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Effect of thermal aging on the leak-before-break analysis of nuclear primary pipes

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HIGHLIGHTS

- Thermal aging embrittlement is considered in LBB assessment of nuclear pipe.
- Effect of thermal aging on growth behavior of partial-through crack is not obvious.
- Detectable leakage crack length of thermally aged material is slightly increased.
- Critical crack length of thermally aged material is significantly reduced.
- Ignorance of thermal aging produces less conservative LBB results.

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ABSTRACT

Three-dimensional finite element analysis (FEA) models were built for pipes with circumferential cracks and the effect of thermal aging embrittlement on the leak-before-break (LBB) behavior was analyzed according to the Level 2 and Level 3 safety assessments. The detectable leakage crack length obtained using the two-phase critical flow model and the critical crack length calculated by the *J*-integral stability assessment diagram method were carried out to assess the LBB behavior. The propagation behavior of partial-through circumferential cracks for both unaged and thermally aged materials was estimated by testing fatigue crack growth rate. The results show that the effect of thermal aging on detectable leakage crack length is not obvious, whereas the critical crack length after thermal aging significantly decreases due to degradation of fracture toughness. The increments of partial-through cracks are insignificant after 40 years of service. In the Level 2 and Level 3 safety assessments for nuclear piping, LBB is shown to have sufficient safety margins, while it is suggested to decrease in the case of thermal aging. This work demonstrates that less conservative LBB assessment results will be produced if thermal aging embrittlement in piping steels is not taken into consideration.

1. Introduction

The leak-before-break (LBB) assessment is essential to the design and evaluation of nuclear power plants against a sudden double-ended guillotine break (DEGB). The fundamental criterion of LBB behavior is that a large through-wall crack, which will result in coolant leaking rates in excess of those detected by leak monitoring system, can still remain stable under all predictable loading conditions (Nam-Su et al., 2001). Over recent years, LBB criterion has been employed to assess the safety of nuclear vessels and pipes containing defects. Beaudoin et al. (1990) described a LBB program for high energy balance-of-plant piping in the United States using fracture mechanics analysis. Bartholomé (1997) explained the 'German Leak-before-break procedures' and presented a general outline of prerequisites and practices for break preclusion. Saxena et al. (Saxena and Ramachandra Murthy, 2004, 2007; Saxena et al., 2009) carried out various experimental and analytical studies on LBB behavior for both straight pipes and piping elbows. At present, the LBB analysis has been extended to new nuclear power technologies such as advanced passive 1000 (AP1000) and fast

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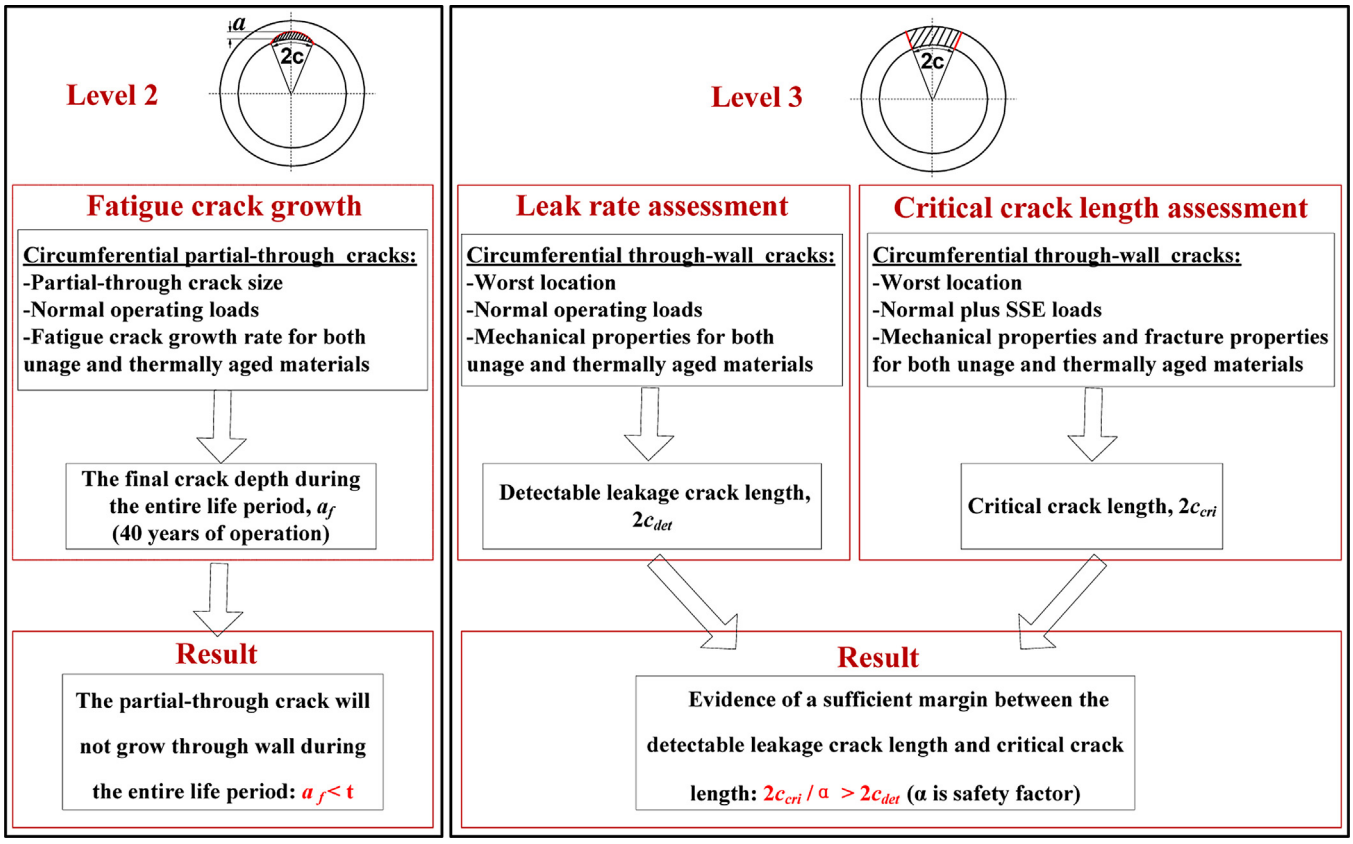

Fig. 1. Flow chart of LBB analysis procedure.

breeder reactors (FBRs). Gong et al. (2013) and Du et al. (2013) applied a LBB approach to a dissimilar metal welded joint connecting safe end to pipe-nozzle of an AP1000 reactor pressure vessel. Yoo and Huh (2013) and Wakai et al. (2013) demonstrated that the LBB assessment procedure is applicable to piping systems of FBRs.

Based on the tiered approach, LBB strategy consists of three levels of safety assessments (Chattopadhyay et al., 1999; USNRC, 2002; Murthy et al., 2007). The Level 1 safety requires that high-toughness materials be used in nuclear power plants because of their high resistance against catastrophic rupture. The Level 2 safety consists of a postulated partial-through crack on the inside surface of nuclear piping, and the crack insignificantly grows during the entire life period. In the Level 3 safety assessment, the postulated through-wall crack ensures that a leakage can be easily detected and the crack remains stable during a safe shutdown earthquake (SSE). Generally, high-toughness materials are used for nuclear components and the Level 1 is ignored, thus the Level 2 and Level 3 safety assessments for the LBB behavior of nuclear piping are presented in this paper.

Cast austenite-ferrite stainless steels are widely used to primary circuit piping in pressurized water nuclear reactors (PWRs) because of their excellent strength, high corrosion resistance, and good weldability. However, these steels are susceptible to thermal aging embrittlement during long-term service at temperatures ranging from 280 to 450 °C (Chung, 1992; Pareige et al., 2011). The effect of thermal aging on microstructure and mechanical properties has been investigated extensively (Chung and Leax, 1990; Danoix and Auger, 2000; Li et al., 2013a), and the structural integrity assessment and probabilistic fracture mechanics analysis of thermally aged nuclear components have been well established (Tujikura and Urata, 1999; Cicero et al., 2009; Li et al., 2013b). However, the effect of thermal aging embrittlement on the LBB behavior has rarely been addressed. Crack-like defects cannot be avoided in the manufacturing and installation processes of large cast components. It is thus imperative to evaluate the effect of thermal aging on the LBB behavior of nuclear piping that is made of cast austenite-ferrite stainless steels.

In this paper, to conduct the LBB assessment for both unaged and thermally aged nuclear pipes, three-dimensional finite element analysis (FEA) models are built for a series of circumferentially cracked pipes. The accurate stress intensity factor, crack opening displacement (COD), and *J*-integral calculations are carried out by the FEA. The detectable leakage crack length is obtained based on a two-phase critical flow model, and the critical crack length is calculated by the *J*-integral stability assessment diagram method. The growth behavior of partial-through cracks for both unaged and thermally aged pipe steels is also estimated by testing fatigue crack growth rate.

2. LBB assessment for unaged and thermally aged nuclear pressure pipes

2.1. LBB analysis procedure

According to the USNRC (2007) on the LBB assessment, an analysis procedure of nuclear pressure pipes with circumferential cracks was improved under consideration of thermal aging embrittlement, as shown in Fig. 1. For the partial-through cracks, the fatigue crack growth analysis for both the deepest point and surface point during the entire life period was performed. For the through-wall cracks, the detectable leakage crack length $2c_{det}$ and the critical crack length $2c_{cri}$ were calculated and compared with each other. If the postulated partial-through cracks cannot grow through wall during the entire life period and $2c_{cri}/\alpha$ is larger than $2c_{det}$, the LBB assessment will be fulfilled; otherwise, catastrophic failure will occur and the LBB assessment is not applicable.