Methodology of Delayed Hydride Cracking Assessment of Spent Fuel Cladding

Jong-Dae Hong*, Euijung Kim, Yong-Sik Yang, and Dong-Hak Kook
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
*jongd@kaeri.re.kr

1. Introduction

During dry storage, the spent fuel claddings could degrade through hydrogen-related degradation mechanisms. DHC (Delayed Hydride Cracking), which is a time dependent crack growth process resulting from stress assisted hydrogen diffusion to the crack tip, is considered as a main concern. In this regard, NRC, DOE, and EPRI also recognized that DHC is a potential cladding breach mechanism after ~100 years of dry storage, but relevant test data are limited. Moreover, there is no methodology to evaluate or regulate DHC phenomenon, because DHC was important only for CANDU pressure tube. In this regard, DHC assessment procedures using threshold stress intensity factor (K_{IH}) are proposed and applied to PWR spent fuel cladding.

2. DHC Assessment Procedure

In spite of scatter in the published data [1-3], the maximum CGR by the DHC phenomenon is estimated to be within the range of 10^{-7}m/s at which the cladding can rupture within a year at high temperature during the early stage of the dry storage period [4]. Thus, to maintain the integrity of cladding during long-term storage, DHC crack growth not supposed to happen.

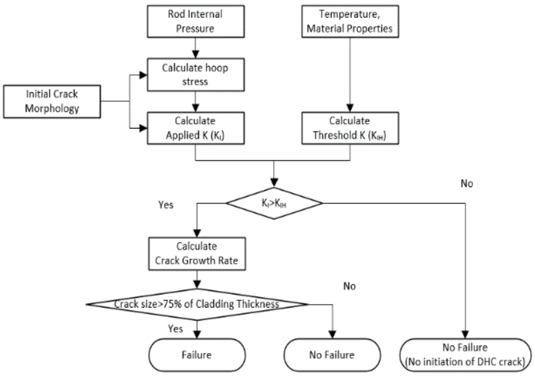


Fig. 1. Flow chart of integrity assessment for DHC [4].

In this regard, the threshold stress intensity factor (SIF), K_{IH}, is selected as principal criteria for DHC assessment. If crack grows, crack length increases according to crack growth model based on the IAEA CRP test data. Also, the cracks are judged as a failure when the grown crack size is greater than 75% of the cladding thickness. The overall flow of DHC assessment procedure is described as **Fig. 1**. Used model is summarized in **Fig. 2**.

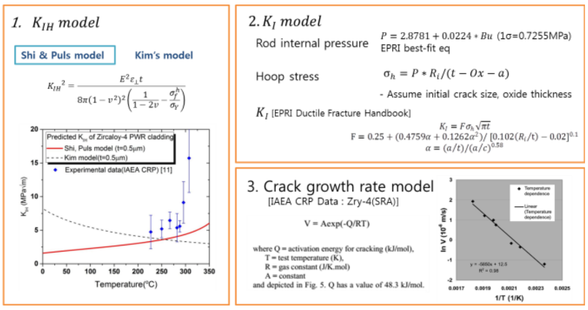


Fig. 2. Used model for DHC assessment.

2.1 Threshold stress intensity factor model (K_{IH})

To predict K_{IH} of Zircaloy-4 fuel cladding, many tests had been performed. But their results are limited and wide scattered with large uncertainties. Instead, theoretical estimations from fracture mechanics approaches were conducted using previous proposed for Zr-2.5Nb pressure tube by Shi and Puls [5]. It is function of hydride thickness, temperature and material properties. More detail is described on previous paper [4].

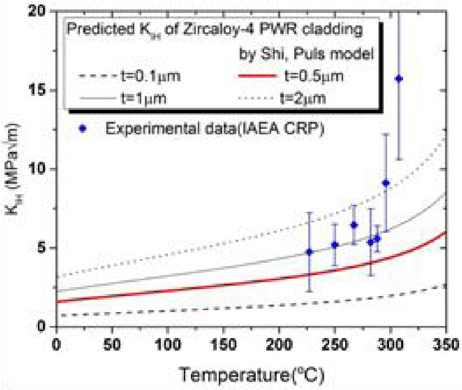


Fig. 3. K_{IH} prediction for Zircaloy-4 PWR cladding [4].

$$K_{IH}{}^{2} = \frac{E^{2}\varepsilon_{\perp}t}{8\pi(1-v^{2})^{2}\left(\frac{1}{1-2v}-\frac{\sigma_{f}^{h}}{\sigma_{Y}}\right)}$$

Also, material properties of Zircaloy-4 accounting for spent fuel cladding were used. The predicted values are described on **Fig. 3**.

2.2 Applied stress intensity factor model (K_I)

Applied SIF is also calculated for a comparison with K_{IH} using axial part-through wall internal flaw model in the EPRI ductile fracture handbook. That reflects the pre-existing crack morphology, hoop stress, and burn-up effect. As fuel burn-up increases, increased rod internal pressure and oxide thickness effects are reflected.

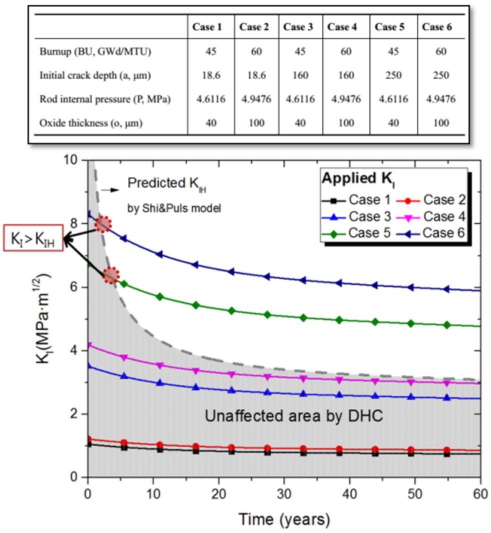
2.3 Crack growth model

The crack growth rate (CGR) of Zircaloy-4 cladding was estimated by following equation according to the IAEA CRP best-fit equation [1,2] once DHC crack growth occurs. The equation is only valid under the temperature below 283°C.

$$\mathrm{CGR(m/s)} = 10^{-8} * \exp(-5850 * \mathrm{T(K)} + 12.5)$$

3. Application to PWR spent fuel cladding

Case analyses were conducted to evaluate the degradation of PWR spent fuel cladding. Basic input values for the case analysis are shown in **Fig. 4**. For simulate low burn-up and high burn-up cladding, two kinds of fuel burn-up values were used. And three different initial crack sizes on Westinghouse 17X17 type cladding (OD = 9.5 mm) are assumed with conservatism.



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Burnup (BU, GWd/MTU)	45	60	45	60	45	60
Initial crack depth (a, μm)	18.6	18.6	160	160	250	250
Rod internal pressure (P, MPa)	4.6116	4.9476	4.6116	4.9476	4.6116	4.9476
Oxide thickness (o, μm)	40	100	40	100	40	100

Fig. 4. Estimated applied stress intensity factor of PWR spent fuel during dry storage [4].

Fig. 4 shows estimated applied SIF of PWR spent fuel during dry storage with comparison to the predicted threshold SIF. As shown in **Fig. 4**, DHC does not degrade cladding integrity for general cases of low burn-up and high burn-up fuels. But for some limiting cases considering damaged fuel (Case 5, 6), DHC crack grows occurs. Nevertheless, PWR spent fuel cladding during dry storage is not immune to DHC because used models were derived from limited data. By obtaining more information on spent fuel, a more accurate and reliable analysis may be possible.

4. Conclusion

DHC is considered as a most potential cladding breach mechanism for spent fuel cladding. The assessment procedures of that using threshold stress intensity factor (K_{IH}) are proposed and applied to PWR spent fuel cladding. From the analysis, degradation of PWR spent fuel by DHC could occur only for some limiting cases considering damaged fuel. But for a more accurate and reliable analysis, it need to obtain more information on spent fuel.

ACKNOWLEGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 2014171020166A).

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