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Evaluation of Flow-Accelerated Corrosion (FAC) Impact in Feedwater Systems under Flexible Operation Scenarios of Nuclear Power Plants

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1. Introduction

As the global deployment of Variable Renewable Energy, such as solar and wind power, rapidly expands to achieve Net-Zero emissions, securing the flexibility of baseload power sources has emerged as an essential requirement for maintaining grid stability. In particular, Small Modular Reactors require load following capabilities to respond to the intermittent power fluctuations of renewable energy, extending beyond conventional baseload operation [1]. According to a recent IAEA report, next-generation SMRs are expected to perform not only daily load following but also deep load following operations, which involve derating the reactor down to 25% of its rated power [2].

The secondary feedwater system of a nuclear power plant, primarily composed of carbon steel piping, is highly vulnerable to wall thinning degradation caused by Flow-Accelerated Corrosion (FAC). FAC is governed by a complex interaction of thermo-hydraulic and water chemistry parameters, including flow velocity, temperature, pH, and dissolved oxygen. Generally, it is understood that a reduction in plant power leads to a decreased flow velocity, which subsequently lowers the piping FAC rate. However, when the power fluctuation range is as broad as 100% to 25%, as anticipated in SMRs, the fluid temperature transition can lead to prolonged exposure to a specific temperature range (130–150°C) where FAC is most highly active [3]. This suggests that during low-power operation, the effect of increased chemical solubility driven by temperature drop may dominate over the FAC rate reduction effect associated with decreased flow velocity, potentially resulting in unexpected localized FAC rate acceleration.

Accordingly, this study utilizes the CHECWORKS code to examine the feasibility of simulating flexible operations in the feedwater system and quantitatively analyzes the impact of various power scenarios on piping integrity. To this end, the thermo-hydraulic variations under four distinct power levels (100%, 75%, 50%, and 25%) were simulated using a large pressurized water reactor (PWR) feedwater system as a reference model. Subsequently, four customized flexible operation scenarios were applied, formulated based on the technical frameworks provided by the IAEA and OECD/NEA. The primary objective is to verify whether an anomalous increase in the FAC rate occurs during power derating and to proactively identify potential hot-spots through a comparative scenario analysis. Ultimately, this study aims to provide baseline data for wall-thinning management strategies that must be considered in future SMR operations.

2. Analysis Model and Methodology

2.1 Analysis Code and Modeling

In this study, CHECWORKS™ SFA (Steam/Feedwater Application), a computational analysis code developed by the Electric Power Research Institute (EPRI), was utilized to predict piping wall thinning. This code calculates the FAC rate based on the Chexal-Horowitz correlation by comprehensively considering the thermo-hydraulic conditions and water chemistry parameters inside the piping. The analysis target is the main pipeline of the secondary feedwater system in a 1000 MWe-class large pressurized water reactor (PWR), encompassing the piping from the downstream of the Deaerator Storage Tank to the inlet of the Steam Generator. Existing modeling data for a total of 632 line & components were utilized. To ensure the realism of the analysis, the original material data specified in the design specifications were input for each component as the primary piping material. Fig. 1 illustrates the Heat Balance Diagram (HBD) that served as the basis for this analysis, visually indicating the locations of the major hot-spots identified as a result of the study.

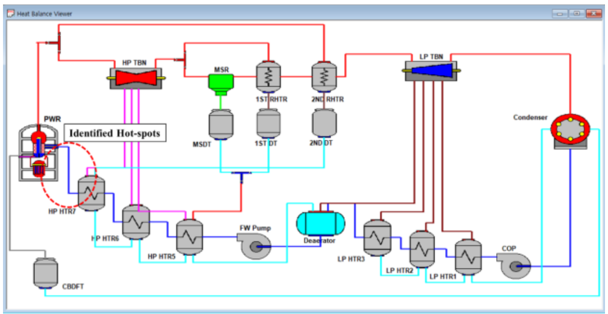

Fig. 1. Location of identified hot spots on heat balance diagram.

2.2 Thermo-Hydraulic & Water Chemistry Inputs

To accurately simulate the internal behavior of the piping according to power variations during flexible operation, a Multi-Case Independent Analysis technique was applied. Based on the plant's HBD design data, the parameters for mass flow rate, temperature, enthalpy, and pressure corresponding to each power level (100%, 75%, 50%, and 25%) were determined, thereby minimizing the uncertainty of the input variables. Assuming from a conservative perspective that the water chemistry parameters (e.g., pH, dissolved oxygen concentration) remain constant across all power levels, only the effects of thermo-hydraulic variations were independently analyzed. This assumption is considered conservative as it excludes potential chemical mitigation effects—such as pH optimization or oxygen control—that might be implemented during actual plant transients to inhibit corrosion. By fixing the chemistry at the rated-power setpoint, the study effectively performs a bounding analysis of the worst-case thermo-hydraulic impact on the FAC rate.

2.3 Load Following Scenarios

To evaluate the FAC rate sensitivity of the piping in an SMR operational environment, a total of four virtual flexible operation scenarios were formulated, as shown in Table 1. The Base scenario represents a 100% rated operation centered on the baseload. Case 1 is a standard load following scenario (50-25-25%), and Case 2 is a conservative scenario with a high frequency of partial load operation. Cases 3 and 4 assume future severe conditions with an extended duration of 25% deep load following operation.

Table 1. Definition of Flexible Operation Scenarios

Operation Scenarios	100% Power	75% Power	50% Power	25% Power
Base	100%	-	-	-
Case 1	50%	25%	25%	-
Case 2	60%	15%	15%	10%
Case 3	40%	15%	15%	30%
Case 4	50%	10%	10%	30%

2.4 FAC Rate Evaluation

The final piping integrity for each scenario was evaluated using a time-weighted average method. The final equivalent FAC rate (W_{total}) was calculated as expressed in Equation (1) by applying the operating time fraction (t_i) of the corresponding power level for each scenario as a weighting factor to the predicted FAC rate (W_{P_i}) derived at each power level (P_i).

$$W_{total} = \sum_i \left(W_{P_i} \times t_i\right) \quad (1)$$

Where, $i \in \{100\%, 75\%, 50\%, 25\%\}$

3. Results and Discussion

3.1 Overall FAC Sensitivity by Flexible Operation Scenario

As a result of evaluating the cumulative FAC rates for a total of 632 feedwater system components by applying four flexible operation scenarios, the FAC rates in the majority of the piping tended to decrease compared to the rated power (100%) operation. This is because as the power is derated, the mass flow rate within the system decreases, which consequently reduces the local velocity inside the piping, thereby lowering the physical mass transfer coefficient.

However, as shown in Fig. 2, in scenarios where the proportion of intermediate load operations at the 50% and 75% levels is significant, a FAC rate reversal was observed, where the cumulative FAC rate increased compared to the 100% rated operation condition. In particular, Case 1 exhibited a distinct and uniform FAC rate increase of approximately 4.4% across five components belonging to a specific single pipeline, and Case 2 also showed a slight FAC rate increase of about 0.4%. On the other hand, in Cases 3 and 4, where the proportion of ultra-low power deep load following at the 25% level is dominant, the FAC rates of all five identified components decreased below the baseline, confirming that the piping integrity is ensured.

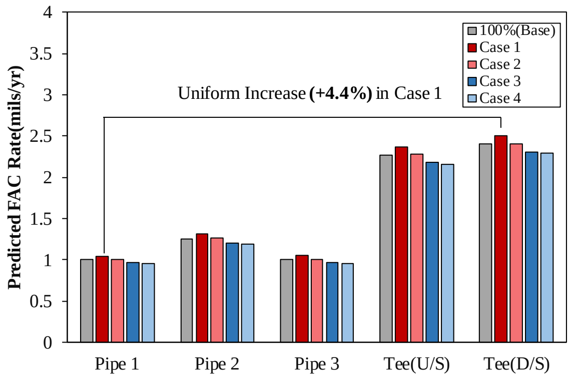

Fig. 2. Comparison of predicted FAC rates for the piping components under different flexible operation scenarios.

3.2 Identification of Hot-spots and Analysis of Wall Thinning Mechanism

The increased FAC rate observed in the five identified hot-spots can be explained by the competing effects of the decreased flow velocity and the increased chemical reactivity driven by the temperature drop. Although these components located on the same line showed differences in absolute FAC rates depending on their geometries, the FAC rate increase ratio was identical at 4.4%. It was confirmed that the local temperature of the corresponding piping line was formed in a high-temperature region of approximately 230°C or higher during 100% rated power operation; however, as the power was derated to the 50% level, the fluid temperature dropped below 200°C, approaching the highly susceptible range. In other words, in the intermediate load range, the effect of increased chemical solubility caused by the temperature drop dominated over the reduction in the FAC resulting from the decreased flow velocity, leading to an increase in the overall FAC rate, as further illustrated in Fig. 3.

To visually confirm these competing effects, Fig. 3 presents the predicted FAC rates for the five hot-spot components as a function of the combined thermo-hydraulic parameter *v*/T, where v is the local flow velocity (ft/s) and T is the absolute fluid temperature (K). As shown in Fig. 3, although the composite parameter *v*/T decreases monotonically with power derating, the predicted FAC rate exhibits a non-monotonic response, with the 50% power condition yielding the highest FAC rate among all operating points. This graphically confirms that at intermediate load, the temperature-driven increase in chemical reactivity outweighs the reduction in flow velocity.

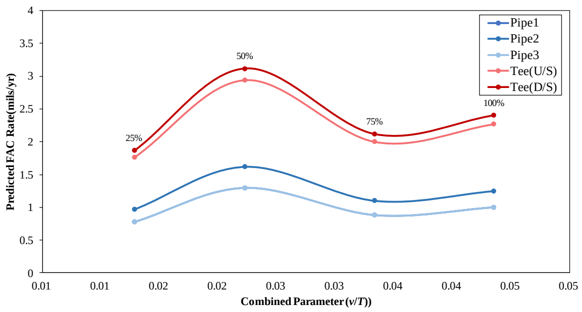

Fig. 3. Predicted FAC rates of hot-spot components as a function of combined parameter *v*/T.

3.3 Mitigating Effect on Wall Thinning under Deep Load Following Operation

It is noteworthy that the piping integrity was evaluated to be relatively superior in Cases 3 and 4, which have a high proportion of 25% power operation. Under the 25% ultra-low power condition, the absolute feedwater velocity decreases significantly even if the temperature remains within the FAC-susceptible range. The physical shear stress, a key driving force of FAC, drops below the critical threshold, thereby offsetting the adverse thermodynamic conditions. This indicates that during flexible operation of SMRs, performing deep load following operation may be relatively more advantageous for managing the integrity of the secondary feedwater piping, compared to prolonged operation in the intermediate load range.

4. Conclusions

In this study, the impact of flexible operations on FAC in the feedwater system piping was quantitatively evaluated, yielding the following conclusions: First, in the majority of the feedwater piping, the overall FAC rate decreased compared to the rated operation, primarily driven by the significant reduction in flow velocity associated with the flexible operations. Second, in certain main feedwater piping lines, it was observed that the FAC rate increased by up to 4.4% during intermediate load operations at the 50–75% levels. This phenomenon occurred because, despite the decrease in flow velocity, the temperature drop shifted the fluid into the FAC-susceptible temperature range. Third, under the 25% deep load following condition, the piping FAC was evaluated to be mitigated again; the drastic reduction in flow velocity offset the adverse effects even when the fluid temperature remained within the susceptible range.

Although this study focused on the thermo-hydraulic variations in the secondary feedwater system, future research needs to expand this analysis to other major systems within the power plant. Furthermore, while the water chemistry conditions were conservatively controlled in this study, the actual startup, shutdown, and power transient processes of a power plant entail transient variations in water chemistry parameters, such as pH and dissolved oxygen concentration. Therefore, by additionally incorporating these power-coupled transient water chemistry conditions into the analysis model, it will be possible to more precisely predict the comprehensive piping integrity in SMR flexible operation environments.

ACKNOWLEDGEMENTS

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