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IMPLEMENTATION OF BURNUP CREDIT METHODOLOGY ON ORANO TN'S NEW GENERATION TRANSPORT CASKS

Marcel TARDY
Orano TN, France
marcel.tardy@orano.group

Stavros KITSOS
Orano TN, France
stavros.kitsos@orano.group

Laurent MILET
Orano TN, France
laurent.milet@orano.group

Gabriele GRASSI
Orano Cycle, France
gabriele.grassit@orano.group

ABSTRACT

Orano TN hasvast experience in implementing BUrnup Credit (BUC) approaches for the transportation of used nuclear fuel. Since the first implementation of a simplified burnup credit approach in 1987, Orano TN has developed and licensed an advanced BUC approach taking into account both major actinides and some fission products which are important for the reduction of cask reactivity. This advanced BUC approach has been implemented since 2013 in different Orano TN casks (TN® 24 E, TN® 17/2).

Recently, Orano TN has licensed a new generation transport cask, namely the TN® 17 MAX cask, for the transportation of used nuclear fuel from European NPPs to the Orano La Hague Reprocessing Plant (France) making use of the advanced BUC approach in the criticality safety assessment. In addition, the TN® 17 MAX cask is designed in accordance with the latest IAEA regulations and will replace, in the short term, the TN® 17/2 cask currently used by Orano TN.

This advanced BUC approach used for the TN® 17 MAX cask optimizes safety margins but requires a more extensive validation process regarding the implementation of the methodology from a criticality safety point of view.

This paper presents the different steps of the advanced BUC methodology implemented in TN® 17 MAX new generation transport cask including the main points required by the French Competent Safety Authority from an operational point of view.

INTRODUCTION

Traditionally the criticality safety assessment for transport cask designs dedicated to used fuel assemblies from commercial reactors is conducted under a "fresh-fuel" assumption leading to a significant, conservative overestimation of the system reactivity. This methodology has been applied by Orano TN as long as the fuel enrichment remained quite low (e.g. less than 4 wt. %).

In the 1980s, a first Burnup Credit (BUC) approach, based only on actinides, was implemented by Orano TN to face the increase of uranium enrichment on the PWR fuel assemblies. This approach reduced the conservatisms in the criticality demonstration for the transport cask designs while containing sufficient reactivity reserve due to omission of fission products. This simplified BUC approach was approved by many Competent Safety Authorities and was used for more than 30 years by Orano TN for transport casks (TN®12, TN®13, TN®17/2, TN®G3) and for a number of dual purpose casks (TN®24 cask family).

Ever-increasing PWR fuel enrichment led to the adoption of less penalizing assumptions on BUC applications that were in line with neutron-related physical effects (e.g. modeling of axial burnup profiles, consideration of some fission products…). Experimental programs led in France in the 1990s by CEA, IRSN and Orano Cycle enabled Orano TN to implement an advanced BUC approach – based on actinides and fission products for criticality assessment – in 2013. This advanced BUC approach was approved by different Competent Safety Authorities and implemented for different Orano TN casks (TN® 24 E, TN® 17/2). This big step forward was dictated by the need to:

− consider higher enriched fuel in the existing transport and cask designs,

− provide adequate casks with increasing performance to the Nuclear Power Plants,

− reduce conservative assumptions in the criticality assessment while still maintaining an acceptable safety margin.

In 2019, Orano TN licensed a new generation transport cask, namely the TN® 17 MAX new generation cask, for the transportation of used nuclear fuel from European NPPs to the Orano La Hague Reprocessing Plant (France) making use of the advanced BUC approach in the criticality safety assessment. The TN® 17 MAX cask, designed in accordance with the latest IAEA regulation, will replace, in the short term, the TN® 17/2 cask currently used by Orano TN.

TN® 17 MAX: ORANO TN'S NEW GENERATION TRANSPORT CASK

The TN® 17 MAX new generation transport cask design (see Figure 1) for used fuel assemblies has been developed by Orano TN for the needs of the Borssele Nuclear Power Plant (Netherlands). This cask was licensed in 2018 in accordance the latest IAEA rules (TS-R-1, 2012 edition) [1].
Up to 9 PWR used fuel assemblies containing uranium oxide (UO_2) and/or mixed oxide (MOX) with maximum initial 235U enrichment of up to 5 wt-% can be loaded in a specially designed basket incorporating boron carbide compound technology to ensure the content sub-criticality.

The advanced BUC methodology has been implemented so far only for UO_2 PWR fuel assemblies, the conservative "fresh-fuel" assumption being still used for MOX fuel assemblies.

Figure 1 TN® 17 MAX general view

CALCULATION PROCEDURE AND CODE VALIDATION

The calculation procedure (see Figure 2) used by Orano TN for the TN® 17 MAX BUC criticality calculations is based on the:

- DARWIN 2 [2] depletion code developed by the CEA and EDF
- CRISTAL V1.2 [3] criticality calculation code developed by the CEA and IRSN in cooperation with Orano Cycle, Framatome and EDF.

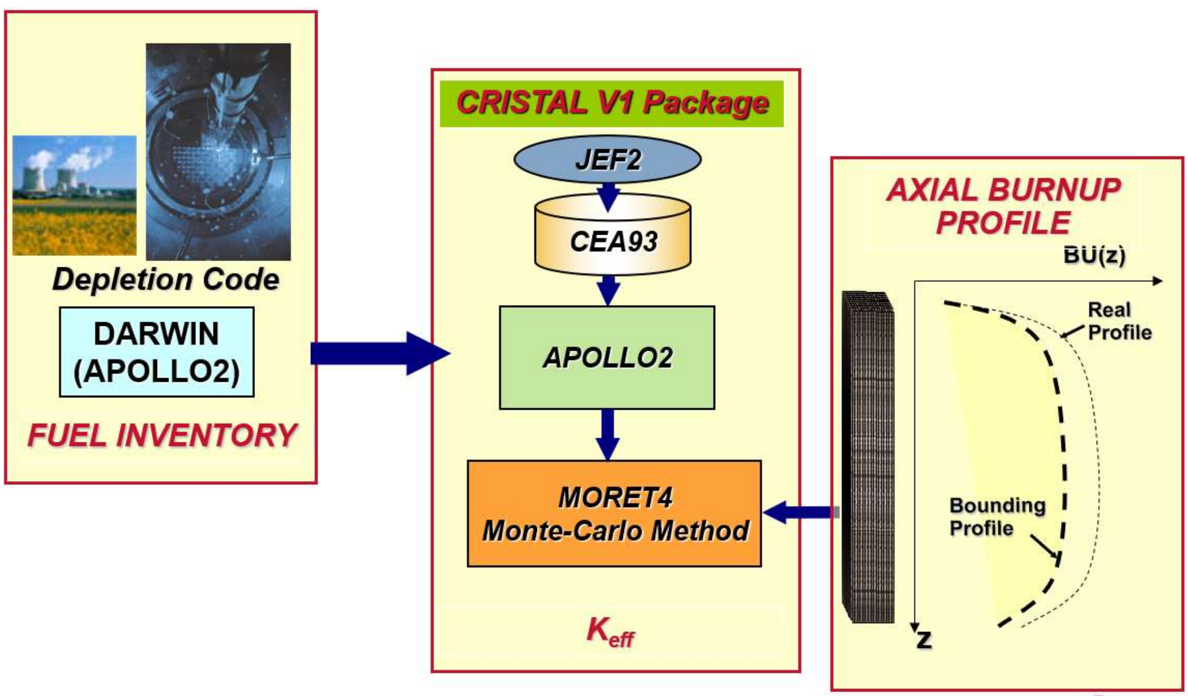

Figure 2 TN® 17 MAX BUC calculation process

DARWIN code system

The physical validation of the DARWIN code system for used fuel inventory calculations is based on a large experiment conducted in France. The experimental data came from chemical analyses carried out on fuel rods irradiated in French PWRs and on fuel dissolutions at the Orano Cycle/La Hague Nuclear Reprocessing Plant. Uranium, plutonium, americium and fission product isotopes were analyzed in PWR samples.

The validation program [4] has shown the capability of the DARWIN package to simulate the fuel inventory versus burnup. It covers a large range of UO_2 fuel assemblies with various ^{235}U enrichments lower than 5 wt. % associated with burnup from 10 to 60 GWd/MTU and, therefore, covers the area of application of the TN® 17 MAX cask.

According to the validation of the DARWIN package on French experiments for the validation of fission product capture cross-sections[5], correction factors are considered for the fuel inventory calculations by maximizing the fissile isotope content and minimizing the high capturing isotope production [6]. For the case of absorbing fission products for which the concentration is underestimated by the DARWIN code, no correction factor is considered on the relevant nuclides in a conservative way (the correction factor is considered equal to 1).

CRISTAL V1 criticality code package

The criticality safety calculations are conducted with the “standard route” of the CRISTAL V1 code package.

CRISTAL V1 is based on the JEF2.2 nuclear data [7].

The “standard route” deals with the CEA 93 172-group nuclear data library (derived from JEF2.2 evaluation), the APOLLO2 deterministic code [8] used for self-shielding, flux calculations, cross-section calculations, and homogenization, and the MORET4 Monte Carlo code [9].

The CRISTAL V1 package was validated based on a large database of benchmark experiments (about 1900) [10], for all the different kinds of configurations encountered in the industrial nuclear fuel cycle including BUC applications. Indeed, a French program was carried out to support the development of a technical basis for BUC validation with industrial configurations (transport, storage, reprocessing of used fuel assemblies). This program was based on two types of experimental data:

- A series of critical high combustion rate experiments, referred to as “*Haut Taux de Combustion” (HTC*) [11] and Fission Products (FP) [12] experimental programs, was conducted in the French CEA/Valduc research facility. These experiments were designed by IRSN and jointly funded by Orano Cycle and IRSN. The aim of these experimental programs was to validate the cross sections of major actinides and 6 main fission products.
- Reactivity worth measurements of the BUC nuclides in question (actinides and fission products) by oscillation of specific fuel rod samples in the MINERVE reactor [13]. The goal of the reactivity worth measurements by the oscillation technique in the MINERVE reactor was to validate the CRISTAL V1 calculation package and nuclear cross section data used to predict the poisoning reactivity worth of individual BUC isotopes as well as to determine the integral reactivity worth of real irradiated fuel rod samples from French reactors [14].

ORANO TN'S ADVANCED BUC METHODOLOGY

In 2018 Orano TN licensed the TN® 17 MAX cask with an advanced BUC method which considers 9 actinides (^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am) and 6 FPs (^{103}Rh, ^{133}Cs, ^{143}Nd, ^{149}Sm, ^{152}Sm, and ^{155}Gd) in criticality assessments. Aminimum burnup of 12 GWd/MTU was used in the criticality safety assessment. In addition, the BUC approach was conducted in accordance with the research programs carried out by the French BUC working group [15], and it dealt with the following requirements:

- the establishment of conservative conditions of irradiation to guarantee the conservatism of the used fuel calculation
- the use of bounding axial burnup profiles for the used fuel assemblies that could be loaded into the cask
- the axial burnup and burnup verification requirements prior to each loading of PWR UO_2 used fuel assemblies into the cask

<u>Conservative conditions of irradiation</u>

A range of irradiation parameters were studied to quantify the potential sensitivity of calculated cask reactivity to these irradiation parameters for a burnup level of 12 GWd/MTU. Therefore, sensitivity studies were conducted on each relevant irradiation parameter (specific power, fuel temperature, temperature and density of the moderator, soluble boron concentration in the moderator…) to define a conservative approach for depletion calculations for PWR UO_2 fuel assemblies loaded in the TN® 17 MAX cask. In addition, reactor operations can involve periods of partial control rod insertion. In order to maximize the reactivity effect due to this insertion, the effect of a full axial control rod insertion during the entire burnup was studied. Despite the low probability of an assembly being irradiated with control rods inserted during the whole irradiation, it is difficult to exclude that possibility. Nevertheless, it is possible to consider a partial axial control rod insertion, provided that the operator guarantees a limited insertion. Finally, for the implementation of the advanced BUC approach for the TN® 17 MAX cask, depletion of the UO_2 assembly was conducted considering the UO_2 assembly surrounded by 8 MOX assemblies at 12 GWd/MTU during the entire irradiation (see Figure 3). This is a conservative approach considering current MOX fuel core management.

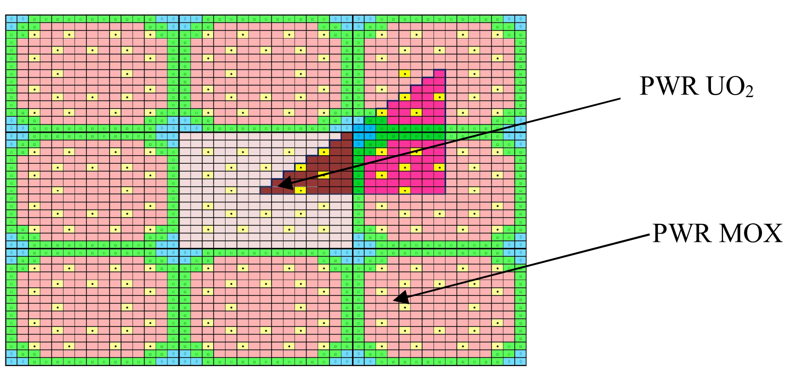

Figure 3 Depleted PWR UO_2 assembly surrounded by 8 MOX assemblies

The results of the sensitivity studies on the relevant irradiation parameters are summarized in the Table below for the TN® 17 MAX cask loaded with 9 PWR UO_2 (5%wt. initial ^{235}U enrichment) used fuel assemblies:

Table 1 Summary of irradiation parameters affecting the TN® 17 MAX reactivity

Irradiation parameter	Range studied	Cask reactivity impact (% Δk)
Specific power	20 to 60 W/g (40 W/g reference case)	<0.2
Moderator temperature (linked to moderator density)	319 to 332 °C (0.683 to 0.645)	<0.3
Fuel temperature	614 to 750 °C (700°C reference case)	<0.1
Natural boron concentration	600 to 2000 ppm (960°C reference case)	~0.2
Control rod insertion	Unrodded vs. rodded (unrodded reference case)	~0.5
Environment of the depleted UO_2 assembly	8 PWR UO_2 vs. 8 PWR MOX (8 PWR UO_2 reference case)	< 0.3

<u>Bounding axial burnup profiles</u>

The criticality of the irradiated fuel assemblies is affected by their axial burnup shapes. Therefore, it is useful to have a simple and practical method to define a bounding axial burnup profile to cover the transportation of several types of PWR UO_2 fuel assembly designs with different irradiation conditions. In this sense, a generic method for the definition of bounding uniform axial burnup profile was developed by Orano TN in accordance with the international BUC standard ISO 27468 [16]. The axial burnup profile considered in the criticality safety evaluation for the TN® 17 MAX advanced BUC application was taken from the most limiting axial burnup profile from a large set of profiles including: profiles calculated from in-core measurements [17], profiles measured at the La Hague Reprocessing Plant (different European PWR UO_2 used fuel assembly designs), and asymmetrical axial burnup profiles [18]. The penalizing profile was given by the definition of a ratio between the average burnup of the fuel assemblies to be loaded in the cask and the average burnup in their 50 least-irradiated centimeters corresponding to the level of burnup used in the criticality analysis. This approach had already been validated by the French Competent Safety Authority (ASN) for the implementation of the advanced BUC methodology on the TN® 17 MAX cask loaded with 9 PWR UO_2 fuel assemblies initially enriched at 5.0 wt. %^{235}U.

Axial burnup and burnup verification requirements

One of the main requirements for the advanced BUC application for TN® 17 MAX transport cask is to perform a burnup verification prior to each loading of PWR UO_2 used fuel assemblies. This procedure ensures that each PWR UO_2 UNF assembly to be loaded meets the conditions of the minimum required average burnup as well as the discharge axial burnup profile bounded by the corresponding bounding axial burnup profile used in the criticality safety assessment. The establishment of such a procedure enables consignors to safely load used fuel assemblies into the TN® 17 MAX cask and guarantees the compliance of such a loading with the national and international criticality safety requirements [1].

Approval for the implementation of the advanced BUC method was obtained in 2018 for the TN® 17 MAX transport cask from the French Competent Safety Authority with the use of an average burnup of 12 GWd/MTU in the criticality calculations. The approval was obtained with the following requirements:

i. Prior to each loading, in accordance with the NPP quality assurance policy, verification had to be done to ensure that the average burnup of each selected PWR UO_2 used fuel assembly met the minimum required average burnup.

ii. Before loading, a qualitative irradiation check (e.g. gamma dose rate measurement) of the PWR UO_2 used fuel assemblies had to be conducted to ensure that fuel assemblies were burned at the core, mainly to avoid any mistake in loading a fresh fuel assembly into the cask.

Additionally, an in-depth defense (events of defense level 2) approach was considered by evaluating an event of mis-loading one fuel assembly into the TN® 17 MAX new generation transport cask. Such a mis-loading risk cannot be totally excluded, even if different administrative and technical actions are taken into account by the consignors during the loading process. Therefore, the sub-criticality of the packages in such a situation is ensured.

BENEFITS OF THE ADVANCED BUC APPROACH ON ORANO TN'S NEW GENERATION TRANSPORT CASK

Table 2 gives a comparison between different methods for the criticality safety assessment of the TN® 17 MAX package loaded with PWR UO_2 used fuel assemblies. The three methods compared are:

1. The "fresh fuel" assumption
2. The actinide-only BUC method, based on the sole consideration of 8 major actinides (^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu)
3. the advanced BUC method, based on 9 actinides(^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am) and 6 fission products (^{103}Rh, ^{133}Cs, ^{143}Nd, ^{149}Sm, $1^{52}Sm$, ^{155}Gd)

The goal is to quantify the performance of the TN® 17 MAX cask in terms of payload and initial enrichment of the used fuel assemblies.

Table 1 Comparison of methods for the TN® 17 MAX criticality safety assessment

<table>
<tr><th>Methods</th><th>Fuel initial Enrichment (wt. %)</th><th>Maximum number of fuel assemblies loaded into the cask</th><th>Fuel initial Enrichment (wt. %)</th><th>Maximum number of fuel assemblies loaded into the cask</th></tr>
<tr><td>Fresh fuel assumption</td><td>3.90</td><td rowspan="3">9</td><td rowspan="3">5.00</td><td>6</td></tr>
<tr><td>Actinides-only BUC (*)</td><td>4.40</td><td>8</td></tr>
<tr><td>Advanced BUC(*)</td><td>5.00</td><td>9</td></tr>
</table>

(*): Minimum burnup required in the criticality analysis equal to 12 GWd/MTU

The comparison between criticality safety methods gives evidence that the advanced BUC method is adequate for high-enriched PWR UO_2 used fuel assemblies and a cask containing a high payload.

CONCLUSIONS

This paper has presented, through the new generation Orano TN transport cask, the TN® 17 MAX, an industrial application of the advanced BUC approach including actinides and fission products. This BUC approach uses an axial burnup profile and fuel assembly irradiation conditions that ensure the conservatism of the calculations (used fuel inventory and criticality). Calculation tools used for the advanced BUC method implementation were validated on suitable experimental programs and proprietary data under nondisclosure agreement.

This paper also highlights that Orano TN’s advanced BUC method ensures an adequate level of criticality safety for the transport and storage cask designs, in light of the fact that cask performance is ever increasing with initially high-enriched PWR fuel assemblies or casks with high payloads.

The use of this advanced BUC approach is now a common practice in France. So far, the different approvals obtained by Orano TN for the implementation of BUC have been limited to PWR UO2 used fuel assemblies. New developments regarding BUC methods for PWR MOX and BWR UO2 are in progress and will soon be implemented for transport and interim dry storage cask designs.

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