PROBABILISTIC ASSESSMENT OF STRUCTURAL INTEGRITY OF REACTOR PRESSURE VESSEL IN SEVERE LOADING CONDITIONS CAUSED BY VARIOUS TRANSIENTS

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Abstract

Assessment of reactor pressure vessel structural integrity is an important issue for long-term operation of nuclear power plant. In our work, the integrity of a pressure vessel structural integrity has been evaluated based on the relationship between stress intensity factor (K_I) and fracture toughness (K_{Ic}) following 13 different scenarios. The changing of temperature margin and conditional probability of crack initiation in various transients are obtained to confirm the risk level in severe loading conditions including stuck open pressurizer relief valve, main steam line break and loss of coolant accident. The evaluation is performed by using probabilistic fracture mechanics analysis code PASCAL (PFM Analysis of Structural Components in Aging LWR).

The results of this analysis showed that comparing to other transients, a large break LOCA lead to the most severe pressurized thermal shock conditions, while the risk of SOV transients are strongly related to the re-pressurization in the pressurizer caused by the increase of water level due to the relief valve stuck open.

Keywords: reactor pressure vessel, structural integrity, probabilistic assessment, pressurized thermal shock.

Acronyms

RPV: Reactor pressure vessel

CPI: Conditional probability of crack initiation

SOV: Stuck opened valve

SOV-O: Stuck open valve, no-close

SOV-C: Stuck open valve, re-close after certain time.

MSLB: Main steam line break

LB-LOCA: Large break loss of coolant accident

PFM: Probabilistic fracture mechanics

DFM: Deterministic fracture mechanics

PTS: Pressurized thermal shock

CEA: French Alternative Energies and Atomic Energy Commission

SIF or K_I: Stress intensity factor

LWR: Light water reactor

NPP: Nuclear power plant

Introduction

Since the early 1980s, PTS has become a non-design condition that all United State NPPs have had to prove adequate toughness relative to a severe over-cooling and pressure increasing transient event [1]. There were many reports on this topic, especially after the United States Nuclear Regulatory Commission (USNRC) created the PTS re-evaluation project in 1998 [2-4]. Followed those results, some investigation of thermal-hydraulic screening analysis to identify most severe PTS transient scenario for a reference NPP were performed [5]. However, the connection between thermal-hydraulic results and RPV material embrittlement is still lacking. Performing DFM and PFM analysis of RPV steel embrittlement after long-term operation, some calculation tools have been implemented such as FAVOR (Fracture Analysis of Vessels: Oak Ridge) of U.S., PASCAL (PFM Analysis of Structural Components in Aging LWR) of Japan, etc. [6]. In current work, PASCAL is used as a tool for calculation 13 selected transients to identify the most severe transient.

Analysis conditions

A Japanese reference NPP is chosen by assuming that the cracks are semi-elliptical form in the surface, under cladding. In deterministic evaluation, the depth and the length are fixed at 10 mm and 60 mm, respectively. For probabilistic assessment, the depth ratio has an exponential distribution, and the aspect ratio has a log normal distribution. The embrittlement of RPV material is predicted based on JEAC4201 equations for the fast neutron (E > 1MeV) fluence from the start of operation to $8x10^{19}$ n/cm^2. The stress intensity factor is calculated with the French Alternative Energies and Atomic Energy Commission (CEA) model for crack in the surface including RPV cladding (figure 1).

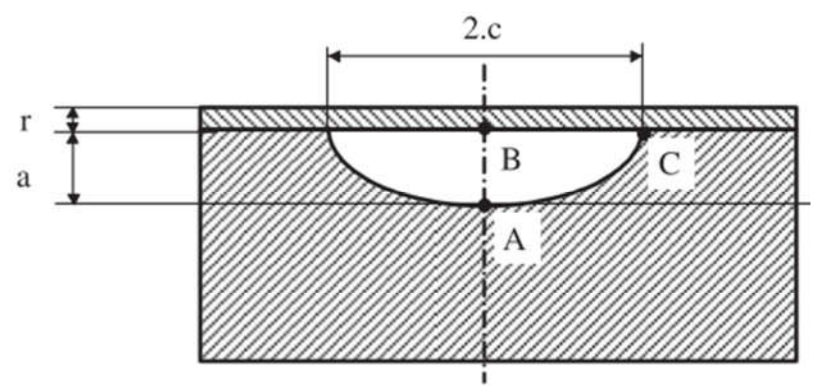

Figure 1. Under crack defect - CEA model

Results and discussion

Temperature margin

The temperature margin (or safety margin) ΔTm is determined by the difference between temperature at maximum stress intensity factor and temperature at the corresponding fracture toughness. In deterministic assessment, the higher value of temperature margin, the safer in structural integrity of RPV.

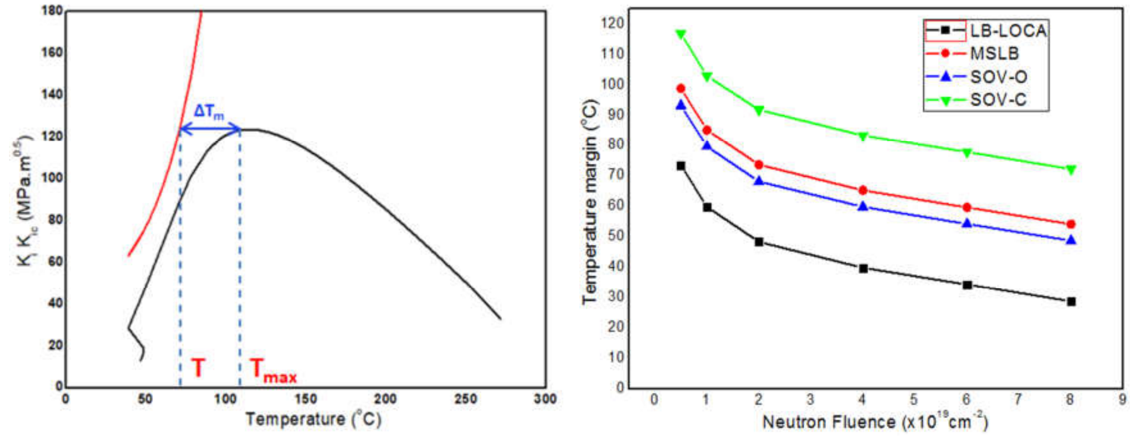

Figure 2. Temperature margin

The calculation results showed that all transients have same tendencies with the long-term degradation of RPV steel. However, the LB-LOCA transient may have the highest risk with the range of temperature margin from 73^{o}C to 29^{o}C corresponding to fast neutron fluence from 0.5x10^{19} n/cm^2 to 8x10^{19} n/cm^2.

Conditional probability of crack initiation (CPI)

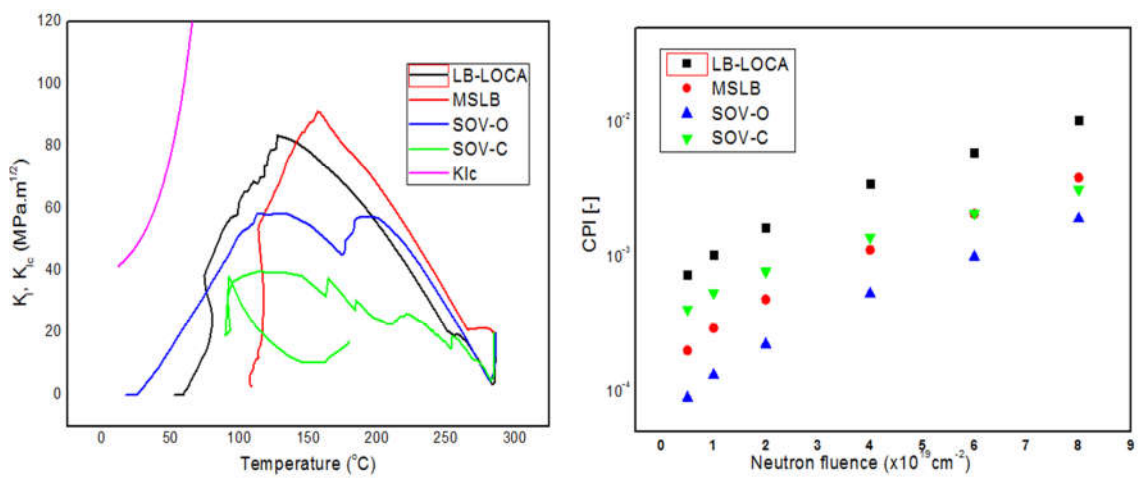

Figure 3. SIF and CPI value

The highest value of CPI in case of LB-LOCA confirms results of temperature margin. The peak of SIF is highest in case of MSLB which found at high temperature point where fracture toughness is also high, so that CPI value in MSLB is still smaller than LB-LOCA. Similar reason is in two cases of SOV transients.

SOV cases are not severe enough to contribute significantly to the PTS risk. The severity of this transient is determined by the time that the pressurizer relief valve remains open.

Conclusion

The risk level of a NPP accident is a combination of many factors. In this work, the evaluation of RPV integrity is done by using probabilistic fracture mechanic code PASCAL to screen out the most severe transients for a reference NPP. In SOV transient, although the results of safety margin and CPI value showed a low risk level, we still need to consider these scenarios due to their high probability of occurrence.

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