Guidelines for Safety Evaluation of a Potential for PWR Steam Generator Tube Failure due to Fluidelastic Instability

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1. Introduction

Failure of a pressurized water reactor (PWR) steam generator (SG) tube leads to a leakage of contaminated primary coolant to the secondary system, which has serious safety implications such as the potential for direct release of radioactive fission products to the environment and the loss of coolant.

Excessive tube vibration excited by dynamic forces of internal or external fluid flow is called flow-induced vibration (FIV). Among the FIV mechanisms, the so-called fluidelastic instability of SG tubes in cross flow is the most important safety issue in the design of SGs because it may cause severe tube failure in a very short time [1, 2]. It was found that both SG tube rupture events [3, 4] occurred at North Anna Unit 1 in 1987 and at Mihama Unit 2 in 1991 were caused by a high cycle fatigue due to fluidelastic instability. Therefore, with regard to nuclear safety it is important to design the SG properly in a conservative manner so that the potential for SG U-tube failures due to fluidelastic instability can be minimized.

This article provides guidelines for assessing the potential for SG U-tube damage due to fluidelastic instability.

2. Mechanism of Fluidelastic Instability

The fluidelastic instability is the most important FIV mechanisms for tube bundles in cross-flow. In 1970, this mechanism was identified and characterized as a self-excited vibration mechanism causing large amplitude vibrations in closely packed tube bundles of heat exchangers including SGs.

Instability occurs when the cross flow velocity is sufficiently high so that the energy from the fluid forces exceeds the energy dissipated by damping. Connors developed a simple stability criterion for predicting critical cross-flow velocity V_c above which large-amplitude cylinder vibration initiates [5].

3. Assessment Procedure

For operating U-tube steam generators (UTSGs) where high cross flow of the secondary coolant forms in the recirculating flow entrance region above the tube sheet and the U-bend region, a procedure for assessing the potential for a tube failure caused by fluidelastic instability was established on the basis of the separate one-way analysis approach [6].

The key steps of the assessment process are

- Evaluation of the SG 2ndary side flow situation
- Determination of added mass and damping ratio
- Evaluation of modal characteristics of each tube
- Determination of fluidelastic instability coefficient
- Evaluation of critical velocity for each tube at its each mode and its effective tube-to tube gap velocity

4. Assessment Guidelines

(1) The detailed SG tube bundle configuration and geometry including tube array type, dimensions of the internal structures and components, tube support conditions, etc. should be identified by referring to the official design documents with available drawings.

(2) Considering impracticality of the measurements of 2ndary flow parameters in operating SGs, the SG 2ndary side flow situation should be evaluated by multi-dimensional steady-state or transient thermal-hydraulic analysis, followed by validation of the analysis code with the numerical models and techniques and by confirmation of the mesh-independency.

(3) It is recommended to determine the added (hydrodynamic) mass m_a of fluid displaced by the tube using the following correlations proposed by Pettigrew et al. [1, 2] unless any better alternatives are available.

$$m_a = \left(\pi\rho D^2/4\right)[(D_R{}^2+1)/(D_R{}^2-1)]$$

$$D_R = (1.07 + 0.56 * P/D)(P/D) \text{ for the square pitch}$$

$$D_R = (0.96 + 0.50 * P/D)(P/D) \text{ for the triangular pitch}$$

where, D and P are the tube outer diameter and the pitch of the tube array, respectively. The total effective mass m_t is the sum of the tube metal mass m_m, the internal fluid mass m_i and the added mass, which is given as $m_t = m_m + m_i + m_a$

(4) Damping ratio ζ is defined as the ratio of actual damping to critical damping. Because damping of multi-span SG tubes depends on geometrical conditions of tubes and their supports, flow conditions, non-linear effects and the multiplicity of energy dissipation mechanisms, the damping ratio is the most difficult parameter to determine. In particular, the 2ndary side of the SG U-bend region is actually two-phase flow field and the damping in such two-phase flow is known to be quite different from that in a single liquid flow. This makes the damping ratio of SG tube one of the most inaccurate input parameters. Total damping ζ_t in two-phase flow is the sum of viscous damping ζ_v, support damping ζ_s, and two-phase damping ζ_{tp}.

The viscous and support damping ratios of a tube, respectively, may be determined either from available measured data or by the empirical expressions. As the support damping of tubes in either liquids or two- phase mixtures is dominant, a large portion of the total damping energy is dissipated at the support [1, 2]. Au-Yang and Brenneman [7] presented that the total damping ratio for vibration amplitude of wide range 1 mil to 10 mils for SG straight tube bundles was in the range of 1% of critical to 5% or more.

Based on the above discussion, it is recommended to determine the total damping ratio of a SG tube using the following values [8] for conservatism unless any further reliable alternatives are available.

- ς_t =1.0% for tightly supported tubes in wet steam
- ς_t =0.1% for tightly supported tubes in air or gas
- ς_t =3.0% for loosely supported tubes

(5) The natural frequencies and their corresponding mode shapes of each tube should be calculated either by analytical solution or FEA as correctly as possible. The tube support conditions and the effective mass distribution along the tube should be modeled realistically. All of the possible vibration modes should be calculated.

(6) The velocity at which the tube becomes unstable is known as the critical velocity V_c. Mean values for the onset of instability can be established by fitting semi-empirical correlation to experimental data. The general correlation form recommended is given as

$$V_{c,n} / f_n D = K\,(2\pi\zeta_t m_{em} / \rho_{em} D^2)^{0.5}$$

where f_n, K, m_{em} and ρ_{em} are the natural frequency of the nth vibration mode of the tube, the Connor's constant (Instability coefficient), the mean values of $m_e(x)$ and $\rho_e(x)$, respectively.

The instability coefficient varies with the P/D ratio and tube arrangement type. The mean values of K for each tube array obtained by fitting of the semi-empirical correlation to the available 170 data points for onset of instability are presented in reference [9] as K =4.5, 4.0, 3.4, 5.8, and 4.0 for the triangular, rotated triangular, square, and rotated square arrays, respectively, but K =4.0 for all the tube arrays. Use of a mean value of K = 3.3 for the entire mass-damping parameter range is recommended in references [1, 2, 7-10]. In addition, a mean value of K = 4.0 and a conservative value of K =2.4 are proposed in references [7, 8].

Based on the above discussion, it is recommended to use K = 3.3 for all the tube arrays in the entire mass-damping parameter range unless any further reliable alternatives are available.

(7) The value of $V_{ge,n}$ equivalent to $V_g(x)$ should be determined by weighting the nth mode shape as follows:

$$V_{ge,n}^2 = (m_{em} / \rho_{em}) \int_0^l \rho(x) V_g^2(x) \varphi_n^2(x)\, dx \Big/ \int_0^l m_e(x) \varphi_n^2(x)\, dx$$

where $\rho(x)$ and $\varphi_n(x)$ are the secondary fluid density distribution along the tube length and the nth mode shape function, respectively.

(8) The stability ratio $R_{s,n}$ should be defined as

$$R_{s,n} = V_{ge,n} / V_{c,n} \quad (\text{ n = 1,2,3, …………})$$

The maximum value of the stability ratios calculated for all vibration modes of a tube is chosen as the criteria to determine the potential for the tube instability. If the maximum stability ratio R_s^m, is greater than unity, the tube is determined to be fluidelastically unstable and its vibration amplitude becomes to diverge rapidly as R_s^m increases beyond unity.

5. Conclusions

This article described guidelines for safety evaluation of a potential for PWR steam generator tube failure due to fluidelastic instability. The guidelines address the requirements for realistically performing the SG thermal-hydraulic analysis and the modal analysis of tubes as well as the criteria for conservatively determining the added mass, the damping ratio and the fluidelastic instability coefficient.

The guidelines can be used to predict the potential SG tubes which are susceptible to failure due to fluidelastic instability at operating nuclear power plants and also to evaluate the safety and structural integrity of new SG designs at the licensing review stage.

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