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PROPOSAL OF NEW ^{235}U NUCLEAR DATA TO IMPROVE k_{eff} BIASES ON ^{235}U ENRICHMENT AND TEMPERATURE FOR LOW ENRICHED URANIUM FUELED LATTICES MODERATED BY LIGHT WATER

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Proposal of New ^{235}U Nuclear Data to Improve k$_{eff}$ Biases on ^{235}U Enrichment and Temperature for Low Enriched Uranium Fueled Lattices Moderated by Light Water

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The under prediction of k_{eff} depending on ^{235}U enrichment in low enriched uranium fueled systems, which had been a long-standing puzzle especially for slightly enriched ones, was studied in this report. Benchmark testing was carried out with several evaluated nuclear data files, including the new uranium evaluations from preliminary ENDF/B-VII and CENDL-3.1. Another problem reviewed here was k_{eff} underestimation vs. temperature increase, which was observed in the slightly enriched system with recent JENDL and ENDF/B uranium evaluations.

Through the substitute analysis of nuclear data of ^{235}U and ^{238}U, we propose a new evaluation of ^{235}U data to solve both of the problems. The new evaluation was tested for various uranium fueled systems including low or highly enriched metal and solution benchmarks in the ICSBEP handbook. As a result, it was found that the combination of the new evaluation of ^{235}U and the ^{238}U data from the preliminary ENDF/B-VII gives quite good results for most of benchmark problems.

Keywords: Nuclear Data Evaluation, Benchmark Testing, Uranium, Enrichment Bias, Temperature Bias, ENDF/B-VII, CENDL-2.1, CENDL-3.1, JENDL-3.3, ICSBEP

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軽水減速低濃縮ウラン燃料格子における^{235}U濃縮度と温度に対するk_{eff}バイアスを改善する新しい^{235}U核データの提案

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本研究では、核データの長年の問題である、低濃縮ウラン燃料体系、特に微濃縮体系で顕著となるk_{eff}過小評価の濃縮度依存性について検討を行った。ベンチマークテストは、プレリミナリ版のENDF/B-VIIとCENDL-3.1のウラン断面積を含む様々な評価済み核データファイルを使用して行った。また、微濃縮体系で最近のJENDLやENDF/Bのウラン断面積評価にみられる温度上昇に伴うk_{eff}の過小評価についても検討を行った。

^{235}Uと^{238}Uの核データの書き換え解析を通して、上記の両問題を解決する新しい^{235}U核データ評価を提案する。新しい評価データのテストは、ICSBEPハンドブックの低濃縮または高濃縮の金属または溶液燃料を含む多様なウラン燃料体系で実施した。その結果、提案する新しい^{235}Uとプレリミナリ版のENDF/B-VIIの^{238}Uのデータを組み合わせると、多くのベンチマーク問題に非常に良い結果を与えることが判明した。

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1 Introduction

Under prediction of k_{eff} depending on ^{235}U enrichment for low enriched uranium fuel lattice assemblies is a long-standing problem [1][2][3] in the current formal published Evaluated Nuclear Data Library ENDF/B-VI.8 [4], JEF-2.2 [5], JEFF-3.0[6], JENDL-3.2[7] and JENDL-3.3[8]. Concerning CENDL-2.1, preliminary CENDL-3.1 (preC31) and preliminary ENDF/B-VII (preVII) [10] the situation is not clear.

Though the possible reasons for under prediction have been widely discussed in the Work Party on International Evaluation Cooperation (WPEC) /sub-group-22 of OEDC/NEA, they were mainly focused on the ^{238} U, ^{1}H and ^{16}O evaluation [11]. In addition, benchmark testing is not sufficient for the experiments using slightly enriched uranium whose enrichment is less than 2.0 wt.%, because such experiments are a few in the ICSBEP handbook [12], which have many experimental data for criticality and is widely used for benchmark testing of nuclear data evaluations now. It should be noted that the dependence of k_{eff} bias is significant especially for the slightly enriched uranium system [3].

Temperature bias for the slightly enriched uranium fueled system was another problem as shown in Ref. [1]. This bias was illustrated as underestimate k_{eff} when the reactor condition changed from “Cold Zero Power (CZP)” to “Hot Zero Power (HZP)” at the temperature of about 245 centigrade degree. The uranium evaluations from ENDF/B-VI.8, JEF-2.2, JENDL-3.2 and JENDL-3.3 all gave more or less under prediction of k_{eff} in HZP comparing with CZP.

To review and solve the enrichment and temperature biases, benchmark testing was carried out with various nuclear data files including preliminary ones. Finally, we propose a new evaluation of ^{235}U and its combination with preferable ^{238}U evaluation to solve the k_{eff} biases on enrichment and temperature.

In addition, the effects on the enrichment bias for modifying fission spectrum of ^{235}U, decreasing first resonance of ^{235}U and ^{238}U were studied. The impact of substituting ^{1}H and ^{16}O data were also studied. These results are listed in appendix.

2 Current Situation with New Uranium Evaluations

2.1 Enrichment Bias in the Prediction of k_{eff}

To test whether the data for ^{235}U and ^{238}U from CENDL-2.1, preC31 and preVII[1] follow the ^{235}U enrichment bias, 6 cases used in Ref. [1] were selected. Table 1 gives a brief description of assemblies used. The continuous energy Monte Carlo code MVP[13] and JENDL-3.3 MVP library [14] were utilized in the calculations. In the library, the thermal scattering law $S(\alpha, \beta)$ for H_2O is taken from ENDF/B-VI.8. Except ^{235}U and ^{238}U, libraries for other nuclides used in the MVP calculations were based on JENDL-3.3. In the MVP calculations, 1000 activity cycles with 10000 particles per cycle were run, and no greater than 0.00030 of statistical errors (1σ) of k_{eff} were obtained.

C/E values of k_{eff} for selected cases were compared in Fig. 1. B7p, C21, C31 and J33 are used for short to represent preVII, CENDL-2.1, preC31 and JENDL-3.3, respectively. Figure 1 shows the under prediction of k_{eff} vs. ^{235}U enrichment decrease still does not disappear with the new evaluations from preVII and preC31. The result of uranium evaluations from preVII gives the smallest bias comparing with the others.

2.2 Temperature Bias in the Prediction of k_{eff}

Criticality measurements for both "cold" and "hot" conditions are included in the KRITZ2 benchmark [15][16] proposed by OECD/NEA. The benchmark testing for KRITZ2 gives information on the prediction accuracy of total temperature coefficient. Here the benchmarks for KRITZ2:1 and KRITZ2:13 cores were employed to examine the temperature bias in slightly enriched uranium cores. Brief information for KRITZ2 cores is listed in Table 2.

Benchmark calculations were done with the MVP code in the same calculation condition as mentioned above. Statistical errors (1σ) of k_{eff} are no greater than 0.00022. Calculated k_{eff} values based on CENDL-2.1, preC31, ENDF/B-VI.8, preVII and JENDL-3.3 are listed in Table 3. Δk_{eff} values from "CZP" to "HZP" condition are compared in Table 4. A smaller Δk_{eff} values means a smaller temperature bias for Isothermal Temperature Coefficient (ITC), because both of the CZP and HZP cores in the KRITZ2 experiment are critical. It can be noticed that there is no significant bias in the results of calculations using uranium evaluations from CENDLs, if the

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[1] Preliminary ENDF/VII evaluation used here are ORNL resonance revised version (^{235}U, Dec 10, 2003; ^{238}U, Feb 28, 2003).

statistical error is considered. For preVII, temperature bias is somewhat enlarged compared with ENDF/B-VI.8.

3 Benchmark Analysis

3.1 Benchmark Analysis with TRX Cores

The TRX cores are most seriously underestimated assemblies in Fig. 1. To find the cause of under prediction, spectra indices[2] ρ28, δ25, δ28 and C* of TRX-1, 2 were calculated with ^{235}U and ^{238}U from different libraries. Fig. 2 shows the comparison of spectra indices. Overestimation of ρ28, δ28 and underestimation of δ25 all indicated the calculated fluxes in TRX cores are too hard. Then, the relationship between C/E values of k_{eff} and $\sigma_c^{238}/\sigma_f^{235}$ at thermal energy point (0.0253eV) was analyzed and plotted in Fig. 3. In the figure, the cross section ratios are normalized to JENDL-3.3. Some correlation between k_{eff} and the ratio is observed. A lower $\sigma_c^{238}/\sigma_f^{235}$ at thermal energy point gives a higher prediction of k_{eff}. The under prediction of k_{eff} for slightly enriched uranium cores is sensitive to the ratio, as pointed out in the previous work [3]. So to improve the prediction, a decrease of the ratio at thermal energy point is expected.

3.2 Benchmark Analysis with KRITZ2 Cores

It is known that the Doppler effect of resonances in fuel plays an important role for total temperature coefficient. In the low enriched uranium systems, the capture resonances of ^{238}U have been considered to be more important than those of ^{235}U. Since uranium evaluations from CENDLs gave no temperature bias in KRITZ2 cores, substitute analysis of nuclear data to find the possible reason of the bias was carried out with uranium evaluation from other nuclear data library. The KRITZ2 benchmark calculation was rerun with the data for ^{235}U fixed and ^{238}U changed, or on the contrary. The calculation condition of the MVP code was not changed.

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[2] $$\rho 28 = \frac{\int_{Epi} N^{238}\sigma_c^{238}\phi dE}{\int_{The} N^{238}\sigma_c^{238}\phi dE} = \frac{C8_{Epi}}{C8_{The}} \qquad \delta 25 = \frac{\int_{Epi} N^{235}\sigma_f^{235}\phi dE}{\int_{The} N^{235}\sigma_f^{235}\phi dE} = \frac{F5_{Epi}}{F5_{The}}$$

$$\delta 28 = \frac{\int_{All} N^{238}\sigma_f^{238}\phi dE}{\int_{All} N^{235}\sigma_f^{235}\phi dE} = \frac{F8}{F5} \qquad C^* = \frac{\int_{All} N^{238}\sigma_c^{238}\phi dE}{\int_{All} N^{235}\sigma_f^{235}\phi dE} = \frac{C8}{F5}$$

Because some correlation between C/E values of k_{eff} and $\sigma_c^{238}/\sigma_f^{235}$ at thermal energy point was observed, a ^{238}U evaluation with only the thermal capture cross section decreased 0.81% based on preVII (B7m7U8) was prepared by using CRECTJ6 [18] to see the effect of thermal capture cross section. J33rU8 is another evaluation prepared based on JENDL-3.3 with the resonance parameters replaced by those used in preVII.

Calculated k_{eff} and temperature effect of KRITZ2 cores are compared in Table 5 and Table 6. With ^{238}U fixed, it can be noticed the temperature effect is still very small when ^{235}U evaluation from CENDL-2.1 is used. In cases 3 and 4, the prediction of k_{eff} for KRITZ2 cores is also better than the other combinations. The impact of substituting ^{235}U is obvious. When ^{235}U is fixed, the influence of substituting ^{238}U is not so significant except when B7m7U8 is used. The calculated k_{eff} in case 2 is not as good as case 3. Almost no difference was observed with ^{238}U changed from J33 to J33rU8. The above situation implies that the difference in resonance parameters of ^{238}U data does not play an important role in temperature bias or the difference itself is small. The main contribution of temperature bias probably comes from ^{235}U.

To make the situation more clear, thermal quantities of ^{235}U and ^{238}U were calculated by nuclear data processing system NJOY97 [19] and compared separately. Comparison in Table 7 shows that the capture resonance integral of ^{235}U from CENDL-2.1 is about 5% lower than that from preVII. And the fission resonance integral of the former is about 1% higher than the latter. As shown in Table 8, the difference of capture resonance integrals among several ^{238}U evaluations is fairly large. It is considered that effects of the difference become larger especially for the low enriched uranium fueled system (^{235}U enrichment <10%).

Finally, above analysis led to a conclusion that the temperature bias was mainly caused by the too large capture resonance integral and too small fission resonance integral of ^{235}U evaluation. The contribution of ^{235}U is more important than that of ^{238}U in the temperature bias. The resonance parameters for ^{235}U used in CENDL-2.1 gives a better estimate of the total temperature coefficient in the slightly enriched uranium system because of the proper resonance integrals. Additionally, it should be noted that the increase of resonance capture cross section of ^{235}U from JENDL-3.2 to JENDL-3.3 made the benchmark results of fast reactors using uranium fuel wrong[20][21].

If we consider k_{eff} calculated with the uranium evaluation from CENDL-2.1, difference in the capture resonance integral of ^{235}U also gives us some possibility to improve the situation of under prediction of k_{eff} in the low enriched uranium fueled systems.

4 Proposal of a New ^{235}U Evaluation

Based on the conclusion in section 3.2 and the good features of ^{235}U from preVII[22], a new ^{235}U evaluation (B7m4U5) was made using existing nuclear data. The resonance parameters were completely replaced with those used in CENDL-2.1 evaluation, which were originally taken from ENDF/B-VI.2. A value of 133.5b for the capture resonance integral at 293.6K was used. The benchmarks for KRITZ2 and TRXes were recalculated with the MVP code in the same condition as before to test the improvement expected.

Calculated k_{eff} values for KRITZ2 and TRXes are listed in Table 9 and Table 10. Good prediction of k_{eff} and total temperature coefficient were obtained at the same time. Also good agreement of k_{eff} was achieved between KRITZ2:1 and KRITZ2:13 cores. The temperature bias observed in preVII was completely removed by replacement of the resonance parameters. The improvement of under prediction of criticality for the KRITZ2 cores gives a sign to solve enrichment bias puzzle. More detailed benchmark testing was done to validate the new ^{235}U data proposed here.

5 Detailed Benchmark Testing on the Proposed ^{235}U

To confirm whether the enrichment bias is completely removed or not and whether the modified resonance parameters do harm to the prediction accuracy of criticality in other systems or not, a detailed benchmark testing on the new ^{235}U data (B7m4U5) was performed with continuous-energy Monte-Carlo code MCNP [23].

In this testing, ^{238}U evaluation from preVII was used both in B7m4U5 and preVII benchmark calculations. Nuclear data libraries in MCNP calculations for H_2O, ^{234}U and ^{236}U were based on MCNP library ENDF60 [24]. The libraries for structure materials used in the calculations are from CENDL-2.1. All libraries from CENDL-2.1 were generated by nuclear date processing system NJOY97. Totally 97 benchmark problems were selected from the ICSBEP handbook except for KRITZ2 and TRXes. The selected problems are categorized as HEU-MET-FAST (HMF), INTER-MET-FAST (IMF), HEU-SOL-THERM (HST), LEU-SOL-THERM (LST), and LEU-COMP-THERM (LCT) in the ICSBEP handbook. All results were compared with those of preVII. Some results for preVII were taken from Ref. [22].

5.1 HEU-MET-FAST System and IEU-MET-FAST Systems

Except HMF001 (GODIVA), HMF004, HMF028 (FLATTOP) and IMF007 (BIGTEN) used in Ref. [22], benchmark HMF002 (JEMIMA), IMF006 and IMF010 were also adopted for fast system testing. C/E values for the above experiments are listed in Table 11. For B7m4U5 evaluation, average of C/E value (<C/E>) and its standard deviation (1σ) is 1.0006±0.0016, and for preVII, <C/E> is 1.0001±0.0016. It is found from the comparison in Fig. 4 that the predictions of k_{eff} for HMF and IMF system are not changed too much from preVII to modified version.

5.2 HEU-SOL-THERM System

Benchmark HST042, HST012, HST013 (ORNL1-4), HST001 and HST009 were selected to test low, middle, and high leakage HEU solution system. Table 12 gives the brief information and calculated results for these benchmarks. <C/E> value and its standard deviation (1σ) for B7m4U5 version is 1.0000±0.0031, and for preVII version it is 0.9989±0.0029.

In Fig. 5, C/E values are plotted against $H/^{235}U$ atomic density. Generally, a case which has a higher value of $H/^{235}U$ corresponds to a lower leakage system. Fig. 5 shows that the prediction accuracy of k_{eff} for the middle and low leakage solution system is slightly improved with ^{235}U evaluation B7m4U5. However, overestimation can be observed in some high leakage cases with B7m4U5 , although good prediction was made with preVII.

5.3 LEU-SOL-THERM System

For the LST system, LST004, LST 007, LST 017, LST 020 and LST021 were selected. LST007 and LST021 are unreflected cylindrical cores of nitrate uranium solution fuel system. LST004 and LST020 are water reflected ones. In Table 13, calculated results for 4 cylindrical solution experiments LST004, LST 007, LST 020 and LST 021 are fairly well. However, both with preVII and B7m4U5 ^{235}U, concentration bias is observed in Fig. 6 for cases named LST017, which are unreflected slab cores. For the LST system, <C/E> value and its standard deviation = 0.9998±0.0020 based on B7m4U5 version, and 1.0007±0.0017 for preVII. Improvement is expected in future to remove the bias in the slab solution system.

5.4 LEU-COMP-THERM System

To confirm whether the ^{235}U enrichment bias is removed or not, benchmark testing for the LCT system was performed for the cores whose ^{235}U enrichment is up to 10%. The enrichment and H/U atomic number density ratio for the selected cores are listed in Table 14.

In Fig. 7, C/E values for these cores are plotted against ^{235}U enrichment. The logarithmic fitting lines for B7m4U5 and preVII (B7p) show that the former has no enrichment bias but the latter has. It is found from Table 15 that the <C/E> value and its standard deviation in the LCT systems are 1.0008±0.0017 and 0.9985±0.0022 based on B7m4U5 and preVII respectively. The prediction accuracy of criticality for the slightly and low enriched uranium systems is confirmed.

A latent problem should be noticed that the C/E values with B7m4U5 for the two DIMPLE cores of 3.0% and 7.0% enrichment are about 0.5% overestimated. The results are out of the trend. The reason for these over predictions of k_{eff} has not been cleared yet. It may infer an overestimation in the LCT system when the leakage is high or a bias of benchmark itself.

5.5 Re-analysis of Spectra Indices of TRXes

Since the prediction accuracy of k_{eff} for the TRXes has been significantly improved, re-analysis of the spectra indices would be valuable to see how the resonances change works.

The spectra indices of TRXes have been recalculated with the MCNP code and are shown in Fig. 8. For TRX-1 and TRX-2, both δ25 are greatly improved by using B7m4U5. It means the fissions of ^{235}U in epithermal and thermal region are in good balance now. Though δ28 of the two cores are also increased by using B7m4U5, they are still within the acceptable region. For the two cores, ρ28 and C* calculated with B7m4U5 are not changed too much comparing with the results of preVII. The imbalance between the fission and capture of ^{238}U still can be observed, if one divides δ28 by C*. That means the spectra are not soft enough and the capture of ^{238}U still a little low. Improvement on the data of ^{238}U is expected.

6 Conclusion

In order to overcome the under prediction of k_{eff} depending on ^{235}U enrichment for slightly enriched uranium fueled cores like TRXes and KRITZ2, a new ^{235}U nuclear data (B7m4U5) is proposed in this study. The data is based on preVII but resonance parameters are replaced with those of CENDL-2.1. The origin of the resonance parameters is ENDF/B-VI.2 whose capture resonance integral is about 5% lower compared with JENDL-3.3 or preVII. The benchmark testing results in sections 4 and 5 shows that the ^{235}U enrichment bias and temperature bias have been successfully solved by using the combination of the new ^{235}U data and the ^{238}U data from preVII. For the KRITZ2 cores with different Vm/Vf and temperatures up to about 245 centigrade degree, quite good agreements with experimental data were achieved not only for criticality but also total temperature coefficient. In addition, spectra indices of TRX cores were improved compared with the current or preliminary nuclear data.

The prediction accuracy of k_{eff} for most of LCT benchmarks in the ICSBEP handbook is also improved. At the same time, the good predictions in the HMF, IMF, HST and LST systems are not changed too much or slightly improved.

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Reference

[1] K. Okumura and T. Mori: "Integral Test of JENDL-3.3 for Thermal Reactors," p.15, JAERI-Conf 2003-006 (2003).

[2] A. C. Kahler: "Monte Carlo Benchmark Calculations with Revised ^{235,238}U Evaluations," Cross Section Evaluation Working Group (CSEWG) Meeting, Brookhaven National Laboratory (2003).

[3] K. Okumura, Y. Nagaya, T. Mori: "Criticality Benchmarks with a Continuous Energy Monte Carlo Code MVP and JENDL-3.3," Proc. of the 2004 Symposium on Nuclear Data, Nov. 11-12 JAERI, Tokai, Japan, p.56, JAERI-Conf 2005-003 (2005).

[4] Victoria McLane and Members of the Cross Section Evaluation Working Group: "ENDF-201, ENDF/B-VI SUMMARY DOCUMENTATION, SUPPLEMENT I ENDF/HE-VI SUMMARY DOCUMENTATION," BNL-NCS-17541, 4th Edition, Suppl.1, Brookhaven National Laboratory (1996).

[5] *http://www.nea.fr/dbforms/data/eva/evatapes/jef_22/.*

[6] http://www.nea.fr/dbforms/data/eva/evatapes/jeff_30/.

[7] T. Nakagawa, K. Shibata and S. Chiba: "Japanese Evaluated Nuclear Data Library version 3 revision-2: JENDL-3.2," J. Nucl. Sci. Technol. **32**, 1259, (1995).

[8] K. Shibata, *et al.*: "Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL-3.3," J. Nucl. Sci. Technol. **39**, 1125, (2002).

[9] http://159.226.2.40/ [In Chinese].

[10] *http://t2.lanl.gov/data/preVII-neutron/U/.*

[11] *http://www.nea.fr/listsmh/ueval/.*

[12] NEA Nuclear Science Committee: "International Handbook of Evaluated Criticality Safety Benchmark Experiments," NEA/NSC/DOC(95)03, September 2004 Edition (ICSBEP Handbook).

[13] Y. Nagaya, T. Mori, K. Okumura and Y. Nakagawa: "MVP/GMVP II: General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations based on Continuous Energy and Multigroup Methods Version 2," to be published in JAERI 1348 (2005).

[14] T. Mori, Y. Nagaya, K. Okumura and K. Kaneko: "Production of MVP Neutron Cross Section Libraries Based on the Latest Evaluated Nuclear Data Files," JAERI-Data/Code 2004-011 (2004) [in Japanese].

[15] E. Johansson: "Data and Results from KRITZ Experiments on Regular H_2O / Fuel Pin Lattices at Temperatures up to 245 °C," STUDSVIK/NS-90/133, Studsvik AB, Sweden, (1990).

[16] I. Remec, *et al.*: "OECD/NEA KRITZ-2 UO_2 and MOX Benchmark," Proc. of Int. Conf. PHYSOR2002, 11B-03, Seoul, Korea, 7-10 October, (2002).

[17] "ENDF-202, Cross Section Evaluation Working Group Benchmark Specifications," Brookhaven National Laboratory report, BNL-19302, (1974).

[18] T. Nakagawa: "CRECTJ: A Computer Program for Compilation of Evaluated Nuclear Data," JAERI-Data/Code, 99-041 (1999).

[19] R. E. MacFarlane, D. W. Muir: "The NJOY Nuclear Data Processing System," LA-12740-M, Los Alamos National Laboratory report (1994).

[20] G. Chiba: "Integral test of JENDL-3.3 for fast reactors," JAERI-Conf, 2003-006 (2003).

[21] S. Okajima, M. Fukushima and M. Andoh: "Benchmark Test for JENDL-3.3 Library by Analyses of a Series of Experiments at the Fast Critical Assembly (FCA) of JAERI," Processings of International Conference on Nuclear Data for Science & Technology, Sep 26 – Oct 1, 2004, Santa Fe, New Mexico (to be published).

[22] R. E. MacFarlane: "Testing New Actinide Cross Sections Proposed for ENDF/B-VII," International Conference on Nuclear Date for Science and Technology (2004).

[23] J. F. Briesmeister, Ed.: "MCNP$^{\mathrm{TM}}$ - A General Monte Carlo N-Particle Transport Code," LA-13709-M, Los Alamos National Laboratory report (2000).

[24] J. S. Hendricks, S. C. Frankle, J. D. Court: "ENDF/B-VI Data for MCNP$^{\mathrm{TM}}$," LA-12891, Los Alamos National Laboratory report (1994).

[25] S. F. Mughabghab: "Thermal Neutron Capture Cross-Sections, Resonance Integrals and g-Factors," INDC (NDS)-440 (2003).

Table 1 Brief description of benchmark cores

Lattice Name	H/U[3]	^{235}U enrichment	pitch (cm)
TRX-1 [17]	3.3	1.29%	1.806
TRX-2 [17]	5.6	1.29%	2.174
KRITZ2:13 cold [15][16]	5.0	1.86%	1.635
LCT006_5(TCAU) [12]	5.3	2.6%	1.956
LCT048_1(DIMPLE3) [12]	3.0	3.0%	1.32
LCT018_1(DIMPLE7) [12]	8.4	7.0%	1.32

Table 2 Brief description of KRITZ2:1 and KRITZ2:13 cores

Core Name	KRITZ2:1		KRITZ2:13	
Fuel	UO_2(1.86% ^{235}U)		UO_2(1.86% ^{235}U)	
Pitch of rod (cm)	1.585		1.635	
Core temperature (°C)	19.7	248.5	22.1	243.0
Experiment k_{eff}	1.0000(8)[4]	1.0000(8)	1.0000(8)	1.0000(8)

Table 3 Calculated k_{eff} of KRITZ2:1, 13 cores

CASE NUMBER	Library Combination		KRITZ2:1 Cold	KRITZ2:1 Hot	KRITZ2:13 Cold	KRITZ2:13 Hot
	^{235}U	^{238}U				
1	B68	B68	0.99001	0.98863	0.99479	0.99251
2	B7p[5]	B7p	0.99601	0.99389	0.99960	0.99759
3	C21	C21	0.99708	0.99696	1.00012	1.00009
4	C21	C31	0.99513	0.99528	0.99821	0.99789
5	J33	J33	0.99176	0.99007	0.99531	0.99346

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[3] H/U: ratio of atomic number densities of hydrogen over uranium.

[4] Read as 1.0000±0.0008

[5] Preliminary ENDF/VII evaluation used here are ORNL resonance revised version (^{235}U, Dec 10, 2003; ^{238}U, Feb 28, 2003).

Table 4 Comparison of temperature effect with KRITZ2 cores

CASE NUMBER	Library Combination		Δk_{eff}[6] (pcm) (k_{Cold} - k_{Hot}, 0 power)	
	^{235}U	^{238}U	KRITZ2:1	KRITZ2:13
1	B68	B68	137.5	228.3
2	B7p	B7p	211.7	201.1
3	C21	C21	11.6	3.0
4	C21	C31	-14.9	31.8
5	J33	J33	169.8	184.3

Table 5 Calculated k_{eff} of KRITZ2 with different ^{235}U & ^{238}U combinations

CASE NUMBER	Library Combination		KRITZ2:1 Cold	KRITZ2:1 Hot	KRITZ2:13 Cold	KRITZ2:13 Hot
	^{235}U	^{238}U				
1	B7p	B7p	0.99601	0.99389	0.99960	0.99759
2	B7p	B7m7U8	0.99685	0.99569	0.99993	0.99878
3	C21	B7p	0.99836	0.99830	1.00163	1.00172
4	C21	C21	0.99708	0.99696	1.00012	1.00009
5	C21	C31	0.99513	0.99528	0.99821	0.99789
6	J33	B68	0.98961	0.98855	0.99462	0.99235
7	J33	B7p	0.99535	0.99397	0.99903	0.99735
8	J33	J33r	0.99495	0.99332	0.99781	0.99616
9	J33	J33	0.99176	0.99007	0.99531	0.99346

Table 6 Temperature effect of KRITZ2 with different ^{235}U & ^{238}U combinations

Library Combination		Δk_{eff} (pcm) (k_{Cold} - k_{Hot}, 0 power)		Library Combination		Δk_{eff} (pcm) (k_{Cold} - k_{Hot}, 0 power)	
^{235}U	^{238}U	KRITZ2:1	KRITZ2:13	^{238}U	^{235}U	KRITZ2:1	KRITZ2:13
B7p	B7p	211.7	201.1	B7p	B7p	211.7	201.1
B7p	B7m7U8	116.0	115.8	B7p	C21	6.1	-9.0
C21	B7p	6.1	-9.0	B7p	J33	138.0	168.0
C21	C21	11.6	3.0				
C21	C31	-14.9	31.8				
J33	B68	106.8	227.0				
J33	B7p	138.0	168.0				
J33	J33rU8	162.3	165.0				
J33	J33	169.8	184.3				

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[6] Δk_{eff}=0.0 is ideal, because both of cold and hot cores are critical.

Table 7 Thermal quantities of ^{235}U at 293.6 K

Thermal Quantities	B7p	C21/B7p-1	J33/B7p-1
thermal fission xsec	5.8494E+02	-0.12%	0.00%
thermal fission nubar	2.4367E+00	-0.11%	-0.02%
thermal capture xsec	9.8673E+01	0.12%	0.00%
thermal capture integral	8.6645E+01	-0.03%	0.00%
thermal capture g-factor	9.9084E-01	-0.16%	0.00%
capture resonance integral	1.4045E+02	-5.03%	0.13%
thermal fission integral	5.0608E+02	0.10%	0.00%
thermal fission g-factor	9.7627E-01	0.22%	0.00%
thermal alpha integral	1.6828E-01	-0.24%	0.00%
thermal eta integral	2.0859E+00	-0.08%	-0.01%
thermal k1 integral	6.4044E+02	-0.10%	-0.03%
equivalent k1	7.2266E+02	-0.10%	-0.03%
fission resonance integral	2.7616E+02	1.04%	-0.08%

Table 8 Thermal quantities of ^{238}U at 293.6 K

Thermal Quantities	B7p	B68/B7p-1	B7m7U8/B7p-1	C21/B7p-1	C31/B7p-1	J33/B7p-1
thermal fission xsec	1.3400E-05	-12.12%	-0.01%	65.77%	-12.12%	-12.12%
thermal fission nubar	2.4921E+00	0.00%	0.00%	-0.11%	-0.11%	-0.18%
thermal capture xsec	2.6801E+00	1.40%	-0.81%	0.28%	1.40%	1.40%
thermal capture integral	2.3797E+00	1.41%	-0.80%	0.34%	1.41%	1.41%
thermal capture g-factor	1.0019E+00	0.02%	0.01%	0.06%	0.02%	0.02%
capture resonance integral	2.7510E+02	1.09%	0.00%	1.51%	1.09%	1.09%
thermal fission integral	1.1885E-05	-12.09%	-0.01%	295.46%	-12.09%	-12.09%
thermal fission g-factor	1.0008E+00	0.04%	0.01%	138.61%	0.04%	0.04%
thermal alpha integral	2.0045E+05	15.34%	-0.79%	-28.03%	15.34%	15.34%
thermal eta integral	1.2433E-05	-13.30%	0.80%	175.19%	-13.40%	-13.46%
thermal k1 integral	-2.3796E+00	1.42%	-0.79%	0.34%	1.42%	1.42%
equivalent k1	-2.6851E+00	1.42%	-0.79%	0.34%	1.42%	1.42%
fission resonance integral	2.7027E+00	-25.09%	0.00%	-25.16%	-25.16%	-24.39%

Table 9 Calculated k_{eff} of KRITZ2 and TRX

Library Combination		KRITZ2:1 Cold	KRITZ2:1 Hot	KRITZ2:13 Cold	KRITZ2:13 Hot	TRX-1	TRX-2
^{235}U	^{238}U						
B7p	B7p	0.99601	0.99389	0.99960	0.99759	0.99708	0.99704
C21	C21	0.99708	0.99696	1.00012	1.00009	0.99796	0.99731
B7m4U5	B7p	0.99913	0.99916	1.00253	1.00243	0.99979	0.99962

Table 10 Temperature dependence of calculated k_{eff} for KRITZ2

Library Combination		Δk_{eff} (pcm) (k_{Cold} - k_{Hot}, 0 power)	
^{235}U	^{238}U	KRITZ2:1	KRITZ2:13
B7p	B7p	211.7	201.1
C21	C21	11.6	3.0
B7m4U5	B7p	-2.6	10.0

Table 11 C/E values for the HEU/IEU-MET-FAST system

Benchmark	^{235}U enrichment	B7p	Un.C/E[7]	B7m4U5	Un.C/E
HMF001	94.00%	0.9994	0.0010	0.9998	0.0011
HMF004_S[8]	97.68%	1.0009	0.0030	1.0019	0.0031
HMF028	93.24%	1.0033	0.0030	1.0030	0.0031
IMF002	16.19%	0.9988	0.0030	0.9998	0.0030
IMF006_D	36.00%	0.9984	0.0023	0.9982	0.0023
IMF007_S	10.00%	0.9999	0.0007	1.0008	0.0007
IMF010	8.98%	1.0001	0.0024	1.0010	0.0024
Average Std. Dev.		1.0001 0.0016		1.0006 0.0016	

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[7] Uncertainty of C/E value

[8] _S means simplified model, _D means detailed model

Table 12 C/E values for the HEU-SOL-THERM system

Benchmark	^{235}U enrichment	H/^{235}U	B7p	Un.C/E	B7m4U5	Un.C/E
HST042_1	93.22%	1603.93	1.0017	0.0039	1.0001	0.0039
HST042_2	93.03%	1634.27	1.0002	0.0036	0.9995	0.0036
HST042_3	93.12%	1821.11	1.0009	0.0028	0.9999	0.0028
HST042_5	93.01%	1980.70	0.9993	0.0034	0.9988	0.0034
HST042_7	92.78%	2003.80	1.0006	0.0036	1.0004	0.0036
HST042_8	92.82%	2052.28	1.0010	0.0035	1.0001	0.0035
HST012_1	93.18%	1272.25	1.0007	0.0058	1.0011	0.0058
HST013_1	93.18%	1374.65	0.9961	0.0026	0.9961	0.0026
HST013_2	93.18%	1173.06	0.9958	0.0036	0.9967	0.0036
HST013_3	93.18%	1029.90	0.9924	0.0036	0.9935	0.0036
HST013_4	93.18%	971.12	0.9943	0.0036	0.9959	0.0036
HST001_1	93.17%	181.79	0.9992	0.0060	1.0000	0.0060
HST001_2	93.17%	70.60	0.9941	0.0072	0.9978	0.0072
HST001_3	93.17%	185.71	1.0025	0.0035	1.0036	0.0036
HST001_4	93.17%	68.15	0.9971	0.0053	1.0027	0.0053
HST001_5	93.17%	499.44	0.9999	0.0049	1.0001	0.0049
HST001_6	93.17%	458.76	1.0030	0.0046	1.0030	0.0046
HST001_7	93.17%	193.28	0.9975	0.0040	0.9987	0.0040
HST001_8	93.17%	181.79	0.9986	0.0038	1.0002	0.0039
HST009_2	93.18%	47.23	1.0005	0.0039	1.0069	0.0040
HST009_3	93.18%	76.08	1.0005	0.0036	1.0043	0.0037
Average			0.9989		1.0000	
Std. Dev.			0.0029		0.0031	

Table 13 C/E values for the LEU-SOL-THERM system

Lattice Name	^{235}U enrichment	H/^{235}U	B7p	Un.C/E	B7m4U5	Un.C/E
LST007_1	9.97%	709.25	0.9992	0.0009	0.9985	0.0010
LST007_2	9.97%	769.97	1.0004	0.0009	0.9997	0.0010
LST007_3	9.97%	842.18	0.9980	0.0010	0.9981	0.0011
LST007_4	9.97%	896.05	1.0004	0.0011	1.0009	0.0012
LST021_1	9.97%	971.00	1.0000	0.0009	1.0001	0.0010
LST021_2	9.97%	1052.69	0.9999	0.0010	1.0003	0.0011
LST021_3	9.97%	1167.99	0.9989	0.0011	0.9977	0.0012
LST021_4	9.97%	1238.87	1.0000	0.0012	0.9998	0.0012
LST004_1	9.97%	719.02	1.0009	0.0008	1.0011	0.0009
LST004_2	9.97%	771.30	1.0018	0.0009	1.0024	0.0010
LST004_3	9.97%	842.18	1.0002	0.0009	1.0000	0.0010
LST020_1	9.97%	971.00	1.0005	0.0010	1.0002	0.0011
LST020_2	9.97%	1053.92	1.0000	0.0010	1.0002	0.0011
LST020_3	9.97%	1167.99	0.9990	0.0012	0.9994	0.0012
LST020_4	9.97%	1239.27	1.0004	0.0012	0.9991	0.0012
LST017_1	9.97%	468.73	1.0051	0.0014	1.0045	0.0014
LST017_2	9.97%	510.85	1.0038	0.0014	1.0048	0.0014
LST017_3	9.97%	610.95	1.0035	0.0015	1.0025	0.0015
LST017_4	9.97%	650.08	1.0014	0.0015	1.0030	0.0015
LST017_5	9.97%	699.21	1.0012	0.0016	1.0025	0.0016
LST017_6	9.97%	729.00	1.0007	0.0016	1.0025	0.0016
Average			1.0007		0.9998	
Std. Dev.			0.0017		0.0020	

Table 14 Benchmark cores for LCT system testing

Case Name	^{235}U enrichment	H/U	Case Name	^{235}U enrichment	H/U
TRX-1	1.29%	6.70	LCT048_1	3.00%	2.86
TRX-2	1.29%	11.46	LCT002_1	4.31%	11.17
KRITZ2_1C	1.86%	3.40	LCT002_2	4.31%	11.17
KRITZ2_1H	1.86%	2.80	LCT002_3	4.31%	11.17
KRITZ2_13C	1.86%	5.00	LCT002_4	4.31%	11.17
KRITZ2_13H	1.86%	4.10	LCT007_1	4.74%	5.25
LCT001_1	2.35%	9.49	LCT007_2	4.74%	10.97
LCT001_2	2.35%	9.49	LCT007_3	4.74%	21.84
LCT001_3	2.35%	9.49	LCT007_4	4.74%	33.24
LCT001_4	2.35%	9.49	LCT052_1	4.74%	5.20
LCT006_1	2.60%	4.33	LCT052_2	4.74%	10.98
LCT006_2	2.60%	4.33	LCT018_1	7.00%	8.39
LCT006_3	2.60%	4.33	LCT025_2	7.41%	10.68
LCT006_4	2.60%	5.28	LCT025_3	7.41%	19.51
LCT006_5	2.60%	5.28	LCT023_1	9.83%	10.99
LCT006_6	2.60%	5.28	LCT023_2	9.83%	10.99
LCT006_7	2.60%	5.28	LCT023_3	9.83%	10.99
LCT006_8	2.60%	5.28	LCT023_4	9.83%	10.99
LCT006_9	2.60%	7.16	LCT023_5	9.83%	10.99
LCT006_10	2.60%	7.16	LCT023_6	9.83%	10.99
LCT006_11	2.60%	7.16			
LCT006_12	2.60%	7.16			
LCT006_13	2.60%	7.16			
LCT006_14	2.60%	8.65			
LCT006_15	2.60%	8.65			
LCT006_16	2.60%	8.65			
LCT006_17	2.60%	8.65			
LCT006_18	2.60%	8.65			

Table 15 C/E values for the LEU-COMP-THERM system

Benchmark	^{235}U enrichment	H/U	B7p	Un.C/E	B7m4U5	Un.C/E
LCT006_1	2.60%	4.33	0.9985	0.0020	1.0008	0.0020
LCT006_2	2.60%	4.33	0.9991	0.0020	1.0022	0.0021
LCT006_3	2.60%	4.33	0.9990	0.0020	1.0022	0.0021
LCT006_4	2.60%	5.28	0.9994	0.0020	1.0022	0.0021
LCT006_5	2.60%	5.28	0.9987	0.0020	1.0015	0.0021
LCT006_6	2.60%	5.28	0.9993	0.0020	1.0015	0.0021
LCT006_7	2.60%	5.28	0.9991	0.0020	1.0006	0.0020
LCT006_8	2.60%	5.28	0.9993	0.0020	1.0015	0.0021
LCT006_9	2.60%	7.16	0.9990	0.0020	1.0018	0.0020
LCT006_10	2.60%	7.16	0.9987	0.0020	1.0004	0.0020
LCT006_11	2.60%	7.16	0.9995	0.0020	1.0015	0.0020
LCT006_12	2.60%	7.16	0.9992	0.0020	1.0005	0.0020
LCT006_13	2.60%	7.16	0.9992	0.0020	1.0001	0.0021
LCT006_14	2.60%	8.65	0.9992	0.0020	1.0011	0.0020
LCT006_15	2.60%	8.65	0.9993	0.0020	1.0008	0.0020
LCT006_16	2.60%	8.65	0.9991	0.0020	1.0008	0.0021
LCT006_17	2.60%	8.65	0.9991	0.0020	1.0009	0.0020
LCT006_18	2.60%	8.65	0.9997	0.0020	1.0007	0.0021
LCT001_1	2.35%	9.49	0.9992	0.0031	1.0017	0.0031
LCT001_2	2.35%	9.49	0.9976	0.0031	0.9997	0.0031
LCT001_3	2.35%	9.49	0.9974	0.0031	0.9991	0.0031
LCT001_4	2.35%	9.49	0.9983	0.0031	0.9998	0.0031
LCT002_1	4.31%	11.17	0.9973	0.0020	0.9995	0.0021
LCT002_2	4.31%	11.17	0.9964	0.0020	1.0008	0.0021
LCT002_3	4.31%	11.17	0.9983	0.0020	1.0000	0.0021
LCT002_4	4.31%	11.17	0.9978	0.0020	0.9997	0.0021
KRITZ2_1C	1.86%	3.40	0.9960	0.0008	0.9991	0.0008
KRITZ2_1H	1.86%	2.80	0.9939	0.0008	0.9992	0.0008
KRITZ2_13C	1.86%	5.00	0.9996	0.0008	1.0025	0.0008
KRITZ2_13H	1.86%	4.10	0.9976	0.0008	1.0024	0.0008
TRX-1	1.29%	6.70	0.9971	0.0020	1.0003	0.0020
TRX-2	1.29%	11.46	0.9970	0.0020	0.9993	0.0020
LCT007_1	4.74%	5.25	0.9962	0.0017	0.9987	0.0017
LCT007_2	4.74%	10.97	0.9984	0.0017	1.0002	0.0017
LCT007_3	4.74%	21.84	0.9981	0.0017	0.9995	0.0017
LCT007_4	4.74%	33.24	0.9988	0.0016	1.0003	0.0017

Table 15' C/E values for the LEU-COMP-THERM system (cont')

Benchmark	^{235}U enrichment	H/U	B7p	Un.C/E	B7m4U5	Un.C/E
LCT023_1	9.83%	10.99	0.9956	0.0044	0.9974	0.0044
LCT023_2	9.83%	10.99	0.9982	0.0044	0.9996	0.0044
LCT023_3	9.83%	10.99	1.0011	0.0044	1.0013	0.0044
LCT023_4	9.83%	10.99	1.0026	0.0044	1.0028	0.0044
LCT023_5	9.83%	10.99	1.0032	0.0044	1.0034	0.0044
LCT023_6	9.83%	10.99	1.0029	0.0044	1.0035	0.0044
LCT025_2	7.41%	10.68	0.9944	0.0041	0.9979	0.0041
LCT025_3	7.41%	19.51	1.0002	0.0044	1.0016	0.0044
LCT052_1	4.74%	5.20	0.9931	0.0023	0.9980	0.0023
LCT052_2	4.74%	10.98	0.9938	0.0036	0.9971	0.0036
LCT048_1	3.00%	2.86	1.0014	0.0025	1.0052	0.0025
LCT018_1	7.00%	8.39	1.0019	0.0020	1.0055	0.0021
Average			0.9985		1.0008	
Std. Dev.			0.0022		0.0017	

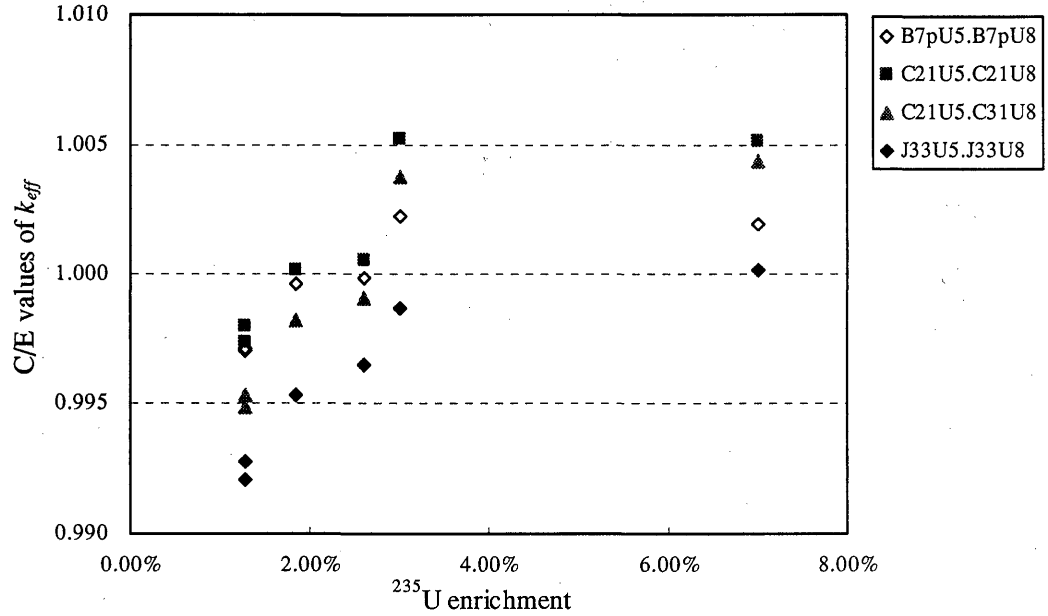

Fig. 1 ^{235}U enrichment bias for the low enriched uranium fueled system

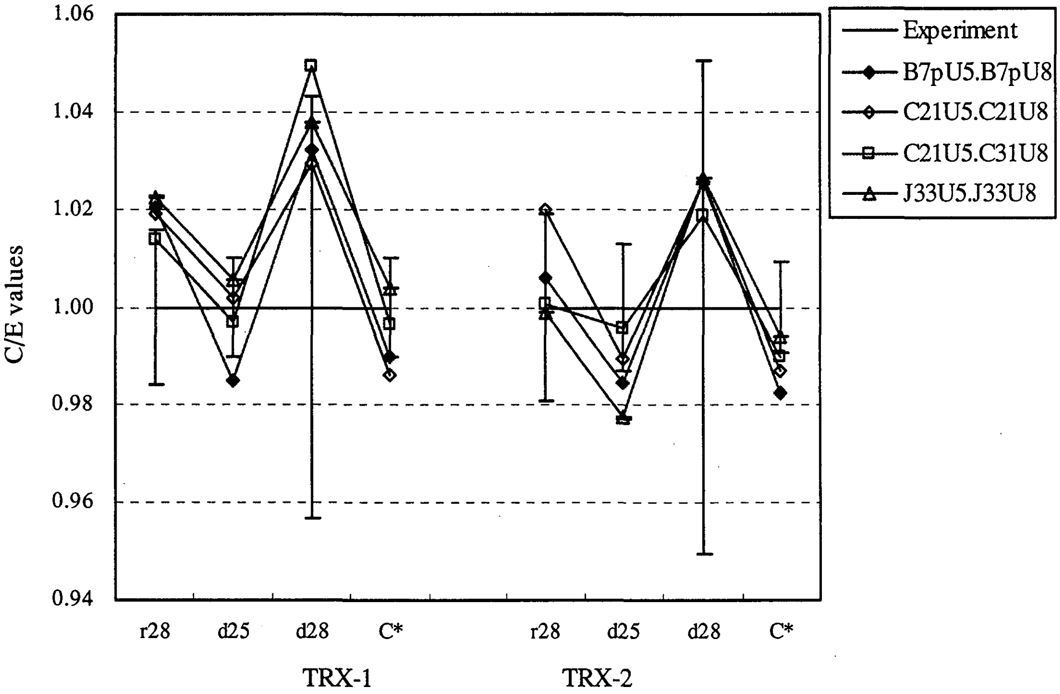

Fig. 2 Comparison of spectra indices for TRX cores

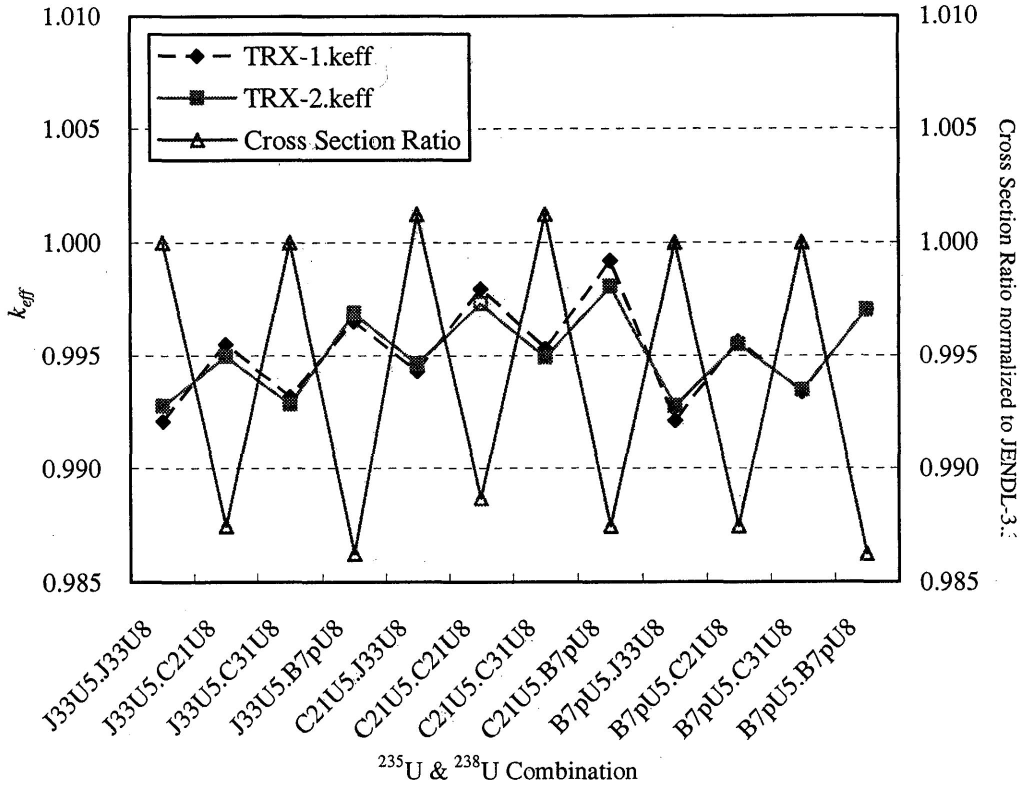

Fig. 3 Relationship between k$_{eff}$ and $\sigma_c^{U238}/\sigma_f^{U235}$ at 0.0253eV (293.6K)

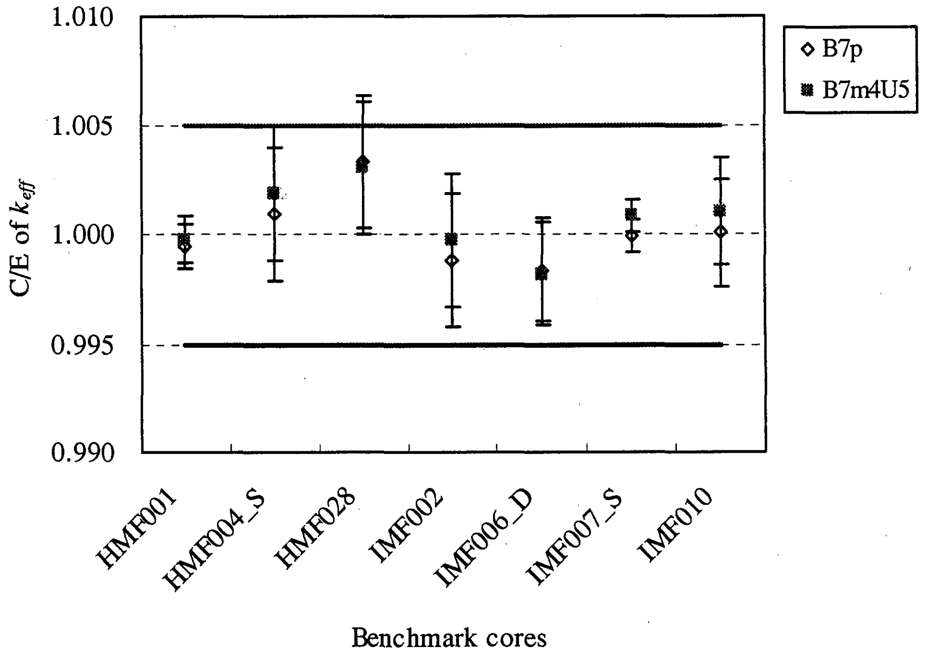

Fig. 4 Highly/Intermediate enriched uranium Metal Fast systems

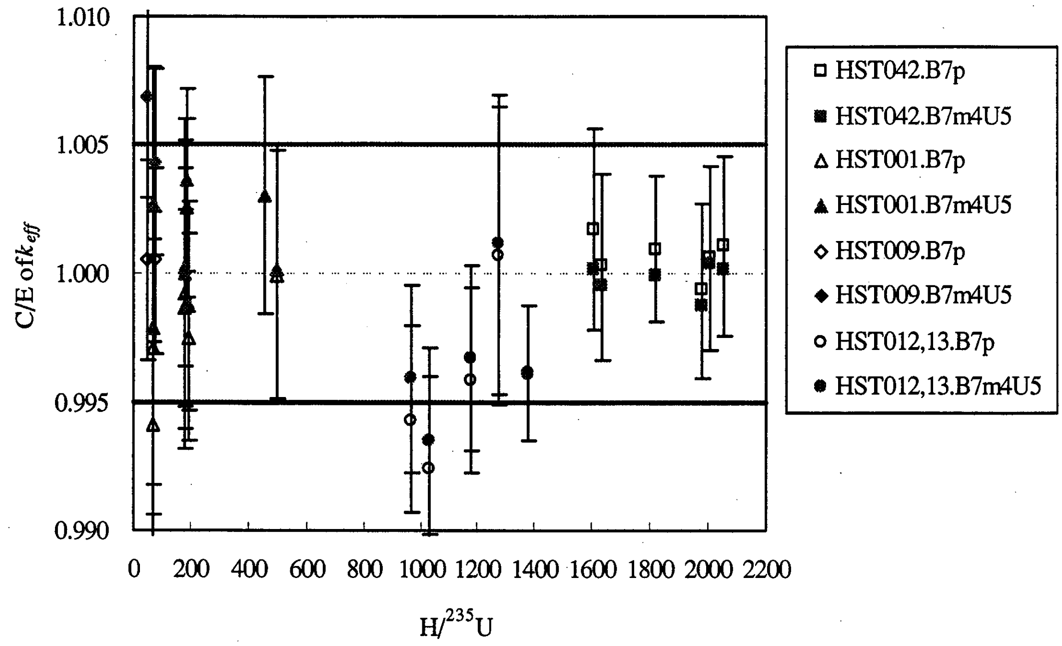

Fig. 5 Highly enriched uranium Solution Thermal systems

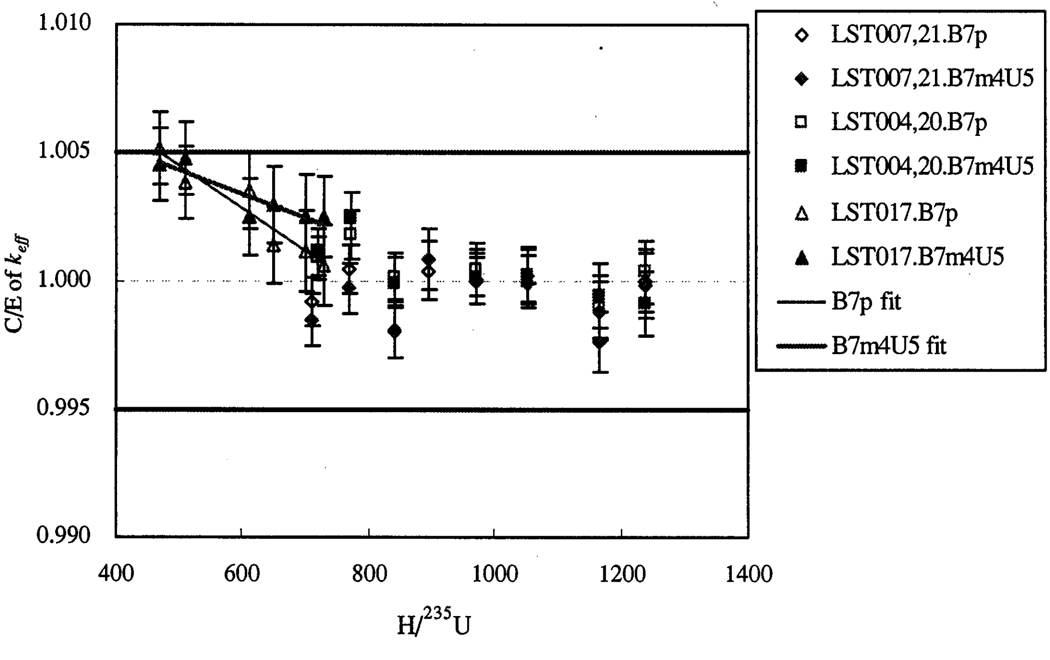

Fig. 6 Low enriched uranium Solution Thermal systems

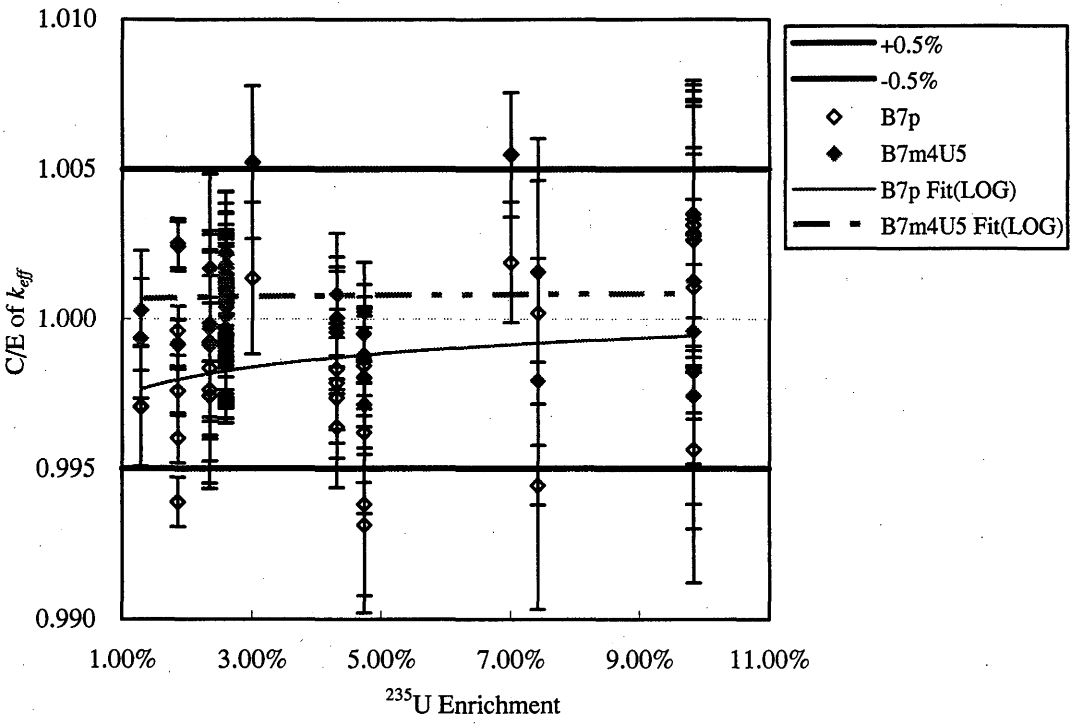

Fig. 7 Low enriched uranium Compound Thermal systems

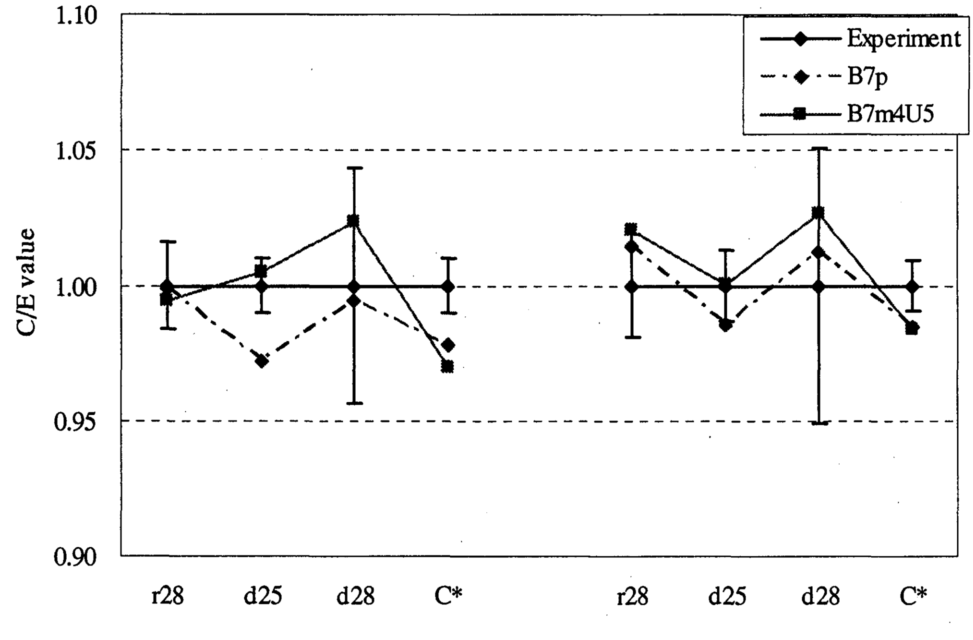

Fig. 8 Comparison of spectra indices of TRXes calculated with B7p and B7m4U5

Appendix

Appendix A. ^{235}U Fission Spectra Modification and Tests

When underestimation of criticality for the low enriched uranium thermal cores occurred, increasing fission rate at low energy region is expected. There are many ways to reach this destination. Increasing the neutron emission possibility at low energy part of fission spectra is one of them. Two different files with fission spectra modified based on ^{235}U from preVII were prepared. Modification was performed by adding several points between 10^{-5}eV and 10eV. Table A.1 gives the points have been added into modified version file B7m1U5 and B7m2U5. The difference between the modified files and original evaluation are shown in Fig.A.1.

Table A.1 Points added into MF5, MT18 of ^{235}U

Energy (eV)	B7m1U5	B7m2U5
1.00000E-05	3.76375E-12	9.21318E-11
1.00000E-04	1.05739E-11	1.51900E-10
1.00000E-03	2.97063E-11	2.50443E-10
1.00000E-02	8.34570E-11	4.12912E-10
1.00000E-01	2.34465E-10	6.80780E-10
1.00000E+00	6.58705E-10	1.12242E-09

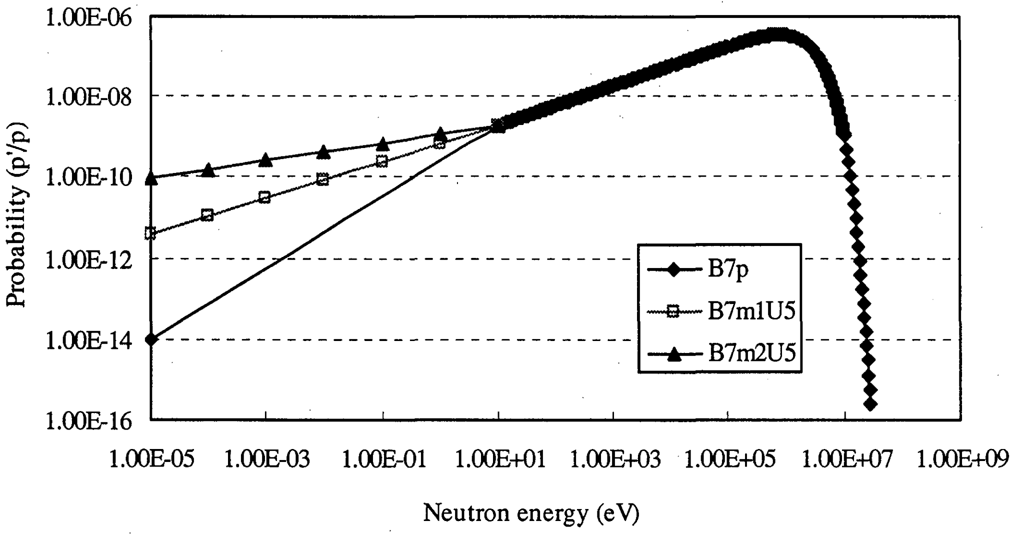

Fig. A.1 Modification on fission spectra of U-235

To test the effect of the modified ^{235}U data, the benchmarks used in section 2.1

were calculated with MVP code, and the results are shown in Table A.2. It is found from the table that all the results are almost unchanged. So the fission spectrum of ^{235}U in thermal region is not sensitive to the under prediction.

Table A.2 C/E values of calculated k_{eff} based on modified ^{235}U

Lattice Name	B7pU5.B7pU8	B7m1U5.B7pU8	B7m2U5.B7pU8
TRX-1	0.9971	0.9971	0.9969
TRX-2	0.9970	0.9970	0.9967
KRITZ2:13 cold	0.9996	0.9992	0.9990
LCT006_5(TCAU)	0.9998	0.9998	0.9992
LCT048_1(DIMPLE3)	1.0022	1.0025	1.0022
LCT018_1(DIMPLE7)	1.0019	1.0020	1.0024

Appendix B. ^{235}U Resonance Modification and Tests

As described in section 3.1 the enrichment bias is sensitive to $\sigma_c^{238}/\sigma_f^{235}$ ratio, a decrease of the ratio at thermal energy point is expected. One way is to adjust the first resonance of ^{235}U at 1.134eV and increase thermal fission cross section. Therefore, a ^{235}U file (B7m3U5) with the fission resonance amplitude at 1.134eV decreased 0.5% was prepared and tested. Table B.1 and Table B.2 show the difference in first resonance between preVII evaluation and B7m3U5.

Table B.1 Difference in the height of the resonance of ^{235}U at 1.134eV

MT	B7pU5	B7m3U5	Δ(%)
1	1.552735E+02	1.542124E+02	-0.68%
2	1.319783E+01	1.319779E+01	0.00%
18	1.111648E+02	1.106075E+02	-0.50%
102	3.091082E+01	3.040715E+01	-1.63%

Table B.2 Thermal quantities of ^{235}U at 293.6 K

Thermal Quantities	B7pU5	B7m3U5
thermal fission xsec	5.8494E+02	0.04%
thermal fission nubar	2.4367E+00	0.00%
thermal capture xsec	9.8673E+01	0.01%
thermal capture integral	8.6645E+01	0.01%
thermal capture g-factor	9.9084E-01	0.00%
capture resonance integral	1.4045E+02	-0.04%
thermal fission integral	5.0608E+02	0.04%
thermal fission g-factor	9.7627E-01	0.00%
thermal alpha integral	1.6828E-01	-0.04%
thermal eta integral	2.0859E+00	0.00%
thermal k1 integral	6.4044E+02	0.05%
equivalent k1	7.2266E+02	0.05%
fission resonance integral	2.7616E+02	0.02%

The benchmarks used in section 2.1 were recalculated with B7m3U5 and compared with the results based on ^{235}U evaluation from preVII. The comparison in Table B.3 shows that the prediction of TRX cores slightly improved with B7m3U5 version. The increase of the thermal fission cross section of ^{235}U by 0.04% cannot remove the enrichment bias.

Table B.3 C/E values of calculated k_{eff} based on modified ^{235}U (B7m3U5)

Lattice Name	B7pU5.B7pU8	B7m3U5.B7pU8
TRX-1	0.9971	0.9975
TRX-2	0.9970	0.9977
KRITZ2:13 cold	0.9996	0.9993
LCT006_5(TCAU)	0.9998	1.0005
LCT048_1(DIMPLE3)	1.0022	1.0026
LCT018_1(DIMPLE7)	1.0019	1.0021

Appendix C. ^{238}U Resonance Modification and Tests

Another way to decrease $\sigma_c^{238}/\sigma_f^{235}$ ratio at thermal energy point is to decrease thermal capture cross section of ^{238}U. Therefore, modifications on the first resonance at 6.67 eV and thermal capture cross section were tried.

Three file with the first resonance modified were prepared. Another ^{238}U file with only the thermal capture cross section decreased 0.81% based on preVII (B7m7U8) was also prepared. The difference between the modified ^{238}U files and preVII one is shown in Table C.1 and Table C.2.

Table C.1 Difference in the height of the resonance of ^{238}U at 6.67eV

MT	B7p	B7m1U8	Δ(%)
1	2.372109E+04	2.364452E+04	-0.32%
2	1.437328E+03	1.428116E+03	-0.64%
18	1.135815E-06	1.136286E-06	0.04%
102	2.228376E+04	2.221640E+04	-0.30%
MT	B7p	B7m2U8	Δ(%)
1	2.372109E+04	2.360965E+04	-0.47%
2	1.437328E+03	1.423931E+03	-0.93%
18	1.135815E-06	1.136500E-06	0.06%
102	2.228376E+04	2.218572E+04	-0.44%
MT	B7p	B7m3U8	Δ(%)
1	2.372109E+04	2.334202E+04	-1.60%
2	1.437328E+03	1.392017E+03	-3.15%
18	1.135815E-06	1.138146E-06	0.21%
102	2.228376E+04	2.195000E+04	-1.50%

All modified ^{238}U data were tested and compared for TRX, KRITZ2, TCAU and DIMPLE benchmarks. In Table C.3, calculated k_{eff} values for TRX cores are improved about 200 pcm and 140 pcm by B7m3U8 and B7m7U8. However, considering that the thermal cross section of ^{238}U was recommended to be 2.680 ± 0.019 b [25], a decrease about 0.8% (σ_0=2.659 b) to improve the estimation of the criticality for TRX cores is not a good choice.

Table C.2 Thermal quantities of ^{238}U at 293.6 K

Thermal Quantities	B7p	B7m1U8/B7p-1	B7m2U8/B7p-1	B7m3U8/B7p-1	B7m7U8/B7p-1
thermal fission xsec	1.3400E-05	0.000%	0.000%	0.000%	-0.01%
thermal fission nubar	2.4921E+00	0.000%	0.000%	0.000%	0.00%
thermal capture xsec	2.6801E+00	**-0.157%**	**-0.228%**	**-0.776%**	**-0.81%**
thermal capture integral	2.3797E+00	**-0.160%**	**-0.231%**	**-0.782%**	**-0.80%**
thermal capture g-factor	1.0019E+00	0.000%	0.000%	0.000%	0.01%
capture resonance integral	2.7510E+02	**-0.153%**	**-0.222%**	**-0.749%**	**0.00%**
thermal fission integral	1.1885E-05	0.000%	0.000%	0.000%	-0.01%
thermal fission g-factor	1.0008E+00	0.000%	0.000%	0.000%	0.01%
thermal alpha integral	2.0045E+05	-0.155%	-0.229%	-0.778%	-0.79%
thermal eta integral	1.2433E-05	0.153%	0.225%	0.788%	0.80%
thermal k1 integral	-2.3796E+00	-0.155%	-0.227%	-0.777%	-0.79%
equivalent k1	-2.6851E+00	-0.156%	-0.227%	-0.778%	-0.79%
fission resonance integral	2.7027E+00	0.000%	0.000%	0.000%	0.00%

Table C.3 C/E values of calculated k_{eff} based on the modified ^{238}U

Lattice Name	B7pU5.B7pU8	B7pU5.B7m1U8	B7pU5.B7m2U8	B7pU5.B7m3U8	B7pU5.B7m7U8
TRX-1	0.9971	0.9974	0.9975	0.9991	0.9985
TRX-2	0.9970	0.9973	0.9974	0.9991	0.9984
KRITZ2:13Cold	0.9996	0.9995	1.0000	1.0002	0.9999
TCA 1.83U	0.9998	1.0001	1.0002	1.0007	1.0002
DIMPLE3	1.0022	1.0025	1.0022	1.0036	1.0033
DIMPLE7	1.0019	1.0028	1.0026	1.0028	1.0026

Appendix D. Contribution of ^{1}H and ^{16}O Data to the Enrichment Bias

In section 5, benchmark testing calculations were performed with ^{1}H and ^{16}O from the ENDF60 MCNP library. The MCNP library data for ^{1}H and ^{16}O is based on ENDF/B-VI(MOD2) and ENDF/B-VI(MOD1), respectively [24]. In order to investigate the effect of ^{1}H and ^{16}O data on the enrichment bias, calculation results with ^{1}H and ^{16}O from ENDF/B-VI.8 are presented here.

Benchmarks LCT001, LCT002, LCT006 (Case 2, 5, 9, 15), LCT007, LCT023 (Case 2, 3), LCT025 (Case 2, 3) and LCT018 were recalculated with the new ^{235}U data proposed in this work and the ^{238}U data from preVII. The libraries for the other nuclides were not changed, except H and O.

Comparison of C/E values for above benchmarks with different H and O data combinations is shown in Table D.1. Slopes and correlated coefficients of logarithmic fit are also listed. Curves in Fig. D.1 show very slight enrichment bias with different data combination of H and O. Therefore, the contribution of H and O to the under prediction of k_{eff} in the LCT system can be neglected.

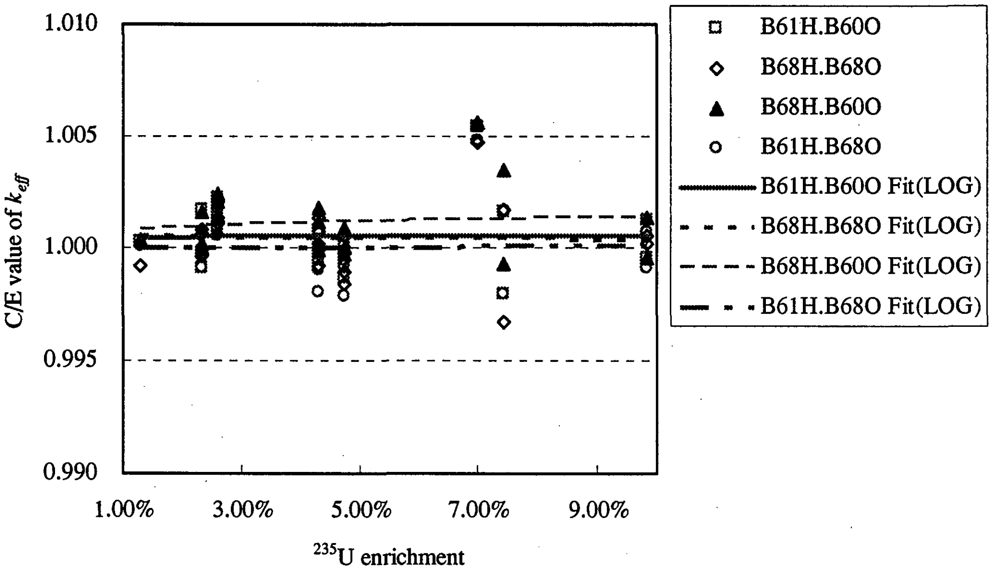

Fig. D.1 The effect of ^{1}H and ^{16}O on under prediction of k_{eff} in the LCT system

Table D.1 Comparison of C/E value of k_{eff} with different ^{1}H and ^{16}O combination[9]

Benchmark	^{235}U enrichment	C/E value of k_{eff}			
		B61H.B60O	B68H.B68O	B68H.B60O	B61H.B68O
TRX-1	1.29%	1.0003	0.9992	1.0004	1.0001
LCT001_1	2.35%	1.0017	1.0007	1.0016	1.0017
LCT001_2	2.35%	0.9997	0.9997	0.9999	0.9996
LCT001_3	2.35%	0.9991	1.0008	1.0005	0.9991
LCT001_4	2.35%	0.9998	1.0008	1.0008	1.0002
LCT002_1	4.31%	0.9995	1.0002	1.0002	0.9980
LCT002_2	4.31%	1.0008	1.0014	1.0018	1.0007
LCT002_3	4.31%	1.0000	1.0007	1.0012	0.9990
LCT002_4	4.31%	0.9997	0.9992	0.9999	0.9991
LCT006_2	2.60%	1.0022	1.0013	1.0024	1.0012
LCT006_5	2.60%	1.0015	1.0011	1.0013	1.0008
LCT006_9	2.60%	1.0018	1.0021	1.0020	1.0006
LCT006_15	2.60%	1.0008	1.0013	1.0014	1.0009
LCT007_1	4.74%	0.9987	0.9984	0.9998	0.9979
LCT007_2	4.74%	1.0002	0.9998	1.0009	0.9995
LCT007_3	4.74%	0.9995	0.9989	1.0000	0.9992
LCT007_4	4.74%	1.0003	1.0006	1.0009	1.0001
LCT023_2	9.83%	0.9996	1.0002	0.9995	0.9991
LCT023_3	9.83%	1.0013	1.0006	1.0013	1.0007
LCT025_2	7.41%	0.9979	0.9967	0.9993	0.9980
LCT025_3	7.41%	1.0016	1.0017	1.0035	1.0016
LCT018_1	7.00%	1.0055	1.0047	1.0056	1.0048
	Average	1.0005	1.0004	1.0011	1.0000
	Std. Dev.	0.0016	0.0015	0.0014	0.0015
	SLOPE	0.0025	-0.0017	0.0053	0.0029
	CORREL	0.0385	-0.0269	0.0896	0.0471

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[9] All the standard deviation(1 σ) of calculated k_{eff} are below 0.00050.

国際単位系(SI)と換算表

表1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表2　SIと併用される単位

名称	記号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$

$1\ u = 1.66054 \times 10^{-27}\ kg$

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$

$1\ b = 100\ fm^2 = 10^{-28}\ m^2$

$1\ bar = 0.1\ MPa = 10^5\ Pa$

$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$

$1\ Ci = 3.7 \times 10^{10}\ Bq$

$1\ R = 2.58 \times 10^{-4}\ C/kg$

$1\ rad = 1\ cGy = 10^{-2}\ Gy$

$1\ rem = 1\ cSv = 10^{-2}\ Sv$

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s($N\cdot s/m^2$)=10 P(ポアズ)(g/(cm·s))

動粘度　$1\ m^2/s = 10^4$St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf•m	kW•h	cal(計量法)	Btu	ft • lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J(計量法)
= 4.184 J　(熱化学)
= 4.1855 J　(15 °C)
= 4.1868 J(国際蒸気表)

仕事率　1 PS(仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Proposal of New ^{235}U Nuclear Data to Improve k_{eff} Biases on ^{235}U Enrichment and Temperature for Low Enriched Uranium Fueled Lattices Moderated by Light Water