

Probabilistic Validation of the 160 μm Critical Crack Depth Criterion for Spent Nuclear Fuel Cladding from the 1980s US Studies

Sangil Choi* and Lee Ju-Chan

Transportation and Storage R&D Section, Korea Atomic Energy Research Institute,
Daejeon 34057, Republic of Korea

*Corresponding author: sichoi89@kaeri.re.kr

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1. Introduction

To prevent the release of radioactive materials during the long-term dry storage and transportation of spent nuclear fuel, assessing the structural integrity of the cladding is essential [1]. In the quantitative evaluation of the cladding failure probability, the crack distribution and the critical crack depth serve as the most critical input parameters. Representative US research reports published in the 1980s (e.g., SAND90-2406) have historically derived crack distributions by assuming a conservative critical crack depth of 160 μm , which corresponds to approximately 28% of the cladding wall thickness [2]. However, it is necessary to verify whether assuming a 160 μm critical crack adequately accounts for the statistical variability of material properties. Accordingly, by introducing the probability density function of fracture toughness (K_{IC}) and an inverse calculation technique, this study aimed to verify whether the 160 μm critical crack depth criterion defined in the US studies of the 1980s is physically and probabilistically valid.

2. Method & Results

This study is based on the crack depth distribution formula from the existing SAND90 model. Moving beyond the conventional practice of using only the mean value of fracture toughness (e.g., 26 $\text{MPa}\sqrt{\text{m}}$), we adopted an advanced probabilistic method that incorporates the probability density function of K_{IC} (mean: 26 $\text{MPa}\sqrt{\text{m}}$, standard deviation: 5 $\text{MPa}\sqrt{\text{m}}$) into the evaluation. As a result, the critical crack size and the corresponding failure probability could be calculated according to the applied stress and fracture toughness, as illustrated in the Figure 1 and 2.

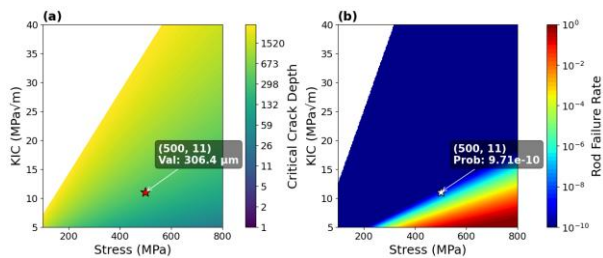


Fig. 1. (a) Critical crack depth (b) failure rate of cladding at various fracture toughness and stress.

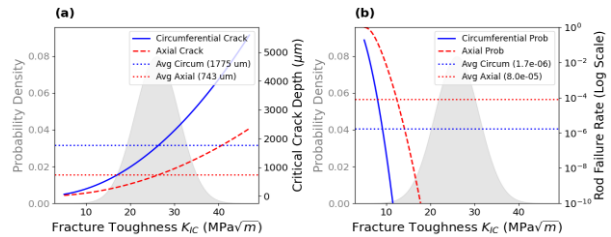


Fig. 2. (a) Weighted average of critical crack depth (b) Weighted average of failure rate of cladding at 500 MPa.

Furthermore, an inverse calculation was performed to validate the historical critical crack depth of 160 μm . By fixing the crack depth at this 160 μm criterion, the applied stress required to trigger cladding failure was back-calculated based on the K_{IC} distribution. Figure 3 shows the required stress.

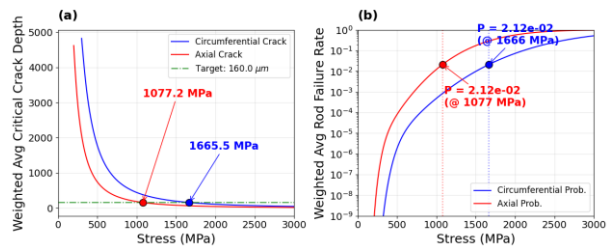


Fig. 3. Required stress for (a) critical crack depth and (b) failure rate of cladding at 160 μm

The analysis confirmed that the load required to cause failure at a 160 μm crack depth represents an extremely severe accident condition that exceeds the yield strength of the material in Figure 3. Figure 4 shows the fracture toughness for required stress at deterministic approach.

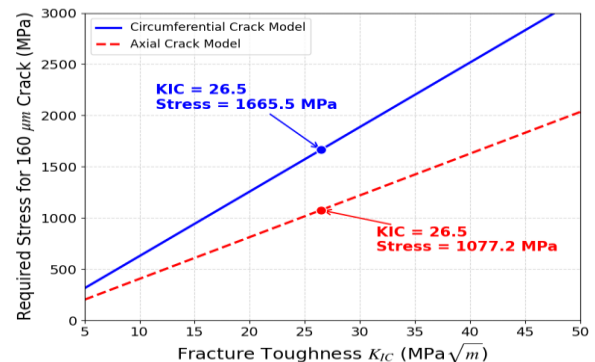


Fig. 4. Fracture toughness for required stress at deterministic approach method

3. Conclusion

Through probabilistic failure assessment and inverse calculation, this study successfully validated the 160 μm critical crack depth criterion—conventionally used in US spent nuclear fuel research since the 1980s—as a physically and statistically robust benchmark that transcends simple conservative assumptions. The evaluation, which accounts for the full probability distribution of fracture toughness, confirmed that the cladding maintains a low failure rate and secures a sufficient structural safety margin, even under external load conditions approaching the yield strength. The probabilistic validation methodology developed in this study is expected to serve as a robust technical basis for refining current safety regulatory guidelines and providing quantitative reliability for the long-term dry storage and transportation of spent nuclear fuel.

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