Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Study on the application of the Supplemental Surveillance Capsule for APR 1400

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***Keywords :** Lead Factor, Fast Neutron, EVND, RAPTOR-M3G, Surveillance Capsule

1. Introduction

The reactor pressure vessel(RPV) of a nuclear power plant is irradiated by fast (E≥1.0 MeV) neutrons during operation. This can cause embrittlement of the RPV material, or reduces the fracture toughness. Therefore, it is important to predict in advance the changes in the mechanical properties of materials due to the neutron irradiation.

In Korea nuclear power plants currently in operation, generally six surveillance capsules consisting of test specimens made of the same material as the reactor vessel and neutron dosimeters are installed between the core and the reactor vessel in the downcomer region near the reactor core or near the reactor vessel wall to evaluate the mechanical properties of the RPV according to neutron irradiation. Theses surveillance capsules are subjected to surveillance tests in accordance with the Nuclear Safety and Security Commission Notification 2021-28[1] and are used to evaluate the neutron irradiation embrittlement of RPV materials during the operating life of the reactor.

In addition, to minimize the uncertainty in reactor vessel embrittlement projections, Ex-Vessel Neutron Dosimetry(EVND) system is installed between reactor vessel insulation and the concrete primary biological shield. This system combines with surveillance capsule data to evaluate the neutron irradiation embrittlement of the reactor pressure vessel material.

The surveillance capsules are closer to the core than the inner surface of the RPV, so it receives a greater neutron irradiation. The lead factor is expressed as the ratio of the neutron flux(E≥1.0MeV) at the surveillance capsule to the neutron flux(E≥1.0MeV) at the reactor pressure vessel surface peak fluence location. For OPR-1000 and APR-1400 reactors, this lead factor was estimated at about 1.2 to 1.4, whereas for Westinghouse(WH) type reactors, it was about 3.0

According to the Nuclear Safety and Security Commission Notification 2021-28, surveillance capsules are required to be withdrawn and stored or evaluated when the accumulated neutron fluence(n/cm^2) of surveillance capsules corresponds to 1.5 times End Of Life(EOL) fluence at the RPV inner surface location.

However, APR-1400 and Korean Standard Nuclear Power Plants(OPR-1000) have difficulties in reaching 1.5 times fluence because of their low lead factor.

Currently, OPR-1000 plants are evaluating or planning to evaluate 1.5 times the EOL neutron fluence by inserting supplemental surveillance capsules into WH-type reactors or Framatome-type reactors. However, there are no plans for APR1400 reactors. In this paper, the neutron fluence at 1.5 times the EOL of APR1400 reactor is evaluated, and the withdrawal plan is described when supplemental surveillance capsules are installed in the WH-type reactors.

2. Methodology

2.1 Neutron transport calculation

The neutron fluence calculations were performed using Saeul Unit 1 and Kori Unit 3 model by RAPTOR-M3G 2.0[2] that USNRC-certified three-dimensional discrete ordinate transport code. The calculation of cumulative neutron fluence at the RPV and surveillance capsules is based on the geometric structures, including internal components of RPV as well as the cavitiy areas, and the operational history of the actual nuclear power plants.

Figure 1 and 2 show the models used for neutron transport calculations in Saeul Unit 1 and Kori Unit 3 using Tecplot[3]. Actual dimensions for each structure were used when precise fabrication data were available. However, in most cases, design values were utilized due to the difficulty in obtaining fabrication data for the reactors.

The neutron source distribution used in neutron transport calculations represents the density distribution of neutrons by energy generated fission reactions within the reactor core. It was calculated based on the initial enrichment and average burnup of nuclear fuel. The key nuclear design data such as initial enrichment, relative power distribution, and burnup for each fuel assembly required for the calculations were obtained from the nuclear design reports for the respective cycles.

Based on the described geometric structures and neutron sources, neutron fluence calculations were performed at the RPV and surveillance capsules locations.

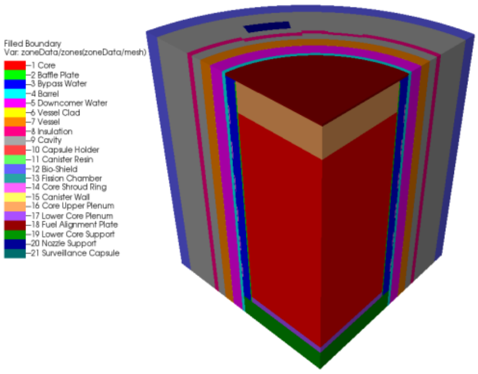

Fig. 1. Neutron Transport Calculation Model of Saeul Unit 1

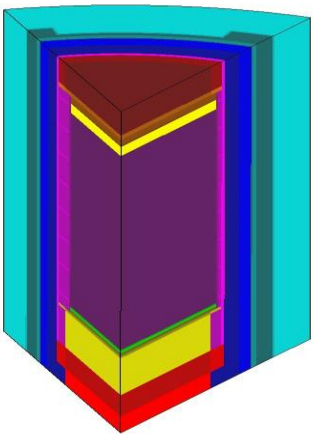

Fig. 2. Neutron Transport Calculation Models of Kori Unit3

2.2 Bias Factor

After calculating the neutron fluence at interested locations, the optimal neutron fluence was evaluated by multiplying the calculated neutron fluence with the optimal Bias Factor obtained from EVND and surveillance capsule as shown in the equation below.

$$\phi_{BestEst.} = K \times \phi_{Calc.}$$

$\phi_{BestEst.}$: Best Estimated the neutron fluence at the location of interest

K : Bias Factor

$\phi_{Calc.}$: Calculated the neutron fluence at the location of interest

The Bias Factor is obtained from the least squares adjustment procedure of the reaction rates calculated using analytical methods utilizing the neutron spectrum and cross-section data from the SNLRML[4] library, and the reaction rate obtain from the radiation measurements of dosimeters inserted into each surveillance capsules and EVND. By synthesizing the ratio of the Best Estimated(BE) value obtained from the least squares analysis and the Calculated(C) value of reaction rates, the bias factor is determined.

3. Result

3.1 Neutron Fluence on the Inner surface of the APR1400 Reactor Pressure Vessel

Table 1 shows the Bias Factor for Saeul Unit 1. Since the surveillance test has not been conducted, the bias factor was calculated using first to third EVND data. The optimal neutron fluence was calculated by weighting the bias factor to the neutron fluence calculated at inner surface of reactor vessel. With operating period of 60 years, which is lifespan of the reactor and 48 effective full power years(EFPY) when assuming an 80% operation rate, The calculated optimal fast neutron fluence at the azimuth angle of 43 degrees, where the highest neutron irradiation is expected, was 2.62E+19n/cm^2, and the fluence at 72EFPY that 1.5 times the EOL fluence is calculated to be 3.93E+19n/cm^2.

Table I : Bias Factor of Saeul Unit 1 EVND

EVND	BE/C
1st	0.97
2nd	0.91
3rd	0.93
AVEAGE [Bias Factor]	0.92

3.2 Neutron Fluence in Surveillance capsule of WH-Type Reactor

For WH-type reactor(Kori Unit 3), the fast neutron fluence at surveillance capsule position was calculated using Bias Factors derived from surveillance test. In the WH-type nuclear power plant, surveillance capsules are distributed across six locations, denoted as U (343˚), V (107˚), X (287˚), W (110˚), Y (290˚), and Z (340˚), as shown in Figure 3. Surveillance capsules U, V, and X are positioned at 17 degrees relative to the core symmetry, representing the locations with the highest lead factor. Surveillance capsules W, Y, and Z correspond to 20 degrees. The supplemental surveillance capsule for evaluating neutron fluence was assumed to be inserted at azimuth angle of 17degrees. After conducting neutron transport calculations at the surveillance capsule location with azimuth angle of 17 degrees in the WH-type nuclear power plant, the optimal fast neutron fluence was calculated by weighting the bias factor from Table 2, determined based on the evaluation results of three surveillance capsules inserted at the azimuth angle of 17 degrees. Considering the recent 8 cycles reactor output and fuel loading pattern of Kori Unit 3, the average effective full power year for one cycle was 1.31EFPY, and the average fast neutron fluence at the 17degree surveillance capsule location was evaluated to be 5.38E+19n/cm^2 for one cycle. Therefore, it has been calculated that for the neutron fluence of the surveillance capsule inserted into the WH-type nuclear power plant to exceed 1.5 times that of the neutron fluence at the EOL of the inner surface of the APR1400, it would need to operate for approximately 11.67years. This is equivalent to 9.34EFPY based on an 80% operation rate. The results of the optimal neutron flux calculations for the APR1400 and WH-type nuclear power plants have been summarized in Table 3 and Figure 4.

Table II : Bias Factor of Kori Unit 3 Surveillance Capsules

Surveillance Capsules	BE/C
Capsule U	0.91
Capsule V	0.95
Capsule X	0.94
AVEAGE [Bias Factor]	0.93

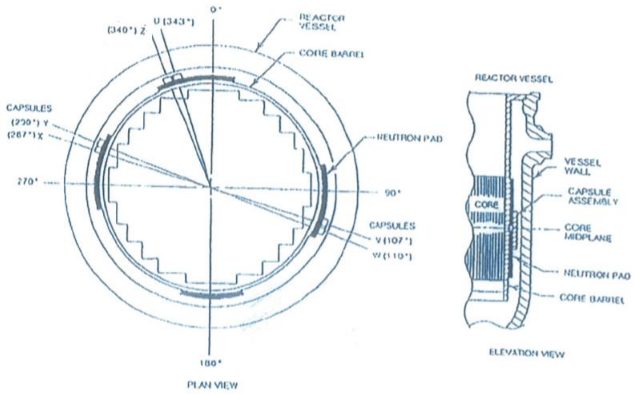

Fig. 3. Azimuthal Location of Surveillance Capsules of Kori Unit 3

Table III : Summary of neutron transport calculations

	Saeul Unit 1 Inner Surface of Vessel		Kori Unit 3 Surveillance Capsule (17 degree)
Irradiation Period [Year]	60 (48EFPY)	90 (72EFPY)	11.67 (9.34EFPY)
Fluence [10^{19}/cm^2]	2.62	3.93	3.93

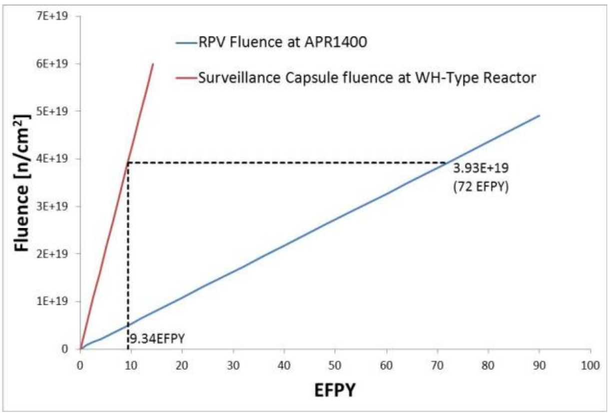

Fig. 4. Comparison of Neutron fluence between APR1400 vessel and WH Surveillance capsule

4. Conclusions

For APR1400 reactors, the calculation results of the fast neutron flux on the inner surface of the RPV and surveillance capsule indicate that the lead factor is approximately 1.2 to 1.4. Therefore, it is difficult to predict embrittlement characteristics for the vessel materials at 1.5 times EOL of APR1400. To evaluate the 1.5 times the RPV fluence at EOL of APR1400, it is predicted that a minimum of 11.67 years of operation period based on 80% operating rate at surveillance capsule position of WH-type reactor. However, the predicted fluence includes considerable uncertainty, as it exceeds 50 years at present. Therefore, to reduce uncertainty, periodic evaluations should be conducted based on accurate data, such as nuclear fuel loading patterns, power uprate, and other factors.

REFERENCES

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