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Integrity analysis of a reactor pressure vessel subjected to a realistic pressurized thermal shock considering the cooling plume and constraint effects

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A B S T R A C T

The fracture mechanic analysis of a reactor pressure vessel subjected to Pressurized Thermal Shock (PTS) loading is one of the most important issues for the assessment of life time extension of a nuclear power plant. The most severe scenario occurs during cold water injection in the cold leg due to a Loss-Of-Coolant Accident (LOCA). Two hypothetical LOCAs are assumed for an adopted reference design of a two-loop pressurized water reactor. Boundary conditions obtained from the RELAP5 code are used as input for three-dimensional computational fluid dynamics which provides the accurate description of the transient including the plume cooling effect. The safety assessment considers the comparison of the stress intensity factor for the deepest point of a surface crack front with the fracture toughness of the material. However, the fracture toughness of the materials is influenced by crack constraints determined by the T-stress. Therefore, safety margin of the reactor pressure vessel should be based on the K-T instead of on the K approach. The existence of a cooling plume affects the stress intensity factor and T-stress. Even if the cooling plume affects the T-stress, it is not translated into an increase of the safety margin. Therefore, in a PTS event with pronounced plume cooling a detailed model of the plume has to be considered in the structural analysis.

1. Introduction

The Reactor Pressure Vessel (RPV) is the part that contains the reactor core and is considered as non-replaceable. Hence, its structural integrity is a limiting factor for the operation time of a nuclear power plant. Furthermore, the RPV is exposed to neutron irradiation which causes embrittlement of the ferritic steel and makes the material susceptible to brittle fracture. This has negative consequences on the RPV integrity, especially in the case of unforeseen extreme loading conditions. One potential challenge to the integrity of an RPV in a pressurized water reactor is posed by a Pressurized Thermal Shock (PTS), which is associated with abrupt cooling of the reactor core together with, or followed by, repressurization of the RPV. Pressurized thermal shock transients are arisen by a number of abnormal events and postulated accidents including a pipe break in the primary circuit, a stuck-open valve in the primary pressure circuit that later re-closes, or a break of the main steamline. Pressurized thermal shock transients lead to high tensile circumferential and axial stresses in the

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Nomenclature

RPV	reactor pressure vessel
PTS	Pressurized Thermal Shock
LOCA	Loss-Of-Coolant Accident
CFD	computational fluid dynamics
FEM	Finite Element Method
LEFM	Linear Elastic Fracture Mechanics
SIF	Stress Intensity Factor
PWR	pressurized water reactor
MLOCA	medium Loss-Of-Coolant Accident
SLOCA	small Loss-Of-Coolant Accident
FE	Finite Element
m	mass flow rate (kg/s)
a	semielliptical crack depth (mm)
c	semielliptical crack length (mm)
h	height of modeled RPV geometry or simplified RPV geometry (m)
K_I	mode I linear elastic stress intensity factor (MPa $m^{0.5}$)
R_i	inner radius of the modeled RPV geometry (m)
t	thickness of RPV wall (mm)
p	pressure on inner RPV surfaces (MPa)
σ_{ij}	stress field tensor, component ij (MPa)
K, K_I	Mode I linear elastic stress intensity factor (MPa·$m^{0.5}$)
J	fracture energy release rate (J/m^2)
T	temperature (°C)
T_{stress}, T-stress	T-stress representing the second term of elastic crack-tip stress field (MPa)
K_{IC}	material fracture toughness (MPa $m^{0.5}$)
θ	angular coordinate in the crack local system
r	radial distance to the closes crack point in the crack local system (m)
Φ	parametric angle of elliptical crack
$f_{ij}(\theta)$	angular functions of crack-tip stress field
T_0	reference temperature in Master Curve method (°C)
T_{0deep}	reference temperature obtained from deeply cracked (high constraint) bars (°C)
P	probability of failure

RPV wall. If a crack like defect exists in the structure, this may result in crack propagation and in the worst case even to the failure of the RPV. Thus, the RPV has to be assessed against cleavage fracture [1–7]. The parameter which usually provides a failure criterion for brittle materials is the Stress Intensity Factor (SIF or K), specially its mode I (K_I).

Accurate temperature distribution is necessary for calculating the stresses resulting from these thermal loads and hence for the assessment of failure probability of the RPV [8,9]. One-dimensional models, used in thermal hydraulic analysis software such as RELAP5 [10], cannot accurately represent the complex mixing phenomena in the downcomer (the annulus space adjacent to the RPV walls) and may even yield non-conservative results [11,12]. The emergency cold water injected in the cold leg mixes with the hot water and/or steam present in the system and flows down in the downcomer annulus where a cold plume with complicated dynamic behavior is developed and affecting the wall temperature distributions. Plume is the non-uniform azimuthal temperature distribution due to cold water during emergency coolant injection. The effect of plume cooling, in particular, cannot be considered in simple models. Therefore, Computational Fluid Dynamics (CFD) models, which include details of geometry, should be used to predict multi-dimensional features of the mixing process between the injected subcooled water and the hot fluid. Otherwise the stress state in the wall is underestimated. This plume effect, or strip cooling, does not happen only in RPVs, moreover it is reported and considered in general structures [13], and therefore should be studied carefully.

The integrity analysis of a RPV involves a comparison of K_I with K_{Ic} for the whole PTS transient. Calculation of K_I is generally based on Linear Elastic Fracture Mechanics (LEFM) for simplification reasons. For the modeling of K_{Ic}, an important aspect is the constraint effect, which is arisen due to the different stresses and strains at the crack tip between components and the tested specimens under the same crack driving force (K_I or J). Fracture toughness testing standards use highly constrained specimens with deep cracks to guarantee conservative fracture toughness data. The effective toughness for the deeper cracks (high constraint) is lower than that for shallow cracks (low constraint) due to the higher hydrostatic stress at the crack tip. If this data from deep cracks is directly used in a structure with low constraint, it may lead to over