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Study of Thermal Stratification in Piping Systems for Operating Nuclear Power Plants Based on MRP-146 Rev.2

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1. Introduction

Thermal stratification in piping systems of operating nuclear power plants poses a significant risk to structural integrity, potentially leading to thermal fatigue and deformation. Since the accident occurred in 1987 at the Farley Unit 2 power plant, where a crack in the branch pipe connected to the Reactor Coolant System (RCS) caused a coolant leak due to thermal stratification, the US Nuclear Regulatory Commission (NRC) has issued Bulletins 88-08 and 88-11 [1, 2]. These bulletins require analytical evaluation, design improvement, or non-destructive testing to demonstrate the integrity of pipes that are likely to experience thermal stratification, such as branch pipes connected to the RCS, and pressurizer surge lines. The Nuclear Safety and Security Commission of Korea also requires satisfaction of piping thermal stratification evaluation through the "Guidelines for Applying Technical Standards for Continued Operation Evaluation of Nuclear Reactor Facilities (No. 2024-1)".

In this paper, we reviewed the latest technical document, MRP-146 Rev.2, published by the Electric Power Research Institute (EPRI) [3]. The MRP-146 Rev.2 document approach includes screening, evaluation, inspection, and monitoring, ensuring that susceptible piping is effectively identified and managed.

2. Review for the assessment methodology in the MRP-146 Rev.2

The MRP-146 Rev.2 document provides screening, evaluation, inspection and monitoring for assessing potential thermal fatigue cracking due to swirl penetration and/or valve in-leakage that may occur in normally stagnant non-isolable piping systems attached to pressurized water reactor main reactor coolant system piping [3].

2.1 Screening of piping system

Screening criteria defined in MRP-146 Rev.2 document include identifying specific piping systems that are more vulnerable to thermal stratification due to their operating conditions and configurations. In Pressurized Water Reactors (PWRs), the piping systems that require screening include safety injection lines, charging lines that are not in service either permanently or on a cycle-by-cycle basis, drain lines, excess letdown lines if applicable in a specific plant configuration, residual heat removal suction lines also called decay heat removal lines in B&W plants and shutdown cooling suction lines in Combustion Engineering plants, and any other normally stagnant lines with a nominal diameter greater than one inch.

Screening methods differ based on pipe configuration, with UH/H configurations being more susceptible to cold water in-leakage due to their orientation and valve placement. In these configurations, upward pipe sections can trap stratified layers of cold water, which may suddenly mix with hotter fluid during operational changes, leading to significant thermal cycling stresses.

Additionally, valve positioning in configurations (UH/H) can contribute to stagnation zones, further exacerbating thermal stratification effects and increasing susceptibility to fatigue damage. These factors necessitate a strong emphasis on valve leakage potential and thermal cycling susceptibility in the screening process. Configurations (DH) are influenced by downward flow dynamics and environmental heat loss, making vertical length limits and external heat dissipation effects critical factors in screening assessments.

For branch lines that meet the screening criteria, further detailed evaluation is necessary. This includes specific vertical length thresholds that dictate the extent of stratification effects and a structured evaluation of the maximum stratification depth based on empirical data and analytical models. If a branch line does not meet the screening criteria, it proceeds to the next phase of thermal stratification evaluation.

Additionally, MRP-146 Rev.2 document allows for exceptions where screening may not be required. This applies in cases where pressure control systems are in place to prevent backflow, thus eliminating thermal fatigue risks. Exceptions may also be considered for piping configurations where empirical data or operational history demonstrate an absence of significant thermal fatigue effects. These conditions should be explicitly documented to ensure accurate assessment and compliance.

The flowcharts (Figure 2-1 and Figure 2-2 in MRP-146 Rev.2 document) show key decision points, such as nominal pipe diameter threshold, the impact of vertical length on stratification effects, swirl penetration assessment, and pressure control system exceptions. By outlining these decision points, the flowchart helps the identification of branch lines requiring further thermal stratification evaluation, ensuring a systematic approach to fatigue risk management.

2.2 Thermal Stratification Evaluation

For branch lines failing the initial screening, MRP-146 Rev.2 mandates a structured evaluation process to determine susceptibility to thermal fatigue. The methodology includes assessing temperature fluctuations, flow stagnation, and the potential for stratification-induced stress. Temperature differential thresholds (ΔT threshold) are applied to determine the significance of stratification effects, and MRP-146 Rev.2 document specifies a baseline ΔT threshold of 50°F as a general criterion for evaluating thermal fatigue risks.

For UH/H configurations, MRP-146 Rev.2 allows plant-specific assessments to justify higher ΔT threshold values, provided that stratification effects and material response to cyclic thermal loads are sufficiently evaluated. DH configurations, particularly drain lines, may also qualify for an adjusted ΔT threshold based on branch size and operational loading conditions as defined in MRP-146 Rev.2.

Evaluation techniques include stress analysis models and fatigue usage factor (CUF) calculations to quantify the impact of cyclic thermal stresses. Piping geometry, operational conditions, and historical data are considered to refine susceptibility assessments. Additionally, MRP-146 Rev.2 document emphasizes evaluating cumulative temperature cycles exceeding design allowances, typically considering thresholds where the number of cycles surpasses fatigue design limits. According to MRP-146 Rev.2 document, cumulative cycles should be compared against material-specific fatigue curves and operational stress factors to determine whether additional assessment or mitigation measures are required, as repeated exposure to high ΔT values can accelerate fatigue damage. If the evaluation confirms high susceptibility, the system proceeds to the inspection phase to verify actual conditions and implement necessary mitigation measures.

2.3 Inspection

Regular inspection is a crucial step in ensuring early detection of thermal fatigue. According to MRP-146 Rev.2 document, inspection strategies should incorporate multiple non-destructive examination (NDE) techniques to provide comprehensive assessments of thermal fatigue risks. The inspection process consists of non-destructive testing (NDT) methods, including ultrasonic testing (UT) & eddy current testing (ECT) for detecting material defects and early fatigue crack formation, thermal imaging for mapping temperature gradients and detecting irregular stratification zones, and visual inspection for assessing external indications of thermal fatigue, such as surface cracks or deformations.

Additionally, Radiographic Testing (RT) can be used in conjunction with UT to detect significant cracking that exceeds ASME Code Section XI, IWB-3500 evaluation standards. While UT remains the primary method, RT can provide supplemental confirmation of flaw depth and propagation. Acoustic Emission (AE) monitoring is a non-invasive technique used for leak detection and early crack formation assessment, detecting acoustic energy emissions from fluid leakage past valve seats. Furthermore, Check Valve Diagnostics Monitoring employs acoustic, magnetic, and ultrasonic technologies to detect disc movement and flow leakage in check valves, providing early fault detection and preventing operational failures.

2.4 Monitoring

Continuous monitoring is essential for detecting thermal fatigue conditions in real-time. Temperature Sensor Placement should follow MRP-146 Rev.2 guidelines, ensuring that sensors are positioned at appropriate locations depending on the pipe configuration. For UH/H configurations, axial sensor placement is recommended to detect in-leakage thermal cycling, while for DH configurations, sensors should be placed at the top and bottom of the elbow-to-horizontal pipe weld to capture thermal ingress. Additionally, MRP-146 Rev.2 document suggests that in cases where branch piping experiences intermittent operation, supplementary sensors may be positioned along horizontal pipe sections to better monitor stratification effects and transient temperature fluctuations.

Proper placement of sensors helps accurately detect thermal stratification and temperature fluctuations. Temperature Sensor Placement should follow MRP-146 R02 guidelines, ensuring that sensors are positioned at elbow joints, branch connections, and stagnant zones where temperature stratification is most likely. Data Collection and Sampling Frequency should align with MRP-146 Rev.2 document recommendations, requiring a minimum 2-hour monitoring duration with data collection at 5-second intervals to ensure accurate trend analysis. For extended monitoring (≥ 25 hours), data acquisition periods of up to 10 minutes are acceptable, provided at least 2004 data points are collected to maintain statistical accuracy.

Additionally, interpretation of monitoring data requires adjustments for pipe metal thermal lag and response attenuation. High-frequency temperature fluctuations may not be fully observable on the pipe's outer surface, necessitating finite difference or finite element analysis to accurately estimate fluid temperatures.

3. Conclusions

The application of MRP-146 Rev.2 document in operating nuclear power plants significantly enhances safety by integrating a structured approach to identifying and managing thermal fatigue risks. Screening differentiates UH/H and DH configurations, ensuring that branch lines prone to cold water in-leakage or thermal ingress are prioritized for further evaluation.

This process minimizes unnecessary inspections and ensures that only high-risk sections undergo detailed evaluation, optimizing resource allocation and safety efforts. Thermal stratification evaluation, including ΔTthreshold analysis (50°F baseline), provides a refined assessment of fatigue susceptibility by incorporating plant-specific criteria and operational conditions.

Ultrasonic Testing (UT) is effective for subsurface defect detection, while Radiographic Testing (RT) provides flaw depth confirmation, and Acoustic Emission (AE) monitoring enables real-time anomaly detection. These complementary methods allow for early detection of fatigue-related damage, reducing the risk of unexpected failures and ensuring long-term structural integrity. Real-time monitoring strategies refine thermal fatigue risk assessment, but sensor data interpretation must account for thermal lag and response attenuation to ensure accurate stratification analysis.

Proper calibration and validation using plant-specific fluid dynamics models enhance the accuracy of monitoring results, enabling proactive maintenance decisions. These combined methodologies enable proactive maintenance and risk mitigation, preventing unplanned failures in nuclear plant piping systems.

REFERENCES

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