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Probabilistic assessment of a reactor pressure vessel subjected to pressurized thermal shocks by using crack distributions

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HIGHLIGHTS

- Probabilistic methods are used to analyze a reactor pressure vessel.
- Crack distribution data from the decommissioned plants, Shoreham and PVRUF is used.
- Weld type, size and its manufacturing process are also considered.
- Embedded and surface short cracks result in the highest probability for failure.

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ABSTRACT

Probabilistic methods are used to analyze a reactor pressure vessel (RPV) subjected to pressurized thermal shocks (PTSs) initiated by a small loss-of-coolant accident (SLOCA) and a medium loss-of-coolant accident (MLOCA). The FAVOR code is applied to calculate the probabilities for crack initiation and failure by considering crack distributions based on cracks observed in the Shoreham and PVRUF RPVs in the U.S. The crack parameters, i.e. crack density, depth, aspect ratio, orientation and location are assumed as random variables following different distributions. The Vflaw code is used to generate FAVOR input files for the crack distribution data from the decommissioned plants. Weld type, size and its manufacturing process are also considered in the calculation.

In this paper it is shown that the calculated failure probability of the RPV subjected to the SLOCA is higher than that subjected to the MLOCA due to different loading. The failure probabilities are compared with those based on a different crack assumption. Among the analyzed cracks, the embedded crack with a depth of 6.83 mm and surface crack with a depth of 5.13 mm result in the highest probability for failure. Maximum stress intensity factors of the simulated cracks range from 36 MPa m$^{0.5}$ to 91 MPa m$^{0.5}$ for the MLOCA and from 30 to 41 MPa m$^{0.5}$ for the SLOCA, respectively. We conclude that considering the observed crack distribution in probabilistic PTS analyses may lead to higher failure probabilities than by assuming cracks of specific size.

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1. Introduction

Reactor pressure vessels (RPVs) of nuclear power plants are exposed to neutron irradiation, which causes embrittlement of the ferritic steel and makes the material susceptible to brittle fracture. A potential scenario for a pressurized water reactor is that its RPV has to withstand a pressurized thermal shock (PTS), which is characterized by severe cooling of the core together with or followed by repressurization, if not avoided by safety valves. PTS transients lead to high tensile circumferential and axial stresses in the RPV wall. If the stresses are high enough they may initiate existing cracks in the embrittled RPV material, which may result in crack propagation and in the worst case in a failure of the RPV. Therefore national safety rules are demanding integrity assessment for PTS loads. This can be done by applying deterministic and/or probabilistic fracture mechanics (PFM) methods. Deterministic methods are used in most countries, while in USA probabilistic methods are used to develop screening criteria for RPV analyses. Deterministic fracture mechanics is assumed to be conservative to ensure the RPV integrity, since it considers the worst case and all the hypotheses, methods and data are chosen to be bounding (conservative). The outcome of the deterministic assessment is whether a crack initiates (or in the worst case whether a RPV fails) or not. Alternative or complementary to deterministic methods are probabilistic

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Nomenclature

a	crack depth, mm
a^*	distance of the crack tip to cladding/base interface of the vessel wall, mm
a_r	ratio of crack depth to the weld bead depth
$2c$	crack length, mm
CPI(i,n)	CPI of the vessel subjected to the i^{th} transient for the nth crack
[CF]	chemistry factor, °C
f_0	fast neutron fluence at the inner surface of a vessel wall, n/cm^2
f	neutron fluence at a distance from cladding/base interface of vessel wall, n/cm^2
K_{I}	Mode I linear elastic stress intensity factor, MPa m$^{0.5}$
K_{Ic}	material fracture toughness, MPa m$^{0.5}$
K_{Ia}	crack arrest toughness, MPa m$^{0.5}$
Margin	safety margin to account for uncertainties of RT_{NDT0} and ΔRT_{NDT}, °C
n	number of cracks
P	cumulative probability level in Master Curve method
$P(F\|E)_i$	conditional failure probability of vessel due to the ith transient
R_i	inner radius of a vessel, mm
RT_{NDT}	nil-ductility transition reference temperature, °C
RT_{NDT0}	initial nil-ductility transition reference temperature, °C
ΔRT_{NDT}	increase of RT_{NDT} due to neutron irradiation, °C
s	distance from the inner crack tip to the inner surface of a vessel, mm
t	vessel wall thickness, mm
t_c	cladding thickness, mm
t_b	base material thickness, mm
t_i	transient time, minute
T	temperature, °C
T_0	reference temperature in Master Curve method, °C
ΔT_{41}	temperature shift at 41 J by Charpy impact test due to irradiation, °C
σ_{I}	standard deviation of RT_{NDT0}, °C
σ_{Δ}	standard deviation of ΔRT_{NDT}, °C
Φ	parametric angle of elliptical crack
$\Phi(E)_i$	frequency of the ith transient
$\Phi(F)$	total failure frequency
BWR	boiling water reactor
CPI	conditional probability of crack initiation
GMAW	gas metal arc welding
LLOCA	loss-of-coolant transient
MLOCA	medium loss-of-coolant accident
MC	Monte Carlo
NDT	nondestructive testing
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PFM	probabilistic fracture mechanics
PTS	pressurized thermal shock
PWR	pressurized water reactor
PNNL	Pacific Northwest National Laboratory
RPV	reactor pressure vessel
SAW	submerged arc welding
SIF	stress intensity factor
SLOCA	small loss-of-coolant accident
SMAW	shielded metal arc welding
WPS	warm prestressing

methods, which yield probabilities, e.g. for crack initiation or failure. A probabilistic analysis provides a more realistic evaluation of the structure condition and the corresponding safety level by incorporating the uncertainties of the governing parameters (Qian et al., 2011; Qian and Niffenegger, 2011). Furthermore, the outcomes from probabilistic methods are useful as a decision making tool for the justification of the further operation and maintenance optimization since the sensitivity of the failure probability due to the different influencing parameters can be evaluated in such analyses. By setting limits on the allowable probability of failure, the reactor vessel integrity is ensured to a certain acceptance level.

During the last three decades, a number of computer codes have been developed to perform the probabilistic analysis of RPVs, such as OCA-P (Chauverton and Ball, 1984), VISA-II (Simonen et al., 1986), PROFMAC-II (Soneda and Onchi, 1996), OPERA (Persoz et al., 2000), FAVOR (Dickson and Malik, 2001; Williams et al., 2004) and PASCAL (Shibata et al., 2001). Different procedures, codes and guidelines have been issued all over the world in order to ensure the RPV integrity. A comprehensive review paper about deterministic and probabilistic procedures and codes on structural integrity assessment is referred in Qian and Niffenegger (2013a).

In the framework of RPV integrity analysis, several research and benchmark projects have been launched, e.g. ICAS (Bass et al., 1999), NESC (Taylor et al., 2005), Prosir (Faidy et al., 2010), Smile (Moinereau and Bezdikian, 2008) and Vocalist (Lidbury and Assurance, 2006). These projects focused on the deterministic and probabilistic methods for the integrity assessment of RPVs, modeling of material toughness, the effect of warm prestressing (WPS) and the crack tip constraint on the RPV integrity. A probabilistic integrity analysis of a model RPV in combination with a SLOCA and a MLOCA has been performed by assuming crack depths of two times the nondestructive examination limit (Qian and Niffenegger, 2013b). Some aspects of numerical PTS analyses as the proper use of thermal expansion coefficients in finite element calculations were addressed in Niffenegger and Reichlin (2012). The constraint effect of a shallow crack tip on the fracture toughness during a transient has been analyzed in Qian and Niffenegger (2013c). González-Albuixech et al. (2013) applied extended finite element method to perform fracture mechanics calculation, thereby providing input for the RPV integrity analysis. Both elastic and elastic–plastic analyses were performed in Qian and Niffenegger (2013d). However, it has been studied that, beside the loading conditions, the crack density, depth, length and location, are the main uncertainty in the analysis. Therefore, it is more realistic to consider crack uncertainty based on nondestructive (NDT) and destructive testing databases. In this study, the crack databases from the decommissioned plants, PVRUF and Shoreham in the U.S. (Simonen et al., 2004) are used to generate crack properties distribution functions. The probabilistic integrity analysis of the RPV subjected to two PTSs transients is performed with the FAVOR code by considering these crack distributions. The two transients and the RPV considered in this paper are the same as those considered in Qian and Niffenegger (2013b,c).

2. Crack uncertainty considered in this study

2.1. Crack assumptions in FAVOR

In the FAVOR code (Williams et al., 2004), three different types of cracks, as shown in Fig. 1, are considered. Crack type 1 is a surface-breaking crack which includes: (1) infinite length crack with aspect ratio $2c/a = 999$, (2) semi elliptical crack with aspect ratio $2c/a = 2$, (3) semi elliptical crack with aspect ratio $2c/a = 6$, (4) semi elliptical crack with aspect ratio $2c/a = 10$. Crack type 2 is an embedded crack, which has fully-elliptic geometry with inner crack tip located between the clad/base metal interface and 1/8 t from the inner

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