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Fracture analysis of the set-in nozzle of a PWR reactor pressure vessel – Part 1: Determination of critical crack

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In this study, fracture mechanics analysis of the set-in nozzle of a reactor pressure vessel (RPV) is being presented. The selected RPV belongs to a 300 MW pressurized water reactor (PWR). For the purpose, a wide range of elliptical surface cracks was analyzed at the nozzle-cylinder intersection under two accidental conditions of the reactor: small-break loss of coolant accident (SB-LOCA), and Rancho-Seco transient (RST). It has been demonstrated that at the location being investigated '$a = 0.05t$' is the critical crack depth; where 'a' is the depth/minor axis of the crack and 't' is the thickness of the wall.

1. Introduction

The reactor pressure vessels (RPV), during their service, have to operate under normal operating and accidental conditions of the plant. The fracture mechanics analysis of different parts of the RPV under normal operating conditions [1–3] is quite straight forward; however the analysis becomes critical under accidental conditions of the plant. In this paper, the fracture analysis of the set-in nozzle of an RPV is being presented under accidental conditions of the plant [4]. The considered RPV is made of nuclear grade steel *'SA-508 Gr.3 Cl.1'* [5] and it belongs to a 300 Megawatts (MW) pressurized water reactor (PWR) [4].

The accidental conditions taken for the analysis are the small break loss of coolant accidental conditions (SB-LOCA), and the Rancho-Seco transient (RST) conditions of the PWR. For the fracture analysis the highest stress concentration point (HSCP) of the nozzle, under normal operating conditions of the plant [1,4] is selected: the nozzle-cylinder intersection. A wide range of corner surface cracks has been analyzed at the nozzle-cylinder intersection under the accidental conditions. The limits of the cracks were '$0.01 < a/t < 0.25$' with '$a = 0.33c$', where 'a' and 'c' represent minor and major axis of the crack respectively; and 't' is the thickness of the vessel's wall at the nozzle-cylinder intersection. The stress intensity factors (SIFs) of all the cracks under the accidental conditions were evaluated using the 'pallet body approach' of the crack modeling [6–8]. It is a finite element methods (FEM) based computational technique for crack analysis.

1.1. Goal of the research

The goal of this study was to investigate the critical crack depth at the nozzle-cylinder intersection of the RPV under the accidental conditions of the plant. For the purpose, the SIFs of a wide range of corner cracks were compared with the fracture

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Nomenclature

a	depth or minor axis of the elliptical corner surface crack
c	major axis of the elliptical corner surface crack
f	neutron fluence
t	thickness of the RPV wall at the set-in nozzle intersection
E	Young's modulus of material
α	angle between set-in nozzle and set-out nozzle
ϕ	angle of the crack tip with major axis of the crack
v	Poission's ratio
E_{neu}	neutron energy
K_{IC}	fracture toughness of a material
K_{JN}^{ps}	EPFM based SIF under both pressure (primary) & thermal (secondary) loadings in normal operating conditions
K_{IS}^{ps}	LEFM based SIF under both pressure (primary) & thermal (secondary) loadings in SB-LOCA accidental conditions
K_{JS}^{ps}	EPFM based SIF under both pressure (primary) & thermal (secondary) loadings in SB-LOCA accidental conditions
K_{IR}^{ps}	LEFM based SIF under both pressure (primary) & thermal (secondary) loadings in RST accidental conditions
K_{JR}^{ps}	EPFM based SIF under both pressure (primary) & thermal (secondary) loadings in RST accidental conditions
σ_h	hoop stress
PWR	pressurized water reactor
RPV	reactor pressure vessel
SB-LOCA	short break loss of coolant accident
RST	Rancho-Seco transient
ICS	integrated control system
EOL	end of life
HSCP	highest stress concentration point
SIF	stress intensity factor
LEFM	linear elastic fracture mechanics
EPFM	elastic plastic fracture mechanics
FF	fluence factor
CF	chemistry factor

toughness value of the RPV's steel (*SA-508 Gr.3 Cl.1*). The effects of the material's embrittlement due to the nuclear environment have also been incorporated in the fracture toughness of the material.

1.2. Literature review

Fracture mechanics analyses or safety analyses of RPVs under various loading conditions have been an active area of research for the last few decades. In this context, Bangash [9] in 1984, performed a finite element based analysis and design of Sizewell-B type RPV under normal and unanticipated events of the plant. He demonstrated that the most important areas of the RPV from the fracture assessment point of view are inlet and outlet nozzles, top and bottom head, and the beltline region of the vessel. He plotted hoop stress distributions under pressure loading of 17.24 MPa for different regions of the RPV and corroborated the results for inlet and outlet nozzles.

In 1999, Siegele et al. [10], performed fracture mechanics analysis of the RPV's nozzle under loss of coolant accident (LOCA). In the study, they have presented that the nozzle regions face higher stresses and lower temperature in the event of the LOCA, and is therefore vulnerable and may threaten the integrity of the RPV. Hence, the safety assessment of the nozzle must be performed. After postulating the circular cracks at nozzle-cylinder intersection, they computed SIFs as functions of crack tip temperatures. In their study, the analytical approaches used for solutions of surface cracks in cylindrical portions were extended for the solutions of corner cracks at the nozzle-cylinder intersection. In the same year, Kim and Jin [11], performed structural integrity analysis of an RPV under the external reactor vessel cooling condition. The integrity analysis of the lower head of the RPV was performed during the transient state of reactor vessel cooling.

In 2000, He and Isozaki [12], performed fracture mechanics analysis of the beltline region of the RPV of a Chinese pressurized water reactor. The authors conducted the fracture analysis under small-break loss of coolant accident, large-break loss of coolant accident and Rancho-Seco transients. They employed ADINA code for development of crack mesh and for the fracture analysis. They investigated that which type of flaw and transient condition is most detrimental for the beltline region of the RPV. They also demonstrated that large-break loss of coolant accident is less severe pressurized thermal shock when compared to small-break loss of coolant accident and Rancho-Seco transients. The authors assessed the fracture integrity of the RPV by comparing the stress intensity factors of different cracks with the fracture toughness of the material.

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