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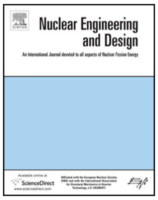

Deterministic and probabilistic analysis of a reactor pressure vessel subjected to pressurized thermal shocks

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HIGHLIGHTS

- Deterministic and probabilistic methods are used to analyze a reactor pressure vessel.
- Assuming shallower cracks can be more conservative than assuming deeper ones.
- Master Curve methods are implemented in FAVOR for fracture toughness analysis.
- Master Curve method is more realistic in modeling fracture toughness.
- Warm prestressing effect decreases failure probability significantly.

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ABSTRACT

Both deterministic and probabilistic methods are used to analyze a reference reactor pressure vessel (RPV) subjected to pressurized thermal shocks (PTSs). The FAVOR code was applied to calculate the probabilities for crack initiation and failure of a RPV subjected to two PTS transients, by considering different crack types, sizes and orientations. The Master Curve methods are implemented in the FAVOR code for a more realistic consideration of fracture toughness of the irradiated RPV.

The analysis shows that a postulated underclad crack is the most conservative crack assumption. Assuming shallower cracks can be more conservative than deeper ones due to the fact that both K_I and K_{IC} at the crack tip increase with crack depth. Considering the warm prestressing effect (WPS) reduces the failure probability by more than two orders of magnitude.

In this analysis, the FAVOR model for the calculation of fracture toughness is more conservative than the Master Curve method. But the Master Curve method is more realistic than the FAVOR model and thus its application is recommended.

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 the crack propagation and in the worst case in a failure of the RPV.

To assess the integrity of RPVs subjected to PTS transients, both deterministic and probabilistic fracture mechanics (PFM) analyses can be performed (Qian et al., 2014a, 2014b; Qian and Niffenegger, 2013a, 2013b). 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. Such alternative or complementary to deterministic methods are probabilistic 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., 2013a, 2013b, 2011; Qian and Niffenegger, 2011). Furthermore, the outcomes from

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probabilistic methods are useful as a decision making tool for the maintenance optimization and repair of components (if possible) 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.

Nomenclature

a	distance of the crack tip to the inner surface of the vessel wall (mm)
a^*	distance of the crack tip to cladding/base interface of the vessel wall (mm)
$2c$	crack length (mm)
[CF]	chemistry factor (°C)
f_0	neutron fluence at the inner surface of a vessel wall (10^{19} n/cm^2)
f	neutron fluence at a distance from cladding/base interface of a vessel wall (10^{19} n/cm^2)
K_I	mode I linear elastic stress intensity factor (MPa m$^{0.5}$)
K_1	preload stress intensity factor at T_1 (MPa m$^{0.5}$)
K_2	stress intensity factor at T_2 (MPa m$^{0.5}$)
K_f	failure stress intensity factor at T_2 (MPa m$^{0.5}$)
K_{Ic}	material fracture toughness (MPa m$^{0.5}$)
K_{Ia}	crack arrest toughness (MPa m$^{0.5}$)
K_0	Weibull mean fracture toughness (MPa m$^{0.5}$)
ΔK_u	difference between K_1 and K_2 (MPa m$^{0.5}$)
Margin	safety margin to account for uncertainties of the RT_{NDT0} and ΔRT_{NDT} (°C)
$P\,(F\|E)_i$	conditional failure probability of vessel due to the ith transient
P	cumulative probability level
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)
RT_{T_0}	reference temperature using T_0 in Master Curve method (°C)
t	vessel wall thickness (mm)
t_i	transient time (min)
T	temperature (°C)
T_1	temperature at preloading (°C)
T_2	temperature at failure (°C)
T_0	reference temperature in Master Curve method (°C)
$T_{41\mathrm{J}}$	temperature measured at 41 J by Charpy impact test (°C)
$\Delta T_{41\mathrm{J}}$	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	$(E)_i$ frequency of the ith transient
Φ	(F) total failure frequency
LLOCA	large loss-of-coolant accident
MLOCA	medium loss-of-coolant accident
NDE	non-destructive examination
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PFM	probabilistic fracture mechanics
PTS	pressurized thermal shock
RPV	reactor pressure vessel
SLOCA	small loss-of-coolant accident
SIF	stress intensity factor
WPS	warm prestressing

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 et al., 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 (Onizawa et al., 2009; Shibata et al., 2001). A comprehensive review paper about deterministic and probabilistic procedures and codes on structural integrity assessment is referred in (Qian and Niffenegger, 2013a).

In this paper, both deterministic and probabilistic methods are used to analyze a model RPV with realistically assumed parameters. The integrity of the RPV subjected to the small loss-of-coolant accident (SLOCA) and medium loss-of-coolant accident (MLOCA) transients was performed by using both the ASME and Master Curve methods for the consideration of the material fracture toughness. The Master Curve method is implemented in FAVOR for the probabilistic analysis of the RPV. The results predicted by using different toughness curves, such as the FAVOR model and the Master Curve are compared. The effects of crack types, depths and its orientations on the vessel failure probability are analyzed. Furthermore, a quantification of the warm prestressing effect (WPS) on fracture toughness is presented.

2. General procedures and methods for RPV assessment

2.1. Physical model and assumptions

For the numerical analysis, the real RPV shown in Fig. 1(a) is reduced to a simple model containing only the characteristic properties of the RPV. The inner side of the RPV is assumed to be subjected to a thermal shock caused by the downstream of emergency cooling water. The RPV is approximated by a rotationally symmetric model that allows the calculation of axial and circumferential stresses as a function of one-dimensional (along the radial direction) transient temperature distribution. This analysis is mainly based on the following conservative assumptions:

(1) The model treats the RPV as if it were made entirely from the most brittle of its constituent materials.
(2) A one-dimensional model is used in the thermal stress analysis. The model assumes that the temperature and heat transfer coefficient distributions are uniform along the inner surface of the vessel wall without consideration of the plumes, which are formed by the cold water flowing down from the inlets. The two-dimensional or even three-dimensional modeling of the RPV by considering plumes would be worth to study the axial and circumferential stress variation.
(3) The calculation of K_I relies on the linear elastic fracture mechanics.
(4) Welding residual stresses are neglected in this analysis. According to (Williams et al., 2004), a compressive residual stress is more likely introduced during the welding process of cladding. The compressive residual stress tends to stop crack propagation. Thus, neglecting welding residual stress is a conservative assumption.
(5) Using RT_{NDT} (based on small specimens) to calculate K_{Ic} yields in general conservative results. RT_{NDT} is obtained by drop weight method together with Charpy impact test, which has a higher strain rate and may give conservative results.
(6) The peak neutron fluence is assumed to be uniform along the inner side of the vessel wall, which results in a conservative result.