33rd International Meeting On Reactor Noise
6th−8th July 2026 | CNRS/LPSC, Grenoble, France

STACY's potential for the Noise Measurements

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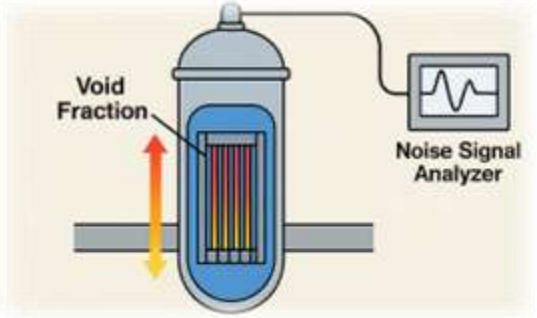
Outline

- ❖“Reactor Noises” in Japan (chronicle)
- ❖Available ZPRs in Japan
- ❖About STACY
- ❖Reactor noise analysis using STACY’s data
  - ➢ Collaborative work JAEA and Nagoya Univ.

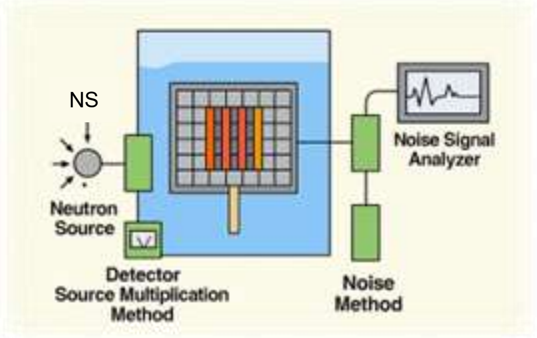
Overview of the modified STACY

Reactor Noise in Japan

- Application to understand BWR core behaviour
  - Evaluation of void fraction variation in BWR systems at JPDR (Japan Power Demonstration Reactor), around 1970.



- Application to measure subcriticality absolutely
  - As a complement to exponential experiments or neutron source multiplication methods.
  - The development and evaluation of these methods were carried out in ZPRs available at the time.
  - Around 2000, Japan was seriously considering developing ADS.
    (mainly at KUCA: Kyoto Univ. Critical Assembly)
  - Before the Fukushima accident, many experimental studies were carried out using ZPR in Japan.



Histories

❖FCA-XIX-1(HEU), XIX-2(Pu+NU), XIX-3(Pu)

➢Rossi-α was used to measure β_{eff}, β_{eff}/Λ

$$\beta_{eff} = \frac{-\rho_S}{N(1-\rho_S)^2-\rho_S} \quad , \qquad N = \left(\frac{2g^*S}{g\bar{\nu}_p\Gamma}\right)\left(\frac{A}{\alpha C}\right) \quad ,$$

Summed the four detectors' signals by cross/auto-correlation mode.

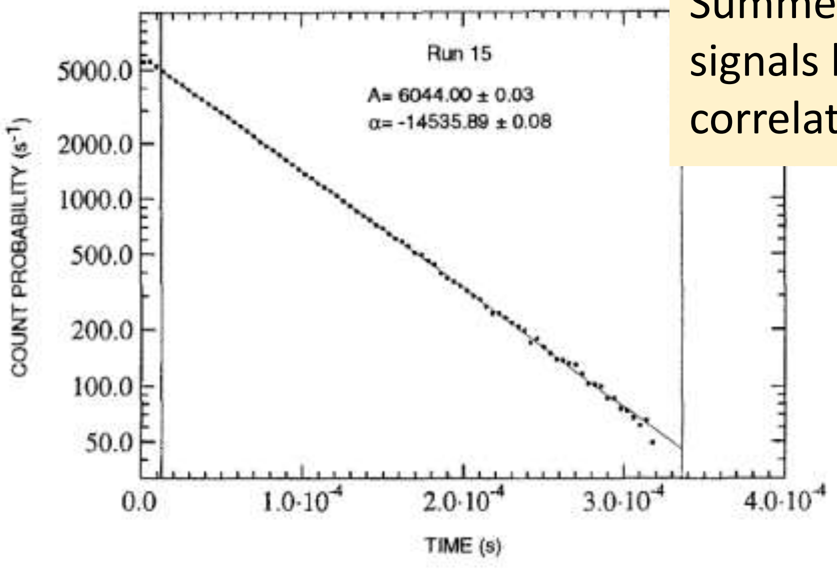
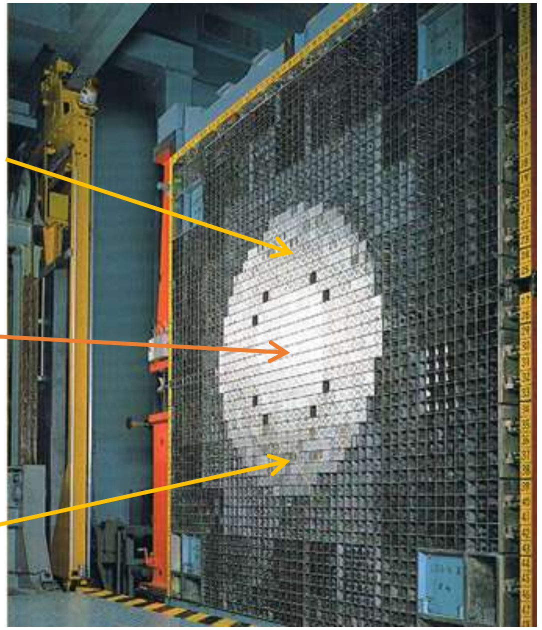


Figure 4. Rossi-alpha data and least-squares fit results.

^{3}He Det. ×2

^{252}Cf NS

^{3}He Det. ×2



https://www.jaea.go.jp/english/04/ntokai/anzen/anzen_05.html

Gregory D. Spriggs, Takeshi Sakurai, and Shigeaki Okajima, Rossi-α and β_{eff} Measurements in a Fast Critical Assembly, *Progress in Nuclear Energy,* **35**(2), pp. 169–181, (1999)

Histories

Taira Hazama, Practical correction of dead time effect in variance-to-mean ratio measurement, *Annals of Nuclear Energy*, **30**, pp. 615–631, (2003)

- DCA (UO_2 / MOX)
  - Feynman-a and Cf-252 source Driven (Mihalczo) Method
  - Subcriticality measurement
    - $0.4 \le k_{eff} \le 0.99$, within 10 min.
  - Adopted difference filters and dead time corrections *1.

$$Y(\Delta T) = D(t_d)\cdot Y_\infty\left(1 - \frac{1-e^{-\alpha\Delta T}}{\alpha\Delta T}\right) - 2\rho\cdot t_d,$$

*1 Dead time correction formula

https://www.jaea.go.jp/04/fugen/about/compilation/report/honbun/446.htm

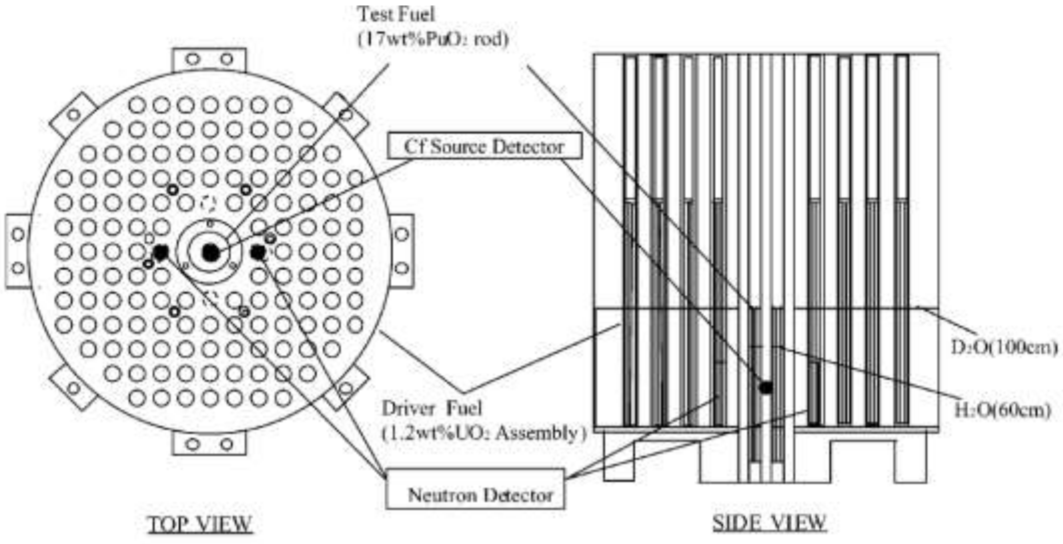


Fig. 1. Modified Deuterium Critical Assembly (DCA).

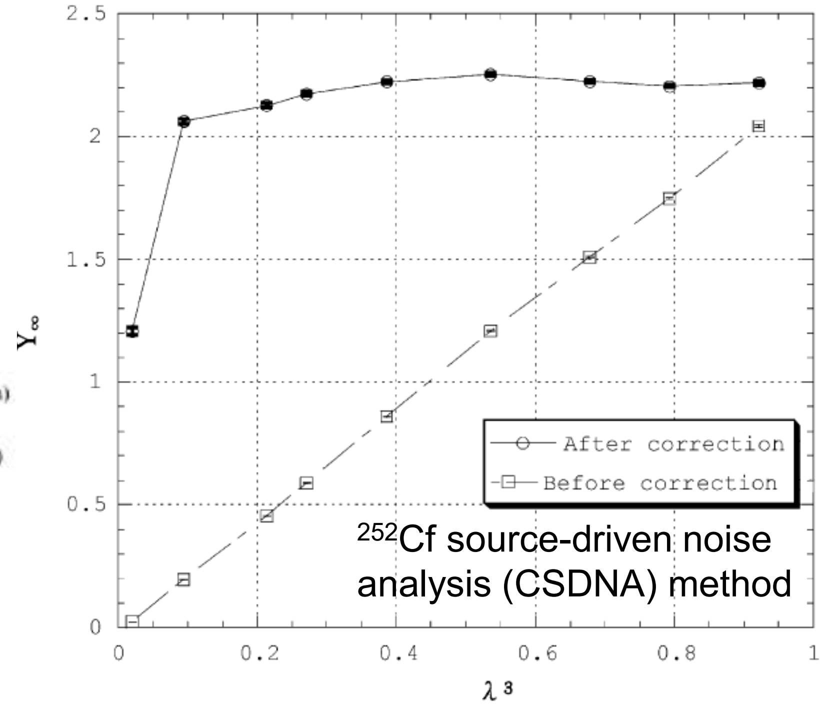


Fig. 4. Effect of the dead time correction for Y_∞.

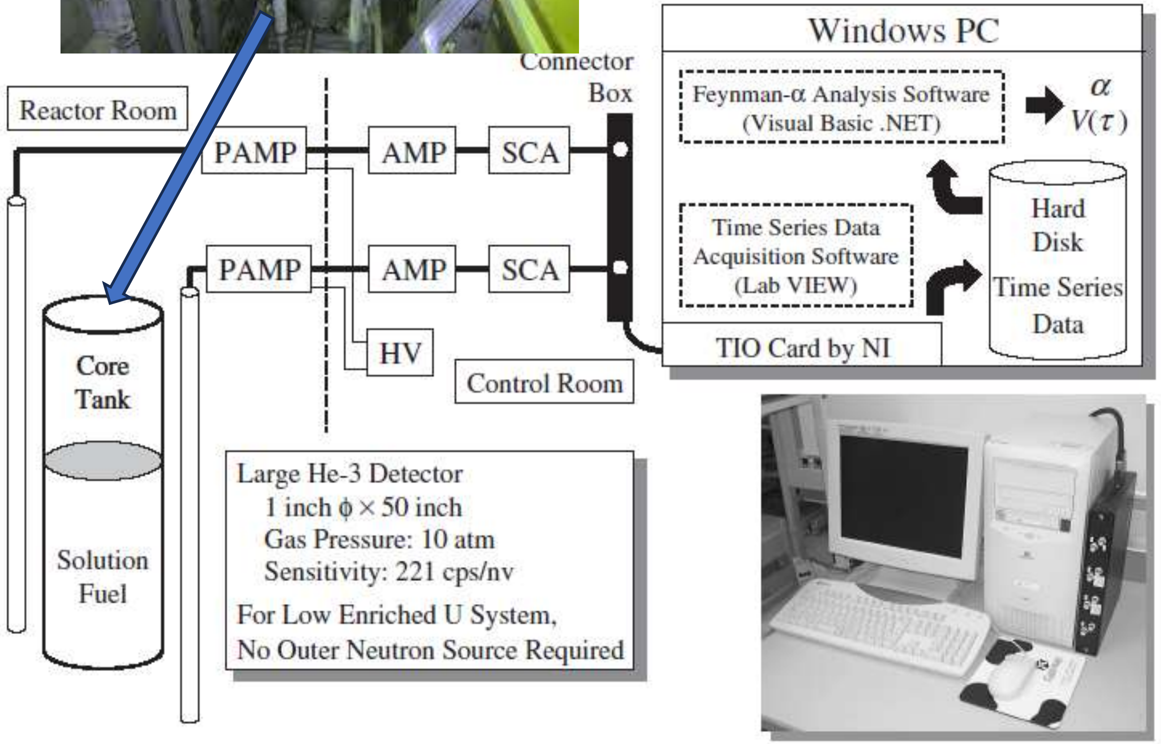
Histories

- Old STACY ($UO_2(NO_3)_2$+ UO_2)
  - To develop a criticality monitoring after the JCO criticality accident
  - Using time series data acquisition
  - Feynman-α + Difference Filter

$$V(\tau) = \frac{\text{Variance } (N_i - N_{i-1})}{\text{Mean } (N_i)}$$
$$= 2 + 2Y_\infty \left(1 - \frac{1.5 - 2e^{-\alpha\tau} + 0.5e^{-2\alpha\tau}}{\alpha\tau}\right).$$

    - For 0, 0.31, 0.52, 1.07, and 2.05 \$ subcriticalities
  - In a state close to criticality where the mean value fluctuates, a second-order difference filter was applied

Kotaro TONOIKE, et al., Real Time a Value Measurement with Feynman-α Method Utilizing Time Series Data Acquisition on Low Enriched Uranium System, *J. Nucl. Sci. Technol.*, **41**(2) pp. 177–182, (2004). 10.1080/18811248.2004.9715474



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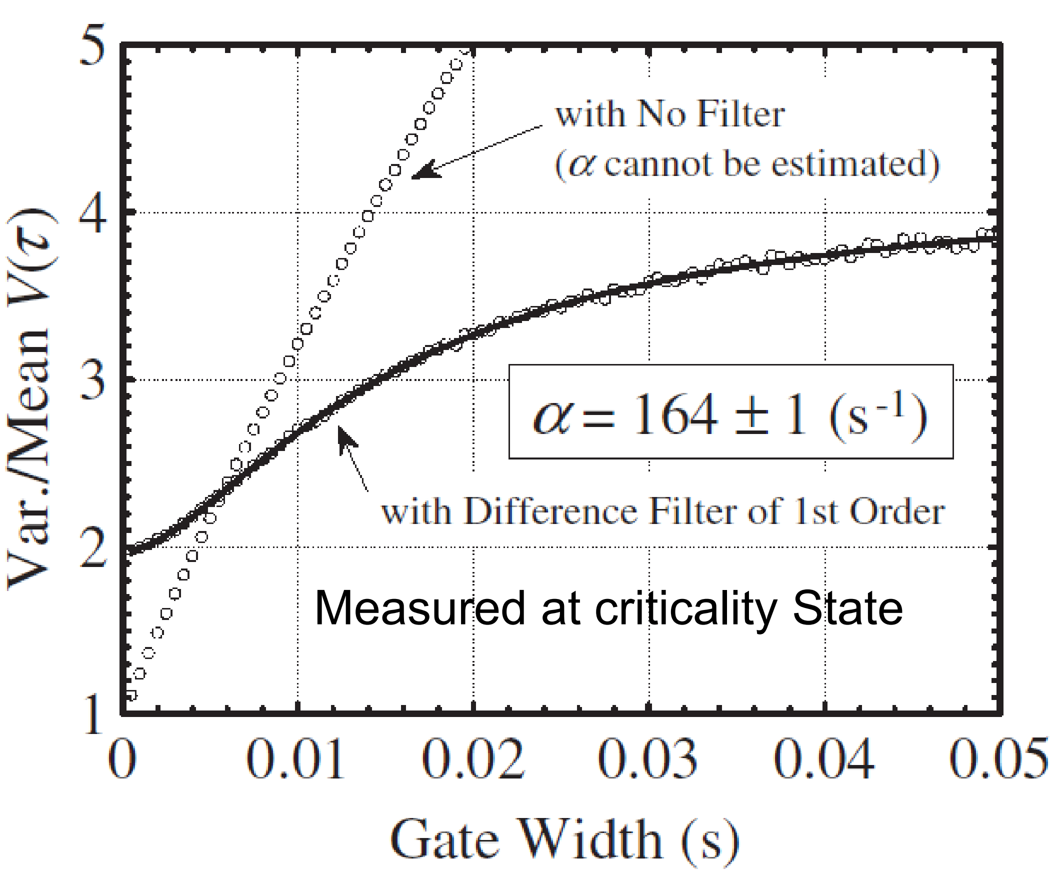
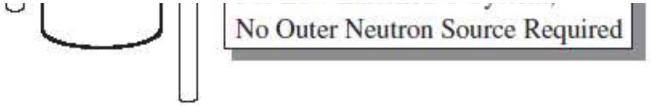
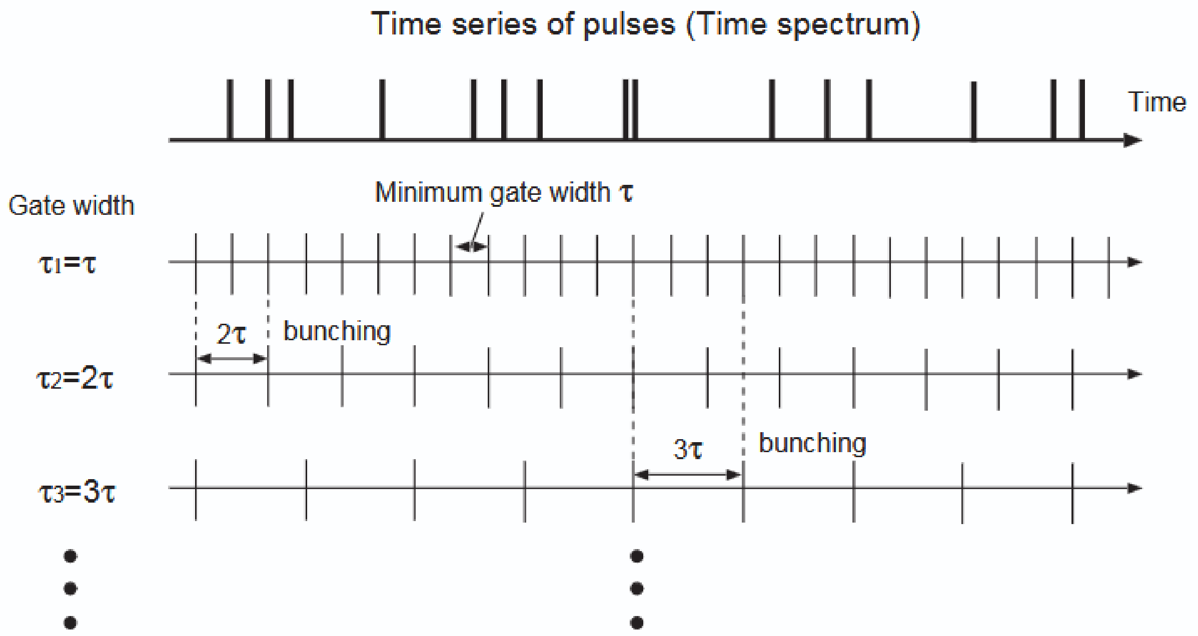
Kotaro TONOIKE, et al., Real Time a Value Measurement with Feynman α Method Utilizing Time





Simulation

- Japanese major MC code called MVP-II (2005) and MVP-3 (2017) can simulate Feynman-α rector noise analysis.
  - Using Terrell's sampling method



- The cumulative probability distribution for the number of neutrons per fission is given by

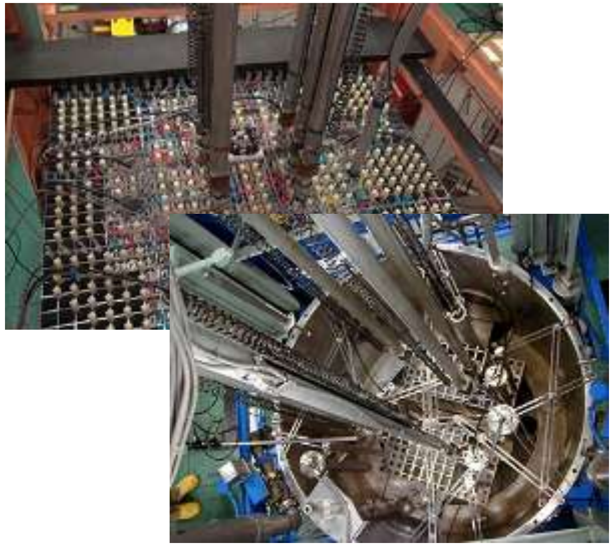
$$\sum_{n=0}^{\nu} P(n) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(\nu-\bar{\nu}+1/2+b)/\sigma} \exp\left(-\frac{1}{2}t^2\right) dt$$
$$= \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{(\nu+1/2)} \exp\left(-\frac{(x-\bar{\nu}+b)^2}{2\sigma^2}\right) dx,$$

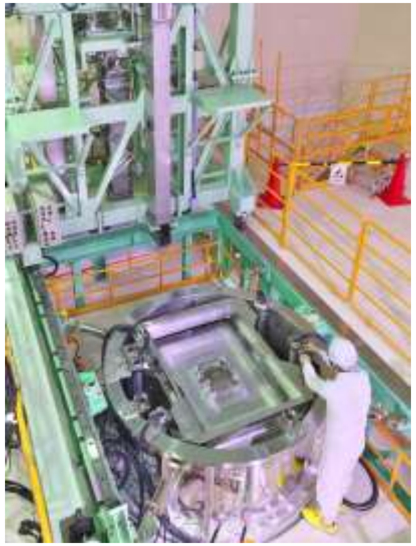
$$Y(\tau_n) = \frac{\sigma^2(\tau_n)}{\overline{C(\tau_n)}} - 1$$
$$\sigma^2(\tau_n) = \frac{N_n}{N_n - 1}\left[\overline{C^2(\tau_n)} - \overline{C(\tau_n)}^2\right].$$

Y. Nagaya, K. Okumura, T. Sakurai and T.Mori, "MVP/GMVP Version 3 : General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations Based on Continuous Energy and Multigroup Methods," JAEA-Data/Code 2016-018 (2017).

Available Experimental Facilities in Japan

- ❖After the Fukushima accident, most of the ZPRs had been shut down
- ❖Only three ZPRs are alive





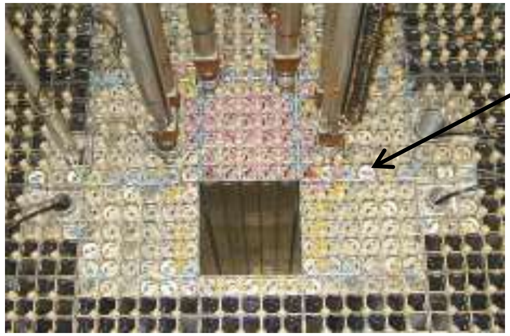
KUCA
(Kyoto Univ.)
Restart after enrichment change is planned in a couple of years.

UTR-KINKI
(KINDAI Univ.)
Enrichment change from HEU to LEU is planned after the KUCA restart.

STACY
(JAEA, Tokai)
Modification was completed and restarted in April 2024.

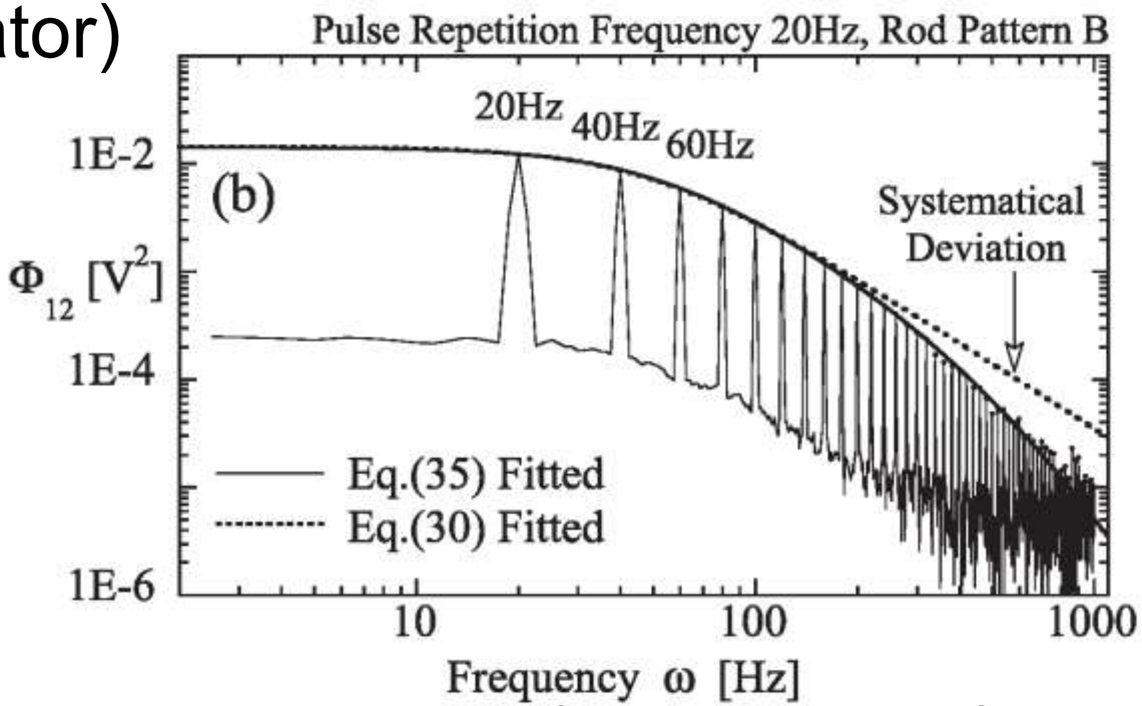
Study on Reactor Noise at KUCA

❖KUCA (HEU, PE/Graphite moderator)



PE or Graphite channels

https://www.rri.kyoto-u.ac.jp/CAD/facility.html



Least-squares fit to peak point data of CPSD with D-T NS (20 Hz)

- ➢Long-term experiences using Feynman-α, Rossi-α
- ➢Development of subcriticality monitor for the ADS application using their D-T NS or FFAG accelerator

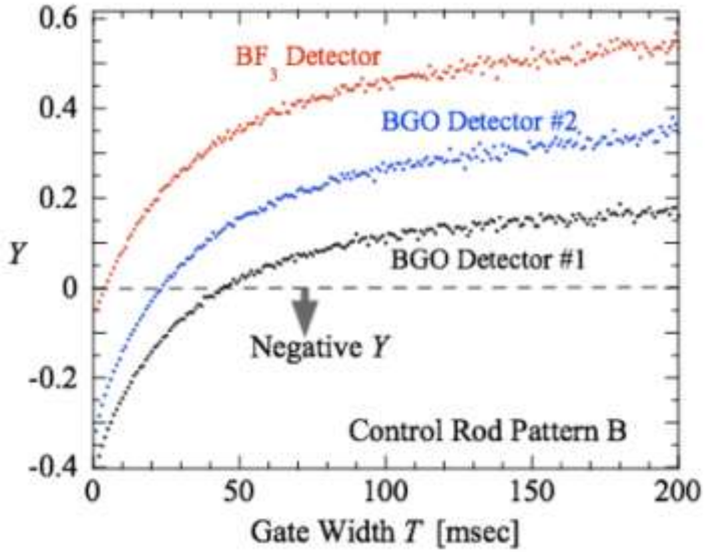
Atsushi Sakon, et al., Power spectral analysis for a thermal subcritical
reactor system driven by a pulsed 14 MeV neutron source, *J. Nucl. Sci. Technol.*, **50**(5), pp. 481492, (2013). 10.1080/00223131.2013.785268

Study on Reactor Noise at UTR-KINKI

❖UTR-KINKI
(HEU, water moderated, graphite reflector)

- They have been studied in many applications using reactor noise. Such as;
  - Subcriticality measurement
  - Nuclear Criticality Safety
  - Evaluations of kinetic parameters, spatial distributions
  - Correction of thermal power
    - From α value, subcriticality, and neutron generation ratio.
- Methods
  - Feynman-α, Rossi-α, PSD, and Correlation analysis

https://www.kindai.ac.jp/english/about/facilities/



Feynman-α by measuring the Neutron or the Gamma-Ray

Masaki Goto, Kengo Hashimoto, et al., Feynman-α Analysis Using BGO Gamma-Ray Detector in UTR-KINKI Reactor, Proc. of PHYSOR2022, (2022)

Current Motivations of Studies on Reactor Noise

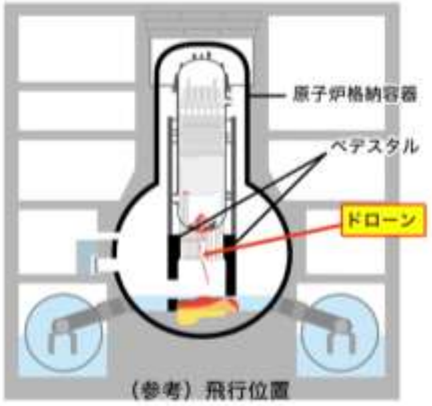
Two different aspects

- ❖ An insatiable desire to measure the subcritical state absolutely.
  - ➢ From the perspective of criticality safety management
  - ➢ <u>Focused on the "accuracy"</u>

- ❖ Estimation of the criticality safety of fuel debris generated in the FDNPS accident.
  - ➢ It is necessary to retrieve fuel debris while minimizing risks as much as possible
  - ➢ The measurement conditions are severe
  - ➢ <u>Focused on the "rough estimation"</u>

Low neutron count rate,
high gamma-ray background,
many constraints (sizes, weights, etc.)

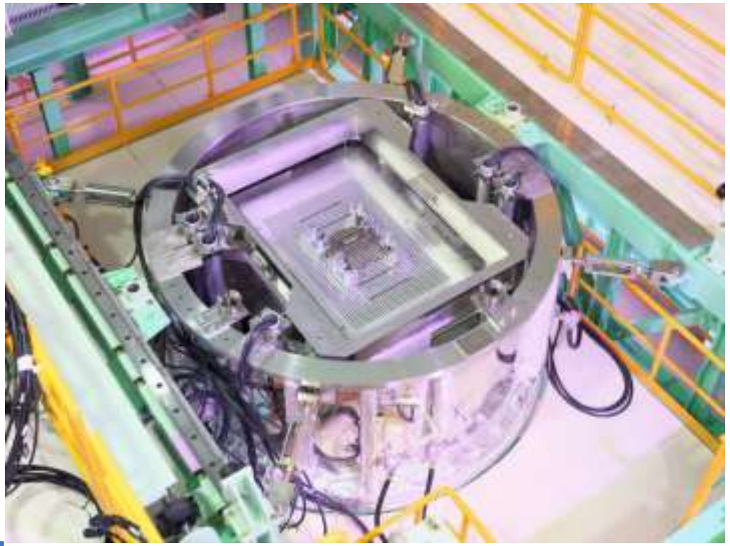
Unit 3 CRD



https://www.tepco.co.jp/library/movie/detail-j.html?catid=61709&video_uuid=15821

About "modified" STACY

- STACY (STAtic experiment Critical facilitY)
  - Modified from Uranium Nitrate Solution system
    - To clarify the criticality characteristics of fuel debris
  - Restart in April 2024
  - Located in JAEA's Tokai (North) site



Specification	Value
Thermal power (Max.)	200 W
Number of UO_2 fuel rods	50 – 900 (< 400 in the beginning)
Critical water height	40 – 140 cm
Excess reactivity (Max.)	0.3 $ (normal operation) 0.8 $ (unanticipated transient)
Reactivity addition rate (Max.)	3 cents par second

From the viewpoint of fuel debris retrieval, there are strong motivations to carry out the LEU-COMP-THERM system.

New challenges for the Fukushima application

❖ JAEA collaborates with Nagoya Univ. from FY2025.

❑ JAEA
- ➢ JAEA has the STACY that can simulate fuel debris conditions.
- ➢ There was a gap in JAEA's research on noise analysis.

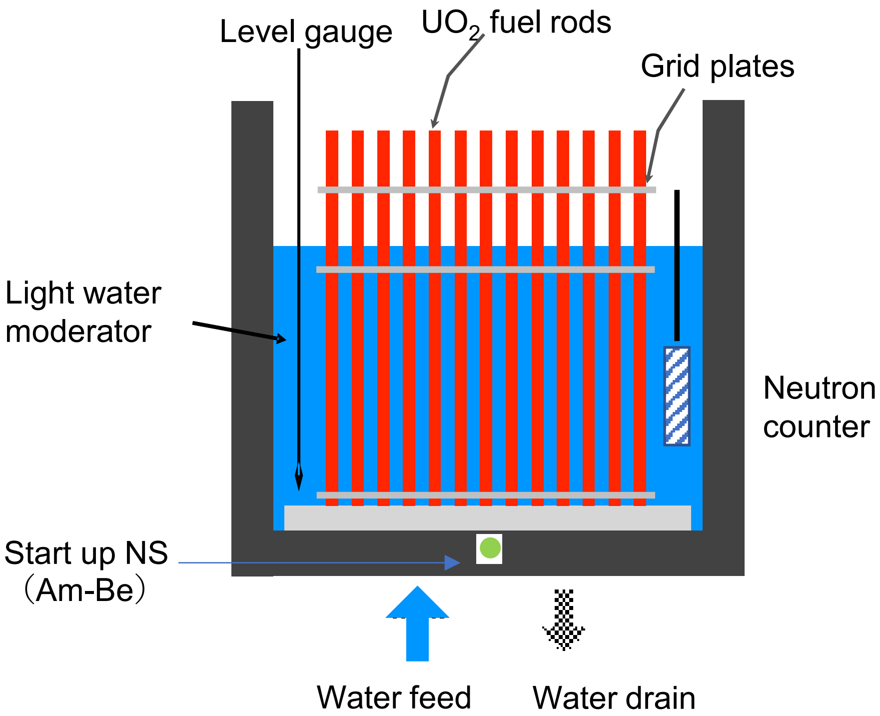
❑ Nagoya Univ.
- ➢ Associate Professor Endo of Nagoya University has made the analysis of reactor noise as his life's work for years.
- ➢ One key is their new theoretical ideas, including noise analysis methods
- ➢ Another key is their noise reduction techniques.

Collaboration in FY2025

- Endo-san and his students worked with us, and they proposed some types of subcriticality measurement methods, including noise analysis
- These brand-new ideas were validated by using STACY's experimental data
  - We jointly obtained some sets of experimental data in FY2025
- In JAEA, a new generation is acquiring know-how of critical experiments, including radiation measurement techniques.

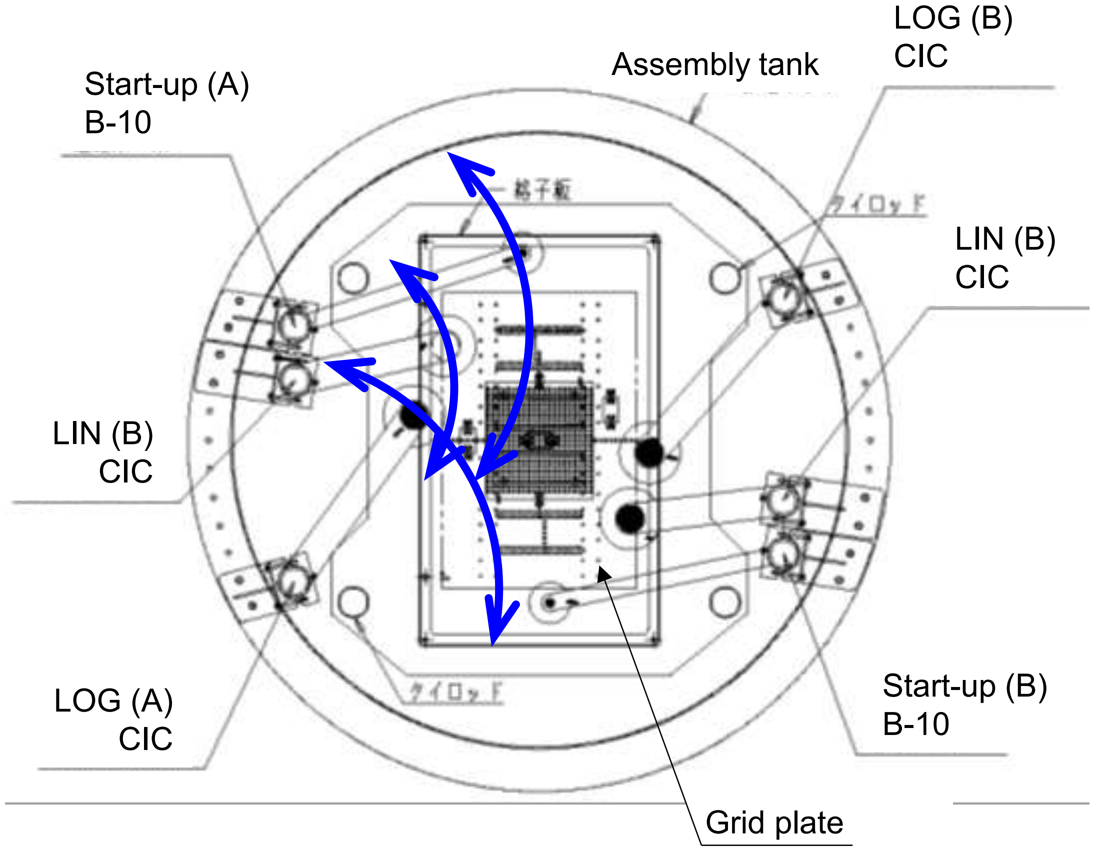
Experimental conditions

❖Operation



STACY has no control rod
Criticality is changed only by adjusting water levels

Am-Be start-up source and ^{252}Cf "experimental" source that can be set anywhere in the grid are available



Locations of neutron detectors for operation

33rd International Meeting
On Reactor Noise (IMORN-33)
6–8 July 2026
CNRS/LPSC Grenoble, FRANCE

Purpose

- Noise measurements using two neutron detectors
  - Consideration that using multiple detectors with low detection efficiency, given the constraints regarding detector size and location.

🤔 Which is more appropriate?

① Sum the signals from the two detectors as a "single detector," and apply the "standard Feynman-α method."

② Analysis based on the "covariance" of two detector signals.

Apply analysis methods ① and ② to reactor noise measurement data from the STACY and compare the methods.

Tomohiro Endo, Ryoga Hirota, Akio Yamamoto, Araki Shouhei, Junichi Ishii, and Satoshi Gunji, Reactor Noise Analysis of the STACY Using the Variance-to-Mean and Covariance-to-Mean Ratios, *AESJ 2026 Spring Annual Meeting*, Kumamoto, March 12, 2026
(Original slides in Japanese)

Variance-to-Mean vs. Covariance-to-Mean

	Variance-to-Mean	Covariance-to-Mean
	$Y_{\mathrm{var}} \equiv \dfrac{\langle (C_1 + C_2 - \langle C_1 + C_2 \rangle)^2 \rangle}{\langle C_1 + C_2 \rangle} - 1$	$Y_{\mathrm{cov}} \equiv \dfrac{\langle (C_1 - \langle C_1 \rangle)(C_2 - \langle C_2 \rangle) \rangle}{\langle C_1 \rangle}$
Dead time (τ) effect [4]	Underestimation of " $-2 \times (cps)\tau$ →Correction required for fitting	Negligible
High-order modes [4]	Depends on two detector locations [4]	Depends on two detector locations (The n-th order amplitude differs from Y_{var}.)
Magnitude of Y value	Proportional to the detection efficiency of two detectors.	Proportional to the detection efficiency of one detector.
Statistical uncertainty	Estimation methods have been established (bootstrap, theoretical) [5]	NOT established Applications of the bootstrap

[4] Y. Yamane et al., *Ann. Nucl. Energy*, **23**(12), pp.981–987 (1996);
[5] T. Endo et al., *Ann. Nucl. Energy*, **124**, pp.606–615 (2019).

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Statistical Error Estimation for reactor noise Circular Block Bootstrap (CBB) method

Original time-series data ($N = 24$)

$C_{1,1}$	$C_{1,2}$	$C_{1,3}$	$C_{1,4}$	$C_{1,5}$	$C_{1,6}$	$C_{1,7}$	$C_{1,8}$	$C_{1,9}$	$C_{1,10}$	$C_{1,11}$	$C_{1,12}$	$C_{1,13}$	$C_{1,14}$	$C_{1,15}$	$C_{1,16}$	$C_{1,17}$	$C_{1,18}$	$C_{1,19}$	$C_{1,20}$	$C_{1,21}$	$C_{1,22}$	$C_{1,23}$	$C_{1,24}$
$C_{2,1}$	$C_{2,2}$	$C_{2,3}$	$C_{2,4}$	$C_{2,5}$	$C_{2,6}$	$C_{2,7}$	$C_{2,8}$	$C_{2,9}$	$C_{2,10}$	$C_{2,11}$	$C_{2,12}$	$C_{2,13}$	$C_{2,14}$	$C_{2,15}$	$C_{2,16}$	$C_{2,17}$	$C_{2,18}$	$C_{2,19}$	$C_{2,20}$	$C_{2,21}$	$C_{2,22}$	$C_{2,23}$	$C_{2,24}$

Periodic boundary condition

Bootstrap sample ($\mathrm{blocksize} = 4$)

$C_{1,10}$	$C_{1,11}$	$C_{1,12}$	$C_{1,13}$	$C_{1,6}$	$C_{1,7}$	$C_{1,8}$	$C_{1,9}$	$C_{1,17}$	$C_{1,18}$	$C_{1,19}$	$C_{1,20}$	$C_{1,14}$	$C_{1,15}$	$C_{1,16}$	$C_{1,17}$	$C_{1,22}$	$C_{1,23}$	$C_{1,24}$	$C_{1,1}$	$C_{1,4}$	$C_{1,5}$	$C_{1,6}$	$C_{1,7}$
$C_{2,10}$	$C_{2,11}$	$C_{2,12}$	$C_{2,13}$	$C_{2,6}$	$C_{2,7}$	$C_{2,8}$	$C_{2,9}$	$C_{2,17}$	$C_{2,18}$	$C_{2,19}$	$C_{2,20}$	$C_{2,14}$	$C_{2,15}$	$C_{2,16}$	$C_{2,17}$	$C_{2,22}$	$C_{2,23}$	$C_{2,24}$	$C_{2,1}$	$C_{2,4}$	$C_{2,5}$	$C_{2,6}$	$C_{2,7}$

$C_{1,23}$	$C_{1,24}$	$C_{1,1}$	$C_{1,2}$	$C_{1,12}$	$C_{1,13}$	$C_{1,14}$	$C_{1,15}$	$C_{1,3}$	$C_{1,4}$	$C_{1,5}$	$C_{1,6}$	$C_{1,7}$	$C_{1,8}$	$C_{1,9}$	$C_{1,10}$	$C_{1,22}$	$C_{1,23}$	$C_{1,24}$	$C_{1,1}$	$C_{1,16}$	$C_{1,17}$	$C_{1,18}$	$C_{1,19}$
$C_{2,23}$	$C_{2,24}$	$C_{2,1}$	$C_{2,2}$	$C_{2,12}$	$C_{2,13}$	$C_{2,14}$	$C_{2,15}$	$C_{2,3}$	$C_{2,4}$	$C_{2,5}$	$C_{2,6}$	$C_{2,7}$	$C_{2,8}$	$C_{2,9}$	$C_{2,10}$	$C_{2,22}$	$C_{2,23}$	$C_{2,24}$	$C_{2,1}$	$C_{2,16}$	$C_{2,17}$	$C_{2,18}$	$C_{2,19}$

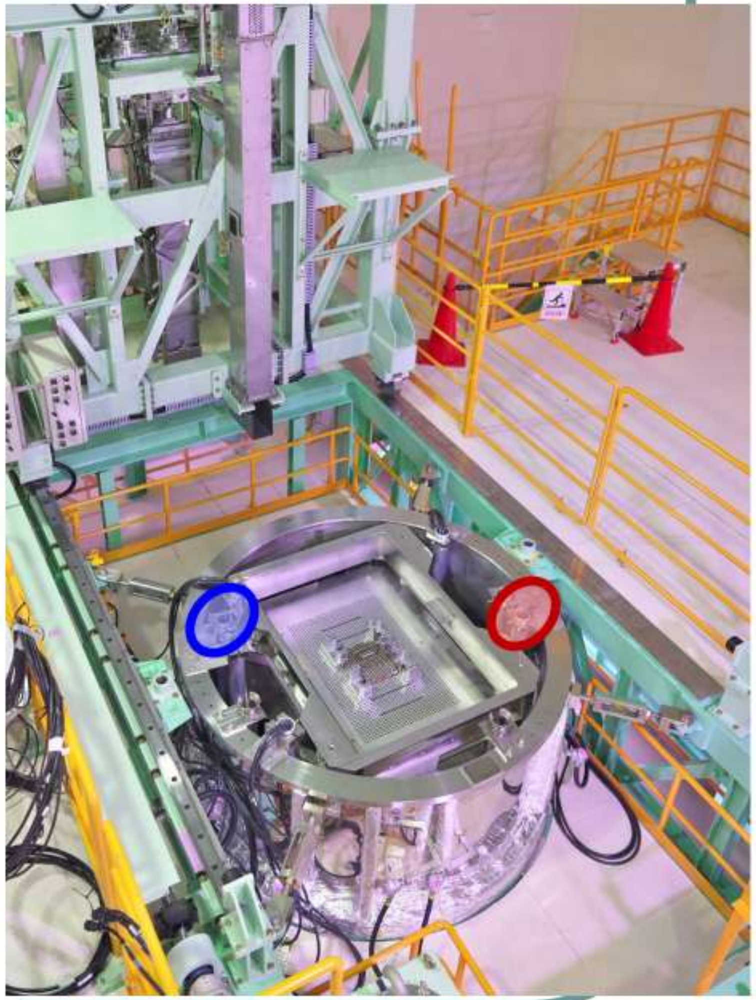
🔑 Generating a large number of data-driven resamples that preserve, to the greatest extent possible, the "correlation between two detectors" and the "autocorrelation within the time-series data."

[6] D.N. Politis et al., *Exploring the Limits of Bootstrap*, Wiley, pp.263–270 (1992).

Tomohiro Endo, Ryoga Hirota, Akio Yamamoto, Araki Shouhei, Junichi Ishii, and Satoshi Gunji, Reactor Noise Analysis of the STACY Using the Variance-to-Mean and Covariance-to-Mean Ratios, *AESJ 2026 Spring Annual Meeting*, Kumamoto, March 12, 2026
(Original slides in Japanese)

Measurement conditions on STACY

- At criticality approach
  - WITH ^{241}Am-Be NS
    Subcriticality state
- Reactor noise measurement
  - Two neutron counters:
    ch1, ch2
  - Measure about 1,500 s
  - $\mathrm{ch1} = 168.3 \pm 0.3$ cps,
    $\mathrm{ch2} = 225.4 \pm 0.5$ cps
  - Basic gate width
    $$T_{\mathrm{base}} = 10^{-4}\ \mathrm{s}$$
    Recursive bunching method [5]



[5] T. Endo et al., *Ann. Nucl. Energy*, **124**, pp.606–615 (2019).

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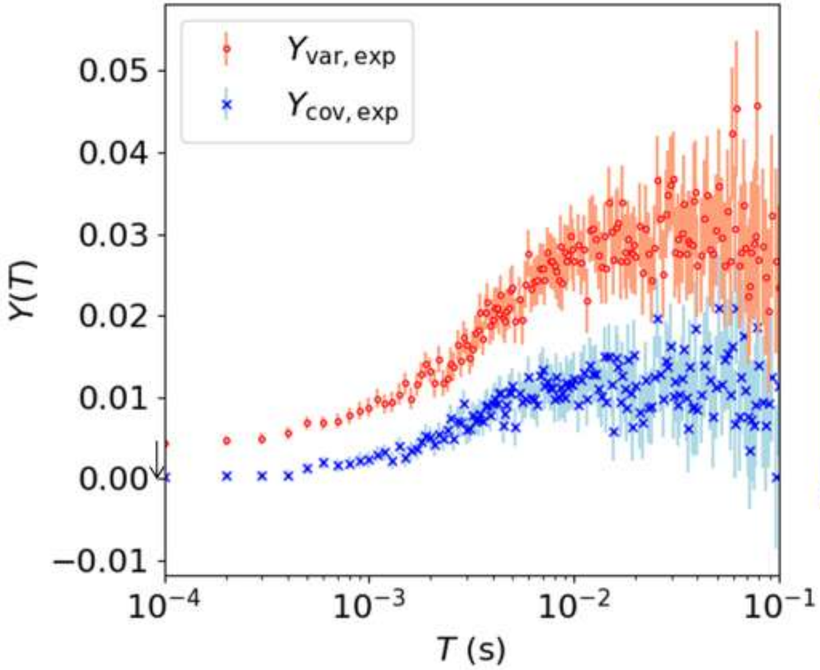
Measurement results of Y-value



📌 Successfully, Y-values were measured by reactor noise in the LCT system.

⚠️ Small Y-value; Low detection efficiency by water moderator

- Y_{cov}: $T \to 0$ leads $Y_{\mathrm{cov}} \to 0$ (Bias can be reduced)
- Y_{var}, Y_{cov}: Absolute statistical error is almost the same (It depends on measurement times)

⇒When combined, Y_{var} which has a higher detection efficiency, has a smaller relative statistical error.

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Considerations Regarding the Statistical Errors of Variance and Covariance

- To simplify the discussion;
  - Number of data points when estimating sample variance/covariance N
  - Approximating the frequency distribution of neutron counts with a normal distribution.

- Statistical error of sample variance (True variance σ^2)

$$SE_{\sigma^2} \approx \sigma^2 \sqrt{\frac{2}{N-1}} \rightarrow \frac{SE_{\sigma^2}}{\sigma^2} \approx \sqrt{\frac{2}{N-1}} \approx \frac{SE_{Y_{\mathrm{var}}}}{Y_{\mathrm{var}}} \quad \text{if } Y_{\mathrm{var}} \ll 1$$

- Statistical error of sample covariance
(True covariance σ_{xy}^2, True variance σ_x^2, σ_y^2)

$$SE_{\sigma_{xy}} \approx \sqrt{\frac{\sigma_x^2\sigma_y^2 + \sigma_{xy}^2}{N-1}} \rightarrow \frac{SE_{\sigma_{xy}}}{\sigma_{xy}} \approx \sqrt{\frac{1}{N-1}\left(\frac{1}{\rho_{xy}^2} + 1\right)}$$

Correlation coefficient

🔑 Data points N ($\propto$Measurement time) dominates the statistical error.

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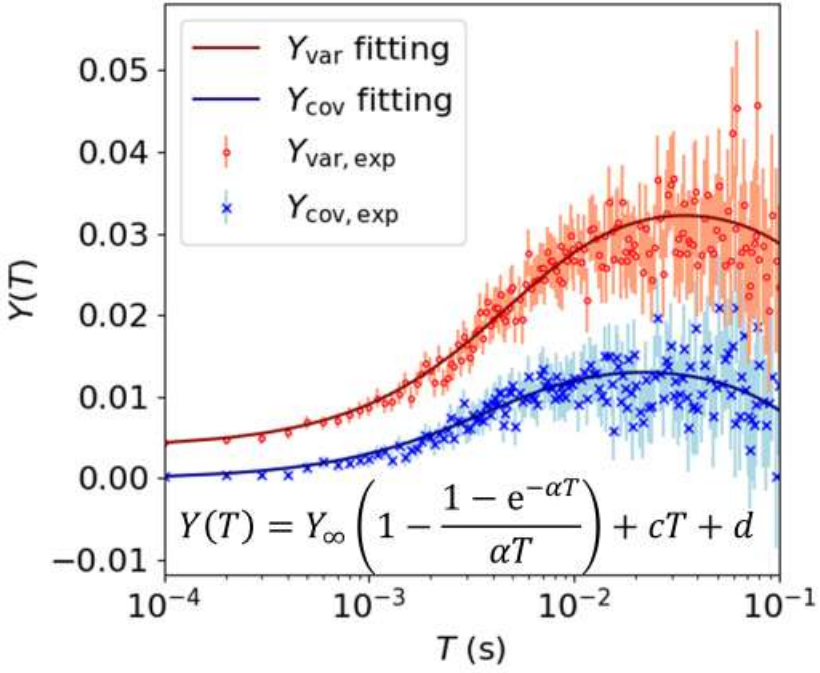
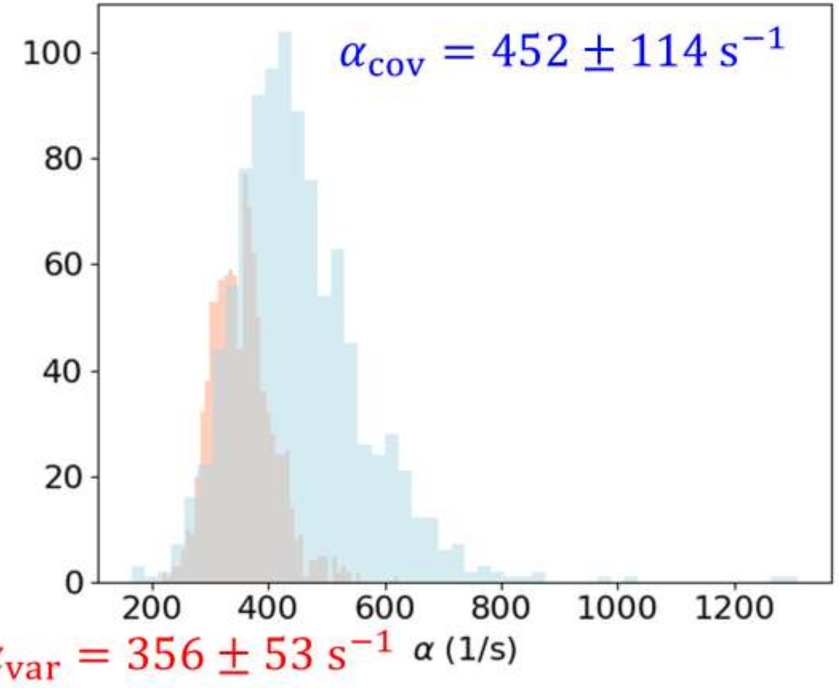
(Original slides in Japanese)

Measurement results of the prompt neutron decay constant α





- α is estimated using the nonlinear least-squares method with a fitting equation that incorporates a correction term $cT + d$ applied to $Y_{\mathrm{var}}, Y_{\mathrm{cov}}$
  - Use the covariance matrix $\boldsymbol{\Sigma}_Y$ of $Y_{\mathrm{var}}, Y_{\mathrm{cov}}$, estimated via the CBB method, as weights.

🔑 Since Y_{var} has high detection efficiency, it is possible to reduce the statistical error of α.

Tomohiro Endo, Ryoga Hirota, Akio Yamamoto, Araki Shouhei, Junichi Ishii, and Satoshi Gunji, Reactor Noise Analysis of the STACY Using the Variance-to-Mean and Covariance-to-Mean Ratios, *AESJ 2026 Spring Annual Meeting*, Kumamoto, March 12, 2026
(Original slides in Japanese)

Summary

- Analysis of reactor noise measurement results in the STACY
  - The Circular Block Bootstrap method can also be used to estimate the statistical error of the covariance.
  - When the detection efficiency per detector is low
    →Neutron correlations of nuclear fission should be summed to facilitate detection.
  - (detection efficiency is improved as a "single detector")
- Future Challenges
  - Derivation of the formula for estimating the statistical error of the ratio of covariance to the mean.
  - Measurement of Subcriticality in Dollars by Reactor Noise Analysis.

Tomohiro Endo, Ryoga Hirota, Akio Yamamoto, Araki Shouhei, Junichi Ishii, and Satoshi Gunji, Reactor Noise Analysis of the STACY Using the Variance-to-Mean and Covariance-to-Mean Ratios, *AESJ 2026 Spring Annual Meeting*, Kumamoto, March 12, 2026
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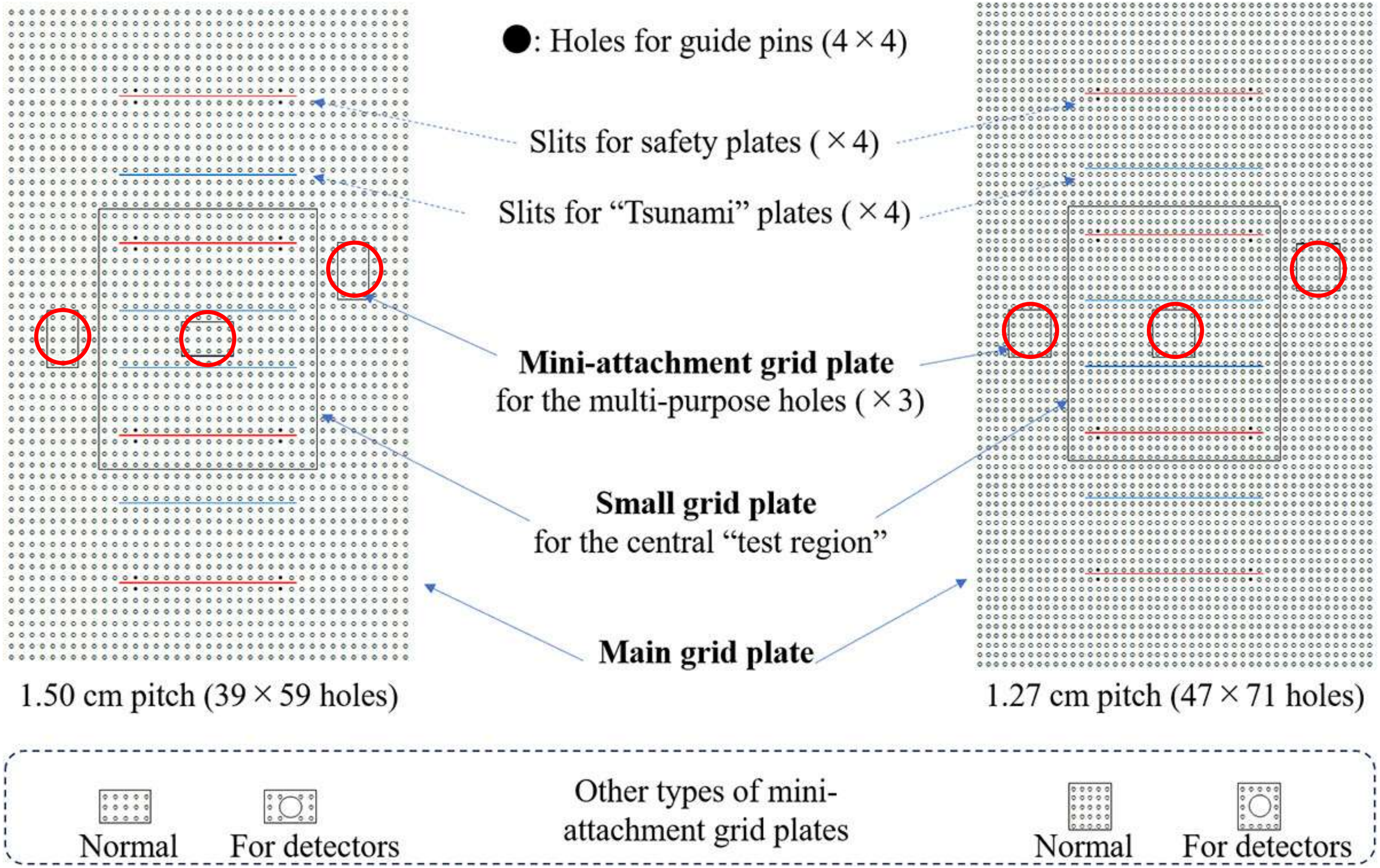
Possible detector positions

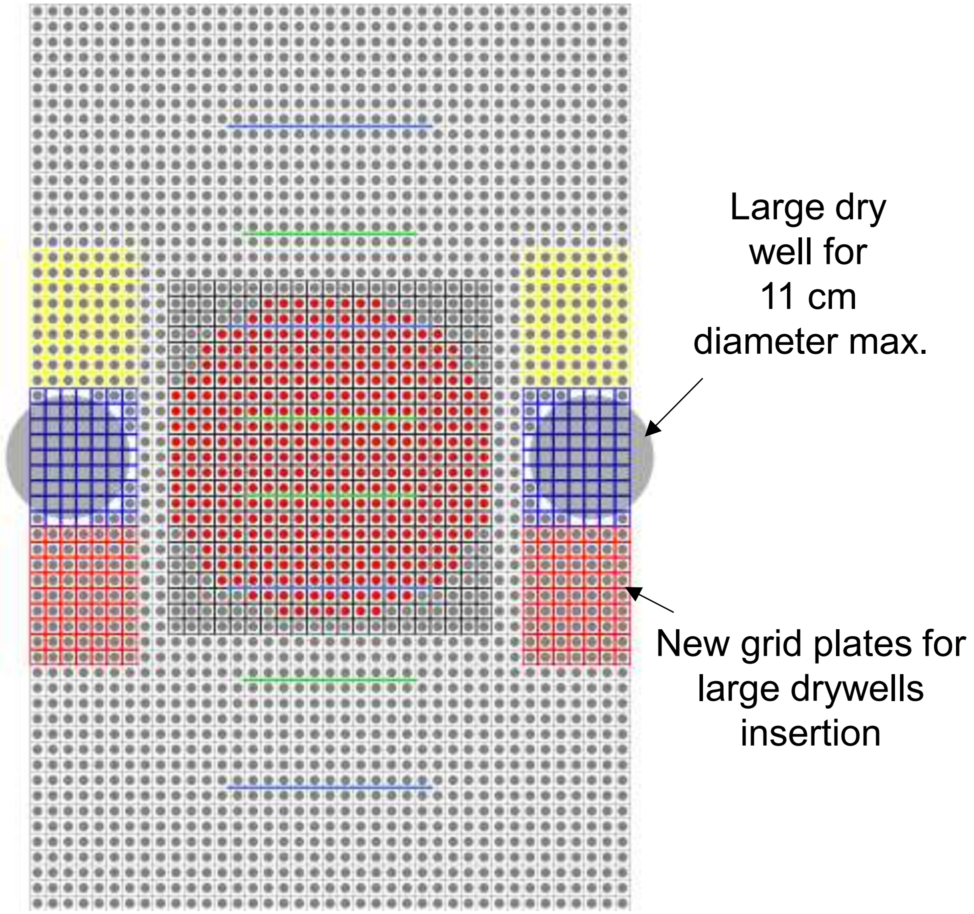


○ Positions of drywells for 1" detectors or other experimental equipment

S. Gunji, et al., Experimental measurements for the first series of the modified STACY critical assembly with simple core configurations and experimental analysis using simplified computational models, *J. Nucl. Sci. Technol.*, **63**(2), (2026). https://doi.org/10.1080/00223131.2025.2592962

STACY's improvement plans

- Improved flexibility
  - Now: The experimenter is permitted to bring in only detectors up to one inch in diameter.
  - Future: We will prepare multipurpose dry wells for various sizes and shapes counters.
  - In addition, we will prepare ^{60}Co sources (up to 1 GBq) to make gamma noise.



Challenges in FY2026

❖ Subcriticality
- ➢ \$1 and more (\$0.9 max in FY2025)

❖ Dynamic changes
- ➢ Try to measure subcritical transients

❖ Measurement conditions
- ➢ Lower neutron count rate
- ➢ Gamma ray background by the ^{60}Co source

❖ Issues
- ➢ Decrease in the number of students specializing in experimental reactor physics

Summary

- ❖ Overview of Japanese studies on noise analysis
- ❖ Most of the experimental facilities had been closed, and three of them are still operational
- ❖ Japanese critical assembly "STACY" restarted in 2024
  - ➢ It can simulate fuel debris' conditions/compositions
  - ➢ JAEA lost its experimental know-how due to the long gap
- ❖ JAEA and Nagoya Univ. started collaboration work on subcriticality measurement, including reactor noise analysis
  - ➢ For the Fukushima issues