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Determination of the Neutron Effective Multiplication Factor for a PWR Spent Fuel Assembly

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Abstract

An Exponential experiment system which is composed of a neutron detector, a signal analysis system and a neutron source, Cf-252 has been installed in order to experimentally determine the neutron effective multiplication factor for a PWR spent fuel assembly. The axial background neutron flux is measured in a preliminary performance test. From the results, the spacer grid position is determined to be consistent with the design specifications within a 2.3 % relative error. The induced fission neutron for four of the assemblies is also measured by scanning the neutron source, Cf-252 or the neutron detector. The exponential decay constants have been evaluated by the application of the Poisson regression to the net induced fission neutron counts. The measured keffs determined on the basis of the exponential decay constants of C15 appeared to be 0.541, 0.540, 0.597 and 0.556, respectively, which are comparable with 0.55195±0.00232 of the MCNP calculation.

1. Introduction

It has been reported that the reactivity related to the neutron effective multiplication factor is proportional to the exponential decay constant of the axial neutron flux of a fuel assembly, which is expressed by $1-1/k_{eff}=K\gamma^2$ where K is a reactivity-buckling conversion factor which can be determined by a diffusion code or a criticality experiment[1-4]. The experimentally measured k_{eff} was reported to be consistent with the calculated k_{eff} using the Monte Carlo method [5] by 3 %[3].

For the determination of the neutron multiplication factor for the PWR spent fuel loaded into the pool, a exponential experiment system has been installed in the Post Irradiation Examination Facility(PIEF) pool at Korea Atomic Energy Research Institute(KAERI). The aim is to validate the criticality calculation code and finally contribute to the implementation of the burnup credit. In this paper, the axial background neutron distribution in the C15, J14 and J44 assemblies are measured and the exponential decay constants for the C15, J14, G23 and J44 assemblies are determined. And the keff for C15 is preliminarily determined on the basis of the exponential decay constant.

The system components and preliminary performance test are explained in Section 2 and the axial background neutron flux measurement is shown Section 3. The exponential decay constant and keff determinations are described in Section 4.

2. Exponential experiment system setup and performance test[6]

The exponential experiment system consists of a Cf-252 neutron source, a neutron detector of the fission chamber type, electronic equipment and a PC including a spectrum analysis program as shown in Fig. 1[6]. The neutron detector is extremely small, ϕ6.3 x 25.4 mm and as is the fission chamber type in which 93 wt% U-235 is coated to the inside of the chamber. The detector is inserted into a ϕ9.5 stainless steel tube which can be loaded into the control rod guide tube of the PWR spent fuel assembly. The neutron source is contained in a stainless steel cylinder of ϕ6.8 x 10 mm in size. The activity and intensity are about 10 mCi and 4 x 10^7 n/s, respectively. The neutron source is inserted in a ϕ9.2 x 50 mm capsule and welded. The capsule is connected to a ϕ6 x 10 mm stainless steel bar which can be loaded into the control rod guide tube of the spent fuel assembly located in the PIEF storage pool which is ten meters deep.

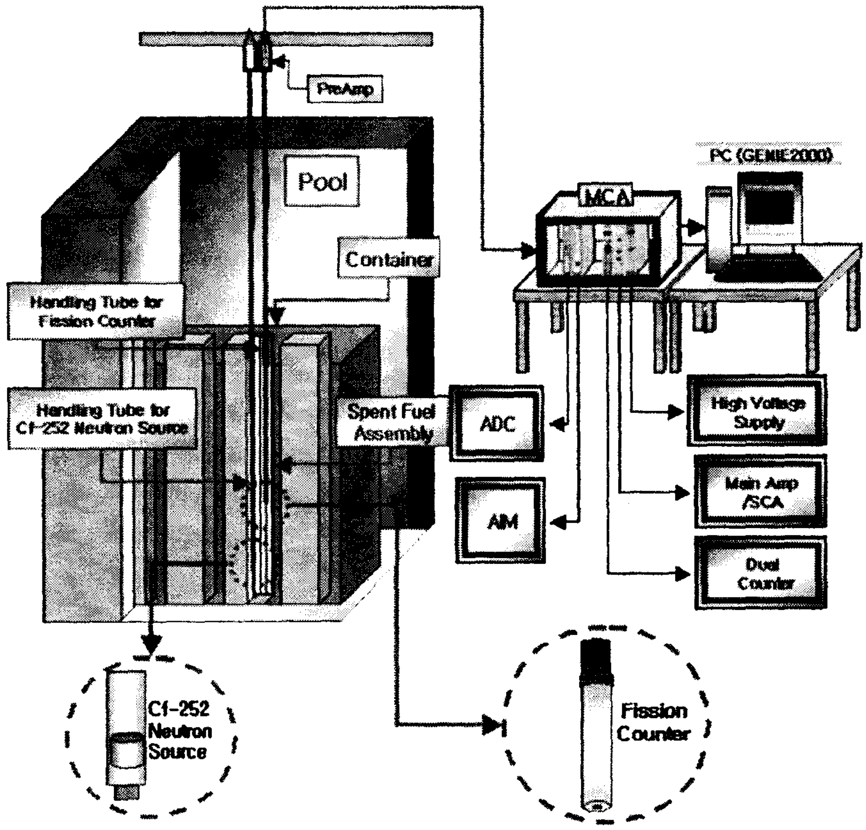

Fig. 1. Schematic Description of the Exponential experiment system installed in PIEF.

The neutron detecting signal transmits to the MCA via a pre-amplifier and a main-amplifier and the neutron counts are analyzed in the PC with a counting analysis software. Although the MCA cannot measure the neutron spectrum, it is useful for discriminating the noises due to the gamma-ray or electrics.

A response test of the exponential experiment system to the Cf-252, 4x10^7 n/s has been carried out. Several peaks appeared in the lower channels from 20 to 30. The peeks seem to result from the gamma-ray, which is similar to the fact reported in a previous result[4]. The gamma-ray effects should be removed by setting the cutoff channel in order to correctly count the neutrons.

Although the cutoff channel has been setup based on the response to a neutron from Cf-252, the test for the spent fuel assembly shows that there are a lot of noises which seem to be gamma-rays emitted from the spent fuel. The noise appears near channel 130 when the neutron counts at 63 cm from the bottom end of the fuel for the J14 assembly are measured. In the case of the C15 assembly the noise appears near channel 190. For discrimination of all the noises occurring, the minimum cutoff channel of the MCA has been chosen as 200.

The stability of the measurement system has been examined. When the neutron counts measured for the C15 assembly at different dates are compared with each other, the measured data has been confirmed to be within a 2σ uncertainty except for the bottom and top area of the assembly. Actually the axial neutron distribution measurement with the Cf-252 neutron source is performed in the center area of the assembly.

3. Measurement of axial background neutron flux distribution

The background neutron flux in the axial direction was measured for 3 minutes and at 5 ~ 10 cm intervals. Design specifications and burnup histories of the C15, J14 and G23 assemblies of Kori Unit 1 and the J44 assembly of Kori Unit 2 which were used in this measurement are listed in Table 1.

The plateau neutron counts per 3 minutes for the C15, J14 and J44 assemblies appear to be about 1900, 3800 and 3200, respectively. The counts seem to be dependent on the burnup and cooling time. The counts decrease when the neutron detector gets closer to the point of the spacer grid because the neutron is shielded by the spacer grid. The neutron count at the point of a spacer grid appears to be much less than the count of the fuel center area by about 30 %.

Table 1 Specifications and declared burnup for the PWR spent fuel assemblies

Item \ Assembly ID	C15	J14	G23	J44
Fuel type	14x14	14x14	14x14	16x16
Initial Enrichment(wt%)	3.199	3.197	3.103	3.486
Discharge Date	1982.4.17	1989.1.20	1986.10.24	1992.5.29
Active fuel length(mm)	3658	3658	3658	3658
Control rod guide tube (ID/OD)(mm)	12.8/13.7	12.8/13.7	12.8/13.7	11.05/11.96
Burnup (GWd/tU)	31.87	37.00	35.50	34.90

The neutron counts for the C15 and J14 assemblies from Kori Unit 1 are compared with the Cs-137 gamma scanning results. Several dips in the neutron flux distributions indicate the space grid positions. On the basis of this measurement, the spacer grid position is determined to be consistent with the design specifications with a maximum 2.3 % relative error.

4. Measurement of exponential decay constant and Determination of Keff

4.1. Net fission neutron measurement

When the neutron source was loaded into a control rod guide tube of the C15, J14 and J44 assemblies, the axial neutron distributions were measured. The detector was scanned in the axial direction from the position of the neutron source by 3 or 5 cm intervals where the neutron source was located at 180 cm from the bottom end of the assemblies. Alternatively the detector was fixed at 180 cm from the bottom end of the assemblies and the neutron source was scanned in the axial direction from the detector location by the same intervals.

The fission neutron counts were measured for the four measured positions in the C15, J14, G23 and J44 assemblies. The slopes of the axial neutron flux appear not to be exactly linear on the semi-log paper, which seems to be partly due to the short measuring time.

The net neutrons resulted from the external neutron source, which are used for the determination of the exponential decay constants, are obtained from the subtraction of the background neutron counts, from the measured neutron counts. The exponential decay constants at the measured points have been evaluated by the application of the Poisson regression to the net neutron count.

4.2. Poisson regression method

Net neutron count y_i detected at an arbitrary distance from the bottom of the assembly is known to follow the Poisson probability density function, $f(y_i)=e^{-\lambda_i}\lambda_i^{y_i}/y_i!$ with the expectation value, $E(y_i)=\lambda_i$ and the variance, $Var(y_i)=\lambda_i$. The regression model representing the relation between the response variable y_i and independent variable x_i is as follows:

$$E(y_i)=\lambda_i=e^{\beta_0+\beta_1 x_i} \quad (1)$$

From the independence assumption, the log likelihood of $y_1, y_2, \cdots, y_n$ is

$$\begin{aligned}\ln L &= \ln\prod_{i=1}^{n}\left[\frac{e^{-\lambda_i}\lambda_i^{y_i}}{y_i!}\right] \\ &= \sum_{i=1}^{n}\left[-e^{\beta_0+\beta_1 x_i}+y_i(\beta_0+\beta_1 x_i)-\ln y_i!\right]\end{aligned} \quad (2)$$

The MLE(maximum likelihood estimator) values of the regression coefficients β_0 and β_1 are the solutions satisfying the two equations below:

$$\frac{\partial \ln L}{\partial \beta_0}=\sum_{i=1}^{n}\left(y_i-e^{\beta_0+\beta_1 x_i}\right)=0 \quad (3)$$

$$\frac{\partial \ln L}{\partial \beta_1}=\sum_{i=1}^{n}\left(y_i-e^{\beta_0+\beta_1 x_i}\right)x_i=0 \quad (4)$$

When the iteratively re-weighted least squared method is applied to eq(3) and (4). b_0 and b_1 MLE of β_0 and β_1 respectively can be found.

The Wald's approximated $100(1-\alpha)\%$ confidence interval for the coefficient β_j is

$$b_j - z_{\alpha/2}se(b_j) \le \beta_j \le b_j + z_{\alpha/2}se(b_j) \quad (5)$$

where $se(b_j)$ is j-th diagonal element of $\sqrt{(X'\hat{V}X)^{-1}}$, $X'=\begin{pmatrix}1 & \cdots & 1\\ x_1 & \cdots & x_n\end{pmatrix}$ and $\hat{V}=diag\{e^{b_0+b_1 x_i}\}$ in the above equation.

4.3. Determination of exponential decay constant

The exponential decay constants have been determined on the basis of the Poisson regression using the Statistical Analysis System (SAS). Through the χ^2 test which is one of the fitting diagnosis in the Poisson regression, it was confirmed that the fitting results were good for most of the cases. That is, the values of χ^2 appear to be lower than the criteria of χ^2.

The exponential decay constants for the four measured positions in the C15, J14, G23 and J44 assemblies, respectively are determined and presented with 95 % confidence limits determined by using eq.(5) in Table 2. As shown in Table 2, for most of the cases, the measured exponential decay constants for each assembly are relatively consistent with each other. But the confidence interval which ranges from a lower limit to an upper limit are unexpectedly much large. Considering that the confidence limit depends on the random error and measuring time, if the detection time is increased in future experiments, the confidence interval will be much decreased.

4.4. keff Determination and comparison

If K, the reactivity-buckling factor is assumed to be 46.55 as evaluated in the previous result[1], the neutron effective multiplication factors(k_{eff}) for the four exponential constants of C15 are preliminarily determined to be 0.541, 0.540, 0.597 and 0.556, respectively using the equation of $1-1/k_{eff}=K\gamma^2$, where γ is the exponential decay constant. Three of the cases seem to be consistent with 0.55195±0.00232 which was calculated with the MCNP code[3], even though there is a big discrepancy in the third case.

Table 2. Exponential decay constant and its 95 % confidence limit for four assemblies

Assembly ID	Detector position	Exponential decay Constant (γ)	95 % Confidence limit	
			Lower	Upper
C15	E05	0.1350	0.1100	0.1620
	E10	0.1350	0.1110	0.1620
	J05	0.1200	0.0960	0.1480
	J10	0.1310	0.1080	0.1560
J14	E05	0.1320	0.1110	0.1540
	E10	0.1190	0.0990	0.1400
	J05	0.1230	0.1030	0.1440
	J10	0.1250	0.1050	0.1470
G23	C12	0.1250	0.1080	0.1430
	E05	0.1250	0.1070	0.1450
	J10	0.1280	0.1060	0.1520
	L03	0.1290	0.1090	0.1510
J44	F06	0.1190	0.1010	0.1380
	F11	0.1200	0.1010	0.1400
	K06	0.1220	0.1040	0.1410
	K11	0.1230	0.1060	0.1400

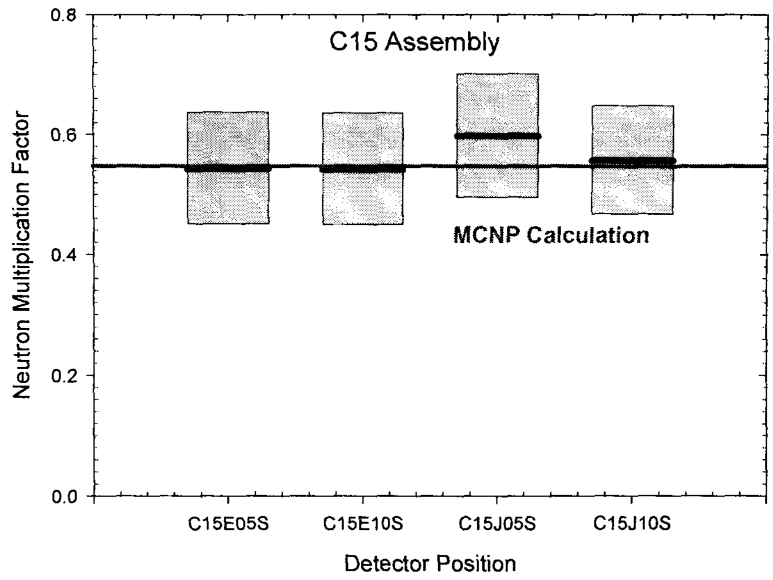

Fig. 2. Comparison of the Measured and Calculated Keff.

5. Conclusions

An exponential experiment system setup and a performance test has been carried out for several PWR spent fuel assemblies. Through the background neutron flux measurements of C15, J14 and J44, the exponential experiment system was confirmed to be successfully setup. The exponential decay constants for the C15, J14, G23 and J44 assemblies were determined using the confirmed exponential experiment system and the keff for the C15 assembly was preliminary determined. But it's necessary for further studies to improve the measuring method in order to decrease the 95 % confidence interval and determine the buckling-reactivity conversion factor for the PWR spent fuel assemblies.

Acknowledgement

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