CO3-1 Development of In-reactor Observation System Using Cherenkov Light (Ⅲ)

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INTRODUCTION: In research reactors, a CCD camera is used to observe reactor core for reactor operation management, e.g. to prevent debris falling. In order to measure the reactor power and fuel burnup exactly by means of observation of Cherenkov light [1] and gamma ray information, the development of the on-line measurement device has been started since 2009. In this study, as a part of development of in-reactor surveillance, wavelength and absolute irradiance of Cherenkov light were measured by spectroscopy, and Cherenkov light was observed by the CCD camera. The neutral density filters (ND-filters) [2] were used to investigate the transmittance of Cherenkov light in these measurements.

EXPERIMENTS: The diagrammatical drawing of in-reactor surveillance system is shown in Fig.1. The system is composed of the spectroscopy system and the visible image system. The spectroscopy system (Maya2000, OptoSirius) is able to measure the wavelength of light in the range from 200nm to 1100nm. The visible image system is composed of the CCD camera (AEC-100ZL, Q・I), monitor recorder and controller. The system is used to observe Cherenkov light with changing the aperture. For in-reactor surveillance, the spectroscope detector and the CCD camera were inserted in core observation pipe of KUR. Cherenkov light was measured while the reactor power was increased from 20kW to 1MW steadily, and when the reactor power was at 1MW and 5MW. The ND-filters were installed into the detector and the CCD camera to investigate transparency of Cherenkov light. The change of the ND-filter and the aperture were carried out during the observation of Cherenkov light. Six kinds of ND-filters were used such as, 50.0, 25.0, 12.5, 6.3, 3.1 and 1.6% of nominal values.

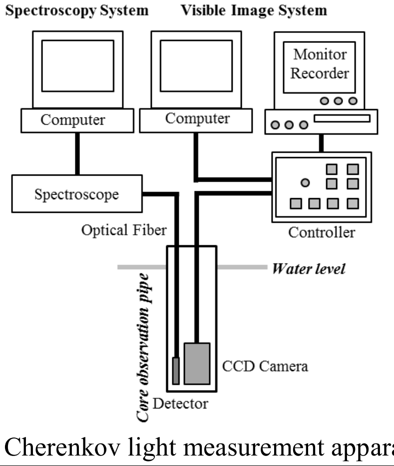

Fig. 1. Cherenkov light measurement apparatus.

RESULTS: The range of the wavelengths of Cherenkov light was from 380 to 700nm, and maximum value of absolute irradiance was recorded at 400nm. Therefore, the wavelength of 400nm of Cherenkov light was focused on, and the effect of ND-filters in absolute irradiance was investigated. The relationship of transmittance between the nominal value and measurement value of ND-filters is shown in Fig. 2. This means the measurement value by the spectroscopy system was well accorded with the nominal value of ND-filters at the reactor power of 0.5, 1, and 5MW. As the result of observation of Cherenkov light by the visible image system, similar transparency tendency was also derived under low reactor power. However, the image was fogged by halation when the reactor power was 1MW and 5MW. Halation could be removed from those images by changing the aperture of the CCD camera.

CONCLUSION: The measurement of Cherenkov light was carried out with the simple in-reactor surveillance system. As a result, correlation between absolute irradiance of Cherenkov light and the nominal value of ND-filters was evaluated by the spectroscope system, and the measurement value was well accorded with the nominal value. As for the observation result by the visible image system, similar transparency tendency to the spectroscopy system was derived. Therefore, it was found that there is a possibility to develop a device to obtain the reactor power and fuel burnup information exactly. From now on, correlation between absolute irradiance of Cherenkov light and gamma ray information will be analyzed in detail.

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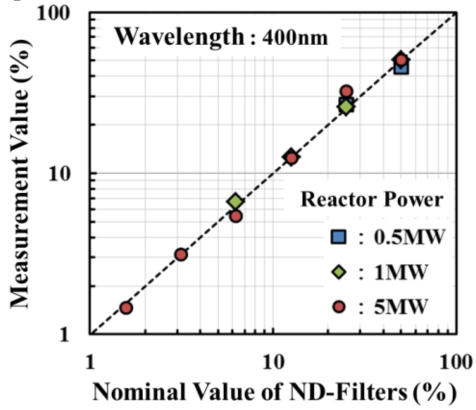

Fig. 2. Relationship of transmittance between the nominal value and the measured value of ND-filters.

採択課題番号 23070　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、谷本政隆、那珂道裕、竹本紀之、木村明博、永田　寛、西方香緒里、木村伸明　（京大・原子炉）中島　健、宇根崎博信、佐野忠史、藤原靖幸、奥村　清

CO3-2 Measurements of Angular Distribution of Epi-thermal Neutrons in Reactors Using the Compact Directional Neutron Detector

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INTRODUCTION: For basic design and performance predictions of nuclear reactors, numerical simulations are quite important. The accuracy of the numerical simulations on the neutron transportation has been quite high and reliable, but basic experiments still play an important role. The validity of the numerical simulations has been confirmed through comparisons with the integral experiments, because it is difficult to experimentally obtain differential information, such as neutron energy and directions. We, therefore, have developed the measurement technique of the neutron angular distribution. So far, we have developed the measurement system of the angular distribution of thermal neutrons. This system can successfully observe the neutron streaming effect between the solid moderators of the Kyoto University Critical Assembly (KUCA). As the next step, we have attempted to measure the angular distribution of epi-thermal neutrons. We have proposed a new directional detector for epi-thermal neutrons. We adopt an activation foil with the neutron resonance absorption in the epi-thermal energy region as the epi-thermal neutron detection element.

DIRECTIONAL EPI-THERMAL NEUTRON DETECTOR: As the activation foil for detection of the epi-thermal neutrons, we adopt a Ag foil. Silver-109 with the isotopic abundance of 48% has a large resonance absorption peak at 5.2 eV. Since the maximum energy of β-rays of radioactive nuclide ^{110}Ag, which is produced by neutron activation from ^{109}Ag, is relatively high (2.89 MeV), the emitted β-rays can be detected using a plastic scintillator easily and effectively. The half life of ^{110}Ag is relatively short (24.6 sec). In order to measure the foil cyclically, the irradiation capsule covered with a Ag foil is transported between inside and outside a reactor with a pneumatic carrier system. Figure 1 shows the schematic drawing of the angular distribution measurement system for the epi-thermal neutrons. We fabricated a prototype detector system without the rotating collimator. The fabricated system was operated at the KUCA (Kyoto University Critical Assembly) to check the fundamental operation of the system. The plastic scintillator for β-ray detection was placed outside the reactor. The activation capsule was transported between inside and outside the reactor by the pneumatic carrier system. As the signal output from the β-ray detector, we counted the number of events with higher signal amplitude than a given discrimination level. The temporal change of the β ray counts obtained by the plastic scintillator is shown in Fig. 2. When the irradiation part was covered by a Cd sheet, the signal intensity dramatically decreased. The foil activation without the Cd cover was confirmed to mainly arise from thermal neutrons. When the irradiation part was surrounded by both the Cd and Ag sheets, the signal intensity additionally decreased. This reduction component corresponds to the activation by epi-thermal neutrons.

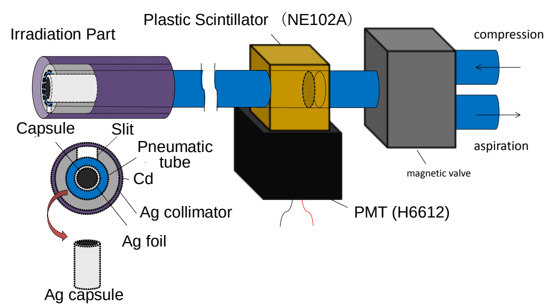

Fig. 1 The schematic drawing of the angular distribution measurement system for the epi-thermal neutrons.

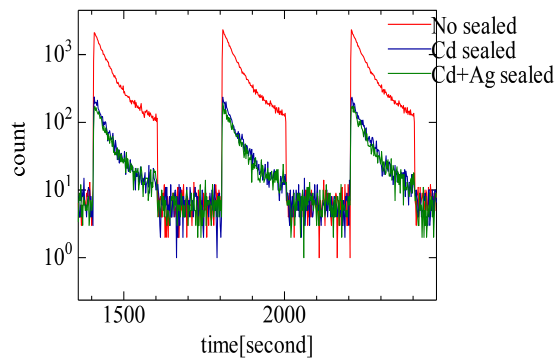

Fig. 2 The temporal change of the β ray counts obtained by the plastic scintillator.

採択課題番号 CA23101 原子炉内の中性子特性評価を目的とした 共同通常
光ファイバ型中性子検出器の開発に関する研究
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CO3-3 **Measurement of Neutron Generation Time by Pulsed Neutron Source**

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INTRODUCTION: The maximum likelihood analysis method for pulse neutron source experiment (PNS-ML) has been developed in experiments using KUCA [1] [2] to monitor sub-criticality of an accelerator-driven system (ADS). In this technique, the most likely sub-criticality can be deduced from a series of counted data from a detector. In the present study, both sub-criticality and neutron generation time are deduced from the same counted data.

REGRESSION METHOD: The next formula is derived from one-point dynamic equation and a periodic boundary condition.

$$n(t) = \hat{S}\left(\frac{1}{\hat{\Lambda}}\frac{1}{1-e^{-\alpha/f}}e^{-\alpha t} + \frac{1}{\hat{\rho}-1}\frac{f}{\hat{\rho}}\right), \qquad \alpha = -\frac{\hat{\rho}-1}{\hat{\Lambda}}$$

Here, $n(t)$ is a time evolution of counting rate from a detector, $\hat{S}$ a variable for normalization, $\hat{\Lambda} = \Lambda/\beta_{\mathrm{eff}}$ a neutron generation time divided by effective delayed neutron, f a pulse repetition frequency of DT neutron source, $\hat{\rho} = \rho/\beta_{\mathrm{eff}}$ a reactivity, and β_{eff} effective a ratio of delayed neutrons.

We fitted this formula to experimental results and obtained the most likely values and errors of $\hat{S}$, $\hat{\Lambda}$ and $\hat{\rho}$ considering statistic error of the counters.

CONVENTIONAL METHOD: There are two analysis methods applicable for the PNS experiments: alpha-fitting method and area method. The alpha value that is a function of $\hat{\rho}$ and $\hat{\Lambda}$ is deduced by the first one, and $\hat{\rho}$ by the second one. Therefore, $\hat{\Lambda}$ is obtained by combining two methods as, $\hat{\Lambda} = \frac{1}{\alpha}\left(1+\frac{N_p}{N_d}\right)$, where N_p and N_d is area of prompt and delayed neutron, respectively.

EXPERIMENTS: A BF_3 counter was set beside the KUCA-A core with a DT neutron source. Three sub-critical cores with different positions of the control and safety rods were employed (Table 1). Period of the DT neutron source was varied from 10 to 100 msec.

Theoretically, the obtained $\hat{\rho}$ and $\hat{\Lambda}$ of each core with different periods should be equal, although the shape of counting ratio is different. The purpose of experiment is to check this equality in the case of conventional method and PNS-ML method.

RESULTS: Figure 1 shows results of sub-criticality deduced by conventional and PNS-ML method from the same experimental data. The three sub-criticalities of each core are equal in the PNS-ML method, while slight dependency on the pulse frequency is observed in the conventional method. This tendency is emphasized in the neutron generation time in Fig. 2. The result of the conventional method is not usable, although the result of the PNS-ML method remains consistency. Another observation is longer neutron generation time for the deeper sub-critical core.

CONCLUSION: The measurement of neutron generation time by pulsed neutron source was demonstrated by using different frequent pulses. The PNS-ML method showed excellent consistency comparing to the conventional method. The comparison of neutron generation time with the calculation is the future work.

REFERENCE:
[1] KURRI Prog. Rep. 2007, CO3-4 (2007).
[2] KURRI Prog. Rep. 2009, CO3-6 (2009).

Table 1 Conditions of the PNS experiment

DT pulse period (msec)	10, 40, 100		
Counters	BF_3		
Core Index	SC1	SC2	SC3
CR position	CR1 full in	CR1 to 3 full in	All CRs& SRs full in
k_{eff} (rod worth)	0.996	0.985	0.959

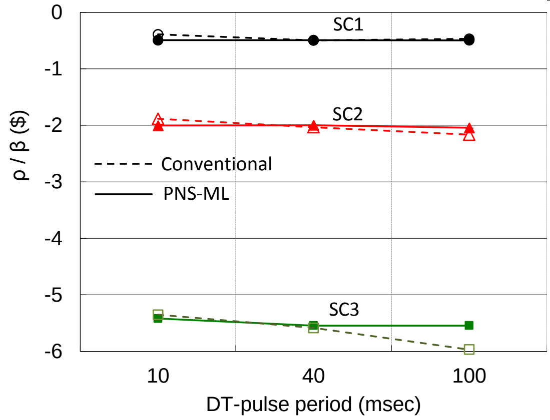

Fig.1. Experimental result (sub-criticality)

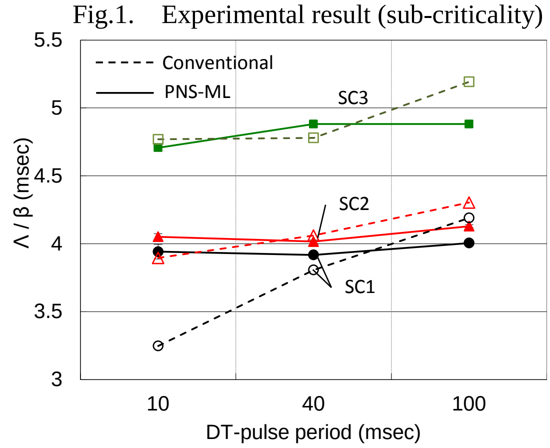

Fig.2. Experimental result (neutron generation time)

採択課題番号 CA23103 パルス中性子源を用いた ADS のための基礎実験 共同通常
（日本原子力研究開発機構）西原健司 菅原隆徳 岩元大樹（京大・原子炉）卞哲浩

CO3-4 Measurements of Thorium-Fueled Core Characteristics and Replacement Worth of Thorium Plates to Aluminum Plates (1)

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INTRODUCTION: Thorium is widely known as a good candidate of Uranium, and is considered as a next generation fuel. However the accuracy of the cross section is quietly lower than that of Uranium because the number of experiments with Thorium is not so many and also validation study is not enough. This low accuracy brings large uncertainty in calculation results of Thorium-fueled core performance such as conversion ratio.

The object of this experiment is to validate the Thorium cross section through the comparison of calculation and measured results for Thorium-fueled core characteristics and replacement worth of Thorium plates to aluminum plates.

EXPERIMENTS: The assembled core is the first core to be critical with unit fuel cell named "7/8PETEETEE" which is shown in Fig. 1.

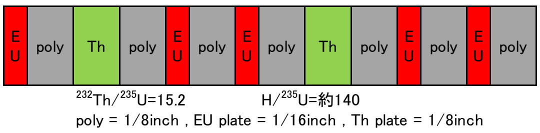

Fig.1. Unit Fuel Cell(7/8"PETEETEE).

In the experiment, critical approach was performed. The number of fuel assembly and control rod arrangements at critical were analyzed before the experiment so as to match the constraints (maximum excess reactivity and control rod worth), and each step from initial core to critical core was also analyzed with the comparison of Uranium-fueled core and the Thorium-fueled core performed with other unit fuel cells. The core arrangements at each step are illustrated in Fig. 2.

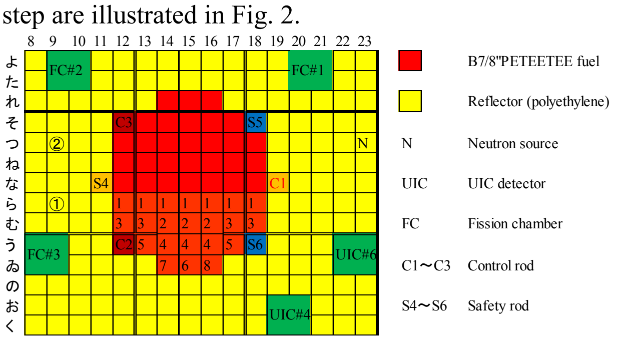

Fig. 2. Core arrangements at each step from initial core to critical core (B7/8"P17ETEETEE).

The number marked in fuel assemblies in Fig.2 shows the fuel assemblies added at each step of critical approach. Initial core was assembled by 29 fuel assemblies, and at next step fuel assemblies marked as "1" in Fig. 2 were added to measure count rate by fission chambers and 3He detector marked as "①" and "②". The number of fuel assemblies was slightly increased, and the critical core was realized at last step:8 with 51 fuel assemblies. The inverse count rate ratio curve obtained through the critical approach is shown in Fig. 3 for the case of all control rods withdrawn(j=3).

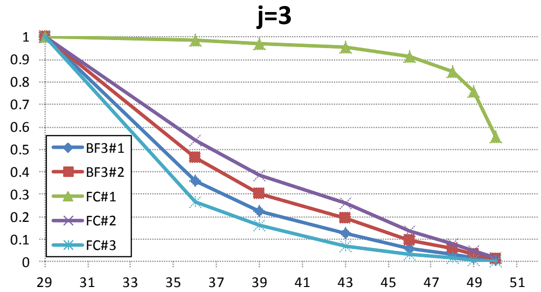

Fig.3. Inverse count rate ratio curve obtained for B7/8"P17ETEETEE core.

The excess reactivity was measured by the period method and the value is about 0.15%dk/k, and the control rod worth for C1, C2 and C3 measured by rod drop method are 0.306, 0.323 and 0.321%dk/k, respectively. These values satisfy their constraints to operate the core.

The core shown in Fig.2 was slightly changed to low excess reactivity state so as to measure the replacement worth. Thorium plates were replaced to aluminum plates to measure the replacement worth by the change in excess reactivity. The position of the replacement was the center fuel assembly named な 15 and the number of the replacement was two or four at around the center in core height. This measurement was done to check the C1 rod position at critical with different replacement situation, because the calibration curve of C1 rod obtained by fitting many experimental results (period method) was confirmed to have enough accuracy to check the excess reactivity. The results are summarized in Table 1, and the results are roughly good agreement in the analysis with continuous energy Monte-Carlo analysis with JENDL4.0.

Table1. Results of excess reactivity at each replacement situation.

core configuration	excess reactivity[Δ k/k]	error
partial+Al4	2.44E-03	1.11E-05
partial+Al2	1.43E-03	3.59E-06
partial	4.35E-04	3.06E-06

RESULTS: Thorium-fueled core which has never assembled at KUCA was assembled. Criticality approach and related measurements were successfully performed. The detailed analysis of the results is in progress.

採択課題番号 CA23104 トリウム燃料炉心の炉心特性およびトリウム置換反応度測定(その 1)共同通常
(阪大院工) 北田孝典、藤井貴志、和田憲拓、Vu Thanh Mai (東海大工)高木直行、渡辺大貴、
山口晃範 (京大・原子炉) 宇根崎博信

CO3-5

Experiments on Subcriticality Measurement Using Neutron Source Multiplication Method Based on Deteced-Neutron Multiplication Factor

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INTRODUCTION: The neutron source multiplication method (NSM) is one of the practical subcriticality measurement techniques, since NSM does not require any special equipment other than a stationary external neutron source and an ordinary neutron detector system. And the correction factors were considered to play important roles in order to accurately estimate subcriticality ($-\rho$) from measured neutron count rates[1]. The aim of the experiments was to clarify how to reduce the impact of correction factors by setting a neutron detector at an appropriate detector position. For this purpose, the detected-neutron multiplication factor k_{det} was utilized[2]. The factor k_{det} is defined by a ratio of total number of detected fission-neutrons to total number of detected all neutrons. By the aid of k_{det}, if effective neutron multiplication factor k_{eff} at a reference state is known beforehand, a value of k_{eff} at target state is estimated as follows:

$$f_{c,\mathrm{target}}\, k_{\mathrm{eff,target}} = 1 - f_s \left(1 - f_{c,\mathrm{ref}}\, k_{\mathrm{eff,ref}}\right) \frac{\langle \Sigma_d \psi_{\mathrm{ref}} \rangle}{\langle \Sigma_d \psi_{\mathrm{target}} \rangle}, \quad (1)$$

where the subscripts “ref” and “target” mean values at reference and target subcritical states, respectively; f_s is a source-flux correction factor to fix the difference of non-fission component of neutron count rate between reference and target states; f_c is conversion factor from k_{det} to k_{eff}, defined by the ratio of k_{det}/k_{eff}. These factors f_s and f_c can be calculated by forward neutron flux calculations only without adjoint calculations. When the neutron detector is set at an appropriate position where k_{det}=k_{eff}, it is expected that correction factor f_c could be negligible. On the basis of this idea, the appropriate detector position can be predicted with the use of numerical analyses of k_{eff} and spatial dependency of neutron count rates.

EXPERIMENTS: The NSM experiments were carried out in A1/8”P60EU-EU(3) core with three types of external neutron sources: Am-Be source in outer reflector region; Cf source in the center of core; DT source. Four He-3 detectors and three fission chambers were put in outer reflector region, and neutron count rates were measured for six subcritical states by changing six control rods. Note that count rates were corrected to eliminate dead-time effect of detector. In order to verify ($-\rho$) measured by NSM, the reference values of ($-\rho$) for six states were evaluated by control rod worth obtained by the rod drop method.

NUMERICAL ANALYSIS: Numerical analyses were conducted with the use of three-dimensional and multi-energy-group S_N neutron transport code THREEDANT [3]. The macroscopic crosssections used in DANTSYS were attained by SRAC2006/PIJ[4] with JENDL-4.0[5]. By the aid of numerical analyses, k_{det} and correction factors, f_s and f_c, can be evaluated for each spatial mesh.

RESULTS: In this paper, the results of Am-Be source were presented. Figure 1 shows one of the numerical results of relative difference between k_{det} and k_{eff} at the axial center of core, for all control rod-in case. In Fig. 1, green colored regions can be regard as the appropriate detector positions of k_{det}=k_{eff}, thus, it is predicted that positions of He3#3 and FC#3 are appropriate detector positions in the NSM experiments. Figure 2 summarizes the experimental results of NSM. As shown in Fig. 2, the measured ($-\rho$) by NSM was confirmed to be improved when f_s and f_c corrections are applied, and ($-\rho$) of He3#3 and FC#3 are relatively well in agreement with reference values even without f_s and f_c corrections because of their appropriate detector positions.

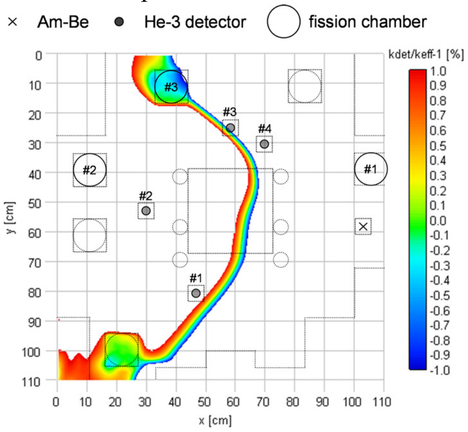
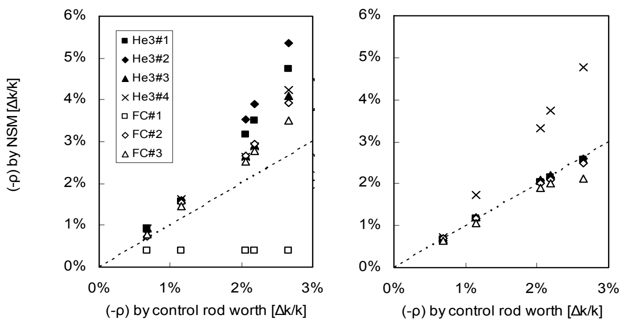


Fig. 1. k_{det}=k_{eff} map for all rod-in, Am-Be case



(a) without f_s and f_c correction (b) with f_s and f_c correction

Fig. 2. Measured subcriticality by NSM for Am-Be case

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採択課題番号 CA23106 出中性子増倍率に基づいた中性子源増倍率法による未臨界度測定実験 共同通常
（名大・工）遠藤知弘、藤田達也、加藤慎也、辻田浩介、中野幸太郎（京大炉）卞哲浩、八木貴宏

CO3-6 Measurement of Gamma Ray Spectrum for Estimation of Subcriticality Index

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INTRODUCTION: The neutron multiplication factor is determined by fission and radiative capture reactions. Some of those reactions emit γ rays of spectrum intrinsic to each reaction. We have conducted development of techniques to quantify the reaction rates by counting the γ rays in order to estimate the multiplication factor of sub-critical systems.

EXPERIMENTS: Subcritcal cores of 2x2 3x2, and 4x2 assemblies driven by a ^{252}Cf source are mocked up in KUCA-C light water tank and γ rays from the cores were measured by a BGO scintillator placed 43cm outside the core (Fig.1). γ rays were measured twice for each core. Each measurement time was 0.5~1h. Count rate of γ rays (3~5MeV) in the second measurement is slightly larger (<1%) than that in the first one for every cores. It indicates accumulation of fission products (FP) even in the low power sub-critical cores. γ rays were also measured for background cases where the ^{252}Cf source was discharged. Comparison of the pulse height spectra is shown in Fig. 2. In the background spectrum, 1.592MeV and 2.521MeV γ rays from ^{140}La are identified and no γ rays were measured in higher energy region (> 3MeV). Background subtracted (net) pulse height spectrum consists of 2.223MeV peak corresponding to H(n,γ) reactions, continuum part (3-6.5MeV) and peak structure in 7~8MeV energy region. Major component of the peak structure is identified Al(n,γ) reaction by additional measurements of γ rays for cases loading either aluminum or SUS 304 plates between the cores and the BGO scintillator.

DATA ANALYSIS: We assumed that the net pulse height spectrum consists of 4 components that are from 1) spontaneous fission of ^{252}Cf, 2) fission of ^{235}U, 3) Al(n,γ), 4) SUS(n,γ). At first, γ ray emission spectra were surveyed. For the 1) and 2) components, an evaluation on prompt γ ray by Verbeke [1] is adopted. In addition, spectra of γ rays from FP accumulated in the ^{252}Cf source and the ^{235}U fuel were calculated with the FPGS90 code [2]. For 3) and 4) components, thermal neutron capture γ ray data [3] were adopted. Pulse height responses of the BGO scintillator for γ rays of the emission spectra are simulated by coupled photon-electron transport calculations with the MCNP-5 code. By the responses and the measured pulse height spectra, γ ray emission and reaction rates are deduced (see plotted lines in Fig.2.). The estimated reaction rates are compared to the neutronics calculations by the MCNP-5 code in Table 1. The reaction rates of Al(n,γ) by the present method agree well with those by the neutoronics calculations. Accordingly quantification of capture reaction rates by γ ray measurements is promising. On the other hand, the present method gives larger fission rates of ^{235}U than those by the neutronics calculations, although ratios of the two fission rates do not vary for the 3 sub-critical cores. The facts indicate that other reactions occur emitting γ rays in energy region 3~6MeV. We shall continue numerical analysis of γ ray yield by coupled neutron-photon transport analysis to establish the quantification method of fission rate.

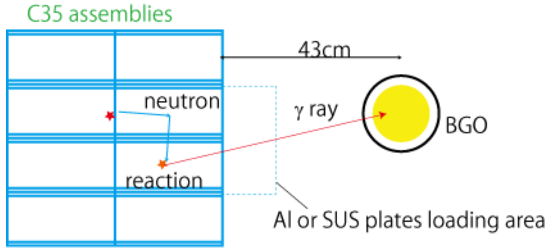

Fig.1 Horizontal geometry of γ ray measurement.

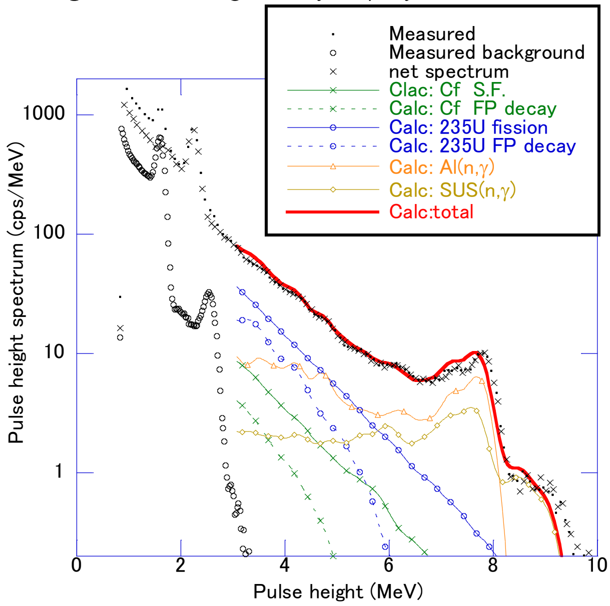

Fig. 2 γ ray pulse height spectra and calculated responses.

Table1. Comparison of reaction rates by γ ray measurements with those by neutronics calculation by MCNP-5

Cores	Al(n,γ) reaction rates		^{235}U fission rates	
	Present	Neutronics Calc.	Present	Neutronics Calc.
2x2	1.48E+05	1.46E+05	1.57E+06	1.05E+06
3x2	2.71E+05	2.72E+05	3.01E+06	1.99E+06
4x2	4.39E+05	4.67E+05	5.39E+06	3.42E+06

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[3] CapGam http://www.nndc.bnl.gov/capgam/

採択課題番号 CA23107 γ線計測を利用した未臨界度指標の計測に関する研究 共同通常
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CO3-7 Reactor Noise Experiments with Time Series Data by High Time Resolution (2)

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INTRODUCTION: Many reactor noise measurements have been conducted and reported so far. Kitamura performed the noise experiments taking advantage of the time series data of pulse train from the neutron detector.[1] In this measurement, the time series data of pulse train was used for the noise analysis of Feynman-α to evaluate the prompt neutron decay constant α_p. The data acquisition system with the time resolution of 2 nsec was constructed with the 8ch 500MHz FADC board driven with FPGA. This FADC board was used for nuclear rare decay experiment to take the waveforms of the radiation detectors originally, developed to save the waveform and timestamp of trigger timing of the B-10 neutron proportional counter as shown in **Fig. 1**.

EXPERIMENTS: This experiment was carried out in the KUCA-A core using the polyethylene moderator.

Three Control rods (C1-C3) and three safety rods(S4-S6) are arranged in this experiment. The noise measurement was conducted for the following conditions, -103.4₵, -38.65₵, -13.4₵ (Case1-3). The time series data obtained as time stamp data by pulse signal from the detectors located around the core was processed to evaluate α_p. The reference values were determined by the control rod worth based on the rod drop experiment and period method.

The delayed criticality was achieved by C1 at the position of 668.53mm from the fully withdrawn position with other control rods withdrawn fully.

RESULTS: As shown in **Fig. 2**, the data acquisition system modified in this study gives the suitable Y value for Feynman-α method. The results of Feynman-α method, shown in **Table 1**, were in good agreement with the reference value within a reasonable range for Case1-4.

CONCLUSION: It was demonstrated that the applicability of the modified data acquisition system with FADC to the measurement of sub-criticality was confirmed by this experiment. This system shows that the discriminated trigger timing is not the rising point of pulse exactly, and the time correction of every signal pulse to determine the real rising time using waveforms will be needed to describe the faster events.

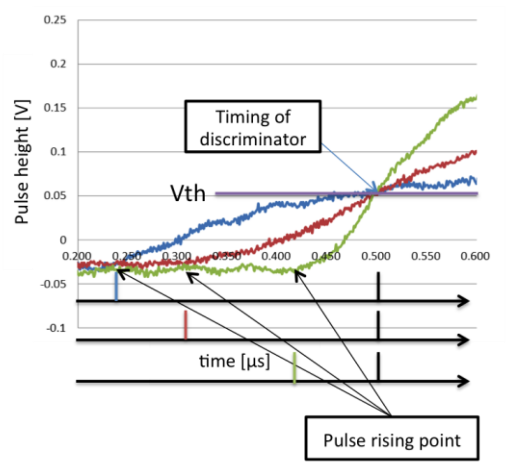

Fig. 1 Relation between pulse height and rising point

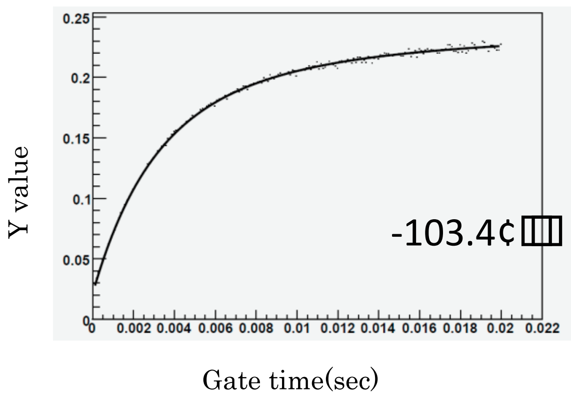

Fig. 2 The results of Feynman-α method in subcritical state by -103.4₵

Table 1 Measured sub-criticality by Feynman-α method

Case	Detector	Sub-criticality (₵) Measurement	Sub-criticality (₵) Reference(a)
1	B-10(b)	−103.4	−90.3
2	B-10(b)	−38.65	−34.3
3	B-10(b)	−13.40	−7.40
4	He-3(c)	−38.65	−41.2

(a) Evaluated by the control position and ctirical point
(b) B-10 lined poroportional counter
(c) He-3 proportional counter

RFERENCE:
[1] Y. Kitamura, et al.,"Reactor Noise Experiments by Using Acquisition System for Time Series Data of Pulse Train", *J. Nucl. Sci. Technol.*, 36[8], 653-600(1999).

採択課題番号 CA23109　高時間分解能データ処理を活用した炉雑音測定(2)　共同通常

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