Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Lifetime Evaluation of Rhodium Self-Powered Neutron Detector (SPND) at the Peripheral Area of the Core

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1. Introduction

The installation of a self-powered neutron detector (SPND) in a reactor core is widely used to monitor neutron fluxes. The rhodium (Rh) fixed in-core self-powered neutron detector (SPND) is currently used in many nuclear power plants for the purpose of safely monitoring the core power. The signal production mechanism of rhodium SPND relies primarily on the beta particles that result from neutron absorption of rhodium isotopes to produce an electric current. As the neutron transmutation process depletes the rhodium isotopes, the signal output per unit neutron flux from the rhodium detector becomes smaller.

Eventually, the rhodium detector signal decreases to a point at which the signal to noise ratio becomes too small to support the power distribution measurement uncertainty required for valid power distribution measurements.

The lifetime of SPND is determined by calculating the relative sensitivity of Rh detector. It is required that the Rh detector should be replaced before the burn-up of Rh detector has reached 66% of its original compositions. [1]

After 18-month long term operation has been adopted, the Rh in-core detectors inside of the core have been burned during 18 months and replaced almost within 2 cycles, that is, even if the detectors have 15 months of remaining lifetime it should be replaced. On the other hand, the Rh detectors at the peripheral area of the core have been burned slowly rather than inside ones. For this reason, the economics of Rh detector operations was so poor, and it is necessary that the life time of Rh incore detector should be re-assessed using relative sensitivity of Rh detector.

To predict Rh detector's relative sensitivity, ANC code which is an advanced nodal code capable of two-dimensional and three-dimensional calculations is used. Then it is determined that the Rh detectors be replaced on the basis of the predicted sensitivity value calculated by ANC code.

2. Lifetime of SPND

The lifetime of a SPND may be expressed either as burn-up life and/or useful life. [2] First, the burn-up life of SPND is the estimated fluence of neutrons of a given energy distribution after which the sensitive material will be consumed to such an extent that the detector characteristics exceed the specified tolerances for a specified purpose. The detector burn-up life is dependent on the signal-to-noise ratio in a particular application. This in turn is dependent on the burn-up rate of the SPND emitter material which can be calculated as follow;

$$burnup\ life\ (t) = -\ln\,(N/N_0)/(\lambda + \sigma_{eff}\,\phi_{th}) \quad (1)$$

where, N/N_0 is equal to the fraction of emitter atoms remaining, and Φ_{th} is the average thermal neutron fluence rate in the reactor.

Recommended signal-to-noise ratios for estimating burn-up life of SPNDs are as follows:

- ≥10 for protection functions;
- ≥ 2 for monitoring functions;
- or burn-up <66 % for emitters such as rhodium.

And, the useful life of SPND is the operational life, under irradiation and environmental conditions restricted within specified limits, after which the detector characteristics exceed the specified tolerances. The useful life of the SPND is dependent on:

- the manufacturing process of the SPND elements, the signal cables, and the materials of construction;
- the manufacturing construction;
- the connected electrical circuit.

3. Characteristics of Rh SPND

In Rh self-powered neutron detectors, the interactions between neutrons and atomic nuclei of Rh are used to produce a current which is proportional to the neutron fluence rate. The Rh emitter possesses relatively high cross sections to thermal neutrons and relatively high melting temperatures, and is compatible with the manufacturing process. The Rh SPND operates on the principle of neutron activation with the Rh^{103} emitter material and produces signals as following process; [3]

$$Rh^{103} + n^1 \rightarrow Rh^{104} \rightarrow Pd^{104} + \text{Beta}$$
$$T_{1/2} = 42\ \text{sec}$$

This process results in a change in the relative detector sensitivity to neutron flux with time due to Rh depletion.

4. Analysis of Detector Sensitivity

4.1 Calculation model of Rh relative sensitivity

The codes (CECOR and COLSS) for fixed in-core detector signal analysis use signals from the Rh in-core detectors to calculate the local power (P) in an instrumented assembly, and the relative sensitivity calculation formulation of the codes is as follows;

$$\text{Relative Sensitivity}\left(\frac{S}{S_o}\right)=\left[1-\frac{Q(t)}{Q_\infty}\right] \tag{2}$$

where, Q_∞ *= 335 Coulombs (theoretical charge)*
$Q(t)$ *= Sensitivity at time t*

Eq.(2) is based on the measured data calculated by In-Core Instrumentation Processing Program of Plant Monitoring System. ANC predicts the sensitivity by calculating rhodium number density as follows;

$$N(t)=N_0-\int_0^t N(t)\sigma_a\varphi dt \tag{3}$$

where, N_0 *: initial Rh number density*
$N(t)/N_0$ *: remaining fraction of emitter atoms*

4.2 Relative Sensitivity for the detectors of core peripheral area

It was assumed that the lifetime of the detectors was 5.11 years. And the N+1 and N+2 cycles were calculated to expect the relative sensitivity of the peripheral detectors in case of its lifetime exceeding 6 years. That is, depletions of 4, 5 or more cycles for the Rh detector in peripheral area of the core shown in figure 1 were calculated virtually in order to ensure that the relative sensitivity of 33% be reached for 6 years or even more than 7 years operation.

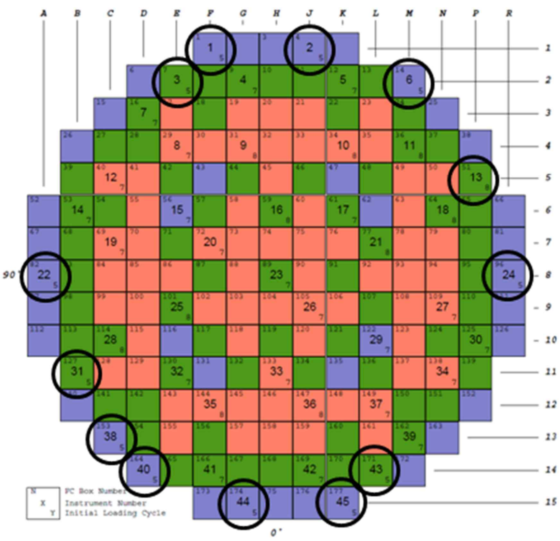

Fig 1. Locations of Rh detectors

As a result of the relative sensitivity evaluation, nine Rh detectors are available for more than 6 years, and four Rh detectors are available for seven years or more as shown in table 1.

Table 1. Operation year of peripheral detectors

UCN #5	Cycle N	Cycle N+1	Cycle N+2
Operation (year)	5.11	6.59	8.02
ICI number	-	1, 2, 6, 22, 24, 38, 40, 44, 45	1, 6, 40, 45

Due to the core power distribution and cycle length, that is, a loading pattern, the number of Rh detectors available at the end of the cycle is changeable. As the fuels located on the outside of the reactor core have relatively low power densities, the Rh detectors located in this area will be depleted slowly, and will be maintain a high value of relative sensitivity even for a long period of time.

5. Conclusions

Evaluations for the relative sensitivity of thirteen Rh detectors positioned in the peripheral area of the core show that nine Rh detectors can be operated for more than 6 years. It was confirmed that the lifetime of the Rh detectors could be extended from 6 years to 7 years.

Therefore, it is able to minimize the number of the Rh detectors to be replaced to the extent that meets the operating constraints of the Rh detectors at the end of the fuel cycle.

REFERENCES

[1] CEOG Final Report, “In-Core Instrumentation (ICI) Life Extension”

[2] IEC 61468, “Nuclear Power Plants - In-Core Instrumentation - Characteristics and Test Methods of Self-Powered Neutron Detectors”

[3] William H. Todt, “Characteristics of Self-Powered Neutron Detectors Used in Power Reactors”.