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PC-Based Random Neutron Process Measurement in a Thermal Reactor

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PC에 의한 열중성자로 중성자의 무작위 특성 측정

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Abstract

A PC-based system for measuring and analysing random neutron process in the thermal reactor is developed and applied to TRIGA Mark-II reactor at KAERI. It is confirmed that this system has several advantages compared to conventional methods. So far, two techniques, autocorrelation and variance to mean ratio (VTMR), have been applied for analysing the count data collected from the single detector by using this system. The results of the two techniques agree within acceptable difference, but VTMR's results show much superior statistical reliability than those of autocorrelation especially when it is near critical. The β/Λ of TRIGA Mark-II reactor is measured to be about 125/sec when the reactivity is within -3 \$ and about 150/sec when it is below -4 \$.

요 약

열중성자로의 무작위 중성자 특성을 PC로써 측정하는 체계를 개발하고 이를 한국에너지연구소의 TRIGA Mark-II 원자로에 응용하였다. 그 결과 이 체계는 재래의 여러 방법에 비하여 많은 장점을 가지고 있음을 확인하였다. 아직은 한개의 계측기를 사용하였고, 즉발중성자만 고려한 시간 영역에 대하여 autocorrelation과 VTMR 두가지 방법으로 분석하였다. 두 방법의 결과는 서로 잘 일치하였으나 통계적인 신뢰도 면에서는 VTMR이 훨씬 나았고, 특히 임계 근처에서 이것이 두드러졌다. TRIGA Mark-II의 β/Λ는 임계에서 -3\$까지는 약 125/초, -4\$ 이하에서는 약 150/초로 측정되었다.

1. Introduction

The chain reaction based nuclear processes in a reactor give rise to non-normal distribution of the detected counts because the individual counts are dependent on the other neutrons in the chain. Hence the statistical properties of the count sequence are closely related to the dynamic characteristics of the reactor. Random neutron techniques measure this neutron pulse sequence and obtain dynamic parameters. The advantage of these techniques compared to other competitive methods such as pulsed neutron source technique and pile oscillator method, is that any special equipments providing external perturbation to the reactor are not needed. The success of these techniques is dependent on the time resolution of individual counts and amount of data. The time resolution should be comparable to the prompt neutron life time ($\sim \mu$ seconds in fast reactors and $\sim 100\mu$ seconds in thermal reactors) and the number of data should be enough to ensure statistical reliability. There are several experimental techniques to satisfy these requirements and several theories to deal with data effectively depending on the instrumentation and reactor type. However, if the count sequence can be measured and saved in a mass storage then numerical simulations for most techniques are possible. Conventional method of this kind is recording a sufficiently long record of detector output on magnetic tape that is to be analysed by digital computer.[1]

Nowadays, PCs have enough mass storage and speed not only for the analysis but also for the measurement of count sequence. If a PC is equipped with a counter/timer board which is commonly used for the speed or cycle measurement, it can be used as a multi-input multi-channel scaler. Its advantages are low instrumentation cost, easy data handling and capacity to receive multi-input channels. However it can be used only for thermal reactors. For fast reactor application, a PC may have to be equipped with a special I/O circuit that shifts pulses and sends pulse timing data by batch to the CPU. In this study, a PC-based system for measuring and analysis random neutron process in the thermal reactor, is developed and applied to the TRIGA Mark-II reactor at KAERI. A 8 MHz 16-bit PC equipped with a 10 MHz counter/timer board is used as a multi-scaler and mass storage. Neutron pulses are counted at every 100 μ seconds by using interrupt technique and pulse sequence data are stored in a hard disk.

Autocorrelation and variance to mean ratio methods have been applied for the data analysis so far. Application of other methods remains for further work.

A fission chamber was installed at the central thimble for the neutron detection. Experiments were performed at various subcritically ranging from -0.05 \$ to near -10 \$. The prompt neutron decay constants and coefficients were obtained from the above two methods and their results are compared.

2. Random Neutron Process in the Reactor

There are several ways that formulate the random neutron process and they are well explained in references[1,2,3,4]. In this paper, two equations for Rossi-α and VTMR methods are derived based on the lumped model (one group point kinetics). The probability of detecting a pair of neutrons at $t=t_1$ and $t_2\ (>t_1)$ is the sum of the random and chain related probabilities:

$$P(t_1, t_2) = P_R(t_1, t_2) + P_C(t_1, t_2) \tag{1}$$

where, $P_R(t_1, t_2) = (\varepsilon F)^2$ = random probability
$P_c(t_1, t_2)$ = chain related probability.
ε = detector efficiency in counts/fission, and
F = average fission rate in the reactor.

The chain related probability is derived in the following manner. If a fission is occured at $t=t_0(<t_1)$ then $\nu(1\text{-}\beta)$ prompt neutrons and $\nu\beta_i$ delayed neutron precursors of each group are expected to be produced and the delayed neutron procursors will emit $\nu\beta_i\lambda_i\exp[-\lambda_i(t-t_0)]$ delayed neutrons respectively after then. These neutrons can be dealt as the source of one group point kinetic equation:

$$\frac{dn}{dt} = \frac{\rho-\beta}{\Lambda}n + \sum_{i=1}^{6}\lambda_i C_i - \nu(1\text{-}\beta)\,\delta(t_0) + \sum_{i=1}^{6}\nu\beta_i\lambda_i\exp[-\lambda_i(t-t_0)] \tag{2}$$

with the initial conditions of $n(t_0) = C_i(t_0) - 0$

Above equation describes only those neutrons chain-related to one fission at t_0 The solution of the above equation is,

$$n(t_0 \to t) = \nu \sum_{i=0}^{6} A_i (1-\rho+\Lambda\omega_i) \exp[\omega_i (t-t_0)] - \nu \sum_{i=1}^{6} \exp[-\lambda_i (t-t_0)] \beta_i \lambda_i \sum_{j=0}^{6} \frac{A_i}{\lambda_i+\omega_j} \quad (3)$$

where ω_i's are the solutions of inhour equation (Eq.4) and A_i's are the solutions of impulse source neutron problem[5] as given in Eq.5

$$\rho = \Lambda\omega + \beta - \sum_{i=1}^{6} \frac{\beta_i \lambda_i}{\omega+\lambda_i} \quad (4)$$

$$A_i = \frac{1}{1+\sum_{j=1}^{6} \frac{\beta_j \lambda_j}{\Lambda [\omega_i+\lambda_j]^2}} \quad (5)$$

The detection probability of this neutrons at t_1 is

$$P(t_0 \to t_1) = \varepsilon v \Sigma_f \; n(t_0 \to t_1) = \frac{\varepsilon}{\Lambda\nu} n(t_0 \to t_1) \quad (6)$$

Therfore, the detection probability of a pair of chain-related neutrons at t_1 and t_2 due to a fission at t_0 is

$$P(t_0 \to t_1, t_2) = \frac{\varepsilon^2}{\Lambda^2 \nu^2} n(t_0 \to t_1) \; n(t_0 \to t_2) \quad (7)$$

Historically $P(t_0 \to t_2)$ has been weighted by $(\nu-1)/\nu$ from the view point of one neutron loss at t_1 by detection. However it is valid only when the neutron detected at t_1 is one of the ν neutrons produced by the fission at t_0. When the detector itself has multiplying material such as fission chamber, it should be weighted by $(2\nu-1)/\nu$ instead of $(\nu-1)/\nu$ and if the neutron detected at t_1 is a daughter or a later descendent of the first generation its validity is lost.

If the detector itself is considered as a part of reactor material then such complexity can be avoided and Eq.7 without any weighting is valid.

The total probability of chain-related detections at t_1 and t_2 is the integration of Eq.7 for all the fissions before t_1

$$P_C(t_1, t_2) = \int_{\infty}^{t_1} F\, P(t_0 \to t_1, t_2) \; dt_0 \quad (8)$$

If delayed neutron terms are included then Eq.8 becomes very complicated. Fortunately all delayed neutron terms are very small compared to the prompt neutron terms, i.e. $A_0 >> A_i$, $|\omega_0| >> |\omega_i|$ and $|\omega_0| >> \lambda_i$, and since $\omega_0 \simeq (\rho-\beta)/\Lambda$ and $A_0 \simeq 1$ Eq.3 can be approximated by

$$n(t_0 \to t) \simeq \nu \; (1-\beta) \; \exp[\omega_0 (t-t_0)] \quad (9)$$

A numerical simulation showed the difference between Eq.3 and 9 being less than 0.5%. If Eq.9 is used for the probability calculations then Eq.8 becomes the detection probability of chain-related pairs considering only prompt neutrons.

$$P_C(t_1, t_2) = \frac{F\varepsilon^2 \; (1-\beta)^2}{-2\omega_0 \Lambda^2} \exp[\omega_0 (t_2-t_1)] \quad (10)$$

Historically the prompt neutron decay constant $-W_0$ has been called as Rossi-α and had simbol α. If t_2-t_1, the count to count time interval, is replaced by τ, then the total detection probability of a pair of counts (Eq.1) is

$$P(t_1, t_2) = P(\tau) = F\varepsilon \; \{F\varepsilon + \frac{\varepsilon (1-\beta)^2}{2(\beta-\rho)\Lambda} \exp(-\alpha\tau)\}$$

$$= B\{B + A \; \exp(\alpha\tau)\} \quad (11)$$

$$\text{where, } B = F\varepsilon \quad (12)$$

$$A = \frac{\varepsilon (1-\beta)^2}{2(\beta-\rho) \; \Lambda} \quad (13)$$

This equation is the same as Rossi-α formula except that the Diven's factor $<\nu(\nu-1)>/<\nu>^2$ is disappeared in A.

$P(\tau)$ can be said as the probability of count-to-count interval. Hence all techniques based on this equation might be grouped as count-to-count interval probability method. They are Rossi-α technique, autocorrelation and endogeneous pulsed neutron source method. From a theoretical point of view Rossi-α technique and autocorrelation are substantially the same. But measuring instruments are entirely different. Rossi-α technique uses delayed coincidence circuit while autocorrelation uses MCS. Endogeneous pulsed neutron source method selects triggering pulses by burst counts which have higher probability of detecting chain-related neutrons.

One of the most popular techniques but using different form of equation, is variance to mean ratio (VTMR) method (Feynman method). The VTMR can be derived by using Eq.10 as following. The number of pairs of counts expected within a time interval T is

$$\left\langle \frac{c\,!}{(c-2)\,!\;\;c\,!} \right\rangle = \frac{\langle c\,(c-1)\rangle}{2}$$

$$= \int_{t_2=0}^{T}\int_{t_1=0}^{t_2} P\,(t_1,\,t_2)\,dt_1\,dt_2$$

$$= \frac{F^2\,\varepsilon^2\,T^2}{2} + \frac{F\varepsilon^2\,(1-\beta)^2\,T}{2\,\alpha^2\,\Lambda^2}\left[1-\frac{1-\exp(-\alpha T)}{\alpha\,T}\right] \quad (14)$$

Since the average counts, $\langle c\rangle = F\varepsilon T$

$$\mathrm{VTMR} = \frac{\langle c^2\rangle - \langle c\rangle^2}{\langle c\rangle} = 1 + \frac{\varepsilon\,(1-\beta)^2}{(\beta-\rho)^2}\left[1-\frac{1-\exp(-\alpha T)}{\alpha\,T}\right] = 1 + Y\,(T) \quad (15)$$

where, $$Y\,(T) = \frac{\varepsilon\,(1-\beta)^2}{(\beta-p)^2}\left[1-\frac{1-\exp(-\alpha T)}{\alpha\,T}\right]$$

$$= A_F\left[1-\frac{1-\exp(-\alpha T)}{\alpha\,T}\right] \quad (16)$$

$$A_F = \frac{\varepsilon\,(1-\beta)^2}{(\beta-\rho)^2} \quad (17)$$

VTMRs can be calculated using the count data gathered by MCS. Then they are fitted by Eq.16 to get α and A_F.

There are some other methods based on different equations such as count probability methods, dead time method, interval distribution(Babala) method, power spectral density method, etc. In this study autocorrelation and VTMR method have been applied so far for the analysis of the count data collected by using PC-based measurement system. Other methods remain for the further work.

3. Experiment and Analysis

The concept of pulse sequence measurement is shown in Fig. 1. A fission chamber is located at the core upper part of central thimble. Pulses coming from the discriminator are fed to the clock input of 10 MHz 16-bit counter/timer. The counter register value is read and moved to buffer memory by interrupt service

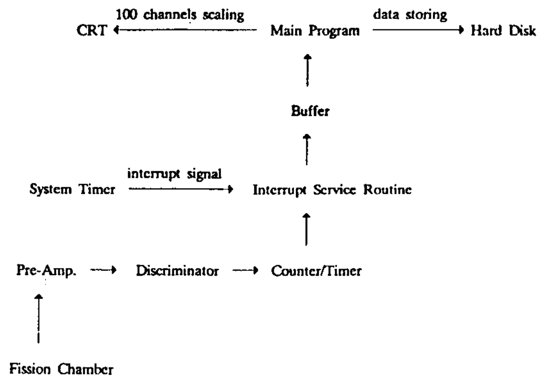

Fig. 1. The Flow Diagram of the PC-Based Measuring System

routine. The interrupt signal is periodically generated by the system timer whose frequency is controlled by the main program. For the case of 8 MHz AT the shortest period achievable is about 50μ seconds. In this experiment the interrupt time interval is fixed by 100μ seconds.

The main program reads buffer, selects time channels containing counts, displays 100 channels scaling on the CRT monitor and stores count sequence in a hard disk. Then these data are used for the calculations of autocorrelation and VTMR, and each result is least square fitted by Eq.11 or Eq.16 respectively. The maximum time interval of both analysis is about 50 mili-seconds that is short enough to neglet delayed neutron effect. However, the delayed neutron effect is taken into account to the data fitting by the following way, If delayed neutron terms are included then Eq.11 is modified to

$$P\,(\tau) = B\,\{B + A\;\exp(-\alpha\tau) + \textstyle\sum_i D_i\,\exp(-\alpha_i\,\tau)\} \quad (18)$$

where $\sum_i$ means the summation of every delayed neutron term. Since $\alpha_i\tau << 1$, Eq.18 can be approximated by

$$P\,(\tau) \simeq B\,\{B + A\;\exp(-\alpha\tau) + D - D_d\,\tau\} \quad (19)$$

where, $D = \sum_i D_i$ and, (20)

$$D_d = \textstyle\sum_i D_i\,\alpha_i \quad (21)$$

Table 1. Reacter State at Each Measurement

No.	1	2	3	4	5	6	7
Safety	up	up	up	up	up	up	up
Shim	up	up	800	630	482	down	down
Regulating	331	down	down	down	down	down	down
Reactivity (−$)	0.05	0.42	1	2	3	4.55	9.56
Measuring Time (sec)	460	3215	7786	15124	22132	33016	67686

Table 2. The Fitted Results of Autocorrelations

No.	1	2	3	4	5	6	7
Average CPS(B)	2697.80	348.37	142.44	73.06	49.86	33.39	16.27
A(/sec)	45.54	37.23	25.98	18.29	14.17	13.09	9.33
α(/sec)	147.34	184.59	255.04	375.02	494.80	816.26	1639.67
(/sec)	140.33	129.99	127.52	125.11	123.70	147.15	155.27
D(/sec)	10.47	0.8855	0.2163	0.2168	0.1310	0.0171	3.78E-3
(/sec²)	75.34	18.83	4.02	3.53	4.49	0.03	0.75
Computing Time (sec)	29600	4600	1975	1072	765	548	325

For the case of VTMR, the exponential is approximated up to the second order, i.e., $\exp(-\alpha_i T) \simeq 1-\alpha_i T+(\alpha_i T)^2/2$. Then Eq.16 is modified to

$$Y(T)=A_F\left[1-\frac{1-\exp(-\alpha T)}{\alpha T}\right]+\Sigma_i D_{Fi}\left[1-\frac{1-\exp(-\alpha_i T)}{\alpha_i T}\right]$$

$$\simeq A_F\left[1-\frac{1-\exp(-\alpha T)}{\alpha T}\right]+\frac{D_{F\alpha}}{2}T \qquad (22)$$

where, $D_{F\alpha}=\Sigma_i D_{Fi}\,\alpha_i$ (23)

The experiments were performed at seven different steady subcritical states from near-critical to reactor shutdown. Reactivity at each state was measured by the inverse point kinetics[6] of the same detector position. The reactor state at each experiment is summarized in Table 1. For the convenience of comparisons the number of time channels containing non-zero counts is fixed by 1,100,000 for each experiment.

Fig. 2 is the result of autocorrelation. As the figure indicates the chain-related portion is getting smaller as it approaches to critical. It can be explained by the fact that base $B(=F\varepsilon=-\varepsilon S/\rho\upsilon)$ is inversely proportional to while the chain related coefficient A is inversely proportional to $(\beta-\rho)$.

If the base B and delayed neutron terms are subtracted from the autocorrelation then only the chain-related part remains. Fig. 3 shows these results. Though data points are scattered rather widely, fitted parameters for the autocorrelation summarized in Table 2 are fairly consistent.

The Rossi-α and 1/A are proportional to $(\beta-\rho)$.Fig. 4 shows this relationship which is well maintained up to -3 \$ from critical. But the linear relationship is broken when the reactively is less than -4 \$. The proportionality of 1/B to $-\rho$ is well maintained up to -10 \$. As the portion of delayed neutron is so small it is hard to estimate quantitative values, but it is apparant that the delayed neutron effect exists at every case.

The computing time is very sensitive to the average count rate, and it takes too long time when the reactor is at near critical.

Fig. 5 is the result of VTMR. Y(T) which is VTMR-1 and has the meaning of chain-related effect to the VTMR, is getting larger as it approaches to cirtical. This trend is just the reverse of autocorrelation. In order to compare VTMR and autocorrelation explicity the exponentional part of Eq.22 is calculated by $A_F+(Y-D_{FD}T/2-A)\alpha T$ and depicted in Fig. 6 for each case. If this figure is compared to Fig. 3, VTMR's superiority, in terms of statistical reliability, to autocorrelation is easily recognized. Y(T)'s in Fig. 5 are fitted by Eq. 22 and their results are summarized in Table 3. Rossi-α can also be obtained by the ratio of autocorrelation's A and VTMR's A_F since $2A/A_F=\alpha$. Fortunately, three

Table 3. The Fitted Results of Variance to Mean Ratio

No.	1	2	3	4	5	6	7
(/sec)	0.741000	0.41815	0.20622	0.099286	0.059168	0.032819	0.011972
(/sec)	121.43	179.93	253.03	369.78	487.67	799.19	1581.67
2A/ (/sec)	122.91	178.09	251.96	368.43	479.08	797.99	1558.80
(/sec)	115.64	126.71	126.52	123.26	121.92	143.99	149.78
(/sec^2)	1.3144	0.6276	0.2448	0.2712	0.1108	0.0	0.0
Computing Time (sec)	8551	8801		9631	9814	9995	10181

·PC: 20 MHz 386 system with 80387 math-coprocessor

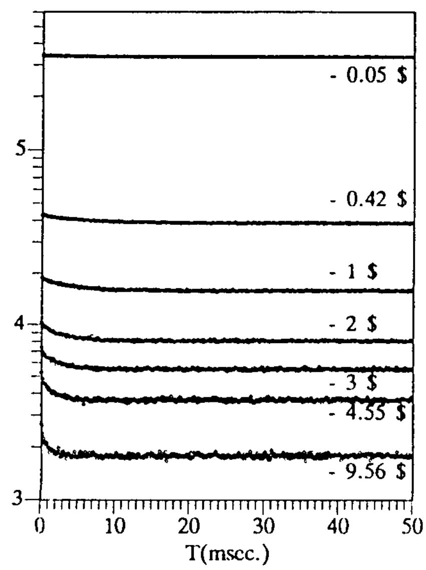

Fig. 2. Results of Autocorrelation

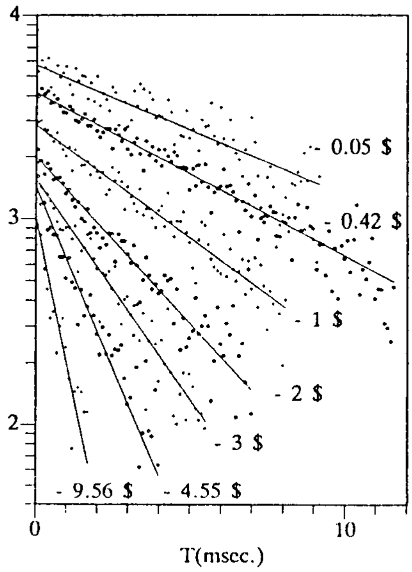

Fig. 3. Chain-Related Parts of Autocorrelation

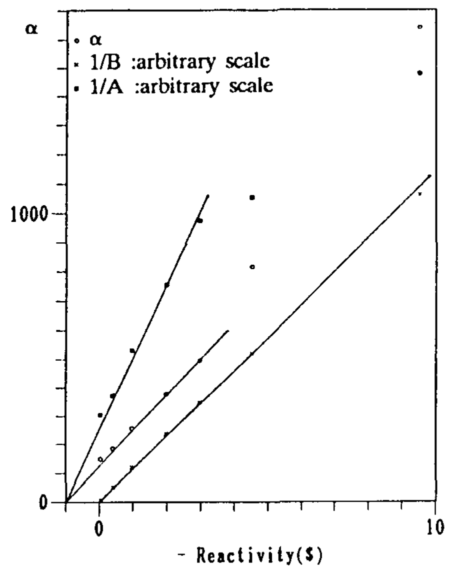

Fig. 4. Autocorrelation Parameters vs. Reactivity

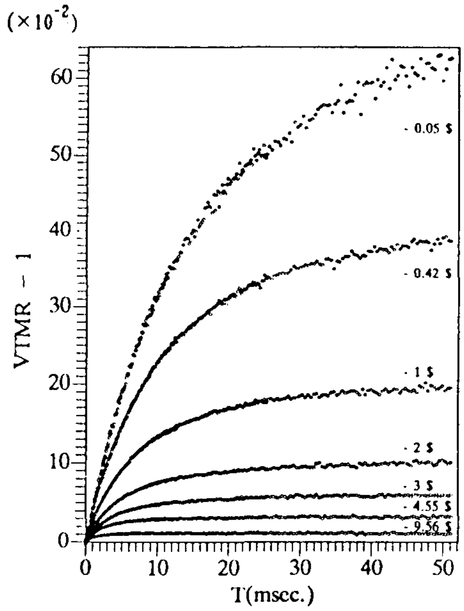

Fig. 5. Results of VTMR

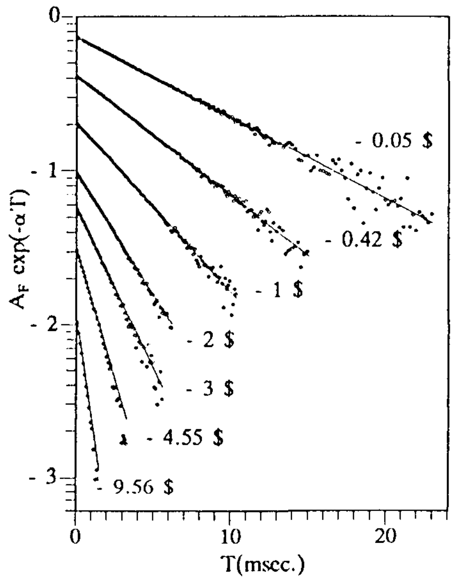

Fig. 6. Exponential Parts of VTMR

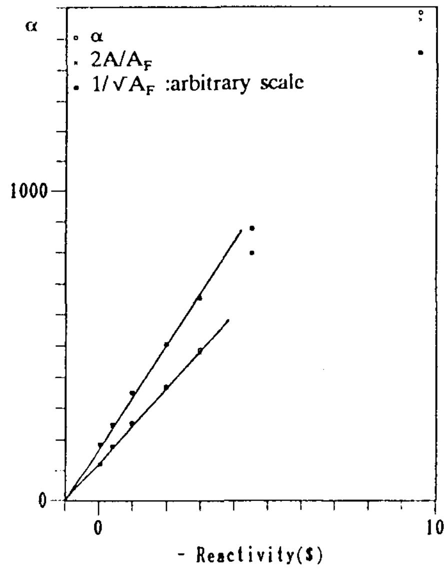

Fig. 7. VTMR Parameters vs. Reactivity

α's from auto-correlation, VTMR and $2A/A_F$ agree among themselves. $1/\sqrt{A_F}$ and α are proportional to (β-ρ). These are drawn in Fig 7 and it is apparant that the neutron generation time becomes shorter when the reactivity is below -4 $ because the neutron spectrum is getting hardened at the highly subcritical state.

Computing time for VTMR is not so dependent on reactivity but slightly more time is consumed as the subcriticality is higher. It can be said that computing time for VTMR is longer than that of autocorrelation except the case of near critical. This is not so serious when 32-bit fast PC is used, might be serious if a 16-bit PC is used which consumes much more than 10 hours for VTMR.

4. Conclusions

A PC-based system for measuring and analysing random neutron process in a thermal reactor has been successfully developed. It is confirmed that a general purpose 16-bit PC can be used as a convenient tool for the random neutron process measurement for thermal reactors, if it has a counter/timer board that is commonly used for the speed or cycle measurement. It can log count sequence data as large amount as its auxiliary memory permits and a real time display of multiscaling is possible. The shortest period of time channel achievable is dependent on the computer speed. For the case of 8 MHz AT which is used in this study, the shortest period is about 50μ seconds sufficient for the thermal reactor random neutron process measurement. In order to use PC for fast reactors, however, a special I/O circuit should be designed even though faster PC is used.

The results of two different methods-autocorrelation and VTMR-agree within acceptable difference, but VTMR's results show much superior statistical reliability than those of autocorrelation especially when it is near critical. The long computing time to calculate VTMR might be serious drawback if a 16-bit PC is used. Thus it is recommanded to use an up-to-dated fast PC for the analysis.

The β/Λ of TRIGA Mark-II reactor at KAERI is measured to be about 125/sec when the reactivity is within-3 \$ and about 150/sec when it is below -4 \$. The reason of higher β/Λ at highly subcritical state might be explained by the shorter neutron generation time due to the spectrum hardening.

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