San Onofre Nuclear Generating Station, Units 2 & 3
REPLACEMENT STEAM GENERATORS

Supplemental Technical Evaluation Report

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Contents

Preface

This Supplemental Technical Evaluation summarizes the information contained in the report "Tube wear of Unit 3 RSG – Technical Evaluation Report" (L5-04GA564 latest revision, Ref. 1) ("TER") and supplements it with information taken from other MHI documents and the AREVA Operational Assessment and with further analysis. It is intended as a guide and introduction to the main findings of the TER as well as an explanation of key information from related documents.

1. Introduction

On January 31, 2012, during the first cycle after steam generator replacement, San Onofre Nuclear Generating Station (SONGS) Unit 3 was shut down to investigate a steam generator tube leak. Steam generator tube inspections confirmed a small leak in one tube in one of the two steam generators. Further inspections of 100% of the steam generator tubes in both Unit 3 steam generators discovered unexpected wear, including tube-to-tube as well as tube-to-tube-support wear. At the time of the Unit 3 leak, SONGS Unit 2 had already completed one cycle of power operation (~22 months) and was in a refueling outage. Inspections of tubes in the Unit 2 steam generators revealed similar wear to that found in Unit 3.

The detailed inspections revealed tube wear in the tube free span sections, at anti-vibration bars (AVBs), at tube support plates (TSPs), and at retainer bars. These indications were labeled as follows:

(i) Type 1 (Tube-to-Tube Wear)
(ii) Type 2 (AVB wear without Tube-to-Tube wear)
(iii) Type 3 (TSP wear without Tube-to-Tube wear or AVB wear)
(iv) Type 4 (Retainer bar wear)

The cause of the first 3 types of tube wear is tube vibration. Type 4 tube wear is caused by vibration of the retainer bars.

The causes of tube vibration are (1) insufficient support for the tubes in the in-plane direction caused by small and uniform tube-to-AVB clearances, and (2) localized high thermal-hydraulic conditions in the SG secondary side. The mechanistic causes of the first three types of tube wear are described in detail in the TER (Ref. 1). The mechanistic causes of Type 4 wear (not discussed in this document) are described in the "Retainer Bar Tube Wear Report" (L5-04GA561 latest revision, Ref. 2).

The numbers of tubes for each type of tube wear in the Unit 2 and Unit 3 steam generators are listed in Table 1-1 and Table 1-2. These numbers are based on the MHI database (refer to "Screening Criteria for Susceptibility to In-Plane Tube Motion" (L5-04GA571 latest revision (Ref. 3), Appendix 3). The MHI database numbers differ from those of the SCE database as explained in TER Section 4.1 (Ref. 1).

Table 1-1 Number of Tubes with Wear in SONGS Unit 2

Wear Type	SG 2A (2E-089)	SG 2B (2E-088)	Total
Type 1 (TTW)	2 (note 2)	0	2 (note 2)
Type 2 (AVB wear)	802	595	1397
Type 3 (TSP wear)	53	137	190
Type 4 (RB wear)	4	2	6
Foreign Object	0	2	2
Total	861	736	1597

Notes:

1) Each tube is only counted once, with the priority given to Type 1 followed by Type 2, Type 3, Type 4 and Foreign Object.

2) The wear characteristics of these two tubes differ from the TTW tubes in Unit 3 in that they exhibit no wear at the top TSP and only contact each other at a single point.

Table 1-2 Number of Tubes with Wear in SONGS Unit 3

Wear Type	SG 3A (3E-089)	SG 3B (3E-088)	Total
Type 1 (TTW)	165	161	326
Type 2 (AVB wear)	714	737	1451
Type 3 (TSP wear)	15	20	35
Type 4 (RB wear)	1	3	4
Foreign Object	0	0	0
Total	895	921	1816

Notes:

1) Each tube is only counted once with the priority given to Type 1 followed by Type 2, Type 3, and Type 4.

2. Wear Mechanism of Type 1 (Tube-to-tube wear)

2.1 Tube Wear Indications of Type 1 (Tube-to-tube wear)

The Type 1 wear pattern is found in the tube free-span sections between or crossing over the AVBs. Type 1 wear can be differentiated from Type 2 wear by its location on the circumference of the tube. Type 2 wear is located on the sides of the tube that are adjacent to the AVBs while Type 1 wear is located on the extrados or intrados of the tube (the top or bottom of the tube cross section). Type 1 and Type 2 wear can be distinguished from each other by rotating ECT.

Type 1 tube to tube wear occurs when there is tube in-plane motion (vibration) with a displacement (amplitude) greater than the distance between the tubes in the adjacent rows, resulting in tube-to-tube contact.[1] These tubes also exhibit significant wear at the AVBs and TSPs in addition to the free-span wear. Tubes with Type 1 wear are shown in Fig. 2.1-1 (Unit 2) and Fig. 2.1-2 (Unit 3). These figures display the same data as shown in Fig.4.1.1-1 in the TER (Ref. 1).

The AREVA Operational Assessment (Ref. 4) at page 16 states:

> Both steam generators in Unit 3 had more than 160 tubes with TTW indications in U-bends. The three most degraded tubes exhibited wear scars that were more than 28 inches long . . .. TTW scars are located on the extrados and intrados locations of U-bends. Wear scars on extrados locations of a given U-bend have matching wear scars on intrados locations of the neighboring row tube in the same column.

[1] Some of the tubes with tube-tube wear did not experience large amplitude vibration but were impacted by tubes that did experience large amplitude vibration. Also the two tubes in Unit 2 with tube-to-tube wear had different wear characteristics than the Unit 3 tube-to-tube wear. Neither of the two Unit 2 tubes exhibits wear at the top TSP and neither exhibits free span wear on both the hotleg and coldleg sides of the U-bend (the free span wear indication is only on one side of the U-bend).

This pattern of wear reflects large amplitude displacement of the tubes in the in-plane direction. Those tubes with the large amplitude displacements also have significant wear at the top tube support plate (TSP 7) (See L5-04GA571 the latest revision (Ref. 3)), which is consistent with large displacement of tubes in the in-plane direction without in-plane AVB support.

2A-SG (Unit 2 E089)

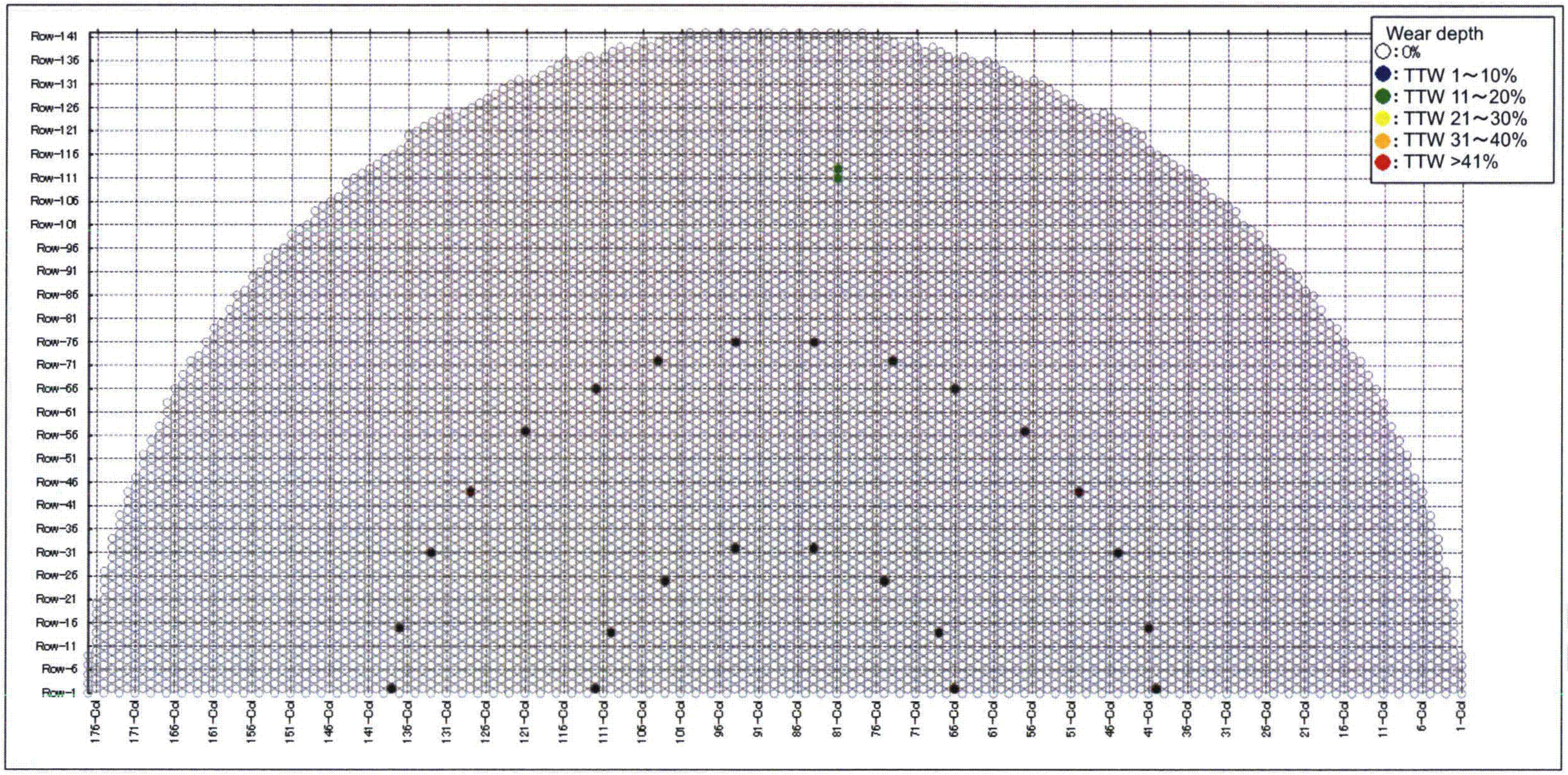


Fig 2.1-1 (1/2) Unit 2 Tubes with TTW indications

2B-SG (Unit 2 E088)

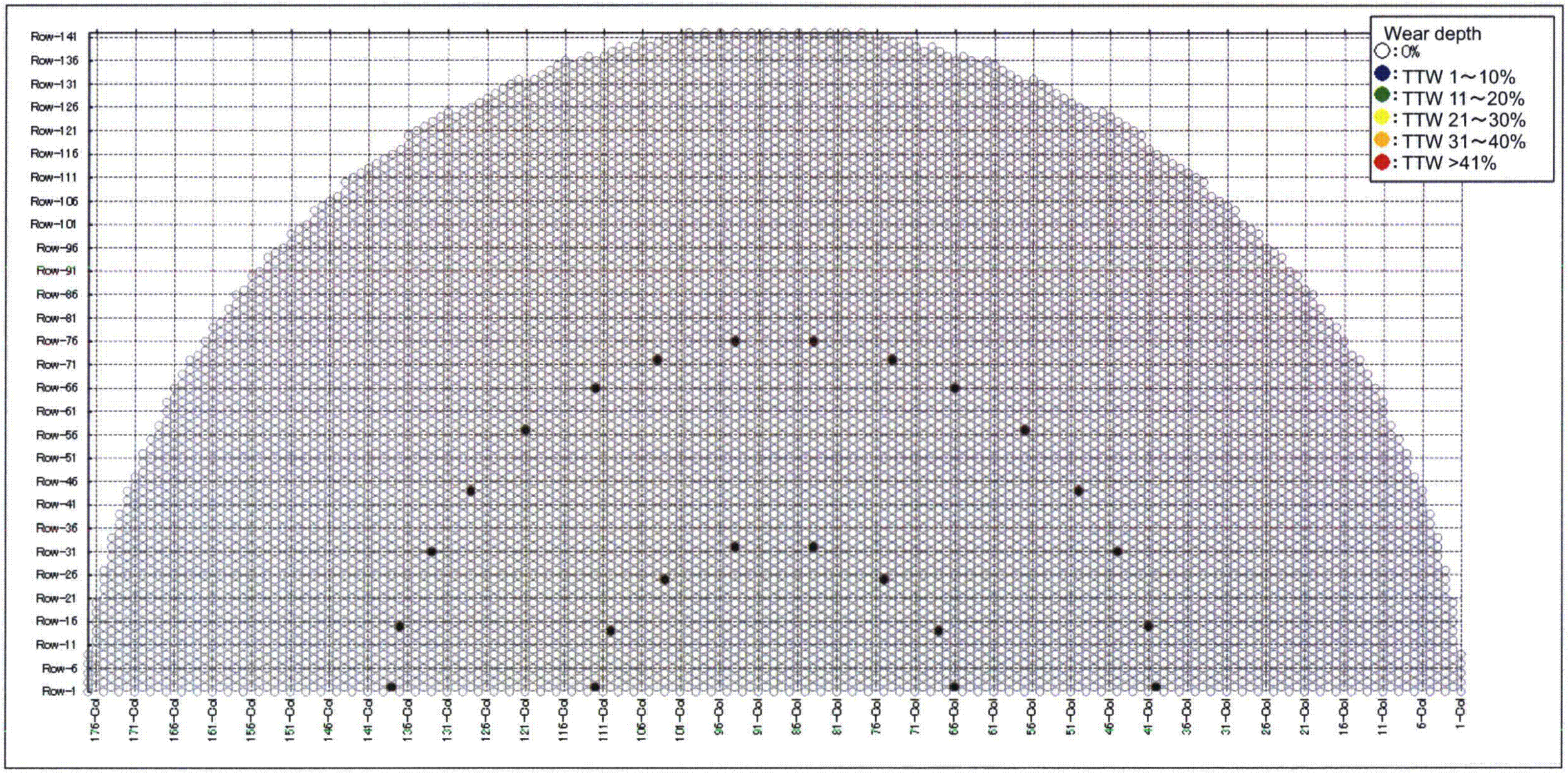


Fig 2.1-1 (2/2) Unit 2 Tubes with TTW indications

3A-SG (Unit 3 E089)

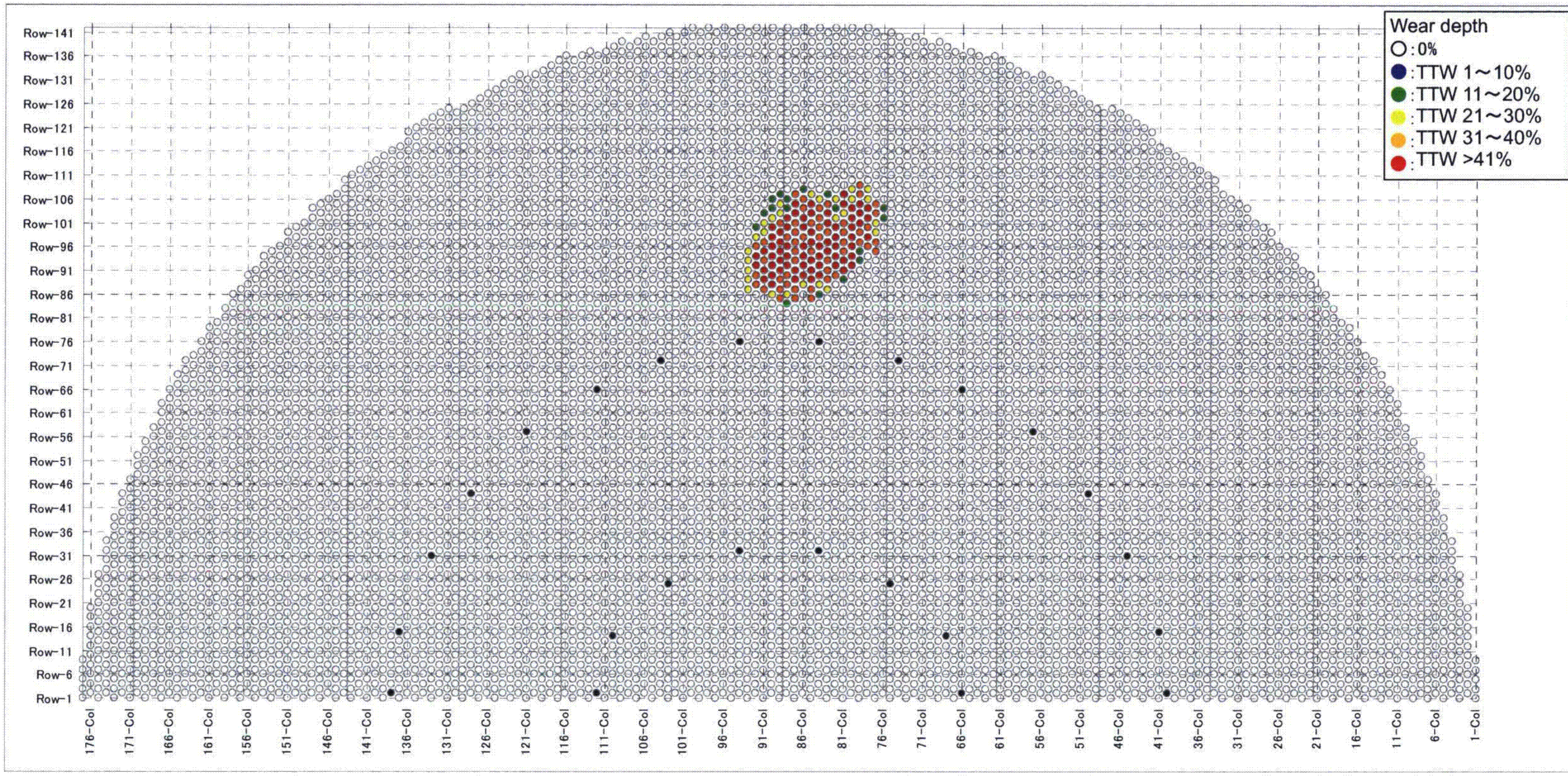


Fig 2.1-2 (1/2) Unit 3 Tubes with TTW indications

3B-SG (Unit 3 E088)

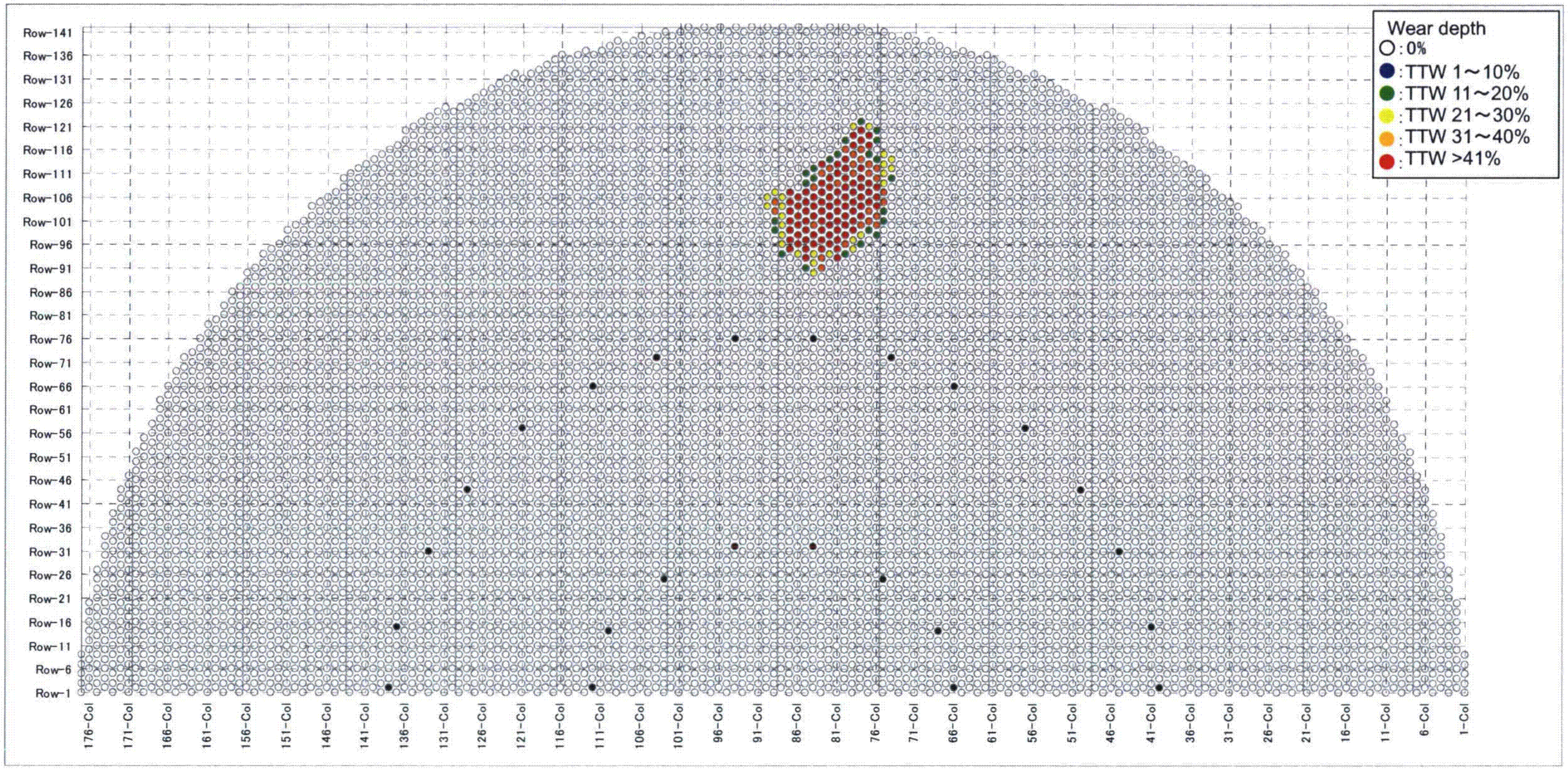


Fig 2.1-2 (2/2) Unit 3 Tubes with TTW indications

2.2 Causes of Type 1 Tube Wear (Tube-to-Tube wear)

As discussed above, most of the Type 1 wear (TTW) indications suggest that the wear is due to tube in-plane motion (vibration) with a displacement (amplitude) greater than the distance between the tubes in the adjacent rows, resulting in tube-to-tube contact. Tube in-plane motion can be caused by turbulence and fluid elastic instability (FEI). However, turbulence induced (random) vibration by itself is insufficient to produce displacements of this magnitude. Displacements as large as those associated with in-plane tube-to-tube contact can only be produced by fluid elastic vibration. Further, the contiguous grouping of the TTW tubes is another characteristic of fluid elastic instability as discussed further in Section 2.3.

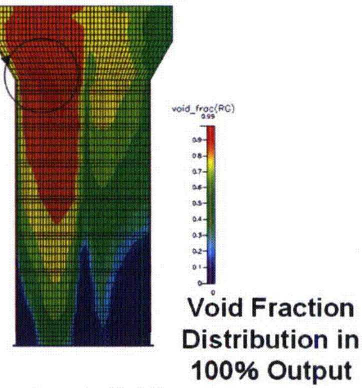
As discussed in Sections 5 and 6.1 of the TER, in order for large in-plane displacements to occur two conditions are necessary. First, the tube needs to be unrestrained in the in-plane direction and second the environment must be conducive to FEI (velocity, density, damping, etc.). These causes are summarized in Fig.2.2-1. This figure shows the same mechanism as Fig.6.1-1 in the TER (Ref. 1).

The following Section provides an explanation of the nature of and conditions necessary for FEI and describes the characteristics of the SONGS RSGs that led to the occurrence of in-plane FEI in the RSGs.

Characteristics of SONGS RSG

【Thermal Hydraulics】

✓ Design with High Steam Quality in U-Bend(max| |)

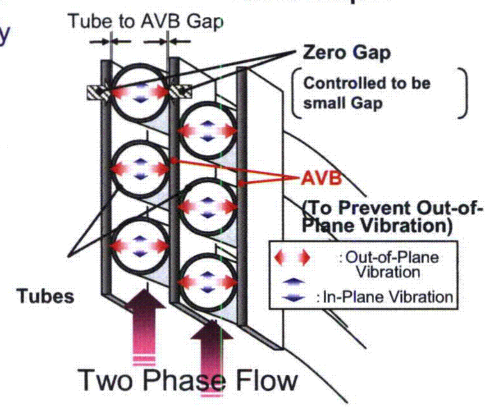


【AVB Structure】

✓ Tube between 2 flat AVBs
- AVB Design Assumes Out-of Plane Vibration
  Since out-of-plane FEI is more likely to happen compared to in-plane FEI, AVBs are placed at the sides of tube to prevent out-of-plane vibration

✓ 6 V-Shaped AVBs (12 support points)
- Number of AVB Support Points are confirmed to satisfy ASME FEI Requirements

✓ Designed and fabricated for effective "Zero" Gap between Tube and AVB in hot condition



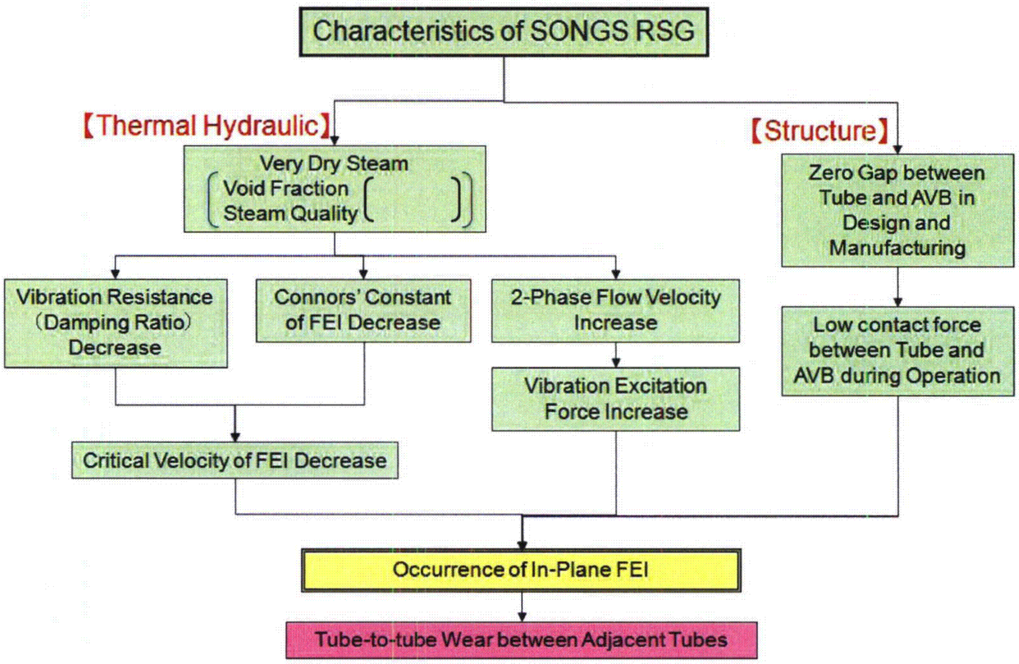


Fig. 2.2-1 Type 1 Wear (TTW) In-Plane Mechanism

2.3 FEI

2.3.1 Conditions Necessary for FEI

In a tube array, a momentary displacement of one tube from its equilibrium position will alter the flow field and change the force balance on the neighboring tubes, causing them to change their positions in a coordinated manner. When the energy extracted from the flow by the tubes exceeds the energy dissipated by damping it produces fluid elastic vibration. The threshold for this instability is shown in Figure 2.3-1 below, where one axis (Y) of the graph is vibration amplitude and the other (X) is flow velocity. The curve shows that as flow velocity increases, vibration initially increases gradually. As velocity continues to increase, it will reach a point where the slope of the vibration line changes abruptly. The point on the curve where the slope changes is termed the "critical velocity".

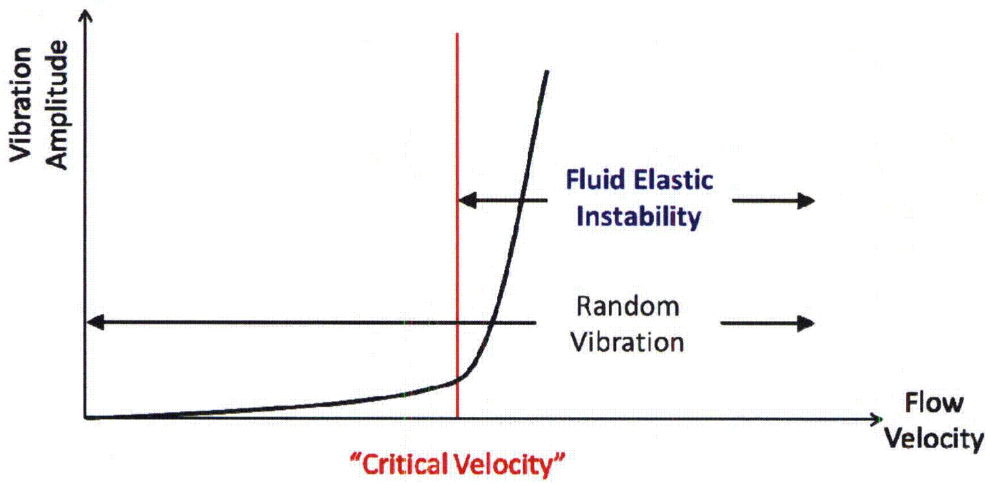


Figure 2.3-1 Relation between Vibration Amplitude and Flow Velocity

The Critical Velocity is a function of the tube's natural frequency, damping, and the Critical Factor among other parameters shown in the equation below.

$$\frac{U_c}{fD_o} = K\left[\frac{m_0\delta}{\rho_o D_o^{\ 2}}\right]^{1/2}$$

Where,

U_c	: Critical velocity
f	: Tube natural frequency
δ	: Damping term
K	: Critical factor
D_o	: Tube outside diameter
m_0	: Average tube mass per unit length
ρ_o	: Density of fluid outside the tube

This equation is based on work done by Dr. H. J. Connors, and the Critical Factor, K, is often referred to as Connor's constant, but as discussed in Section 7.1 of L5-04GA567 (Ref. 5), the Critical Factor may vary.

The tube natural frequency is dependent on tube geometry and tube supporting conditions. The density of the fluid outside the tube depends on the secondary side fluid environment. The tube outside diameter and the average tube mass per unit length are set by the design.

For U-bend tubes in two phase flow, there are four sources of damping: structural damping, external fluid (two-phase) damping, viscous damping and squeeze film damping. For the SONGS RSG, the relevant sources are structural, external fluid and squeeze film damping. Damping is discussed in more detail in Section 2.3.4 below.

The Critical Factor is an experimentally determined value, which is a function of the tube pattern and the fluid environment. The Critical Factor varies for each tube as a function of void fraction and location of the tube within the U-bend (See Section 7.1 of L5-04GA567 the latest revision (Ref. 5)).

The tube natural frequency and the Critical Factor differ in the in-plane and out-of-plane directions. For the SONGS RSG tube geometry, based on experimental data, MHI estimates that the Critical Factor for in-plane FEI is at least 50% higher than the Critical Factor for out-of-plane FEI (See Section 2.3.2 below for details). The tube natural frequencies for the in-plane and out-of-plane directions depend on the number of supports. For U-bend SGs, when the number of supports are equal in both directions, the U-bend natural frequency out-of-plane is lower than the U-bend natural frequency in-plane (See Appendices 1 and 2 for details).

2.3.2 Critical Factor (K) for the SONGS RSGs

The Critical Factor for in-plane FEI can be related to the Critical Factor for out-of plane FEI and the tube pattern pitch-to-diameter (P/D) ratio (this is discussed in more detail in Section 7.1.1.2 of MHI's "Evaluation of Stability Ratio for Return to Service" L5-04GA567 latest revision (Ref. 5)). Based on its analysis and test data, MHI has developed the following relationship reflected in the figure and table below.

$$K_i = k \times K_o$$

Where,

- k : Ratio of Critical Factor of In-plane FEI and Out-of-plane FEI
- K_i : Best-estimate Critical Factor of In-plane FEI
- K_o : Best-estimate Critical Factor of Out-of-plane FEI

Ratio κ

Vc(In-flow)/Vc(Out-of-flow)

[ ]

P/D	Fluid	Ratio of critical flow velocity κ=Vc(In-plane) /Vc(Out-of-plane)	Note
1.5	Air-Water	2.7	Violette et al. (2006)
1.37	Air	1.7	Khalvatti et al. (2010)
1.2	Air	0.71	Nakamura et al. (2012)

Fig.2.3.2-1 Critical Factor Ratio to P/D Relationship

This figure shows the relationship between the Critical Factor Ratio for in-plane / out-of-plane FEI and the tube pitch-to-diameter ratio. The SONGS P/D ratio in most of the tube bundle is | |. However, in the U-bend, where the tubes are further apart due to straight-leg indexing, the P/D ratio increases to a maximum value at the top of the U-bend. Thus, from Figure 2.3.2-1 it can be seen that the Critical Factor for in-plane FEI is | | times as large as the Critical Factor for out-of-plane FEI for the SONGS tube pattern (or greater where tube indexing is present). This indicates that, given identical support conditions, the onset of out-of-plane FEI will occur much sooner than in-plane FEI.

2.3.3 Natural Frequency / Support Conditions / Contact Force

As discussed above, tube natural frequency is dependent on tube geometry and tube supporting conditions. Following is an analysis of the supporting conditions associated with the Unit-3 TTW tubes.

The locations of the Unit 3 and Unit 2 TTW wear indications along the U-tube arc length are depicted in Fig. 2.3.3-1 taken from AREVA's "SONGS U2C17 Steam Generator Operational Assessment for Tube-to-Tube Wear " No. 51-9187230-000 (Ref. 4).

Fig. 2.3.3-1 Location of deepest wear along the length of each TTW wear scar

From this figure it can be seen that the TTW indications are grouped at the 45/135 degree positions of the U-bend. This figure also identifies the theoretical tube-to-tube contact points associated with the first three natural frequency modes for in-plane tube vibration. The Mode-1 tube-to-tube contact points are also located at the 45/135 degree positions of the U-bend.

Fig. 2.3.3-2 is also taken from the AREVA Operational Assessment report (Ref. 4). This figure shows the large amplitude deformation of a U-bend tube in the first in-plane mode (i.e. Mode 1).

Fig.2.3.3-2 The large amplitude deformation of a U-tube in the first in-plane mode

In order for the tubes to touch in this in-plane mode shape, the tubes must be free of restraint at the 12 AVB intersections and only supported at the top TSP.

For the reasons stated in the discussion of the Critical Factor in Section 2.3.2 above, out-of-plane FEI will occur at a lower velocity threshold than in-plane FEI when the support conditions are the same for both directions. Also, as discussed in Appendices 1 and 2, out-of-plane FEI will occur at a lower velocity threshold than in-plane FEI, when the support conditions are the same for both directions, because the tube out-of-plane natural frequency is lower than tube in-plane frequency. Therefore, since out-of-plane FEI did not occur, the tube out-of-plane support must be effective (as intended by the designers).

The absence of out-of-plane FEI and the presence of in-plane FEI can only happen when all or most of the 24 tube-to-AVB intersections (AVB on both sides of a tube with 12 locations) have gaps small enough to be effective in the out-of-plane direction and lack sufficient contact forces to be effective in the in-plane direction. As shown in Appendix 2, the critical velocity threshold for in-plane FEI will occur before that for out-of-plane FEI if the number of active supports against in-plane FEI becomes sufficiently smaller than the number needed to prevent out-of-plane FEI.

MHI performed a comprehensive statistical evaluation of the tube-to-AVB contact forces based on manufacturing data and concluded that the Unit 2 contact forces are approximately double that of the Unit 3 RSGs (See Section 5.2.3 of the TER (Ref. 1)). This offers an explanation of why almost all of the TTW indications were in the Unit 3 RSGs.

The difference in the contact forces between the Unit 2 and Unit 3 RSGs is mainly associated with better control of the AVB and tube fabrication dimensions in the Unit 3 RSGs. As discussed in Section 5.2.3 of the TER (Ref. 1), a [ ] pressing force was used on the Unit 3 AVBs to reduce the twist and flatness, while a [ ] pressing force was used for the Unit 2 AVBs. Additional evidence that the Unit 3 AVB dimensions were more uniform and that the tube-to-AVB contact forces were smaller is that the Unit 2 RSGs had more ding signals than the Unit 3 RSGs. Ding signals are evidence of tiny marks on the tube outer surface caused by interference between AVBs and tubes. Almost all of the Unit 2 ding signals were at the AVB nose regions.

Fig. 2.3.3-3 lists the variations in the tube and AVB dimensions for the Unit 2 and Unit 3 RSGs and the resulting difference in the tube-to-AVB contact forces based on these dimensional differences. This figure displays the same data as Figure 5.2-1 in the TER (Ref. 1).

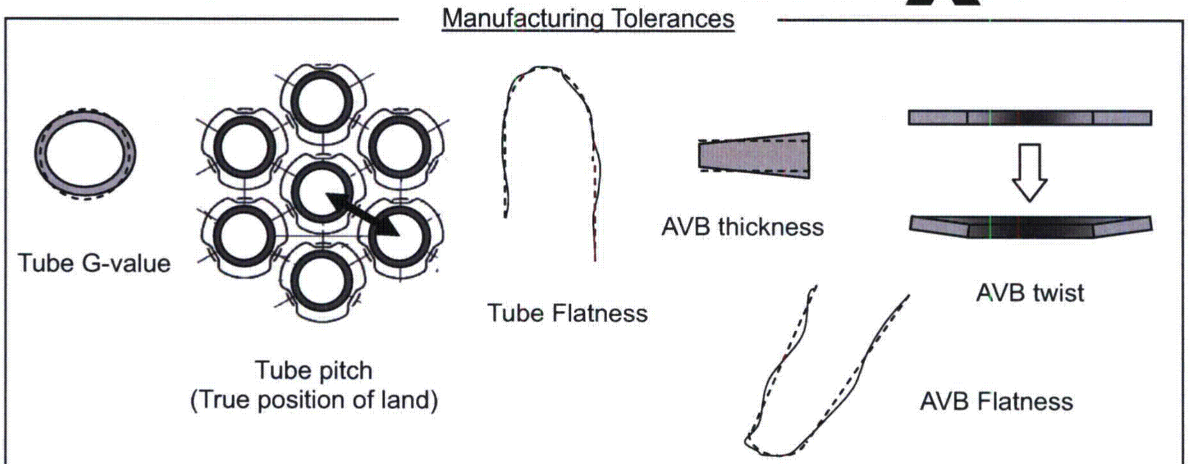


Fig.2.3.3-3 Contact Force Simulation with Manufacturing Tolerances

2.3.4 Thermal Hydraulic Conditions and Tube Damping

The U-bend region is where all of the steam produced by the steam generator exits and the top of the U-bend has the greatest concentration of steam. This region with the greatest concentration of steam is also where most of the tube wear is located. Steam quality is defined as the ratio of the mass of steam divided by the total mass of a mixture of steam and water in a given space (or, the percentage of vapor mass in a saturated mixture). Void fraction is based on volume rather than mass. Therefore, void fraction is the ratio of the total volume occupied by steam divided by the total volume occupied by water and steam in a given space (or, the percentage of vapor volume in a saturated mixture).

Fig. 2.3.4-1 shows the results of the three-dimensional thermal hydraulic analysis of SONGS Unit 2 and 3 SGs. This analysis was performed after the discovery of the tube wear, using the ATHOS computer code developed by EPRI. The highest void fraction is located in the U-bend region, where the maximum value is estimated by ATHOS to be (of the volume is occupied by saturated liquid water). The highest void fraction calculated using ATHOS for prior MHI-designed SGs is The higher void fraction is a result of a large and tightly packed tube bundle and the relatively high heat flux in the upper hot leg side of the tube bundle.

The Unit 2 and Unit 3 RSGs have identical operating conditions and the displayed thermal hydraulic results are applicable for all four SONGS RSGs.

Fig.2.3.4-1 Thermal Hydraulic Analysis Results for the Unit 2 and Unit 3 SGs

Structures in a two-phase flow field have lower resistance to vibration when the steam quality (void fraction) is high. At all but the highest void fraction conditions, a liquid film can form between the tube and the AVB. This film provides liquid film damping (also called squeeze film damping), which "damps" vibration. In the high void fraction region, there is little or no film damping effect. The density and viscosity of the fluid outside the tube also provide damping (called external fluid or two phase damping). When a tube passes through a region of high steam quality (void fraction) the fluid density is low and the associated level of fluid damping is low. The relationship between steam quality (void fraction) and damping is depicted in Fig. 2.3.4-2.

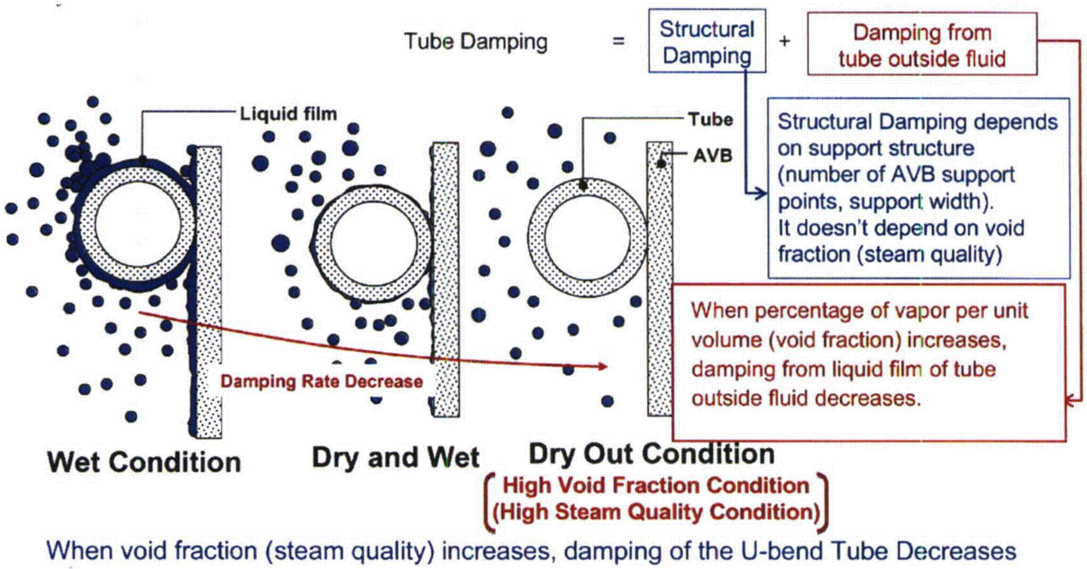


Fig 2.3.4-2 Relation between Steam Quality (Void Fraction) and Damping

The two-phase fluid (water and steam) in the high void fraction has low density and high velocity. It is also the location of the lowest tube damping. The increase of the velocity (v) is a larger effect than the reduction in density (ρ), so the hydrodynamic pressure (proportional to ρv^2) is largest in the high void fraction region. The hydrodynamic pressure is a measure of the energy imparted to the structure by the flow field, and damping is a measure of how easily the structure can dissipate this energy.

Flow forces and damping vary along the length of each tube. Fig. 2.3.4-3 shows the average of the variation in the void fraction along individual tubes in the U-bend region. A comparison between Fig. 2.3.4-3 and the tube-to-tube wear indications shown in Figs. 2.1–1 and 2.1-2 shows that the tubes with TTW generally pass through the region with the highest average void fraction.

Fig.2.3.4-3 Average Void Fraction along Individual Tubes in the U-bend Region

Fig. 2.3.4-4 shows the correlation between void fraction and steam quality with the percentage of tubes at different levels of void fraction and steam quality that have Type 1 wear. The 328 tubes that had Type 1 wear fall within the region of steam quality of   to   and void faction of   to   . However, less than   of the Unit 3 tubes in this region of high steam quality and high void fraction have Type 1 wear. Fig. 2.3.4-4 displays the same data as shown in Fig. 5.1-2 in the TER (Ref. 1). The TER (Ref. 1) also discusses the relationship between high velocity and Type 1 wear for which the correlation is not as strong.

Fig.2.3.4-4 Correlation between Type 1 Wear (TTW) and Void Fraction (Steam Quality)

2.4 Conclusion

The TTW indications show that almost all of the TTW tubes experienced large displacement flow induced vibration. The locations of the TTW indications are well correlated with the first in-plane mode of U-bend vibration, indicating that none of the tube-to-AVB supports were active in the in-plane direction. The only known flow induced vibration mechanism capable of producing such large tube displacements, and in a contiguous group like that of the Unit 3 RSGs, is fluid elastic excitation. Since out-of-plane FEI did not occur instead of in-plane FEI, it is concluded that the out-of-plane support conditions for the TTW tubes were active (as designed). This leads to the conclusion that the tube-to-AVB intersections of the TTW tubes had small and uniform gaps and that the tube-to-AVB contact forces were too small to prevent in-plane tube displacement.

All of the TTW tubes are located in the region of highest average void fraction, where velocities are highest and damping is lowest. Both Unit 2 and Unit 3 have the same thermal hydraulic conditions. The tube-to-AVB contact forces in the Unit 3 RSGs are smaller by a factor of two than those of the Unit 2 RSGs. Almost all of the TTW tubes were found in the Unit 3 RSGs. The difference in the contact forces explains this large difference between the two units.

MHI concludes that the SONGS U-bend design prevented out-of-plane FEI as intended; but that some level of tube-to-AVB contact force is required to prevent in-plane FEI at the SONGS secondary thermal-hydraulic conditions.

3. Wear Mechanism of Type 2 (AVB wear)

3.1 Tube Wear Indications of Type 2 (AVB wear)

Tubes with Type 2 (AVB wear) indications are characterized by wear at the tube-to-AVB intersections with no free-span wear indications. They are produced primarily by U-bend tube vibration without any contribution from straight leg vibration although there are a few TSP wear indications on some of them. The locations of the tubes with wear indications at the tube-to-AVB intersections, including Type 2 wear, are shown in Fig. 3.1-1 (Unit 2) and Fig. 3.1-2 (Unit 3). The same data is shown on Fig 4.1.1-2 of the TER (Ref.1).

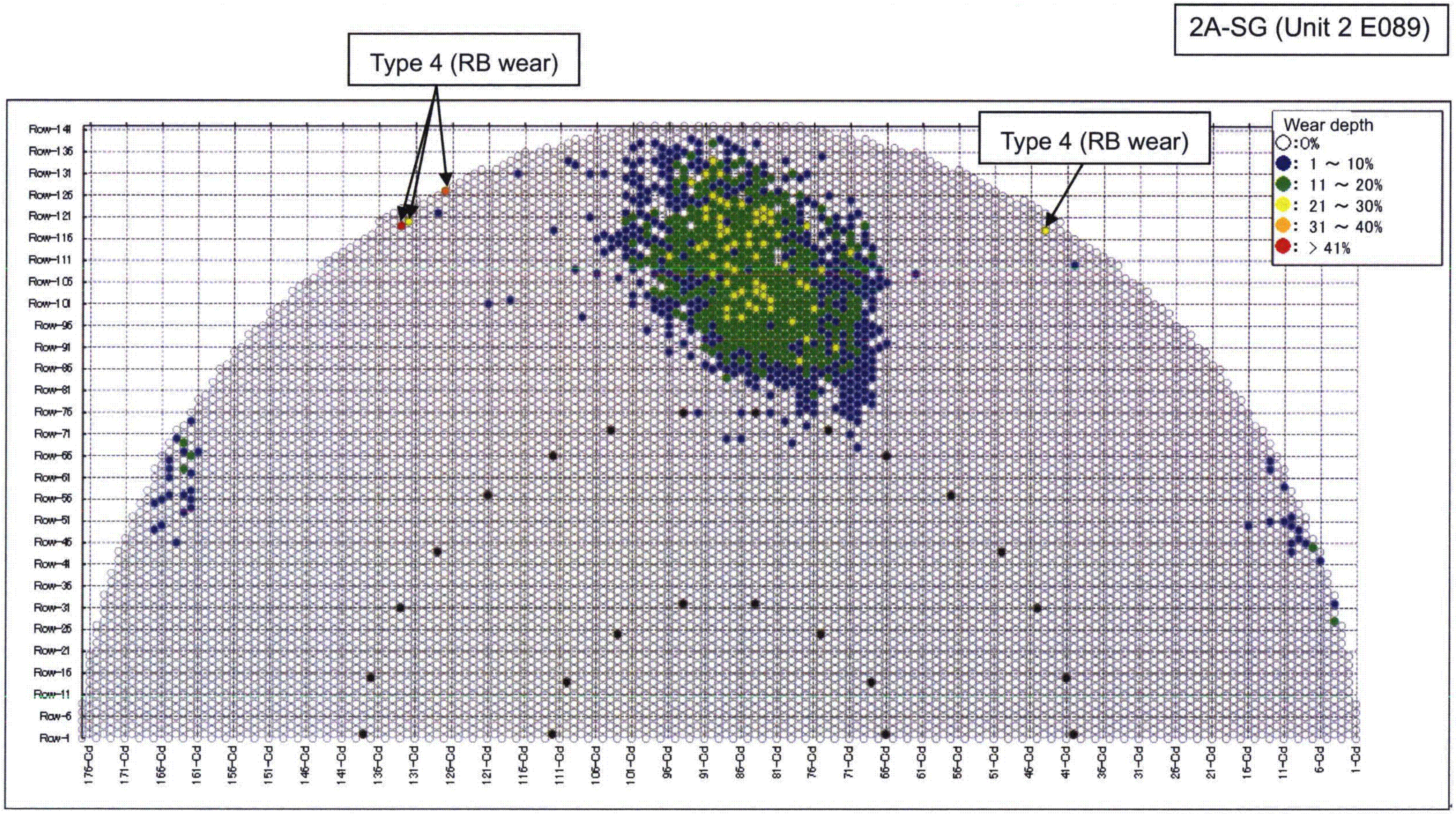


Fig 3.1-1 (1/2) All Unit 2 U-bend tube indications

(Type 1 TTW, Type 2 Tube-to-AVB and Type 4 Retainer Bar to Tube)

2B-SG (Unit 2 E088)

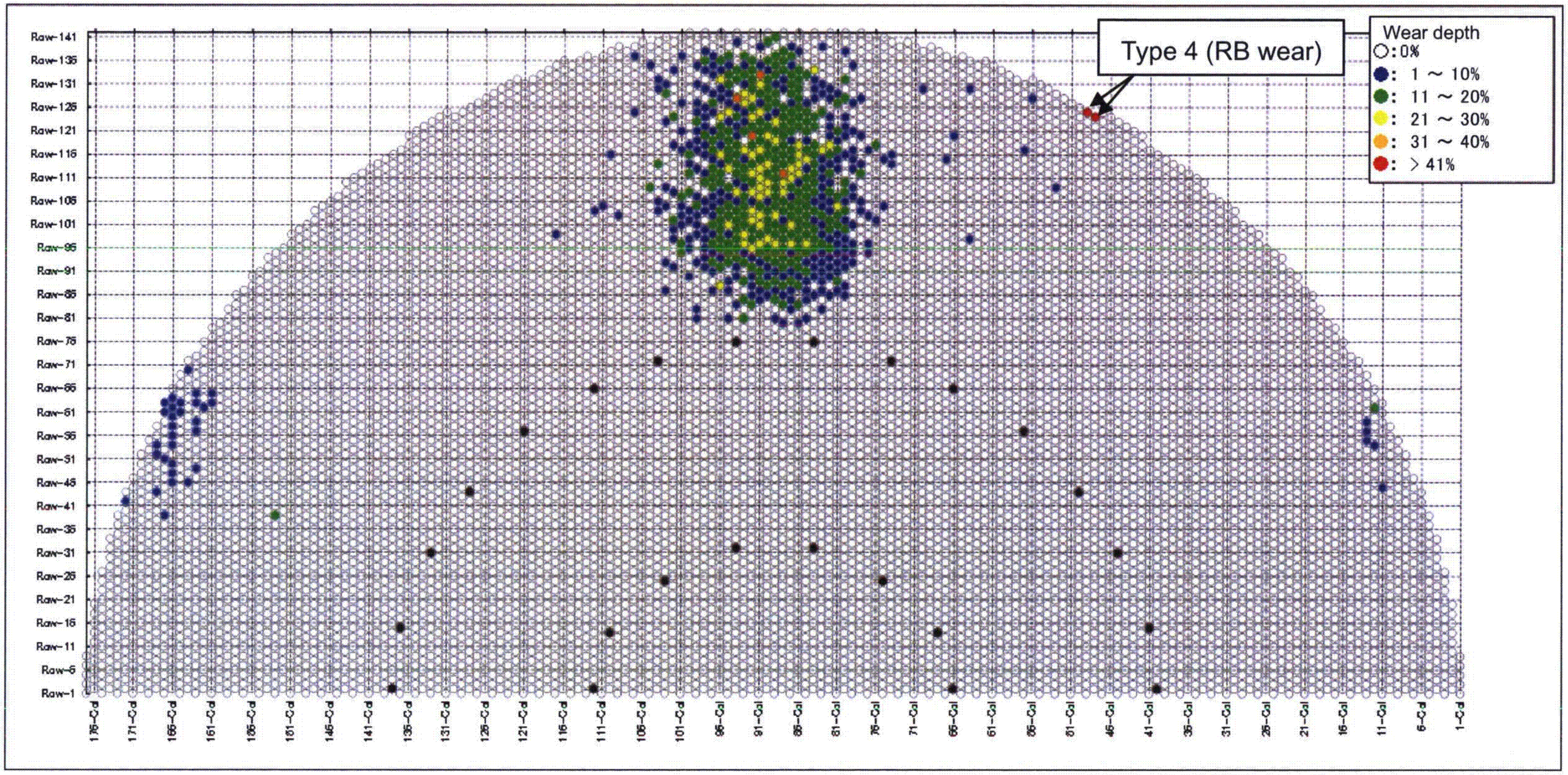


Fig 3.1-1 (2/2) All Unit 2 U-bend tube indications

(Type 1 TTW, Type 2 Tube-to-AVB and Type 4 Retainer Bar to Tube)

3A-SG (Unit 3 E089)

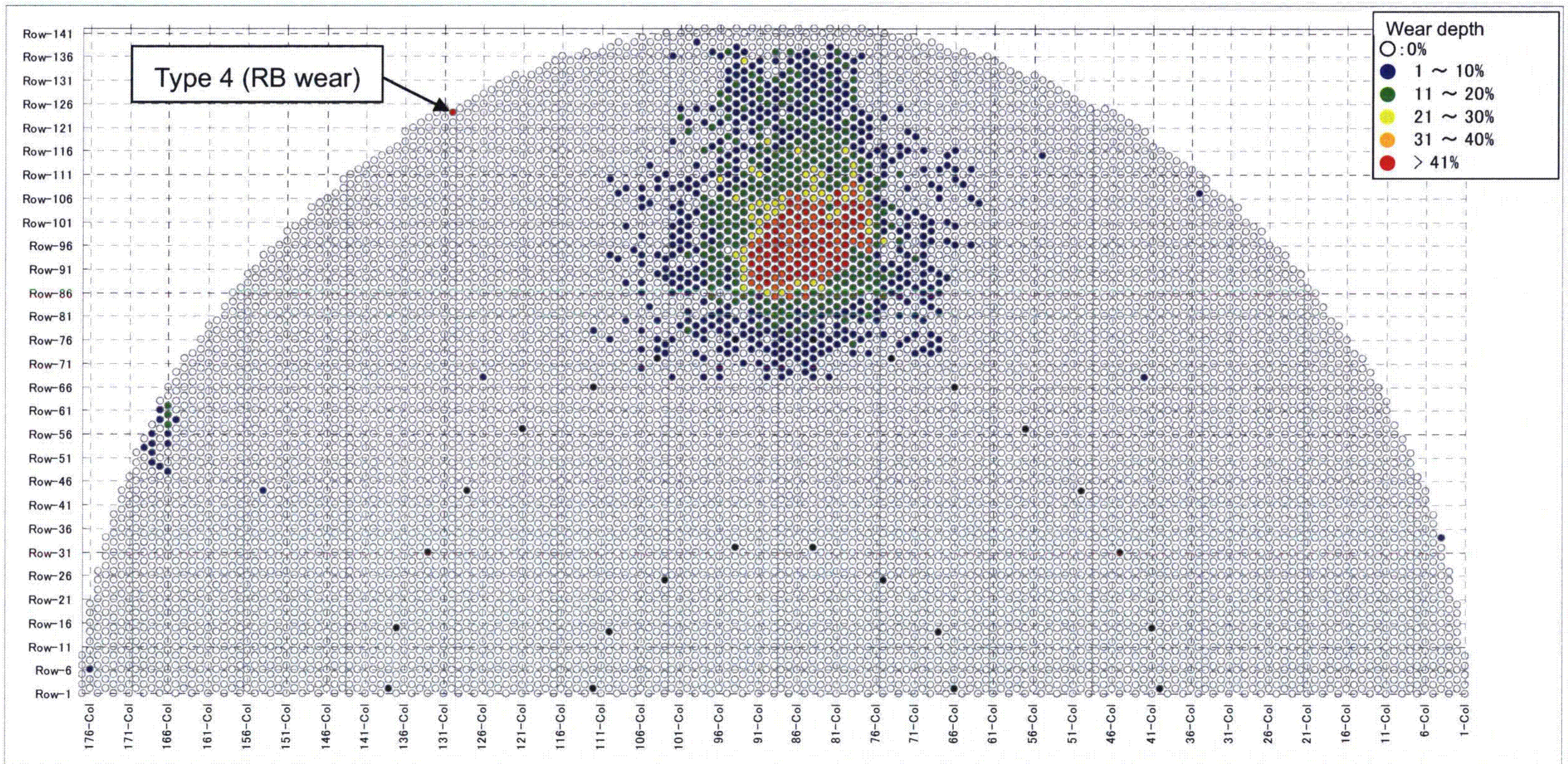


Fig 3.1-2 (1/2) All Unit 3 U-bend tube indications
(Type 1 TTW, Type 2 Tube-to-AVB and Type 4 Retainer Bar to Tube)

3B-SG (Unit 3 E088)

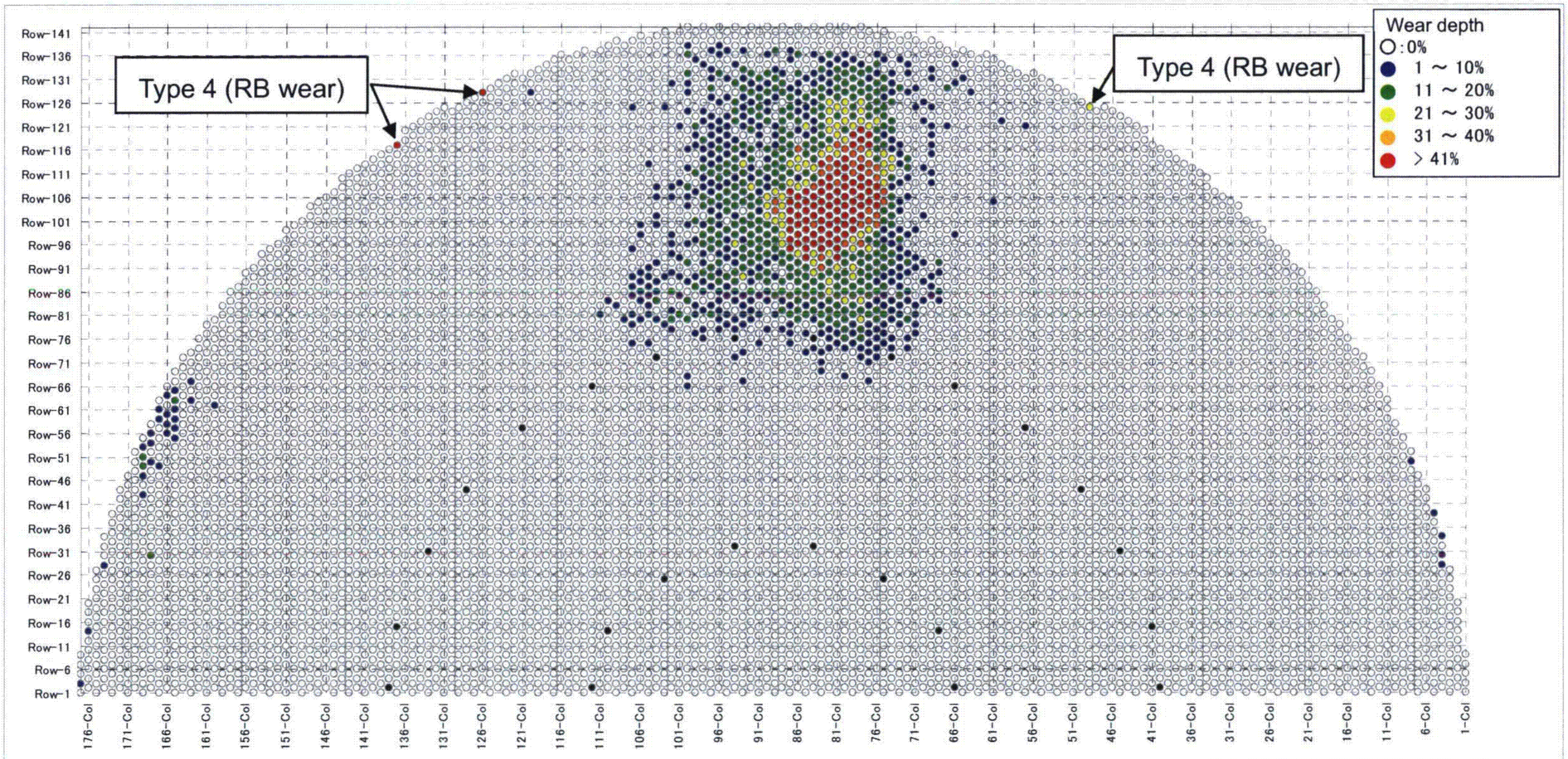
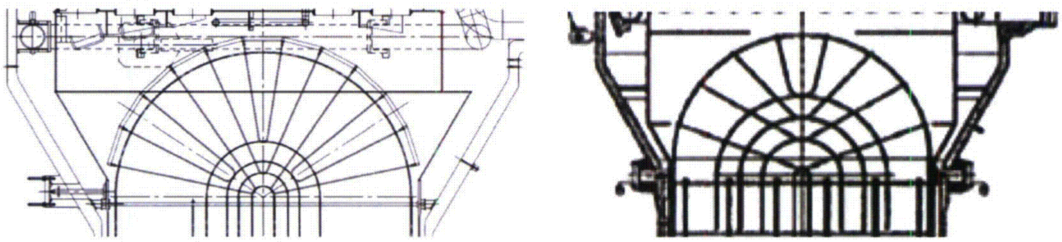


Fig 3.1-2 (2/2) All Unit 2 U-bend tube indications
(Type 1 TTW, Type 2 Tube-to-AVB and Type 4 Retainer Bar to Tube)

3.2 Tube-to-AVB Wear Experience in Other Large CE-Plant RSGs

Tube wear patterns similar to those observed at SONGS were reported at the Plant-A large U-bend steam generators that were replacements for CE manufactured OSGs (See NRC ADAMS ML11270A015 and ML093230226). The Plant-A steam generators were designed by another vendor. They are slightly smaller than the SONGS steam generators but have U-bend tubes, flat bar AVBs, and BEC type TSPs, that are similar to the SONGS RSGs, except SONGS features a 12 AVB design and Plant-A has an 8 AVB design.



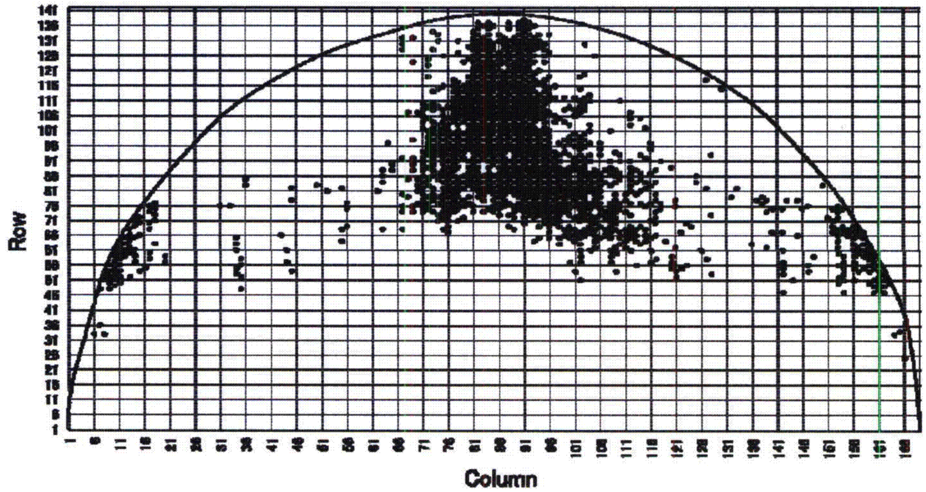
(a) SONGS (12AVB design) (b) Plant-A (8 AVB design)

Fig.3.2.1-1 Comparison between 12 and 8 AVB Design

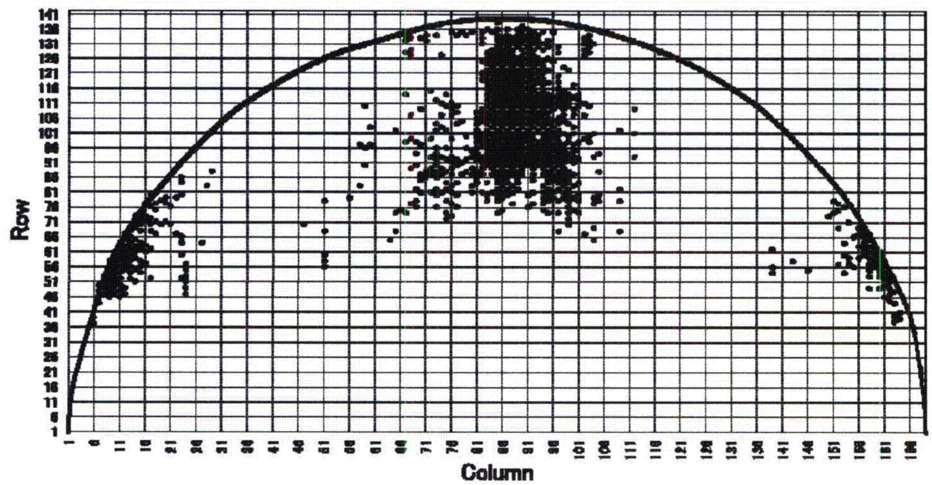
The Plant-A inspection results show a wear pattern with many tubes in the center of the U-bend that have tube-to-AVB wear similar to that found in the SONGS steam generators. Figure 3.2.1-2 shows the tubes with tube-to-AVB wear identified at Plant-A during the first inspection following installation of the RSGs and Figure 3.2.1-3 shows the tubes with tube-to-AVB wear identified at Plant-A during the second cycle inspection. Note that the locations of the Plant-A indications are very similar to those for SONGS shown in Figs. 3.1-1 and 3.1-2.

Figure 3.2.1-4 compares the total number of tube-to-AVB wear indications for Plant-A, SONGS Unit 2, and SONGS Unit 3 as a function of time and Figure 3.2.1-5 shows the average wear depths for the three plants (six RSGs) as a function of time. As can be seen from these figures, the total number of indications and average wear depth at Plant-A are comparable to that at SONGS.

Figure 3.2.1-5 suggests that the tube-to-AVB wear depths at Plant-A have reached a plateau. The reason for such a plateau is unclear. It may be indicative of the type of tube vibration mechanism or an effect of the support condition. But it is clear that the number of tubes with tube-to-AVB wear at Plant-A is growing (refer to Fig. 3.2.1-2 and 3.2.1-3).

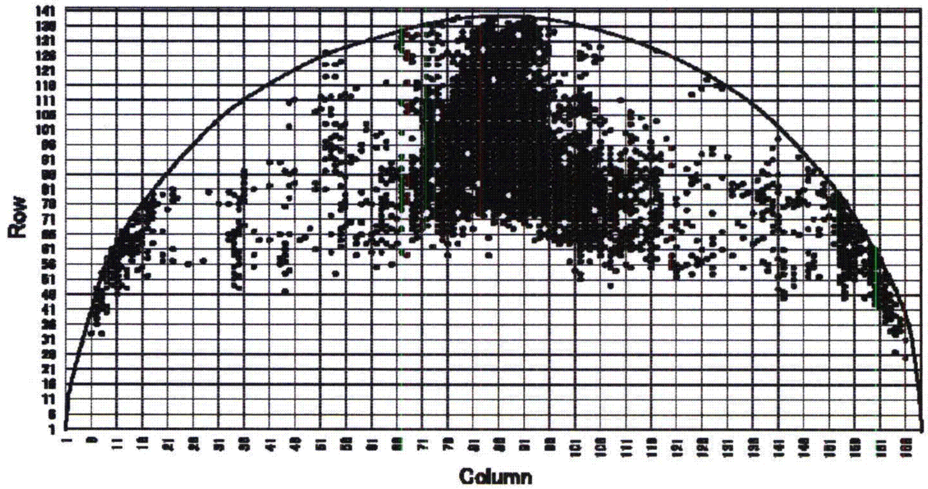


(a) 2A-SG

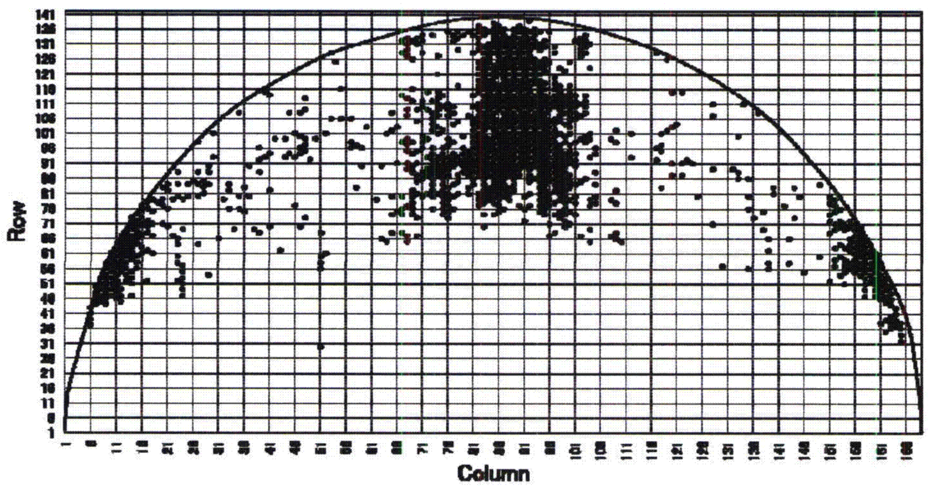


(b) 2B-SG

Fig.3.2.1-2 Plant-A Tubes with AVB Indications at first inspection
(based on information from NRC ADAMS ML11270A015 and ML093230226)

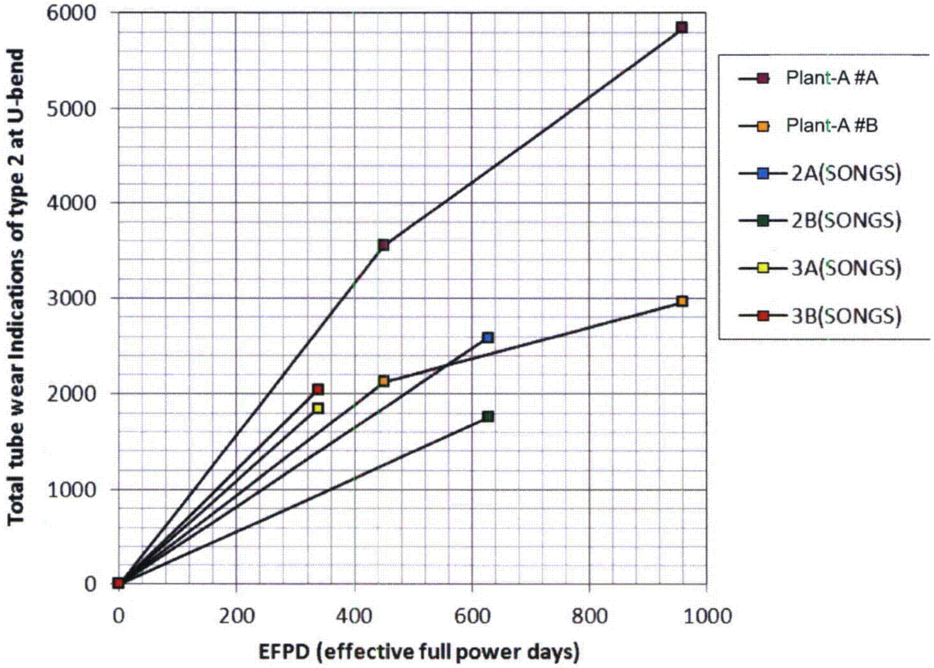


(a) 2A-SG



(b) 2B-SG

Fig.3.2.1-3 Plant-A Tubes with AVB Indications at second inspection
(based on information from NRC ADAMS ML11270A015 and ML093230226)



b

Fig.3.2.1-4 Total Tube-to-AVB Wear Indications
(based on information from NRC ADAMS ML11270A015 and ML093230226)

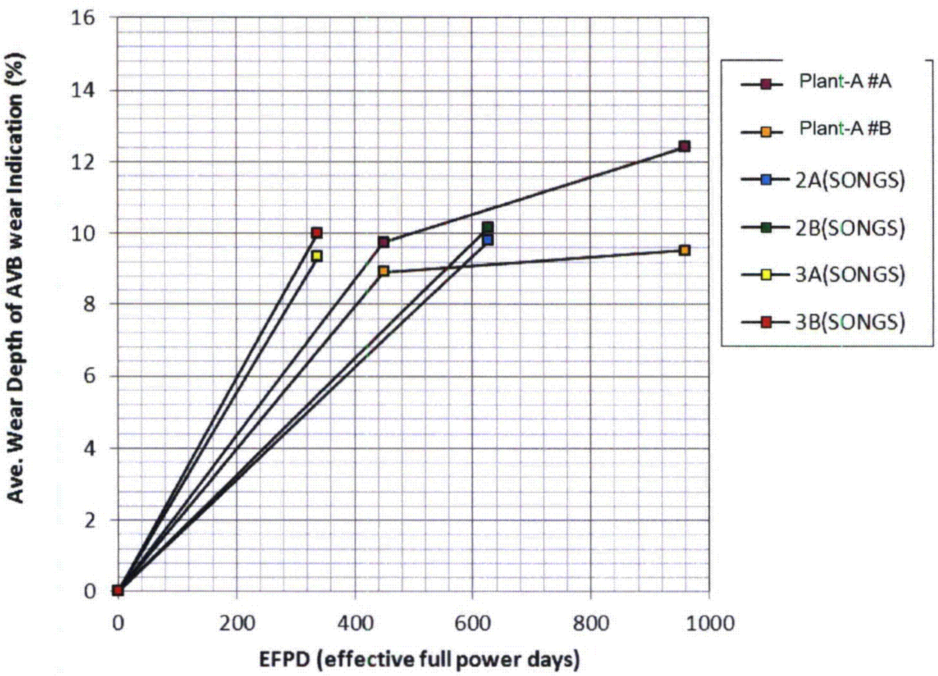


Fig.3.2.1-5 Average Tube-to-AVB Wear Rate
(based on information from NRC ADAMS ML11270A015 and ML093230226)

3.3 Causes of Type 2 Tube Wear (Tube-to-AVB wear)

The cause of the Type 2 wear is turbulence induced (random) tube vibration. The following discussion explains the basis for this conclusion.

Fig. 3.3-1 (this figure is similar to Fig. 6.2-1 in the TER (Ref. 1)) provides a summary of the basis for establishing the cause of the Type-2 (tube-to-AVB) wear. Extensive inspections, including visual, eddy current, and ultrasonic methods, indicate that the tube-to-AVB gaps are small at each of the wear sites. This indicates that there are small clearances. Such conditions are sufficient to prevent out-of-plane FEI but not sufficient to prevent turbulence induced (random) vibration and wear.

The Type-2 wear indications are in the region of high void fraction and dynamic pressure. Referring to Fig. 2.3.4-3 of the previous section, it can be seen that the area of the U-bend occupied by the high average void fraction (values above [ ] where the max value is [ ]) is very similar to the Type-2 wear map in Figs. 3.1-1 and 3.1-2.

As shown in the figure at the upper left corner of Fig.3.3-2, insufficient contact force has an adverse effect on tube wear caused by random tube vibration up to the point where the contact force is sufficient to prevent tube lift-off from (or sliding along) the AVB. The amount of contact force necessary to prevent random vibration is a function of the thermal-hydraulic condition. As the void fraction (steam quality) increases, the amount of contact force necessary to prevent random vibration increases. This is because the higher void fraction (steam quality) results in lower external fluid damping and a reduction in the liquid film damping (squeeze film damping).

A comparison of Fig. 2.3.4-3 showing the average void fraction and the figures on the bottom of Fig. 2.3.3-3 showing Unit 2 and Unit 3 contact forces indicates that the tubes in the area of average high void fraction also generally have low contact forces, which generally correspond as well to the Type 2 wear maps in Figs. 3.1-1 and 3.1-2. The turbulence induced (random) tube vibration associated with the small gaps and small contact forces combined with the lower tube damping in the high void fraction regions is sufficient to produce the observed wear.

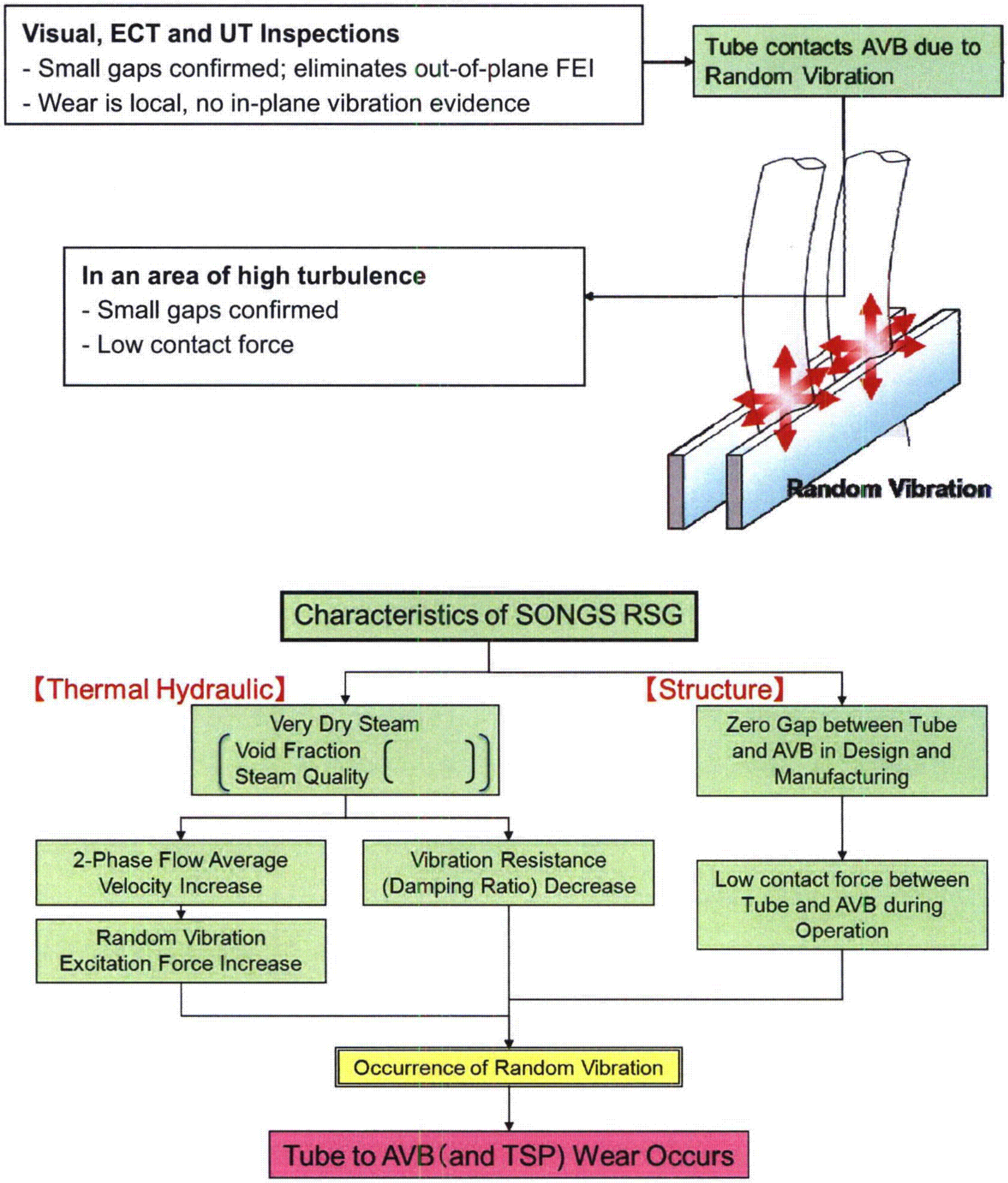


Fig.3.3-1 Type 2 Wear (AVB wear) Mechanism

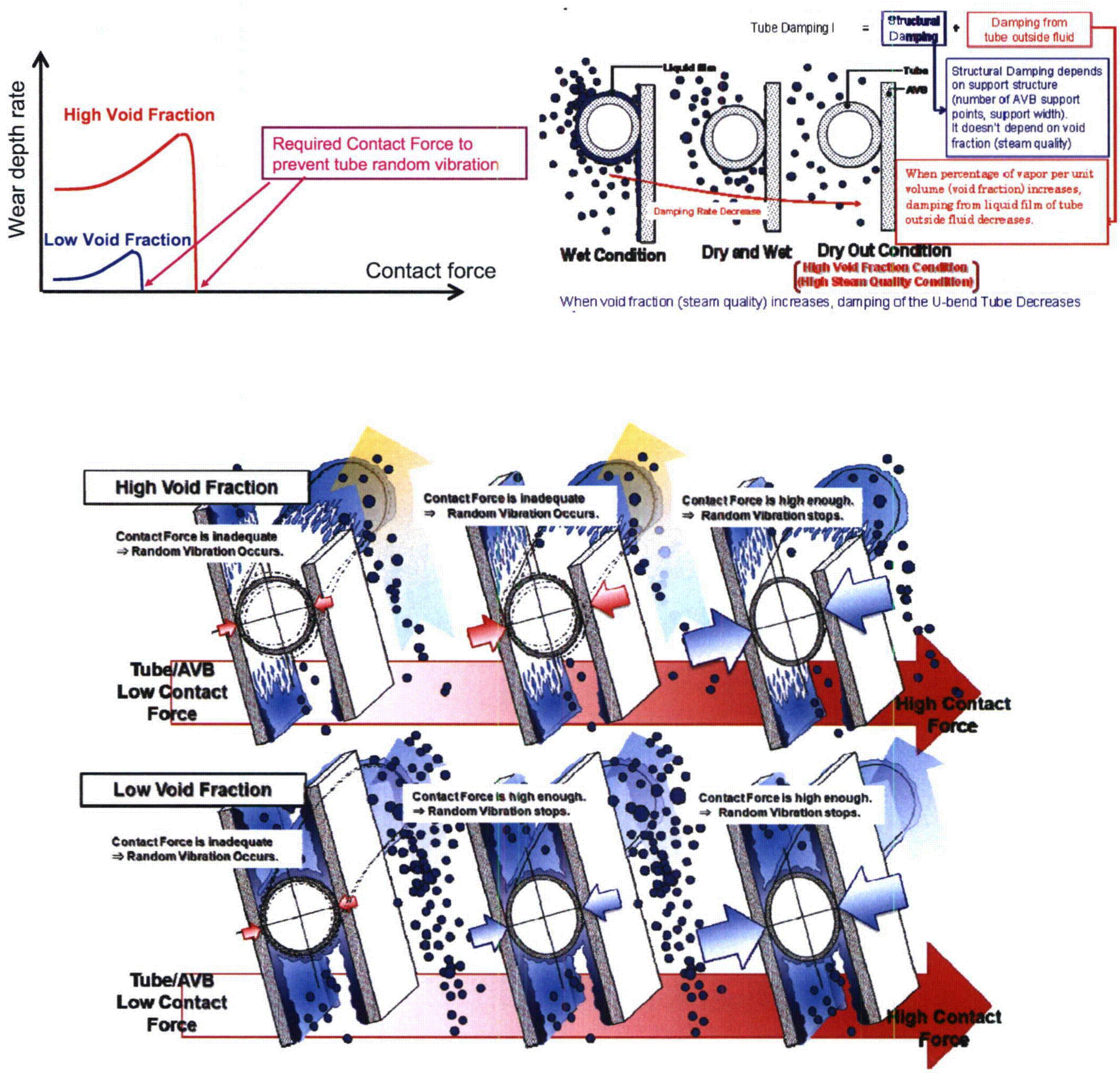


Fig.3.3-2 Contact force sufficient to prevent random tube vibration

3.3.1 Evaluation of U-bend Support Conditions

The SONGS SG tube bundles were conservatively designed for U-bend support with effective "zero" gaps in the hot condition and featured 12 AVBs to provide additional support margin. Based on visual inspections and ECT gap measurements, no significant gaps between the tubes and AVBs are present leading to the conclusion that the tubes were well supported. Despite the gap control and additional support provided by the 12 AVB design, an unexpected amount of Type 2 wear was been experienced in the SONGS RSGs.

While the number of tubes with Type 2 wear is very similar for Unit 2 and Unit 3 (Compare Table 1-1 and Table 1-2), Unit 2 has operated approximately twice as long as Unit 3. As a result, as shown in Fig. 3.2.1-5. the wear rate in Unit 3 is faster than that for Unit 2. An explanation for this difference is found in the manufacturing assessment which concluded that the tube to AVB contact forces in Unit 3 were less than half than those in Unit 2. (See Section 2.3.3 above.)

The increased Unit 3 tube wear is attributable to a different contact force distribution between the tubes and AVBs. When the contact force is sufficiently high to prevent random tube vibration, the tube-to-AVB wear becomes negligible. The magnitude of the contact force that prevents random tube vibration is a function of the void fraction, with a higher contact force being needed in the regions of higher void fraction (steam quality).

3.3.2 Secondary Side Thermal Hydraulic Conditions

Figure 3.3.2-1 (this Fig. displays the same data as Fig. 5.1-4 in the TER (Ref. 1)) shows a strong correlation between void fraction (steam quality) and the percentage of tubes at different levels of void fraction and steam quality that have Type 2 wear. Of the 38,908 tubes in the Unit 2 and 3 RSGs, 2,848 tubes had Type 2 wear and of those tubes 2,702 fall within the region of a maximum steam quality equal to or greater than | | and a void faction equal to or greater than | |. In addition, the tubes with Type 2 wear indications typically have high cross flow velocity as shown in Fig. 3.3.2-2 (this Fig. displays the same data as Fig. 5.1-5 in the TER (Ref. 1)).

Consequently, it is concluded that the thermal-hydraulic conditions in the SG secondary side, particularly the high void fraction (steam quality) and high flow velocity, are associated with the Type 2 wear. The amount of contact force necessary to prevent random vibration is a function of the thermal-hydraulic condition. As the void fraction (steam quality) increases, the amount of contact force necessary to prevent random vibration increases. This is because the higher void fraction (steam quality) results in lower external fluid damping and a reduction in the liquid film damping (squeeze film damping). Thus, tubes in the region of highest void fraction are most susceptible to this mechanism.

This correlation to high void fraction area is also supported by the tube-to-AVB wear observed at the Plant A RSGs. As with the SONGS RSGs, the great majority of the tube-to-AVB wear occurred in the center column region where the void fraction is high.

[ ]

Fig.3.3.2-1 Correlation between Type 2 Wear (AVB wear) and Void Fraction (Steam Quality)

Fig.3.3.2-2 Correlation between Type 2 Wear (AVB Wear) and Flow Velocity

3.4 Out-of-plane FEI is not the cause of AVB wear

MHI evaluated the potential for out-of-plane FEI to cause Type 2 wear and has concluded for three reasons that out-of-plane FEI did not occur.

First, gap measurements were made in Unit 2 and Unit 3 RSGs. These included ultrasonic gap measurements and over 117,000 eddy current gap measurements (See AREVA Operating Assessment (Ref. 4)). The gap measurements show no excessive gaps between the tubes and AVBs. For most tubes the average of the 24 tube to AVB gap measurements is less than 0.003". Visual inspections of the AVB and tube intersections (see TER Section 4.2 and Appendix 7 (Ref. 1) also revealed that (i) the gaps between the tubes and AVBs are small without any large gaps, (ii) the AVBs appeared to be straight without detectable abnormalities, (iii) there were no abnormalities in the orientation between the AVBs and the tubes, and (iv) there were no abnormalities in the AVB positions or end cap to retaining bar welds.

Second, research literature shows that gaps significantly larger than the SONGS RSG AVB-to-tube gaps are required for out-of-plane FEI to occur. Based on the research report by Weaver (Ref. 6), no out-of-plane FEI in the U-bend tube bundle with AVBs occurred when the symmetric tube-to-AVB gaps were 0.3 mm (12 mils), while out-of-plane FEI occurred when the symmetric gaps were 0.51 mm (20 mils). From the research by Yang (Ref. 7), no out-of-plane FEI occurs even when the tube-to-AVB gap was 1.5 mm (60 mils). These research results indicate that out-of-plane FEI will not occur when the gaps on each side of the tube are smaller than 20 mils.

Third, MHI has performed wear calculations using IVHET assuming random vibration force to reproduce the observed wear at SONGS (see TER, Appendix 10 (Ref. 1), Section 7.2). The wear simulations assumed that some of the supports were active (in contact with the AVB by sufficient contact force) and that other supports were inactive, some with very small tube-to-support clearances and some with very small (or zero) contact forces. In the latter (inactive) support condition, the tube can interact with the support (i.e. repeatedly impacting it) and cause turbulence induced (random) wear. In the analysis, the inactive supports were assumed to have | | symmetric gaps between the tube and AVB. Many wear depth simulations were evaluated by varying the number of inactive supports.

The calculated wear depths assuming random vibration are consistent with the actual measurement results of tube wear. Fig. 3.4-1 shows the results for a single tube-to-AVB intersection with large wear assuming different numbers of inactive supports with impact. This figure shows that assuming 8 consecutive AVB support points are inactive (but with impact), the calculated random wear depth is similar to the observed wear (see Fig. 3.4-1). These wear simulations show that with the small clearances at the inactive supports, random vibration is sufficient to reproduce the observed wear.

[ ]

Fig.3.4-1 Wear Analysis Results for Type 2 AVB Wear at Tube R106 C78 of Unit 2A SG (2E089)

3.5 Relationship between Random Vibration and In-plane FEI

MHI has analyzed whether random vibration was a precursor to the in-plane FEI that was observed in Unit 3. Two possible scenarios were considered.

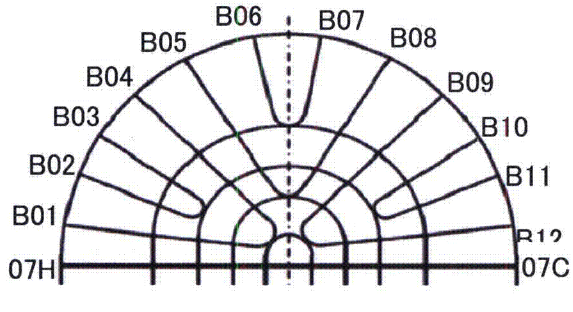
Scenario #1: In-plane FEI in Unit 3 had no precursor

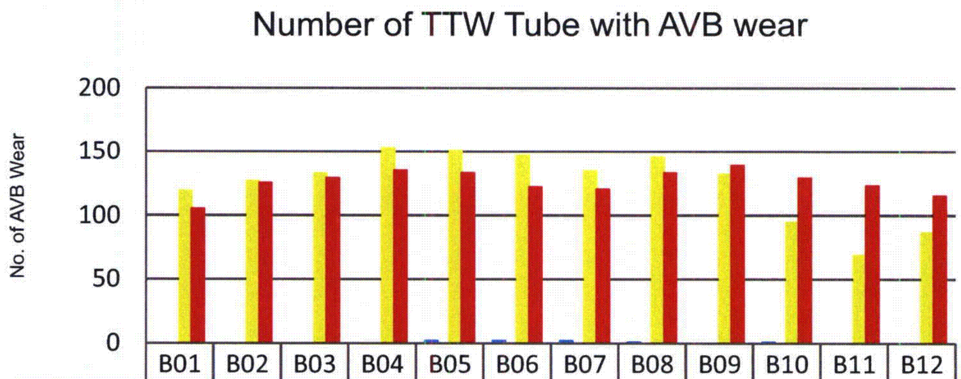
Scenario #2: Wear from random vibration progresses to the point of loss of in-plane support, followed by the onset of in-plane FEI

The first scenario is more likely supported based on the investigation below (See Fig.3.5-1 and Fig.3.5-2):

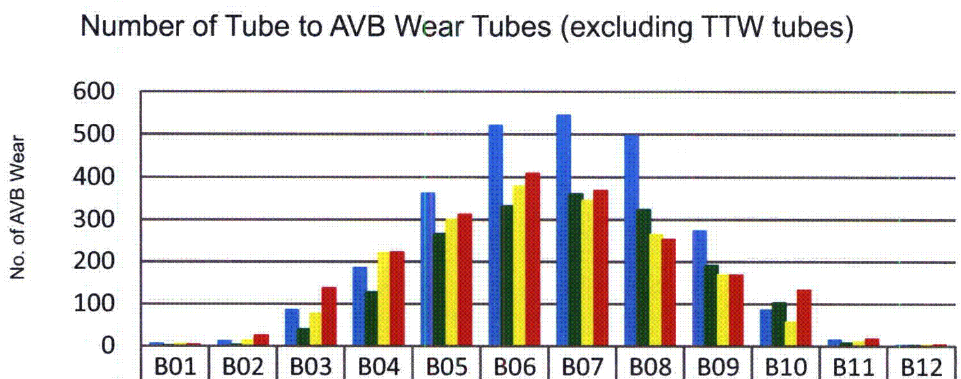
1) While the number of tubes with tube-to-AVB wear without in-plane TTW is greatest at the top of the tube bundle, the number of TTW tubes with tube-to-AVB wear is almost uniformly distributed along the different AVB intersections. (See Fig. 3.5-1.) If random vibration wear were a precursor for in-plane FEI TTW, then the pattern of AVB wear for TTW tubes should resemble the tube-to-AVB wear pattern (i.e. be concentrated at the top of the tube bundle). However, this is not observed for tubes with TTW.
2) While the tube-to-AVB wear depth for tubes without in-plane TTW is greatest at the top of the tube bundle, the tube-to-AVB wear depths for tubes with in-plane TTW is almost uniformly distributed along the AVB intersections. (See Fig. 3.5-2.) If random vibration wear were a precursor for in-plane FEI wear, then the AVB wear for the tubes with in-plane FEI would be greatest at the top of the U-bends. But for TTW tubes, the average wear depth is almost the same in all AVB support locations and there is no tendency to concentrate at the top of the tube bundle.

3) The average 10% of AVB wear depth in Unit 2 and Unit 3 excluding TTW tubes is almost the same. (See Fig. 3.5-2.) Therefore, if random vibration were a precursor to in-plane FEI one would expect to see a similar number of tubes with tube-to-tube wear in the two RSG units. However, Unit 2 only has 2 tubes with TTW.



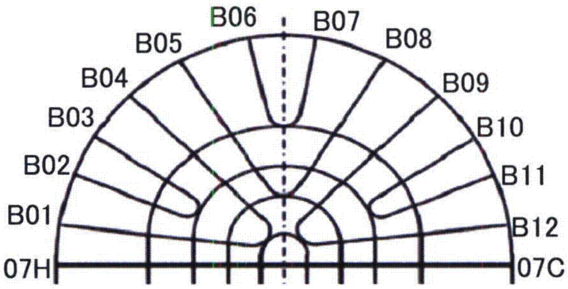


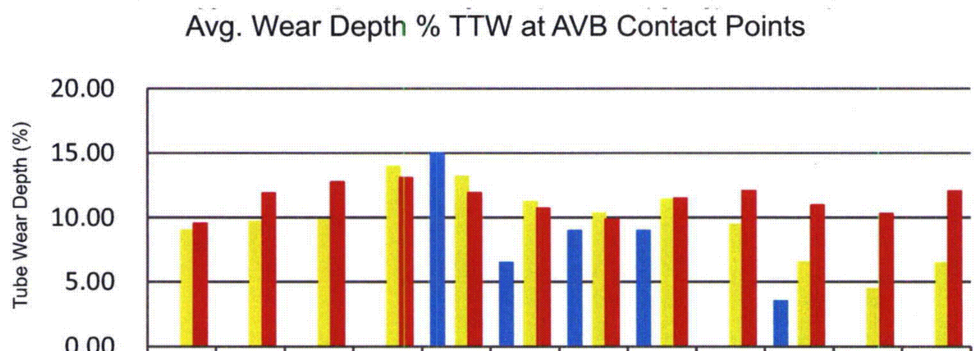
	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A TTW	0	0	0	0	2	2	2	1	0	1	0	0
2B TTW	0	0	0	0	0	0	0	0	0	0	0	0
3A TTW	119	127	133	153	151	147	135	146	132	95	69	87
3B TTW	105	125	129	135	133	122	120	133	139	129	123	115



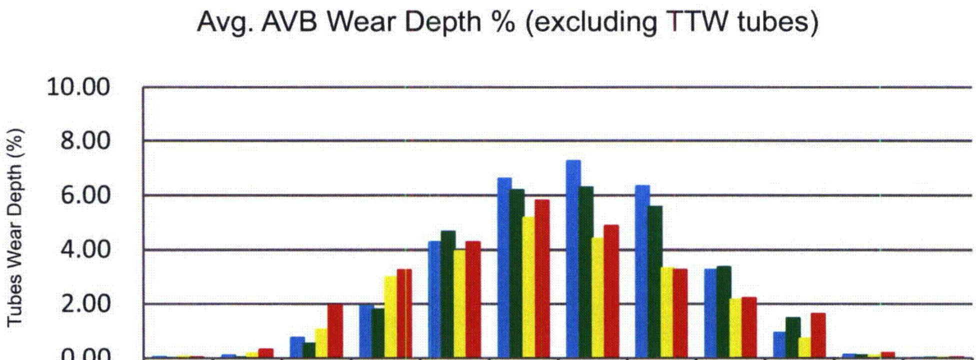
	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A AVB	5	11	85	185	362	520	544	497	273	85	14	2
2B AVB	1	3	40	127	266	333	361	324	191	102	8	2
3A AVB	5	13	77	222	301	380	346	265	169	57	10	3
3B AVB	3	25	137	222	312	408	369	252	167	132	16	3

Figure 3.5-1 AVB Tube Wear Number Comparison





	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A TTW	0.00	0.00	0.00	0.00	15.0	6.50	9.00	9.00	0.00	3.50	0.00	0.00
2B TTW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3A TTW	9.05	9.69	9.81	13.9	13.2	11.2	10.3	11.4	9.48	6.58	4.47	6.51
3B TTW	9.55	11.8	12.7	13.0	11.9	10.7	9.86	11.4	12.0	10.9	10.3	12.0



	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A AVB	0.04	0.09	0.75	1.92	4.27	6.60	7.24	6.32	3.25	0.93	0.13	0.01
2B AVB	0.01	0.04	0.53	1.80	4.66	6.19	6.29	5.58	3.36	1.48	0.10	0.02
3A AVB	0.07	0.18	1.07	2.98	3.94	5.18	4.41	3.32	2.16	0.72	0.10	0.03
3B AVB	0.04	0.31	1.95	3.24	4.27	5.79	4.88	3.26	2.21	1.64	0.19	0.04

Figure 3.5-2 Tube Wear Depth Comparison

3.6 Conclusion

MHI concludes that under the secondary thermal-hydraulic conditions such as in the SONGS SGs, certain tube-to-AVB minimum contact force is required to prevent tubes from vibrating and eventually causing wear at AVB intersections.

According to the manufacturing dimensional tolerance analysis, the average contact force in the Unit 3 SGs was found to be smaller than the average contact force in the Unit 2 SGs, as shown in Fig. 2.3.3-3. Therefore, it is concluded that the contact forces of Unit 3 were more likely to be insufficient to prevent turbulence induced (random) vibration of tubes and the Unit 3 SGs were more susceptible to turbulence induced (random) vibration, as shown in Figs. 3.2.1-4 and 3.2.1-5.

4. Design Approach

4.1 Design Approach (circa 2005-06)

4.1.1 General Design and Performance Requirements

In September 2004, MHI was awarded a contract to replace SCE's OSGs at SONGS Units 2 and 3. The general design requirements, performance requirements, and design criteria for the SONGS RSGs were set forth in SCE's "Certified Design Specification (CDS), SO23-617-01 (Ref. 8)". Significant features of the CDS were the intended use of the provisions of 10 C.F.R. §50.59 to minimize the impact of the RSGs on the existing plant licensing basis (CDS 3.6.1) and the requirement to closely match the dimensions and function of the OSGs (CDS 3.9.1). These features meant that the RSGs needed to "be as close as possible to the existing steam generators in form, fit, and function" (CDS 3.6.1.1).

While the overall RSG had to fit within the size, weight, and volume limits related to those of the OSG, the tube bundle heat transfer area was to be maximized (CDS 3.8.1.1).

The CDS specified Alloy 690TT tube material (CDS 3.9.3.8), which has a thermal conductivity that is approximately 10% less than that of the OSG tube material. In addition, the number of tubes had to be increased by 8% to accommodate future tube plugging (CDS 3.9.1). These factors led to the increase of the tube bundle heat transfer surface area from 105,000ft^2 (OSG) to 116,100 ft^2 (an 11% increase), an increase in the number of tubes from 9,350 (OSG) to 9,727 (RSG), and to the RSG tube bundle being taller than that of the OSG.

4.1.2 U-bend Design Approach for Vibration Control

Minimizing tube wear resulting from vibration was a high priority in the design of the SONGS RSGs. The design approach used to prevent flow induced tube vibration has two main elements. The first is to establish the required distance between tube supports (the tube span) and the second is to establish the minimum practical tube-to-support clearance. In general these design elements have been established and proven in earlier operating SGs.

<u>Tube Span</u>: The purpose of supporting a tube at multiple locations along its length is to increase the tube natural frequency. The design basis for such spacing is that the first mode of the supported tube be greater than the anticipated forcing frequency. In U-tube steam generators with ¾" diameter tubes, the typical span in the straight legs is | |– | |. A shorter span is typically applied to the arc length of the U-tube with the largest

bend radius. In the case of the SONGS RSGs, the straight leg tube support span is [ ] and the maximum U-bend span is less than half that of the straight leg spans (< [ ] everywhere).

Tube-to-Support Clearance: The reason for maintaining clearance between the tube and its supports (both tube support plates and AVBs) is to permit the tube to move freely in the axial direction, while restraining it in the lateral direction. Freedom to move in the axial direction is needed to assemble the tube bundle and also allows the tubes to expand due to increased temperature and pressure during operation without binding. The general goal is to design and assemble the tube bundle with the smallest possible clearances between the tubes and the supports without imposing compressive forces on the tubes. In tube support plates the minimum clearance is typically between [ ] and [ ]. For U-bend supports (AVBs) the clearance is typically controlled to an average gap of 0.005" with allowances for larger gaps on the bundle sides.

The effect of decreasing the tube-to-support clearance is to increase the probability that the tube is contacting the support (on one side), which is believed to provide the best fully supported condition. Small clearances also tend to dampen vibratory tube displacements when they happen. The SONGS tube-to-AVB clearances were controlled to a nominal of 0.002" in the cold condition, with a smaller dimensional variation than that achieved by MHI on prior SGs. The gap variations in Unit 3 were smaller than those of Unit 2, reflecting the improvement in precision gained during the manufacturing process.

At the time of the SONGS RSG design, these were the design elements used to prevent tube vibration. The AVB tube support concept had been validated by multiple experiments and by years of operating SG experience. It was based on the evidence that placing AVBs between tube columns to prevent out-of-plane tube vibration also prevented tube vibration in the in-plane direction.

As stated above, the design choices available to the designer and fabricator are limited to tube span and tube-to-support clearance. The flow conditions are largely a function of the plant power level, operating conditions, and SG size limitations.

The Role of Analysis: A variety of analyses are performed during the design process to estimate the tube vibration and wear characteristics of the design.

These analyses include a performance calculation that determines the flow resistances throughout the SG recirculation path (downcomer, bundle, primary moisture separators, recirculating pool) and calculates the circulation ratio. Then there is a 3D tube bundle thermal / hydraulic analysis that uses the circulation ratio as a boundary condition. This is the code that produces fluid velocities and densities throughout the tube bundle. Such codes are typically "single fluid" codes and are not capable of modeling the trajectories of water and steam separately. So, they are rough approximations of the actual flow behavior. Next are the post-processors that organize the output from the flow model. Sometimes at this stage flow multipliers are added to account for geometric features not modeled (for instance, sometimes the flow peaking effects of the AVBs is added at this stage).

Next is a vibration analysis program that uses the output from the flow analysis post processor and the assumed tube support conditions to calculate tube response. This program is used to analyze each of the various U-tube geometries that are found within the U-bend. This analysis calculates tube displacements at the supports for fluid elastic vibration, turbulence excitation, and vortex shedding. Generally, in the U-bend the dominant mechanism is fluid elastic vibration with turbulent excitation providing a smaller contribution. Vortex shedding is not applicable in the two-phase U-bend region. All analysis is directed toward the tube out-of-plane response.

Once the tube motions are established, a wear analysis program is used to determine material loss over time. This calculation needs the inputs of tube travel distance and tube-to-support contact (normal) force, plus a wear coefficient to determine wear volume, which is converted to tube wall wear depth. The normal forces (and motions) come from the out-of-plane response to fluid elastic forces. The sliding distance in the in-plane direction comes from the cross flow turbulence forces. Gap elements in the tube model quantify the normal force time history and sliding time history at the tube support points. The tube-to-support wear coefficient is a function of temperature, pressure, water chemistry, steam-to-water ratio, material form, surface hardness, and is taken from prototypic tests of materials in SG environments. This calculation considers both impact wear and sliding wear. A central premise of the analysis is that tube wear and impact forces are proportional to the size of the tube-to-AVB gap. Therefore, minimization of tube wear is the natural result of minimizing the tube-to-support clearances.

The suite of codes used by each vendor to perform tube wear calculations are developed as a set and are generally calibrated against experimental data or field experience so that together they produce results that are reasonably similar to what has been observed in operating SGs and experiments. However, they are only an approximation, so conservatisms are often included throughout the process.

<u>SCE / MHI AVB Design Team</u>:
In mid-2005 a joint SCE / MHI AVB Design Team was formed for the purpose of minimizing the potential for tube vibration and wear in the SONGS RSGs. For the first six months, video meetings were scheduled every two weeks and technical or design review meetings were held on a two month cycle. The AVB Design Team generated

many action items and answered many questions, several of which dealt with high void fraction and how to minimize it. This process continued through the end of 2006.

The AVB team investigated instances of U-bend tube degradation using the INPO, NPE (Nuclear Power Experience), and NRC databases and studied whatever could be found describing the design of other similarly large SGs.

The SONGS RSG design was compared to the design for another large RSG that was operating at another CE-type plant. The RSGs for the comparison plant had reported 22 tubes with U-bend wear after the third operating cycle (July 2005). The end product was a design for the SONGS RSGs with more AVB supports and shorter spans in the U-bend region than the comparison plant, along with effective zero tube-to-AVB gaps during operation. The resulting tube vibration potential was judged to be ~70% that of the comparison plant.

The tube bundle design specifically focused on preventing out-of-plane tube vibration. Industry practice and experience dictated that controlling out-of-plane vibration would preclude in-plane vibration. Reflecting this industry practice, the Japan Society of Mechanical Engineers' "Guideline for Fluid-elastic Vibration Evaluation of U-bend Tubes in Steam Generators" (Ref. 9) states that in-plane vibration does not need to be considered if out-of-plane vibration is controlled. (See Appendix 1.)

An important experiment studying FEI in U-bends (Ref. 6) by Weaver and Schneider states that "The effect of flat bar supports with small clearance is to act as apparent nodal points for flow-induced tube response. They not only prevented the out-of-plane mode as expected but also the in-plane modes. No in-plane instabilities were observed, even when the flow velocity was increased to three times that expected to cause instability in the apparently unsupported first in-plane mode". Weaver and Schneider also increased the clearances between flat bar supports and U-tubes, but were not able to produce in-plane instability.

The NRC, in its Augmented Inspection Team (AIT) report (Ref. 12), recognized this existing industry practice, noting that

> Traditional design of anti-vibration bar systems have not considered in-plane fluid forces since it was accepted that the rigidity and dampening strength of the tube in this direction preclude it. This event at SONGS is the first US operating fleet experience of in-plane fluid-elastic stability, sufficient to cause tube-to-tube contact and wear in the U-bend region." AIT at page 49.

In February 2005 a paper was published (Ref. 10) that described an experiment of a small U-bend with a single flat bar support at the apex of the U-tubes. It reports that the experimenters were able to generate both out-of-plane FEI and in-plane FEI. However, U-tube FEI in the in-plane direction has never been observed in the U-tube SGs before its occurrence in the SONGS SGs. The textbook by M. K. Au-Yang (Ref. 11), states that "In-plane modes have never been observed to be unstable even though the computed fluid-elastic stability margins are well below 1" (the fluid-elastic stability margin, FSM, is the inverse of the stability ratio).

The AVB Design Team included an independent U-bend tube vibration expert who explained that rapid tube wear is driven more by fluid elastic vibration than by turbulence, so the effectiveness of the tube supports is very important. In the analytical evaluation, considering the possibility of missing supports is a way of assuring the design has margin against fluid elastic vibration. This is the reason that the MHI vibration analysis included an evaluation of inactive (missing) supports to demonstrate margin against FEI.

Tube and AVB Fabrication and U-bend Assembly

During the fabrication and assembly of the SONGS RSGs, many steps were taken to achieve the essentially effective zero gap, parallelism and uniformity of the U-bend assembly specified by the CDS[2] and believed to be critical based on existing industry practice and experience to minimize tube vibration.

Reducing the tube-to-AVB gaps has the potential to increase the contact force and reduce tube damping. Tube mechanical damping, which is present when there are small gaps, is particularly important to inhibit FEI when the void fraction is high and fluid damping is low. The AVB Design Team decided on an AVB gap design basis with the most uniform gaps achievable and as near zero without excessive preload. So the variation of tube-to-AVB gap sizes was minimized to avoid an increase of contact force (preload) by increasing the nominal AVB thickness, reducing the AVB thickness tolerance, reducing the allowable value for twist, and decreasing the tolerance for the tube G-value (diameter).

Manufacturing mockups were used to quantify, improve, and qualify the tube-to-retaining bar welding process. Improvements in the manufacturing processes for the SONGS RSGs included the use of metal spacers during retaining bar welding, changing of SG orientation during welding, reduction of weld size to minimize deformation, measurement of every 10 column pitch, and measurement of outer

[2] Revision 3 of the CDS, to which the SONGS RSGs were designed and fabricated, specified "an effective 'zero' tube-to-flat bar gap, gap uniformity and parallelism of the tube bundle in the out-of-plane direction . . ." CDS 3.10.3.5.

peripheral gaps.

Based on experience gained in the fabrication of the Unit 2 RSGs, additional precision was incorporated into the fabrication of the Unit 3 RSGs to more effectively implement the effective zero gap, uniformity and parallelism of the U-bend assembly. (See TER at section 5.2.3 and section 2.3.3 above.)

4.1.3 Evaluation of Design Changes to Reduce Void Fraction

In the May 2005 Design Review meeting, MHI presented an RSG performance calculation showing high projected void fraction. It was decided that MHI would perform a parametric analysis to determine how the void fraction could be reduced while maintaining the other design requirements.

Over the next five months, MHI evaluated alternative design modifications to increase the RSG circulation ratio (and thereby reduce the maximum void fraction). The design alternatives included a larger downcomer, larger TSP flow area, and removing one TSP. None of these alternatives had a large enough effect on the maximum void fraction to justify such a significant change.

However, the net result of the effort was to select the 2V x 3 AVB design from among several competing AVB configurations, which had a smaller pressure loss than the competing concepts, but the reduction in maximum void fraction was negligible. The 2V x 3 AVB design provided significant design margin for minimizing tube vibration.

In October 2005 the AVB Design Team agreed that the RSG design was optimized for the SONGS application. At the time of shipment of the SONGS RSGs it was believed that they had greater margin against U-bend tube vibration and wear than other similar SGs.

4.2 U-bend Design Approach (circa 2012)

4.2.1 <u>A New Paradigm</u>

The forced outage of Unit 3 and the subsequent discovery of thousands of U-bend tube wear indications in both Unit 2 and Unit 3 after such a short operating period was wholly unexpected. Such an outcome should have been prevented by the conservative design and the precision manufacture.

The inspection data revealed two significant, heretofore, unexpected conditions. The first condition was the Unit 3 tubes with in-plane FEI, whose in-plane flow induced displacements were large enough to produce tube-to-tube contact (and wear). As stated, in-plane FEI is a new SG tube degradation phenomenon that prior to SONGS had never been observed in U-tube steam generators.

The second condition was the appearance of thousands of tube-to-AVB wear indications in just one operating cycle. A similar condition had appeared in the replacement SGs for another CE plant (Plant A) subsequent to the design and fabrication of the SONGS RSGs. After the first operating cycle, Plant A had 5,668 wear indications compared to SONGS Unit-2 with 4,341 (a full operating cycle) and SONGS Unit-3 with 3,894 (a partial operating cycle) (see Fig. 3.2.1-4). The tube degradation experienced at both Plant A and SONGS is inconsistent with prior operating SG experience and design expectations.

The identification of the unexpected tube degradation led to an extensive evaluation as to the causes the degradation and the questioning of the original design assumptions..

4.2.2 Assessment of the New Paradigm

Based on the numerous technical reports prepared by MHI and others, summarized in this report, it is clear that in-plane FEI occurred in the Unit-3 RSGs. The primary evidence of in-plane FEI discussed in Section 2 includes the following:

1. The tubes in adjacent rows (same column) have matching wear scars on the intrados and extrados, which are roughly at the 45° (hot leg side) and 135° (cold leg side) locations. This correlates with the displacement shape of the 1st in-plane vibration mode (mode-1) of the U-tubes.

2. The TTW tubes exhibit deep wear at the top TSP, which confirms that the tubes were experiencing large-amplitude, mode-1 in-plane vibration.

3. There are some "victim" tubes on the periphery of the TTW population that were struck by tubes with in-plane FEI. These tubes can be identified by the absence of top-TSP wear.

Extensive evaluations by MHI indicate that the in-plane FEI was caused by insufficient contact forces between the tubes and the AVBs to restrain movement of the tubes in the in-plane direction under high localized thermal hydraulic conditions. The in-plane vibration associated with the wear observed in the Unit 3 RSGs could only have occurred if essentially all of the AVB supports were inactive in the in-plane direction. The Unit 3 tube-to-AVB contact forces on the TTW tubes that were the result of the precise U-bend assembly process are so low that they do not restrain the tubes in the in-plane direction.

Based on the analysis, the lack of sufficient contact force to restrain the in-plane movement of the tubes is the primary cause of the in-plane FEI tube wear observed at SONGS. The high localized thermal hydraulic conditions of the SONGS RSGs are also an important factor, in that tube-to-tube wear was only observed on tubes in areas of high void fraction (steam quality). However, thermal hydraulics are not the controlling factor. SONGS Unit 2 and Unit 3 have identical thermal hydraulic conditions and virtually all of the TTW tubes were found in Unit 3. The explanation for this difference is that the contact forces in Unit 2 are approximately double those in Unit 3. Also, while the TTW was only found in the high void fraction regions of Unit 3, less than | | of tubes in the high void fraction region exhibited TTW. Furthermore, analyses using ATHOS instead of FIT-III still indicate the tubes are stable assuming no inactive supports but with lower bound damping.

The numerous technical reports prepared by MHI and others, summarized in this report also evaluated the unexpected tube-to-AVB wear observed in the Unit 2 and Unit 3 RSGs. The evaluation has led to the conclusion that the thousands of premature tube-to-AVB wear indications are caused by the presence of thousands of small tube-to-AVB gaps with insufficient contact force in the presence of high void fraction. The number of Unit 2 indications and their wear rates are less than that of Unit 3. This is consistent with the fact that the Unit 2 RSGs have higher tube-to-AVB contact forces than the Unit 3 RSGs.

4.2.3 Design Implications of the New Paradigm

Study of the recently collected data has led to a re-evaluation of the original design basis for the SONGS RSGs. Several preliminary conclusions have been drawn for developing a design that is resistant to vibration:

1. The "effective zero gap" design concept is effective against "out-of-plane FEI" but for the AVB supports to be active and provide restraint in the in-plane direction requires sufficient tube-to-AVB contact force to generate friction that inhibits in-plane tube displacement. Therefore, the zero gap assembly definition should have included a requirement for small, uniform contact forces (preloads).
2. The magnitude of the required contact force increases in regions of high void fraction (steam quality). Tubes in the high void fraction (steam quality) region of the tube bundle U-bend are more susceptible to in-plane FEI and random vibration because the higher void fraction (steam quality) reduces the external fluid damping and the liquid film damping (squeeze film damping). Therefore it is important to assure that upper bound thermal hydraulic values (void fraction, steam quality, flow velocities, damping, etc.) are assumed in the analysis of the design.
3. If small, uniform contact forces are incorporated, the design basis no longer needs to assume inactive supports and the number of supports does not need to be

greater than what is needed to prevent out-of-plane FEI (i.e. four sets of AVBs instead of six would be sufficient).

The tube degradation experience also has implications for evaluating the sufficiency of the design to prevent wear from turbulence induced (random) vibration. In the absence of out-of-plane FEI and in-plane FEI, the next most powerful tube vibration mechanism is turbulence induced (random) vibration. Given the small gaps and small contact forces, it is a reasonable conclusion that the turbulent flow conditions are sufficient to produce tube-to-AVB impact wear. However, evaluation of the wear data has led to the conclusion that different assumptions need to be made in evaluating wear from random vibration, at least under the conditions present in the SONGS RSGs. To explain the wear rate observed at SONGS using conventional methods, it is necessary (1) to assume consecutive supports with small clearances and/or small contact forces that permit tube-to-AVB impacting to occur within the gap; (2) to replace the fretting wear coefficients, typically used, with impact wear coefficients that are significantly larger; and (3) to use the random excitation forcing function that is based on recent MHI internal two-phase flow test data (Ref. 14). Sample wear calculations using the impact wear coefficient, plus the assumption that tubes have small gaps and/or contact forces at several consecutive AVB locations match the reported wear rates using a turbulence induced (random) vibration assumption (see Appendix-3 and Section 3.4).

5. References

[1] MHI report, "Tube wear of Unit-3 RSG – Technical Evaluation Report", L5-04GA564 the latest revision

[2] MHI report, "Retainer Bar Tube Wear Report", L5-04GA561 the latest revision

[3] MHI report, "Screening Criteria for Susceptibility to In-Plane Tube Motion", L5-04GA571 the latest revision

[4] AREVA report, "SONGS U2C17 Steam Generator Operational Assessment for Tube-to-Tube Wear", 51-9187230

[5] MHI report, "Evaluation of Stability Ratio for Return to Service", L5-04GA567 the latest revision

[6] Journal of Engineering for Power, Vol. 105, pp. 775-781, "The Effect of Flat Bar Supports on the Crossflow Induced Response of Heat Exchanger U-Tubes", D. S. Weaver, W. Schneider, October 1983

[7] Transactions of the ASME, Vol.120, pp. 138-142, "Flow-induced wear in steam generator tubes-Prediction versus operational experience", Au-Yang, M. K, 1998

[8] SCE document, "Certified Design Specification of SONGS Unit 2&3 RSGs", SO23-617-01 revision 3

[9] JSME, S016-2002, Guideline for Fluid-elastic Vibration Evaluation of U-bend Tube in SG, March 2002

[10] ASME, "Fluidelastic Instability and Work-Rate Measurements of Steam-Generator U-Tubes in Air-Water Cross-Flow", V.P.Janzen, E.G.Hagberg, M.J.Pettigrew, C.E.Taylor. February 2005

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[12] NRC Augmented Inspection Team Report, "SAN ONOFRE NUCLEAR GENERATING STATION", 05000361/2012007 and 05000362/2012007.

[13] EPRI technical report, "Steam Generator Vibration and Wear Prediction", TR-103202, March 1998

[14] MHI report, "Steam Generator Tube Wear Test Data Set", WJS17906, March 2011

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Appendix-1
Definition of "active" support condition for FEI and random vibration

1.1 Understanding of "active support" at the time of design

Based on accepted industry understanding and practice at the time of design an active support condition for "out-of-plane FEI" was considered to be active (meaning that the support prevented tube displacement) for "in-plane FEI" and for "random vibration." Analytically an active support was achieved by adding a pinned support condition to the tube that prevented tube displacement in the out-of-plane and in-plane directions while allowing the tube to rotate.

With active pin support conditions, out-of-plane FEI will occur before in-plane FEI because tube U-bend natural frequency in the out-of-plane direction is lower than that in the in-plane direction. It is reasonable to expect that the active pinned support condition is a valid assumption for both the out-of-plane and in-plane directions, because the resulting contact forces between tubes and AVBs will also produce in-plane tube restraint due to friction. This expectation was supported by the field experience at the time of the design of the SONGS RSGs. At the time of design, MHI investigated the field experience of U-bend tube degradation using the INPO, NRC and NPE databases, and found no tube wear in prior operating U-tube SGs caused by in-plane FEI.

Based on this accepted industry understanding, the JSME "Guideline for Fluid-elastic Vibration Evaluation of U-bend Tube in SGs" states that in-plane FEI does not need to be considered if out-of-plane FEI is controlled. The JSME guideline (Ref. 9) shows the following examples of a comparison of tube U-bend natural frequency in the out-of-plane and in-plane direction.

Fig. A1-1 Example of evaluation of tube U-bend natural frequency with AVBs

Thus, based on accepted industry understanding and practice at the time of design, the “effective zero gap” design incorporated into the SONGS RSGs was considered to be effective with respect to out-of-plane FEI as well as in-plane FEI and random vibration.

1.2 Post SONGS tube wear understanding of “active support”

Based on the investigation and analysis of the tube wear in the SONGS RSGs, MHI has now determined that:

- The “effective zero gap” design concept is effective against “out-of-plane FEI” and analytically can be represented by a pinned support that is active in the out-of-plane direction.
- The conditions necessary for a pinned support to be active in the in-plane direction requires sufficient tube-to-AVB contact force to generate friction that inhibits in-plane tube displacement
- A sufficient level of contact force between tube and AVB is necessary for the support to be active in the in-plane direction. The magnitude of the required contact force increases in regions of high void fraction (steam quality).Tubes in the high void fraction (steam quality) region of the tube bundle U-bend are

more susceptible to in-plane FEI and random vibration because the higher void fraction (steam quality) results in lower external fluid damping and a reduction in the liquid film damping (squeeze film damping), plus higher fluid velocities. High void fraction is an important (but not controlling) factor in the occurrence of in-plane FEI and impact wear due to turbulence induced (random) vibration.

1.3 Summary

The discussion above is summarized in Table A1.3-1.

Table A1.3-1 Active or Inactive as to design concept of "effective zero gap"

	At design stage	Post SONGS tube wear
Out-of-plane FEI	Active	Active
In-plane FEI	Active (*Note)	Inactive (insufficient contact forces)
Random vibration	Active	Inactive (small gap and/or small contact forces at AVB intersections)

(*Note) At the time of design an active support condition for "out-of-plane FEI" was also considered to be active for "in-plane FEI", based on accepted industry understanding and practice.

Appendix-2
Effect of support conditions on FEI out-of-plane and in-plane Critical Velocity

The critical velocity for FEI (out-of-plane or in-plane) depends on the support condition, namely the number of "active" supports (in both the in-plane and out-of-plane directions).

In U-bend SGs, if the number of active supports against out-of-plane FEI is identical to the number of active supports against in-plane FEI, the critical velocity for out-of-plane FEI is always lower than what is required to produce in-plane FEI because the natural frequency of out-of-plane FEI is lower than that of in-plane FEI. Therefore out-of-plane FEI will occur before in-plane FEI.

However, based on the investigation and analysis of the tube wear at SONGS, MHI concludes that the meaning of "active" is different with respect to "out-of-plane FEI" and "in-plane FEI" as follows:

- Active condition against out-of-plane FEI: Narrow gap that is small enough to produce tube-to-AVB contact and mechanical damping (contact force is not necessary)
- Active condition against in-plane FEI: Tube-to-AVB contact force sufficient to produce friction that inhibits in-plane tube displacement is required

Based on the investigation of the tube wear at SONGS, MHI concludes that the number of active supports against out-of-plane FEI is not identical to the number of active supports against in-plane FEI.

In the case of the SONGS RSGs, the number of active supports against out-of-plane FEI is considered to be the same as designed because narrow or effective zero gaps are confirmed by ECT measurements and visual inspection at tube-to-AVB intersections along representative tubes with wear. On the other hand, for tubes that exhibited tube-to-tube (Type-1) wear, the number of active supports against in-plane FEI is reduced because the contact force is not sufficient.

If the number of active supports that prevent in-plane FEI becomes sufficiently less than the number of supports that prevent out-of-plane FEI, the critical velocity of in-plane FEI becomes lower than that of out-of-plane FEI.

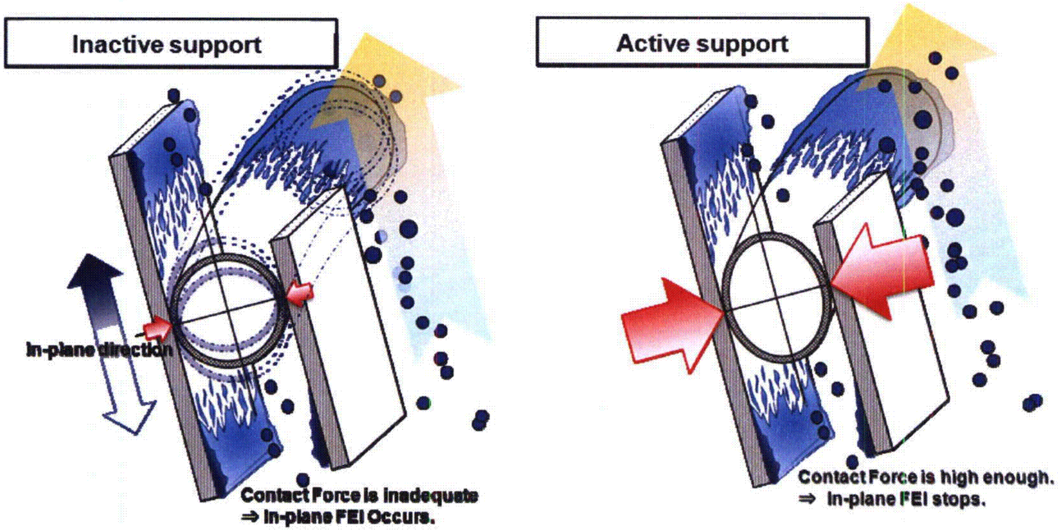

Fig. A2-1 Correlation between Number of inactive supports and Critical velocity

Appendix-3
Tube Wear Analysis Evolution

The tube wear analysis that was performed at the time of design concluded that the wear levels over 40 years would be negligible. At that time, MHI considered that “effective zero gap” (and low contact force) would provide active support conditions against tube vibration and FEI. The assumed support conditions for the tube wear analysis were as follows:

- Nine (9) active pinned supports in the out-of-plane direction but unrestrained (free) in the in-plane direction
- Two (2) consecutive inactive supports but with a symmetric| |mil gap between the tube and AVB
- A third inactive consecutive support with the AVB contacting the tube on one side where the fretting wear depth was calculated, which was larger than that at the two other inactive supports

Based on the investigation and analysis of the actual tube wear at SONGS, MHI concludes that a sufficiently large contact force is necessary to produce active support conditions against random tube vibration and that the required contact force is dependent on the void fraction (steam quality). It is concluded that the support conditions assumed during the design stage led to an underprediction of the actual wear rate.

By increasing the number of inactive supports (but with small clearances or small contact forces sufficient to permit tube-to-AVB impacting to occur) to 8, using the impact wear coefficient instead of the fretting wear coefficient, and using the random excitation force based on recent MHI internal two-phase (steam and water) flow experiments (Ref. 14) instead of single flow test data (Ref. 13), the tube wear analysis simulates the observed wear depth for the tube-to-AVB intersections with the largest wear.

Table A3-1 Comparison of Tube Wear Analysis
(At the time of design / Post-SONGS tube wear mechanistic cause evaluation)

	At the time of design	Post-SONGS tube wear mechanistic cause evaluation	
The purpose of analysis	To calculate wear due to FEI and random vibration in the out-of-plane direction	To calculate wear due to random vibration in both the in-plane and out-of-plane directions	
Support condition (Number of consecutive inactive supports)	2 (symmetric 10-mil gaps in out-of-plane direction plus free in-plane)	8*1 (symmetric 2 mil gaps in the out-of-plane direction plus free in-plane)	8*1 (symmetric 2 mil gaps in the out-of-plane direction plus free in-plane)
Random excitation force basis	Single phase (water) flow test data (Ref. 13,)	Two phase (steam/water) flow test data (Ref. 14)	
Thermal-hydraulic code	FIT-III*2	ATHOS	FIT-III*3
Wear coefficient ratio	Fretting wear value: [ ]	Impact wear value: [ ]	Impact wear value: [ ]
Gap between tube and AVB	Contact with one side (Constant)	Gap variation according to wear progression	Gap variation according to wear progression
Wear after 2 years operation	Approx.[ ]	Approx.[ ]	Approx.[ ]

Note: *1) Wear at AVB locations at the top of the bundle is assumed under the condition 8 AVBs inactive for random vibration. Other AVB locations closer to TSP have fewer inactive AVBs and wear would be less.

*2) Inappropriate definition (not consistent with ASME Section III Appendix-N) of the gap between tubes was used to obtain the gap velocity.

*3) Appropriate definition (consistent with ASME Section III Appendix-N) of the gap between tubes was used to obtain the gap velocity.

*4) A fretting wear coefficient based on MHI internal test results (Ref. 15) was used to evaluate the wear depth of the tube at the point in contact with the AVB, because the work rate at this contacted point was much larger than the work rates at the other 2 inactive support points.

*5) An impact wear coefficient based on AECL test results was used to match the impact wear that can occur when the tube-to-AVB clearances and/or the contact forces are very small.