A Special Thermal Fatigue Failure Mode of Pipe in Nuclear Power Plant and Its Countermeasures

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Abstract: Thermal fatigue phenomenon is well known and feedbacked in the nuclear power industry. Targeted screening principles has been developed and applied. However, a thermal fatigue failure, “Swirl Penetration” of small-diameter pipeline, was identified through a Reactor Coolant System (RCS) leakage in a nuclear power plant. Unexpectedly, this failure is not within the scope of previous screening principles of thermal fatigue. It is characterized in that the high-temperature main piping is connected downward with a certain length of vertical small-diameter piping, and then the vertical piping turns horizontally through an elbow. The reactor coolant in the lower pipeline does not flow under normal operation conditions. Subject to long-term cyclic thermal fatigue, cracks initiate and propagate in the elbow. Through researches, corrective measures are put forward to prevent, mitigate or discover it.

1. Event Summary
Recently, during the normal operation of a nuclear power plant, inspectors had to enter Nuclear Island to investigate an unknown small leakage. Steam was observed coming from underneath the main piping of Reactor Coolant System (RCS Piping). Because the leak was not isolable, the reactor was forced to shut down. The failure Pipeline is connected in the form of butt weld underneath the Reactor Coolant Piping, and then turns horizontally through an elbow. (See Fig. 1)

The information of the failed pipeline is as follows:
Material: 316L
Size: φ60.3x8.74
Vertical segment length: 394mm
Turning form: 90° Elbow

![Fig. 1 Sketch of the failure Pipeline]
2. Failure Analyses
The failure section of the pipeline was cut off and sent to the laboratory (See Fig.2). The elbow was sectioned in half longitudinally to allow in-depth inspection of the inner surface (See Fig.3). Dye penetrant testing (PT) was applied to the elbow to enhance the crack indication. An approximately 50mm long indication was detected on the inner surface and a 5mm on the outer surface. The length of internal indication is obviously longer than that of external (See Fig.4 and Fig.5).

Penetrant testing and Metallographic examination (See Fig.6) shows that the crack initiated from the inner surface. Photographs of Penetrant Testing and Metallographic examination also hint that the cracks initiated at the toe of weld, in the downstream weld side of the elbow, and then propagated in the base metal (See Fig. 7). Utilizing a scanning electron microscope (SEM), further fracture analysis was executed (See Fig.8). The longitudinal direction of the crack indicates failure due to thermal fatigue. The existence of striations along the elbow crack further confirms that the failure is the result of fatigue process. The open crack surface is oxidized, indicating a long-term cracking process.
3. Failure Mode Analyses

Failure mode that were considered but excluded include the following: primary water stress corrosion cracking, general corrosion, and flow accelerated corrosion (FAC), high cycle mechanical vibration, based on material properties, pipe arrangement and crack characteristics.

Then the failure mode focused on thermal fatigue. The reason for thermal fatigue is cycles of high and low temperature on the pipe wall, caused by the temperature variation of the fluid in the pipe. The stress cycle generated by this complex thermal phenomenon eventually leads to the origin and development of fatigue cracks. In the nuclear power industry, thermal fatigue phenomenon is well known and feedbacked.

According to analysis based on a lot of industry feedbacks, the main modes of thermal fatigue phenomenon in Nuclear Power Plant can be summarized into the following categories:[1][2][3][4]:

1) Farley-Tihange Phenomenon

Farley-Tihange Phenomenon (See Fig.9 and Fig.10) is the most common thermal fatigue failure mode associated with unexpected valves leakage of branch pipe. If there is internal leakage in the closed valves of the branch pipe boundary due to corrosion and other reasons, the temperature difference between the hot water flowing intermittently in the main pipe and the cold water in the branch pipe will alternate, which will cause periodic changes in thermal stratification, i.e. the hotter and lighter medium stays in the upper layer, while the colder and heavier medium stays in the lower layer, thus generating a certain temperature gradient and induce thermal fatigue cracks.
It should be noted that the pressure difference between the two sides of the valves determines the direction of the internal leak. This is helpful to judge whether the thermal fatigue is caused by valves internal leakage and where the fatigue crack is located.

2) Mixing Flow
The low-temperature coolant and the high-temperature coolant (alternately) contact and mix in a certain area. This creates thermal stress. (See Fig.11)

3) Swirl Penetration (See Fig. 12)
The traditional understanding is that swirl penetrates approximately 18D (Diameter) in length. Because the turbulences end may move slightly (backward or forward) according to operating conditions, this movement is unstable and random. Due to the movement, the pipe elbow and horizontal section will be subjected to alternating cold and heat shocks which form thermal stress, resulting in thermal fatigue crack.
Based on this physical model, current screening principles of Swirl Penetration: when L/D = 12–24, the influence of thermal fatigue should be considered. It should be also noted that when the pipe diameter is small, it is not easy to form unstable thermal stratification. When the pipe diameter is less than or equal to 100mm, the thermal fatigue effect does not need to be considered.

Returning to this case, according to the pressure on both sides of valves, Farley-Tihange Phenomenon can be explicitly excluded. Since the fluid in the branch does not flow, Mixing Flow can also be excluded. After excluding the above two modes, comprehensive analysis shows that this case should still be classified as Swirl Penetration, although the pipe diameter is small. Because parameters of this case (L/D ≤ 10, φ = 60.3), clearly exceeds the screening criteria, this illustrates the limitations of the current industrial generic model used to predict "swirl Penetration-thermal fatigue" of RCS Auxiliary Piping. In other words, the risk of thermal fatigue is seriously underestimated when the branch pipe is vertically downward. In this special case, it is much easier to form thermal stratification in the lower horizontal section.

4. Corrective Measures
In order to avoid the recurrence of similar defects, it is suggested that the nuclear power company (the Utility) take the following Countermeasures (corrective measures) in the later period.

1) Re-evaluate the thermal fatigue risk of components to determine whether there are thermal fatigue risks that were not originally estimated, and if so, revise the In-Service Inspection Programs to add volume testing requirements (e.g. test once every three refueling).

2) Reducing the number of Valves switches during operation helps to reduce thermal stress and thermal fatigue. Valves’ switches, such as routine chemical sampling, increase the number of thermal cycles, the risk of thermal fatigue as well.

3) It is suggested to carry out Ultrasonic testing (UT) on similar component during refueling Outage. Replace defective elbows (if any) according to UT test results or evaluate their materials. According to the analysis of the characteristics of detection methods and practical experience, on the whole, UT is more sensitive and efficient than Radiographic testing (RT), especially for base metal; and RT has a good performance on the cracks located in the toe immediately adjacent to the weld.

4) Optimizing the UT inspection method, especially the inspection area and probe scanning direction based on thermal fatigue crack analysis. The toe of the weld is a key inspection area where cracks can be detected at an early stage.

5) Implement thermal fatigue prevent/mitigate measures: strengthen insulation (which can reduce the rate of temperature change and the degree of thermal stratification. See Fig.13); pipe geometric size modification (The risk of Swirl Penetration can be reduced by lengthening the vertical section length, especially by changing the Pipe slope. See Fig.14); replace elbow with bend pipe. (Avoid welds in sensitive area or reduce the number of welds. Weld heat affected zone is weak area where cracks often initiate. See Fig.15)
5. Conclusions
Thermal fatigue cracks can cause LOCA (Loss of Coolant Accident), which need to be paid more attention to. This failure event enriches our understanding of thermal fatigue in nuclear industry.

Experimental research on mocks and digital simulation based on new physical models need to be initiated and developed. The screening principle and In-service Inspection (ISI) Strategy also needs to be re-established.

In addition to strengthening In-service inspection and supervision, modification (such as changing pipe geometric size) is a very good and effective active defense measure.

References
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