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Fracture Mechanics Analysis of RPV during PTS using Critical Crack Depth Diagram

Myung Jo Jhung*, Young Hwan Choi
Korea Institute of Nuclear Safety, 19 Guseong-dong, Yuseong-gu, Daejeon
**mjj@kins.re.kr*

1. Introduction

USNRC introduced the concept of RT_{PTS} the reference temperature of nil-ductility transition, RT_{NDT}, evaluated for the end-of-life (EOL) fluence for each of the beltline materials, and defined the pressurized thermal shock (PTS) screening criterion as 270°F for plates, forgings, and axial weld materials, and 300°F for circumferential weld materials in 10CFR50.61 “Fracture toughness requirements for protection against pressurized thermal shock events”[1]. Also, for each pressurized water nuclear power reactor for which the value of RT_{PTS} for any material in the beltline is projected to exceed the PTS screening criterion using the EOL fluence, the licensee is required to implement those flux reduction programs that are reasonably practicable to avoid exceeding the PTS screening criterion, for which detailed plant-specific analyses is required.

USNRC issued Regulatory Guide 1.154 “Format and Content of Plant-Specific Pressurized Thermal Shock Safety Analysis Reports for Pressurized Water Reactors”[2] to describe a format and content acceptable to the NRC staff for these plant-specific PTS safety analyses and describe acceptance criteria that the NRC staff will use in evaluating licensee analyses and proposed corrective measures.

According to Regulatory Guide 1.154, the plant specific analysis should include both probabilistic and deterministic fracture mechanics analyses. The probabi1istic analyses should be used to determine the statistical likelihood of vessel through-wal1 crack penetration assuming a crack size distribution appropriately justified for the vessel being analyzed and appropriate uncertainties and distribution of the significant input parameter such as material properties. The deterministic analyses should be used to evaluate the critical time interval in the transient during which mitigating action can be effective.

Especially for the deterministic analysis, Regulatory Guide 1.154 suggests the procedure as follows;

For each transient of interest, a deterministic analysis that includes a set of critical crack-depth curves as functions of time, i.e., a plot of crack depths corresponding to initiation and arrest events versus time, should be carried out. This plot should also have curves indicating the depth of crack at which upper-shelf toughness is effective. These curves, which graphically represent the worst-case condition for each transient of interest, will be used in the evaluation of the critical time interval from the initiation of the transient during which mitigating action can occur.

In this study, therefore, the procedure for the deterministic fracture mechanics analysis of RPV during PTS is investigated using the critical crack depth diagram and the computer program is developed.

2. Analysis

Using transient histories such as pressure, temperature and heat transfer coefficient, the temperature distribution in the vessel wall is computed and stresses due to the temperature and pressure are determined. For various penetration depths, the stress intensity factors are calculated. The flaw arrest K_{IA} and flaw initiation K_{IC} fracture toughness profiles are also determined. For each time during the transient, the variations of K_I, K_{IC} and K_{IA} through the thickness are determined. The flaw penetration at which the calculated stress intensity factor exceeds K_{IC} profile corresponds to the critical flaw size for initiation a_i, and the penetration at which the stress intensity factor goes below the K_{IA} curve corresponds to the critical flaw size for arrest a_a. Curves are prepared for a number of selected times following each postulated accident to establish the critical time.

A critical crack depth (CCD) diagram consisting of graphs of a_i and a_a versus time can be prepared as shown in Figure 1 for each transient. The smallest value of a_i determined by the above procedure after all postulated transients have been considered represents the minimum critical initiation crack size. The behaviour of crack initiation and arrest can be predicted from the critical crack depth diagram. For example, if there is a crack with a/w = 0.2 in Figure 1, it is initiated twice following the dotted line resulting in the through-wall propagation. In Figure 1, a_1 and t_1 is a crack size and time when the first initiation occurs and t_1 is especially the critical time interval from the initiation of the transient during which mitigating action can occur. The crack depth between a_2 and a_3 is the range of the crack sizes which can be initiated during a transient. If a crack is smaller than a_2 or larger than a_3, it is not initiated. The smallest value of crack initiation, a_2 in this case, is used for comparison with acceptance criteria for inspection capability.

According to the classical linear elastic fracture mechanics, flaws will begin to initiate when K_I exceeds K_{IC}. For each flaw depth, the time (θ_{max}) for the peak K_I to occur is determined. The variation of θ_{max} with crack depth is then plotted on the same graph as a_i and a_a versus time. Therefore warm prestressing curve (dK_I/dt = 0) is also included in the critical crack depth diagram. For a given flaw depth, if the θ_{max} curve is crossed before initiation curve, no initiation will occur because of warm prestressing. In Figure 1, a crack is initiated once, arrested at about a/w = 0.372 and is not initiated again. Considering a WPS effect, the interactions of the θ_{max} curve and initiation curve define the range of flaw sizes that would initiate. In Figure 3, the crack depth between a_4 and a_5 is the range of the crack sizes which can be initiated during a transient. The minimum flaw (a_4) that would initiate is determined by the lowest interaction of the θ_{max} and the initiation curves, which can be comparable with a_2 not considering WPS effect.

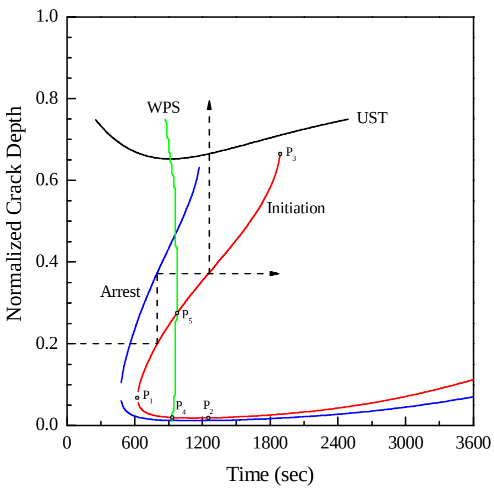

Fig. 1. Typical critical crack depth diagram

3. Results and Discussion

The example case developed for International PFM Round Robin project among Asian countries as a part of ASINCO (Asian Society for Integrity of Nuclear Components) project is solved. The reactor vessel considered is typical PWR with an inner surface radius of 2000 mm and a base metal thickness of 200 mm with the material properties of ASTM A533B-1. The postulated flaw is surface breaking crack with aspect ratio of 1/6 in the axial direction.

One overcooling transient due to assumed leak is defined with the temperature starting to decrease with cold emergency cooling water injection and system pressure to be constant.

Using the program developed here, the temperature distributions are calculated and also stress analyses are performed to generate the stress intensity factor for surface crack with a/l =1/6 in the axial direction.

For each time during the transient, the variations of K_I, K_{IC} and K_{IA} through the thickness are determined. The crack depth at which the calculated stress intensity factor exceeds K_{IC} corresponds to the critical size for crack initiation (a_i), and the depth at which the stress intensity factor goes below the K_{IA} curve corresponds to the critical size for crack arrest (a_a). Graphs of a_i and a_a versus time, called a critical crack depth diagram, are then prepared as shown in Figure 2. From this diagram the critical crack depth for the transient considered is a/w = 0.0184 which means that for the crack with depth smaller that this value will not be initiated during the transient. Also the critical time interval in the transient during which mitigating action can be effective is 630 seconds, within this time the operator should take actions to mitigate the PTS event not proceeding to the through-wall penetration.

If WPS effect is considered, the WPS line is obtained from the K_I histories and it is included in the CCD diagram. In this case, the critical crack depth and critical time interval are a/w = 0.0193 and 630 seconds, respectively.

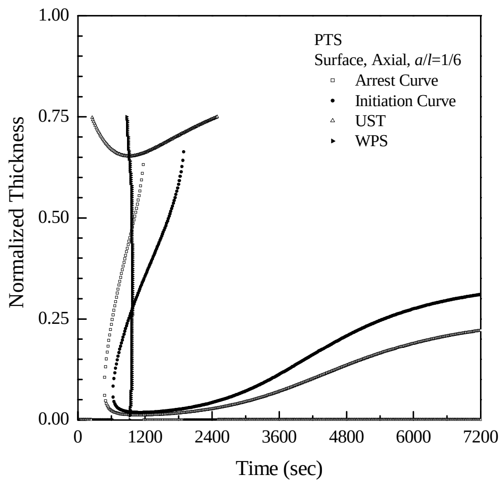

Fig. 2. Critical crack depth diagram for PTS

4. Conclusions

In this study, temperature and stress distributions through the vessel wall are determined and then stress intensity factors are calculated for various crack sizes. A critical crack depth diagram is generated by comparing the stress intensity factors with the material fracture toughness values to check the possibility of crack growth during the transient. Using the critical crack depth diagram, the critical crack depths and their times at the initiation of propagation and the crack sizes at first initiation and the corresponding times can be determined as required by USNRC Regulatory Guide 1.154.

REFERENCES

[1] USNRC. Fracture toughness requirements for protection against pressurized thermal shock events. 10CFR50.61, US Nuclear Regulatory Commission, 1996.

[2] USNRC. Format and content of plant-specific pressurized thermal shock safety analysis reports for pressurized water reactor. Regulatory Guide 1.154, US Nuclear Regulatory Commission, 1987.