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Probabilistic integrity assessment of pressure tubes in an operating pressurized heavy water reactor

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ABSTRACT

Even though pressure tubes are major components of a pressurized heavy water reactor (PHWR), only small proportions of pressure tubes are sampled for inspection due to limited inspection time and costs. Since the inspection scope and integrity evaluation have been treated by using a deterministic approach in general, a set of conservative data was used instead of all known information related to in-service degradation mechanisms because of inherent uncertainties in the examination. Recently, in order that pressure tube degradations identified in a sample of inspected pressure tubes are taken into account to address the balance of the uninspected ones in the reactor core, a probabilistic approach has been introduced. In the present paper, probabilistic integrity assessments of PHWR pressure tubes were carried out based on accumulated operating experiences and enhanced technology. Parametric analyses on key variables were conducted, which were periodically measured by in-service inspection program, such as deuterium uptake rate, dimensional change rate of pressure tube and flaw size distribution. Subsequently, a methodology to decide optimum statistical distribution by using a robust method adopting a genetic algorithm was proposed and applied to the most influential variable to verify the reliability of the proposed method. Finally, pros and cons of the alternative distributions comparing with corresponding ones derived from the traditional method as well as technical findings from the statistical assessment were discussed to show applicability to the probabilistic assessment of pressure tubes.

1. Introduction

Pressure tubes in a PHWR (Pressurized Heavy Water Reactor) are periodically inspected according to a plant specific long-term plan with related documents [1]. Although the pressure tube is a major component as a pressure boundary of the PHWR, at present, only small proportions of pressure tubes are sampled for inspection due to the limitation of inspection time and expense. When a detected flaw indication does not satisfy relevant acceptance standards of the examination or the pressure tube to calandria tube contact is detected or predicted, a fitness-for-service assessment is necessary to decide whether continued service is available or not. To provide an evaluation guideline for protection against fracture of pressure tubes, the CANDU (CANada Deuterium Uranium) Owners Group developed a FFSG (Fitness for Service Guideline) which includes acceptance standards and criteria, material properties and derived quantities used in the evaluation procedure to confirm safety of in-reactor pressure tubes.

The FFSG is based on applicable rules of Section XI of the ASME Boiler and Pressure Vessel Code [2]. However, since the ASME Code does not provide specific requirements for PHWRs, additional rules were included in the FFSG to address PHWR specific features, for instance, DHC (Delayed Hydride Cracking) mechanism, terminal solid solubility limits, deuterium ingress, stress concentration for a fretting flaw, blister formation and growth etc. The guideline for zirconium alloy pressure tubes was firstly published on a trial basis by AECL (Atomic Energy of Canada Limited) in 1991, which was updated in 1994 and 1996 to incorporate advances in ad hoc researches [3,4]. In these incipient issues, the inspection scope and structural integrity have been treated by using a deterministic evaluation concept but conservative data were used instead of all known information related to in-service degradation mechanisms due to inherent examination uncertainties.

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By considering the large uncertainties associated with diverse degradation mechanisms and limited data as well as changing regulatory philosophy based on risk-informed decision, nuclear industries devoted lots of efforts to make prudent risk-based frameworks; establishment of management techniques for reactor core safety in operating plants, development of augmented material and operating experience databases and incorporation of several on-going researches to gain a better understanding of the degradation mechanisms of the pressure tubes. Recently, N285.8 [5] was published through registering the FFSG in the standard of CSA (Canadian Standards Association). Therein, a probabilistic approach as well as an advanced deterministic approach is addressed in order that degradations identified in a sample of inspected pressure tubes are accounted for the balance of uninspected ones in the reactor core [6–8].

The objective of current paper is to introduce structural integrity assessments of pressure tubes in an operating PHWR. With respect to this, flaw evaluation procedures in accordance with the CSA Code are recalled in Section 2. Subsequently, probabilistic parameters are defined taking into account defect shape, delayed hydride cracking velocity, fracture toughness and so on. Then, parametric analyses on important variables such as deuterium uptake rate, dimensional change rate of pressure tube and flaw size distribution are conducted in Section 3. In Section 4, a method to decide optimum statistical distribution by using a robust genetic algorithm is proposed and applied to the most influential variable to examine reliability of the proposed method. Pros and cons of the resulting alternative distributions comparing with corresponding ones derived from the traditional method and technical findings from the assessment are fully discussed to show applicability to the flawed pressure tubes. Finally, in Section 5, concluding remarks of this paper are described.

2. Brief description of flaw evaluation procedures [5]

The CSA N285.8 provides analytical procedures for protection against fracture, in which the evaluation shall be completed by using either deterministic method or probabilistic method. For the former, to demonstrate a postulated part-through-wall or through-wall axial flaw in the most limiting pressure tube is stable, effects of full range pressure and temperature combinations have to be examined along with appropriate fracture toughness. For the latter, the probability over the evaluation period of the postulated flaw being unstable has to be less than the maximum acceptable probability. The relevant descriptions are summarized as follows.

2.1. Planar and laminar flaws

The pressure tube containing planar and laminar flaws is acceptable for continued service if the technical requirements for fracture initiation and plastic collapse are satisfied through a subcritical flaw growth analysis:

(a) An evaluation period is established considering the end of the pressure tube design life.
(b) The flaw geometry and material properties including the effects of irradiation and hydrogen equivalent concentration are determined.
(c) Loading conditions and stresses at the flaw location are determined.
(d) Flaw growth is evaluated to determine the maximum flaw dimensions at the end of the evaluation period.
(e) The calculated final flaw is evaluated for fracture initiation and plastic collapse.

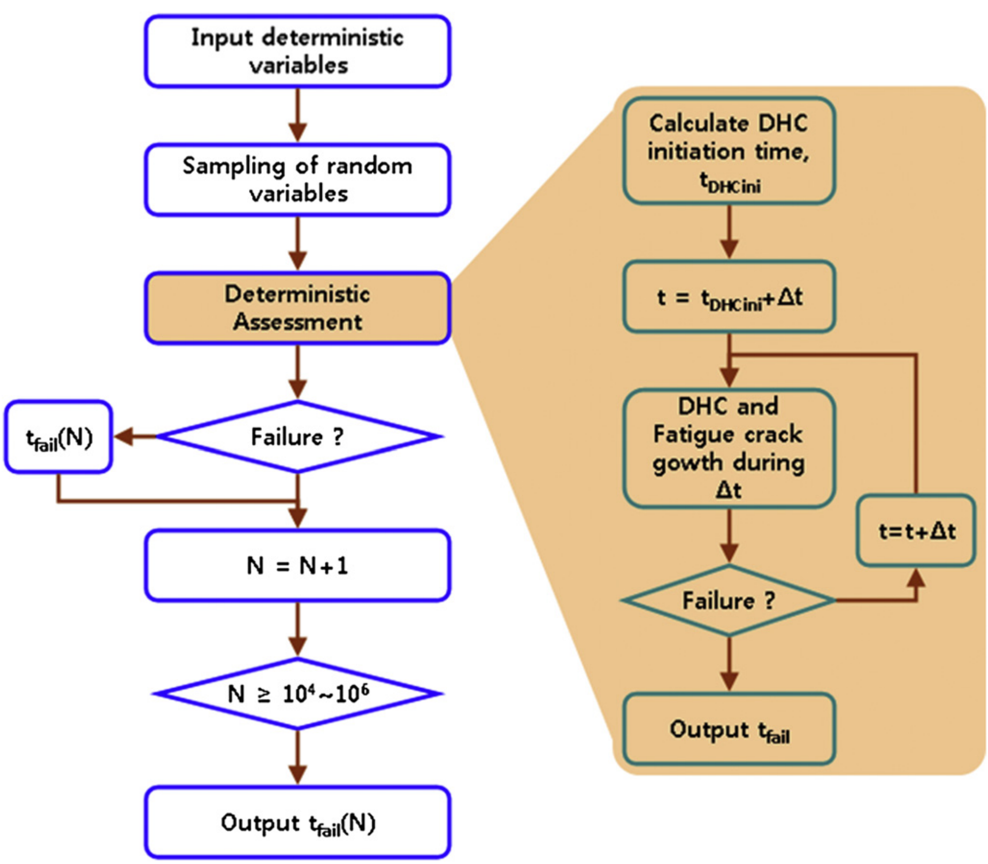

Fig. 1. The process of probabilistic integrity assessment based on the Monte Carlo method.