RHODIUM SELF-POWERED NEUTRON DETECTOR'S LIFETIME FOR KOREAN STANDARD NUCLEAR POWER PLANTS

CHOON SUNG YOO*, BYOUNG CHUL KIM, JONG-HO PARK[1], ARNOLD H. FERO and S. L. ANDERSON[2]
Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseung-gu, Daejeon 305-353, Korea
[1]Chungnam National University
220 Gung-dong, Yuseung-gu, Daejeon 305-764, Korea
[2]Westinghouse Electric Company, Nuclear Service
P.O. Box 158, Madison, PA 15663, USA
*Corresponding author. E-mail : csyoo@kaeri.re.kr

Received March 7, 2005
Accepted for Publication June 27, 2005

A method to estimate the relative sensitivity of a self-powered rhodium detector for an upcoming cycle is developed by combining the rhodium depletion data from a nuclear design with the site measurement data. This method can be used both by nuclear power plant designers and by site staffs of Korean standard nuclear power plants for determining which rhodium detectors should be replaced during overhauls.

KEYWORDS : SPND, Sensitivity, Rhodium Detector, Lifetime, ICI Replacement, KSNP

1. INTRODUCTION

The fixed in-core instrumentation (ICI) system is used in Korean Standard Nuclear Power (KSNP) plants to determine the neutronic behavior inside the reactor core and to satisfy core monitoring and surveillance requirements. This fixed ICI system utilized in KSNP plants must permit the determination of core power peaking factors and core power tilts through each operating cycle such that the uncertainties in these calculated quantities are within the limits that have been licensed for the plants. The ICI systems must also enable the detection of misloading of any fuel assembly in the core at the beginning of each cycle of operation. Furthermore, the ICI system must satisfy operability requirements as defined in the plant Technical Specifications.

A significant advantage of fixed ICI systems, as compared to movable in-core detector systems and ex-core detector based systems, is the capability to measure the core power distribution directly and continuously to provide input to on-line surveillance and monitoring systems. By comparison, movable in-core detector systems can monitor the core power distribution only periodically; therefore, they cannot provide timely information to plant operators or monitoring systems. Ex-core based detector systems can be used to infer the core power distribution only indirectly; therefore, they are less accurate than fixed in-core detector based systems. The higher accuracy permitted by fixed ICI systems translates into a reduction of the uncertainties and conservatism that are applied to measured parameters (e.g., DNBR, local power density, and linear heat rate) which are monitored for the purpose of reactor safety. Consequently, a gain in the margin to licensed thermal limit can be achieved. The thermal margin gain can be translated into higher allowable power peaks, wider operating ranges, and additional flexibility in fuel management.

Most PWRs with an installed fixed ICI system rely on fixed in-core rhodium self-powered neutron detectors (SPNDs) which have a long and successful history of proven plant operation. However, due to the depletion of rhodium and the resultant decrease in rhodium detector sensitivity, ICIs utilizing rhodium detectors must be replaced periodically, as the uncertainties associated with the inferred core power distribution increase. As a result, the use of rhodium detectors results in maintenance costs associated with ICI hardware procurement, installation, disposal, and other ICI replacement operations.

The current criterion for ICI replacement due to rhodium detector depletion is when the rhodium detector is reduced to 1/3 of its initial sensitivity over the ICI lifetime. This

Table 1. ICI Replacement of Yonggwang Nuclear Unit 3

Overhaul Series	# of ICIs replaced at Overhaul	Average Relative Sensitivity (Level 3)
3	25	0.415
4	7	0.351
5	5	0.410
6	24	0.371
7	11	0.384
Total	72	0.389

criterion ensures that the uncertainties in core power peaking factors derived from fixed in-core detector signals are maintained within the limit specified in the CECOR Topical Report [1]. According to the ICI replacement criterion, all ICIs of which relative sensitivities will become less than 1/3 at the end of the next cycle should be replaced during the overhaul in advance, because the replacement of ICIs cannot be permitted during reactor operation.

In this paper, a new method of estimating the relative sensitivity of a rhodium detector for an upcoming cycle is introduced. This method can be used both by nuclear power plant designers and by plant site staffs responsible for selecting ICI strings that should be replaced during an overhaul.

2. THEORY

Table 1 shows an ICI replacement situation at Yonggwang Nuclear Unit 3. The average relative sensitivity of the axially centered detectors (level 3) for 72 replaced ICIs is about 0.389, which is considerably greater than the replacement criterion of 1/3 sensitivity (0.333). Generally, it would take more than 150 effective full power days (EFPDs) for the relative sensitivity of the detectors to decrease from 0.389 to 0.333, even inside of the core, where the assembly power is above average during the entire cycle. Replacement in advance is necessary, however, because the relative sensitivities of the 72 ICIs are estimated to become less than the 1/3 criterion at EOC of the next cycle. Therefore, a precise estimation of the detector depletion for the next cycle is the best way to reduce cost, maintenance time, and radiation waste.

The KSNP plants (Yonggwang units 3, 4, 5, and 6 and Ulchin units 3, 4, 5, and 6) each contain 45 ICI strings [2]. Each ICI string installed in the center guide tube of the instrumented assembly contains 5 rhodium detectors, 1 background detector, and 1 core exit thermocouple. The five 40-cm-long rhodium detectors are axially centered at 10, 30, 50, 70, and 90% of the active core height. This permits a gross three-dimensional power distribution mapping of the core from 10% to 125% of full power (2815 MWth). The background detector is used for compensation of background gamma rays, and the core exit thermocouple measures the primary coolant flow outlet temperature. In accordance with Technical Specifications, an ICI string is considered operable if at least 3 rhodium detectors in the string are operable. In addition, more than 75% of the total ICI strings should be operable during reactor operation.

The local power in an instrumented fuel assembly over each length of the detector (40 cm) is calculated from

$$P = \frac{I \cdot W'}{S} \tag{1}$$

where at any time

I = background corrected detector signal
S = detector sensitivity
W' = power-to-activation conversion factor

The W' conversion factor is the ratio of the assembly local power to the rhodium activation rate in the detector, i.e.,

$$W' = \frac{Local\ Power}{1/V \cdot \iint \sigma \phi dE dV} \tag{2}$$

where

σ = neutron energy dependent rhodium neutron capture cross section
ϕ = neutron energy and position dependent flux in the rhodium emitter
V = volume of the rhodium emitter
E = neutron energy

The W' conversion factor is calculated by the core design code ROCS [3] as a function of detector depletion and fuel assembly exposure. Such W' conversion factors are dependent on the detector depletion and fuel assembly exposure, as well as on the power sharing of the surrounding fuel assemblies. Because the rhodium detectors are located in the center of the fuel assembly, the detector activations are less influenced by the surrounding assembly power than by the interested assembly power itself. These W'

conversion factors are pre-calculated for the as-built core and then input to COLSS [4] and CECOR [5] for core monitoring and mapping.

The signal from the rhodium detector decreases with detector depletion, even in an unchanging neutron flux. The rhodium detector operates on the principle of neutron activation of ^{103}Rh, so that the decrease of rhodium number density results in a decrease of detector sensitivity. The detector sensitivity based on activation is defined as the ratio of the signal to activation, i.e.,

$$S = \frac{I}{1/V \cdot \iint \sigma\phi dEdV} \tag{3}$$

The signal current (I) of the above equation is proportional to the product of the neutron absorption in the rhodium emitter and the average beta escape probability, i.e.,

$$I = \varepsilon P_\beta N \iint \sigma\phi dEdV \tag{4}$$

where at any time

σ= electron charge
P_β= average beta escape probability
N= average rhodium number density

Using equations (3) and (4), the detector sensitivity is expressed as follows:

$$S = \varepsilon P_\beta NV \tag{5}$$

In KSNP plants, the detector sensitivity is considered as a linearly decreasing function, α =1.0 in equation (6), with respect to the accumulated detector charge Q, which is the time integration value of the background corrected detector signal [5], i.e.,

$$S = S_0\left(1 - \frac{Q}{Q_\infty}\right)^\alpha \tag{6}$$

where

S_o= initial detector sensitivity based on activation
Q= accumulated detector charge at any time during the depletion
Q_∞ = total theoretical charge (335 Coulomb for KSNP)
α = experimentally determined fitting parameter

Using equation (6), the relative sensitivities (S/S_o) for each detector are continuously calculated in the ICI processing program of a plant computer system to provide input to COLSS and CECOR for core monitoring and mapping. To confirm that the core monitoring and mapping system is valid at a particular state, detector signal reliability and detector sensitivity are essential. Therefore, site's staffs continuously checks the accumulated charges and the corresponding relative sensitivities for each detector.

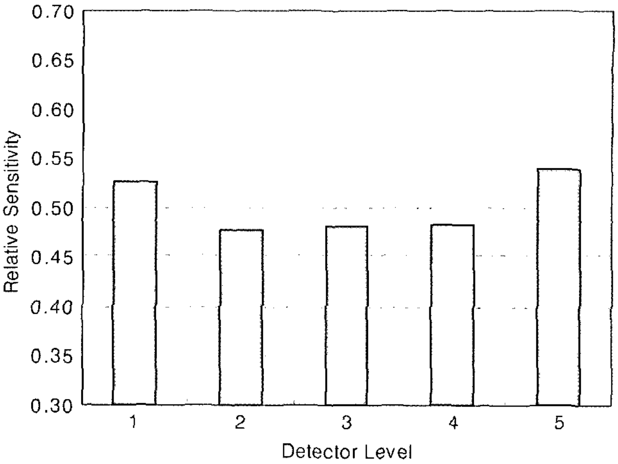

Fig. 1. Average Relative Sensitivity for Yonggwang Unit 3 Cycle 6 at EOC

As stated above, an ICI string is considered operable if at least 3 rhodium detectors in the string are operable. Essentially, the detector depletion trends of ICI levels 2, 3, and 4, which are axially centered at 30, 50, and 70% of the active core height, respectively, are very similar to one another in KSNP reload cycles since the flat axial power shapes are preserved from beginning of cycle (BOC) to end of cycle (EOC). On the other hand, the relative sensitivities of levels 1 and 5 are always greater than those of the three mid detectors, because the relative axial powers for the top and bottom of the core are relatively small in most PWRs. Figure 1 shows the average relative sensitivities with respect to the detector level for Yonggwang Nuclear Unit 3 Cycle 6 at EOC; this figure illustrates well the detector depletion trends mentioned above. Because the relative sensitivities of levels 1 and 5 are always greater than the other levels, in the absence of any failure, the ICI string can be considered operable if at least one of the three mid detectors is operable. In this study, detector level 3 was selected as a reference detector for a detector lifetime evaluation.

Fundamentally, the accumulated detector charge is the product of electron charge (ε), average beta escape probability (P_β), and the number of rhodium destroyed, i.e.,

$$Q(t) = \varepsilon P_\beta [N_0 - N(t)]V \tag{7}$$

where

ε = electron charge
P_β = average beta escape probability from $t = 0$ to $t = t$
$N(t)$ = average rhodium number density at time t
N_o = average rhodium number density at time zero
V = rhodium emitter volume

On the other hand, the total theoretical charge can be expressed as

$$Q_\infty = \varepsilon P_{\beta\infty} N_0 V \tag{8}$$

where

$P_{\beta\infty}$ = average beta escape probability from $t = 0$ to $t = \infty$

From equations (6), (7), and (8), we obtain

$$\frac{S}{S_0} = 1 - \frac{P_\beta}{P_{\beta\infty}}(1 - \frac{N}{N_0}) \tag{9}$$

Thus, the ratio of the beta escape probability can be expressed as

$$\frac{P_\beta}{P_{\beta\infty}} = (1 - \frac{S}{S_0})/(1 - \frac{N}{N_0}) \tag{10}$$

In the above equation, $(1\text{-}S/S_0)$ can be obtained from site measurement sources, such as a CECOR snapshot or a CECOR output file, while $(1\text{-}N/N_0)$ can also be obtained from the nuclear design depletion calculation for the as-built core. In this study cycles 4 through 6 of Yonggwang Nuclear Unit 3 were evaluated using CECOR core follow results and ROCS as-built depletion results; these results are shown in Figure 2. The ratio of beta escape probability $(P_\beta/P_{\beta\infty})$, as shown in Figure 2, is a slightly increasing function with respect to the detector depletion and a linear least square fit was performed, i.e.,

$$\frac{P_\beta}{P_{\beta\infty}} = 1 - 0.1(\frac{N}{N_0}) \tag{11}$$

This increasing function contradicts previous reports in this field. Generally, the beta escape probability decreases as the rhodium depletes, because the betas are generated deeper inside as the rhodium depletes [6,7]. The observed inconsistency can be explained with two reasons. The first reason is the fact that the relative sensitivity is being considered as linear with respect to the accumulated detector charge, even though α is less than 1.0, as described in Ref. [6] for equation (6); thus, the relative sensitivity is being underestimated as the detector depletes in KSNP plants. This underestimation makes the beta escape probability $(P_\beta/P_{\beta\infty})$ of equation (10) increase as the detector depletes. The second reason is the escaping of trapped betas. Betas having low kinetic energy when they are born in the emitter are trapped in the insulator, and they accumulate as the detector depletes. These betas can escape via interactions with high-energy fission gamma rays in the reactor, and the probability of escape increases in high-power fuel assemblies; thus, the power measurement uncertainties also increase for the highly depleted detectors. These measurement uncertainties with respect to the detector depletion are being studied for detector lifetime extension in KSNP plants.

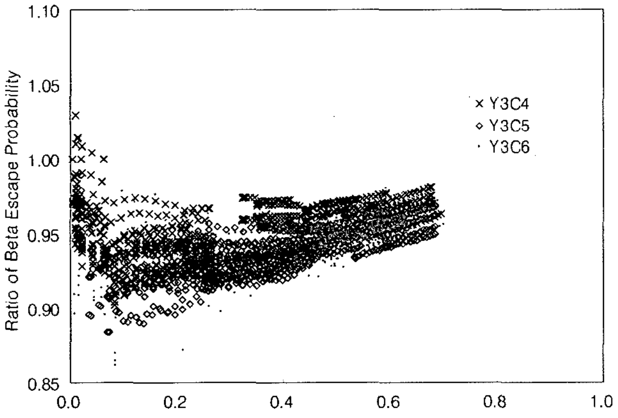

Fig. 2. Ratio of the Beta Escape Probability $(P_\beta/P_{\beta\infty})$ for Cycles 4 to 6 of Yonggwang Unit 3, Evaluated Using CECOR and ROCS Data

Note that the ratio of beta escape probability $(P_\beta/P_{\beta\infty})$ expressed by equation (11) was generated on the basis of rhodium depletion trends obtained from ROCS results and thus it could be changed when the cross section libraries used in ROCS were changed or if other design codes were used instead of ROCS.

Using equations (9) and (11) the relative sensitivities for BOC and EOC of the next cycle can be expressed as

$$(\frac{S}{S_0})_{boc} = 1 - [1 - 0.1(\frac{N}{N_0})_{boc}][1 - (\frac{N}{N_0})_{boc}] \tag{12}$$

$$(\frac{S}{S_0})_{eoc} = 1 - [1 - 0.1(\frac{N}{N_0})_{eoc}][1 - (\frac{N}{N_0})_{eoc}] \tag{13}$$

Using equations (12) and (13)

$$(\frac{S}{S_0})_{eoc} = (\frac{S}{S_0})_{boc} - [(\frac{N}{N_0})_{boc} - (\frac{N}{N_0})_{eoc}] \cdot Bias \tag{14}$$

where

$$Bias = -0.1 \cdot [(\frac{N}{N_0})_{boc} + (\frac{N}{N_0})_{eoc}] + 1.1 \tag{15}$$

The relative sensitivities at BOC of the next cycle, $(S/S_0)_{boc}$, are equivalent to those at EOC of the current cycle; therefore, a snapshot file, including accumulated detector charges and associated relative sensitivities, should be taken just before the reactor shutdown. The rhodium depletion fraction, (N/N_0), is calculated by a 3-dimensional coarse and fine mesh depletion calculation with a nuclear design code, such as ROCS. In such a case, the as-built depletion calculation is recommended for more precise results.

Equations (14) and (15) can be used to obtain the best-

Table 2. Comparisons of EOC Relative Sensitivity Data Estimated by Equations (14)-(15) of this Paper and CECOR Measurements for Yonggwang Unit 3 Cycle 7 and Ulchin Unit 3 Cycle 5

ICI #	YGN-3 CY-7			UCN-3 CY-5		
	This Paper	CECOR	Difference	This Paper	CECOR	Difference
1	*	*	*	0.512	0.514	-0.002
2	0.714	0.715	-0.001	0.395	0.396	-0.001
3	0.640	0.643	-0.003	0.795	0.800	-0.005
4	*	*	*	0.557	0.562	-0.005
5	0.412	0.412	0.000	0.774	0.779	-0.005
6	0.404	0.404	0.000	0.518	0.522	-0.004
7	0.451	0.453	-0.002	0.759	0.764	-0.005
8	0.779	0.782	-0.003	0.522	0.525	-0.003
9	0.548	0.551	-0.003	0.514	0.515	-0.001
10	0.755	0.753	0.002	0.374	0.374	0.000
11	0.760	0.759	0.001	0.513	0.518	-0.005
12	0.408	0.412	-0.004	0.537	0.544	-0.007
13	0.641	0.641	0.000	0.795	0.797	-0.002
14	*	*	*	0.774	0.774	0.000
15	0.774	0.775	-0.001	0.518	0.520	-0.002
16	0.767	0.766	0.001	0.500	0.500	0.000
17	0.767	0.763	0.004	0.520	0.522	-0.002
18	0.761	0.761	0.000	0.516	0.520	-0.004
19	0.774	0.774	0.000	0.496	0.497	-0.001
20	0.772	0.768	0.004	0.513	0.514	-0.001
21	0.776	0.776	0.000	0.502	0.504	-0.002
22	0.884	0.884	0.000	0.398	0.398	0.000
23	*	*	*	0.537	0.535	0.002
24	0.884	0.885	-0.001	0.395	0.395	0.000
25	0.776	0.775	0.001	0.500	0.499	0.001
26	0.775	0.773	0.002	0.533	0.534	-0.001
27	0.774	0.776	-0.002	0.497	0.500	-0.003
28	0.761	0.763	-0.002	0.516	0.520	-0.004
29	0.774	0.773	0.001	0.518	0.520	-0.002
30	0.413	0.414	-0.001	0.774	0.775	-0.001
31	*	*	*	0.491	0.496	-0.005
32	0.787	0.784	0.003	0.505	0.507	-0.002
33	0.779	0.777	0.002	0.511	0.513	-0.002
34	0.775	0.777	-0.002	0.537	0.543	-0.006
35	0.755	0.755	0.000	0.506	0.509	-0.003
36	0.777	0.780	-0.003	0.510	0.510	0.000
37	0.779	0.782	-0.003	0.524	0.530	-0.006
38	*	*	*	0.455	0.458	-0.003
39	0.457	0.459	-0.002	0.759	0.765	-0.006
40	0.395	0.394	0.001	0.511	0.514	-0.003
41	0.406	0.405	0.001	0.774	0.775	-0.001
42	*	*	*	0.554	0.558	-0.004
43	0.645	0.649	-0.004	0.795	0.801	-0.006
44	0.872	0.872	0.000	0.390	0.391	-0.001
45	0.382	0.382	0.000	0.504	0.504	0.000

* Not available due to detector fail

estimated detector relative sensitivities at any time of the upcoming cycle for site staffs and nuclear power plant designers. Even though these formulas were created by using the level 3 data of Yonggwang Nuclear Unit 3, they can also be applied to other detector levels for any KSNP plants after verifying the coefficients of the bias factor in equation (15). To verify equations (14) and (15), two test calculations were performed and the results are discussed in the results section that follows.

3. RESULTS AND DISCUSSION

The relative sensitivities of detector level 3 of Yonggwang Nuclear Unit 3 cycle 7 at 14,000 MWD/MTU were estimated by using equations (14) and (15) and then the results were compared to the measurement data from the CECOR output. Another test was performed for Ulchin Nuclear Unit 3 cycle 5 at 16,200 MWD/MTU. Table 2 shows a comparison of the two test cases and that the calculations were in good agreement with the measurement data.

An accurate estimation of the rhodium detector relative sensitivities for upcoming cycles during the selection of ICIs to be replaced is connected directly with a reduction of management cost and radiation waste.

In this paper, a new method to estimate the relative sensitivity of a rhodium detector for an upcoming cycle has been presented, and the results of this method are in good agreement with actual measurement data. The proposed method can be used by site staffs for selecting ICI strings that should be replaced during overhauls, as well as by KSNP nuclear designers.

If the cross section libraries of ROCS were changed, then the coefficients of bias in equation (15) should be re-evaluated for the new cross section libraries, because the rhodium depletions might be affected by the cross section libraries. In addition, if the design code used in rhodium depletion calculations were changed, then the bias should also be re-evaluated, though the main theory of this paper would still be applicable.

A study for the extension of rhodium detector lifetime is recommended as a further work to augment the findings of the present work.

REFERENCES

[1] A. Jonsson, W. B. Terney and M. W. Crump, "Evaluation of Uncertainty in the Nuclear Power Peaking Measured by the Self-Powered, Fixed In-core Detector System," CENPD-153-P, Rev. 1-P-A (1980).

[2] Final Safety Analysis Report for Yonggwang Unit 3 & 4, Korea Electric Power Company..

[3] "Users Manual for ROCS: Coarse- and Fine-Mesh Advanced Diffusion Theory Code for Reactor Core Analysis," Combustion Engineering, Inc., CE-CES-4-P Revision 11-P (1996).

[4] "Overview Description of the Core Operation Limit Supervisory System (COLSS)," CEN-312-P, Revision 01-P, Combustion Engineering, Inc. (1986).

[5] W. B. Terney, J. L. Biffer, C. O. Dechand, A. Jonsson, and R. M. Versluis, "The C-E CECOR Fixed In-Core Detector Analysis System," *Trans. Am. Nucl. Soc.*, **44**, 542 (1983).

[6] G. G. Kim and N. Z. Cho, "Investigation of the Sensitivity Depletion Lows for Rhodium Self-Powered Neutron Detectors (SPNDs)," *J. of KNS*, vol. 33, no. 2, p.121-131, April (2001).

[7] T. G. Ober and J. W. Malloy, "An Advanced Model for the Prediction of the Total Burnup-Dependent Self-Powered Rhodium Detector Response," Proc. Int. Conf. on Mathematics and Computations, Reactor Physics and Environmental Analysis, vol. 2, p.22-31, Portland, Oregon (1995).