CO3-1 Activation Evaluation of Metals in Nuclear Power Plants

T. Kosako, T. Watanabe, T. Nakashima, M. Atlas, and K. Yano

Graduate School of Engineering, The University of Tokyo

INTRODUCTION: In order to conduct decommissioning safely and reasonably, evaluation of radioactive inventory is necessary information. According to previous studies [1], the accuracy of the activation of concrete included in biological shielding was obtained within an error of 20 or 70 percent. On the other hand, that of the reactor pressure vessel in Fugen in particular ^{60}Co was overestimated within an error of 270 percent [2]. This indicates that the activation estimation of metallic elements can be significantly improved. This study is focused on activation evaluation of metals, considering the difference of neutron flux and elemental composition data.

EXPERIMENTS: Before experiment, we conducted two calculations. The neutron flux was calculated by MCNPX and the degree of activation was calculated by ORIGEN-S. We used two types of neutron flux; Thermal and Fast. Thermal is the original flux in Slant and Fast is the changed flux by using moderator. Slant is curved exposure tube which is next to the core. In activation calculation, we used three elemental composition data; NUREG CR-3474 and chemical analysis date of sample in Fugen and Tokai.

In neutron irradiation experiment, we used three samples: carbon steel in the biological shielding, carbon steel in the reactor pressure vessel, and stainless steel in cover of fuel element samples. They are used in practical commercial reactor. The neutron spectrum in Slant is different from a typical LWR.Then, in order to reproduce the neutron spectrum in a commercial LWR, we used Cd as moderator. After irradiation experiment, sample is measured by Ge semiconductor detector.

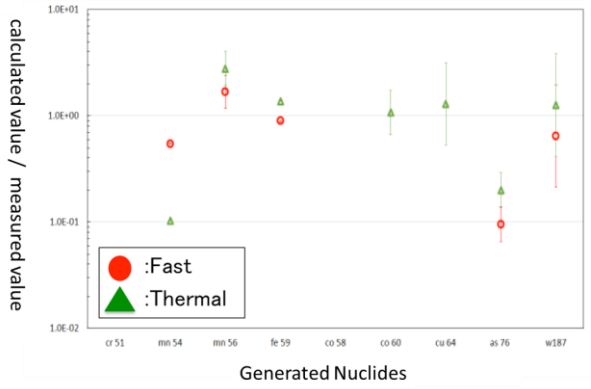


Fig. 1. Carbon steel in the biological shielding

RESULTS: The results of the ratio of calculation to experiment are shown in Fig. 1-3. We used the mean value of the three elemental composition datasets and the standard deviation to give the differences between the three. These results show that there are large differences in ^{56}Mn, ^{60}Co, ^{64}Cu, ^{76}As, ^{187}W, which are formed from the minor elements ^{55}Mn, ^{59}Co, ^{63}Cu, ^{75}As, and ^{186}W, respectively. ^{54}Mn is made from ^{54}Fe which is the main component, however it is underestimated (maximum 1/10). ^{54}Mn is made by (n, p) reactions by fast neutrons, so the underestimation may be affected by the neutron flux distribution. Furthermore, it is possible that the fast flux changed in the calculation in ORIGEN-S, which uses the cross sections optimized for calculating burnup.

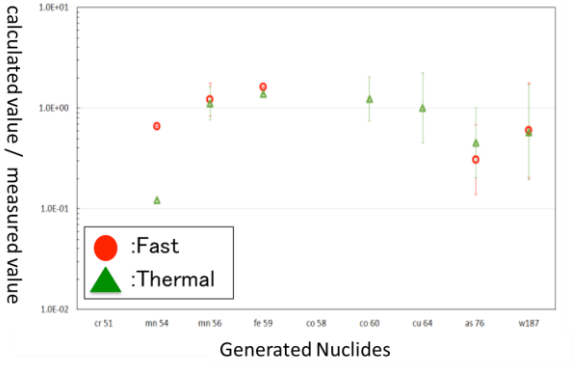


Fig. 2. Carbon steel in the reactor pressure vessel

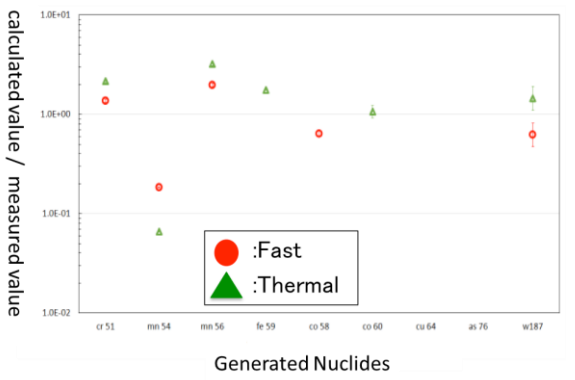


Fig. 3. Stainless steel in cover of fuel element

REFERENCES:

[1] T. Aratani, Improvement of the accuracy on the estimation of induced activity regarding a shielding concrete used in nuclear power plant (2012)

[2] Y. Shiratori *et al.*, Evaluation of activated nuclides for Fugen Nuclear Power Station's decommissioning, NESI (2002)

採択課題番号 25052　　放射性核種生成量評価のための中性子による材料照射の研究　　一般通常

（東大院・工）小佐古敏荘、渡邉貴裕、中嶋丈嘉、アトラス・ミッチェル、矢埜孝三

CO3-2 Development of In-Reactor Observation System Using Cherenkov Light (V)

N. Ohtsuka, T. Takeuchi, K. Yamamoto, A. Shibata, N. Kimura, N. Takemoto, M. Tanimoto, K. Tsuchiya, T. Sano[1], H. Unesaki[1], Y. Fujihara[1], Y. Takahashi[1] and K. Nakajima[1]

Neutron Irradiation and Testing Reactor Center, JAEA
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: The surveillance system which can visualize and quantitatively evaluate reactor statuses will contribute to reactor operation management. We started the development of the on-line reactor core imaging system using Cherenkov light [1] in 2009. In this study, the Cherenkov light was observed by a CCD camera at the core of KUR and the correlation between the image brightness of the Cherenkov light and the reactor power was evaluated.

EXPERIMENTS: The developing visible surveillance system was composed of the CCD camera (AEC-100ZL, Q·I Inc.), an image recorder, and a analyzer to obtain the correlation between the brightness of the Cherenkov light and the reactor power. The CCD camera was inserted into core-observation pipe of KUR during increasing the reactor power from 1 MW to 5 MW. The brightness signal of the output image from the CCD was dissolved to RGB color signals (R:700nm, G:546.1nm, B:435.8nm) [2] to evaluate the change in each color signal with the reactor power. Additionally, the wavelength distribution of spectral irradiance of the Cherenkov light was also obtained by a spectroscope.

RESULTS: Figure 1 shows the brightness values of the RGB signals of the Cherenkov light with the reactor power. While the brightness of the R signal was proportional to the reactor power, the G and B signals tended to saturate above about 2-3 MW. Conversely, the shape of the wavelength distribution of spectral irradiance of the Cherenkov light observed by the spectroscope remained unchanged.

These contradictory results were caused by the halation of the CCD images. Analyzing the brightness value at each pixel, some of the G and B brightness values reached the maximum value of 8-bit binary number, i.e. 255, above about 2-3 MW, and the proportion of the pixels with maximum value increased with the reactor power. Therefore, we corrected the G and B brightness values by the R signals whose brightness value did not saturate even at 5 MW. Figure 2 shows the total brightness value with the reactor power before and after the correction. The total brightness value is in proportion to the reactor power after the correction.

CONCLUSION: As part of the development of the visible on-line core surveillance system, the Cherenkov light at the core of KUR was observed by a CCD camera to obtained the correlation between the image brightness of the Cherenkov light and the reactor power. As a result, the reactor power can be estimated using the CCD camera by the method of dissolving the total image brightness to the RGB brightness components due to suppress the halation of the CCD image.

REFERENCES:

[1] J.V. Jellry, Cherenkov Radiation and its Applications (Pergamon, New York, 1958).
[2] Commission internationale de l'Eclairage proceedings, 1931, Cambridge.

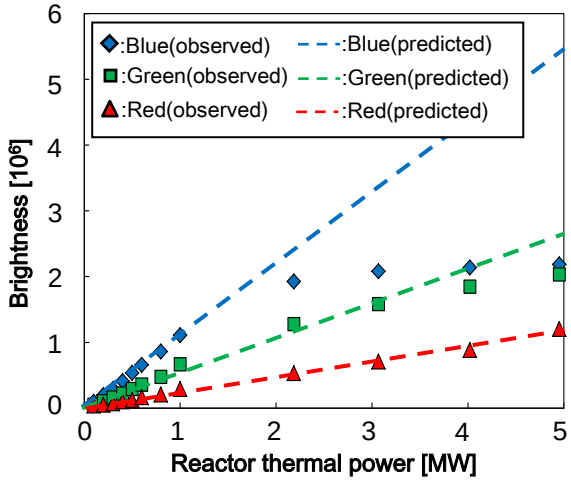


Fig. 1. RGB components of the brightness of the Cherenkov light as a function of the reactor thermal power of KUR.

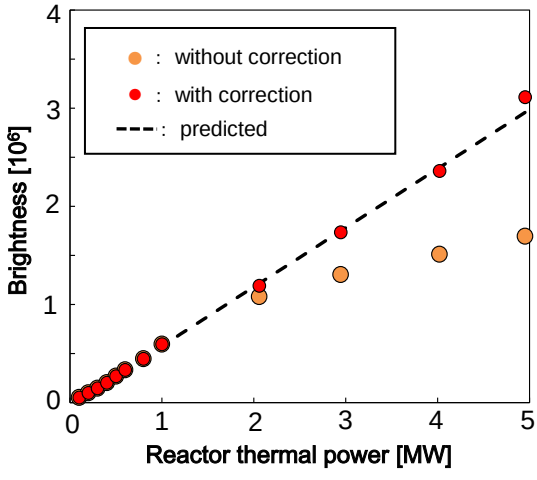


Fig. 2. Effect of the correction on brightness of the Cherenkov light as a function of the reactor thermal power of KUR.

採択課題番号 25073　チェレンコフ光を用いた試験研究炉の炉内監視手法の研究開発　　共同通常
（原子力機構）土谷邦彦、木村伸明、武内伴照、柴田　晃、谷本政隆、那珂道裕、竹本紀之
（京大・原子炉）中島　健、宇根崎博信、佐野忠史、藤原靖幸、高橋佳之

CO3-3 Development of a Novel Neutron Spectrometer Using a Single Bonner Sphere with Onion-like Structure

K. Watanabe, A. Uritani, A. Yamazaki, M. Ushida
T. Yagi[1], C. Pyeon[1] and T. Misawa[1]

Graduate School of Engineering, Nagoya University
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: Bonner Sphere Spectrometers (BSS) have widely been used to measure neutron spectra. The conventional BBS consists of five or six spheres which are thermal neutron detectors with sphere polyethylene moderator spheres. These spheres show different energy response each other. To determine the neutron spectrum, we have to unfold a neutron spectrum from outputs of several Bonner spheres by using response functions of these spheres. Since measurements with several Bonner spheres are required to determine the neutron spectrum, operators must bring these spheres many times to the measurement point, where the radiation dose might be relatively high. A single Bonner sphere that utilizes information of the spatial distribution of thermal neutrons in the sphere was proposed and developed several years ago. Since the conventional single BSSs have several small thermal neutron detection elements, such as TLDs or scintillators, discretely arranged in the sphere or three one-dimensional position sensitive counters perpendicularly arranged, they have considerable directional dependence in the detector response [1-2]. We, therefore, propose a single Bonner sphere spectrometer with onion-like structure, which has multiple spherical shells sensitive to thermal neutrons. The conceptual drawing of the newly proposed system is shown in Fig.1.

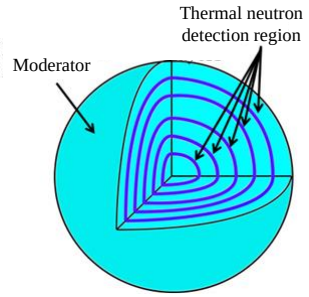


Fig. 1 Conceptual drawing of the proposed single Bonner sphere with onion-like structure.

As thermal neutron sensitive spherical layers, the mixed powder of LiF neutron convertor and ZnS(Ag) scintillator. This neutron sensitive scintillation powder was formed into a thin sheet. The scintillation photons were collected by using a wavelength-shifting fiber.

SENSITIVITY EVALUATION: We designed the detector configuration, such as thickness of layers and amount of LiF neutron converter etc., by using Monte Carlo simulations. We fabricated the prototype detector with three sensitive layers and evaluated the neutron sensitivity. The sensitivity evaluation was performed at the solid moderator core (A core) in the KUCA. Figure 2 shows the experimental setup.

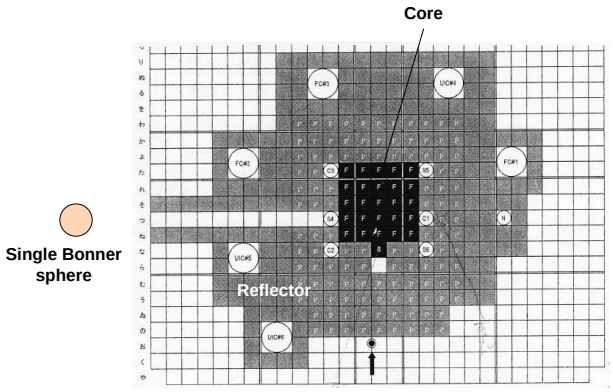


Fig. 2 Experimental setup at KUCA-A core. F: uranium fuel, P: Polyethylene, C#: control rod, S#: Safety rod, FC#: fission chamber, UIC: uncompensated ion chamber

Neutrons from the core were irradiated through a slit of the polyethylene reflector. The neutron flux at the detector position was experimentally determined to be 42 n/cm^2/s. The evaluated sensitivity of each layer is shown in Table 1.

Table 1 Sensitivity of each layer.

	Inner layer	Medium Layer	Outer layer
Count rate (counts/600sec)	1285	1942	2662
Sensitivity (cm^2)	5.2×10^{-2}	7.8×10^{-2}	1.1×10^{-1}

The designed sensitivity to thermal neutrons is 5×10^{-2}, 1×10^{-1} and 2×10^{-1} cm^2 for the inner, medium and outer layers, respectively. The experimentally determined sensitivities were confirmed to be comparative with the expected values using Monte Carlo calculations.

[1] S. Yamaguchi *et al.*, Nucl. Instrum. Methods A, **422**, (1999) 600-605.
[2] H. Toyokawa *et al.*, Nucl. Instrum. Methods A, **381**, (1996) 481-487.

採択課題番号 CA25102 中性子場特性評価を目的とした新型中性子検出器の開発に関する研究 共同通常
（名大・工）渡辺賢一、瓜谷 章、山﨑淳、丸山秀典、川端勇矢、牛田雅人
（京大・原子炉）三澤 毅、卞 哲浩、八木貴宏

CO3-4 Development of Subcriticality Measurement for Accelerator-Driven Reactor (VIII)

K. Hashimoto, W. Sugiyama, S. Hohara, A. Sakon[1], M. Kawasaki[1], R. Okuda[1], C. H. Pyeon[2], T. Sano[2], T. Yagi[2] and T. Misawa[2]

Atomic Energy Research Institute, Kinki University
[1]Interdisciplinary Graduate School of Science and Technology, Kinki University
[2]Research Reactor Institute, Kyoto University

INTRODUCTION: An accelerator-driven subcritical reactor system has been constructed in A-loading facility of the KUCA and a series of cross-power spectral analyses between time-sequence signal data from a neutron detector and a beam current meter have been performed to develop the methodology of on-line subcriticality monitoring for future accelerator-driven system. The results of the unique cross-power spectrum analyses are presented in this report

EXPERIMENTS: These measurements were performed in a reactor system referred to as A1/8"P60EU-EU. A tritium target was placed outside polyethylene reflector and pulsed neutron beam was emitted from the target. As pulse repetition frequency, 20Hz was employed. Not only cross-power spectral density between time-sequence signal data from two BF_3 counters placed in the core, but also the spectral density between the signal data from the neutron counter and a current meter for accelerator beam were analyzed to determine the prompt-neutron decay constant. The experiments were carried out in four subcritical states. The subcritical reactivity was adjusted by changing the axial position of the central fuel loading, as well as the positions of safety and control rods. These experimental patterns are shown in Table 1, where a critical pattern is also included.

Table 1 Subcritical patterns employed

Subcritical Pattern	Axial Position of Control Rods			Central Loading
	C1&C2	C3	S4~S6	
Critical	U.L.	679.09mm	U.L.	U.L.
B	L.L.	L.L.	U.L.	U.L.
C	L.L.	L.L.	L.L.	U.L.
D	U.L.	679.09mm	U.L.	L.L.
E	L.L.	L.L.	L.L.	L.L.

L.L.:Lower Limit, U.L.: Upper Limit

RESULTS: We formulated the cross-power spectral density between accelerator-beam current and neutron detection signals to obtain the following formula for phase of the imaginary spectral density.

$$\angle\Phi(\omega) = -\tan^{-1}(\omega/\alpha), \qquad (1)$$

where angular frequency ω is the integral multiple of pulse repetition frequency. The above equation can be written as

$$\alpha = -\omega/\tan(\angle\Phi(\omega)). \qquad (2)$$

Figure 1 shows the phase of a cross-power spectral density measured in a subcritical system (subcritical pattern D) driven by pulsed neutron source at the integral multiple of pulse repetition frequency of 20Hz. This figure includes the prompt-neutron decay constant α derived from the phase data, based on equation (2). The decay constant non-physically decreases with an increase in frequency and eventually becomes negative in a higher frequency range than 700Hz. This troublesome feature indicates a definitive inapplicability of equations (1) and (2) to the phase analysis. In the present experiment, a response of neutron detector to pulsed neutron generation must be delayed by a transmission time of pulsed neutrons from tritium target from fuel region, a thermalization time in fuel region and another transmission time of thermalized neutrons from fuel region to neutron detector. We use a dead time element (also called wasted time element) to model these delays. If the detector response is delayed for a lag time L (sec), equation (1) is modified as

$$\angle\Phi(\omega) = -\tan^{-1}\left(\frac{\omega}{\alpha_0}\right) + \omega L. \qquad (3)$$

Fitting the above equation to phase data, we can obtain the decay constant of 1768±36[s^{-1}] and the lag of 86±2[μs]. The decay constant is consistent with that done by a pulsed neutron experiment and a power spectral analysis between two neutron detectors [1,2].

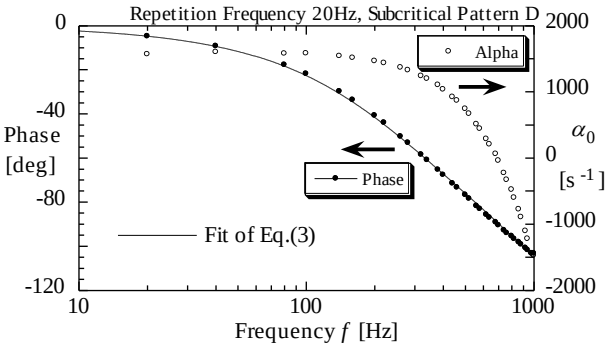


Fig.1 Phase data between beam ammeter and neutron detector B1, and prompt-neutron decay constant derived from the phase data.

REFERENCES:

[1] A. Sakon *et al.*, J. Nucl. Sci. Technol., **50** (2013) 481-492.
[2] A. Sakon *et al.*, J. Nucl. Sci. Technol., **51** (2014) 116-126.

採択課題番号 CA25103　　加速器駆動未臨界炉における未臨界度測定高度化のための　共同通常基礎実験（Ⅷ）

（近大・原研）橋本憲吾、杉山 亘、芳原新也（近大院・理工）左近敦士、河崎将大、奥田遼平
（京大・原子炉）卞 哲浩、佐野忠史、八木貴宏、三澤 毅

CO3-5 Neutron Induced Gamma Ray Spectroscopy for Subcritical Assemblies Containig Stainless Steel

Y. Nauchi, H. Ohta, H. Unesaki[1], T. Sano[1] and Y. Takahashi[1]

Central Research Institute of Electric Power Industry
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: Neutron induced gamma (γ) ray spectroscopy (NIGS) has been studied for estimation of subcriticality margin of once melt fuels mixed with stainless steel. In the previous work, γ rays from capture and fission reactions had been measured with a bismuth germinate (BGO) detector for 3 subcritical cores in which U-Al fuel plates were loaded with SUS-304 plates. The ratio of count rate of 6-10MeV γ rays to 3-5MeV ones was found increasing with the SUS-304 loading ratio [1]. In this work, γ rays were measured for other assemblies of different loading ratios to understand the trend of the count rate. The capture γ ray spectra were also measured with high energy resolution to study the spectra.

EXPERIMENTS: Five light-water-moderated subcritical assemblies listed in Table 1 were mocked up in the C-core of KUCA. An intense ^{252}Cf neutron source (~5x10^{6}n/s) was loaded near the center of the assemblies. γ rays were measured outside the core with a germanium detector of 20% relative efficiency as shown in Fig. 1. The γ rays were also measured with the BGO detector. The thickness of water between the wall of the tank and the outer surface of the assemblies was 46cm [2]. Complementally, capture γ rays were also measured for reference pure substances: chromium, iron and nickel metals.

Table 1. Assemblies mocked up in KUCA-C core.

Assembly	S0	S30	S45	S60	S90
U-Al (Number)	180	150	135	120	90
SUS304 (Number)	0	30	45	60	90
SUS/U mass ratio	0.0	8.6	14.3	21.5	42.9

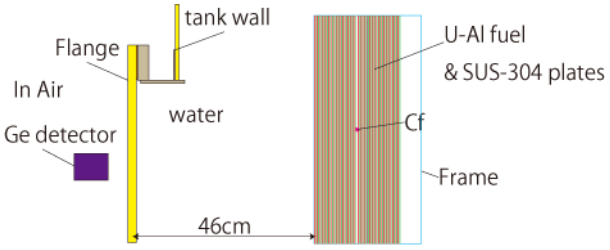


Fig. 1 Geometry of KUCA C-core and detector.

RESULTS: In Fig. 2, the measured pulse height spectra for S0 and S90 are shown. 7631 and 7646keV γ ray spectra (Pair) from ^{56}Fe(n,γ) reactions are prominent in S90 core. The origin of higher energy (>7.8MeV) γ rays are identified as capture reactions of ^{50,52,53}Cr, ^{54}Fe, ^{58,60}Ni by comparison of the spectra to those for the reference samples and the CapGam database [3]. Since γ ray yields per capture reactions of ^{52,53}Cr and ^{54}Fe are not reported in CapGam, correlations of their count rates to those of other well known reactions shall be studied further.

For the spectra measured by the BGO detector, the ratio of the count rates of 3-5MeV γ rays to those of 6-10MeV, RCRs, were estimated. Neutronics calculations were also performed and the ratios of reaction rates of capture to fission, Cap/Fs, were estimated. RCR and Cap/F are compared in Fig. 3. RCR monotonously increases with the SUS-304 loading ratio and the calculated Cap/F. Thus, the RCR is a good indicator of Cap/F. However, RCR does not increase linearly with Cap/F. This is due to overlap of pulse height spectra of capture in 3-5MeV energy region caused by the Compton scattering, etc. The author shall unfold the pulse height spectra to obtain the number of γ rays from fission and capture reactions since that is considered linear to the reaction rate. For the unfolding, the capture reactions identified by the present work shall be taken into account.

REFERENCES:

[1] KURRI Progress Report 2012 CO3-7.
[2] Preprints 2014 Annual Meeting of AESJ, O01.
[3] J. K. Tuli ed. "Thermal Neutron Capture γ's (CapGam)", BNL, 2012.

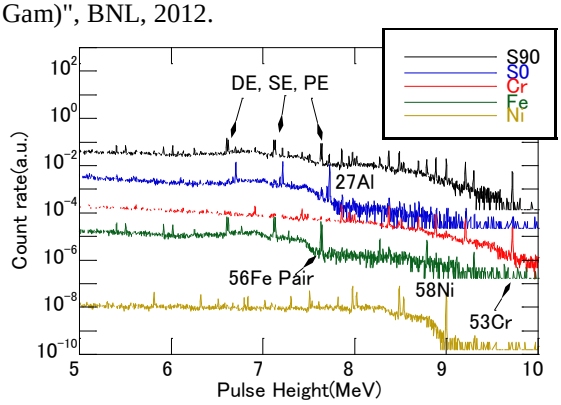


Fig. 2 Measured γ ray pulse height spectra in Ge detector.

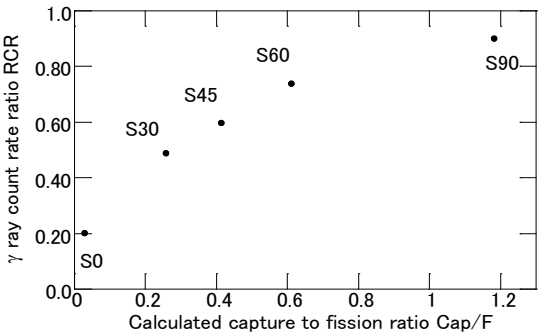


Fig. 3 Count rate ratio of (6-10) /(3-5) MeV γ rays,RCR in relation to the calculated Cap/F.

採択課題番号 CA25104　γ線計測を利用した未臨界度指標の計測に関する研究(3)　共同通常
（電中研）名内泰志、太田宏一、（京大・原子炉）宇根崎博信、佐野忠史、高橋佳之

CO3-6 Basic Experiment for Kinetics Analysis in Sub-Critical Sate

A. Kitano, Y. Kishimoto, T. Misawa[1] and T. Hazama

Japn Atomic Energy Agency
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: The approach to criticality is conventionally performed by the inverse multiplication method. The method uses neutron count rate at a steady state attained in a certain waiting time after a reactivity insertion; thus it requires long time (for example, several hours from the startup in Monju reactor). We have developed a more efficient method based on Critical Index (CI) featuring the time behavior of delayed neutrons.

METHOD: CI is defined by

$$CI = \frac{\lambda_1 C_1}{\lambda_6 C_6} \cdot \frac{\beta_6}{\beta_1} \quad , \qquad (1)$$

where C, λ, and β are the concentration of precursor of delayed neutrons, the decay constant, and the delayed-neutron fraction, respectively. The subscript denotes the precursor group. CI can be evaluated from neutron count rate data by solving a recursion formula.

When a positive reactivity is inserted, CI drops down and then recovers slowly to the initial value of 1.0 as shown in Fig.1. The recovery becomes more slowly as the reactivity is closer to zero, which is clearly shown in Fig.2.The values in the figures show the reactivity in cent (¢) when the corresponding CI value was evaluated. We can estimate the sub-criticality level from the recovery speed of CI. This method can be used consecutively without waiting the stability, which makes the approach to criticality faster than the conventional method.

EXPERIMENTS: The new method was applied to the approach to criticality in a KUCA-A core.

The recovery speed of CI depends on CI value as well, thus the relation of the recovery speed and CI value was simulated in advance with kinetic parameter data of the core as the lines in Fig.3. The experiment proceeded as follows (see Fig.1): At an initial steady state, a control rod was withdrawn. The withdrawal length was determined so that CI value was kept larger than 0.6. Then the CI change rate was evaluated. If the CI change rate was outside the lines of ±5¢, the next withdrawal was made. The procedures were repeated till the CI change rate appeared inside the lines of ±5¢.

RESULTS: Measured values are plotted in Fig.3. The last step was confirmed within ±5¢ in all cases, which demonstrates the new method is successfully applied to the approach to criticality. In addition, the method has a capability to evaluate the reactivity, whose results agreed to the reference values within ±1¢.

CONCLUSION: The applicability of the new criticality approach was confirmed by the experiments. The criticality was judged within ±5¢. The reactivity could be also estimated by this method within ±1¢.

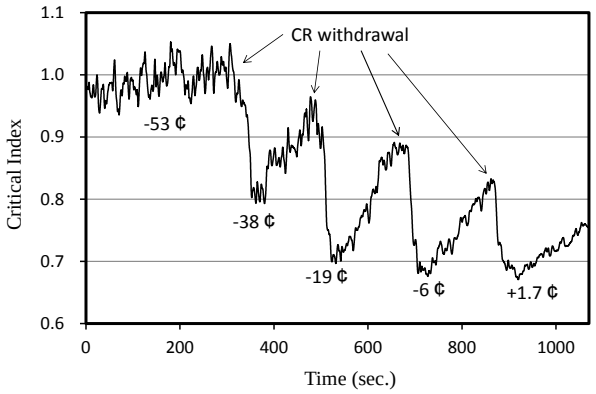


Fig. 1. CI behavior after reactivity insertion

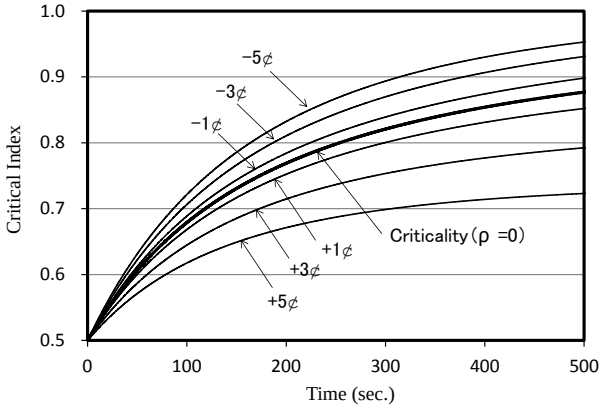


Fig. 2. CI recovery behavior from 0.5 (numerical simulation)

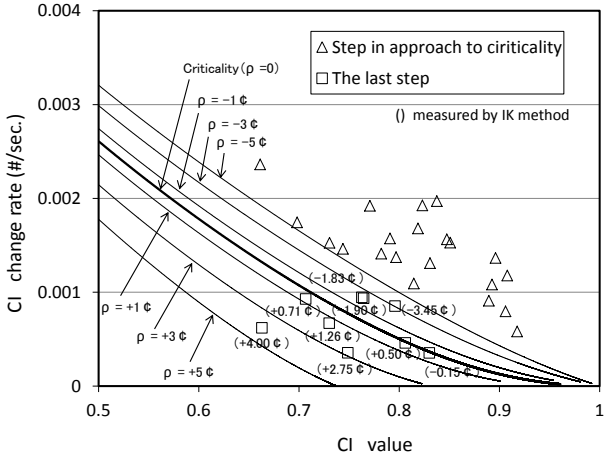


Fig. 3. Relation of CI change rate and CI value

採択課題番号 CA25105　逆動特性分析による未臨界測定に関する基礎実験　共同通常

（原子力機構）北野彰洋、岸本安史、羽様　平
（京大・原子炉）三澤　毅

CO3-7 Basic Experiment on the Variation of Beam on Accelerator-Driven System

N. Aizawa, T. Iwasaki, T. Takani, T. Tani, S. Kanemochi
T. Yagi[1] and C. H. Pyeon[1]

Graduate School of Engineering, Tohoku University
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: Beam transient is the inherent transient on the accelerator-driven system (ADS), and has a possibility to cause the core damage according to the core analyses [1, 2]. This study was started from last fiscal year (2013) to examine the core behavior from the experimental aspect with the use of the Kyoto University Critical Assembly (KUCA). The study in last fiscal year aimed at the establishment of experimental procedure to measure the core characteristics including the neutron flux distribution and the subcriticality in the condition of beam variation.

EXPERIMENTS: The experiment system consisted of the high energy spectrum core of A1/8"P60EU-EU and 14 MeV neutron source generated by deuteron beam and tritium target as shown in Fig. 1. The subcriticalities were examined with the variety of rod insertion patterns in the dynamic experiments, and the reaction rate distributions were also measured at the cases of normal beam injection and horizontal movement of beam incident position in the static experiments. The movement of beam incident position was conducted by the adjustment of magnetic deflection. The subcriticalities were measured with the use of the pulse neutron source method (PNS). The reaction rate distributions were measured for the core with all rod insertion by the application of neutron activation analysis (NAA) of ^{115}In$(n,\gamma)^{116m}$In reactions (see Fig. 1 about In wire position). The measured reaction rates were evaluated with the use of MVP code with JENDL-4.0 library and subcriticalities were deduced from the results of control rod calibration.

RESULTS: In the dynamic experiments, the subcriticalities in three rod insertion pattern (3, 5 and 6 rod insertions) were measured. Measured subcriticalities derived from prompt neutron decay constant were within 0.4% compared with the values deduced from the rod calibration results.
The results of measured reaction rate distributions in the static experiments were compared with ones by MVP. They showed the similar tendencies such as the presence of two large peaks in polyethylene region on the whole, but some discrepancies were seen especially around the peaks. The disagreements were considered the insufficient activation of In wire. Fig. 2 shows the comparison between measured reaction rate distributions with different beam incident position. Both distributions had two large peaks but the difference of two peaks in abeam movement was found larger than that in normal beam state (the values at 10cm had large disaccords with calculations and not being taken into account in this consideration). These results indicated that the variation of neutron distribution was able to be measured with NAA. However, the accuracies of NAA in the experiment were not adequate, and we are setting up an experiment to improve the accuracies in this fiscal year of 2014.

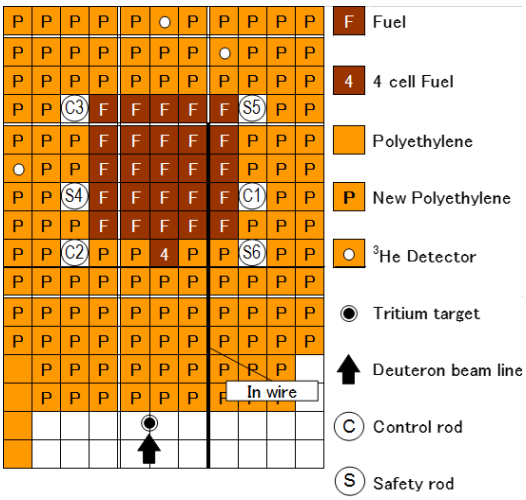


Fig. 1. Top view of A1/8"P60EU-EU core configuration

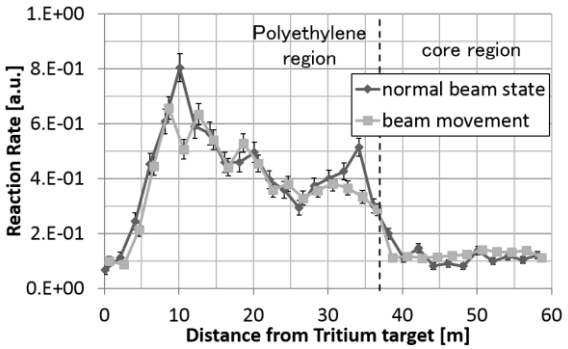


Fig. 2. Comparison between the results with different beam incident position in experiment of In reaction rate distributions

REFERENCES:

[1] N. Aizawa *et al.*, J. Nucl. Sci. Technol., **48** (6) (2011) 892-901.
[2] N. Aizawa *et al.*, J. Nucl. Sci. Technol., **49** (9) (2012) 888-896.

採択課題番号 CA25106　加速器駆動システムにおけるビーム挙動変化に関する基礎研究　共同通常
（東北大院・工）相澤直人、谷　貴志、高荷達郎、金持俊亮（京大・原子炉）八木貴宏、卞　哲浩

CO3-8 Subcriticality Measurement Experiment Using Inherent Neutron Source (2)

T. Endo, T. Buma, T. Shiozawa, C. H. Pyeon[1] and T. Yagi[1]

Graduate School of Engineering, Nagoya University
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: In facilities where nuclear fuel is treated, it is considered to install a real-time subcriticality monitoring system. However, it is often unfavorable or impractical to bring an external neutron source into a nuclear facility to carry out subcriticality measurement. Thus, we focus on the inherent neutron source in nuclear fuel such as spontaneous fission and (α,n) reaction. In this study, the Feynman-α method and the neutron source multiplication (NSM) method are chosen as techniques which can be carried out only with the inherent neutron source, and have affinities with a real-time monitoring system [1]. The purpose of this study is comparison of the measured subcriticality results by the Feynman-α method and the NSM method, only with the inherent neutron source.

METHODOLOGY: In the Feynman-α method, the time series data of detected neutrons $C(T)$ within a counting gate width T is measured. Then, the neutron correlation factor $Y(T)$ is evaluated. $Y(T)$ means a difference of "variance-to-mean ratio of $C(T)$" from unity, thus $Y(T) = 1$ if the frequency distribution of $C(T)$ is subjected to the Poisson distribution. On the basis of the one point reactor kinetic equation, theoretical expressions of $Y(T)$ and subcriticality $(-\rho)$ can be described as follows:

$$Y(T) = Y_\infty\left(1-\frac{1-e^{-\alpha T}}{\alpha T}\right), \quad (1); \qquad \frac{(-\rho)}{\beta_{\text{eff}}} = \left(\frac{\alpha}{\alpha_0}-1\right), \quad (2)$$

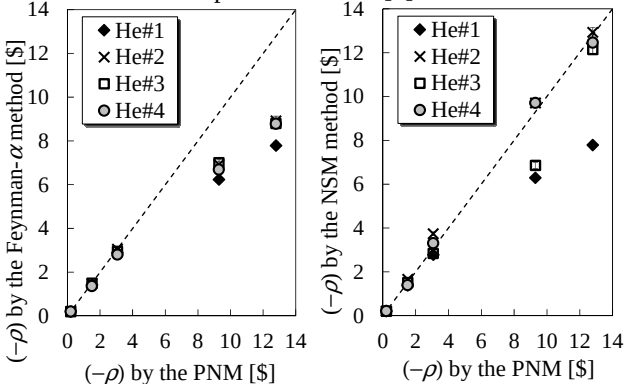
where Y_∞ is the saturation value of $Y(T)$; α and α_0 is the prompt neutron decay constant for target and critical systems, respectively; and β_{eff} is the effective delayed neutron fraction. Note that α_0 can be written as $\alpha_0 = \beta_{\text{eff}}/\Lambda$, where Λ is the neutron generation time. Using the Feynman-α method, α can be obtained by the least square fitting of Eq. (1) to measured $Y(T)$. Finally, subcriticality in dollar unit, $(-\rho)/\beta_{\text{eff}}$, can be obtained by substituting α into Eq. (2), when the value of α_0 is estimated by another measurement or numerical analysis. In the NSM method, $(-\rho)$ can be estimated from measured neutron count rate CR. If $(-\rho)$ at a reference system is known in advance, $(-\rho)$ at a target system is estimated as follows:

$$(-\rho)_{\text{target}} = (-\rho)_{\text{ref}} \times CR_{\text{ref}}/CR_{\text{target}}, \qquad (3)$$

where the subscripts "ref" and "target" mean values at reference and target system, respectively. Note that in the NSM method, the one point reactor approximation is used, and the detector efficiency and neutron source strength are approximated to be the same value for the reference system and target system. Thus, the accuracy of the NSM method becomes low when the approximations mentioned above do not hold.

EXPERIMENTS: The experiments were carried out in A3/8"p36EU-NU(3) core without external neutron source. Five subcritical states were measured: 3 shallow subcritical states were achieved by different patterns of six control rods; other 2 deep subcritical states were achieved by withdrawing fuel and reflector assemblies in shutdown, and by replacing fuel assemblies by reflector assemblies. Four ^{3}He detectors were placed in outer reflector region. In fuel plates used in KUCA, the inherent neutron sources mainly consist of spontaneous fission of ^{238}U and (α,n) reaction of ^{27}Al. Reference values of $(-\rho)$ were evaluated by the pulsed neutron method (PNM).

RESULTS: The results of the Feynman-α method are shown in Fig. 1(a). Note that the values of $Y(T)$ were analyzed with the bunching method [2], and α values obtained by the least square fitting of Eq. (1) to measured $Y(T)$. Then, $(-\rho)$ in dollar unit is estimated by converting α on the basis of Eq. (2). The value of α_0 for each detector was approximately estimated by extrapolation of measured α for 3 shallow subcritical systems into $(-\rho) = 0$. In Fig. 1(b), the results of the NSM method are shown. Note that the value of $(-\rho)_{\text{ref}}$ in Eq. (3) equals to $(-\rho)$ of the shallowest subcritical state. From these two figures, it is clarified that both techniques have advantages and disadvantages. The Feynman-α method has an advantage that the variation of estimated $(-\rho)$ is relatively small among detectors. However, at deep subcritical systems, $(-\rho)$ does not agree with $(-\rho)$ measured by the PNM. The reason is the value of α_0 which assumed constant in Eq. (2) could be changed for subcritical systems. In order to consider this reason in detail, numerical analysis of β_{eff} and Λ is necessary. On the other hand, $(-\rho)$ estimated by the NSM method showed significant detector dependency. Meanwhile, the results obtained by He#2 and He#4 detectors agree well with $(-\rho)$ by the PNM even at deep subcritical systems. This suggests that the results can be improved by the investigation of appropriate detector positions, such as a numerical analysis based on the detected neutron multiplication factor [3].



(a) the Feynman-*α* method (b) the NSM method

Fig. 1 Estimated subcriticality

REFERENCES:

[1] D. G. Cacuci, Handbook of Nuclear Engineering:Vol. 3 Reactor Analysis, Springer, (2010).
[2] T. Misawa *et al.*, Nucl. Sci. Eng., **104** (1991) 53-65.
[3] T. Endo, *et al.*, Ann. Nucl. Energy, **38** (2011)2417-2427.

採択課題番号CA25108　　固有中性子源を利用した未臨界度測定実験（2）　　共同通常

（名大・工）遠藤知弘、武馬孝仁、塩澤武司（京大・原子炉）卞哲浩、八木貴宏