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Criticality Analysis of Highly Enriched Uranium/Thorium Fueled Thermal Spectrum Cores of Kyoto University Critical Assembly

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A series of critical experiments on thermal spectrum cores containing highly enriched uranium and thorium have been performed at Kyoto University Critical Assembly (KUCA) of Research Reactor Institute, Kyoto University, Japan. Analysis of criticality (k-effective) have been performed using continuous energy Monte Carlo code MVP and various nuclear data libraries such as JENDL-3.2, JENDL-3.3, ENDF/B-VI.8 and JEFF3.0.

It has been found that the large overestimation of k-effective observed for JENDL-3.2 is significantly reduced by the use of JENDL-3.3. However, C/E values by JENDL-3.3 range from 1.007 to 1.009 and are significantly larger than C/E values of cores without thorium. Considerable spread among the ^{232}Th cross sections exist and have been shown to have considerable impact on nuclear characteristics of thorium fueled thermal systems. Among the nuclear data libraries considered in this study, ENDF/B-VI.8 showed the best results in terms of criticality prediction.

KEYWORDS: Kyoto University Critical Assembly, critical experiment, criticality, Thorium, Monte Carlo code, JENDL-3.2, JENDL-3.3, ENDF/B-VI.8, JEFF3.0

1. Introduction

Studies on thorium-based fuel cycle and reactors have emerged in the very early days of reactor study, and extensive studies have been made in the past. Nevertheless, thorium has recently regained a growing interest from nuclear society. This is due to the attractive potential of thorium-based fuel cycle, such as its rich natural resource, less possibility of generating TRU wastes and excellent non-proliferation characteristics.

For the reliable design of thorium-based systems, the accuracy of neutron cross section, especially that of ^{232}Th, will be of primary importance. Due to the recent developments in computing environment, the major ambiguity in the predicted nuclear characteristics are now considered to be coming from the ambiguity in the nuclear data. However, compared to the uranium-plutonium fuel cycle, less attention have been paid to the validation of nuclear data related to thorium fuel cycle. This may be best seen in the current status of thorium cross section in evaluated data libraries; Fig. 1 shows the comparison of ^{232}Th capture cross sections from JENDL-3.2, JENDL-3.3, ENDF/B-VI and JEFF3.0, where the cross section values were taken from the 107-group libraries of SRAC code system[1]. It could be seen that significant difference among the data libraries exist, especially in the resonance and thermal energy range.

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Such difference among the data libraries may have certain impact on the calculated nuclear characteristics of thorium-based systems. Therefore, it is inevitable to assess the performance of current nuclear data libraries on prediction of nuclear characteristics of thorium-based systems.

For this point of vies, a series of critical experiments on thorium fueled thermal spectrum cores are being performed at the Kyoto University Critical Assembly (KUCA), Japan, in order to accumulate experimental information on thermal spectrum systems containing thorium[2][3]. This paper describes the results of the recently completed highly enriched uranium / thorium mixed single zone core experiments and their analysis using the most recent nuclear data libraries, with emphasis on criticality prediction performances of the nuclear data libraries.

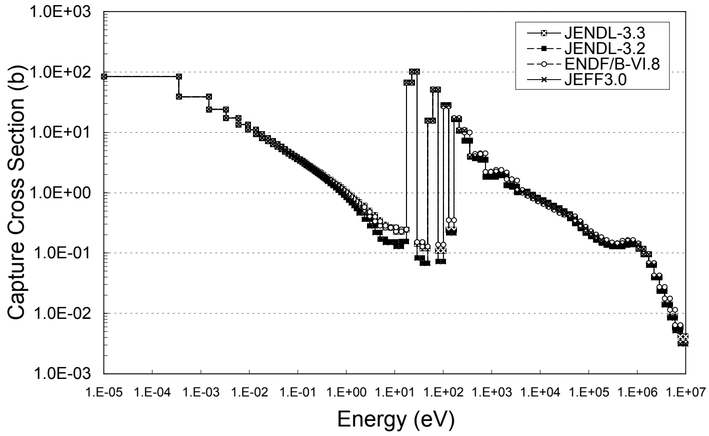


Fig.1 ^{232}Th Capture Cross Section from JENDL-3.3, JENDL-3.2, ENDF/B-VI.8 and JEFF3.0 (in 107 groups)

2. Experimental

2.1 Kyoto University Critical Assembly

The KUCA is a multi-core type critical assembly constructed in 1974 for the reactor physics study and education. KUCA has two solid moderated cores, where solid moderator materials such as polyethylene and graphite are used, and one light water moderated core. The critical experiments on thorium-uranium fueled have been performed using one of the solid moderated cores, B-core. A schematic view of the critical assembly is shown in Fig. 2.

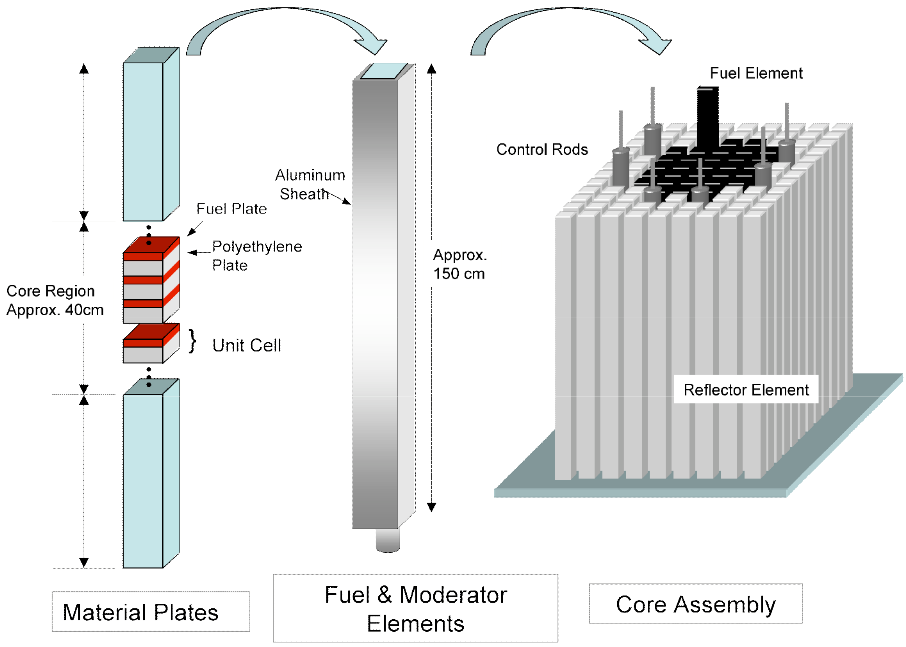


Fig. 2 Schematic View of the KUCA Solid Moderated Core

The materials used in the solid moderated cores are in the form of 5.08cm by 5.08cm (2" by 2") square plate. In the present experiments, the fuel plates (93% enriched uranium-aluminum alloy) are combined with thorium metal plates and polyethylene moderator plates to form an appropriate unit cell with desired $H/^{235}U$ ratio and $^{232}Th/^{235}U$ ratio. The unit fuel cells are then piled up to form the core region of approximately 40 to 45 cm in height. The core region is then sandwiched with lower and upper reflectors, and is stacked into aluminum sheaths to form fuel elements. Finally, the fuel elements are arranged onto a core grid plate to construct the critical core. Figure 3 shows an example of the horizontal cutaway view of the core treated in this study.

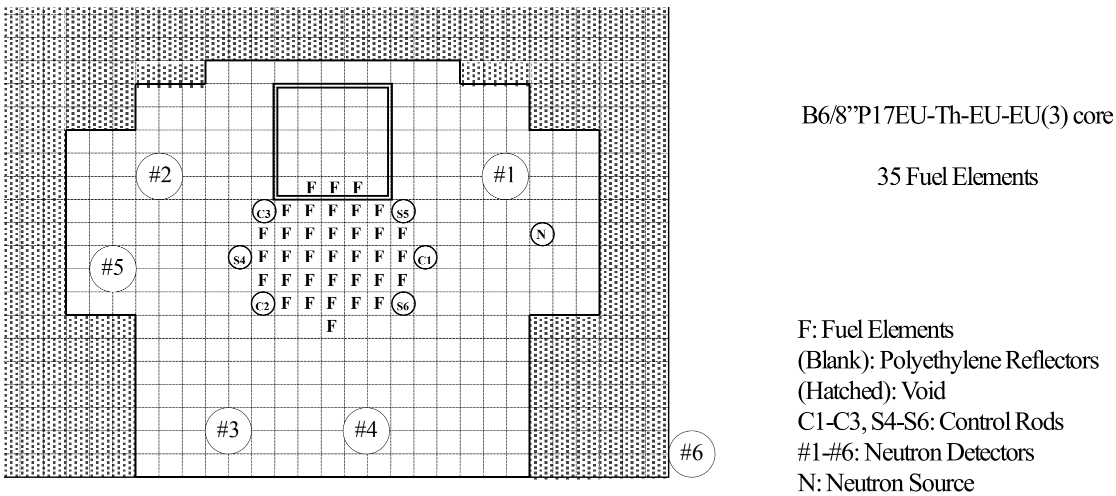


Fig. 3 Example of Experimental Core Configuration

2.2 Highly Enriched Uranium / Thorium Loaded Cores of KUCA

2.2.1 Core Specifications

In the present experiment, core parameters such as $H/^{235}U$ ratio and $^{232}Th/^{235}U$ ratio were systematically varied by changing the number of uranium, thorium and polyethylene plates contained in a unit fuel cell. Seven cores have been hitherto constructed as summarized in Table 1, with $H/^{235}U$ ratio ranging from 138 to 316, and $^{232}Th/^{235}U$ ratio from 12.7 to 19.0. In order to quantitatively describe the neutron spectrum of the core, spectrum index, defined here as the ratio of neutron flux below 1eV to total flux (upper energy bound = 10MeV), i.e.;

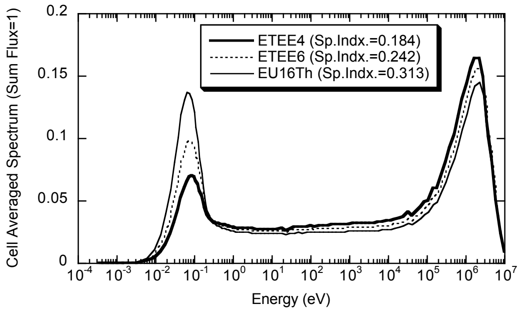
$$Spectrum\ Index = \frac{\int_{E \le 1eV} \phi(E)\frac{dE}{E}}{\int_{E \le 10MeV} \phi(E)\frac{dE}{E}}, \tag{1}$$

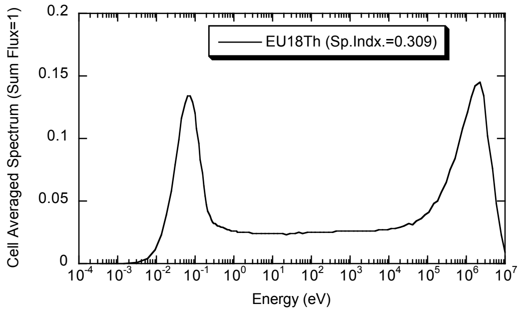
will be hereafter used and are also shown in Table. 1.

Table 1 Specifications of the Uranium/Thorium Fueled Cores

Core ID	Unit Cell ID	$H/^{235}U$ ratio	$^{232}Th/^{235}U$ ratio	Spectrum Index	Core Volume (liter)
B4/8"P24EU-Th-EU-EU(5)	ETEE4	138		0.184	56.8
B6/8"P24EU-Th-EU-EU(3)	ETEE6	211	12.7	0.242	48.8
B3/8"P48EU16Th(3)	EU16Th	316		0.313	58.5
B3/8"P45EU18Th(3)	EU18Th	316	15.2	0.309	65.9
B3/8"P30EU-Th-EU(5)	ETE3	155		0.191	93.4
B4/8"P17EU-Th-EU(5)	ETE4	207	19.0	0.230	81.2
B6/8"P17EU-Th-EU(5)	ETE6	316		0.297	89.1

Figure 4 shows the cell-averaged neutron spectrum of unit fuel cells of the cores (see Table 1) obtained using SRAC code system and JENDL-3.3. It could be seen that the cores with spectrum index of approximately 0.3 has a well-moderated neutron spectrum, whereas those with spectrum index of approximately 0.2 are more under-moderated.





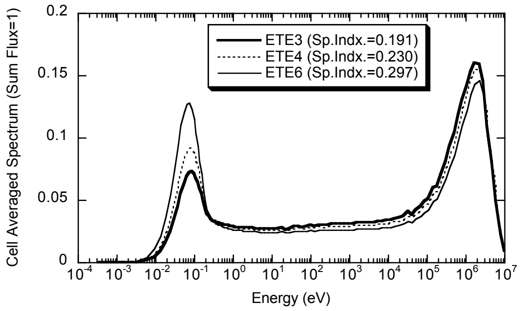


Fig. 4 Cell-Averaged Neutron Spectrum of Unit Fuel Cells of Uranium/Thorium Fueled Cores
(Sp. Indx. = spectrum index: see Eq.(1))

3. Analysis of Criticality

Analysis of criticality (k-effective) was performed using the continuous energy Monte Carlo code MVP [4] together with JENDL-3.2, JENDL-3.3, ENDF/B-VI.8 and JEFF3.0 cross section libraries. 3,300,000 neutrons (10,000 neutrons per cycle, 30 skip + 300 active cycles) have been tracked in a MVP calculation, yielding the statistical error (1σ) of about 0.05% for k-effective.

Figure 4 shows the C/E value of k-effective obtained by using the four libraries. C/E values are overestimated by all data libraries used. JENDL-3.2 shows the most significant overestimation of 1.3% to 1.8%. This overestimation is considerably reduced to 0.6% to 1.0% by the use of JENDL-3.3. However, compared to C/E values of uranium fueled cores of KUCA obtained by JENDL-3.3 [5] as shown in Fig. 5, the C/E values of uranium / thorium fueled cores are considerably larger. Thus it could be concluded that the prediction accuracy of JENDL-3.3 for thorium fueled thermal systems still need to be improved.

Among the four libraries, ENDF/B-VI.8 shows the most moderate C/E values with overestimation of 0.4% to 0.6%. JEFF3.0 shows the largest C/E values among the recent libraries (JENDL-3.3, ENDF/B-VI.8 and JEFF3.0), with overestimation of 0.8% to 1.2%.

The C/E values become generally larger with increasing ^{232}Th/^{235}U ratio for JENDL libraries and JEFF3.0, but this trend could not be seen in ENDF/B-VI.8. This spread among C/E values of cores with different ^{232}Th/^{235}U ratios are less than 0.3%.

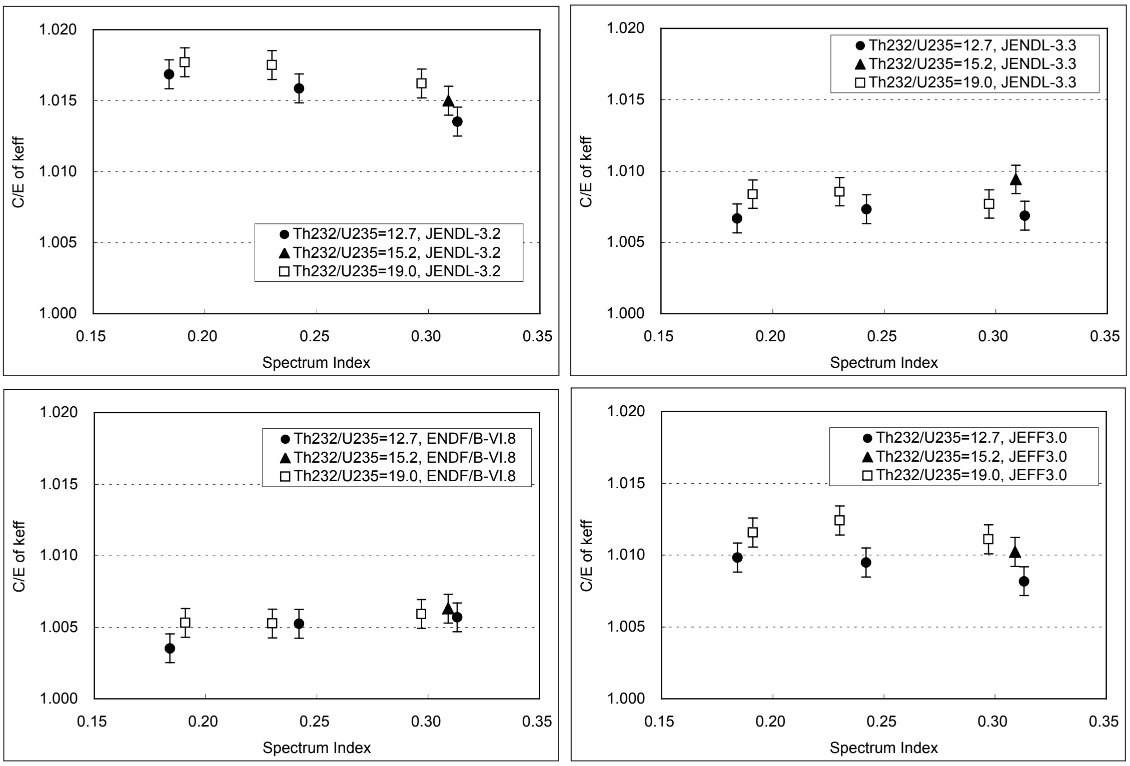


Fig. 4 C/E Values of KUCA Uranium/Thorium Cores by JENDL-3.2, JENDL-3.3, ENDF/B-VI.8 and JEFF3.0

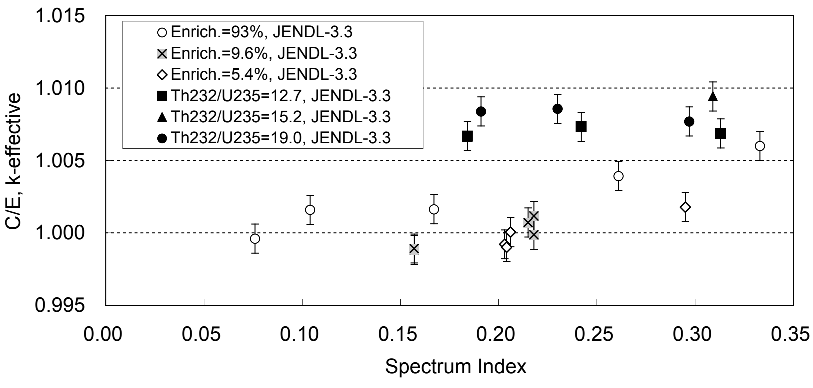


Fig. 5 C/E Values of KUCA Uranium Fueled Cores and Uranium / Thorium Fueled Cores by JENDL-3.3
(Enrich.: averaged U-235 enrichment of uranium fueled cores)

From the criticality analysis of thorium fueled cores, it is apparent that the spread among the results based on different data libraries are still considerably large; this is mostly attributable to difference in the current ^{232}Th cross section evaluations.

Hereafter, we will make use of deterministic fuel cell calculation code to investigate the impact of different ^{232}Th evaluations on cell parameters of KUCA thorium loaded fuel cells.

Infinite cell calculations were performed using SRAC code system for one-dimensional infinite slab fuel cells of the fuel elements. The 107-group SRAC libraries for JENDL-3.3, ENDF/B-VI.8 and JEFF3.0 were used.

Table 2. Comparison of k-infinity of uranium / thorium fueled cells of KUCA

Unit Cell ID	H/^{235}U ratio	^{232}Th/^{235}U ratio	Spectrum Index	k-infinity, JENDL-3.3	k-infinity, ENDF/B-VI.8	k-infinity, JEFF3.0
ETEE4	138	12.7	0.184	1.5077 (-)*	1.5033 (-0.20%)*	1.5120 (0.19%)*
ETEE6	211		0.242	1.5071 (-)	1.5042 (-0.13%)	1.5100 (0.12%)
EU16Th	316		0.313	1.4649 (-)	1.4629 (-0.09%)	1.4664 (0.07%)
EU18Th	316	15.2	0.309	1.4263 (-)	1.4240 (-0.11%)	1.4281 (0.09%)
ETE3	155	19.0	0.191	1.3888 (-)	1.3836 (-0.27%)	1.3942 (0.28%)
ETE4	207		0.230	1.3948 (-)	1.3908 (-0.21%)	1.3990 (0.22%)
ETE6	316		0.297	1.3534 (-)	1.3508 (-0.14%)	1.3560 (0.15%)

* % difference from JENDL-3.3.

Table 2 shows the comparison of k-infinity values obtained using the three libraries and the reactivity differences from JENDL-3.3 results. Similar to the criticality prediction results, ENDF/B-VI.8 gives the smallest k-infinity, and JEFF3.0 gives the largest k-infinity among the three libraries. The spread among the k-infinity values is shown as relative standard deviation (standard deviation / average k-infinity) in Fig. 6. The spread increases with ^{232}Th/^{235}U ratios and also with decreasing spectrum index, which implies that the spread is mostly due to ^{232}Th cross section in the resonance energy range.

Finally, the impact of different ^{232}Th cross section evaluations to k-infinity was evaluated for the most thorium-rich cells, i.e. ETE3, ETE4 and ETE6 cells (^{232}Th/^{235}U ratio=19.0). SRAC calculations were performed by using ^{232}Th cross section from JENDL-3.3, ENDF/B-VI.8 or JEFF3.0, whereas the cross sections for all other nuclides were taken from JENDL-3.3. The differences of k-infinity from JENDL-3.3 results are summarized as reactivity difference in Fig. 7. Comparing with Table 2, it could be seen that the most of the reactivity difference among the nuclear data libraries are due to ^{232}Th cross section. In the most significant case of ETE3 cell (spectrum index = 0.184), the reactivity difference caused by different ^{232}Th cross section evaluation (ENDF/B-VI.8 or JEFF3.0) alone reaches up to 0.6%dk/kk'. These reactivity difference could be attributed to the ^{232}Th capture rate difference between the nuclear data libraries; the differences in the cell-averaged ^{232}Th capture rate from JENDL-3.3 are shown in Fig. 8 for the ETE3 cell. It could be seen that the capture rate difference between JENDL-3.3 and ENDF/B-VI.8 is in the resolved resonance range of 10eV to 10^3eV, whereas the difference between JENDL-3.3 and JEFF3.0 is mainly in the thermal energy range.

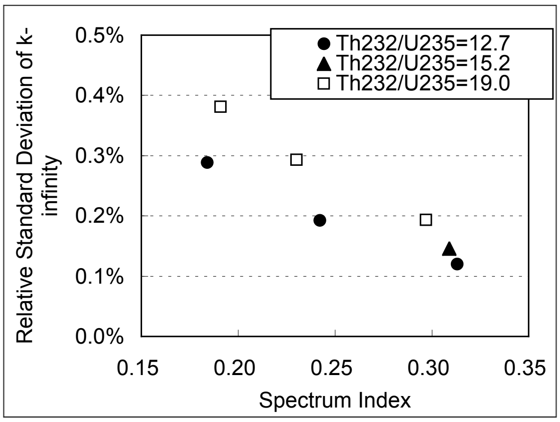


Fig. 6 Relative Standard Deviation of k-infinity obtained by JENDL-3.3, ENDF/B-VI.8 and JEFF3.0

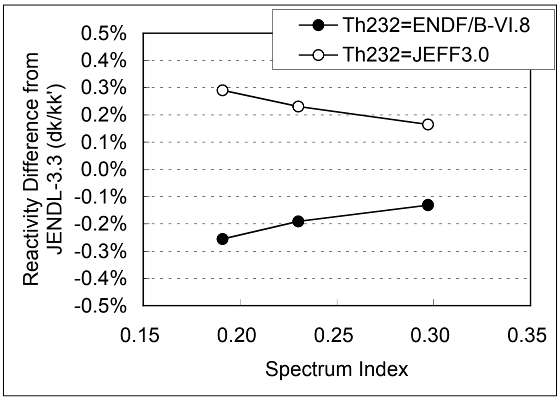


Fig. 7 k-infinity Difference from JENDL-3.3 Results

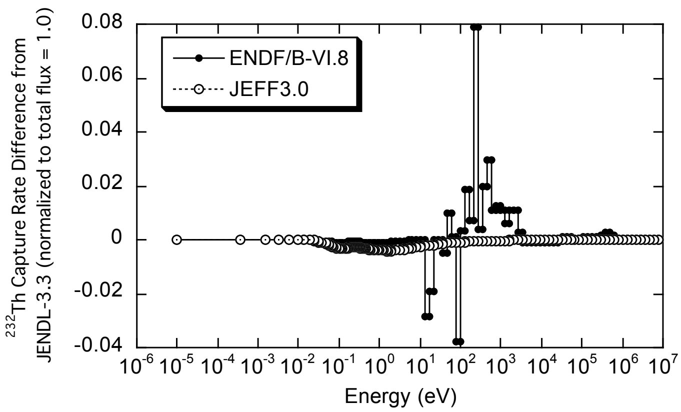


Fig. 8 ^{232}Th Capture Rate Difference from JENDL-3.3 Results for ETE3 Cell

4. Conclusion

The criticality analysis of the present KUCA experiments on uranium/thorium fueled thermal spectrum cores showed that the prediction accuracy of thorium fueled thermal systems have been improved by the use of recent data libraries such as JENDL-3.3 and ENDF/B-VI, but is still inferior to that of the conventional uranium fueled systems. The major cause of this issue is of course due to the ^{232}Th cross section itself; considerable discrepancy between the ^{232}Th evaluations exist and has been shown to have considerable impact on nuclear characteristics of thorium fueled thermal systems. Among the current evaluated nuclear data libraries, ENDF/B-VI.8 showed the best results in terms of criticality prediction, and thus may be recommended for use in the design studies of thorium fueled thermal systems.

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