A case study of fuel failure fission product escape rate in conjunction with rod power and fuel defect size using the CHIRON and CADE code

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1. Introduction

Several codes have been used to assess fuel failure through evaluating volatile fission products release in coolant from the defective fuel. There are well-known codes such as EPRI's CHIRON and Westinghouse's CADE in US. These codes use a fission product diffusion model coupled with a mass balance in the gap and coolant. CHIRON and CADE use 3-region model that the ANS 5.3 subcommittee proposed.[3][4] These codes use a factor deduced from a fission product diffusion model in order to evaluate failure. Especially fission product escape coefficients(i.e., α : from pellet to gap, ε : from gap to coolant) are important to develop more simulative model.

In order to study this fission product escape coefficients in conjunction with reactor power and defect size, we benchmarked the two codes(CHIRON, CADE) with a lot of real fuel failure plant data

2. Three Region Model

A fission product diffusion model coupled with a mass balance in the gap and coolant can be used to predict the coolant activity behavior for steady-state. 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. So through the governing equation in fuel pellet, gap, and coolant, the model predicting coolant activity can be written as:[4]

$$A_i \approx \frac{\lambda_i}{(\lambda_i + \beta_i)M_C} \cdot \left[\frac{\varepsilon_i v_i F Y_i}{\lambda_i(\varepsilon_i + \lambda_i)} + kF^T Y_i^T \right] \quad (1)$$

Where A is the coolant specific activity, Bq/gm, λ is the radioactive decay constant i^{th} fission product, sec^{-1}, M_C is active primary coolant mass(excluding pressurizer), gm/sec, ε_i is rod escape rate coefficient for the i^{th} fission product, sec^{-1}, υ_i is fuel escape rate coefficient for the i^{th} fission product, sec^{-1}, F is Average fission rate of the defective rod, fissions/sec, Y_i is cumulative fission yield of the i^{th} fission product, k is tramp activity direct release fraction, F^T is average fission rate of the tramp material, fissions/sec, Y_i^T is cumulative fission yield of the ith fission product at tramp burn-up condition. β_i is coolant purification rate for the i^{th} fission product. sec^{-1}.

According to Booth's diffusion model[5], the diffusion coefficient through the fuel can be represented as $\upsilon_i = \alpha\sqrt{\lambda_i}$ where α is a proportionality constant that is primarily a function of fuel temperature and the number of failed fuel rods. In addition, the cladding release rate parameter, ε_i, can be assumed to be constant for all nuclides having the same chemical reaction characteristics(e.g., all iodine isotopes, or all noble gas isotopes). With these additional assumptions, Eq. (1) can be expressed as:

$$\frac{\dot{A}_i}{Y_i\lambda_i} = \left(\frac{R}{B}\right)_i \cong \frac{a\varepsilon}{\sqrt{\lambda_i}\,(\varepsilon + \lambda_i)} + \frac{kF^T Y_i^T}{FY_i} \quad (2)$$

An equivalent form of Eq (2) has been proposed by the ANS 5.3 Subcommittee. This formulation utilizes the ratio of the release rate of nuclide activity into the coolant to the "birth" rate of the nuclide in an average fuel rod. This "release-to-birth" ratio can be determined from coolant measurements. CHIRON and CADE use the factor α and ε deducted from coolant measurements through the nonlinear regression method in order to predict fuel failure. [4][5]

3. Code Benchmarking

To benchmark the two codes, coolant activity data of single failed rod are used for evaluation. Five iodine isotopes data are selected among the coolant activity data. At each case we assume the power and the purification rate are in steady state. The details of fuel failures are summarized in Table-1. For running the codes, we used the assembly and maximum rod power and its fuel burn-up from NDR(Nuclear Design Report) and the defect size are well defined from PIE(Post Irradiation Examination) measurement.

TABLE I : Summary of benchmarked failure cases

	CASE1	CASE2	CASE3	CASE4
Defect size	7.1mm crack	Unidentified (Just discoloration)	Unidentified (Just discoloration)	10mm diameter
Assembly power	1.157	1.074	1.057	0.948
Max. rod power	1.433	1.174	1.231	1.23

Assembly burn-up	19599	40221	19109	13225
Rod burn-up	21518	41999	19162	13482
Estimated Rod power	1.23	1.074 ~ 1.174	1.02	0.998

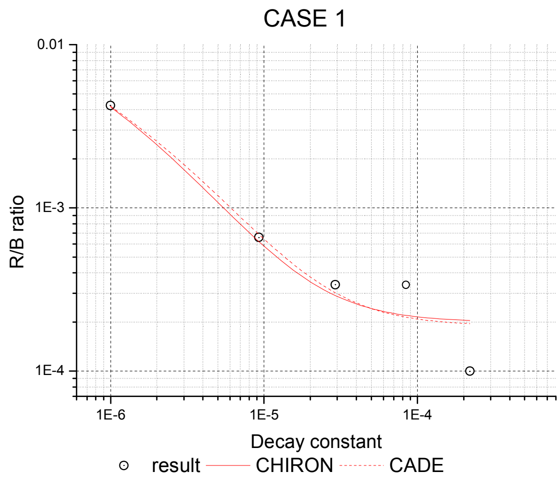

Figure 1 : Iodine distribution on case 1

Figure 1 shows that CHIRON and CADE simulate the R/B ratio well. The open circles in figure 1 are the R/B ratio calculated by left equation of Eq. 2 and the lines in figure 1 are the results calculated by codes. In conclusion, the results in this study have reliability because the escape factors (ε and α) calculated by codes (i.e., right equation of Eq. 2) simulate the R/B ratio well.

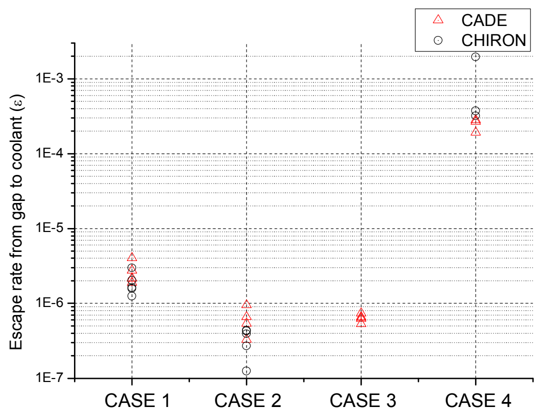

Figure 2 : Rod escape coefficient ε from gap to coolant

Figure 2 shows the relation between rod escape rate (ε, Calculated values by codes) and fuel defect size (Real values by PIE measurement). In case 1 (7.1mm crack), the rod escape rate (ε) from gap to coolant ranges from 1e-6 to 1e-5. In case 2 and 3(Unidentified, tiny defect), the rod escape rate (ε) is smaller than 1e-6. In case 4 (10mm diameter), the rod escape rate (ε) is very high because fuel defect size is large. As a result of figure 2, Rod escape rate(ε) is proportional to defect size from figure 2.

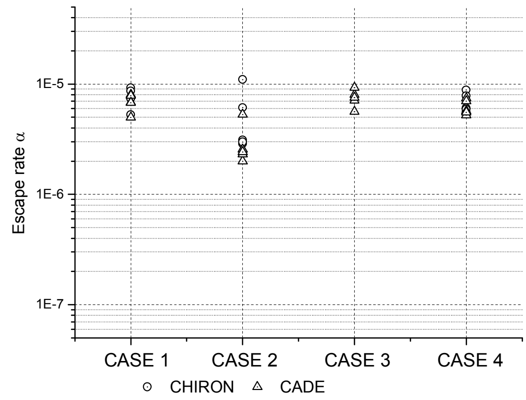

Figure 3 : Fuel escape coefficient α from pellet to gap

Figure 3 shows the relation between fuel escape rate(α) and fuel rod power. In table1, Estimated rod powers of all cases range from 0.998 to 1.23. As a result of code calculation, the range of fuel escape rate (α) is from 2e-6 to 2e-5. So fuel escape rate (α) is similar when the range of rod power is 1~1.2.

4. Conclusion

The method of CHIRON and CADE is some different but the results of codes are similar and simulates well.

In the relation between rod escape rate (ε) and defect size, rod escape rate (ε) usually is proportional to defect size. Especially, rod escape rate (ε) is smaller than 1e-6 in tiny defect size. (Fig. 2)

In the relation between fuel escape rate (α) and rod power, the fuel escape rate (α) has the range between 2e-6 and 2e-5 when the range of rod power is from 1 to 1.2. Additionally, If we can define the fuel escape rate (α) in various rod power, Code can predict the number of defect fuels more exactly.

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