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Sensitivity Study Applied to the CB4 VVER-440 Benchmark on Burnup Credit

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Abstract

A brief overview of four completed portions (CB1, CB2, CB3, CB3+, CB4) of the international VVER-440 benchmark focused on burnup credit and a sensitivity study as one of the final views of the benchmark results are presented in the paper.
Finally, the influence of real and conservative VVER-440 fuel assembly models taken for the isotopics calculation by SCALE sas2 on the system k_{eff} is shown in the paper.

KEYWORDS: burnup credit, criticality safety calculations, multiplication factor, VVER reactor type

1. Introduction

In 1996, when the Czech Republic joined OECD NEA, the Nuclear Research Institute at Rez (NRI) presented an international VVER Burnup Credit Calculational Benchmark Proposal to participants of the Atomic Energy Research (AER) research activity of the countries operating VVERs. The specification of the benchmark was based on the previous and current work of the OECD/NEA/NSC Burnup Credit Criticality Benchmark Working Group. One of benchmark goals was to start with performing the burnup credit studies in the VVER application area and compare the results with those obtained previously for PWR under OECD/NEA/NSC activity.

Step by step, four phases (CB1, CB2, CB3 and CB4) of the benchmark were specified, calculated and completed. In the course of evaluations, the fuel of 3.6 % enrichment specified in the first benchmark and widely used in VVER-440 as well had to be changed to prove that its 'end effect' could also be positive, as in the case of the PWRs of the western type. The change of fuel enrichment to 4.4 % created a need to specify a new, modified portion of the benchmark, CB3+, similar to CB3. Further, a modification of the CB2, named CB2-S, centring on source calculations, was specified additionally. The individual benchmark results were compared with one another and then compared as a whole with the results of the adequate OECD/NEA/NSC benchmark phases for PWR.

After the CB2 benchmark completion, the study of multiplication factor sensitivity to the spread of VVER spent fuel isotopics resulting from the CB2 calculations with different codes for an infinite array of the VVER-440 spent fuel pin cells was performed using MCNP code and published as an IAEA TCM 2000 contribution.
As in this previous study, the present paper assesses multiplication factors resulting from a series of criticality calculations for a more complicated system - the conceptual cask of CB4 benchmark. Using KENO VI code and changing the isotopics input data resulting from the CB2 calculations, the multiplication factors of the finite array of the VVER-440 fuel pin cells were calculated. The evaluation of the results shows the sensitivity of the calculated finite system reactivity to different calculational methodologies used for the spent fuel inventory computation. The previously performed sensitivity study mentioned above differs from these calculations just due to the finite system of the CB4 conceptual cask. On the other hand, spent fuel of uniform burnup and 3.6 wt.% ^{235}U initial enrichment is used in this study in contrast with the original CB4 benchmark specification using 4.4 wt.% and axially profiled burnup.

2. Overview of the VVER Burnup Credit Calculational Benchmark Portions

Table 1, below, provides a brief description of the individual phases of the VVER benchmark.

Table 1 VVER Burnup Credit Benchmark: A Brief Description

Phase	Primary Objective	Specified/ Completed Reference
CB1	Criticality calculations of an infinite array of fresh and spent VVER-440 fuel pins were aimed at the examination of calculational effects of major actinides and major fission products on the multiplication factor and the methodology intercomparison. Isotopics specified: initial enrichment of 3.6 % ^{235}U, 0-30-40 GWd/t_U burnup and 1-5 y cooling time.	1996/1998 1)
CB2	Computation of nuclide concentrations for depletion in a simple VVER-440 pin cell followed by the methodology intercomparison . Specification: fuel initial enrichment of 3.6 wt % ^{235}U, 30-40 GWd/t_U burnup and 0-1-5 y cooling time.	1997/2000 2)
sensitivity study	Using the MCNP 4B code and changing the isotopics input data as resulting from CB2, the multiplication factor of an infinite array of the VVER-440 fuel pin cells was calculated. The spread of the k-results relative to the mean was found to be less than or about ±1%.	2000 3)
CB3	Criticality calculations of a radially infinite array of fresh and spent VVER-440 fuel pins with axially distributed burnup were aimed at the examination of effects of burnup profile as well as major actinides and major fission products. The methodology intercomparison followed. Isotopics specified at 3.6 wt % ^{235}U, 0-10-30-40 GWd/t_U (Jaslovske Bohunice NPP axial burnup profile) and 1-5 y cooling time.	1998/2000 2)
CB3+	The same objectives as CB3 but isotopics specified at 4.4 wt % ^{235}U (Kola NPP axial burnup profile).	2000/2001 4)
CB2-S	Based on the CB2 specification, the portion is aimed at source calculation and intercomparison.	2000/2002 5)
CB4	Criticality calculation of a conceptual VVER-440 spent fuel cask, the intercomparison followed. Isotopics specified at 4.4 wt % ^{235}U, 0-10-30-40 GWd/t_U (Kola NPP axial burnup profile) and 1-5 y cooling time.	2001/2002 6)
sensitivity study	Using the KENO VI code and changing the isotopics input data, as resulting from CB2, the multiplication factor of the conceptual VVER-440 cask system, as defined by CB4, was calculated. The spread of the k-results relative to the mean can be seen in Table 2.	2003 the present work

3. Sensitivity Study

The CB2 benchmark results consist of 12, 10, 11 and 10 sets of 26 nuclide concentrations[2] submitted by the CB2 benchmark participants for cases involving 30 GWd/t_U burnup and 1 year of cooling time (30_1), 30 GWd/t_U burnup and 5 years of cooling time (30_5), 40 GWd/t_U burnup and 1 year of cooling time (40_1), and 40 GWd/t_U and 5 years of cooling time (40_5) respectively. Each set of nuclide concentrations resulted from a calculation using a calculational methodology specific to the given participant. The nuclides selected for CB2 evaluation consisted of 11 actinides and 15 major fission products, the main contributors to the spent fuel reactivity recommended for the burnup credit calculations, were: U-235, 236, 238, Pu-238, 239, 240, 241, 242, Am-241, 243, Np-237, Mo-95, Tc-99, Ru-101, Rh-103, Ag-109, Cs-133, Nd-143, Nd-145, Sm-147, Sm-149, Sm-150, Sm-151, Sm-152, Eu-153, Gd-155.

The CB2 evaluation[2] showed the spread of nuclide concentrations calculated by the participants. If the estimated standard deviation of 10% was chosen to define the difference between 'good' and 'poor' agreement in the calculations of the nuclide concentration for a given isotope by the participants, there were several more spread isotopes: Am-241 (11%), Am-243 (12%), Ag-109 (13%), Sm-149 (12%), Sm-151 (15%) and even Gd-155 (52%). It should be

noted that a similar spread resulted from the evaluated results of the similar OECD benchmark (Pu-238 (14.78%), Am-243 (10.71%), Ag-109 (10.62%), Sm-149 (14.92%), Sm-151 (22.15%) and Gd-155 (33.23%))[7].

Each set of original final CB2 results[2] was used as the input data for a reference criticality calculation by KENO VI with the 44GROUPNDF5 library. Thus, in total, 12, 10, 11 and 10 sets of multiplication factors for the CB4 finite system (VVER-440 conceptual cask loaded with spent fuel of 3.6% ^{235}U initial enrichment) were computed. As in the case of the previous sensitivity study for the infinite system[3], it was believed that the k-results should be normally distributed for each separate case of a given burnup and cooling time if the calculational methodology was adequate and used appropriately. In order to either confirm or reject this hypothesis, all the sets were statistically explored and tested (α=0.05). The statistical evaluations found three outliers (see Fig. 1 – Fig. 4, below); two of them were also indicated in the previous sensitivity study[3] as being due to the use of a fixed (non-problem-dependent) library for the isotopic concentration calculations. After removing the outliers, the sets of k-results were explored once again and found to be distributed normally. The outliers and the mean and estimated standard deviations are mentioned in the titles of the separate figures.

4. Revised CB2 Calculations

Before the KENO VI calculations and the evaluation described above, data for the SCALE sas2 calculations of the CZ- and SK- participants were changed to model the VVER-440 fuel assembly more exactly than in their original CB2 calculations. Both isotopics resulting from the latest SCALE sas2 calculations and the original CB2 results then entered the KENO VI criticality calculations but only k_{eff} obtained for the revised isotopics represented the CZ- and SK-participants in the statistical evaluation.

All the calculated values of k_{eff} are shown in Fig. 1-Fig. 4 and also can be found in Table 2, below. Since the revised VVER-440 fuel assembly model used in the new SCALE sas2 calculations is less conservative, the multiplication factors resulting from the KENO VI calculations using the revised isotopics data are lower, which decreases the spread of the results.

Table 2 The CB2-CB4 k_{eff} results (±0.0004)

isotopics data[2]	**30_1**	**30_5**	**40_1**	**40_5**
SCALE, Finland	0.8612*	0.8408*	0.8018*	0.7685*
Casmo-4, Finland	0.8840	0.8615	0.8311	0.7945
Origen2, Cuba	0.8537*	not calculated	not calculated	not calculated
HELIO S1.5, CZ	0.8780	0.8592	0.8209	0.7955
SCALE, CZ - the original CB2 results***	0.8919	0.8774	0.8456	0.824
SCALE, CZ - fuel assembly corrected model	0.8804	0.8644	0.8274	0.8068
WIMS7, CZ	0.8900	0.8726	0.8391	0.8153
NUKO, Germany	0.8779	not calculated	0.8201	not calculated
WIMS7B, UK	0.8890	0.8713	0.8379	0.8141
MCU, Russia	0.8794	0.8629	0.8234	0.8012
SCALE, SK - the original CB2 results***	0.8866	0.8709	0.8397	0.8184
SCALE, SK- fuel assembly corrected model	0.8759	0.8605	0.8231	0.8011
SCALE4.4, Spain	0.8896	0.8742	0.8419*	0.8206
TVS-M, Russia	0.8834	0.8719	0.8286	0.8138
mean **	**0.8828**	**0.8665**	**0.8280**	**0.8070**
estimated StD [%]**	**0.6**	**0.7**	**0.8**	**1.2**

* recognized as an outlier in the course of the statistical evaluation
** outliers excluded from the sample
*** not considered in the evaluation

5. Conclusions

The calculations presented above were performed at the end of VVER-440 burnup credit benchmarking so that the influence of different methodologies for the isotopic concentration prediction on the multiplication factor computation could be assessed in a finite case similar to that of a real spent fuel system.

In agreement with the conclusions of the sensitivity study previously performed for TCM 2000[3], it is shown (see Tab. 2, above) that the relatively big differences among the CB2 isotopics[2] leads to a spread of less than or about 1% in the multiplication factors for all the calculated cases of different burnups (30 and 40 MWd/kgU) and cooling times (1 and 5 year) in this finite case of the conceptual VVER-440 cask. In other words, hypothetic cask designers using the different methodologies for isotopics prediction compute the loading curve by putting values that can differ up to about 1% into criticality criteria.

As far as the assessment of the conservativeness of the simplified model used in SCALE sas2 calculation (see Fig. 1 - 4, above) is concerned, the results support a recommendation for VVER SCALE users to model the VVER-440 fuel assembly in the SCALE sas2 input as follows

3 0.44 5 0.515 3 0.640545 **500 7.2185 3 7.3505** 6 7.56053

instead of the SCALE sas2 problem inputs in 8) which could be considered to be only a rather conservative simplification

3 0.44 5 0.515 3 0.640545 **500 7.3505** 6 7.56053 .

The paper is available at ftp://nri.cz/pub/OECD/BUC.

6. References

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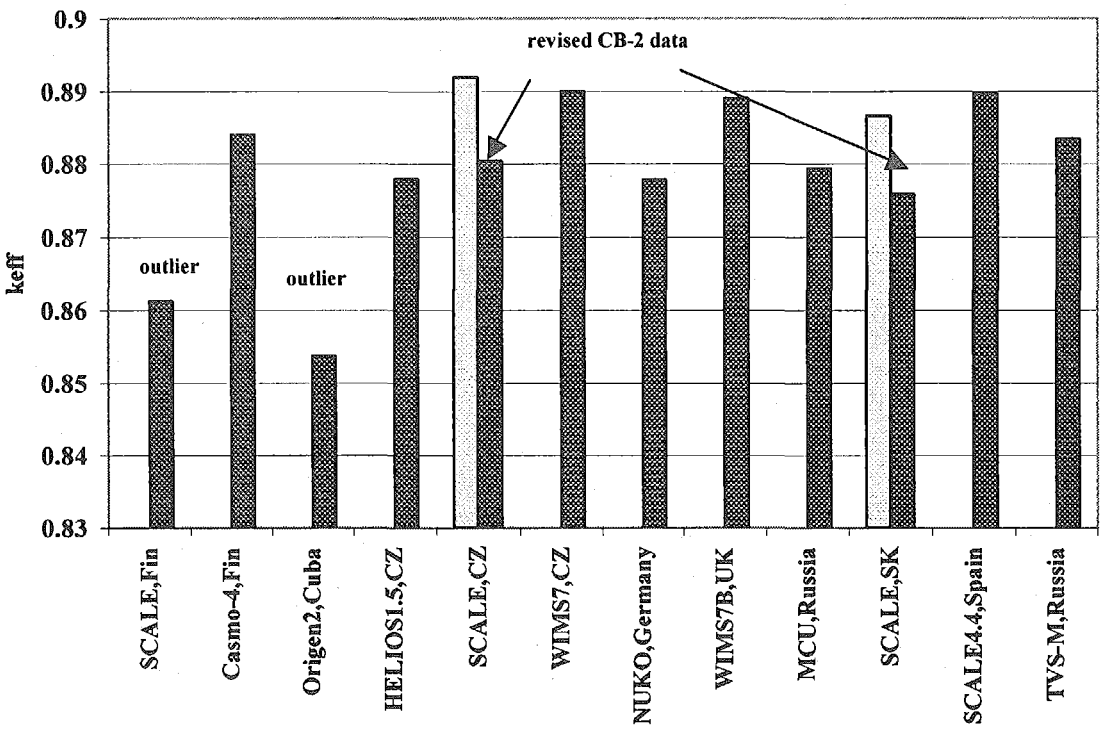

Fig. 1 KENO VI keff sensitivity calculations for VVER conceptual cask with 3.6% fuel, 30 MWd/kg uniform burnup, 1y cooling time (the mean of the original data: 0.879, σ=1.3%, the mean of the data without the outliers: 0.883, σ=0.6%)

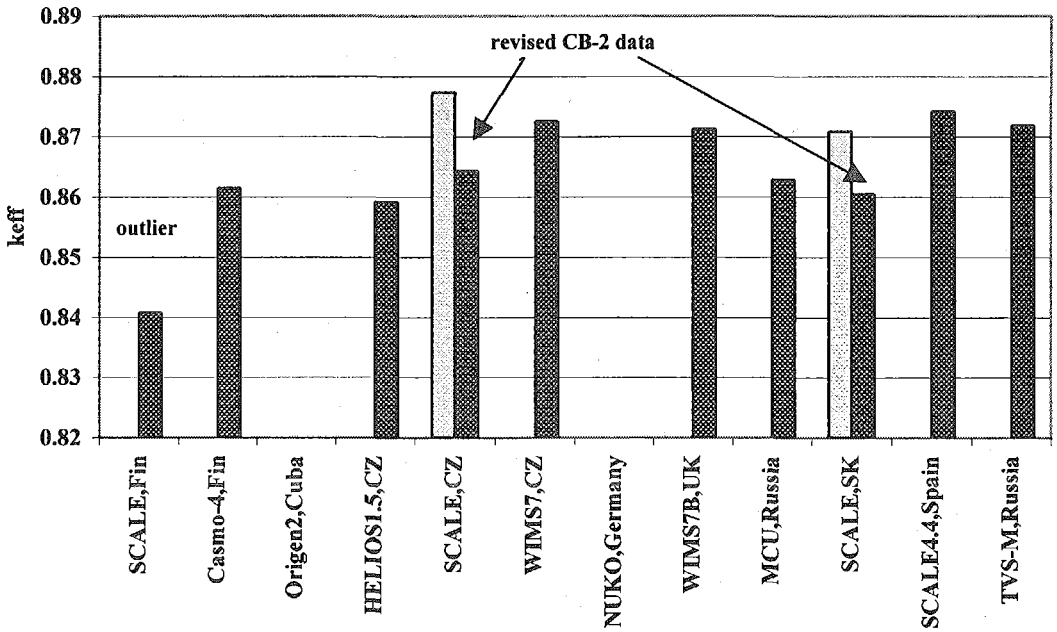

Fig. 2 KENO VI keff sensitivity calculations for VVER conceptual cask with 3.6% fuel, 30 MWd/kg uniform burnup, 5y cooling time (the mean of the original data: 0.864, σ=1.1%, the mean of the data without the outlier: 0.867, σ=0.7%)

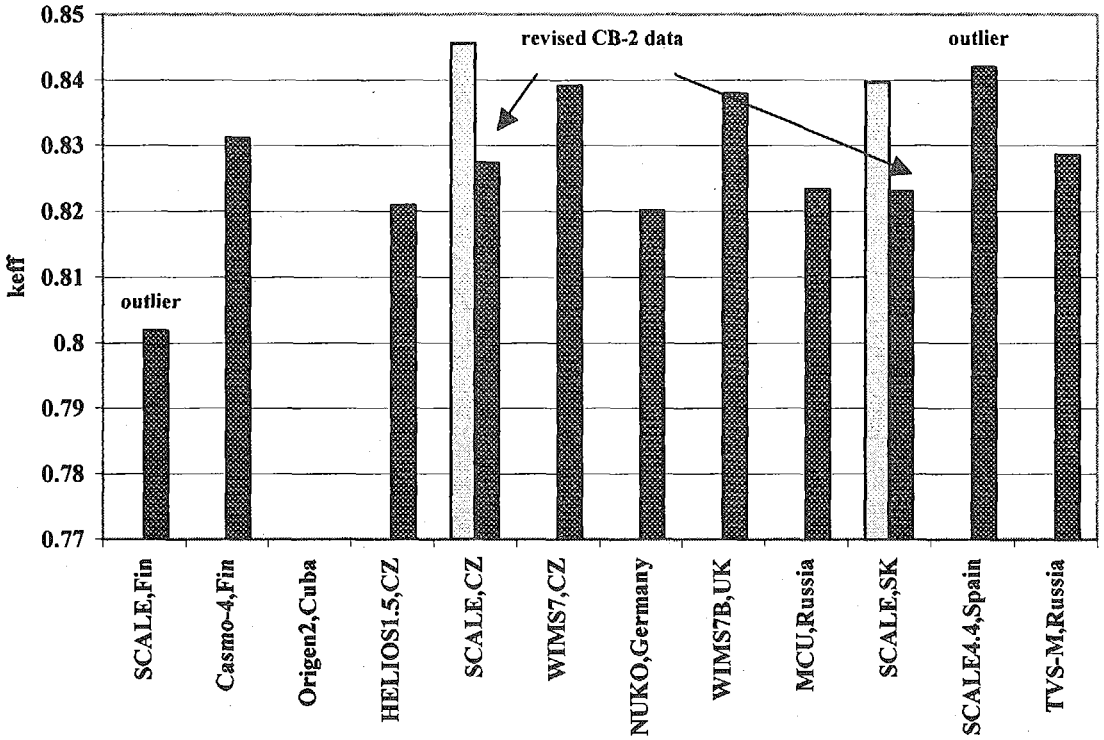

Fig. 3 KENO VI keff sensitivity calculations for VVER conceptual cask with 3.6% fuel, 40 MWd/kg uniform burnup, 1y cooling time (the mean of the original data: 0.827, σ=1.4%, the mean of the data without the outliers: 0.828, σ=0.8%)

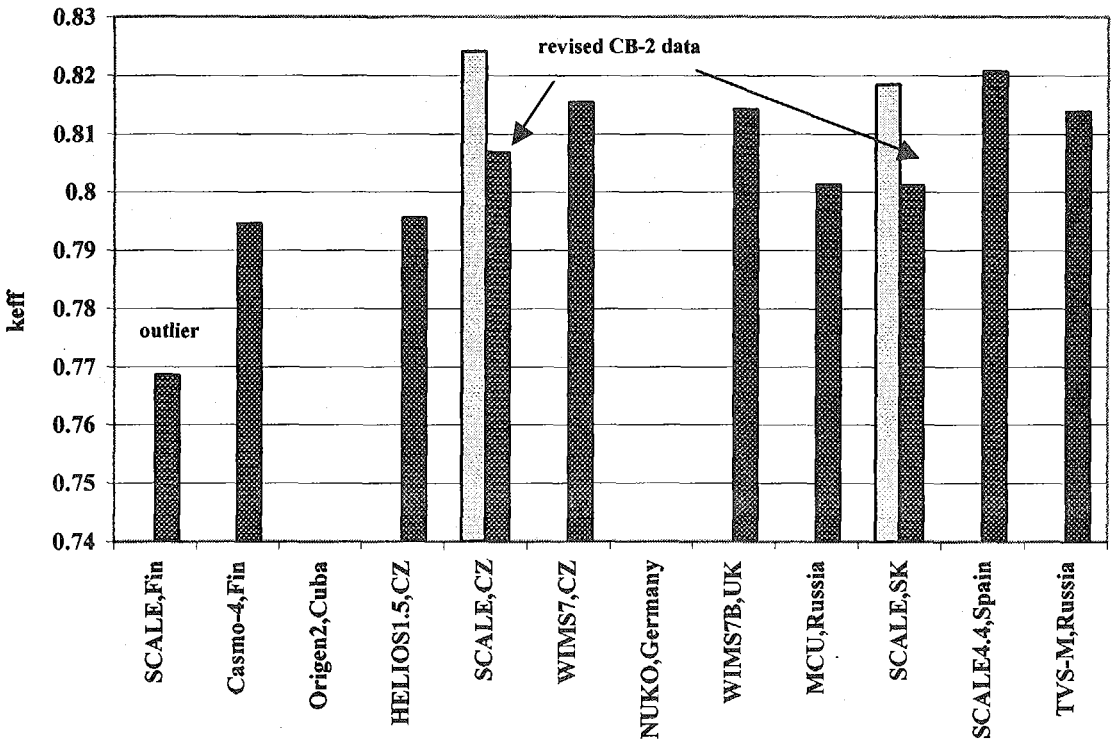

Fig. 4 KENO VI keff sensitivity calculations for VVER conceptual cask with 3.6% fuel, 40 MWd/kg uniform burnup, 5y cooling time (the mean of the original data: 0.803, σ=1.9%, the mean of the data without the outlier: 0.807, σ=1.2%)