pcm |

Due to the spectrum hardening, the presence of CRs in the UOx assembly leads to a significant increase in reactivity. This one is all the more significant as CRs are inserted for a long time or when it occurs later in the assembly burnup. The maximum value reaches +4000 pcm when the CRs are inserted during the entire burnup.

However, in the previous calculations, we have considered a full axial CR insertion, whereas CRs are not fully inserted during French power operations.

To quantify the effect of a partial insertion, we have also modelled that CRs are inserted from 0 to 40 GWd/t in the upper portion of the active fuel with a depth of 70 cm, as shown in Fig.4.

This study was performed using the CRISTAL package in a RZ geometry.

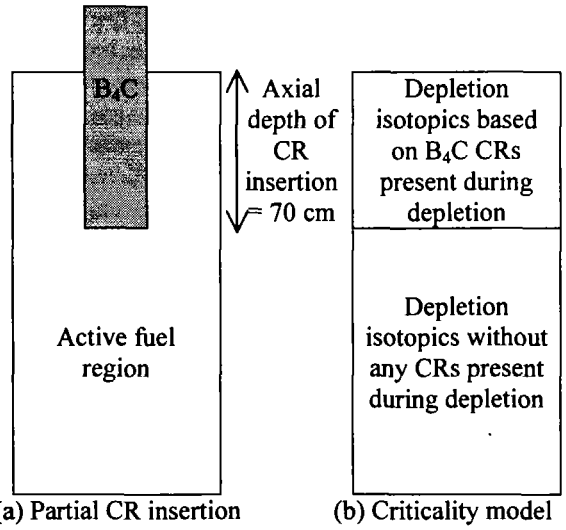


**Figure 4** : Illustration of (a) partially inserted control rods and (b) a cross section of the criticality model

The impact of the partial CR insertion for an infinite array of UOx assemblies irradiated at 40 GWd/t is +1220 pcm.

### 4.4 Effect of both CR insertion and MOx environment

Table 7 gives the impact of both CR insertion and MOx environment on reactivity (configuration 5), considering a full axial CR insertion.

**Table 7**: Impact of both CR insertion and MOx environment

| | ρ (UOx with CRs, MOxenv) - ρ (UOx without CRs, UOxenv) | |
|---|---|---|
| UOx depletion calculation BU | UOx with CRs from 0 to 40 GWd/t | UOx with CRs from 24 to 40 GWd/t |
| 10 GWd/t | +410 pcm | - |
| 20 GWd/t | +1500 pcm | - |
| 30 GWd/t | +3090 pcm | - |
| 40 GWd/t | +5240 pcm | +3280 pcm |

The effects of CR insertion and MOx environment are added, leading to an increase in reactivity of +5200 pcm at 40 GWd/t for the studied configuration. This increase is all the more significant that we have considered a full axial CR insertion.

## 5. Conclusion

This paper has presented the reactivity effects of the main parameters which have an impact on nuclides concentration: the presence of control rods during depletion and the presence of MOx fuels around an $UO_2$ assembly.

The criticality calculations, carried out with the CRISTAL package, have pointed out the significant impact in reactivity of a full axial CR insertion (+4000 pcm for an insertion from 0 to 40 GWd/t) and of a MOx environment (+1200 pcm for 8 MOx surrounding assemblies) for an infinite array of UOx assemblies irradiated at 40 GWd/t. However, these values are very conservative because (i) an UOx assembly is not completely surrounded by MOx fuels in PWR (30% MOx - 70% UOx), and (ii) CRs are not fully inserted during French power operations. This parametric studies will be carried on in order to take into account the current French PWR operation.

Furthermore, we are looking at some others depletion modelling parameters, such as fuel temperature, moderator temperature, moderator boron concentration and power density, whose impacts in reactivity are less important than CR insertion or MOx environment, but have to be considered for BUC implementation.

Other studies are also planned such as the determination of corrections factors on nuclides concentration deduced from the validation of the DARWIN package [12] and from French experiments for the fission products capture cross-section validation [13].

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