(From Minutes of SG39 Meeting in Nov. 2013)

C4. Role of integral βeff measurements in the adjustment of delayed neutrons (and availability of related nuclear data covariance).

Action on I. Kodeli, E. Ivanova, M. Ishikawa (for deadline see point C7 below): to look into BERENICE experiments and ANL βeff experiments (accuracy, relevance etc.).

Survey on Integral Beta-effective Measurements

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Since the author was not familiar with the integral beta-effective experiments at all, he studied some related references. This memo is the summary he learned so far.

1. Measurement method

There are lots of techniques to measure the βeff integral values. Typical ones are as follows:

1) Boron substitution technique (Ref.1)

Perez-Belles proposed this idea in 1962. The βeff value is obtained as $\beta_{\mathrm{eff}} = -\frac{1}{\sum_i \delta\rho_i}$ where, $\delta\rho_i$ is the substitution reactivity of fuel and absorber material at the position i in a reactor. This method is intuitionally understandable, but there is a large assumption that the scattering and absorption cross-section of the absorber must be identical with those of fuel material. Further, the substitution reactivity must be measured at the whole reactor region and integrated. Maybe, this method is not realistic for the actual application.

2) Cf-252 neutron source method (Ref.2, 3)

This method was proposed by Carpenter in 1972, and adopted by many experimental researchers. The idea is to utilize the apparent reactivity increase with the insertion of Cf-252 by the equation $\rho_{\mathrm{Cf}} = \frac{S_{\mathrm{Cf}}}{\beta_{\mathrm{eff}}\ \overline{\nu} R_f\ F}\left(\frac{\Phi^+_{\mathrm{Cf}}}{\Phi^+_f}\right)$ where, ρ_{Cf} is apparent reactivity of Cf-252 source. This method needs three physical properties besides the reactivity, that is, the absolute value of the Cf-252 neutron source intensity, S_{Cf}, and the other is the absolute value of fission rate integrated in the whole core, $R_f\ F$, and the core-averaged nu-value, $\overline{\nu}$. Further, the importance effect by the spectrum difference between Cf-252 and fissile material, $\Phi^{+}_{Cf}/\Phi^{+}_{f}$, must be corrected by calculation.

3) Reactor noise method (Ref.4 ~ 11)

There are many variations to apply the reactor noise, which are classified into a) variance-to-mean method (Feynman, 1956), b) Rossi-α method (Orndoff, 1957), and c) Cf-252-driven noise analysis method (Mihalczo, 1972), etc. The basic principles of these noise methods are rather similar with each other. Below is an equation of the variance-to-mean method,

$$\frac{\overline{m^2} - \overline{m}^2}{\overline{m}} = 1 + \epsilon D_\nu \cdot C_F \cdot \left(\frac{1-\beta_{\rm eff}}{\beta_{\rm eff}-\rho}\right)^2 \left[1 - \frac{1-\exp(-\alpha\tau)}{\alpha\tau}\right] + 2\,\epsilon D_\nu \sum_{p=2}^{7} \frac{A_p T(s_p)}{s_p} \times \left[1 - \frac{1-\exp(-s_p\tau)}{s_p\tau}\right]$$

where, m is the number of counts during time τ, ϵ is the detector efficiency, D_ν the dispersion in nu (Diven factor), C_F the spatial correction factor, α prompt decay constant, that is, the absolute reactivity divided by neutron life time, etc.

As a summary, all measurement techniques need the absolute value of either fission rate, neutron source intensity, or detector efficiency, and the integration in the whole core region, and the nuclear data information such as the Diven factor or the neutron life time. In other words, the beta-effective value measured in a reactor seems not to be pure unlike ordinary experimental values such as reaction rate or reactivity, but to be rather an evaluated or combined value with the help of calculation or other supplemental experiments such as distributed-foil irradiation.

2. International beta-effective measurement

In the past, the international benchmark experiments to measure βeff were held twice, at MASURCA (1993) and at FCA (1995~97).

1) Measurement at MASURCA (Ref.12)

The βeff values were measured in two cores with different core compositions. The βeff values in pcm unit measured by JAERI and CEA both of which commonly used the Cf-252 source method are below:

	Mean value		JAERI	CEA	Mean value between JAERI and CEA
	JAERI calculations	CEA calculations			
R2 core	716 ± 20	728 ± 20	697 ± 20	739 ± 22	718 ± 16
ZONA 2 core	348 ± 10	351 ± 10	346 ± 9	356 ± 10	351 ± 7

The measured properties are the absolute fission rate at the core center and the worth of Cf-252. Other parameters needed to obtain βeff, that is, fission integral, fission neutron importance, worth ratio of Cf-252 source and fission neutrons at the core center were calculated. The large differences between JAERI and CEA in uranium-fueled R2 core was considered as the unlucky sum of different effect such as Cf-252 source strength, source reactivity, absolute power calculation and calculated parameters. On the other hand, the agreement of Pu-fueled ZONA2 core was judged to be satisfactory.

2) Measurement at FCA (Ref.13, 14)

The βeff values were measured in three cores, that is, the uranium-fueled core, the MOX core with 23% enrichment, and the 92% fissile Pu-fueled core. Unlike MASURCA, the parameters needed to obtain the βeff values, that is, the relative fission integral, the normalization integral, the Diven factor, the spatial correction factors were given by JAERI, and commonly used by the participants. The measured results of βeff are below:

unit:pcm

Organization	(Meas. Tech.)	XIX-1	XIX-2	XIX-3
CEA	(Noise)	743±19	---	250±6
IPPE	(Rossi-α)	771±25	---	---
IPPE	(Cf)	706±30	351±10	244±7
JAERI - KAERI	(Cf)	735±20	358±10	249±7
JAERI	(Cov. to Mean)	724±13	---	252±5
LANL	(Nelson #)	737±20	---	---
Nagoya	(Bennett)	782±16	368±6	256±4

Although quite large differences appeared among the participants, especially in the uranium-fueled XIX-1 core, there was no interpretation reported. Further, the evaluated uncertainties of the parameters commonly used were reported as below, however, the reason or basis of the uncertainty was unknown:

Parameters for experimental determination of β_{eff} in FCA cores

Core name	XIX-1	XIX-2	XIX-3
F_r (cm^3)	$1.106 \times 10^5 \pm 1.0\%$	$1.567 \times 10^5 \pm 1.0\%$	$1.475 \times 10^5 \pm 1.0\%$
F_t (cm^3)	$6.69 \times 10^4 \pm 1.1\%$	$9.25 \times 10^4 \pm 1.1\%$	$8.72 \times 10^4 \pm 1.4\%$
D_D	$0.803 \pm 2\%$	$0.816 \pm 2\%$	$0.816 \pm 2\%$
D_S	$1.110 \pm 1\%$	$1.126 \pm 1\%$	$1.127 \pm 1\%$
g^*	$1.655 \pm 1\%$	$1.668 \pm 1\%$	$1.671 \pm 1.2\%$
g^*_ν	$1.662 \pm 1\%$	$1.658 \pm 1\%$	$1.661 \pm 1.2\%$
$\bar{\nu}$	$2.466 \pm 0.5\%$	$2.949 \pm 0.5\%$	$2.924 \pm 0.5\%$
$\bar{\nu}_R$	$2.477 \pm 0.5\%$	$2.895 \pm 0.5\%$	$2.924 \pm 0.5\%$

Finally, the uncertainties of the measured βeff including the calculated parameters were evaluated as 2.5% (1 sigma) in MASURCA, and better than 3% in FCA.

3. Adjustment of beta-effective (Ref.15, 16)

In 2002, JAEA and CEA independently made the adjustment study of βeff using the integral βeff experimental data. These materials would be the starting points of SG39 work if we try to adopt the MASURCA and FCA data in the adjustment.

4. Concluding remarks

In the case of ADJ2010 based on JENDL-4.0, the adjusted results, that is, the alteration of β values and the improvement of their uncertainties, of the delayed neutron data are shown below:

Isotope	Alteration by adjustment	Uncertainty (1 sigma)	
		a priori	a posterior
U-235	-0.52 %	±2.7 %	±1.3 %
U-238	+2.89 %	±3.4 %	±2.4 %
Pu-239	+5.38 %	±4.4 %	±2.8 %

Since a priori uncertainty of values are evaluated as ±3~4%, it will be worth adopting the integral βeff experiments in the adjustment, if the uncertainty of the integral experiment can be less than ±3% as reported by MASURCA and FCA benchmarks. Remember that when the value of the neutron-induced-error of an integral parameter, GMG, is almost same with the integral errors, Ve+Vm, the error of the posteriori integral parameter, GM'G, will be reduced to be roughly a half of GMG by the adjustment.

However, the concerns of the author are on the uncertainty evaluation of the integral βeff experiments. As seen in section 1, the measured βeff values are a combination of measured values and calculated values. We have to carefully investigate the basis of the uncertainty uncertainty evaluation of the parameters which were used to obtain the βeff values, especially stemmed from the nuclear data errors and from the analytical-modeling errors. A review report of NEA/WPEC/SG6 also warned that the uncertainty value of ±3% reported by MASURCA and FCA for Cf-252 and Rossi-α methods seems optimistic (Ref.17, p.37).

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