CO3-1 Development of Real-time Subcriticality Monitor Using an Optical Fiber Type Detector

K. Watanabe, T. Endo, A. Uritani, A. Yamazaki, and C. H. Pyeon[1]

Graduate School of Engineering, Nagoya University
[1] Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: The accelerator-driven system (ADS) has been developed for transmuting minor actinides and long-lived fission products [1-2]. For the ADS system, development of a real-time subcriticality monitor is desired to be developed in order to ensure to keep subcritical condition in any case. Therefore, we are developing a real-time subcriticality monitoring system. For the ADS experiments in Kyoto University Critical Assembly (KUCA), optical fiber neutron detectors were developed. To realize high sensitivity of the detector, neutron scintillator is coated around the wavelength-shifting fiber, which can collect photons from the side surface of the optical fiber. The detector with a long coated region has high sensitivity. In the last year experiments, we used a LiF/Eu:CaF_2 eutectics scintillator, because this scintillator material is transparent and can be thick to improve the sensitivity without attenuation loss of the scintillation photons. However, since this scintillator has relatively low α/β, which is the ratio of light yield for alpha (high LET) and beta (low LET) particles. Therefore, this detector has relatively high beta-ray sensitivity. This detector is influenced from the beta particles, which are emitted from the activated material, such as aluminum sheath of fuel elements, especially under low neutron intensity situation.

In this study, we attempted to fabricate the optical fiber detector with low beta sensitivity but high neutron sensitivity.

EXPERIMENTS: We fabricated the optical fiber neutron detector using LiF/ZnS scintillator. This scintillator material has been used for the optical fiber neutron detector conventionally. In this study, the detector with quite long sensitive region was realized. Figure 1 shows the fabrication processes of the detector. This detector has a sensitive region of 100 mm long. In addition, since the sensitive region was covered by a stainless steel tube with 3 mm outer diameter, this can easily be inserted into a space between fuel elements. We compared the beta sensitivity of the detectors using LiF/Eu:CaF_2 and LiF/ZnS scintillators in the KUCA experiments.

RESULTS: Figure 2 shows the time trends of the measured count rate by the fabricated detectors. We can see that the both detectors have the almost same neutron sensitivity. However, the detector using LiF/ZnS scintillator showed lower count rates when the reactor was shutdown. On the other hand, the detector using LiF/Eu:CaF_2 scintillator showed the decay component after reactor shutdown.

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[1] Pyeon CH, Lim JY, Takemoto Y et al, *Ann. Nucl. Energy,* **38** (2011) 2298–2302.

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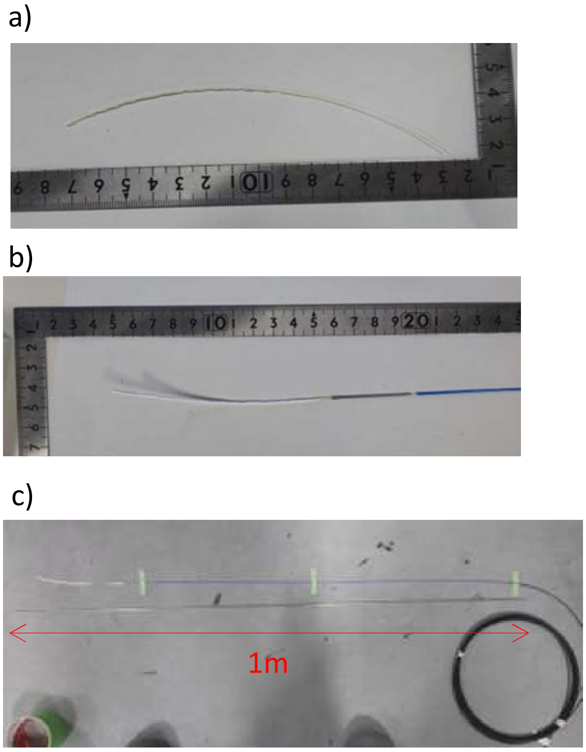

Fig. 1 Photographs of the fabricated optical fiber neutron detector. a) LiF/ZnS scintillator powder coated around a wavelength-shifting fiber. The length of coated region was about 100 mm. b) The scintillator coated region was wrapped by Teflon tape reflector. c) Just before inserting the optical fiber into a stainless tube (for ambient light shielding and support structure) with 1 m long.

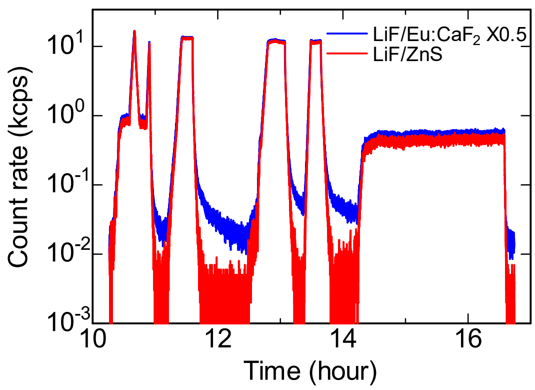

Fig. 2 Time trends of the count rates of the optical fiber detectors using the LiF/ZnS and LiF/Eu:CaF_2 scintillators. The count rates was normalized at the maximum count rate.

CO3-2 Void reactivity measurements of lead and bismuth in the KUCA-A core

R. Katano[1], A. Oizumi[1], M. Fukushima[1] and C. H. Pyeon[2]

[1]*Nuclear Science and Engineering Center, Japan Atomic Energy Agency*
[2]*Institute for integrated Radiation and Nuclear Science, Kyoto University*

INTRODUCTION: The Japan Atomic Energy Agency (JAEA) has investigated neutronics of the accelerator-driven system (ADS) of a lead bismuth eutectic (LBE) cooled-tank-type core to transmute minor actinides discharged from nuclear power plants. For the design study of ADS, integral experimental data of nuclear characteristics of LBE is necessary to validate cross sections of lead (Pb) and bismuth (Bi). Previously, Pb and Bi void reactivity using aluminum (Al) void spacer was measured in a low-enriched uranium (LEU) modeling core [1]. In present study, experiments of Pb and Bi void reactivity using Al void spacer were conducted in a highly-enriched uranium (HEU) core.

EXPERIMENTS: The reference configuration had five test rods as shown in **Figure 1**. **Figure 2** shows each test unit composed of two HEU plates (1/16 inch×2) and two Al plates (1/16 inch×2). The test units were axially and radially surrounded by normal fuel units composed of two HEU plates and a polyethylene plate.

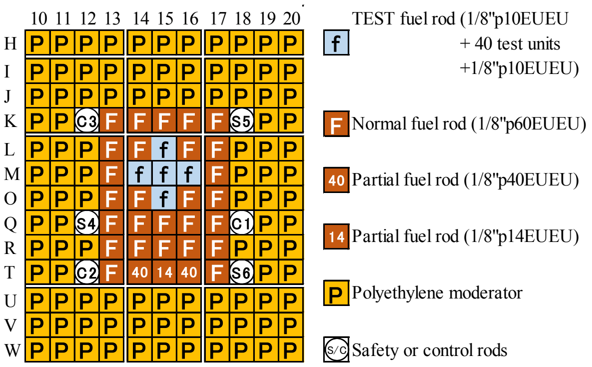

Figure 1. Reference core configuration

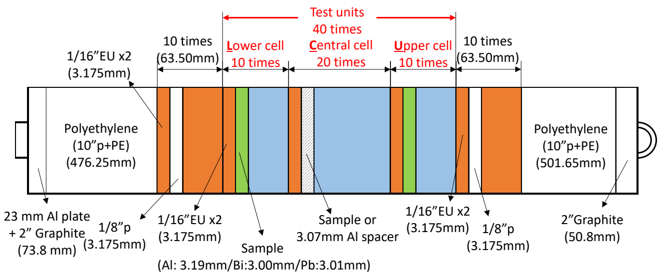

Figure 2. Schematic drawing of test fuel rod

In the previous experiments for sample reactivity worth [2], solid Al plates were substituted for Pb (or Bi) ones, so Al cross sections should be considered as well as Pb one (or Bi) when verifying them. Instead, we used Al void spacers with a low density that was about 1/10 that of solid Al plates to mitigate the Al contribution to reactivity. For the Pb sample reactivity worth, Pb plates instead of Al ones (See Figure 2) were installed in five test rods beforehand, and after then the Pb plates in the central 20 units were substituted for Al void spacers. The Pb sample reactivity worth was estimated as difference between excess reactivities before and after the substitution. Other substitution patterns were summarized together with experimental results in **Table 1**.

Table 1 Experimental results

Case	Pattern (U/C/L)*1	Excess reactivity (pcm)	Sample Case	Sample worth (pcm)
A	Pb/**Pb**/Pb	241.9 ± 2.4	-	-
B	Pb/**V***2/Pb	37.3 ± 3.3	Pb sample (A - B)	204.7 ± 5.7
C	Pb/**Al**/Pb	158.2 ± 0.6	Al sample (C - B)	121.0 ± 3.9
D	Bi/**Bi**/Bi	163.0 ± 0.2	-	-
E	Bi/**V***2/Bi	0.0 ± 0.0	Bi sample (D - E)	163.0 ± 0.2
F	Bi/**Al**/Bi	120.3 ± 7.8	Al sample (F - E)	120.3 ± 7.8

*1(Upper 10 units / **Central 20 units** / Lower 10 units) of test regions.
*2 **V** indicates Al voided spacer. *3 **Al** indicates solid Al plate.

RESULTS: Numerical analyses were preliminary conducted with MCNP6.2 together with JENDL-4.0 (J40) and ENDF/B-VII.1 (B71). The sample reactivity worth was estimated as the difference between the effective multiplication factors of the sample-loaded and reference configurations, without considering the criticality bias. **Figure 3** shows that MCNP6.2 calculations tend to overestimate sample reactivity worth comparing with experiments. Uncertainty quantification of sample reactivity worth derived from cross sections could be a future task.

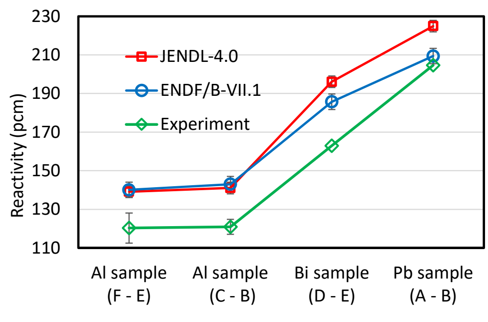

Figure 3. Results of sample reactivity worth

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R2CA02

Measurement of Reaction Rates of Intermediate Neutrons on Critical Core with Various Neutron Spectra Zone

N. Aizawa, H. Akatsu, T. Abe, K. Kawabata[1] and C. H. Pyeon[2]

Graduate School of Engineering, Tohoku University
[1] School of Engineering, Tohoku University
[2]Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: The generation of various neutron energy spectra in a reactor core has a potential to apply to the effective transmutation of the radiotoxic nuclides and production of useful radioisotopes. The neutron energy spectrum of reactor core depends on in-core structure and materials. The intermediate neutron energy from several eV to hundreds of keV corresponds to the resonance region of a cross section, and is considered effective for the transmutation and production of nuclides. In the previous study, the measurement of neutron reaction rates has been carried out with using some activation foils sensitive to the intermediate neutron energy ranges for the core composed of polyethylene (PE) moderated highly-enriched uranium fuel and the low-enriched uranium mockup fuel in the critical and the subcritical conditions combined with spallation neutron source, and the knowledge of the measurement of reaction rates of intermediate neutrons has been obtained [1]. The present study performed the measurements of reaction rates for intermediate neutrons in the relatively soft and hard spectrum zone of the critical core to investigate the effect of neutron spectrum on the reaction rate characteristics.

EXPERIMENTS: Figure 1 shows the core configuration in the experiment. The core was constructed in in KUCA A-core with PE-moderated highly-enriched uranium fuel (PE-fuel: brown in Fig. 1) and the Pb-zoned highly-enriched uranium fuel (Pb-fuel: green in Fig.1). The activation foils employed in this study were Ta, W, Cu , In and Au, and set at either (L-M,15) of the Pb-fuel zone or (Q-R,15) of the PE-fuel zone. The Au foils were also set at (Q-R,15) in both irradiation conditions to employ as the normalization factor of reaction rates. The foils were set with and without Cd cover to examine the effect of thermal neutrons.

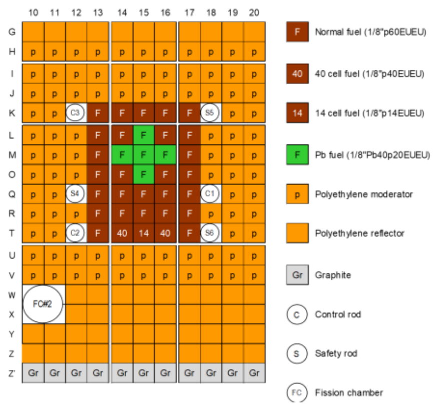

Fig. 1 Core configuration of KUCA A-core

The experimental results of the reaction rates were compared with the numerical calculation results derived by MVP3 [2] for the verification.

RESULTS: The comparison of experimental results with the calculation ones showed that the calculation of the Cd ratios of the reaction rates with/without Cd cover, which is the one of spectrum index, were coincident to the experiment within 1σ range, and the ratios of calculated reaction rate to experiment one (C/E) were almost the same in the case with/without Cd cover in the same zone, and the measured reaction rates was confirmed valid.

Figure 2 shows the experimental results of capture reaction rates of Ta, W, Cu, and In in the PE- and Pb-zone without Cd cover normalized by the Au(n,γ) at (Q-R,15). Some measurement data of In were not included below due to the insufficient accuracy. The Au(n,γ) reaction rate in the Pb-zone was 42.4 % of that in the PE-zone, and Ta, W and Cu capture reaction rates in Pb-zone were 51.6 %, 38.5 % and 34.1 %. These results indicated that the reaction rates of W and Cu were more sensitive to thermal neutrons than Au whereas the influence of harder neutron spectrum became strong in Ta reaction rate.

Table 1 shows the Cd ratios of Ta, W and Cu in PE- and Pb-zones derived from the measurement data. These results meant that the utilization of Cd cover was very effective especially for Cu and W to separate the influence of thermal neutrons and measure the influence of intermediate neutrons.

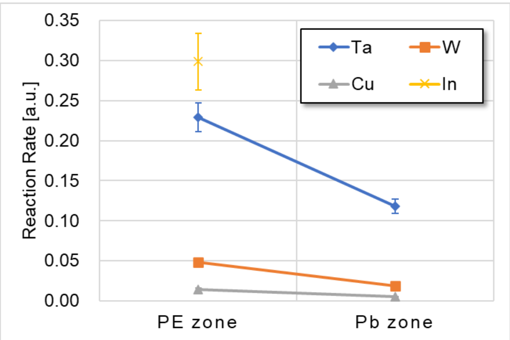

Fig. 2 Reaction rates of activation foils without Cd cover normalized by Au(n,γ) reaction rate

Table 1 Cd ratios of Ta W and Cu in two zones

nuclide	PE-zone	Pb-zone
^{181}Ta	1.17 ± 0.09	1.04 ± 0.08
^{186}W	1.55 ± 0.12	1.08 ± 0.08
^{63}Cu	2.15 ± 0.16	1.28 ± 0.09

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[1] N. Aizawa *et al.*, KURNS Progress Report 2019, PR2-2, (2019).
[2] Y. Nagaya *et al.*, JAEA-Data/Code 2016-018 (2017).

CO3-4 Measurements of ^{237}Np and ^{243}Am Fission Reaction Rates in Lead Region at A-core of KUCA

A. Oizumi[1], R. Katano[1], R. Kojima[1], M. Fukushima[1], K. Tsujimoto[1], and C. H. Pyeon[2]

[1]Nuclear Science and Engineering Center, Japan Atomic Energy Agency
[2]Institute for integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: To transmute minor actinides (MAs) partitioned from the high-level wastes, the Japan Atomic Energy Agency has investigated neutronics of the accelerator-driven system (ADS) of a lead (Pb) bismuth eutectic cooled-tank-type core. In the nuclear transmutation system such as ADS, the nuclear data validation of MA is required to reduce the uncertainty caused by the nuclear data of MA. To validate the nuclear data, many independent experimental data need to be mutually compared. An expansion of integral experimental data is the important issue since there is a limited number of experimental data of MA. Previously, experiments of measuring fission rate ratio of neptunium-237 (^{237}Np) and americium-241 (^{241}Am) to fission reaction rate of uranium-235 (^{235}U) were carried out in several cores using highly-enriched uranium (HEU) fuel [1, 2]. This study aims to measure the ratios of MA, such as ^{237}Np or the americium-243 (^{243}Am), and ^{235}U fission reaction rates in Pb region at the Kyoto University Critical Assembly (KUCA).

EXPERIMENTS: The irradiation experiments of ^{237}Np, ^{243}Am, and ^{235}U were conducted in the KUCA A-core. Fission reaction rates were measured by using single fission chamber (diameter: 48 mm, height: 120 mm) having a foil such as ^{237}Np (83 μg), ^{243}Am (12 μg), or ^{235}U (10 μg). The simultaneous measurements of MA/^{235}U fission reaction rates were conducted at the void region in the center of the core surrounded by HEU/Pb rods as shown in Fig. 1. The HEU/Pb rod was composed of HEU fuel and Pb plates shown in Fig. 2. The pulsed height distributions from the fission chambers were acquired under the condition at critical state corresponding to reactor powers of 1.5W (^{237}Np/^{235}U) and 3.5W (^{243}Am/^{235}U). The irradiation time was almost 1 hour in both cases.

RESULTS: The distributions of pulsed height of ^{237}Np, ^{243}Am, and ^{235}U fission reactions were observed under the critical condition as shown in Fig. 3. The fission reaction signals need to be separated from noises due to α and γ rays in small pulsed height. For example, the fission reaction events of ^{237}Np and ^{235}U in Fig. 3(a) were determined by integrating the counts at voltages greater than 1.008 and 1.025, respectively. Similarly, the fission reaction counts of ^{243}Am and ^{235}U in Fig. 3(b) were obtained by the integration of signals at voltages greater than 1.078 and 1.038, respectively. Finally, the fission reaction rate ratios of ^{237}Np/^{235}U and ^{243}Am/^{235}U obtained by the total counts, the number of atoms, and a detection efficiency of the fission chamber were 0.048 ± 0.003 and 0.042 ± 0.004, respectively. The measured values will be used for verification of evaluated nuclear data by conducting detailed analyses.

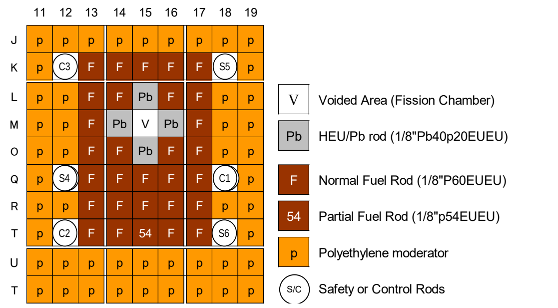


Figure 1. Location of the fission chambers in the A-core of the KUCA.

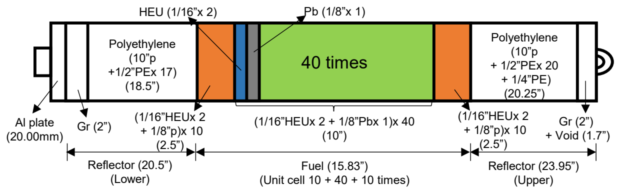
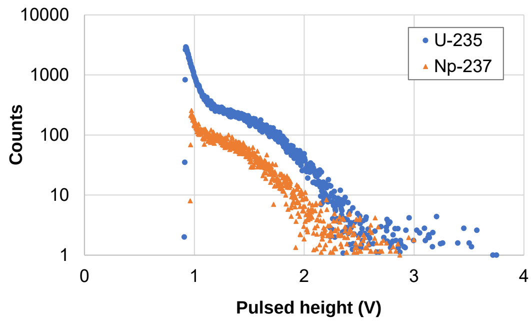
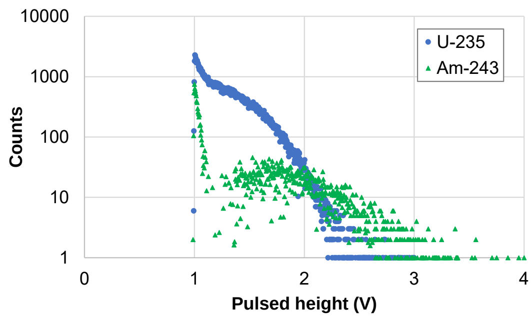


Figure 2. Schematic drawing of HEU/Pb rod in the KUCA-A core showing in Figure 1.



(a) ^{237}Np and ^{235}U



(b) ^{243}Am and ^{235}U

Figure 3. Measured results of fission reaction signals.

REFERENCES:
[1] C. H. Pyeon, et al., Nucl. Sci. Eng., **193**, pp.1023-1032 (2019).
[2] C. H. Pyeon, et al., J. Nucl. Sci. Technol., **56**, 8, pp.684-689, (2019).

CO3-5 Measurement of Very Large Subcriticality by Using Spallation Neutron Source

K. Hashimoto, T. Sano, S. Hohara, A. Sakon, K. Nakajima[1], C. H. Pyeon[2], Y. Takahashi[2]

Atomic Energy Research Institute, Kindai University
[1]Graduate School of Science and Engineering, Kindai University
[2]Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: Feynman-α analysis and pulsed neutron-source experiment have been conducted to determined prompt-neutron decay constant α in subcriticality range from 0 (critical) to around 10 %Δk/k. However no systematic experiment for much more subcritical core has been reported. The objectives of this study are to measure the decay constant of much more subcritical core than 10 %Δk/k and to investigate the validation of the decay constant.

EXPERIMENTS: Two reactor cores were constructed on the A loading of the Kyoto University Critical Assembly (KUCA). One is referred to as EE05 core consisting of thirty 1/16"P80EUEU(EE05) fuel elements shown in Fig.1. Another is referred to as EE1 core consisting of twenty-one 1/8"P60EUEU(EE1) fuel elements shown in Fig.2. The former core has a much harder neutron energy spectrum than the latter. The subcriticality of the EE05 core ranges from 10 to 25 %Δk/k, while that of the EE1 core ranges from 0.1 to 13 %Δk/k/ A series of Feynman-α analyses and pulsed-neutron-source experiments was carried out for several subcritical states of each core to determine prompt-neutron decay constant. The present Feynman-α analysis was done using a neutron source inherent in the highly enriched uranium fuels of KUCA [1]. In the PNS experiment, the pulsed spallation source of KUCA was used [2].

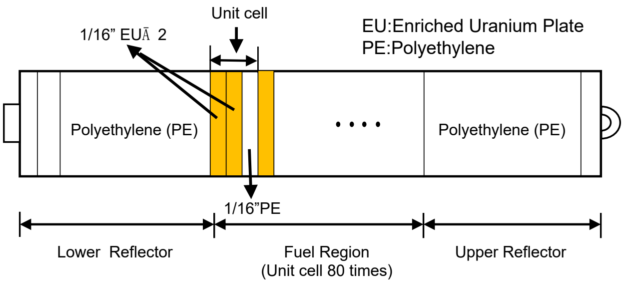


Fig.1. 1/16”P80EUEU (EE05) fuel element.

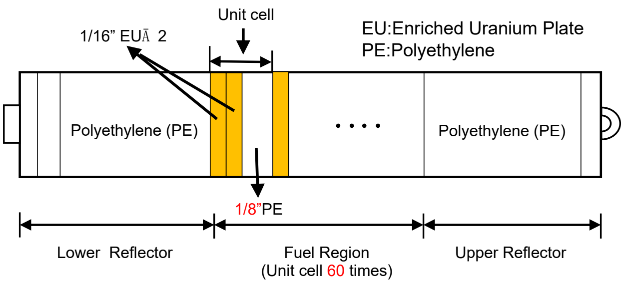


Fig.2. 1/8”P60EUEU (EE1) fuel element.

RESULTS: Figure 3 shows a subcriticality dependence of the prompt-neutron decay constant obtained from Feynman-α analysis, while Fig.4 shows another dependence of the decay constant from pulsed-neutron source (PNS) experiment. Except for a most subcritical state, the decay constants determined from Feynman-α analysis well agree with those from PNS experiment. The difference in the only state is currently under consideration.

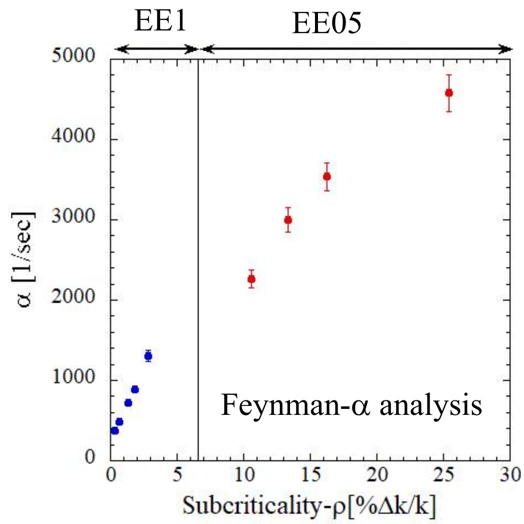


Fig.3. Prompt-neutron decay constant α determined from Feynman-α analysis.

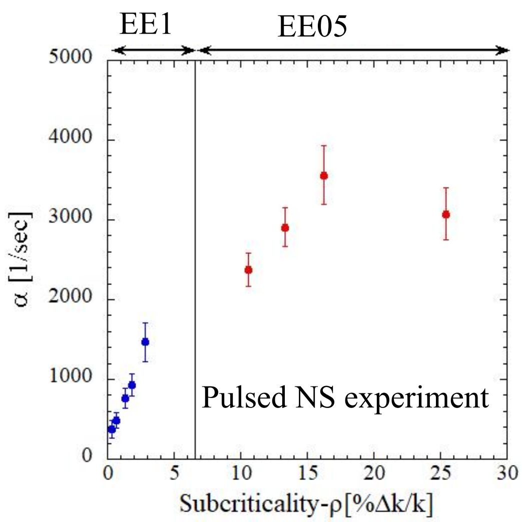


Fig.4. Prompt-neutron decay constant α determined from pulsed neutron source experiment.

REFERENCES:
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[2] C.H. Pyeon *et al.*, J. Nucl. Sci. Technol., **46** (2009) 1091-1093.

CO3-6 Basic Research for Sophistication of High-power Reactor Noise Analysis (III)

S. Hohara[1], T. Sano[1], A. Sakon[1], K. Nakajima[2], K. Hashimoto[1]

[1]*Atomic Energy Research Institute, Kindai University*
[2]*Graduate School of Science and Engineering, Kindai University*

INTRODUCTION:
Reactor noise for high-power reactors were actively measured in the 1960's and 1970's. The major focuses of those researches were for the abnormality diagnosis or the output stabilization diagnosis, and almost researchers were in the field of system control engineering or instrumentation engineering. High-power reactor noise measurements for dynamics' analysis of reactivity change, reactivity feedback or reactor characteristics itself were few in the time (1960's and 1970's), because of the powerless measurement system. In this research, we plan to measure KUR's output with present-day measurement system and plan to analyze with several analysis methods. The results of this work will supply some knowledges and technics in the aspect of sophistication of reactor noise analysis or simulation methods.
In this year, we tried to measure the reactor nuclide noise of the critical state KUR core via a 1-inch ^{3}He counters at CN-1 port. The experimental work was done in 5th November 2020. As the result of the experiment, a result looks like the nuclear reactor noise was observed in 1kW critical state.

EXPERIMENTS:
In this experiment, the output signal of the ^{3}He counters (LND 25291×3) were put into Spectro Scopy AMPs (2022: Canberra and 590A: ORTEC), and the output of the SSAs were measured with a time-series measurement system (HSMCA4106_LC: ANSeeN Inc.). A schematic view of the measurement is shown in Fig.1, and the counter installation overview is shown in Pic.1.

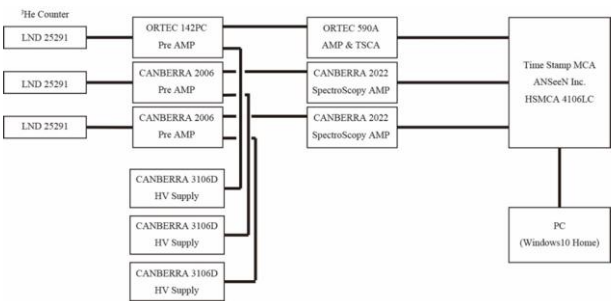
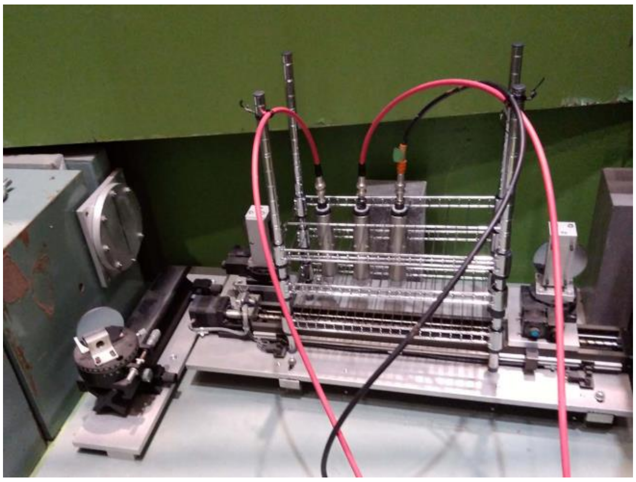


Fig. 1. Schematic view of the measurement.

The experimental condition is shown in Table.1. The reactor Power was set from 20W to 1kW. The measurement time was 800 – 3,600 sec.



Pic. 1. An overview of the counter installation

Table 1. Experimental condition

No.	Reactor Power [W]	Measurement Time [sec]	Count Rate [cps]
1	1k	3,600	0.7 (#1) 1.1 (#2) 1.4 (#3)
2	10k	5,000	7.2 (#1) 10.3 (#2) 14.1 (#3)

RESULTS:
The measurement results were analyzed by Feynman-α / bunching method, Rossi-α method and Covariance to Mean Ratio method.
As a result of the Feynman-α analysis, plot shapes like Feynman's theoretical formula were obtained for 1kW on #1 & #3 counters and for 10kW on #1 & #2 counters. As a result of the Rossi-α analysis, plot shapes like Orndoff's theoretical formula were obtained for both 1kW and 10kW on the combined value of 3 counters. As a result of the Covariance to mean ratio analysis, plot shapes like Feynman's theoretical formula were obtained for 1kW.
The analysis result is shown in Fig.3. From the results, it is determined that the CN-1 port is likely a place where KUR nuclide noise measurement is possible. However, as can be seen from the measurement results, many of the time correlation information is attenuated, so it takes a long time to measure the KUR nuclide noise on the CN-1 port.