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Evaluation on codes to estimate the number of failed rods using Korean PWR activity data

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1. Introduction

The coolant activity analysis to obtain the information about the fuel failure has been studied long before. And several codes have been developed to estimate the number of fuel failures through evaluating volatile and inert fission products release in coolant from the defective fuel. These codes use a fission product diffusion model coupled with a mass balance in the gap and coolant. But each code has a different model to assess fuel failure.

In order to develop the model to estimate the number of fuel failures we analysis well-known code's models such as CHIRON, CADE, IODYNE, and CAAP and compare accuracy through Korean PWR activity data.

2. Failure prediction model

With the occurrence of defective fuel, coolant can enter into gap in fuel rod. And fission products (i.e., notably the volatile species of noble gas and iodine) will be released into the primary coolant.

There are three release mechanisms from pellet to gap such as recoil, knock-out, and diffusion, but in general plant condition diffusion release is dominant. And according to Booth's diffusion model, $v_i = a\sqrt{\lambda_i}$, isotopes have same release behavior except decay effect. Each code's model is derived by this characteristic.

2.1 IODYNE

The IODYNE code uses I-131 and I-133. And the model is derived from a mass balance in the pellet and coolant except the gap.[1] So coolant activity can be expressed as:

$$(A_i)^C = y_i v_i' \lambda_i \dot{F} / (v_i' + \lambda_i)(\beta + \lambda_i) \tag{1}$$

Where $(A_i)^C$ is the coolant specific activity, Bq/gm, y_i is the cumulative fission yield of the i^th^ fission product, v_i' is rod escape rate coefficient for the i^th^ fission product, sec^{-1}, λ is the radioactive decay constant i^th^ fission product, sec^{-1}, $\dot{F}$ is average fission rate of the defective rod, fissions/sec, β is coolant purification rate for the i^th^ fission product. sec^{-1}.

So the escape rate of I-131 is obtained by combination of coolant activity of I-131 and I-133 and Booth's model. Thus the IODYNE code can predict general coolant activity from one failure rod and estimate the number of fuel failures.

$$X = (A_i)^C_{meas} \times \frac{(v_i' + \lambda_i)(\beta + \lambda_i)}{F Y_i v_i' \lambda_i} \tag{2}$$

The IODYNE code can be performed in transient condition differently from other codes. It simulates the decreasing activity after failure to adjust effective rod length.

2.2 CAAP

The CAAP code has two models derived from a mass balance in the pellet, gap, and coolant differently from IODYNE.[2] When the code evaluates that defect size is small, the number of failures is estimated by the diffusion model. This model is derived from the assumption that when the defect size is small, fission products diffuse through the gap and pellet to coolant release rate is proportional to pellet to gap release rate. So from the factor, f_{ij}, derived from diffusion equation and rod design, the diffusion model can be expressed as:

$$\left(\frac{R}{B}\right)_i^C = \left(\frac{R}{B}\right)_i^f \sum_j X_j f_{ij} + C^T \tag{3}$$

Where $(R/B)^C$ is measured ratio of the release rate of nuclide activity into the coolant to the "birth" rate of the nuclide in an average fuel rod, $(R/B)^f$ is determined ratio by database, C^T is the tramp uranium effect.

When the code evaluates that defect size is large, the number of failures is estimated by the kinetic model. In the kinetic model the fuel rod escape rate (ε) is obtained by combination of the release-to-birth ratio about decay constant, Booth's model, and three-region mass balance equation. Thus the kinetic model is expressed as:

$$\left(\frac{R}{B}\right)_i^C = \frac{Xa\varepsilon}{\sqrt{\lambda_i}(\varepsilon + \lambda_i)} + C^T \tag{4}$$

Where X is the number of failures, a is the pellet escape parameter (a).

2.3 CADE

The CADE code's model is based on ANS 5.3 sub committee recommended model and use iodine isotopes.[3] ANS 5.3 model is expressed as:

$$\frac{\dot{A}_i}{Y_i\lambda_i}=\left(\frac{R}{B}\right)_i \cong \frac{a\varepsilon}{\sqrt{\lambda_i}\,(\varepsilon+\lambda_i)}+\frac{kF^T Y_i^T}{FY_i} \qquad (5)$$

The parameters obtained by nonlinear regression analysis are used to estimate the number of failures. Because Eq. (5) is derived from following Eq. (6), the pellet escape parameter is a function of temperature and the number of failed fuel rods.

$$\frac{\dot{A}_i}{Y_i\lambda_i}=\left(\frac{R}{B}\right)_i \cong \sum_{j=1}^{x}\frac{a_j\varepsilon_j F_j}{\sqrt{\lambda_i}\,(\varepsilon_j+\lambda_i)F}+\frac{kF^T Y_i^T}{FY_i} \qquad (6)$$

So the CADE code estimates the number of failures rod by following Equation.

$$X = a/a_0 \qquad (7)$$

Where a_0 is a constant determined by database.

2.4 CHIRON

The CHIRON code has two models based on ANS 5.3 subcommittee recommended model and use iodine and offgas(xenon, krypton) isotopes.[5] The general model is similar to the CADE model. But if the fuel escape rate coefficient (ε) is very smaller than decay constant, it's difficult to separate the pellet escape parameter from numerator in ANS 5.3 model. In this case CHIRON fixes the fuel escape rate coefficient (ε) to 0. The general model is expressed as:

$$X = C_0\left[a\varepsilon/(\varepsilon+\varepsilon_0)\right]^{C_1} \qquad (8)$$

Where C_0, C_1, and ε_0 are a constant determined by database.

The combined model is developed to consider power effect. The pellet escape parameter (a) is a function of temperature (power) and the number of failed fuel rods. So power affects on estimation of the number of fuel failures. The combined model based on the ideas of different in diffusion velocity between iodine and offgas estimates power of defect rod and the number of failures. In Eq. (6) if the rod escape coefficient (ε) is similar in each defect rod, pellet escape parameter (a) in ANS 5.3 model is expressed as:

$$a = Xa_0\left(\frac{LHGR}{LHGR_0}\right)\exp\left(C\cdot\frac{LHGR-LHGR_0}{LHGR_0}\right) \qquad (9)$$

Through the pellet escape parameter (a) by nonlinear regression analysis and constants(C, a_0) determined by database about iodine and offgas the number of failures can be obtained.

3. Evaluation on code result in Korea PWR coolant activity

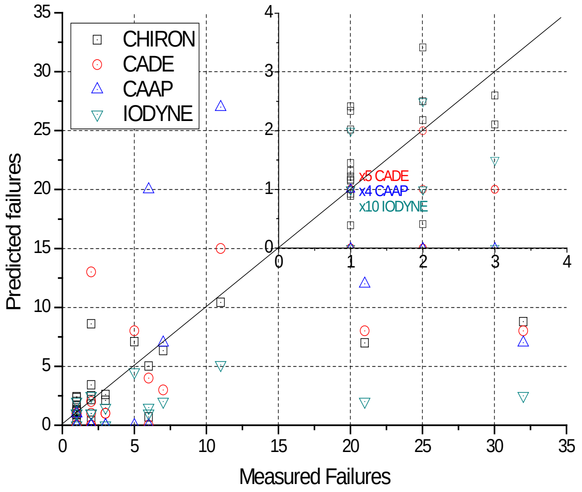

Fig.1. Each code failure comparison

Due to lack of offgas data the combined model in the CHIRON can't be performed. Generally the most accurate code is the CHIRON. The IODYNE code has a tendency to underestimate the number of failures and the number of failures doesn't go down to zero if the IODYNE code experience failure. When rod escape rate coefficient (ε) is very small, the CHIRON code is better than the CADE code. Otherwise the result of the CHIRON and CADE is similar.

4. Conclusions

According to the result the codes based on the model proposed by ANS 5.3 subcommittee are more accurate than others. But in the ANS 5.3 model when the rod escape coefficient (ε) is small, it's difficult to estimate the number of failures.

And the key parameter for estimating the number of failures is the pellet escape parameter (a). Because the pellet escape parameter (a) is affected by power, it's important to consider power effect.

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