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# FRAMATOME ANP France UO2 Fresh Fuel Transportation Criticality Application of the IAEA TS-R-1 Regulations

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**Abstract** - For more than 25 years, FRAMATOME ANP has been delivering fuel elements to various French and foreign NPP sites including Belgium, China, South Africa, and Sweden.
With the FCC, its new fresh fuel transportation package, which completely satisfies the 1996 IAEA regulations, FRAMATOME ANP has a safe container to transport any type of PWR fuel assembly from the 14x14 to the 18x18 design with enrichments up to 5.0 w/o $^{235}U$.
The new IAEA regulations (TS-R-1) in force since 2002 require that the criticality studies had to be validated against benchmarks to deduce uncertainties. These uncertainties are added to gross computer code results for comparison with the criticality safety criterion. The uncertainties described in the IAEA guidelines document are derived from both systematic bias and the different statistical uncertainties.
FRAMATOME ANP uses the CEA/IRSN CRISTAL computer code system to perform criticality safety evaluations for transportation packages. Exhaustive efforts have been made to get a qualification report which covers the entire lifecycle of the fuel from the enrichment process through fuel transportation to the recycling backend. This qualification report is based primarily on information from the well known ICSBEP working group (International Criticality Safety Benchmark Evaluation Project). This group compares the main world criticality computer codes for different fissile media, shapes, spectra, etc. Among the various configurations several are for arrays of UO2 rods with various enrichments, rod pitches, and neutron absorbers. This subset provides a good qualification database to qualify the transportation package calculations.
After a brief description of the CRISTAL chain, the paper shows our approach used to determine the uncertainties required by the IAEA regulations. The methodology is discussed and illustrated by numerical applications.

## I. INTRODUCTION

The new IAEA regulations (TS-R-1) in force since 2002 require that the criticality studies had to be validated against benchmarks to deduce uncertainties. These uncertainties are added to gross computer code results for comparison with the criticality safety criterion. The uncertainties described in the IAEA guidelines

document are derived from both systematic bias and the different statistical uncertainties.

The qualification of the CRISTAL package is mainly based on the ICSBEP criticality databank where configurations of arrays of $UO_2$ rods with various $^{235}U$ enrichments, rod pitches and neutron absorbers can be found, helping to determine the uncertainties and qualifying the code for fresh $UO_2$ fuel assembly transportation.

## II. THE REGULATION

Annex VII [1] "Criticality Safety Assessments" describes the way to determine uncertainties. The so called "Upper Safety Limit" is defined as follows:

$$\mathbf{USL = 1.00 - \Delta K_m - \Delta K_u} \quad /1/$$

Where $\Delta K_m$ is an administrative safety margin (typical value = 5% $\Delta K$) and $\Delta K_u$ is the reactivity bias derived from the experiment-calculations comparisons.

This paper deals with the determination of the calculational uncertainty $\Delta K_u$.

## III. THE CRISTAL PACKAGE [2]

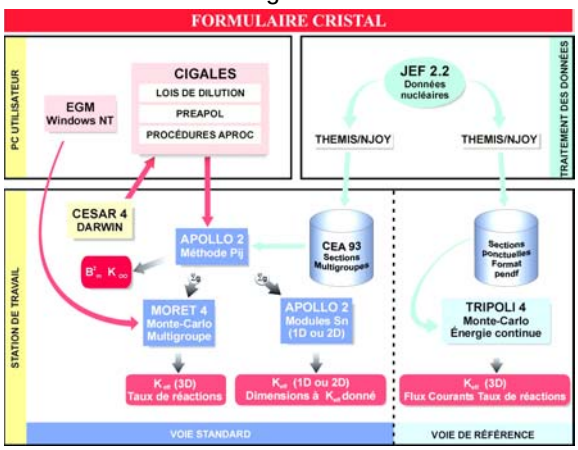
CRISTAL V0.x, a French calculation package for criticality-safety studies, has been developed and validated as part of a joint project between IRSN, CEA and COGEMA.

This package includes two calculation routes: on the one hand, the "standard route" dealing with the nuclear data library CEA93 (derived from JEF2.2 evaluation), the APOLLO2 cell code and the Monte Carlo MORET4 code, and, on the other hand, the "reference route", using the Monte Carlo TRIPOLI4 code with a JEF2.2 continuous-energy cross-section library.

In the past years, extensive validation work has been performed by CEA and IRSN using a large experimental database (more than 500 critical experiments) taking into account most of the different operations encountered in the nuclear fuel cycle.

In this framework, a significant effort has been devoted to providing CRISTAL's users with a comprehensive and useful synthesis of the different validation studies. The flow chart is given in Figure 1.

Figure 1




## IV. UNCERTAINTY DETERMINATION

The size of the uncertainties determines the quality of the calculation codes. The codes used to obtain approval from the safety authorities for the transport cask are based on the CRISTAL V0 scheme. The qualification is based on a wide benchmark database covering all the "fuel life" from the enrichment through fabrication, transport to reprocessing. The qualification document [3] is mainly based on the International ICSBEP Working Group extended to some French CEA Valduc and Cadarache experiments.

## V. UNCERTAINTIES TO APPLY TO COMPUTED RESULTS

Global configuration reactivity is given by:

$$Keff = Keff^{cal} + \Delta Keff^{bias} + 2\sqrt{\sigma_s^2 + \sigma_{\exp}^2 + \sigma_t^2}$$

Where:

$Keff^{cal}$ = gross computed $K_{eff}$,

$\Delta Keff^{bias}$ = systematic bias,
$\sigma_s$ = computation statistic,
$\sigma_{exp}$ = experiment statistic,
$\sigma_t$ = fabrication tolerance.

### *V.A. Systematic bias*

Systematic bias is derived from reactivity comparisons between experiment and calculation.

As far as fresh $UO_2$ fuel rod arrays in transport configurations are concerned, the ICSBEP LEU-COMP-THERM 010 – 017 – 027 – 040 benchmarks include 25 configurations of interest. They deal with fresh $UO_2$ rods with various $^{235}U$ enrichments, rod pitches, neutron screens and reflectors. Table 1 gives the CRISTAL results compared with the benchmarks.

Table 1

| Série | Cas | Benchmark | | APOLLO2 - MORET4 | | C-M (pcm) |
|---|---|---|---|---|---|---|
| | | Keff | ΔKeff | Keff | ΔKeff | ρi |
| 010 | 01 | 1,0000 | 0,0021 | 1,01765 | 0,00098 | 0,01765 |
| | 09 | 1,0000 | 0,0021 | 1,02001 | 0,00094 | 0,02001 |
| | 11 | 1,0000 | 0,0021 | 1,01609 | 0,00095 | 0,01609 |
| | 13 | 1,0000 | 0,0021 | 1,00238 | 0,00095 | 0,00238 |
| | 14 | 1,0000 | 0,0028 | 1,01475 | 0,00093 | 0,01475 |
| | 16 | 1,0000 | 0,0028 | 1,01238 | 0,00094 | 0,01238 |
| | 19 | 1,0000 | 0,0028 | 1,00592 | 0,00092 | 0,00592 |
| | 20 | 1,0000 | 0,0028 | 1,01152 | 0,00094 | 0,01152 |
| | | | | | | |
| 017 | 01 | 1,0000 | 0,0031 | 1,00951 | 0,00092 | 0,00951 |
| | 10 | 1,0000 | 0,0031 | 1,00864 | 0,00092 | 0,00864 |
| | 12 | 1,0000 | 0,0031 | 1,00655 | 0,00095 | 0,00655 |
| | 14 | 1,0000 | 0,0031 | 1,00394 | 0,00093 | 0,00394 |
| | 15 | 1,0000 | 0,0028 | 1,00741 | 0,00088 | 0,00741 |
| | 17 | 1,0000 | 0,0028 | 1,00824 | 0,00091 | 0,00824 |
| | 21 | 1,0000 | 0,0028 | 0,99899 | 0,00092 | -0,00101 |
| | 23 | 1,0000 | 0,0028 | 1,00231 | 0,00091 | 0,00231 |
| | | | | | | |
| 027 | 01 | 1,0000 | 0,0011 | 1,01949 | 0,00098 | 0,01949 |
| | 02 | 1,0000 | 0,0011 | 1,02214 | 0,00097 | 0,02214 |
| | 03 | 1,0000 | 0,0011 | 1,01911 | 0,00097 | 0,01911 |
| | 04 | 1,0000 | 0,0011 | 1,01943 | 0,00098 | 0,01943 |
| | | | | | | |
| 040 | 03 | 1,0000 | 0,0041 | 1,00649 | 0,00096 | 0,00649 |
| | 04 | 1,0000 | 0,0041 | 1,00590 | 0,00096 | 0,00590 |
| | 07 | 1,0000 | 0,0042 | 1,00213 | 0,00097 | 0,00213 |
| | 08 | 1,0000 | 0,0044 | 1,00168 | 0,00096 | 0,00168 |
| | 10 | 1,0000 | 0,0046 | 1,00205 | 0,00097 | 0,00205 |
| | | | 0,00276 | 1,00979 | 0,00094 | 0,00979 |

σexp Keff moyen σcal Em

From this table it can be observed that the CRISTAL (APOLLO2–MORET4) results overestimate the benchmarks results with a singular underestimation (C-M Table 1). This last comparison is also observed with other codes (KENOIV-ENDF/BVI and MCNP-ENDF/BV), which highlights some experimental problems. As the average bias value is negative (-Em Table 1), and in line with the regulations, it has to be neglected; this item will be discussed and confirmed in section VI.

### *V.B. Statistical uncertainties*

Statistical uncertainties include three items:

$\sigma_s$ = computation statistic,
$\sigma_{exp}$ = experiment statistic,
$\sigma_t$ = fabrication tolerance.

V.B.1. Computation statistic ($\sigma_s$)
The entire transport cask CRISTAL configurations will be computed with a $\sigma_s$ = 0.2 % $\Delta K$ standard deviation.

V.B.2. Experiment statistic ($\sigma_e$)
As each group of benchmark configurations has a small number of experiments, we keep the average overall experiment deviation ($\sigma_{exp}$ = 0.276 % $\Delta K$ - Table 1).

V.B.3. Fabrication tolerance ($\sigma_t$)
The upper reactivity bounding values are accounted for in the nominal calculations. One of the most important is the density of the neutron absorber which is set to the averaged measured value decreased by 3 standard deviations.

## VI. GLOBAL UNCERTAINTY SET UP

Section V.A. showed a negative systematic bias. This value has to be corrected by combining both experimental and theoretical standard deviations. The following equation is used to confirm that, to meet the safety authority requirements, it is mandatory to neglect the systematic bias:

$$\Delta Keff^{biais} = \Delta Keff^{biais^*} - 2\sqrt{\sigma_{exp}^2 + \sigma_{cal}^2}$$

Where:
$\Delta Keff^{biais^*}$ = average C-M
$\sigma_{exp}$ = average experiment deviation
$\sigma_{cal}$ = average calculation deviation

$$\Delta Keff^{biais} = +0.4\ \%\ \Delta Keff$$

It can be concluded that no systematic bias will be accounted for in equation /1/ and $\Delta K_u$ becomes:

$$\Delta K_u = 2\sqrt{\sigma_{\exp}^2 + \sigma_s^2 + \sigma_t^2} \quad /2/$$

The global uncertainty derived from equation /2/ with:

$\sigma_{exp}$ = 0.276 % $\Delta$K (IV.B.1.)
$\sigma_s$ = 0.200 % $\Delta$K (IV.B.2.)
$\sigma_t$ = 0.000 % $\Delta$K (IV.B.3.)

$\Delta K_m$ = 5.0 % $\Delta$k
$\Delta K_u$ = 0.682 % $\Delta$k

**USL = 1.0 – $\Delta K_m$ – $\Delta K_u$ = 0.943**

## VII. CONCLUSION

This paper demonstrates how FRAMATOME ANP proceeds with the application of the IAEA TR-R-1 regulations as far as safety criticality is concerned. The CRISTAL code package is used to justify transport approval; it has been qualified against the available benchmarks. Uncertainties have been defined, showing the accuracy of the computational tools and their adequacy to perform criticality safety calculations for fresh low enriched (< 5% $^{235}$U) UO2 fuel assembly transport.

## REFERENCES

[1] TS-R-1 (ST1 révisée) – Collection Normes de Sûreté de l'AIEA – Règlement de transport de matières radioactives – Edition de 1996 (Révisée).

[2] J. M. Gomit, P. Cousinou, A. Duprey, C. Diop, J.P. Grouiller, L. Leyval, H. Toubon, E. Lejeune, "The new CRISTAL Criticality-Safety Package", Proc. Int. Conf. on Nuclear Criticality Safety, ICNC'99, Versailles, France, Sept. 20-24, 1999, **I**, 308 (1999).

[3] CRISTAL-V0 /DT/02.01/A – Résultats de la voie de qualification standard APOLLO2-MORET4 du formulaire de criticité CRISTAL (version V0).