LATEST STUDIES RELATED TO THE USE OF BURNUP CREDIT IN FRANCE

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for
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OVERVIEW

1. Burnup Credit context in France
2. Process to take Burnup Credit into account in criticality calculation with CRISTAL package
3. PWR fuels studies
   - Determination of an axial burnup profile for UOX fuel
   - Determination of correction factors for isotopic composition of UOX fuel
   - Determination of a bounding isotopic MOX composition
4. BWR UOX fuels studies
5. Burnup Credit gain estimation
6. Conclusion and prospects
Burnup Credit context in France

$^{235}\text{U}, ^{239}\text{Pu}, \ldots$

$^{238}\text{U}$

Fission Products (FP)

50 least-irradiated cm

$^{235}\text{U}$

$^{238}\text{U}$

$^{239}\text{Pu}$

50 cm
Burnup Credit context in France

UOX fuel initial enrichment
Storage needs for spent fuel

Need for less penalizing method to implement Burnup Credit (take into account fission products and a bounding axial burnup profile)

Creation of a working group composed of AREVA, EDF, CEA, ANDRA and IRSN

Depletion calculation → Criticality calculation → $k_{eff}$
Process to take Burnup Credit into account in criticality calculation

Burnup profil

Penalizing history

CESAR or DARWIN (JEF-2)

Depletion codes validation

APOLLO2 (JEF-2)

Criticality calculation validation

Geometry description

MORET

K_{eff}

Penalizing history

BU₁

BU₂

BU₃

... 

BUₕ
Conclusions from early studies about PWR UOX fuels:

It is conservative to consider for the depletion calculations:

- Presence of the control rods
- Maximum boron concentration
- Maximum moderator temperature
- Maximum fuel temperature
- Maximum specific power (when no cooling time is considered)
- Minimum cooling time justified by operators (<50 years)

Latest studies about PWR fuels concerns:

- Determination of an axial burnup profile for UOX fuel
- Determination of correction factors for isotopic composition of UOX fuel
- Determination of a bounding isotopic MOX composition
Axial burnup measurements from hundreds of French UOX assemblies with

- U235/U (% w) ~ 3.1%
- Average burnup ranging between 30 - 40 GWd/t

*Cf. “Recommended Bounding Axial Burnup Profiles In BUC Applications From Actual Burnup Measurement of French PWR Assemblies” presented by C. Riffard*
Correction factors for isotopic composition of UOX fuel

Validation of depletion codes relies on comparisons between calculated and measured concentration values

\[(C-E)/E\] is the relative error between calculations and measures of each actinide and fission product

In a conservative approach, correction factors are needed to:

- Underestimate absorbing isotopes,
- Overestimate fissile isotopes.
Two sets of correction factors for UOX fuel have been determined:

1. Estimation of isotopic correction factors for the depletion calculations: it takes into account the total (C-E)/E uncertainties (uncertainties on chemical assays, determination of the burnup and calculations used in the validation process)
   - Fissile isotopes are corrected by a factor > 1
   - Absorbing isotopes are corrected by a factor < 1
   - Overestimated fissile isotopes and underestimated absorbing isotopes are not corrected.

2. The correction factors are based on the experimental validation of the spent fuel inventory carried out with DARWIN package and on the experimental validation of the reactivity worth carried out with CRISTAL package.

Cf. “Correction Factors Derived from French Experiments with the Recent JEFF3.1.1 Library for PWR-UOx BUC Applications” presented by C. Riffard
Determination of a bounding isotopic MOX composition

The conservatism of the inventory of the irradiated PWR MOX fuel depends on the irradiation conditions and the fresh fuel characteristics.

The influence on the conservatism of depletion calculations of the main parameters is studied for a given MOX fuel composition:

- Control rods penalty ~ 65%
- Moderator temperature penalty ~ 20% (of the total penalty)
- Boron concentration penalty ~ 10%

To simplify MOX Burnup implementation, a bounding fresh MOX that remains conservative during depletion should be defined.

A fresh fuel with a conservative isotopic vector of Pu

The most reactive fuel after irradiation for PWR.
Determination of a bounding isotopic MOX composition

1. Method based on a reactivity equivalence between an UOX enrichment and a MOX fuel composition

This method consists in three steps:

- For each isotope in the MOX composition, a reactivity weight is set to construct a reactivity equivalent equation between MOX and UOX compositions.
  - An equivalent uranium enrichment ($^{235}\text{U}_{eq}$) is obtained for each MOX composition.
- A correlation equation corresponding with the decay of the reactivity versus irradiation of each MOX composition is determined to take into account MOX fuel irradiation.
- Finally, this method is applied for each MOX fuel composition to select the most reactive composition.

$K_{\text{eff,max}}$ (MOX)

$\%^{235}\text{U}_{eq}$ (MOX)

Minimum Conservative vector = Max (MOX 1 & MOX 2)
Determination of a bounding isotopic MOX composition

2. Method based on plutonium isotopes relative abundance

For each MOX composition, the isotopic vector of Pu is \( ^{238}\text{Pu}_k / ^{239}\text{Pu}_k / ^{240}\text{Pu}_k / ^{241}\text{Pu}_k / ^{242}\text{Pu}_k \)

\[
\begin{align*}
^{240}\text{Pu} &= \text{Min}(^{240}\text{Pu}_k) \\
^{241}\text{Pu}_{\text{min}} &= r_1^{\text{min}} \times ^{240}\text{Pu} \\
^{241}\text{Pu}_{\text{max}} &= r_1^{\text{max}} \times ^{240}\text{Pu} \\
^{239}\text{Pu}_{\text{min}} &= 100 - ^{240}\text{Pu} - ^{241}\text{Pu}_{\text{max}} \\
^{239}\text{Pu}_{\text{max}} &= 100 - ^{240}\text{Pu} - ^{241}\text{Pu}_{\text{min}} \\
^{238}\text{Pu} &= ^{242}\text{Pu} = 0 \\
F_1 &= ^{239}\text{Pu}_{\text{min}} / ^{240}\text{Pu} / ^{241}\text{Pu}_{\text{max}} \\
F_2 &= ^{239}\text{Pu}_{\text{max}} / ^{240}\text{Pu} / ^{241}\text{Pu}_{\text{min}} \\
\text{Max} \left( k_{\text{eff}} (F_1) ; k_{\text{eff}} (F_2) \right)
\end{align*}
\]

\( r_1^{\text{*}} = ^{241}\text{Pu} / ^{240}\text{Pu} \)
A first study based on a GE 8x8 assembly has focused on the void fraction parameter:

- influence of the void fraction during the irradiation of the spent fuel content
- comparison of the results obtained with 2 depletion codes (TRITON and VESTA)

Maximum void fraction $\times$ $k_{eff}$ maximum

Good agreement between TRITON and VESTA results

The different axial regions of void fraction considered with VESTA 3D calculation do not have much influence between them.
Burnup Credit gain ($\Delta K$) is defined as the difference of reactivity between an irradiated fuel and the same fresh fuel.

<table>
<thead>
<tr>
<th>Assembly Type</th>
<th>$\Delta K$ (pcm)</th>
<th>$\Delta K$ (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly surrounded by 20 cm of water</td>
<td>18300</td>
<td>10000</td>
</tr>
<tr>
<td>Storage pool (fallen assembly)</td>
<td>19200</td>
<td>10400</td>
</tr>
<tr>
<td>Storage pool (of-centered assemblies)</td>
<td>18300</td>
<td>10200</td>
</tr>
<tr>
<td>Storage pool (higher standing assemblies)</td>
<td>16000</td>
<td>8800</td>
</tr>
<tr>
<td>Transport cask</td>
<td>19600</td>
<td>10900</td>
</tr>
</tbody>
</table>

Burnup Credit gain estimation (Burnup ~ 44 GWd/t, no cooling time)

- Burnup Credit gain mainly comes from actinides for UOX fuel (~65%) and from fission products for MOX fuel (~65%).
- For an infinite array of BWR assemblies, $\Delta K$ reach 14000 pcm if standard profile of burnup and void fraction are taken into account.

Even with penalizing irradiation conditions, Burnup Credit gains are significant for industrial applications.
The state of knowledge of the French working group covers all steps of process to take fuel burnup into account considering fission products and an axial profile for PWR UOX fuel.

\textbf{new objective: to make use of this knowledge}

For PWR MOX fuel, the methods to determine a bounding isotopic MOX composition have to be evaluated to check if Burnup Credit gain is large enough for industrial applications.

Concerning BWR fuel, the French working group knowledge is limited. Further studies should focus on:

\begin{itemize}
  \item the combined influences of an axial profile of burnup and a void fraction with other profiles
  \item other BWR assembly designs with more heterogeneities
  \item influence of parameters like control blades, neighborhood assemblies, irradiation history.
\end{itemize}