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Crack initiation, arrest and tearing assessments of a RPV subjected to PTS events

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ABSTRACT

Although the resistance of reactor pressure vessel (RPV) against fast fracture has to be proven by comprehensive analyses, there are few published literatures systematically discussing the crack initiation, arrest and tearing instability assessment in the pressurized thermal shock (PTS) events. In this paper, three types of assessment are discussed and studied. For the rapid cool-down of the typical PTS transients, the temperature of the deepest point along the crack tip is often high enough to ensure that both crack arrest assessment and crack tearing instability assessment can be used to prevent the RPV failure after the crack initiation occurs. When the assessment is changed from the crack initiation assessment to the crack arrest assessment, the transition temperature region of the material toughness curve moves towards to the right which leads to an increase of the area in which the brittle cleavage fracture may occur. It is not possible to determine the most dangerous moment before the detailed analysis of fracture mechanism. So the method of assessment the most dangerous moment which is given in the initial input data may be non-conservative. As the conservative crack shape parameter and method to consider the plastic correction are used in the French RCC-M code, the size of critical crack is very small in the case study. While according to the new study results, the tearing process of the RPV is still stable even for a big initial crack which is larger than the maximum hypothetical crack size in the code.

1. Introduction

The PTS event poses a potentially significant challenge to the structural integrity of RPV during the LTO of the NPPs (IAEA, 2010; Qian, 2015). For aged RPVs, the stress in the PTS events could be high enough to initiate a running cleavage crack, a crack that could propagate all the way through the vessel wall. Therefore the structural integrity of the RPV during PTS event should be assured for the safe operation (Cao, 2011; He, 2000).

Although only the crack initiation criteria is considered in the codes, such as the ASME Code Section XI Appendix E (ASME, 2014), cracks which initiate in the cool inner region of the vessel may arrest in a region of the wall where temperature is much higher and neutron fluence is lower (Moinereau, 2001; Chen, 2015). As shown in Fig. 1, the gradient of the neutron fluence in the vessel wall during operation is plotted, and thermal gradients are also calculated in PTS events. At any point during a PTS transient, intersection of the applied SIF curve (stress and flaw geometry dependent) with K_{IC} curves (temperature, fluence and material dependent) defines the crack initiation and the intersection with K_{Ia} curve defines crack arrest (Brumovsky, 2015; Chen, 2016). At the same time, the tearing toughness induced from the J-R curve applicable to the embrittled RPV material is often higher than K_{IC} or K_{Ia} (RCC-M, 2002) in the upper shelf region of the toughness curve. However, the tests (Pennell, 1997) showed that the RPV may fail due to ductile tearing. So the crack tearing instability assessment must be assessed. In fact, the safety assessment of the PTS should contain crack initiation, arrest and tearing instability assessment.

Notwithstanding the resistance of RPV against fast fracture has to be proven by comprehensive analyses, there are few published literatures to systematically discuss the three types of assessments. In this paper, the crack initiation, arrest and tearing instability assessment are discussed and studied. As there are limited data about the J-R curve for the embrittled RPV material, the French RCC-M code (RCC-M, 2002), in which the J-R curve of the RPV base metal is given, is used in this study.

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Nomenclature

a	crack depth (mm)	K_{CP}	SIF considering plastic correction (MPa$\sqrt{m}$)
Δa	crack extension (mm)	LTO	long time operation
c	1/2 crack length (mm)	NPPs	nuclear power plants
dJ/da	rate of increase of J-crack growth resistance (MPa)	PTS	pressurized thermal shock
E	elastic modulus (MPa)	RPV	reactor pressure vessel
ν	Poisson's ratio	RT_{NDT}	nil-ductility-transition temperature (°C)
F	best estimate neutron fluence (10^{19} n/cm^2)	$RT_{NDT(U)}$ = RT_{NDT}	in the pre-service condition (°C)
J-R curve	J-crack resistance curve	ΔRT_{NDT}	change of RT_{NDT}(°C)
J_R	ductile tearing toughness of the J-crack resistance curve (kJ/m^2)	R_i	inner radius (mm)
J_{1C}	critical initial fracture toughness (kJ/m^2)	SIF	stress intensity factor (MPa$\sqrt{m}$)
K_{Ia}	arrest fracture toughness (MPa$\sqrt{m}$)	T	temperature (°C)
K_{Id}	dynamic fracture toughness (MPa$\sqrt{m}$)	t	thickness of base metal (mm)
K_{IC}	static lower bound fracture toughness (MPa$\sqrt{m}$)	$t_{cladding}$	thickness of cladding (mm)
K_{JC}	ductile tearing crack initiation toughness calculated from the J-R curve (MPa$\sqrt{m}$)	σ_0	flow stress (MPa)
		σ_y	yield strength (MPa)

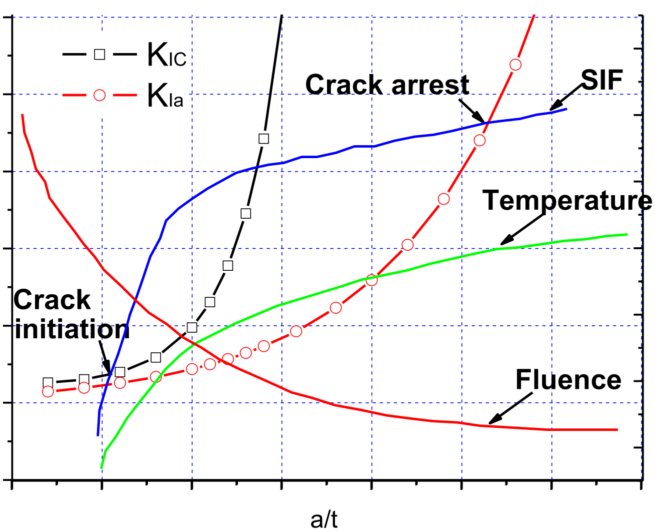

Fig. 1. Safety assessment of the PTS transient.

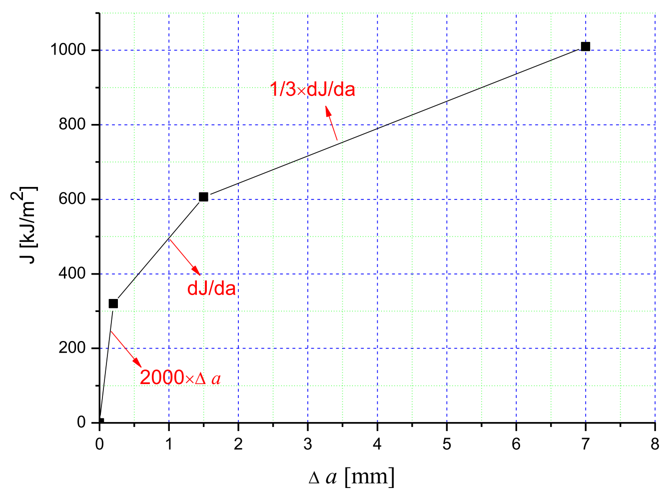

Fig. 2. The J-R curve of the RPV base metal in the RCC-M code. (For the weight-percent measured values of sulfur is not higher than 0.005%, the J_{IC} = 190 kJ/m^2 and dJ/da = 180 MPa).

2. Methodology

2.1. Fracture toughness

In the RCC-M Code Sec. Z G (RCC-M, 2002), the analytical expression of the lower bound K_{IC} and K_{Ia} versus temperature is as follows:

$$K_{Ia} = 29.43 + 1.355e^{0.0261(T-RT_{NDT}+88.9)} \quad (1\text{-a})$$

$$K_{IC} = 36.5 + 3.1e^{0.036(T-RT_{NDT}+55)} \quad (1\text{-b})$$

$$K_{IC}, K_{Ia} \leqslant 195 \quad (1\text{-c})$$

In fact, J-R curves are different for different values of neutron fluence. The J-R curve of the base metal at the end life is shown is shown in Fig. 2 (RCC-M, 2002). When the crack extension distance is larger than 0.2 mm, the tearing toughness induced from the J-R curve is higher than the value of K_{IC} or K_{Ia} .

The material is likely embrittled, and the degree of embrittlement is quantified by the change in RT_{NDT}. In RCC-M code, the analytical expression of the $RT_{NDT}$is as follow:

$$RT_{NDT} = RT_{NDT(U)} + \Delta RT_{NDT} \quad (2\text{-a})$$

$$\Delta RT_{NDT} = [22 + 556(\%Cu - 0.08) + 2278(\%P - 0.008)][F/10^{19}]^{0.5} \quad (2\text{-b})$$

In Eq. (4), % Cu is the copper content (by weight) of the material (when the content is less than 0.08%, the value 0.08% shall be introduced into the formula), and% P is the phosphorus content (by weight) of the material (when the content is less than 0.008%, the value 0.008% shall be introduced into the formula).

The methodology to calculate the neutron fluence at arbitrary depths of the reactor vessel wall is contained in Regulatory Guide 1.99 Rev. 2 (U.S. NRC, 1988). And, the neutron fluence F at the depth in the vessel wall is determined as follows:

$$F = F_{sur} \cdot e^{-0.24 \cdot x} \quad (3)$$

where, x (in inches) is the depth into the vessel wall measured from the clad-base metal interface (wetted surface), and F_{sur} is the best estimate neutron fluence at the clad-base metal interface (energy greater than 1 MeV).

2.2. Crack driving force

In the RCC-M code (RCC-M, 2002), the SIF is determined from the crack size under consideration, its position and the associated