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THE FAILURE ROOT CAUSE ANALYSIS OF RECIRCULATING SENSING LINE IN TAIWAN CHINSHAN NUCLEAR POWER PLANT

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Abstract

Leakage resulting from sensing line broken at the weldolet to the recirculating riser was found in Chinshan Nuclear Power Plant. A systematic failure root cause analysis, including fractographic examinations, vibration tests, stress analysis, and failure scenario reconstruction, was established. The root cause for this failure has been identified and effective corrective actions can be implemented.

1. Introduction

The leakage of sensing line at the weldolet to the recirculating riser was found in Taiwan Chinshan Nuclear Unit 2. By the dye penetrant test, a circumferential through-wall-crack between the matrix and the weld was detected[1]. Fractographic examinations revealed a cleavage fracture zone near the outer surface and following with the fatigue striation across the thickness. The preliminary evaluation was initiated by the high-rate loading and then propagated by the cyclic loading.

Taiwan Power Company performed a series of vibration tests to measure the responses of F017 spherical valve and pumps in Residual Heat Removal system(RHR), sensing lines and recirculating risers[2]. The results showed that the sensing line vibration amplitude for one pump operation with valve F017 opening with 7% is approximately six times larger than those for two pumps operating with valve opening 15% and the dominant response frequencies of the sensing line with one pump operation are approximately 17N Hz. The fluid-instability of valve F017 occurred due to fluid pressure drop. This implies that sensing line is excited by the RHR pump and F017 valve.

The finite element package ANSYS[3] is also used to study the dynamic behavior of the sensing line. Applying the harmonic motion to the riser, the sensing line is responded at 17 Hz and 21 Hz. During the plant normal operation, the excited frequencies of the recirculating pump is approximately 21 Hz to induce the vibration of sensing line. Thus, the source of crack propagation due to high cycle fatigue is proven and the root cause for this failure event has been identified. Then, the effective corrective actions can be implemented.

2. Description of Sensing Line Failure in Chinshan Nuclear Power Plant

In Chinshan Nuclear Power Plant, there are two recirculating loops as shown in Fig.1. The coolant in the recirculating loop will be injected into the reactor through 10 risers. Risers N2F, N2G, N2H, N2J and N2K belong to A loop. Risers N2A, N2B, N2C, N2D and N2E belong to B loop. Corresponding to each riser, a pressure sensing line is attached by weldolet, reference to Fig.2. However, sensing lines for N2D and N2E are combined to an unified U-type line which use the common sensor in loop B. The sensing lines for N2G and N2F in loop A are the same type as loop B, displayed in Fig.3.

All the recirculating lines including risers were replaced by the new pipe material to prevent the stress corrosion cracking during 1989. But the sensing lines were still unchanged. For Unit 2, the increased leakage flow was detected in March 1991. A circumferential through- wall-crack between the matrix and the weld of N2E sensing line was found by the penetrant test after the shutdown, as shown in Fig.4.

Some phenomena related to this event can be observed as following:

(1) The reactor had been shutdown before the leakage occurred.
(2) The failed sensing line was U-type line.
(3) The crack location was the supported points of vertical bending near the weldolet.

The fractographic examinations of failed sensing line had been conducted[1]. Fig.5 shows the cross section of the fracture surface and there was no evidence of the plastic deformation to be found. Fig.6 displays the SEM examinations at the localization of the fracture surface. The slip line was discovered near the outer surface which the crack was initiated by the over-stress loading. As following, the fatigue striation was also observed due to high cycle fatigue. Based on the fractographic examinations of failed sensing line, the phenomena can be concluded as following:

(1) The locations of failure were always at the bottom of the fracture cross section near the weldolet. In that region, there existed a notch effect to induce the stress concentration.
(2) The fracture process could be divided into two steps:
    (i) the crack was initiated by the high-rate loading,
    (ii) the crack was then propagated by the high-cycle fatigue.
(3) The material properties are still unchanged during the welding process.

3. Root Cause Analysis for Failed Sensing Line

The contributing factors for each phenomenon in the event observations and the fractographic examinations can be described as follows.

(1) The failure of the sensing line took place after the shutdown of plant. At that time, one pump of RHR system operated. There were several evidences to identify the spherical valve F017 of RHR system as the excited source.
    (i) Valve F017 stem had been replaced several times according to TAIPOWER staff. This was an indication that severe vibration of the valve was a potential cause of RHR piping vibration.
    (ii) RHR piping supports were damaged. The damaged supports were located within about 25 ft from valve F017. This showed that damage was most likely associated with the valve.
(2) Only N2E sensing line which presents the U-type line failed. The differentiation with the other sensing lines must be proven by vibration test and stress analysis.
(3) Crack initiation occurred at pipe outside surface. The fracture locations were the regions of the bottom of the fracture cross section near the weldolet. This showed that large-amplitude vibration was a cause for pipe break and bending vibration in the out-of-plane direction was a critical mode.

The RHR system pumps were designed for accident response and as a result develop too much head for optimal shutdown operation. To control the system flow during shutdown, a control valve existed in the shutdown return line, it was too large to adequately control shutdown flow rates. This led the fluid-elastic instability at the valve.

In order to find the root cause of the sensing line failure, TAIPOWER performed a series of vibration test to measure the responses of RHR pumps, sensing lines, risers and valve F017. The results are listed as follows[2]:

(1) The N2E sensing line vibration amplitudes for one-pump operation with valve F017 opening at 7% were approximately six times larger than those for two pumps operating with valve opening 15%.
(2) The excitations to all sensing lines can be transmitted by fluid or wave through risers. The dominant response frequencies f_s of N2E sensing line with one-pump operation were approximately 17N Hz, where $N = 1,2,3,$etc.
(3) At a given flow rate, the vibration amplitudes of a riser operating with a single pump or with two pumps were smaller.
(4) RHR pumps were operated about 1780 rpm (29Hz) with a 7-vane impellers. The pump excitation frequency f_p would approximately be 203 Hz. It is worthily to note that there existed a relationship between f_s and f_p,i.e. $f_s = f_p/N$, $N = 12, 6, 4, 3$

Based on the results as mentioned above, the valve F017 and one-pump operation with small opening were the probable sources of excitation. The fluid-instability of valve F017 happened due to fluid pressure drop. The large vibration amplitudes transmitted to the sensing line through the riser. The excitation frequencies of N2E line could be sub-harmonic excited by the pump of RHR system. Thus, the crack was initiated by the high-rate loading due to unstable vibration of valve.

The ANSYS finite element package[3] is also employed in this root cause analysis to realize the dynamic response of the sensing line. The harmonic motions including various frequencies are applied to the risers. Fig.7 shows the vertical bending moments of N2D and N2E sensing lines versus the various frequencies. Both of two sensing lines have the peak response at 17Hz which can be excited by the pump operation of RHR system. The response of N2E sensing line is higher than that of N2D sensing line. Therefore, the N2E sensing line failed other than of N2D one. Fig.8 displays the response of N2C sensing line. There is no 17N Hz frequencies which can be excited by the RHR pump. Thus, the reason why only the N2E sensing line failed is proven. In Fig.7, the other one peak response is also found at 21Hz which can be excited by the operation of the recirculating pump during the normal operation (1200 rpm $\sim$ 1300 rpm, i.e. 20 $\sim$ 22 Hz). This vibration will induce the crack growth of high cycle fatigue.

4. Conclusions

The N2E sensing line of Unit 2 was excited at 17Hz which can be sub-harmonic resonance with the excited frequencies of the RHR pump. Access to the large vibration amplitude of the RHR valve F017 due to fluid-elastic instability, the crack was initiated by this high rate loading. During the normal operation, the N2E sensing line was excited again by the recirculating pump at 21 Hz. Thus, the crack propagated owing to high cyclic vibration and went through the wall.

The corrective actions can be considered as short-term and long- term.

(1) Short-term
  (i) The opening of F017 valve must be larger than 15% and two pumps of RHR system will be operated during shutdown period.
  (ii) The PT examinations must be conducted during the outage period.
(2) Long-term
  The spherical valve F017 can be replaced to the drag valve.

Reference

1. Cheng,S.Y. et. al.; 1991, Inspection Report of N2E Sensing Line Failure of Chinshan Unit 2, (in Chinese), INER-Report.
2. Chen,S.S; 1991, Identification of Root Cause and Recommendation of Solution for Sensing Lines and RHR System Components, Chinshan Nuclear Power Station, TAI-POWER Report.
3. Desalvo G. and Gormin R.; 1991, User Information Manual and Theoretical Manual, ANSYS Engineering System.

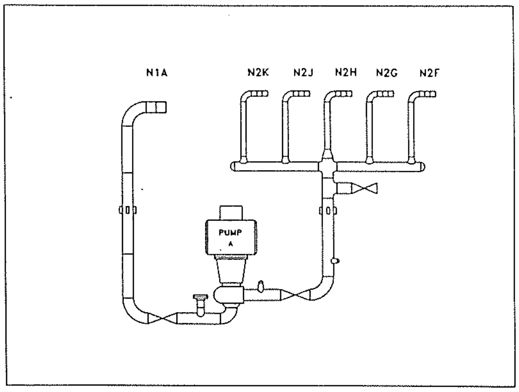

Fig.1 Recirculating piping system

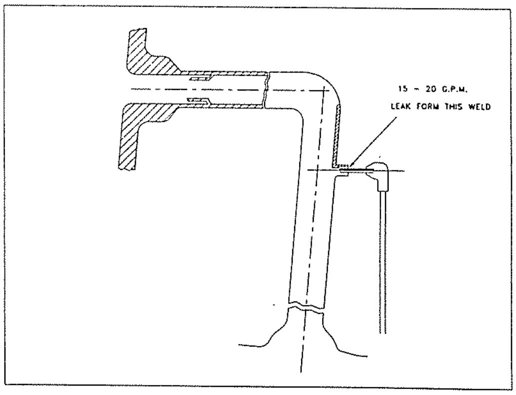

Fig.2 Sensing line attached to riser

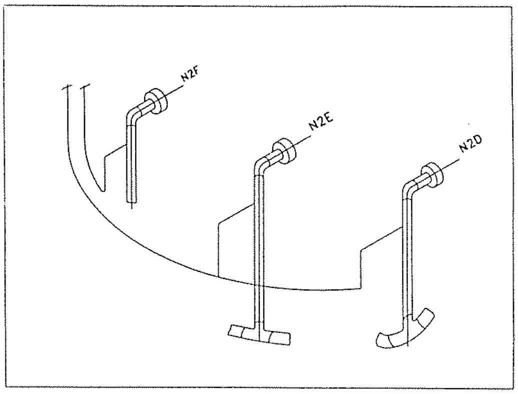

Fig.3 Sensing lines combined to U-type line

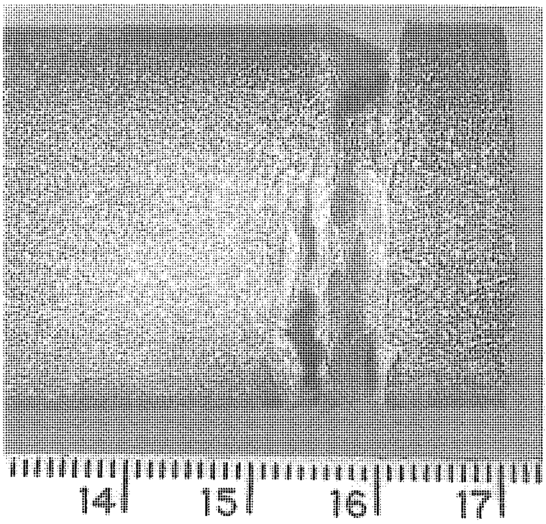

Fig.4 Crack in N2E sensing line

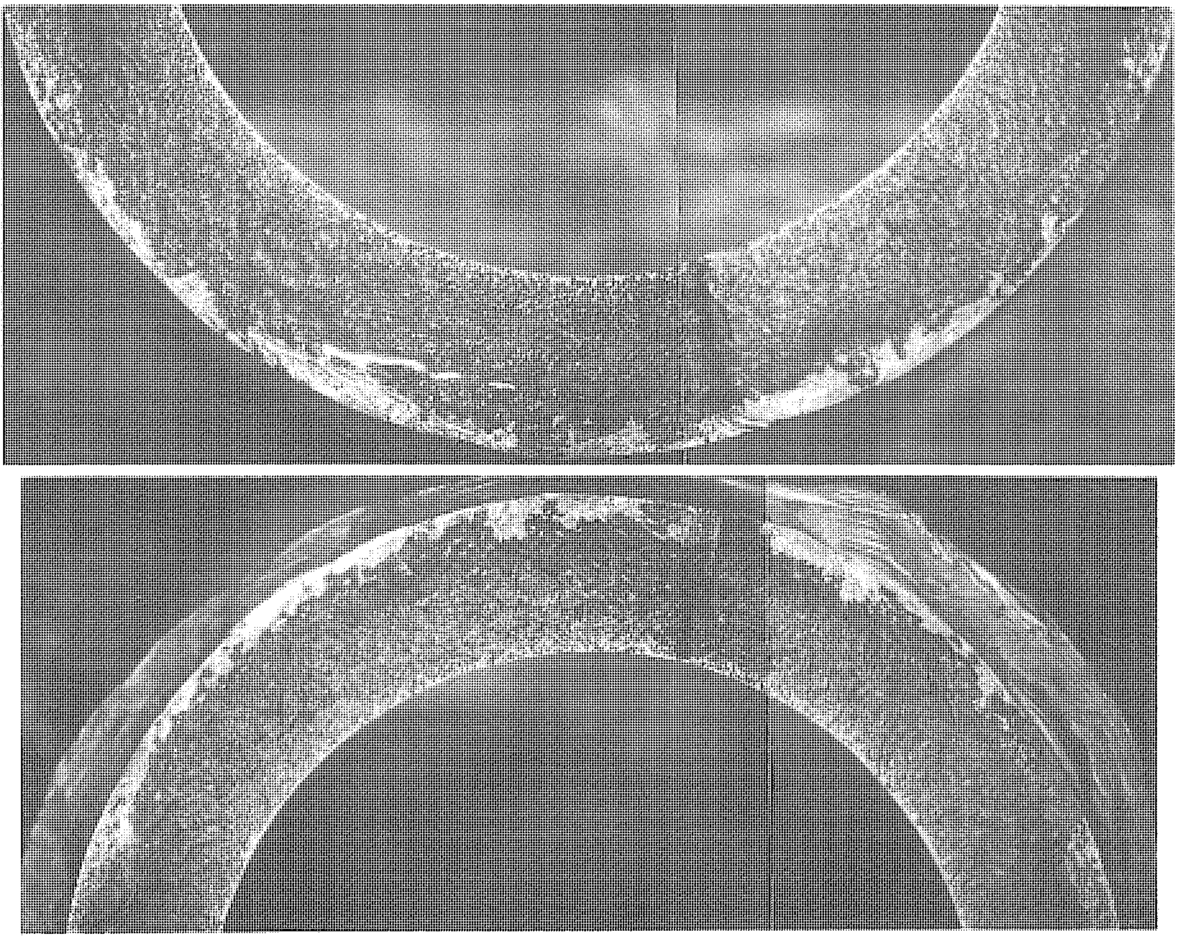

Fig.5 Fracture surface of N2E sensing line

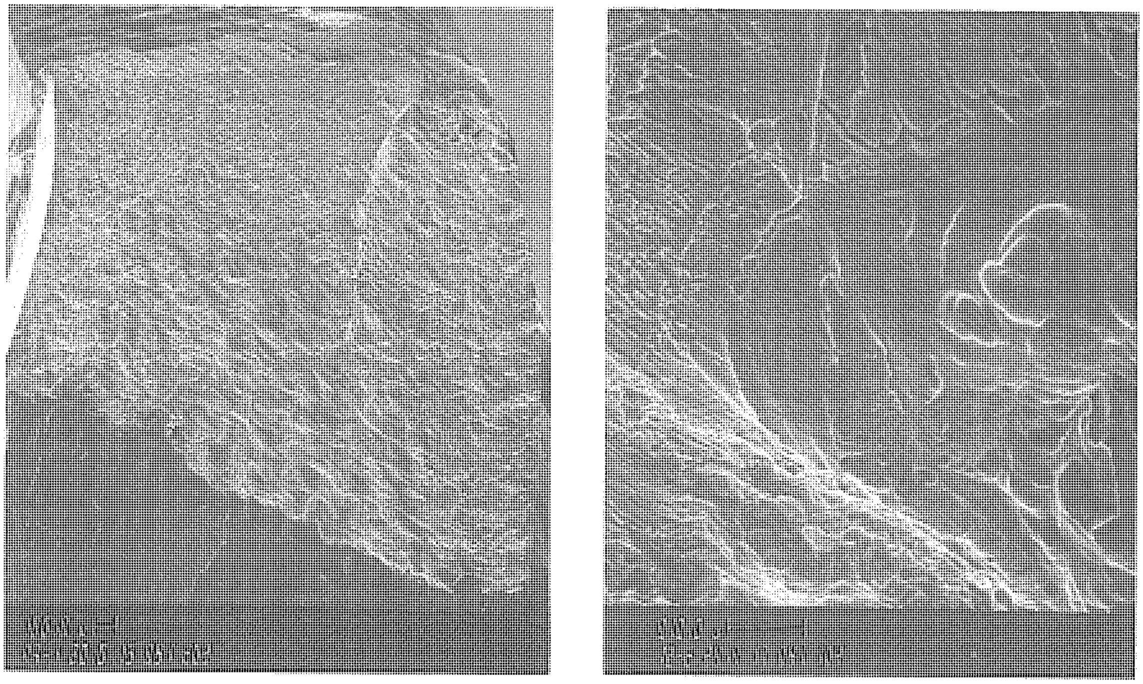

Fig.6 SEM examinations of N2E sensing line

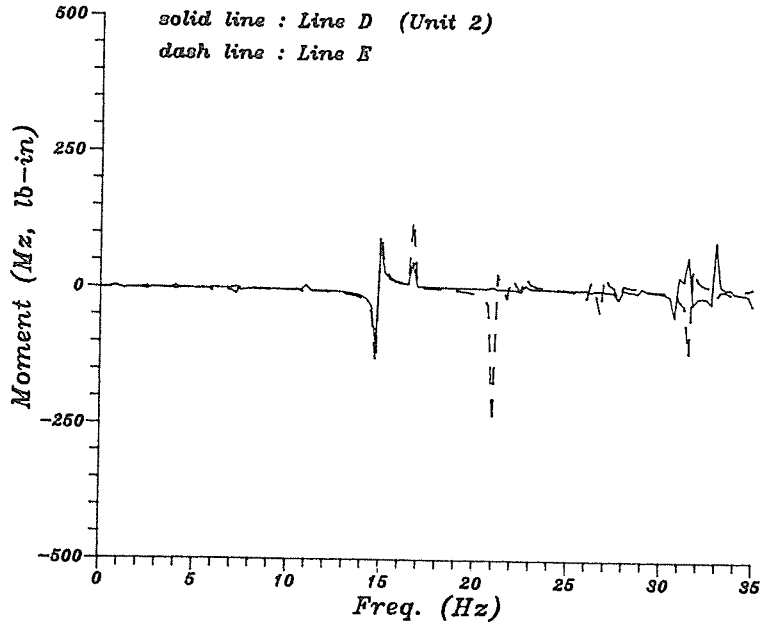

Fig.7 Vertical moments versus frequencies for N2D and N2E sensing lines

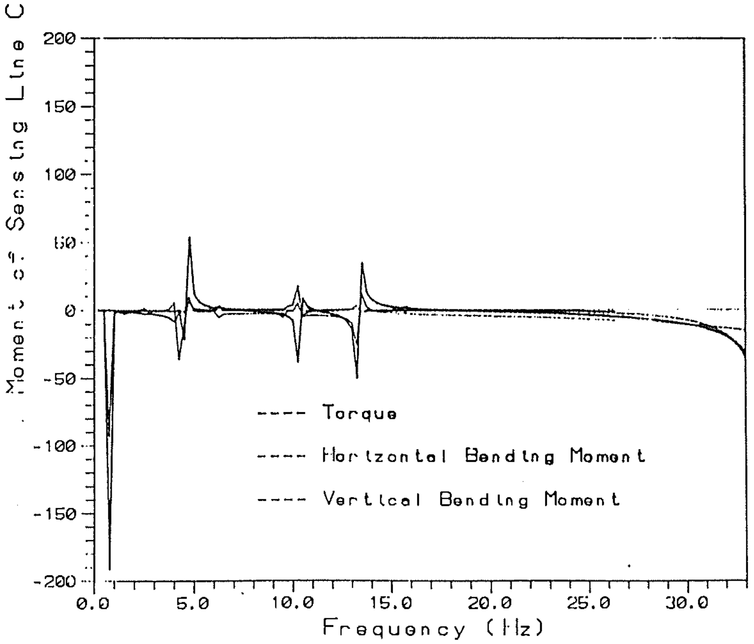

Fig.8 Vertical moments versus frequencies for N2C sensing line