Sufficiency of Available MOX Experiments for Criticality Validation of VVER Burnup Credit Applications

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Background

For safety analysis, uncertainty of k_{eff} calculated by criticality codes due to error of nuclear cross sections should be determined.

Regulations generally prescribe the use of critical experiments which are “similar” to examined application.

For burnup credit application, usually MOX experiments are used for this purpose. However, composition of such publicly available experiments are different from the burned fuel (natural or depleted uranium, different plutonium composition), so decision of applicability is particularly difficult by „traditional” methods based on a few physical parameters and spectral characteristics.

Background

Incorporation of sensitivity/uncertainty (S/U) methods into the SCALE package gives new tools for such investigations:

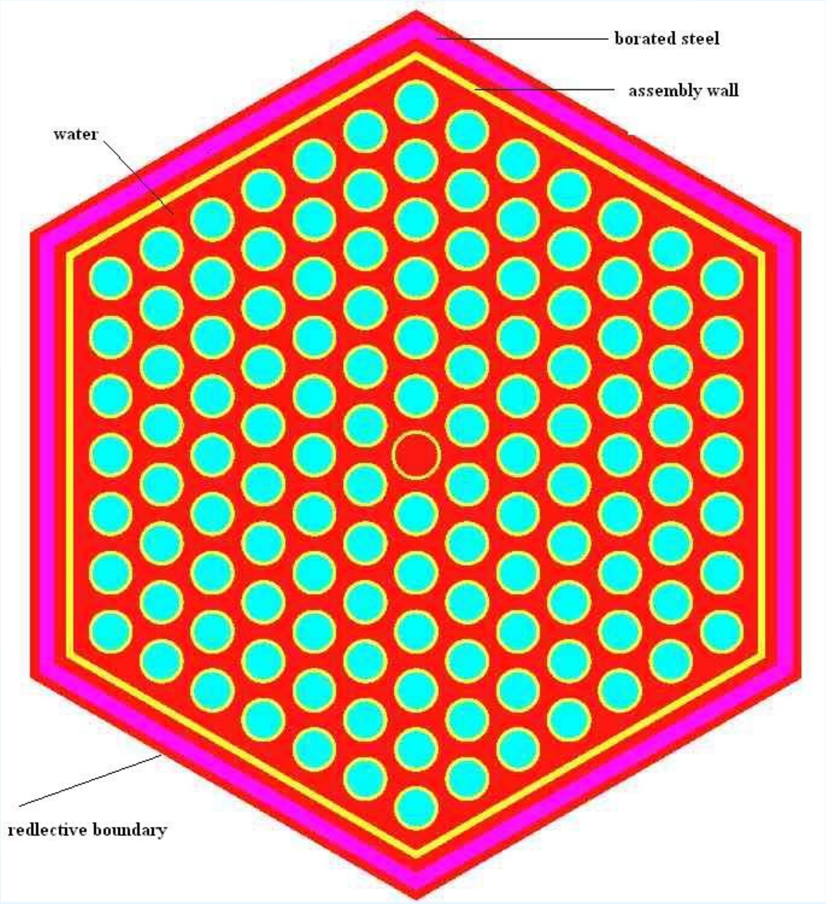
- TSUNAMI-3D calculates keff and its sensitivities, using the nuclear covariance data evaluates the uncertainty in keff.
- TSUNAMI-IP calculates quantities quantifying similarity among systems, and investigates the coverage of application by experimental sensitivities.
- TSURFER modifies the cross sections to extent allowed by their uncertainty data to achieve best agreement by experiments. Method of generalized linear least squares (GLLSM) is used.

Investigated application

Sample application: compact storage pool containing VVER-440 fuel.

Reason of choice : compact storage at Paks NPP is used with reduced capacity, with absorbers at some positions.

e=4.4 %, B=25 MWd/kgU, U-235, U-238, Pu-239, Pu-240, Pu-241



Benchmark selection

235 critical configurations from the IHCSBE

- MOX: 96 cases, compound and solutions, mainly thermal
- Pu: 55 cases, thermal solutions
- LEU: 84 cases, all from the ZR-6 facility at KFKI, thermal

Reason of mixing cases: ensure high coverage for the application sensitivities. The number of benchmark is not too high, including more cases from IHCSBE is planned.

TSUMAMI-3D calculations

TSUMAMI-3D results for the benchmark: for all cases the measured multiplication factor was included in the interval of calculated multiplication factor ± 3 σ_x (σ_x due to nuclear data)

For application: keff = 0.88870, σ_x=0.6 %.

Main source of application uncertainty: Pu-239 nubar, U-238 (n,gamma), U-235 nubar, Pu-239 fission and Pu-239 (n,gamma) cross section uncertainty.

TSUMAMI-IP calculations

S: relative sensitivity matrix of keff for a number of system to the group wise cross section, $\boldsymbol{C_\alpha}$: relative covariance matrix of nuclear data

$\boldsymbol{C_k = S\, C_\alpha S^T}$ is the uncertainty matrix of the systems. Its (i,j) element gives the correlations between uncertainties of systems i and j and varies from -1 to +1

If we have calculated and measured keff for N critical experiments and calculated keff for an application, than using Ck as a trending parameter, and extrapolating ck to 1, the uncertainty in the application Keff can be determined by appropriate statistical analysis.

TSUMAMI-IP calculations

Generally it is supposed, that ck values grater than 0.9 or 0.95 are the most suitable for this purpose and 0.8 is sometimes considered as minimal appropriate value.

The composite sensitivity profile of the application for a nuclide-reaction pair: the best available experiment sensitivity in energy groups where it is not grater than the application sensitivity, and equal with application sensitivity at other group.

The completeness parameter is defined by comparing the magnitude of each group-wise sensitivity coefficient for the application with respect to each of the corresponding sensitivities of the benchmark systems. It is normalized to unity.

TSUMAMI-IP calculations

Maximal ck with selected benchmark for the application was 0.82

type of experiments	Ck values
thermal MOX	0.6 - 0.82
fast MOX	0.1 - 0.2
Pu solution thermal	0.5 - 0.67
LEU compound thermal	0.3 - 0.45

Inclusion of more MOX experiments from the IHCSB may increase somewhat the maximal ck, but not dramatically. Other, much more extensive investigations have shown, that these experiments hardly approximate 0.9 for burnup credit applications.

(D.E. Mueller, K.R. Elam, and P.B. Fox, ORNL/TM-2007/083)

TSUMAMI-IP calculations

Clearly, this range of ck is not appropriate for trending analysis to determine a safety limit for keff of the application, and no conclusion on the uncertainty caused by the nuclear data error can be drawn by this extrapolation.

However, for methodological purposes such calculations were performed with increasing the minimal value of considered ck. USLTATS code was used with method 1 (confidence band with administrative safety margin).

The following parameters were used in the calculation:

P = proportion of population falling above lower tolerance level, 0.999

1 - γ = confidence on fit, 0.95

α = confidence on proportion P, 0.999

Δkm = administrative margin used to ensure subcriticality, 0.050

TSUMAMI-IP calculations

Minimal ck	Number of experiments	Normality	USL-1
0.1	235	Yes	0.9261
0.3	206	Yes	0.9251
0.4	168	No	0.9225
0.5	147	No	0.9092
0.6	118	Yes	0.9022
0.7	42	Yes	0.8807

Recalling, that σ_x=0.6 % was found for the application in the TSUNAMI-3D calculation, the calculated USL values are not reasonable, as it was expected.

TSUMAMI-IP calculations

However, the completeness parameter was 0.91. It was calculated so , that in each energy group at least 10 experiment sensitivity should be greater, than 0.9 times the application sensitivity. Using only MOX experiments, the completeness parameter would be 0.43 only.

Composite sensitivity profiles for most actinides reactions were practically identical with the application sensitivity profiles. On the contrary, B-10(n,α) reaction was largely uncovered.

These results suggested to try the application of TSURFER.

TSUSFER calculations

TSURFER: included in the latest version of SCALE, ver. 6.0 . It is based on the generalized linear least square (GLLSM) method.

The discrepancies of the calculated (**k**)and measured (**m**) multiplication factors of experiments are reduced by adjusting the cross sections (**α**) so that the overall consistency of cross sections and measured keff values is maximized. Cross sections are modified using the information gained from the critical experiments.

Correlations in nuclear data and critical experiments are taken into account in the process.

TSUSFER calculations

The goal of the GLLS method is to vary the nuclear data (**α→α′)** and the measured multiplication factors (**m→m′),** such that the expression

$$\chi^2 = [\Delta\alpha]^T C_\alpha [\Delta\alpha] + [\Delta m]^T C_m [\Delta m]$$

is minimized. Here $\mathbf{C}_\alpha$ and $\mathbf{C}_m$ is the uncertainty matrix of the nuclear data and the criticality measurements, the elements of **Δα** and **Δm** vectors are the relative difference of **α** and **α**’, **m** and **m′** vector elements. Here within the limitation of first order sensitivity theory **m’** = **k’(α’).**

chi-square indicates the squared magnitude of the combined data variations with respect to their uncertainties. In simplest cases, it is the quadratic sum of differences divided by the corresponding standard deviation.

TSUSFER calculations

Using the cross section adjustment that results this minimum, the corrected multiplication factor of the application and its accuracy can be estimated.

TSURFER performs checks for benchmark set consistency; that is, that the input responses have chi square value acceptably low. The code progressively removes individual experiments until the calculated χ^2 is less than the target value specified in the input. Each iteration removes one experiment estimated to have the greatest impact on chi-square per degree of freedom.

TSUSFER calculations

The errors of measured multiplication factor were taken from the ICSBEP handbook.

No correlation data was found for the selected experiments from DICE, so

•constant correlation was assumed among measurements due to the same evaluations

•zero correlation was assumed among measurements due to different evaluations.

This constant originally was chosen to 0.7 but it resulted a warning, that the correlation matrix is not positive definite, so its value was changed to 0.4.

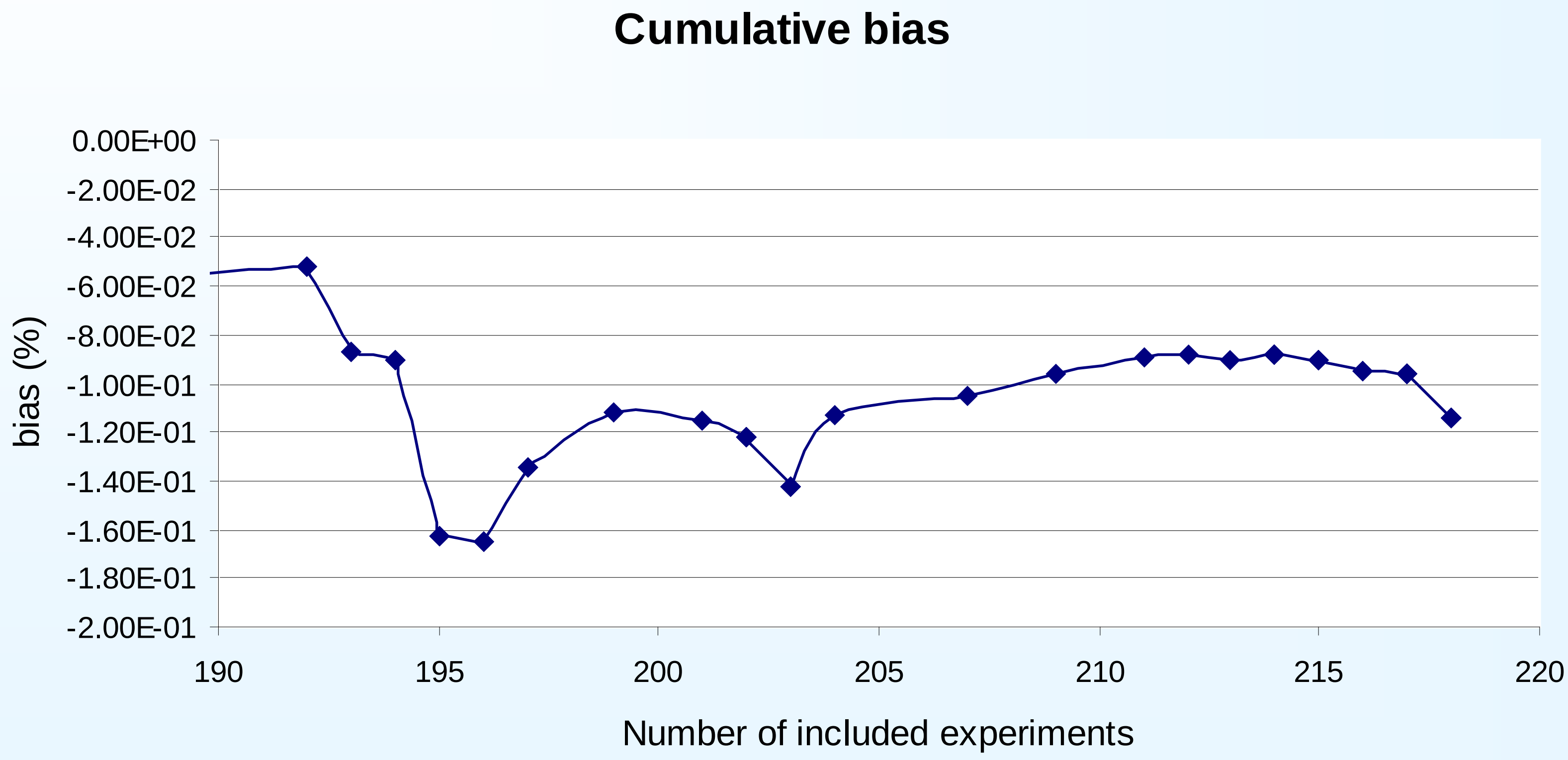
Delta chi-square filtering was used with target value 1.2, which excluded 14 experiments from the analysis.

TSUSFER calculations

Initial $\chi 2$ per degrees of freedom	2.567E+00
Target $\chi 2$ per degrees of freedom	1.200E+00
Final $\chi 2$ per degrees of freedom	1.171E+00

calculated k_{eff}	prior std dev (%)	bias	adjusted k_{eff}	adjusted std dev %
0.88870	0.55207	1.140E-03	0.88756	0.17955

TSUSFER calculations



TSUSFER calculations

The procedure eliminated about 70 % of the uncertainties due to nuclear data. Main contributors are U-238(n,gamma), U-235 nubar, U-238(n,n‘), Pu-239 fission, U-235 fission and U-235(n,gamma).

Trial calculations show, that modifying the correlations may increase the bias from 1.14e-03 to 3.1e-03.

The result of χ^2 filtering suggests that the procedure was correct. However, the change of calculated bias with the number of included experiments shows, that the convergence was not achieved.

This might be eliminated by including more experiments into the analysis.

CONCLUSIONS

Using trending analysis with the ck from TSUNAMI-IP, MOX experiments from IHCSB are probably insufficient for burnup credit criticality validation.

Applying GLLSM method incorporated into TSURFER to larger set of experiments may be good solution for this problem. However, this needs further investigations.

Thank you for your attention!