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Development of Regulatory Guides on the Evaluation and Inspection of RCS branch lines Subject to Thermal fatigue

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1. Introduction

Piping failures due to thermal fatigue have been widely reported in normally stagnant non-isolable reactor coolant system (RCS) branch lines. The main cause of these failures is known as the hot swirl penetration from the RCS main pipes and the thermal stratification which can be formed due to the difference in fluid density between hot and cold water. Since nuclear class 1 design code, ASME Boiler and Pressure Vessel Code Section III (ASME Sec. III), does not take account of thermal stratification in the piping fatigue design, some of domestic nuclear power plants (NPPs), especially constructed before 1990s, didn't consider thermal stratification in their piping fatigue design. It is important to evaluate the effect of thermal stratification on the integrity of branch lines and to prepare inspection and management program against the thermal fatigue.

In United States, EPRI issued MRP-146[1] and 146S which provide common industry approaches to thermal fatigue problem in RCS branch lines in response to US NRC bulletin 88-08. In Korea, however, a specific regulatory guideline has not yet established.

In this study, regulatory guides on the evaluation and inspection of branch lines subject to thermal fatigue are developed to provide regulatory position on thermal fatigue problem in RCS branch.

2. Analysis

2.1 Thermal stratification mechanism in branch lines

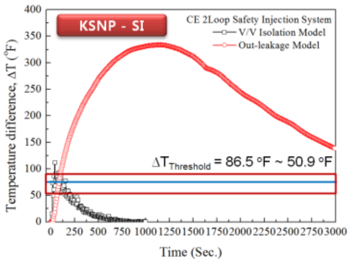
Brach lines are generally connected to the top, side, or bottom of RCS loop piping. Thermal stratification mechanism is different based on its line configurations. The branch line geometry can be classified into two generic configurations: the up-horizontal/horizontal (UH/H) and the down-horizontal (DH) configuration. Thermal stratification in UH/H lines is caused by the interaction of hot swirl penetration with cold leakage water from a normally closed valve. On the contrary, thermal stratification can occur only with hot swirl penetration from RCS loop piping in DH branch lines.

2.2. CFD analyses for screening criteria

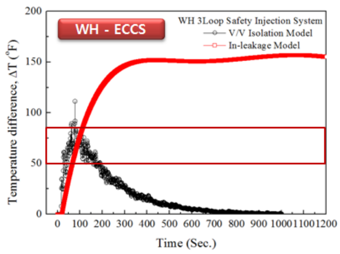
Stress and fatigue analysis of RCS branch lines considering thermal stratification require the temperature-time history which can be obtained from a thermal-fluid analysis. However, it is a time-consuming job to perform detailed thermal-fluid and stress/fatigue analyses for all of the branch lines having various geometries.

Screening criteria is developed to identify branch lines that are not susceptible to thermal stratification and eliminate them from the subjects of detailed analyses. A valve leakage and vertical length and diameter of branch lines are important elements in the screening criteria. CFD analyses are performed to evaluate their effect on the formation of thermal stratification in the selected branch lines in domestic KSNP 2-loop and Westinghouse 3-loop type NPPs. It is determined that thermal stratification is not significant if temperature difference between the top and the bottom of the branch line is below 86.5˚F. Analysis results are depicted in Fig. 1.

In the case of a UH configuration, thermal stratification is not formed without a valve leakage. In addition, in-leakage (leakage from a RCS loop piping to a branch line) gives more impact on the magnitude and duration time of thermal stratification than out-leakage (the reverse of in-leakage). It is also confirmed that thermal stratification can occur in a DH configuration without a valve leakage in contrast to a UH line.



(a) KSNP 2-loop safety injection line (UH)



(b) WH 3-loop Emergency core cooling line (UH)

Fig. 1. Temperature difference history for domestic NPPs

Length of the vertical part and diameter of a branch line affect hot swirl penetration distance, which is one of the main contributors to thermal stratification, so those can be used as the screening criteria. If a vertical leg of branch is long enough such that swirl penetration cannot reach the horizontal section, then thermal stratification will not occur.

3. Regulatory guides

Regulatory guides on the evaluation and inspection of branch lines subject to thermal fatigue are developed to provide regulatory position on thermal fatigue problem in RCS branch. Regulatory guides are composed of six parts, which are 1) screening criteria, 2) simplified criteria, 3) thermal-fluid analysis, 4) stress and fatigue analysis, 5) flaw tolerance analysis, and 6) inspection.

3.1 Screening criteria

Regulatory guide for screening criteria provides conditions that can be applied to rule out the branch lines not susceptible to thermal stratification.

First of all, all branch lines connected to RCS loop piping should be identified including information related to their geometries, materials, operating conditions. If selected branch lines meet the following conditions, then no further evaluations are required for them.

(1) Branch lines between the RCS nozzle and the first check valve that are 1-inch nominal pipe size or less.
(2) UH/H lines that has no potential of in-leakage
(3) Branch lines that satisfy the vertical line length condition with its applicability limit.

3.2 Simplified criteria

Regulatory guide for simplified criteria provides the threshold of temperature difference for UH and DH configuration which can be used to determine whether thermal stratification is significant or not. If the temperature difference between upper and bottom portion of the branch line is lower that the threshold in the regulatory guide, no further evaluations are required. The threshold for UH/H lines are 86.5 ˚F and 50.9 ˚F for a base metal and a butt weld, respectively. The threshold for DH lines has different values based on the nominal pipe size. In the case of branch lines with socket welds, simplified criteria are not applicable and thermal stratification and cycling in socket welded lines are considered significant.

3.3 Thermal-fluid analysis

Thermal-fluid analysis is needed in order to obtain thermal loading condition for stress and fatigue analysis. The thermal loading can be obtained by using MRP-132[2] methodology with modification of MRP-146S or by using computational analysis with verified software.

In the case of using MRP-132 methodology, applicability limit of MRP-132 should be satisfied.

In the case of using computational analysis, sensitivity analyses should be performed to determine appropriate parameters such as element density, time step, turbulence model, buoyancy model which can affect analysis results.

Valve leakage flow rate used in the analysis should be larger than the minimum leakage rate that can produce cold stratified layer. If the valve leakage rate is not available from plant measurement, it is necessary to perform an analysis to determine the range of leakage rate that results in thermal stratification/cycling.

3.4 Fatigue analysis

Fatigue analysis should be conducted to determine that the cumulative usage factor (CUF) is acceptable. This fatigue analysis must consider the effects of design transients and the effects of thermal stratification/cycling. The predicted CUF should be less than 1. If not, repair, replacement, modification, or other mitigation action should be taken. ASME Sec. XI Appendix L, flaw tolerance analysis, can be used to determine acceptability to operate to next refueling outage.

3.5 Flaw tolerance analysis

The flaw tolerance analysis can be used when CUF is predicted lager than 0.7 to determine the inspection interval or the operability to next refueling outage according to ASME Sec. XI Appendix L. It can be also utilized for plants where the original CUF is not known.

3.6 Inspection

Branch lines that pass the screening and the simplified criteria should be inspected according to current inspection program. If the predicted CUF is 0.7~1.0, inspection should be performed every refueling outage. The Flaw tolerance analysis can be used to determine inspection interval. If the predicted CUF exceeds 1, repair, replacement, modification, or other mitigation action should be taken. The flaw tolerance analysis can be used to determine acceptability to operate to next refueling outage.

Inspection should be performed by properly trained examiners to detect thermal fatigue cracking. In the case of UT, performance demonstration is required according to ASME Sec. XI Appendix VIII.

REFERENCES

[1] EPRI, 2005, “Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch lines”, MRP-146
[2] EPRI, 2004, “Thermal Cycling Screening and Evaluation Model for Normally Stagnant Non-Isolable Reactor Coolant Branch Line Piping with a Generic Application Assessment”, MRP-132