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The San Diego Union-Tribune

San Onofre: Brown must do far better

By The San Diego Union-Tribune Editorial Board | 6 a.m. Feb. 2, 2016

http://www.sandiegouniontribune.com/news/2016/feb/02/san-onofre-edison-responsibility-union-tribune-edi/

The San Onofre nuclear power plant , now idle, once produced 20 percent of San Diego's electricity, — *K.C. Alfred*

The latest Union-Tribune Watchdog story by Jeff McDonald on the engineering, management and regulatory fiasco at the San Onofre nuclear power plant should only add to Californians' incredulity over the state Public Utilities Commission's 2014 decision to assess utility ratepayers $3.3 billion of the $4.7 billion cost of shuttering the failed facility on the north San Diego County coast. It should also persuade Jerry Brown to finally try to fix this mess.

The governor needs to stop sitting on the sidelines nitpicking proposed reforms to prevent the backroom dealings that led to the PUC decision — dealings that triggered an ongoing criminal investigation.

The Watchdog story outlined how officials at Southern California Edison, San Onofre's majority owner, became concerned over how they would replace steam generators that were wearing out without having to obtain an amendment to their operating license from the Nuclear Regulatory Commission. They settled on a plan to buy replacement steam generators from Mitsubishi Heavy Industries, a $680 million decision that ended up going disastrously wrong. The replacement generators were installed in 2009 and 2010. But after a small radiation leak in 2012, the utility found that a design flaw had damaged hundreds of tubes that were used to generate energy by pushing steam through the nuclear plant's turbines. Eventually, Edison and San Diego Gas & Electric (San Onofre's minority owner) decided they had no choice but to shutter the plant.

Edison says it only became aware of design flaws after the radiation leak and that it believed Mitsubishi's assurances on two fronts: that the replacement generators' design was safe and that it was similar enough to previous generators that getting an amended federal license was unnecessary. The problem with this assertion is the existence of a 2004 letter from Edison Vice President Dwight E. Nunn raising specific questions about design issues, questions that were prescient in hindsight.

Yet two years later, when Edison officials met with federal regulators to make the case that the replacement generators shouldn't trigger a costly, time-consuming license amendment process, they didn't mention Nunn's concerns. The utility says it was because Nunn's worries weren't relevant since the eventual design was not even in place at the time of his letter. But it is more than reasonable to wonder if Edison didn't disclose his concerns because utility leaders didn't want the hassles associated with having their license amended.

This isn't necessarily reckless; utility officials may well have believed that the replacement generators would do just fine, given the expertise and experience of Mitsubishi's and Edison's engineers. But it makes the PUC's decision to have ratepayers cover 70 percent of the cost of San Onofre's shuttering appear both incoherent and indefensible.

This view seems to be shared by state lawmakers. Two reform bills meant to limit improper contacts between state regulators and utilities passed the state Senate last week on unanimous votes, and related measures seem likely to pass as well.

Brown vetoed similar reforms in October, calling them "conflicting" and "unworkable." We need far better this time around from the governor.

If he believes the PUC reform proposals coming out of the Legislature are flawed, he should suggest reforms of his own. Unless, that is, Jerry Brown somehow thinks state utility regulators are doing a good job.

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http://www.sandiegouniontribune.com/news/2016/jan/30/san-onofre-anniversary/

It's not just the steam generators that failed

Four years after San Onofre shutdown, questions remain about flawed project

By Jeff McDonald | 9 a.m. Jan. 30, 2016

In 2009, project manager Mike Wharton inspected a recently installed steam generator within the San Onofre nuclear power plant's Unit 2 generator. — *Charlie Neuman / Union-Tribune*

When alloy tubing in one of the new steam generators at San Onofre leaked a small amount of radiation four years ago this week, engineers at Southern California Edison immediately instituted emergency protocols and shut down the nuclear plant.

Neither of the twin domed reactors on the north San Diego County coast have produced a spark of electricity since.

No one disputes what caused the failure — excessive wear in hundreds of tubes designed to drive hot steam through massive turbines is the confirmed culprit, numerous investigators and analysts found.

But what has become increasingly disputed since the plant went dark is the question of who is responsible for flawed replacement steam generators being installed and who should pay for the failure.

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Edison, the San Onofre operator and majority owner, said it had no knowledge of design flaws that led to the Jan. 31, 2012, breakdown. Edison places the blame with Mitsubishi Heavy Industries, the Japanese firm hired to design and build the replacement steam generators.

“SCE was unaware of the steam generator defects until they were discovered after the tube leak in 2012,” spokeswoman Maureen Brown said in a statement. “It was up to MHI, as the designer and manufacturer, to decide what design features to include that would result in safe RSGs” or replacement steam generators.

Billions of dollars are at stake in the plant’s failure, and so far, the lion’s share of the tab is being covered by the ratepaying public.

Following a November 2014 vote by the California Public Utilities Commission, customers of Edison and minority owner San Diego Gas & Electric have been paying $3.3 billion of the $4.7 billion in identified closure costs, or 70 percent.

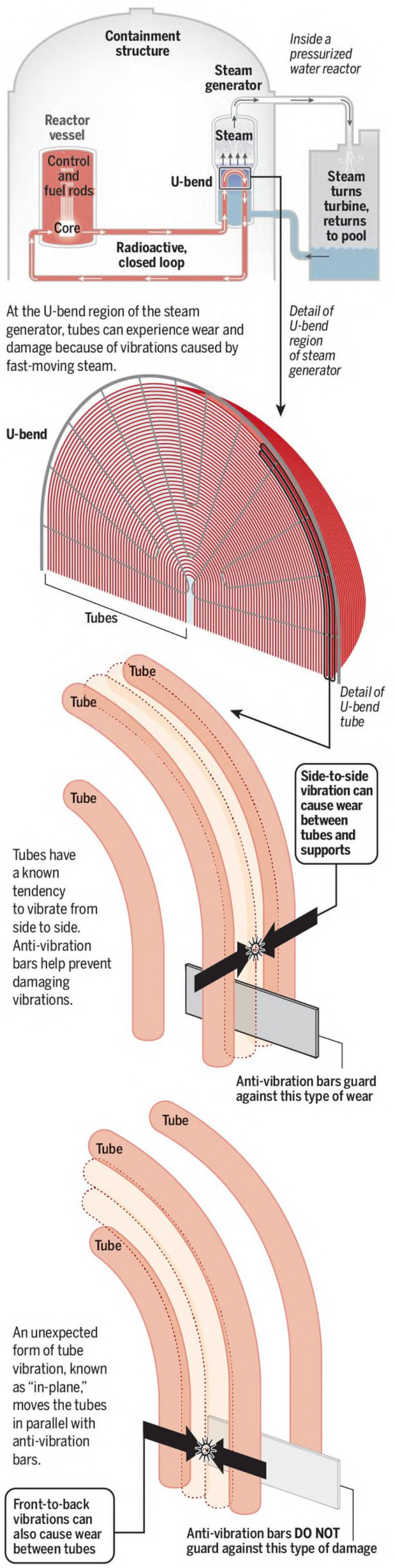
That balance remains controversial, as numerous lawsuits wind their way through various courts and the commission itself is the subject of state and federal criminal investigations over its ties to utility companies, which own the plant.

Sidebar: Steam generator tube wear

By Aaron Steckelberg | 3:14 p.m. Jan. 30, 2016

http://www.sandiegouniontribune.com/news/2016/jan/30/Steam_generator_tube_wear/

San Onofre Nuclear Generating Station’s four generators each contain nearly 10,000 tubes that transfer heat from one high-pressure steam loop — circulating through the reactor core — to a second circuit of piping that turns turbines to create electricity.



Sources: Southern California Edison;

Nuclear Regulatory Commission (End Sidebar.)

Both of the consumer groups that negotiated the deal have since withdrawn support for the agreement, citing revelations of undisclosed meetings and backchannel communications between utility executives and state regulators after the shutdown.

At the same time, a number of legal actions and investigations have revealed documents that shed light on the $680 million steam generator project that ended so badly. A key question regarding the ill-fated project at San Onofre is whether the new engines were significantly changed from the old ones.

Edison made no secret that its plan was to make certain changes to the generators, but not so many that it would bring the additional cost and delay of a federal license amendment from the Nuclear Regulatory Commission. That approach brought the project online sooner, but may have caused a missed opportunity to scrutinize a project that turned out to be fatally flawed.

“From Edison to the NRC to the PUC, the system clearly didn’t work,” said John Geesman, an attorney for the Alliance for Nuclear Responsibility, a San Luis Obispo consumer group that is fighting to overturn the San Onofre settlement. “And these documents indicate what Edison knew in advance of the leak, what Mitsubishi knew in advance of the leak, what was concealed from the NRC in advance of the leak.”

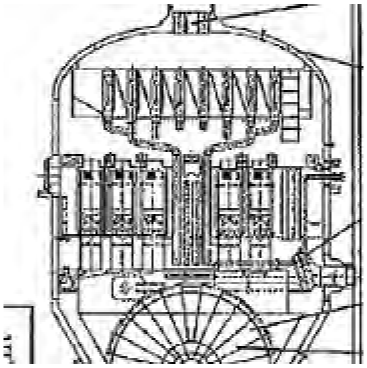
Daniel Hirsch, who runs the Program on Environmental and Nuclear Policy at the University of California Santa Cruz, said there is a lesson to be learned from any oversights or missteps: There are huge public risks if regulators become too cozy with companies they oversee — especially in the nuclear arena.

“Fortunately San Onofre was permanently closed before a major accident occurred,” Hirsch said. “NRC estimated a meltdown could result in as many as 130,000 immediate deaths, 300,000 cancers and 600,000 genetic defects. We dodged an awfully big radioactive bullet.”

Improved generator

San Onofre’s steam generators were installed in 1983 and 1984. By the end of their third decade of service, their pipes were getting plugged up, and the units needed replacing.

Document



ASME proceedings, Chan and Calhoun

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In July 2010, the replacement steam generator installation was all but completed and the equipment was close to being fully activated. Two Edison engineers, James K. Chan and David J. Calhoun, presented a white paper that same month during a special conference of the American Society of Mechanical Engineers in Bellevue, Washington.

Their nine-page report detailed the various improvements in the RSGs.

In addition to new alloy tubing, Chan and Calhoun identified several design changes they said contributed to an improved steam generator. They singled out the higher number of tubes — 377 more in each of the new generators — and their thinner wall thickness, which dropped from 0.048 inches to 0.0429.

"With (the) larger number of tubing and taller tube bundles, the RSG nominal heat transfer surface area is 116,100 sq. ft., which (is) larger than the OSG (original steam generator) surface area of approximately 105,000 sq. ft.," the engineers reported.

A larger heat transfer surface area can help produce additional power.

Improvements were also laid out in an article in January 2012 — the same month as the radiation leak — by Edison engineer Boguslaw Olech and Tomoyuki Inoue of Mitsubishi Heavy Industries for the prestigious trade publication Nuclear Engineering International.

The title: "Improving like-for-like RSGs."

Document

'Improving like-for-like RSGs'

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The four-page report lays out many of the design challenges and successes the engineers encountered as they drew up plans for the replacement steam generators at the San Onofre Nuclear Generating Station.

“At SONGS, the major premise of the steam generator replacement project was that it would be implemented under the 10 CFR 50.59 rule, that is, without prior approval from the U.S. Nuclear Regulatory Commission,” they wrote. “To achieve this goal, the RSGs were to be designed as ‘in-kind’ replacement.”

Although the replacement was to be “in-kind” in terms of form, fit and function within the power plant, the team wanted to make “all possible improvements” to the steam generator itself, in the hopes of boosting the plant’s “longevity, reliability, performance and maintainability.”

Critics say a drive to improve the generator design while avoiding more intensive federal review was a profit-driven exercise that proved reckless.

“It was all about greed, and expediency, and they risked lives in the process,” said Charles Langley, a longtime San Diego consumer advocate. “They would have lost millions and millions of dollars in revenue by going through a license amendment process. It would have delayed the deployment of the steam generators for years.”

The company says safety is its priority, and that it wanted to avoid federal review because that step is only required if there are adverse safety implications to the project at hand.

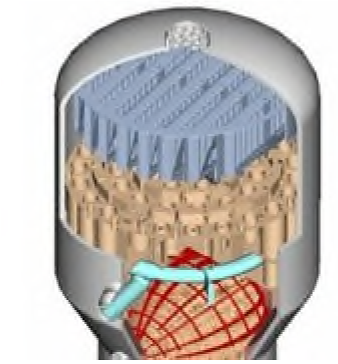
“The 50.59 process permits changes to plant equipment without a license amendment where the changes satisfy certain criteria, for example, where the changes do not adversely affect the safety function of components,” Brown said. “SCE’s goal was to obtain RSGs that would remain within the bounds of 50.59, in order to help ensure that design changes would not adversely affect the safety of the plant. In fact, SCE made clear both in the contract and in the design review process that its overriding priority was to ensure safety.”

Root cause

Mitsubishi Heavy Industries kept careful track of the San Onofre steam generator project. It was, after all, a $680 million undertaking that required extensive discussion and documentation.

In October 2012, nine months after the failure, Mitsubishi delivered a lengthy internal report to federal regulators detailing what caused the breakdown.

Document



Mitsubishi's root cause analysis

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A heavily redacted version of the so-called Root Cause Analysis was released in March 2013. It discussed high "void fraction," a gas-to-liquid measurement that — when elevated — can contribute to the very kind of tube wear that caused San Onofre's radiation leak.

The report discusses the actions of the design team for active-vibration bars or AVBs, designed to protect tubes from excessive wear.

"The AVB Design team recognized that the design for the SONGS RSG resulted in higher steam quality (void fraction) than previous designs and had considered making changes to the design to reduce the void fraction … But each of the considered changes had unacceptable consequences and the AVB Design Team agreed not to implement them."

Then this: "Among the difficulties associated with the potential changes was the possibility that making them could impede the ability to justify the RSG design under the provisions of 10 CFR 50.59," or without the added NRC review.

The design team in question was a joint Edison-Mitsubishi effort, and federal nuclear regulators cited both parties for failures leading up to the San Onofre leak.

As the NRC put it, the problem was "the failure to verify the adequacy of the thermal-hydraulic and flow-induced vibration design of the San Onofre replacement steam generators, resulting in excessive and unexpected steam generator tube wear."

Edison officials say they relied on Mitsubishi Heavy Industries for advice about whether a federal license amendment was required.

"Had MHI told SCE that a design change was needed to make the RSG's safe, SCE would have approved it, even if that change would have required a license amendment," Brown wrote. "MHI repeatedly told SCE that the design MHI proposed was safe, and the design did not require a license amendment."

Mitsubishi did not respond to a request for comment for this story. The company in the past has said it could not have anticipated the unprecedented type of tube vibrations that occurred in exceptionally large generators commissioned by Edison.

The NRC has since confirmed that no license amendment was required for the San Onofre steam generators, and in fact, the issue may be irrelevant to the plant failure.

"The San Onofre steam generator tube degradation occurred as a result of issues introduced during the design phase that were unrecognized and, thus, were not considered in the licensee's 10 CFR 50.59 evaluation," the agency said in a March 2015 "lessons learned" memo about San Onofre.

Whether the amendment was required or not, investigators have probed whether the project would have received approval after undergoing such a review.

Document

Inspector General's report on San Onofre

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Elmo Collins, the former federal administrator who oversaw San Onofre until March 2013, told the NRC's inspector general for an October 2014 report that if the license amendment review had been conducted, it is unlikely the steam generators would have been approved.

"The steam generators as designed were basically unlicensable," he said. "We wouldn't approve them."

He said inspectors conducting a review would have noticed, in particular, the high "void fraction" of 95 percent when no other plant in the industry was above 90 percent.

"Some reviewer would have said this as an outlier," Collins told investigators, "and we need to understand that."

Disastrous outcome

Some of the first documents made public that raised questions about Edison's oversight of the San Onofre project were written by Dwight Nunn, a now-retired company vice president. They surfaced in 2013, right before Edison decided to close the plant for good.

More than 10 years ago, Nunn wrote to the Mitsubishi Heavy Industries general manager.

Document

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Mr. Akira Sawa
General Manager
Mitsubishi Heavy

Nunn letter to Mitsubishi

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"I am concerned that there is the potential that design flaws could be inadvertently introduced into the steam generator design that will lead to unacceptable consequences (e.g. tube wear and eventually tube plugging)," Nunn wrote. "This would be a disastrous outcome for both of us and a result each of our companies desire to avoid."

Ray Lutz of Citizens Oversight, a San Diego nonprofit group fighting to reverse the San Onofre settlement, said the letter shows Edison could have prevented the failure.

"The Nunn letter really showed us that the utility knew they had a big problem," Lutz said. "It's clear when you read it that SCE was taking a very close look at everything going on with the design, so for them to say they didn't know it could fail just isn't true."

For Edison's part, it says Nunn's letter shows how thorough the company was in making its concerns known to Mitsubishi, and gaining assurances from the manufacturer that the steam generators would be safe.

"Mr. Nunn's questions could not have reflected a recognition that the design was flawed as the design did not even exist at that point," Brown wrote. "On the contrary, his letter reflects the questioning attitude that is the hallmark of the strong safety culture in the nuclear industry. In response to Mr. Nunn's questions, MHI assured SCE that it would carefully address the design of anti-vibration bars, recognizing the need to modify and improve the design from those it had developed for smaller RSGs."

Experience invalid

While Edison and Mitsubishi executives traded correspondence in the early days of the project, engineers from the two companies convened in Japan to tackle the more technical issues. Notes from some of those meetings have been posted on the Edison website as part of the company's effort to keep ratepayers informed about the shutdown.

The non-proprietary version of records from five days of meetings in March and April 2005 show how complicated the design challenges were and how detailed the discussions could get.

Document

Discussion
Edison is concerned that waiting until the end of April to approve the Tube Specification conflicts with [ ]'s schedule indicating that they need an approved Spec by April 8.

Edison said that specifications cannot be approved with "holds" on subsections. This differs from a drawing with "ballooned holds" that are allowed.

2005 design team minutes

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According to the public meeting notes, Edison was aware that Mitsubishi was venturing into new ground when it won the $680 million bid to design and manufacture the San Onofre replacement steam generators.

"MHI has experience with small (steam generators) and the SONGS RSGs have large U-bends, therefore the prior MHl experience is invalid," notes from the first day of those meetings state.

On another page, one attendee makes this notation: "The SONGS OSGs (original steam generators) had tube wear problems so they don't see why the RSGs will be any different. They suggest a comparative analysis of the OSG and RSG."

Brown said Mitsubishi was responsible for designing the replacement steam generators, and that Edison challenged the process along the way. SCE pointed out, for example, that Mitsubishi was experienced building smaller steam generators and "MHI should not assume that a scaled up design would work," she said.

"MHI agreed with SCE's comment and repeatedly assured SCE that it was engaged in a rigorous evaluation of the safety of its design for the SONGS RSGs," she wrote. "Unfortunately, unbeknownst to SCE at the time, MHI did not in fact live up to its promises, due largely to flaws deeply embedded in its proprietary computer codes."

Edison's presentation

In the run-up to a key meeting with federal regulators in 2006, Edison produced a 22-page slide show outlining its replacement steam generator project.

Document

Edison presentation to NRC

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The presentation shows Edison planned to design, build, install and operate the RSGs at San Onofre before the close of 2010. The PowerPoint notes that Edison planned to replace the steam generators without going through the lengthy license-amendment process.

At the meeting, Edison touted the plant history and performance. The report does not include any reference to "void fraction" or other design challenges discussed by Nunn and other Edison officials prior to the presentation.

Hirsch, the UC Santa Cruz nuclear policy expert, said Edison "absolutely" should have reported its design concerns to federal regulators.

"It took NRC one day — one day! — to discover the computer error that was at the heart of the steam generator failure," Hirsch said. "But because Edison tried to avoid a license amendment that would have required NRC review and a potential public license amendment hearing, and didn't disclose to NRC problems like the void coefficient concern, NRC only did that review after the steam generator failed."

Brown said there was no relevant concern to disclose to the NRC at the 2006 meeting, and the utility kept regulators in the loop throughout the project.

"We routinely shared status on the project with the NRC," she said. "We addressed questions that they raised, and when they did inspections, we participated fully and provided them with information to address those questions. During the design phase, we also briefed the NRC headquarters staff at a high level."

The utility told regulators at the 2006 presentation that the project had an "improved AVB design" and "improved materials for tube supports." It would also use a stronger metal — thermally treated Alloy 690 TT — to construct the tubing.

The company said the new steam generators would hold 9,727 tubes each, a 4 percent increase, without adding to the height or diameter of the equipment. They would jump in weight from 620 tons to 644, Edison reported.

The new RSGs would be shipped by heavy-lift cargo from Kobe, Japan, to Long Beach, Calif., where an ocean barge would deliver them to Camp Pendleton.

Eleven months after it was equipped with replacement steam generators, Unit 3 was shut off due to the radiation leak. Its sister unit, offline that day for pre-scheduled maintenance, later was found riddled with the same excessive wear.

Edison and Mitsubishi are litigating their dispute through a private arbitration process. Edison is contesting a contract provision that caps at $138 million the liability for Mitsubishi.

"The RSG project was expected to extend the life of SONGS by decades," Brown said. "Had the RSGs worked as MHI promised, utility customers would have benefitted."

Jeff McDonald

Proceedings of the ASME 2010 Pressure Vessels & Piping Division / K-PVP Conference
PVP2010
July 18-22, 2010, Bellevue, Washington, USA

PVP2010-25897

STEAM GENERATOR REPLACEMENT AT SAN ONOFRE NUCLEAR GENERATING STATION UNIT 2

James K. Chan and David J. Calhoun
Southern California Edison
San Onofre Nuclear Generating Station
San Clemente, CA 92672

ABSTRACT

This paper describes the design and installation of the replacement steam generators at San Onofre Nuclear Generating Station (SONGS) Unit 2. The design improvements of the replacement steam generators are compared to the old steam generators. The difficulties encountered during the installation of the replacement steam generators are also described. Lesson learned are summarized to benefit the execution of the SONGS Unit 3 replacement steam generators installation.

INTRODUCTION

Due to the degradation of SG tubes made of Alloy 600 material, many steam generators in the pressurized water reactor (PWR) have been undergone replacement. Steam generator replacement projects had started more than 20 years ago in the United States. Most of the PWR nuclear power plants in the United States have completed their Steam Generator Replacement projects. Steam generators at the San Onofre Nuclear Generation Station (SONGS) are the second largest in size in the United States after Palo Verde Nuclear Generating Station steam generators. Southern California Edison is the primary owner of SONGS and is also a part owner of Palo Verde Nuclear Generating Station. The original steam generators (OSGs) were manufactured by Combustion Engineering and the replacement steam generators (RSGs) are manufactured by Mitsubishi Heavy Industry (MHI). MHI was chosen based on cost and quality of products and services, and their experience of manufacturing Fort Calhoun Nuclear Power Plant steam generators. Fort Calhoun has a smaller version of steam generators in SONGS. Replacing steam generators at SONGS will save customers hundreds of millions in the next two decade compared to the cost of replacement power. Steam generator replacement is also the first step of plant life extension. The operating license of SONGS will expire in 2022. SONGS units have been operating for more than 25 years since Unit 2 and Unit 3 came on line in 1983 and 1984 respectively. Southern California Edison plans to extend the operating license for twenty more years.

DESIGN IMPROVEMENTS OF STEAM GENERATORS

NSSS System and Steam Generator Design Functions

The San Onofre Nuclear Generating Station Unit 2 Nuclear Steam Supply System (NSSS) consists of a reactor vessel, two steam generators, four reactor coolant pumps, and a pressurizer. They are connected by the reactor coolant loop piping and act as the primary (2500 psia) and secondary (1100 psia) pressure boundary. The two replacement steam generators transfer heat generated in the reactor core to the secondary system by producing high quality steam with a moisture content of less than 0.1% to the main turbine. Approximately 1100 MWt of electricity is generated from each unit for the residents of Orange and San Diego counties in California.

Design and Operating Parameters

The RSG design pressure and temperature are the same as the OSG design pressure and temperature but the operating pressures are slightly different. Table 1 provides a comparison of the major design and operating parameters for the RSG and the OSG. All numerical values in the table are per steam generator, where applicable. The thermal ratings of the RSGs and OSGs are the same. The RSGs have larger number of tubes but the tube wall thickness is slightly thinner. Therefore, the heat transfer area is about 10% higher which compensates for the lower heat transfer coefficient of Alloy 690 tubing compared to Alloy 600. The RSG primary side volume is slightly greater than that of the OSG due to a larger internal volume of the tube bundle.

The RSGs are qualified to operate in the Thot range from 598 to 611F. The reactor coolant flow rate and the steam flow rate are slightly higher for the RSGs. The steam generator blow down rate is designed to be at least 2% of the feed water flow rate.

Design Features

Many design improvements were made to address operating experiences of the OSGs and to enhance the RSGs overall reliability and maintainability. These included the use of forgings for the steam generator shell, instead of plates, improved materials for tubing, tube supports and feedwater distribution system, improved design of the tube-to-tubesheet joints, tube supporting structures, feedwater ring and the channel head, as well as inclusion of an integral steam flow limiter. The RSGs have improved access provisions for maintenance and inspections, and improved access to the internal components.

The steam generators consist of several major components: the upper and lower shell with transition cone and elliptical upper head, tube bundle, tube supports, tubesheet and channel head, feedwater distribution system, moisture separation equipment and access provisions. The elevations of the RSG level taps are such that the level setpoints for the RSGs are the same as for the OSGs. The elevations and orientations of the other RSG instrument taps are similar to those for the OSGs, and are such that the existing sensing lines can be easily reconnected. The locations of the large hot leg, cold leg, mainsteam and feedwater nozzles in RSG are identical to those of the OSG, in order to eliminate the need for modification of the major piping. The RSGs are supported in the same manner as the OSGs, utilizing the existing sliding base, key brackets and snubber assemblies. The overall dimensions and weights of the RSG and OSG are almost the same as shown in Table 2.

Tubing

The main reason to replace the existing steam generators is the OSG tubes are made of Alloy 600 material which is susceptible to inter-granular attack (IGA) and stress corrosion cracking. The RSG tube material is thermally treated Alloy 690 (Alloy 690 TT). Alloy 690 TT has been under development since the early 1970s, and based on extensive industry-wide tests, has been determined to be the material of choice for use in the replacement steam generators industry-wide. Both laboratory testing and operational experience have proven that Alloy 690 TT is much more resistant to IGA and stress corrosion cracking in both primary and secondary water environments than Alloy 600.

The number of heat transfer tubes in RSG is 9727 and is 9350 in OSG. The RSG tube bundle is approximately 17 inches taller than the OSG tube bundle. The outside diameter of the RSG and OSG tubing are both 0.75". However, the RSG tubing wall thickness is 0.0429 inch which is smaller than the OSG tubing wall thickness of 0.048 inch. This is because the RSG tubing uses a higher strength material of Alloy 690 TT as compared to OSG material of Alloy 600. With larger number of tubing and taller tube bundles, the RSG nominal heat transfer surface area is 116,100 sq. ft. which larger than the OSG surface area of approximately 105,000 sq. ft.

Tube Supports

The RSG tubes are supported by tube support plates in the straight-leg region and by an anti-vibration bar (AVB) structure in the U-bend region. In the RSG, the tubes are supported in place by seven tube support plates with broached and trefoil tube holes. The tube support plates are designed to reduce the tube-to-tube support plate crevice area while providing for a maximum steam/water flow in the open areas adjacent to the tube. Flat-land tube-to-tube support plate contact geometry provides additional margin for dryout. The tube support plates are made of Type 405 ferritic stainless steel. Materials are selected to minimize the potential for tube wear and denting due to tube support plate corrosion. In the OSG, the tubes are supported by egg-crate grid type tube supports, constructed from straight bars that are sized to fill the interstitial space between the tubes. The egg-crate bars are made of carbon steel.

In the RSG, six sets of V-shaped AVBs, providing up to 12 support points per tube, are installed in the U-bend region to provide support in the region where the tubes are most susceptible to degradation due to wear from flow-induced vibration. During RSG fabrication, the thickness of the AVBs and the tube-to-AVB gap were tightly controlled. The 12 tube support points provide redundancy, so that all the tubes remain fluid-elastically stable even if some of the support points are inactive. The AVBs are nearly perpendicular to the centerline of the tubes at all 12 support locations to provide support while minimizing the tube-to-AVB contact length (to minimize the potential for local corrosion and wear). These features of the U-bend support system provide significant margin against flow stagnation, corrosion, and tube vibration. In the OSG, tube U-bend configuration includes two 90-degree bends on either side of a horizontal run, and the support system includes relatively wide diagonal batwings and vertical strips for supporting the horizontal run of the bends, all made of carbon steel.

Tubesheet and Channel Head

In the OSG, the channel head design includes a tubesheet with center supported by a stay cylinder, which permits the tubesheet thickness to be minimized. In the RSG, he tubesheet is thicker and is supported only by a structural divider plate. This design approach allows for more heat transfer tubes and eliminates the "cold zone" in the center region of the tube bundle, which is considered a likely contributor to tube wear in the bundle U-bend central region. The RSG tubesheet is a single piece forging with integral weld preparations. The RSG reactor coolant volume is approximately 5% more than the OSG volume, but still within the allowable limit dictated by the containment building flooding analysis.

In the RSG, the channel head has a flat bottom and the outlet plenum is self-draining. The inlet and outlet nozzles contain integral grooves for installation of the nozzle dams with quick locking pins and inflatable seals for primary side inspection and maintenance operations. The design also includes provisions for preventing reactor coolant spillage during manway cover removal. The RSG reactor coolant inlet nozzle design incorporates a flow limiting orifice in order to offset the effect of increased number of tubes (in terms of the primary side flow resistance) on the reactor coolant flow rate, and maintain this rate within the allowable limits. The OSG design does not include the provisions mentioned above.

Upper and Lower Shell

In the RSG, forgings are used for fabrication of all pressure boundary parts: channel head, lower and upper shell, transition cone, and major nozzles. This method is used to minimize the number of pressure boundary welds. The OSG shell is fabricated from plates and includes both circumferential and longitudinal welds. The RSG upper shell diameter is the same as the OSG diameter; the RSG lower shell diameter is approximately 2 inches larger than the OSG diameter. The RSG main steam outlet nozzle has a flow-limiting device, consisting of seven venturi nozzles with a throat ID of 8.56 inches. This devise is used to reduce the rate of mass/energy release into the containment during a postulated Main Steam Line Break (MSLB) inside containment. It also reduces the loads on the steam generator internals during such an event. The OSG design does not include an integral steam flow limiting device.

The RSG blowdown provisions are in a form of a peripheral open channel on the secondary side of the tubesheet, with the 4-inch blowdown nozzle attached to the tubesheet. The channel provides for complete drainage of the secondary side, so the blowdown nozzle serves also as a secondary side drain nozzle. The OSG design includes 2-inch carbon steel internal blowdown piping with a 2-inch blowdown nozzle attached above the tubesheet.

Feedwater Distribution System

Feedwater is introduced into the RSG through a feedwater nozzle located on the upper shell. The nozzle contains a welded Alloy 690 thermal sleeve, which minimizes the impact of large temperature transients on the nozzle and shell during cold auxiliary feedwater injection. The feedwater ring design includes an internal "goose neck" extending above the elevation of the feedwater spray nozzles. This feature eliminates thermal stratification in the feedwater nozzle and the connecting feedwater piping, and prevents the feedwater ring from draining on loss of main feedwater flow, thus minimizing the potential for water hammer. The OSG design employs a thermal sleeve and a distribution box, and does not include features preventing thermal stratification or water hammer on loss of feedwater flow.

The RSG feedwater ring is designed to uniformly distribute the feedwater flow around the upper shell. Special perforated nozzles are spaced around the top of the feedwater ring to distribute the feedwater into the upper shell recirculation water pool without impinging on any internals. The purpose of the perforated nozzle design is to capture loose parts that may enter the RSG with feedwater and provide for feedwater flow pressure reduction. The nozzle location prevents the feedwater ring from draining, thus eliminating the potential for water hammer on steam generator water level decrease. The OSG feedwater ring utilizes "J-nozzles" to reduce the potential for water hammer on steam generator water level decrease.

The RSG feedwater ring is fabricated from Cr-Mo alloy steel with Alloy 690 TT fittings, which provide increased resistance to erosion/corrosion. The OSG feedwater ring is fabricated from carbon steel, which has a much lower resistance to erosion/corrosion.

Moisture Separation Equipment

The moisture separation equipment includes the moisture separators and steam dryers. The RSG design includes 38, 20-inch, high performance centrifugal moisture separators welded to the lower deck plate. The moisture separators use swirl vane, riser separating, and outlet orifice design features, and are made of Cr-Mo low-alloy steel resistant to erosion/corrosion. The OSG design includes 212 moisture separators of a smaller diameter made of carbon steel, which are bolted to the lower deck plate.

The RSG design includes eight banks of single-tier dryers with perforated panels on the inlet side and layers of tightly packed dryer vanes inside each bank. The RSG single-tier dryer bank spacing and the total length of the banks provides much more separating capacity than is available in the OSG dryer arrangement. RSG steam dryer performance is further enhanced through the use of peerless double-pocket high-capacity dryer vanes. Drain pipes carry the captured water from the dryers downward into the recirculation pool. The OSG design includes a set of 162 steam dryers that have much smaller moisture separation capacity.

Access Provisions

The RSG and OSG access provisions are compared in Table 2. The RSG has two 18-inch primary manways on the channel head, and two 16-inch secondary manways on the upper shell. The OSG has two smaller 16-inch primary manways on the channel head and two 16-inch secondary manways on the upper shell. The RSG has four 8-inch handholes located on the extension ring just above the tubesheet and two 8-inch handholes located on the transition cone just above the uppermost tube support plate. The OSG only has two 6-inch handholes on the secondary side above the tubesheet. In addition, the RSG has twelve 2.5-inch inspection ports. Two inspection ports, 180-degrees apart, are located above each of the six lower tube support plates. Each handhole and inspection port provides access to the tube bundle via a sleeve and a closable penetration in the wrapper. The OSG does not have shell penetration provisions for upper bundle or individual tube support inspection access.

The RSG elliptical upper head design offers more upper shell space for access as compared to the OSG hemispherical head design. Access to the RSG bottom and top of the steam dryers and the steam nozzle is provided via hinged hatches. The OSG design does not provide such access. The RSG downcomer annulus at the feedwater nozzle orientation is much wider at the top than in the OSG, thereby facilitating access to the nozzle and feedwater ring. The access above the feedwater ring is provided via an annular space between the lower moisture separator deck plate and upper shell. The feedwater ring is equipped with two closable access ports, 180 degrees apart, for remote inspection and foreign material retrieval. The OSG annulus above the feedwater ring is of a smaller size, thereby restricting accessibility for maintenance or inspection. The feedwater ring itself does not have any access provisions. The access to the tube bundle U-bend region in the RSG is provided via hinged hatches while the OSG is provided via a manway with bolted cover. The RSG also has a unique design of moisture separators that permit direct access of video equipment to the tube bundle U-bend for remote inspections.

OTHER RELATED CHANGES

There are many changes required to support the steam generator replacement. The major change packages prepared are
(i) Containment Opening,
(ii) Reactor Coolant System (RCS) Tie-in,
(iii) Rigging and Handling of Steam Generators
(iv) Mainsteam, Feedwater, and Blowdown Lines,
(v) New Thermal Insulation

Containment Opening

The existing equipment hatch at SONGS is too small and is not in a location that would permit the movement of the steam generators. Therefore, a temporary containment opening construction was required. After the installation of the steam generators, the containment opening was closed and restored to the original design condition. The containment building is a safety related post-tensioned reinforced concrete structure with 52" thick walls containing conventional horizontal and vertical reinforcing steel near the inside and outside face, horizontal and vertical tendons encased in tendon sheaths embedded in the center portion of the wall, radial reinforcing ties, and a ¼" thick steel liner plate on the inside face of the wall. The creation and closure of the construction opening involved the removal and reinstallation of each of the above components as well as electrical commodities installed on the liner plate..

RCS Tie-in

In order to remove the OSG and install the RSG, the RCS piping were cut at the hot leg and at both cold legs, in conjunction with installation of any required temporary supports. After cutting of the RCS piping, the severed end of the remaining RCS hot leg and cold legs were decontaminated. Temporary covers were provided and installed over the open ends of the remaining RCS pipe to protect the openings from damage, to prevent the intrusion of foreign materials into the RCS, and to reduce local dose rates. Once proper fit-up between the RSG nozzles and the RCS hot leg and cold legs was achieved, proper fit-up of permanent RSG supports, and any required steam generator temporary restraints were installed to maintain fit-up. Then the weld between the steam generator nozzles and the RCS piping (hot leg and cold legs) was performed. Automated welding process was used and qualified by NDE process. Temporary RCS supports were removed after the RCS was secured in place.

Rigging and Handling of Steam Generators

The rigging and handling of the OSGs and RSGs outside the containment building were accomplished by the use of Outside Lifting System (OLS). The support towers of the runway and OLS are constructed of reusable, multifunction, Vertical Pole System (VPS) components. The VPS structural connections consist primarily of high-strength bolts and pins to facilitate assembly and disassembly. The runway and OLS girders consist of side-by-side built-up plate girders which span the support towers. As with the majority of the components, these girders have also been designed for reuse and have been used previously in heavy rigging operations.

The rigging of the RSGs was in reverse order of the OSGs. RSGs are provided with welded in place lifting trunnions located on the upper shell. The RSGs were moved from the on-site storage area to the Containment Building with the trunnions in the horizontal position, lifted by the OLS using belly slings, and moved into the Containment.

The rigging and handling of the OSGs and RSGs inside the containment building were accomplished by the use of Polar Crane, Temporary Handling Device (THD) and Temporary Support Structure (TSS). THD is a hydraulically operated gantry type trolley that is designed to travel on the existing polar crane bridge girder rails. It is designed to lift the full weight of a steam generator and attached rigging appurtenances. The THD has a larger lift capacity and higher lift range than the existing polar crane hoist trolley, and was used to lift the OSGs out of their compartments and down-end them onto transfer carts on the inside runway system. The RSGs likewise were upended from the transfer carts and rigged to their final position within the cubicles using the THD. The THD and its associated rigging components (such as link plates, key-hole plates, and swivel/spreader beams) were attached to the OSG lifting plug and the RSG trunnions. The TSS is a frame used to temporarily support the SGs during rigging The SGs were temporarily set and secured in the TSS during the SG rigging process to allow rotation of the polar crane without the load from the SGs.

Mainsteam (MS), Feedwater (FW), and Blowdown (BD) Lines

In order to remove OSGs and install RSGs, the MS, FW, and BD lines were cut in conjunction with the installation of any required temporary supports. The MS pipe cut is located near the OSG nozzle. The other MS pipe cut is located further downstream from the SG nozzle along the horizontal pipe run to minimize the potential for foreign material entry into the piping. The cut pipe spool was temporarily removed and stored for reuse. Portions of the FW piping and the associated supports and pipe whip restraints were removed to facilitate the removal of the OSGs and the installation of the RSGs. The cuts are located at the SG FW nozzle and at 20 inches check valve downstream outside the SG cubicle. Temporary covers were installed over the open ends of the removed spool pieces of piping to avoid foreign material intrusion. The BD line was removed and modified due to the new RSG BD nozzle location 3 feet lower than the existing BD nozzle and the nozzle size is also slightly different. Design improvements such as material upgrade and modifications to facilitate service inspections are made for the MS, FW, and BD lines.

New Thermal Insulation

The insulation of the OSGs and portion of the piping connected to the OSGs was removed. New thermal insulation was installed on the RSGs and portions of connected piping of the reactor coolant system, mainsteam, feedwater, and blowdown piping. The original thermal insulation system consists of encapsulated mineral wool and reflective metal insulation (RMI). The replacement thermal insulation is entirely RMI. The replacement RMI panels are supported by steel rings that are friction clamped to the SG shell. Each support ring consists of segments of steel angle joined with fasteners. Clamping force is provided by torquing of the fastener bolting. A support ring is typically installed between each level of panels. The individual panels are buckled to each other. No screws are utilized in the installation of the panels. The panel design and layout facilitate the access to handholes, manways, and other areas for maintenance and inspection.

DIFFICULTIES DURING INSTALLATION

There were many difficulties encountered during the installation of the RSGs. A few significant cases are mentioned below.

Tendon

In order to create an opening on the containment wall, 82 tendons had to be removed. The tendon anchor wedge type design does not permit partial detensioning. It can only be removed by burning off the strands fixed at the anchor. Since there is grease along the strands or tendon, they can catch fire easily. Fire watch and fire control were carried out to avoid the tendon or strands catching fire during the tendon removal process. Proper procedure had to be followed. Nevertheless, there were several minor fire events during the detensioning process.

Piping Tie-in

Cold pulling was used to fit up and weld the removed portion of the main steam piping to the RSG. The pulling of the main steam pipe spool caused some modifications of a number of supports. The RCS piping has a short section of piping between the steam generator nozzle and RCS elbow. The piping is of wall thickness about half an inch less than the steam generator nozzle and the RCS elbow. Welding back the existing elbow with the piping extension piece to the steam generator created a great challenge to enable pre-service and future in-service inspections of these welds. The change in surface level caused extreme ultrasonic examination restrictions. Extended work to weld the RCS in place caused more radiation exposure for the steam generator replacement operation.

Blowdown Whip Restraints

Since the blowdown nozzle of the RSG is 3 feet lower than before, the blowdown line had to be rerouted and the supports redesigned. The blowdown whip restraints were found to have field interference during installation. Field walkdowns during outage and redesign work were needed to accomplish the installation of the blowdown whip restraints.

Rigging and Handling

During the transportation of the second RSG, just outside the containment opening, one non-load bearing component of the transporter broke. The event happened at around 1 AM in the morning. Responsible personnel were called in from home and worked with the vendor to get the problem fixed since the operation was in critical path. The component was redesigned and reinstalled to move the RSG inside the containment successfully within a short period of time.

LESSONS LEARNED

In order to avoid fire during the removal of tendons, grease will be minimized and additional compensatory measures will be implemented. Spare sections of replacement piping will be purchased to avoid cold pulling. The existing piping between the SG nozzle and RCS elbow will be replaced with piping of matching thickness. Careful consideration of the field problems will be made for the design of new or modified supports. It is recommended video are taken during walkdown to have a better view of the surrounding areas for the identified problems or systems. The components of the transporter for the RSGs will be modified to withstand larger loads. These are a few of the main lessons leaned. More than a hundred lessons learned were compiled.

CONCLUSION

To extend the service life of a PWR, steam generator replacement is inevitable and the expenditures will be recouped by continued generation efficiently. SGs are and will be replaced in many more PWRs with SG tubes made of Alloy 600 in the world. This paper provides some insight for the latest RSG design by one of the SG manufacturers and associated changes due to SG replacement at SONGS. Due to complexity of the installation, certain problems were encountered during the installation of RSGs for the first replacement Unit in SONGS. SONGS management and engineering had compiled lessons learned in the Unit 2 project which will be implemented in for Unit 3 SG replacement during the fall of 2010.

REFERENCES

[1] Southern California Edison Conformed Specification for Design and Fabrication of the Replacement Steam Generators for Unit 2 and Unit 3.

[2] Southern California Edison Replacement Steam Generators Installation, San Onofre Generation Station Unit 2 and Unit 3.

[3] San Onofre Nuclear Generating Station NSSS Units 2 and 3 Licensing Topical Report.

ACKNWOLEGEMENT

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TABLE 1: COMPARISON OF DESIGN AND OPERATING PARAMETERS

Parameter	OSG	RSG
General		
Thermal rating, MWt	1729	1729
Number of Tubes	9350	9727
Heat Transfer Area, ft2	105,000	116,100
Heat Transfer Rate, Btu/hr	5.819 x 109	5.900 x 109
Tubes Outside Diameter, in.	0.750	0.750
Tube Wall Thickness, in.	0.048	0.0429
Tube Pitch, in.	1.0 triangular	1.0 triangular
Tube Plugging Margin, %	8	8
Primary Side		
Design Pressure, psia	2500	2500
Design Temperature, °F	650	650
Operating Pressure, psia	2250	2250
Operating Temperature (Thot), °F	611.2	598.0
Operating Temperature (Tcold), °F	553.0	541.3
Reactor Coolant Flow (at cold leg temperature), gpm	198,000	209,880
Reactor Coolant Volume, ft3	1895	2003
Secondary Side		
Design Pressure, psia	1100	1100
Design Temperature, °F	560	560
Operating Pressure (@100% power), psia	900	833
Operating Temperature (@100% power), °F	532	523
Steam Flow, lb/hr	7,414,000	7,588,000
Steam Moisture Content, %	<0.20	<0.10
Feedwater Temperature, °F	445	442
Blowdown Flow, lb/hr	151,000	154,860

TABLE 2 – COMPARISON OF PHYSICAL FEATURES

Access Provisions	**OSG**	**RSG**
Primary Manways, Qty - ID, in.	2 - 16	2 - 18
Secondary Manways, Qty - ID, in.	2 - 16	2 - 16
Secondary Handholes, Qty - ID, in.	2 - 6	6 - 8
Secondary Inspection Ports, Qty - ID, in.	----	12 - 2.5
Outline Dimensions	**OSG**	**RSG**
Overall Height (including support skirt), in.	786	785.6
Upper Shell OD, in.	264.125	264.125
Lower Shell OD, in.	172.375	174.65
Weights	**OSG**	**RSG**
Dry, lbm	1,242,366	1,286,200
Flooded, lbm	1,971,840	2,041,300
Operating, lbm	1,505,437	1,548,700

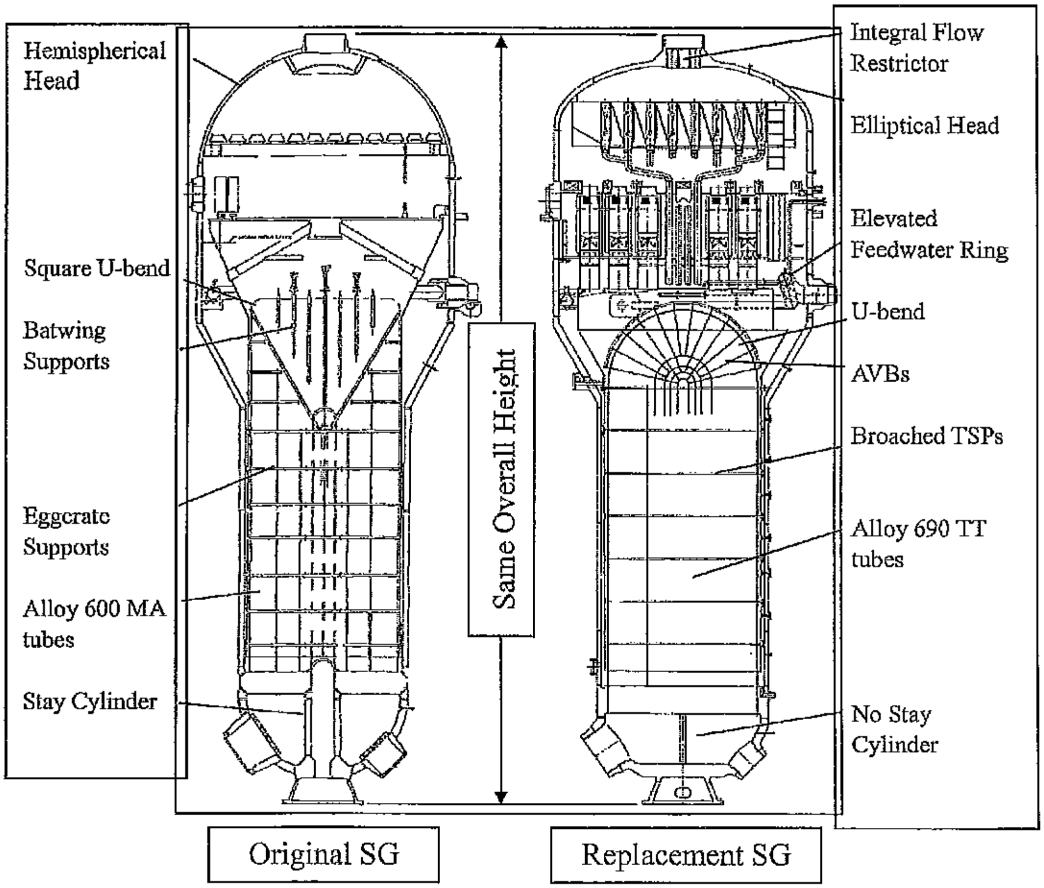


FIGURE 1 – COMPARISON OF ORIGINAL SG AND REPLACEMENT SG DESIGN

Improving like-for-like RSGs

The RSG is lifted onto a purpose-build platform, skidded into the building, and then set into its final position by the containment vessel's internal crane

Although in a recent project Mitsubishi Heavy Industries suppled what were nominally replacements-in-kind of original steam generators at the San Onofre Nuclear Generating Station, the specifications in fact included many new requirements to improve longevity, reliability, performance and maintainability. By Boguslaw Olech and Tomoyuki Inoue

SONGS is a two-reactor Pressurized Water Reactor (PWR) nuclear power plant (NPP) located in California, USA. SONGS consists of two twin units (unit 2 and unit 3) each rated at 3358 MWt (1180 MWe). SONGS is majority owned and operated by Southern California Edison Company (Edison). SONGS unit 2 began commercial operation in 1983 and unit 3 in 1984.

Each of the SONGS units were originally equipped with two CE Model 3340 recirculating steam generators. The OSGs were designed for a 40-year service life.

Over the years of operation of the PWR plants, it became evident that the steam generator tubes, made predominantly of Alloy 600, were susceptible to inter-granular attack (IGA) and primary water stress corrosion cracking (PWSCC). These corrosion mechanisms were resulting in tube degradation necessitating plugging large numbers of tubes. In addition, the SONGS OSG design has shown to be susceptible to tube through-wall wear and severe corrosion of the tube supports. It became evident that the OSGs would have to be replaced much sooner than stipulated by their design service life.

Replacement of the steam generators has typically been performed when the utility concluded that they were reaching their economic end-of-life. This occurs when forecasts of maintenance and repair costs exceed the amortized benefits of the reduced costs achievable with the replacement steam generators. Continuing to operate with highly degraded steam generators can involve substantial economic risks from forced outages, extended refuelling outages, as well as the direct costs of inspections and repair. Several plants have been required by safety analysis to conduct mid-cycle inspection and repair outages. The repair levels (including plugging, sleeving, or using alternative repair criteria) at the replacement plants averaged 25%. Edison has set a 21.4% plugging level as the technical end-of-life of the SONGS steam generators. Forecasting when this would occur resulted in a range of years depending on the level of confidence in the projection. The SONGS worst case forecast indicated that the 21.4% plugging level could be reached as early as 2012.

All the considerations mentioned above prompted Edison to undertake a conservative decision to replace the SONGS steam generators in both units during their respective cycle 16 refueling outages. The contract for design and fabrication of the RSGs was awarded to MHI and the unit 2 RSGs were delivered and replaced in 2009; unit 3 RSGs were delivered and replaced in 2010.

Design bases

The SONGS CE recirculating steam generators employed heat transfer tubing made of Alloy 600 Mill Annealed (MA) and the carbon steel egg-crate type tube supports with batwings in the tube bundle U-bend region. Because of the unit two-loop design, the SONGS steam generators were one of the largest in the industry. The major shortcoming of such large steam generators, as seen during their operating history, was tube wear, particularly in the U-bend region.

At SONGS, the steam generators have the following design functions:

- To function as a part of the reactor coolant system (RCS) pressure boundary (the primary side and the tubes)
- To remove heat from the RCS and transfer it to the main steam system (MSS)
- To remove heat from the RCS to achieve and maintain safe shutdown following design-basis accidents (except for a large break LOCA) and other transients
- To provide high-quality steam to the main turbine

The steam generators also have the following design bases:

- To transfer a total of 3458 MWt with two steam generators from the RCS to the MSS
- To produce 15.176×10^6 lbs/hr (6.88×10^6 kg/hr) of saturated steam at a pressure

ensuring safe and efficient plant operation, and with a very low moisture content
- To ensure that a blowdown rate of at least 2% of the feedwater flow can be achieved and maintained continuously, if necessary or desired.

At SONGS, the major premise of the steam generator replacement project was that it would be implemented under the 10CFR50.59 rule, that is, without prior approval by the US Nuclear Regulatory Commission (USNRC). To achieve this goal, the RSGs were to be designed as 'in-kind' replacement for the OSGs in terms of form, fit and function. The design limitations were identified by performing a preliminary 50.59 Safety Evaluation, a standard tool used in the US nuclear power industry for determination whether or not prior NRC approval is required for a proposed plant change.

Also, the replacement was to be designed such that it involved no, or only minimal, permanent modifications to the plant systems, structures or components (SSCs) other than the steam generators themselves. Also, the replacement was to be designed with no intended changes to the plant set points or plant computer software.

In order to meet all these objectives, the specification for design and fabrication of the SONGS RSGs imposed several requirements and limitations on the RSG design. These requirements and limitations for the key RSG parameters are listed in Table 1 and are compared to the values of these parameters as-designed by MHI. This comparison clearly shows that the MHI design satisfied all specified requirements.

However, imposing the requirements listed in Table 1 did not mean that the RSGs were intended to be merely OSG duplicates. The SONGS RSGs were intended to include all possible improvements introduced by the industry into the steam generator design and fabrication processes based on the US industry operating experience with all PWR plants, inside and outside of the USA.

Therefore, the SONGS specification also incorporated design and fabrication requirements derived from the SONGS operating experience with its OSGs, and the industry experience with the plants with both the OSGs and RSGs installed, including those supplied by MHI. These requirements were aimed at addressing these experiences and overall improving longevity, reliability, performance and maintainability of the steam generators. During RSG fabrication, strict quality controls were in effect at MHI to ensure as best as possible execution of the improved design and fabrication processes. All these requirements were imposed with the following goals in mind:

Table 1: Key design parameters

	Parameter	units	As-required	As-designed
1	Thermal rating (@ 100% reactor power)	MWt	1729	1729
2	Design pressure: primary side	MPa (Psia)	17.24 (2500)	17.24 (2500)
3	Design temperature: primary side	°C (°F)	343 (650)	343 (650)
4	Design pressure: secondary side	MPa (Psia)	7.58 (1100)	7.58 (1100)
5	Design temperature: secondary side	°C (°F)	293 (560)	293 (560)
6	Steam pressure (at RSG outlet nozzle)	MPa (Psia)	≤6.21 (900)	5.74 (833) (1)
7	RCS design flow (0% tubes plugged)	% /lpm (gpm)	≤106.5/958,615 (210,870)	106/954,114 (209,880)[(1)]
8	Tube plugging margin	%	≥8	8
9	Primary coolant volume	m^3 (ft^3)	≤57.2 (2020)	56.7 (2003)
10	Moisture carryover (at 100% design steam flow)	%	< 0.10	<0.10
11	Continuous blowdown (at 100% power)	%	≥2	2
12	Upper shell outside diameter	mm (in)	≤6709 (264 1/8)	6709 (264 1/8)
13	Lower shell outside diameter	mm (in)	≤4531 (178 3/8)	4436 (174.65)
14	Overall vessel height	mm (in)	19,964 (786)	19,954 (785.6)
15	Steam/water weight (at 0% power)	kg (Lbm)	≤127,458 (280,991)	122681 (270,460)
16	Steam/water weight (at 100% power)	kg (Lbm)	≤83,474 (184,026)	77,679 (171,250)
17	Total operating weight (at 100% power)	kg (Lbm)	≤710,181 (1,565,654)	702,490 (1,548,700)
18	Operating centre of gravity (at 100% power)	mm (in)	9681-9703 (381 9/16-382)	9855 (388)

[(1)] Best estimate values

- To minimize wear of the steam generator tubes
- To eliminate susceptibility of the steam generator tubes to inter-granular attack (IGA) and primary water stress corrosion cracking (PWSCC)
- To provide tube-to-tubesheet joints with proper strength, leak resistance and corrosion resistance
- To minimize general corrosion within the steam generators
- To eliminate susceptibility to thermal stratification in the feedwater inlet piping to the feedwater ring
- To eliminate potential for feedwater ring water hammer
- To maintain operating characteristics the same as that of the OSGs in terms of water level stability and controllability
- To optimize the materials of construction for the intended applications.

Design and fabrication

Including all these requirements and improvements in the RSG design without affecting their form, fit and function and their ability to be installed under the 50.59 rule, and satisfying the design requirements without exceeding imposed limitations presented many challenges for the Edison and MHI project teams. Table 2 summarizes the challenges which both teams faced over the design and fabrication cycle of the SONGS RSGs. The table lists the RSG components/assemblies for which meeting the specification requirements was particularly challenging in the areas of design, fabrication and/or quality control, the reason for which it was challenging and the area of the challenge. Below it is described how these challenges were addressed by the Edison and MHI project teams in order to obtain a satisfactory outcome.

Channel head

The RSG had to have the same thermal rating as the OSG, the number of heat transfer tubes had to be maximized, the stay cylinder supporting the tubesheet had to be eliminated and the channel head had to have a flat bottom. On the other hand, limitations were imposed on the maximum allowable reactor coolant flow rate to prevent the potential for fuel pin fretting and on a relative increase of the primary side volume to prevent exceeding containment allowable flooding levels.

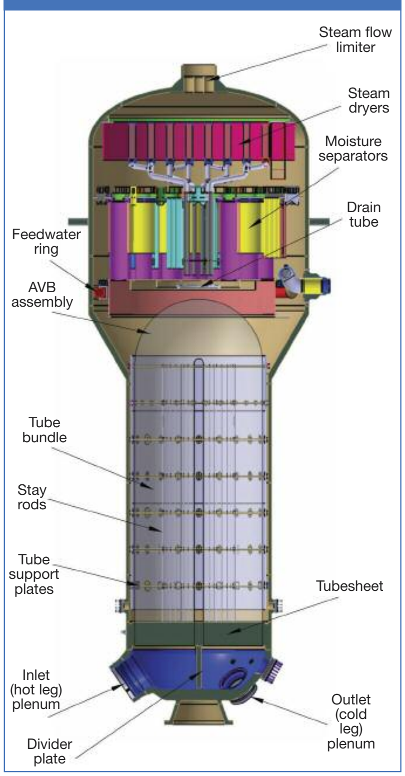
These requirements presented two unique design and fabrication challenges. First, elimination of the stay cylinder allowed for installation of more tubes than there were in the OSG, but having more tubes was leading to higher reactor coolant flow rates. Second, having more tubes and no stay cylinder was leading to primary side volume increase. The first challenge was addressed by performing

Table 2: Summary of Challenges

	RSG Component/ Assembly	Specification Requirements	Challenges	Design	Fabrication	QC
1	Channel head	■ Maintain thermal rating ■ Maximize number of heat transfer tubes ■ Eliminate stay cylinder	■ Maintaining reactor coolant flow rate within specified limits ■ Optimizing primary side volume	X X	X	
2	Tubesheet	■ Withstand primary-to-secondary full dP ■ Limit on tube hole runout ■ Minimize number of hole surface imperfections	■ Optimizing tubesheet thickness ■ Tubesheet drilling	X	X	X
3	Tube bundle	■ Limit on number of tube dings at time of delivery	■ Controlling tube bundle sag during assembly ■ Monitoring temperature distribution during PWHT of the channel head-to-tubesheet weld		X X	X X
4	Tube-to-tubesheet joints	■ Ensuring adequate tube-to tubesheet joint strength, leak resistance and corrosion resistance ■ Limit on allowable tube-to-tubesheet crevice depth	■ Qualifying tube-to-tubesheet joint ■ Controlling tube-to-tubesheet joint crevice depth	X	X X	X X
5	Tube supports	■ Preventing tube wear ■ Preventing tube denting at tube supports	■ Configuring tube-to-tube support interface	X		
6	AVB support structure	■ Preventing tube wear	■ AVB structure assembly	X	X	X
7	Feedwater distribution system	■ Elimination of susceptibility to water hammer and thermal stratification ■ Resistance to erosion/corrosion	■ Configuring inlet piping to feedwater ring	X		
8	Moisture separators	■ Limit on allowable moisture carryover	■ Designing moisture separator assemblies	X		

extensive computer modeling and 1:5.2 scale model testing of the RSG primary side, which resulted in incorporation of a carefully-sized reactor coolant flow limiting orifice in the RSG hot leg. The flow orifice had to limit the flow rate somewhat, but not to the degree to which it might affect the reactor core thermal-hydraulics. The second challenge was addressed by reducing the volume of the channel head by lowering the tubesheet while still maintaining the channel head vertical clearance sufficiently to perform tube inspections and maintenance.

Schematic of RSG internals



Tubesheet

The tubesheet had to be designed such that it could withstand the differential pressure resulting from the primary side being at the design pressure and the secondary side at atmospheric pressure, without excessive deformation. To meet this objective, the tubesheet had to be made thicker than in the OSG, as it was supported only by a flat structural divider plate in lieu of the stay cylinder. Also, the tubesheet had to be clad with Alloy 690 equivalent to provide a surface suitable for welding the heat transfer tubes made from Alloy 690. In addition, the tubesheet had to be fabricated with a very tight tolerance on tube hole runout, and with a minimal number of tube hole surface imperfections (for example, tool marks) to meet the requirements for tube-to-tubesheet joints.

A thicker tubesheet clad with a very hard material, along with these fabrication requirements, presented a unique challenge for tubesheet drilling and quality control. This challenge was addressed starting with the use of the BTA drilling technique, through extensive mockup qualification testing and extensive quality control, and ending with utilizing modified drill bits having much better performance characteristics.

Tube bundle

The RSG tube bundle had to be fabricated such that the number of tube dings was minimized, and remained within the specified limit.

Considering the size and weight of the SONGS RSG tube bundles, this requirement presented two unique fabrication challenges. The first challenge was tube bundle assembly when dings could be generated as a result of the bundle sagging considerably. The second challenge was during post-weld heat treatment (PWHT) of the channel head-to-tubesheet weld when dings could be generated by bowing of the RSG vessel due to its uneven thermal expansion as a result of temperature stratification within the vessel. The first challenge was addressed by customizing the assembly process, analytically determining the maximum allowable sag and monitoring the sag throughout the assembly process. The second challenge was addressed by analytically determining the maximum shell distortion and 1:1 scale model mockup testing to empirically determine the magnitude of shell distortion necessary to result in tube dinging.

Tube-to-tubesheet joints

The tube-to-tubesheet joints had to be designed such that they had adequate strength, leakage resistance and corrosion resistance, and that the tube-to-tubesheet crevice depth was kept within the specified limits. The single biggest challenge here was to devise and implement a competent joint qualification process. To address this challenge, an extensive and in-depth joint qualification program was developed, comprising both analytical and empirical elements, and was meticulously implemented in the MHI R&D centre, and properly documented.

Tube supports

The tube supports had to be designed such that the potential for tube wear due to flow-induced vibration was minimized, and the potential for tube denting at tube supports due to corrosion product deposition was eliminated. To achieve this objective, seven tube support plates made from Type 405 ferritic stainless steel with broached, trefoil tube holes were installed in each RSG. The tube support plates were designed with a flat-land tube-to-tube support plate contact geometry to reduce the tube-to-tube support plate contact and crevice areas, while providing for a maximum steam/water flow in the open areas adjacent to the tube.

AVB support structure

The term 'AVB structure' describes tube supports in the tube bundle U-bend region. The AVB structure had to be designed such that the potential for tube wear due to flow induced vibration was minimized.

To achieve this objective, six sets of V-shaped AVBs made from Type 405 ferritic stainless steel, providing up to 12 support points per tube bend, were installed in the U bend region to provide support in the region where the tubes are most susceptible to degradation due to wear from flow-induced vibration. The single major challenge here was control of the AVB thickness and flatness, and tube-to-AVB gap size. This challenge was addressed by customizing the fabrication and assembly processes and implementing strict quality control in various stages of AVB fabrication and AVB structure assembly.

Feedwater distribution system

The feedwater distribution system consisted of the feedwater distribution ring and the inlet piping to the feedwater ring internal to the RSG. The feedwater distribution system had to be designed such that it was not susceptible to water hammer, the inlet piping had to be configured such that no thermal stratification occurred in this piping, and the inlet piping had to be especially resistant to erosion/corrosion. To address these requirements, the feedwater spray nozzles were mounted on the top of the feedwater ring to prevent it from draining, thus eliminating the potential for water hammer on steam generator water level decrease. The design of the inlet piping included a vented goose-neck extending above the elevation of the feedwater spray nozzles. This feature eliminated thermal stratification in the RSG feedwater nozzle and the inlet piping to the feedwater ring, and prevented the feedwater ring from draining on loss of main feedwater flow, thus also eliminating the potential for water hammer. The feedwater ring was fabricated from Cr-Mo alloy steel with the tee and elbows made from Alloy 690 TT, which provided excellent resistance to erosion/corrosion.

Moisture separators

The moisture separators had to be designed such as to provide the first stage of moisture separation adequate to limit the moisture carry-over in the steam leaving the RSG to no more than 0.1% by weight. For this purpose, MHI had to come up with a brand-new separator size and separator assembly configuration. In order to verify that the new design could meet this requirement, and to optimize the size of the individual separators and their number, MHI utilized the results of an extensive R&D programme conducted to develop the design of moisture separators for its smaller steam generators.

Results

Even though all design and fabrication challenges were addressed during manufacturing, it was not known if the as-designed and fabricated RSGs would eventually perform as specified. To verify this, the RSGs were functionally tested after installation in the plant after unit re-start from the replacement outage. The following essential operating parameters were verified through functional tests.

Heat transfer (steam pressure)

As-designed, the RSGs operating at full (100%) reactor rated power with the reactor coolant temperature at the design point were expected to generate steam whose pressure was to be no less than 816 psia (and no greater than 900 psia) at the steam outlet nozzle. As-tested, one RSG generated steam at approximately 831 psia (5.73 MPa) and the other one at approximately 837 psia.

Water level stability

As-designed, in the RSGs operating at any power level between 0 and 100% reactor rated power, including ramp power level changes of up to +/-15% per hour, the maximum amplitude of the water level fluctuations was expected not to exceed +/-1% of the narrow range span. The test was performed in a form of simulator runs using the plant long-term cooling (LTC) model, as the 15% per hour reactor power changes could not be imposed on the plant during normal startup, shutdown, or power operation. The simulator runs have shown that the amplitude of water level fluctuations was less than 1% under all specified transient conditions.

Moisture carryover

As-designed, the RSGs operating at full (100%) reactor rated power were expected to generate steam with moisture content less than 0.1% by weight. As-tested, one RSG generated steam with moisture content of approximately 0.0037% and the other one with approximately 0.0042%.

Reactor coolant flow rate

As-designed, with the RSGs operating at full (100%) reactor rated power with reactor coolant temperature at a design point, the 'as-measured' reactor coolant flow rate was expected not to exceed 106.5% of the original volumetric design flow rate. As-tested, the reactor coolant flow rate was 104.35% of the original design flow rate.

Primary-to-secondary leakage

As-designed, the RSGs were not supposed to exhibit a detectable primary-to-secondary leakage with the primary side at 2250 psia, and the secondary side at the normal operating pressure and temperature. As-tested, a primary-to-secondary leakage of less than 1 gallon per day (3.87 litres/day) was reported when the plant stabilized at full (100%) reactor rated power.

Blowdown capacity

As-designed, with the RSGs operating at full (100%) reactor rated power with reactor coolant temperature at the design point, the continuous blowdown capacity with the RSG installed was expected to be no less than that with the OSGs installed. As-tested, it was verified that with the RSGs installed the same blowdown flow rate could be attained as with the OSGs installed. ■

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The authors wish to acknowledge all Edison and MHI personnel involved in the SONGS steam generator replacement project for their efforts to make this project a success.
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UNITED STATES
NUCLEAR REGULATORY COMMISSION
REGION IV
1600 EAST LAMAR BLVD
ARLINGTON, TEXAS 76011-4511

March 6, 2013

Edmund Baumgartner, Esquire
Corporate Counsel
Mitsubishi Nuclear Energy Systems, Inc.
1001 19th Street North Suite 2000
Arlington, VA 22209

SUBJECT: MITSUBISHI HEAVY INDUSTRIES – REQUEST FOR WITHHOLDING ROOT CAUSE ANALYSIS AND SUPPLEMENTAL TECHNICAL EVALUATION REPORT INFORMATION FROM PUBLIC DISCLOSURE

Dear Mr. Baumgartner:

In a February 14, 2013, letter to you, the NRC requested Mitsubishi Heavy Industries (MHI) to provide the MHI document “Root Cause Analysis Report for tube wear identified in the Unit 2 and Unit 3 Steam Generators of San Onofre Nuclear Generating Station,” and a redacted version of that document. You provided the requested documents in a letter (ML13057A012) dated February 25, 2013, and requested that certain information contained within the root cause analysis (RCA) and a supplemental technical evaluation report (STER), provided as a supplement to the RCA, be withheld from public disclosure pursuant to 10 CFR 2.390. Redacted versions of the RCA and STER documents were provided as Enclosures 4 and 6 of your letter, respectively (ML13057A013 and ML13057A014).

Mitsubishi Heavy Industries stated in affidavits dated February 22, 2013, that it considered certain information within MHI’s RCA and STER to be proprietary and confidential and requested that the information be withheld from public disclosure pursuant to 10 CFR 2.390. A summary of the key points in the affidavits is as follows:

1. The information has been held in confidence by MHI.

2. The information describes unique design, manufacturing, experimental, and investigative information developed by MHI and not used in the exact form by any of MHI’s competitors.

3. The information was developed at significant cost to MHI.

4. The RCA is MHI’s organizational and programmatic root cause analysis, which is a sensitive, internal document of the type that MHI and others in the industry do not make public, because its purpose is to set forth a critical self-appraisal, with the benefit of hindsight, containing information and analyses that are the result of candid assessments performed by MHI.

5. MHI provided the information to the NRC voluntarily in confidence.

6. The information is not available in public sources and could not be gathered readily from other publicly available information.

7. Disclosure of the information would assist competitors of MHI in their design and manufacture of nuclear plant components without incurring the costs or risks associated with the design and manufacture of the subject component.

We have carefully reviewed your original redacted documents and the information contained in your request. Additionally, we held several discussions with you regarding the redacted information in your documents. Based on these discussions, MHI made some revisions to release additional information. Subsequently, MHI provided final revised versions of Enclosures 4 and 6 via e-mail on February 28 and March 6, 2013, respectively. We have concluded that the submitted information sought to be withheld in the final revised versions contains proprietary and confidential information. Therefore, the final revised versions of the submitted information marked as proprietary will be withheld from public disclosure pursuant to 10 C.F.R. 2.390(a)(4).

Withholding from public inspection shall not affect the right, if any, of persons properly and directly concerned to inspect the documents. If the need arises, we may send copies of this information to our consultants working in this area. We will, of course, ensure that the consultants have signed the appropriate agreements for handling proprietary information.

If the basis for withholding this information from public inspection should change in the future such that the information could then be made available for public inspection, you should promptly notify the NRC. You also should understand that the NRC may have cause to review this determination in the future if, for example, the scope of a Freedom of Information Act request includes your information. In all review situations, if the NRC makes a determination adverse to the above, you will be notified in advance of any public disclosure.

Sincerely,

/RA/

Ryan E. Lantz, Chief
SONGS Project Branch

Dockets: 50-361, 50-362
Licenses: NPF-10, NPF-15

Enclosures:
MHI's Revised Non-Proprietary RCA and STER

Internal Distribution
A. Howell, TM
J. Andersen, DTM
R. Lantz, C:SPB
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J. Weil, OCA
A. Powell, OCA

R:_REACTORS_SONGS\2013\Review of MHI and STER MNES 2-25-13 Letter_Agreement with Revised NonProp Reviews
G:\ORA\SPB\MHI Letter and RCA and STER Enclosures ML13065A097

ADAMS: ☐ No ☒ Yes	☒ SUNSI Review Complete	Reviewer Initials: GEW
	☒ Publicly Available	☒ Non-Sensitive
	☐ Non-publicly Available	☐ Sensitive

RIV:I&AL:SPB	RC	C:SPB	
GEWerner;dlf	KDFuller	RELantz	
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3/6/13	3/6/13	3/6/13	

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

Root Cause Analysis Report for tube wear identified in the Unit 2 and Unit 3 Steam Generators of San Onofre Nuclear Generating Station

Purchase Order No.	4500024051
Specification No.	SO23-617-01R3

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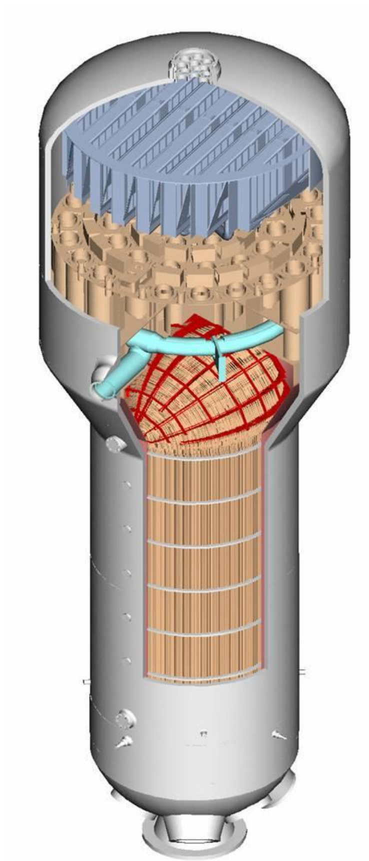
MITSUBISHI HEAVY INDUSTRIES, LTD.

Revision History

Rev.	Summary of Changes	Date issued	Approved By	Checked by	Prepared by
0	Original Issue	See Cover Page	See Cover Page	See Cover Page	See Cover Page

Root Cause Analysis Report for tube wear identified in the Unit 2 and Unit 3 Steam Generators of San Onofre Nuclear Generating Station



Disclosure Statement

The following organization and programmatic Root Cause Analysis has been prepared in accordance with the Mitsubishi Heavy Industries (MHI) corrective action program, which uses an after-the-fact hindsight-based analysis. The information identified in this evaluation was discovered and analyzed using all information and results available at the time it was written. These results and much of the information considered in this evaluation were not available to the organizations, management, or individuals during the period that relevant actions were taken and decisions were made.

This evaluation does not attempt to make a determination whether any of the actions or decisions taken by management, internal organizations, or individual personnel at the time of the event was reasonable or prudent based on the information that was known or available at the time they took such actions or made such decisions. Any individual statements or conclusions included in the evaluation as to whether incorrect actions may have been taken or improvements are warranted are based upon all of the information considered, including information and results learned after-the-fact and evaluation in hindsight after the results of actions or decisions are known, and do not reflect any conclusion or determination as to the prudence or reasonableness of actions or decisions at the time they were made.

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1.0 Executive Summary

On January 31, 2012, after the replacement steam generators (RSGs) supplied by MHI had been operating for approximately 11 months, SONGS Unit 3 was brought into an unplanned shutdown due to primary to secondary leakage of approximately 82 gallons/day in one RSG. The direct cause of the leakage was determined to be tube to tube wear in the free span section of the U-bend region of the RSG, leading to a leak from one of the tubes in that region.

SONGS Unit 2 was in a refueling outage when the event occurred in Unit 3. During the normally scheduled outage inspections of the Unit 2 RSGs, tube wear was discovered in the vicinity of the retainer bars in the U-bend region of both RSGs. This wear was determined to have been caused by random vibration of the retainer bars.

It was determined that all four RSGs experienced higher than expected tube wear. This wear is comprised of: (i) tube to tube wear in the tube free-span sections between the Anti-Vibration-Bars (AVBs) located in the U-bend region observed almost exclusively in Unit 3; (ii) tube to AVB wear, observed at discrete tube to AVB intersections, with no wear indications in the tube free-span sections (the tube to AVB wear indications are short in length, and are associated with small tube motions); (iii) tube to Tube Support Plate (TSP) wear; and (iv) retainer bar to tube wear. One RSG experienced minor tube wear from a foreign object, which has since been removed.

MHI, working in conjunction with SCE personnel and other industry experts, determined the mechanistic causes of the tube wear. MHI formed a team composed of personnel from MHI and its U.S. subsidiary, plus outside consultants, to perform the Root Cause Analysis (RCA) of the tube wear identified in the SONGS Unit 2 and Unit 3 RSGs. The two wear mechanisms that produced the deepest wear are evaluated in this report. They include:

1. Tube to tube wear in the in-plane direction due to fluid-elastic instability (FEI)
2. Retainer bar to tube wear due to turbulence induced vibration (also referred to as random vibration) and the low natural frequency of the retainer bar

Additionally, because many tubes exhibit it, this report also addresses a third wear mechanism:

3. Tube-to-AVB wear caused by turbulence induced vibration (also referred to as random vibration).

The RCA team used Cause-effect analysis, Barrier analysis and Change analysis to arrive at two Root Causes and three Contributing Causes. The Root Causes are:

1. Insufficient programmatic requirement to assure effective AVB contact force to prevent in-plane fluid elastic instability and random vibration and subsequent wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).
2. The design control process did not provide sufficient direction to assure that an evaluation of the need for an analysis of flow induced vibration of the retainer bar was performed and verified.

The corrective actions to preclude repetition include:

1. Revise Procedure 5BBB60-N01 *"Procedure for Controlling of the Design Activities"* to require that the need for effective tube to AVB contact force under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure) be addressed in all MHI SG designs.

   1.a Further revise Procedure 5BBB60-N01 *"Procedure for Controlling of the Design Activities"* to require that sufficient contact force is assured under high localized thermal-hydraulic conditions (steam quality (void fraction) flow velocity and hydro-dynamic pressure), e.g., compare to the design parameters of previous successful MHI steam generator designs.

2. Revise procedure 5BBB60-N01 *"Procedure for Controlling of the Design Activities"* to require that retainer bars and other steam generator parts subject to flow induced vibration be evaluated to determine the different analyses and the level of analysis that need to be performed to support the steam generator design.

2.0 Background of the Incident

2.1 Project Background

In September 2004, MHI was awarded a contract to replace Southern California Edison's (SCE) original steam generators (OSGs) at Units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS). The MHI-supplied replacement SGs (RSGs) had a number of differences from the OSGs provided by Combustion Engineering. One of the main differences was the substitution of Inconel 690 for Inconel 600 as the tube material. Inconel 690 is more resistant to corrosion than Inconel 600. However, Inconel

690 has a thermal conductivity approximately 10% less than that of Inconel 600. The requirement that the SG's thermal performance be maintained, in conjunction with maintaining a specified tube plugging margin, necessitated increasing the tube bundle heat transfer surface area from 105,000 ft^2 to 116,100 ft^2 (an 11% increase).The Certified Design Specification SO23-617-01, Rev. 3 stated that SCE intended to use the provisions of 10 C.F.R. §50.59 as the justification for the RSG design, which imposed physical and other constraints on the characteristics of the RSG design in order to assure compliance with that regulation. The RSGs were also required to fit within the same space occupied by the OSGs.

The Certified Design Specification issued by SCE also required that MHI incorporate many design changes to minimize degradation and maximize reliability. The following are the design requirements specified for the U-bend supports:

> *"3.10.3.5 … The Supplier shall develop and submit for Edison's approval an Engineering and Fabrication Gap Control Methodology describing control of an effective "zero" tube-to-flat bar gap, gap uniformity and parallelism of the tube bundle in the out-of-plane direction prior to tube fabrication. The gap statistical size (mean value +3sigma) shall not exceed 0.003", and shall be validated by empirical data."*

The Unit 2 RSGs were delivered to SONGS in February 2009 and installed during a refueling outage between September 2009 and April 2010. The Unit 3 RSGs were delivered to SONGS in October 2010 and installed during a refueling outage between October 2010 and February 2011.

On January 31, 2012, after the Unit 3 RSGs had been operating for approximately 11 months, the unit was brought into an unplanned shutdown due to maximum primary to secondary leakage of approximately 82 gallons/day in one RSG. The direct cause of the leakage was determined to be tube to tube wear in the free span section of the U-bend region of the RSG, leading to a leak from one of the tubes in that region.

Inspections of the Unit 2 RSGs(which was offline undergoing a refueling outage) revealed significant tube wear in the vicinity of the retainer bars in the U-bend region.

In addition to these two forms of tube wear, all four RSGs were found to have experienced higher than expected tube to Anti-Vibration-Bar (AVB) and tube to Tube Support Plate (TSP) wear. One RSG had experienced minor tube wear due to a foreign object.

2.2 Technical Specification requirements potentially involved in the Problem

Technical Specification (TS) 3.4.17 requires that SG tube integrity be maintained and that all SG tubes meeting the tube repair criteria be plugged in accordance with the Steam Generator Program.

TS 5.5.2.11 requires a Steam Generator Program to be established and implemented to ensure that SG tube integrity is maintained.

TS 5.5.2.11.b specifies three performance criteria that must be met for SG tube integrity:

1. “Structural integrity performance criterion: All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, and cool down and all anticipated transients included in the design specification) and Design Basis Accidents (DBAs). This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials. Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst or rupture. In the assessment of tube integrity, those loads that do significantly affect burst or rupture shall be determined and assessed in combination with the loads due to pressure with a safety factor of 1.2 on the combined primary loads and 1.0 on axial secondary loads.”

2. “Accident induced leakage performance criterion: The primary to secondary accident induced leakage rate for any DBA, other than a SG tube rupture, shall not exceed the leakage rate assumed in the accident analysis in terms of total leakage rate for all SGs and leakage rate for an individual SG. Leakage is not to exceed 0.5 gpm per SG and 1 gpm through both SGs.”

3. “The operational leakage performance criterion is specified in LCO 3.4.13, “RCS Operational Leakage.” [This LCO is applicable in Modes 1-4 and states RCS operational leakage shall be limited to: (a) no pressure boundary leakage; (b) 1 gpm unidentified leakage; (c) 10 gpm identified leakage; and (d) 150 gallons per day (gpd) primary to secondary leakage through any one SG.”]

3.0 Statement of Problem

This Root Cause Analysis (RCA) was performed based on the following problem statement, which was adopted as part of the Root Cause Analysis Team Charter:

(1) Requirement
No Primary-to-Secondary Leakage due to Defects in any of the RSG Units for the duration of the Warranty Period. (per 17.2.3 of General T&C with EMS)

(2) Deviation
Unit 3 SG-B (SCE SG088) experienced tube leakage during operation and failure of eight tubes during in-situ pressure testing. (Both due to Defects)

(3) Consequences (For MHI)
- 10CFR21 Report required

4.0 Extent of Condition Evaluation

To determine the extent of condition, other MHI SGs with similar design and construction were analyzed to see if the same tube wear conditions identified at the SONGS RSGs were present.

The replacement steam generators for OPPD's Fort Calhoun Nuclear Generating Station are the only other steam generators designed by MHI operating in the United States. The OPPD RSGs replaced Combustion Engineering OSGs and are of a similar design and construction as the SONGS RSGs with certain differences, including:

- Identical tube diameter (3/4") and wall thickness (0.043")
- Identical tube pitch (1.0" equilateral triangle)
- Identical pitch-to-diameter ratio (P/D = 1.33)
- OPPD has greater average tube to AVB gap
- OPPD RSGs are smaller than SONGS RSGs
- Fewer AVBs than SONGS
- Fewer tubes than SONGS
- Smaller U-bend radius than SONGS
- Lower maximum steam quality (void fraction) than SONGS

The Fort Calhoun RSGs have operated more than three fuel cycles with no evidence of U-bend tube degradation (no tube-to-AVB wear, no tube-to-tube wear, and no retainer bar-to-tube wear).Other steam generators designed by MHI (operating outside of the United States)are of a different design and have a variety of tube sizes, tube pitches and operating conditions. These steam generators have years of operation without significant tube wear. Therefore, it is concluded that the MHI SGs in operation today are not part of extent of condition. However, these other MHI SGs will be evaluated for susceptibility based on extent of cause.

5.0 Analysis, Results, and Conclusions

5.1 Evaluation Team Formation

On March 23, 2012 MHI formed a team composed of personnel from MHI and its U.S. subsidiary, plus outside consultants, to perform the Root Cause Analysis of the tube wear identified in the SONGS Unit 2 and Unit 3 RSGs. The team was given the task of investigating the organizational and programmatic Root Causes of the tube wear. SCE also performed separate technical and Root Cause evaluations.

The Root Cause Analysis commenced on March 26, 2012, and was conducted concurrently with the development of MHI's technical evaluation reports.

5.2 Evaluation Methodology

The evaluation team used the results of the technical investigations (identified below) as the basis for its analysis of the organizational and programmatic Root Causes for the tube to tube wear, retainer bar to tube wear, and tube to AVB wear seen in the RSGs. The extent of cause was evaluated based on organizational and programmatic causes.

The team closely consulted with the MHI engineering team performing the technical evaluations, and with SCE representatives, in order to understand fully the technical causes of the tube wear. Additionally, the evaluation team gathered evidence through interviews, examination of procedures and plans and previous audits and surveillances, review of design and technical review meeting documents, and analysis of technical work products.

To determine the organizational and programmatic Root and Contributing Causes of the three wear mechanisms evaluated in this report, the evaluation team used three cause analysis tools: Cause-effect analysis, Barrier analysis, and Change analysis. The Root and Contributing Causes were determined primarily through the Cause-effect analysis. The results of the Barrier analysis and the Change analysis support the findings of the Cause-effect analysis. In addition to supporting the Cause-effect analysis, the Change analysis identified an additional Contributing Cause.

In performing these analyses, the evaluation team closely looked at and took into account the technical evaluations prepared by MHI and SCE to understand fully the mechanistic causes of the tube to tube wear, the retainer bar to tube wear, and the tube to AVB wear, in order to better assess the underlying organizational and programmatic Root and Contributing Causes. The team then reviewed and evaluated, with the benefit of what is now known in hindsight, the design process for the RSGs to identify what could have been done differently that would have prevented the tube wear from occurring. Based on its reviews, the evaluation team identified the programmatic Root Causes of the RSG tube wear.

5.3 Technical Investigation of the Incident

MHI performed technical evaluations to identify the mechanistic causes of the tube wear, which identified fluid elastic instability as the mechanistic cause of the tube to tube wear, turbulence induced vibration (often referred to as “random vibration” because the excitation modes over time are unpredictable) as the mechanistic cause of the tube to AVB wear, and turbulence induced vibration of the retainer bar as the mechanistic cause of the retainer bar to tube wear. These evaluations are reflected in the MHI reports *Tube Wear of Unit-3 RSG Technical Evaluation Report*, L5-04GA564 Rev.9; *Retainer Bar Tube Wear Report,* L5-04GA561 Rev.4; *Validity of Use of the FIT-III Results During Design*, L5-04GA591 Rev. 3;and Supplemental Technical Evaluation Report, L5-04GA588 draft. SCE also performed Root Cause evaluations.SCE reports *Root Cause Evaluation NN201843216 Steam Generator Tube Wear San Onofre Nuclear Generating Station, Unit 2dated April 2, 2012,* and *Root Cause Evaluation: Unit 3 Generator Tube Leak and Tube-to-Tube Wear Condition Report: 201836127, Rev.0*contain the SCE Root Cause evaluations.

The MHI and SCE mechanistic cause analysis reports used Fault Tree Analysis and Kepnor-Tregeo (respectively) as the primary analysis tools. Each of these analyses considered a broad range of potential causes. The following causes were evaluated in detail:

Manufacturing/fabrication	Shipping
Primary side flow induced vibration	Divider plate weld failure and repair
Additional rotations following divider plate repair	TSP distortion
Tube bundle distortion during operation (flowering)	T/H conditions/modeling

Each of these causes is evaluated in the MHI and SCE technical evaluation reports.

These technical evaluations identified five different wear categories for the tubewear observed in the SONGS RSGs. Two of these wear categories are responsible for the most significant instances of tube degradation(in terms of the depth of wear and potential for failing to meet the technical specification requirements) and are being evaluated in this report to determine their organizational and programmatic causes. The two significant wear categories that are evaluated in this RCA are:

1. Tube to Tube Wear due to in-plane FEI: Tube to tube wear was found in the U-bend region, located between AVBs, in the free span. Many of the tubes exhibiting tube to tube wear also exhibited wear at the AVBs and TSPs, in particular at the top tube support plate. For tubes with wear at the top tube support plate, it is considered that the entire tube, including its straight region, is vibrating. 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]
2. Retainer Bar to Tube Wear due to Flow Induced Vibration: Tube wear occurred on tubes at the periphery of the U-bend, adjacent to the retainer bars. These tubes have no wear indications at any other location along their length, which

[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.

indicates that they are stationary, and that the wear is caused by the movement (vibration) of the retainer bars.

Additionally, because many tubes have smaller-depth wear indications at the AVB intersections, this report also addresses another wear category:

3. Tube to AVB Wear (for tubes without free span wear) due to random vibration: Tube wear occurred at discrete tube-to-AVB intersections, with no wear indications in the tube free-span sections. These wear indications are short in length and are associated with small tube motions.

The other two categories of wear identified were: (i) wear at the TSPs (small bend radius tubes and tubes at the tube bundle periphery), and (ii) wear due to a foreign object. These two categories are not considered in this report because the degree of wear due to them is relatively small.

The conclusions of the MHI and SCE technical evaluations have been accepted as the basis of this analysis. To the extent these evaluations are revised or amended to reflect additional information or new understandings, this evaluation may be affected.

5.4 Description of Main Wear Mechanisms

Fluid Elastic Instability

In a tube array, a momentary displacement of one tube from its equilibrium position will alter the flow field and change the forces to which the neighboring tubes are subjected, causing them to change their positions in a vibratory manner. When the energy extracted from the flow by the tubes exceeds the energy dissipated by damping it produces fluid elastic vibration.

Fluid Elastic Instability (FEI) is a term used to describe a range of tube vibrations that starts at a point on a curve of vibration amplitude versus flow velocity. As depicted in Figure 1, one axis (Y) of that curve is vibration amplitude and the other (X) is flow velocity. The graph shows that as flow velocity increases vibration amplitude increases at a small linear rate until it reaches a point where the slope of the curve increases abruptly. The point in the curve where the slope changes is termed “critical velocity”. The critical velocity is a function of several variables. These include tube natural frequency, which is dependent on the tube geometry and support conditions, damping, which is a function of the steam-to-water ratio, flow velocity, which is dependent of the tube spacing.

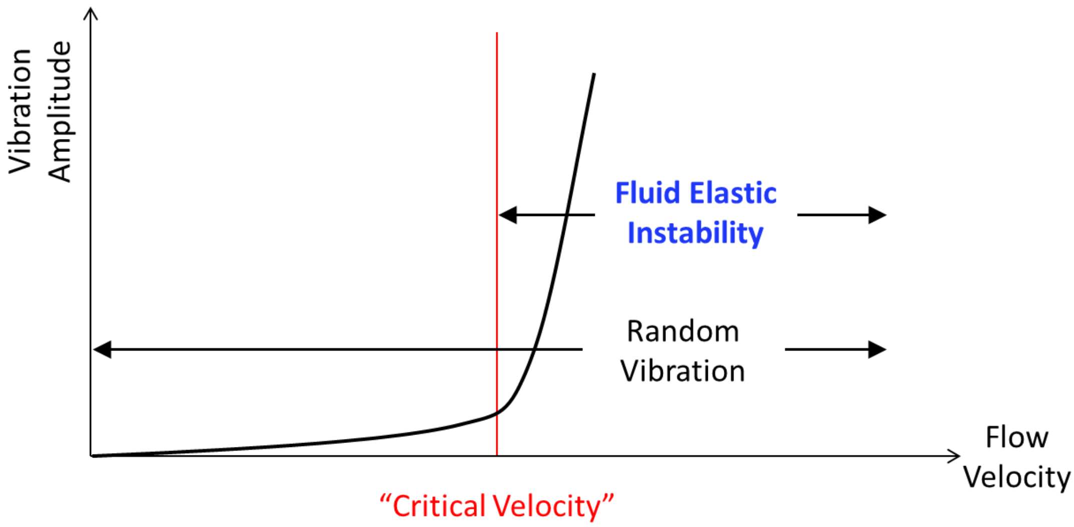

Figure 1

As discussed below and in the technical reports referenced above (See Supplemental Technical Evaluation Report), MHI has determined that, due to ineffective support for the tubes in the in-plane direction resulting from the very small and uniform tube-to AVB gaps, some of the tubes exceeded the fluid elastic critical velocity resulting in in-plane FEI, which in turn produced the large amplitude tube-to-tube wear. This mechanism is influenced by the local thermal hydraulic conditions around the tube. Regions of high void fraction have lower tube damping, which reduces the fluid elastic critical velocity threshold. High void fraction regions also have higher cross flow velocities. Therefore, tubes with low or no contact force in the region of highest void fraction are most susceptible to this mechanism.

Random Vibration

Random vibration is the vibration mechanism caused by flow turbulence that changes proportionately to changes in the fluid flow forces(dynamic pressure) and is present at all flow velocities. Turbulent flow forces are random in nature, so this form of vibration is referred to as random vibration. As discussed below and in the technical reports referenced above, MHI has determined that the tube wear at the AVB intersections with no wear indications in the tube free span sections is due to turbulence induced vibration caused by insufficient contact force between the tube and the AVBs due to very small, uniform tube-to-AVB gaps. Since dynamic pressure and damping is proportional to the void fraction, tubes in the region of highest void fraction are most susceptible to this mechanism.

Tube to Tube Wear

Tube-to-tube wear was caused by large displacements of tubes in the in-plane direction. Tubes are known to have moved in-plane because of the locations and magnitudes of their wear scars. The wear scars indicate that the tubes were generally vibrating in their first fundamental in-plane mode, which implies that none of the twelve (12) AVB supports were restraining the tube motion. Yet, it also indicates that the tube-to-AVB gaps are very small and uniform, because none of the tubes exhibited out-of-plane FEI, which is the tube's preferential fluid elastic vibration mode.[2] It can therefore be concluded that the tube-to-AVB contact forces were negligible and the tube-to-AVB gaps (on both sides of each tube at each of the 12 AVB intersections) were very small. Both of these conclusions are consistent with the original design intent discussed below.

In-plane FEI is a phenomenon that had not been experienced in nuclear U-tube steam generators prior to its being identified in the SONGS RSGs. The practice in the nuclear industry at the time the SONGS RSGs were designed was to provide measures to preclude out-of-plane FEI in the U-bend region, which was based on the understanding set forth above. Reflecting this industry practice, the Japan Society of Mechanical Engineers' "Guideline for Fluid-elastic Vibration Evaluation of U-bend Tubes in Steam Generators" states that in-plane FEI does not need to be considered if out-of-plane FEI is controlled. The design of the SONGS RSGs is consistent with the contemporary industry practice and guidance. The RSGs were designed to provide effective tube support (by means of AVBs) to avoid out-of-plane FEI. MHI sought to maximize the

[2]In U-bend SGs, because the tubes are curved, for the same support conditions the critical velocity for out-of-plane FEI will be lower than that for in-plane FEI because the natural frequency of tubes in the in-plane direction is higher, due to the tubes greater stiffness in-plane, than the natural frequency of the tubes in the out-of-plane direction.

adequacy of the supports against out-of-plane FEI by increasing the number of AVBs to a number, 12, that exceeds that in other U-tube SGs designed by MHI or by other major U-tube SG manufacturers.

Minimizing tube vibration wear in the U-bend region was given high priority in the SONGS RSG Design Specification, the RSG design program, and in the manufacturing processes. Early in the project, SCE and MHI formed an AVB Design Team with the goal of minimizing U-bend tube vibration and wear. The AVB Design Team conducted numerous technical and design review meetings. The agreed-upon tube bundle U-bend support design and fabrication were as follows:

- Six (6) V-shaped AVBs (three sets of two) were to be provided between each tube column (12 AVB intersections total around the U-bend).
- Tube and AVB dimensional control, including increasing the AVB thickness was to achieve an effective “zero” tube-to-AVB gap under operating (hot) conditions with gap uniformity and parallelism being maintained throughout the tube bundle. Effective “zero” gap was desirable as an industry practice in order to maximize the effectiveness of the supports. The tube and AVB tolerances were to be tighter than that of any prior MHI SG.
- Excessive preload contact force was to be avoided in order to minimize ding/dent indications, and to maintain mechanical damping and thus minimize tube vibration.

MHI investigated field experience with U-bend tube degradation using INPO, NRC and NPE data bases, and concluded that the SONGS RSGs were designed to minimize the potential for tube wear by providing extra support points with shorter spans in the U-bend region along with effective zero tube-to-AVB gaps.

In the fabrication process, MHI manufacturing focused on achieving very small, uniform tube-to-AVB gaps during assembly.

The AVB Design Team included consultants with knowledge and experience in the design and construction large U-bend SGs. One consultant had experience with the design of a plant whose SGs were similar to the proposed RSGs (the “comparison” or “reference” plant). Together, the AVB Design Team concluded that the SONGS RSGs had more tube vibration margin than the comparison plant, which had experienced only a small number of tube wear occurrences. This conclusion was due to the following considerations:(i) SONGS RSG tubes are larger, have thicker walls, and are stiffer than those of the comparison plant; (ii) the SONGS distances between AVB tube supports are shorter than those at the comparison plant; (iii) SONGS has 12 AVB tube supports where the comparison plant only has 10; (iv) SONGS's tube-to-AVB gap requirement was more stringent than that of the comparison plant.

The Certified Design Specification SO23-617-01, Rev. 3, issued by SCE required an effective zero gap and gap uniformity and parallelism of the tube bundle in the out-of-plane direction. Establishing the goal to reduce tube-AVB gaps to an effective zero gap was in accordance with well accepted industry practice and understanding that minimizing gaps was highly desirable in preventing tube vibration wear. MHI had sought to minimize tube-AVB gaps in its previous SG designs. However, MHI took additional steps to minimize the tube-AVB gaps for the SONGs RSGs and to provide for gap uniformity throughout the U-bend region of the tube bundle.

These steps included increasing the nominal thickness of the AVB compared to previous MHI SGs and reducing the manufacturing tolerance of AVB thickness and twist in order to achieve effective zero gaps and provide gap uniformity. Steps were taken as well to minimize tube ovality and to minimize variations from the design value. Also, numerous additional steps were taken in fabricating the tube bundle to assure gap uniformity throughout the U-bend region. Additionally, in the fabrication of the Unit 2 RSGs MHI identified other enhancements that were implemented in the fabrication of the Unit 3 RSGs. These included, for example, taking steps to minimize AVB twist by applying a larger(from[ ]tons to[ ]tons) pressing force in the Unit 3 fabrication and thus providing for more uniform AVBs in the Unit 3 RSGs.

The adequacy of the design against out-of-plane FEI was confirmed through test data and analyses that conservatively assumed that one of the AVBs provided in the design was inactive (that is, ineffective against out-of-plane FEI).Analyses using this criterion showed that an adequate margin against out-of-plane FEI exists in the SONGS RSGs. An additional AVB had been added to the design to provide further margin against out-of-plane FEI.

The MHI technical evaluations performed after the January 2012 incident determined that, despite the robustness of the MHI design, in-plane FEI had occurred. This occurrence was due to a combination of a lack of effective contact forces between the tube and AVB in the in-plane direction and localized thermal-hydraulic (T/H) conditions (high steam quality (void fraction) and high fluid velocity).The evaluations found that the average contact force in the Unit 3 RSGs was smaller than the average contact force in the Unit 2 RSGs. Therefore, the contact forces of the Unit 3 RSGs were more likely to be ineffective in preventing in-plane motion of tubes so that the Unit 3 RSGs were more susceptible to in-plane tube vibration than those in Unit 2. The difference in the contact forces between the Unit 2 and Unit3 RSGs is caused by the reduction in dimensional variations during the manufacture of the Unit 3 RSGs, mainly due to improvement of the control over tube and AVB dimensions in the manufacture of the Unit 3 RSGs. The reduced contact forces resulted in far more tubes in the Unit 3 RSGs experiencing tube-to-tube wear than those in the Unit 2 RSGs. For those tubes, given these support conditions, the vibratory energy in high localized thermal-hydraulic (T/H) environment produced in-plane FEI that led to large amplitude displacement of the tubes in the in-plane direction, which caused wear from contact between adjacent tubes.

Tube Wear at AVBs

Tube-to-AVB wear is a function of the amplitude of the random tube vibration and the tube-to-AVB gap. Where there is a gap between the AVB and the tube and the vibration amplitude is less than the gap, there will be minimal or no wear. If the AVB is in contact with the tube but there is insufficient contact force to lock the two together, there will be relative motion between the two and wear will occur. In the case where there is sufficient contact force to lock the two together, there will be minimal or no relative motion and only minimal wear will occur. In the SONGS RSGs, the zero gap design philosophy resulted in the AVBs being in contact with the tubes or very close to the tubes, but there was insufficient contact force to lock the two together, thus allowing tube wear at the AVBs.

The degree of wear is also affected by the amount of damping provided by the water film between the tubes and AVBs. In the SONGS RSGs, damping was reduced in areas of high steam quality (void fraction)because there is less two-phase damping and little or no water film in the gaps between the tubes, resulting in more pronounced wear.

Tube Wear at Retainer Bars

The tubes exhibiting retainer bar wear have no indications of tube-to-tube or tube-to-AVB wear, which indicates that the wear is caused solely by retainer bar vibration. The SONGS RSGs have two types of retainer bars: [ ] diameter and [ ] diameter. Tube wear was only found on tubes adjacent to the smaller diameter retainer bars. The retainer bars with the smaller diameter have a relatively long span as compared with those for other SGs fabricated by MHI, which means that the natural frequency of these retainer bars is lower, making them more likely to vibrate. This type of wear is caused by random flow-induced vibration of the retainer bars caused by the secondary fluid exiting the tube bundle.

5.5 Discussion of Tube to Tube Wear

Tube Contact Force

During the fabrication of the AVBs and the tubing and assembly of the tube bundle, MHI's manufacturing practices achieved dimensional control that resulted in smaller tube-to-AVB gaps and smaller tube-to-AVB contact forces. It was not recognized at the time that a certain amount of tube-to-AVB contact force was required to prevent in-plane FEI under high steam quality (void fraction) conditions, because the contact force serves to increase the in-plane natural frequency of the tube.

The technical investigations after the tube leak incident determined that the amount of contact force necessary to prevent in-plane FEI depends on the localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).As the steam quality (void fraction) increases, the amount of contact force necessary to prevent vibration increases. This increase in required contact force occurs because as the steam quality (void fraction) becomes higher, the damping provided by the liquid phase in the form of a liquid film decreases.

The reduced in-plane contact force due to the SONGS "effective zero gap" design and the avoidance of "excessive preload" resulted in lowering the tubes' natural frequency in the in-plane direction. The combination of the localized high steam quality (void fraction) and reduced tube to AVB contact force resulted in exceeding the in-plane critical velocity, which created a condition that led to tube to tube contact.

The dominant role played by the low contact force is reflected by the differences in the tube-to-tube wear that was observed in the Unit 2 and the Unit 3 RSGs. Each of the Unit 3 RSGs had approximately 160 tubes that experienced tube-to-tube wear whereas only one of the Unit 2 RSGs experienced tube-to-tube wear in just two tubes, even though the Unit 2 RSGs have operated twice as long as the Unit 3 RSGs. MHI did a comprehensive statistical evaluation of the contact forces between the tubes and the AVBs of the two units and concluded, based on the manufacturing data , that the contact force between the tubes and the AVBs in the Unit 2 RSGs is approximately double the contact force in the Unit 3 RSGs. Thus, the lower contact forces in Unit 3 are consistent with the conditions determined necessary to permit in-plane FEI to occur and with the fact that tube-to-tube wear occurred almost exclusively in Unit 3.

Thermal-hydraulic Conditions

Many analyses are performed during the steam generator design process. One of these is MHI's FIT-III tube bundle flow analysis, which calculates tube bundle thermal / hydraulic parameters, including U-bend flow velocity and steam quality (void fraction).An after-the-fact comparison between the T/H parameters that FIT-III predicted and those predicted by ATHOS, another T/H code, determined that FIT-III's calculated values are lower than those obtained using ATHOS. Part of the difference was because the pressure loss coefficients for the tube bundle and the two-phase mixture density utilized in the two codes were different.

Also, during the computation of the flow velocity, MHI used an inappropriate definition of the gap between tubes, with the result that the flow velocities were underestimated.

These differences between MHI's use of the FIT-III model and the ATHOS model resulted in a higher margin to out-of-plane FEI than the margin that would have been determined using the appropriate the definition of the gap and an ATHOS-calculated steam quality (void fraction). The margin calculated using ATHOS, nonetheless, would still have resulted in adequate margin against out-of-plane FEI. Using the ATHOS outputs, with all AVBs assumed active, the stability ratio was less than 1.0 for out-of-plane FEI, even for those case studies assuming reduced damping that could occur under high void fraction conditions.[3] Thus, the use of ATHOS as opposed to FIT-III would not have identified an inadequate design margin against FEI.

Moreover, because industry practice was focused on out-of-plane FEI, use of ATHOS would not have identified the potential for in-plane vibration. Both the academic literature and subsequently conducted tests show that the thermal-hydraulic environment under which in-plane FEI arises is different from those that result in out-of-plane FEI. (See Supplemental Technical Evaluation Report). If the steam quality (void fraction) predicted by FIT-III had been the same as the ATHOS calculated value,

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[3]The maximum stability ratio based on ATHOS outputs for all supports are active is[ ], which is less than 0.75, which is the conservative industry practice for judging acceptability of stability ratios (which in turn is less than the ASME Section III Appendix N-1330 recommended stability ratio criterion of 1.0). Assuming reduced damping, the maximum stability ratio calculated using ATHOS is[ ].

and if the appropriate tube to tube gap value had been utilized to compute the flow velocity, MHI would have identified a decreased margin against out-of-plane FEI. In that case, MHI might have incorporated an additional AVB to increase the design margin against out-of-plane FEI, but would not have taken measures to protect against in-plane FEI, for it was assumed (as was the practice and guidance in the industry) that the controlling effect of a well-designed AVB system was adequate to preclude it.

Thus, not using ATHOS, which predicts higher void fractions than FIT-III at the time of design represented, at most, a missed opportunity to take further design steps, not directed at in-plane FEI, that might have resulted in a different design that might have avoided in-plane FEI. However, the AVB Design Team recognized that the design for the SONGS RSGs resulted in higher steam quality (void fraction) than previous designs and had considered making changes to the design to reduce the void fraction (e.g., using a larger downcomer, using larger flow slot design for the tube support plates, and even removing a TSP). But each of the considered changes had unacceptable consequences and the AVB Design Team agreed not to implement them. Among the difficulties associated with the potential changes was the possibility that making them could impede the ability to justify the RSG design under the provisions of 10 C.F.R. §50.59. Thus, one cannot say that use of a different code than FIT-III would have prevented the occurrence of the in-plane FEI observed in the SONGs RSGs or that any feasible design changes arising from the use of a different code would have reduced the void fraction sufficiently to avoid tube-to-tube wear.

For the same reason, an analysis of the cumulative effects of the design changes including the departures from the OSG's design and MHI's previously successful designs would not have resulted in a design change that directly addressed in-plane FEI.

Summary

Thus, the organizational and programmatic Root Cause for the in-plane FEI as set forth in this RCA is the insufficient programmatic requirement to assure effective AVB contact force to control in-plane FEI under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydrodynamic pressure). The underlying reason for this insufficiency is that the MHI SONGS RSG design did not consider the phenomenon of in-plane FEI because contemporary knowledge and industry U-tubeSG operation experience did not indicate a need to consider in-plane FEI.

5.6 Discussion of Tube to AVB Wear

Tube-to-AVB wear in the SONGS RSG occurs at the tube-to-AVB intersections and is produced by turbulence induced (random) vibration. This population only includes tubes with wear at the tube-to-AVB intersections with no wear indications in the tube free-span sections.

Tube wear at the AVB intersections (in the absence of tube-to-tube free span wear) occurs when the tube movement causes it to impact or slide along the supporting AVBs. The most common cause of this condition is out-of-plane FEI. In the SONGS RSG design, the large number of AVB supports and the superior gap control prevent out-of-plane FEI. However, because of the low contact forces between tubes and AVBs, the very small and uniform tube-to-AVB gaps, and the localized T/H conditions (high steam quality (void fraction) and high flow velocity), turbulent flow conditions are sufficient to produce tube wear at the AVB intersections. Again the effect of the different contact forces between Unit 3 and Unit 2 can be seen in the observed tube-to-AVB wear populations of the two units. Unit 2 had about two-thirds as many tube-to-AVB indications than Unit-3 and Unit 2 operated longer than Unit 3, indicated that the wear rate is greater at Unit 3. This is attributable to the lower contact forces. (See Supplemental Technical Evaluation Report).

As was the case with tube-to-tube wear, it was not recognized at the time of the RSG design that a certain amount tube to AVB contact force is required to prevent random vibration under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).The combination of the reduced tube to AVB contact force and the localized T/H conditions (high steam quality (void fraction) and high flow velocity) resulted in tube to AVB wear.

5.7 Discussion of Retainer Bar to Tube Wear

The design function of the retainer bar is to support the AVB assembly during manufacturing and prevent excessive AVB assembly movement during operational transients. The retainer bar must be strong enough to support the AVB assembly and fit within the physical constraints of the U-bend.

The tubesheet drilling pattern is one of the first design decisions made for a new steam generator and it is at that time that each tube location along the periphery of the tube bundle is established. The tube bundle design thus determines the retainer bar's length and thickness. At SONGS, in order to accommodate the increased number of tubes, the retainer bars are relatively long and thin as compared to the retainer bars in other SGs designed by MHI, resulting in their having low natural frequencies.

The engineer responsible for the retainer bar design did not recognize the need to analyze the retainer bar for flow induced vibration because no such analysis had been performed on previous MHI SG designs. The design control procedure for this design activity did not identify this issue, nor was it recognized during the design review process.

During operation, the secondary flow velocity and steam quality (void fraction) created turbulent flow conditions capable of causing high amplitude vibration if the retainer bar natural frequency was low enough, which turned out to be the case. The high amplitude vibration resulted in the retainer bar contacting some tubes and causing tube wear.

5.8 Root Causes

As used in this evaluation, "*Root Causes*" are defined as the basic reasons (e.g., hardware, process, or human performance) for a problem, which if corrected, will prevent recurrence of that problem.

The programmatic Root Causes of the RSG tube wear are:

1. Insufficient programmatic requirement to assure effective AVB contact force to prevent in-plane fluid elastic instability and random vibration and subsequent wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).
   Basis: The evaluation team concluded that the fundamental Root Cause for the in-plane FEI and the resulting tube-to-tube wear was the fact that in-plane FEI was not considered in the design of the SONGS RSGs. The fundamental reason for this lack of consideration was that industry practice and guidance, supported by the operating experience up to that time of U-bend type steam generators, indicated that the control out-of-plane FEI would prevent the occurrence of in-plane FEI.

   Likewise, the evaluation team concluded that the tube to AVB wear was caused by insufficient contact force under high localized thermal-hydraulic conditions, which was not recognized at the time of the design of the SONGS RSGs, and that the fundamental reasons for the ineffectiveness of the contact force were the established industry practice of minimizing the tube support gaps and avoiding an excessive preload as well as other steps to control gap uniformity and parallelism.

2. The design control process did not provide sufficient direction to assure that an evaluation of the need for an analysis of flow induced vibration of the retainer bar was performed and verified.
   Basis: The evaluation team concluded that the fundamental reason for the retainer bar FIV was the lack of clear direction in the MHI design procedures to require an evaluation to determine the different analyses and the level of analysis that were required for the RSG design in light of changes in the SONGS RSG design from previous MHI steam generator designs.

5.9 Contributing Causes

As used in this evaluation, "*Contributing Causes*" are defined as causes that by themselves would not create the problem but are important enough to be recognized as needing corrective action. Contributing causes are sometimes referred to as causal factors. Causal factors are those actions, conditions, or events that directly or indirectly influence the outcome of a situation or problem. The evaluation team closely evaluated the mechanistic causes and the design process for the potential existence of Contributing Causes.

The programmatic Contributing Causes of the RSG tube wear are:

6.0 Corrective Action Matrix

Cause	Corrective Action	Due Date
Root Cause 1:Insufficient programmatic requirement to assure effective AVB contact force to prevent in-plane fluid elastic instability and random vibration and subsequent wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).	***CAPR 1:***Revise Procedure 5BBB60-N01 "Procedure for Controlling of the Design Activities" to require that the need for effective tube to AVB contact force under high localized thermal-hydraulic conditions(steam quality (void fraction), flow velocity and hydro-dynamic pressure) be addressed in all MHI SG designs.	Completed
	CAPR 1.a:Further revise Procedure 5BBB60-N01 "Procedure for Controlling of the Design Activities" to require that sufficient contact force is assured under high localized thermal-hydraulic conditions (steam quality (void fraction) flow velocity and hydro-dynamic pressure), e.g., compare to the design parameters of previous successful MHI steam generator designs.	11/15/2012
	CA 1:Provide training for all Steam Generator Engineers (included new hires and continuing training) covering this event and the details concerning in-plane FEI and tube-AVB wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).	Completed

Cause	Corrective Action	Due Date
Root Cause 2:The design control process did not provide sufficient direction to assure that an evaluation of the need for an analysis of flow induced vibration of the retainer bar was performed and verified.	***CAPR 2:***Revise procedure 5BBB60-N01 *"Procedure for Controlling of the Design Activities"* to require that retainer bars and other steam generator parts subject to flow induced vibration be evaluated to determine the different analyses and the level of analysis that need to be performed to support the steam generator design.	10/31/2012
	CA 2:Revise Engineer Training program (included new hires and continuing training) to include the necessary assessment for required analyses of each Steam Generator part subject to flow induced vibration.	10/31/2012

Cause	Corrective Action	Due Date

Cause	Corrective Action	Due Date
Extent of Cause	***CA 6:*** Conduct a program design review for other SG design procedures and primary pressure boundary components (Reactor vessel, Core internals, Pressurizer, Reactor coolant piping, CRDMs) using senior engineers to determine if other design features have assumptions that are not programmatically captured and evaluated.	3/31/2013
	CA 7: Reconfirm MHI steam generator designs using the procedure developed for Root Cause 2.	11/30/2012 for SONGS SG design 3/31/2013 for OTHER SG designs
	CA 8: Reconfirm that the appropriate analyses were performed and that correct values were used as inputs for each thermal hydraulic analysis, vibration analysis, and wear analysis (FIT-III, FIVATS, IVHET) in the design and fabrication processes of MHI steam generators.	Completed for SONGS SG design 10/31/2012 for OTHER SG designs
	CA 9: Reconfirm that the computer validation was performed adequately for each thermal hydraulic analysis, vibration analysis, and wear analysis (FIT-III, FIVATS, IVHET). *If necessary, additional comparison to other validation methods shall be performed.	Completed

Cause	Corrective Action	Due Date
Effectiveness Review	In accordance with MHI's QA program, "Corrective action reports" will be issued for all CAPRs and CAs and the confirmation of effectiveness of completed corrective actions will be performed by the Nuclear Plant Quality Assurance Section. Effectiveness reviews will be completed in six (6) months by verifying corrective actions for the addressed problems. In addition, review the results of the initial Unit 2 & 3 mid-cycle outage and SG inspections to determine the effectiveness of corrective actions. There is no evidence of : ・Additional tube to tube wear (in-plane FEI) ・Additional tube to retainer bar wear (turbulence induced vibration (random vibration)) ・Additional tube to AVB wear (turbulence induced vibration (random vibration)).	-

7.0 Extent of Cause Evaluation

The Root Causes were evaluated for the extent to which they would be applicable and present elsewhere in the MHI steam generator design process.
The two Root Causes are:

1. Insufficient programmatic requirement to assure effective AVB contact force to prevent in-plane fluid elastic instability and random vibration and subsequent wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).
2. The design control process did not provide sufficient direction to assure that an evaluation of the need for an analysis of flow induced vibration of the retainer bar was performed and verified.

Root Cause 1 is associated with the design program and procedures not capturing necessary design elements affecting the primary pressure boundary. MHI has different nuclear engineering sections responsible for different aspects of the primary pressure boundary design, and each section has its own controlling design programs and procedures. Therefore, the extent of cause applies to the SG design program and areas of design outside the SG design program that could impact the primary pressure boundary. Sections outside the SG program with design responsibility related to the primary pressure boundary include:

a. Reactor Vessel
b. Core internals
c. Pressurizer
d. Reactor coolant piping
e. Control Rod Drive Mechanisms

To address this extent of cause evaluation, each MHI engineering section will conduct a program and procedures review, based on what was learned from this event, to determine if there are other SG program elements or other primary components that rely on design assumptions that are not captured in the design program or procedures.

For Root Cause 2, an analysis that should have been performed was not. Therefore, this extent of cause applies to other SG design analyses that should have been performed but were not. Because there is no controlling document that identifies what analyses should be performed for each component, CAPR 2 must be developed and then a complete review of the different MHI SG project needs to be performed to confirm that all required analyses have been completed.

8.0 Safety Culture Review

A safety culture review was performed using the NRC's Inspection Manual Section IMC0310 *COMPONENTS WITHIN THE CROSS-CUTTING AREAS* and applying the guidance in that section to the Root and Contributing Causes identified in this report. The review examined all four safety culture areas, the thirteen cross-cutting and other area components, and the thirty-seven aspects comprised in those components. A summary table 1 that compares the identified Root and Contributing Causes with the requirements of each of the safety culture areas, components and aspects is provided below.

As the table 1 shows, both Root Causes and all Contributing Causes are associated with aspect 6 (H.2(c)) of the "resources" component in the Human Performance Area. One Root Cause and all Contributing Causes are associated with aspect 2 (H.1(b)), of the "decision-making" component in the Human Performance Area. One Root Cause and all Contributing Causes are associated with aspect 4 (H.2(a)), of the "resources" component in the Human Performance area. Finally, one Root Cause and two of the Contributing Causes are associated with aspect 12 (H.4(c)) of the "work practices" component in the Human Performance Area.

The component from the Human Performance Area applicable to the second Root Cause and the three Contributing Causes is aspect 6 (H.2(c)) of the "resources" component, which calls for complete, accurate and up-to-date design documentation, procedures, and work packages, and correct labeling of components. This aspect of the resources component was not satisfied because, while the decision making and the designs were properly documented, they were inaccurate in that they did not require analyses to evaluate the potential FIV of the retainer bars (Root Cause 2);

This component from the Human Performance Area is also associated with Root Cause 1, in that the design procedures did not contain any requirement to assure effective AVB contact force. However, there is no safety culture related deficiency with respect to Root Cause 1 in that MHI was following accepted industry practices to design AVB and in fact sought to make its design more conservative than previous AVB designs.

An aspect of a component from the Human Performance Area applicable to one of the Root Causes and the three Contributing Causes is aspect 2 (H.1(b)) of the "decision-making" component, which requires that conservative assumptions be used in the design. The design did not require analyses to evaluate the potential FIV of the retainer bars (Root Cause 2);

The discrepancies between the design and aspect 2 (H.1(b)) of the "decision-making" component also apply to aspect 4 (H.2(a)) of "resources" component.

Finally, an aspect of a component from the Human Performance Area applicable to one Root Cause and two of the Contributing Causes is aspect 12 (H.4(c)) of component 4 ("work practices"), which requires that appropriate supervision and management oversight be applied to the design. While design activities were reviewed and confirmed by the design section the design supervision and review process failed to recognize that FIV analysis of the retainer bars was needed (Root Cause 2);

MHI has identified a number of corrective actions, which are being taken or will be completed in the near future, to address the safety culture discrepancies identified in this review. These corrective actions are described in Section 6.0 above. . The predominant safety culture aspect was determined to be H.2.(c) Work Documents because the decision making and work practices were not influenced by programmatic requirements. The H.2.(c) safety culture aspect has the associated corrective action to establish the programmatic requirements for both Root Causes and the Contributing Causes.

Table 1 Safety Culture Review – Cross Cutting Components and Aspect

X: Not sufficient

Safety Culture Area, Component, Aspect	Root Cause 1	Root Cause 2	Contributing Cause 1	Contributing Cause 2	Contributing Cause 3
	Insufficient programmatic requirement to assure effective AVB contact force to prevent in-plane fluid elastic instability and random vibration and subsequent wear under high localized thermal-hydraulic conditions (steam quality (void fraction), flow velocity and hydro-dynamic pressure).	**The design control process did not provide sufficient direction to assure that an evaluation of the need for an analysis of flow induced vibration of the retainer bar was performed and verified.**			
Area 1. Human Performance (H)					
Component 1. Decision-Making					
Aspect 1. Risk significant decisions H.1(a)	Sufficient - MHI's AVB and tube bundle designs were reviewed and confirmed followed a decision-making process to evaluate and review the technical aspects of the design.				
Aspect 2. Conservative assumptions H.1(b)	Sufficient - The AVB design decision was based on a FIT-III analysis which had a built in safety margin and assumed one inactive support as an additional measure of conservatism additionally MHI's design had more AVBs than previous designs.	**X** Not sufficient - The engineer responsible for the retainer bar design did not recognize the need to analyze the retainer bar for potential flow induced vibration			
Aspect 3. Timely communication H.1(c)	Sufficient - The decisions of the AVB and SG team were documented and distributed to the team members in a timely manner.				
Component 2. Resources					
Aspect 4. Managing maintenance H.2(a)	Sufficient - The FIT-III analysis had a built in safety margin and assumed that one inactive support as an additional measure of conservatism.	**X** Not sufficient - The engineer did not recognize the need to analyze the retainer bars for potential FIV.			

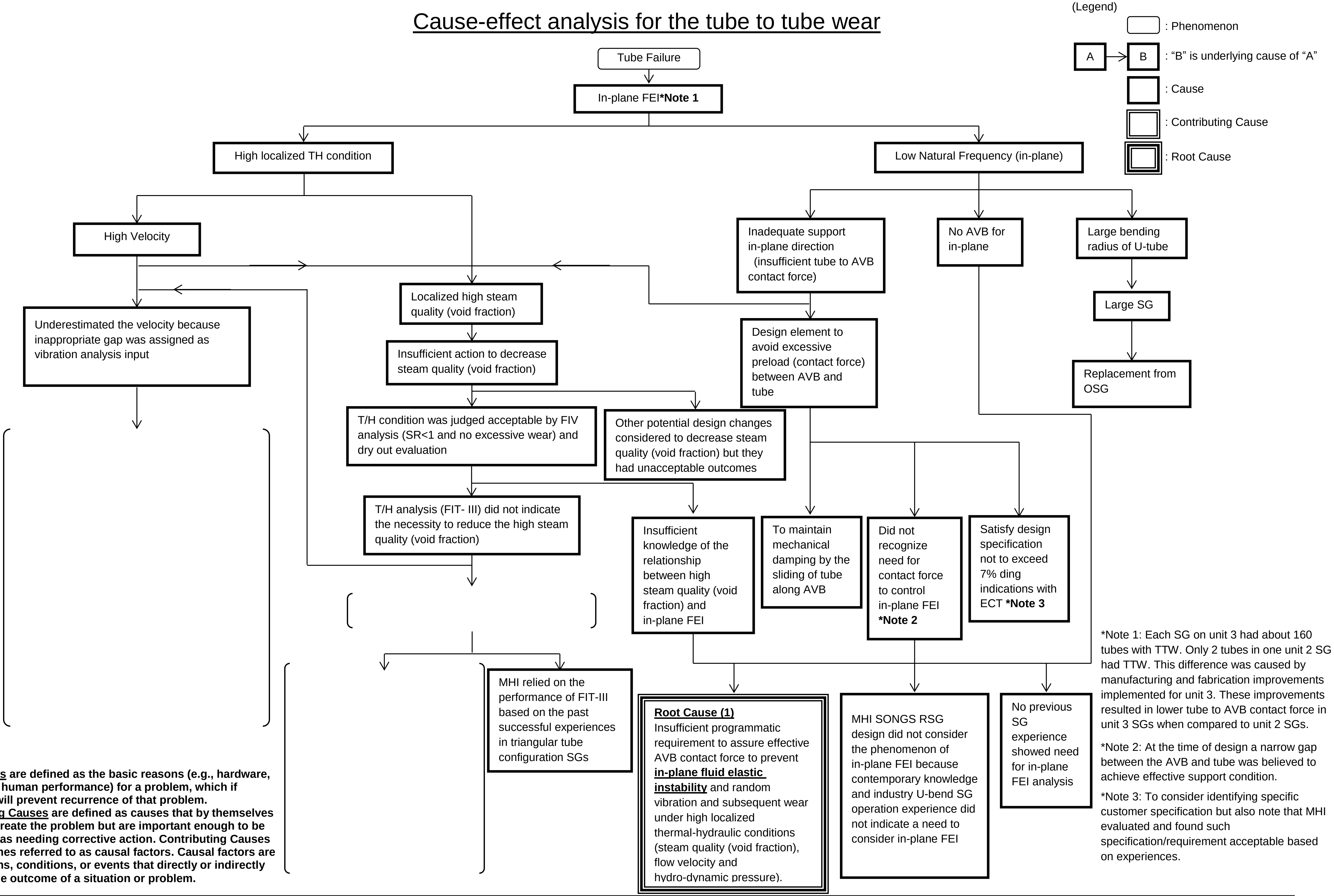
Safety Culture Area, Component, Aspect	Root Cause 1	Root Cause 2	Contributing Cause 1	Contributing Cause 2	Contributing Cause 3
Aspect 5. Training and qualification personnel H.2(b)	X Not sufficient - While the design section included experts in SG design and manufacture, however procedure for training program was not sufficient because the training materials and procedures were inadequate.				
Aspect 6. Work documents H.2(c)	Not deficient The decision making and design were documented, but the design procedures did not include a requirement to prevent in-plane FEI and random vibration related wear under high localized thermal-hydraulic conditions. There was no programmatic requirement to prevent in-plane FEI and random vibration, but MHI sought to make the AVB design more conservative than previous designs so no safety culture deficiency is found. A corrective action is nevertheless provided to address this new understanding based on the tube wear observed at SONGS.	X Not sufficient - The decision making and design were documented, but the design procedures did not include a requirement to evaluate the retainer bars for potential FIV. The predominant safety culture aspect was determined to be H.2.(c) Work Documents because there was no programmatic requirement to influence the engineer. The H.2.(c) safety culture aspect has the associated corrective action to establish the programmatic requirement to evaluate for the need for an FIV analysis			
Aspect 7. Facilities and Equipment H.2(d)	Sufficient - The SG design section was provided with adequate facilities and other resources to conduct design review meetings and decision-making.				
Component 3. Work Control					
Aspect 8. Work planning H.3(a) Aspect 9. Work coordinationH.3(b)	Not applicable - Aspects 8 and 9 are not applicable because they address work in the plant and coordination of removal of safety systems during plant maintenance.				
Component 4. Work Practices					
Aspect 10. Error prevention techniques H.4(a)	Sufficient - Design activities were established in compliance with QA programs to prevent error and personnel followed appropriate procedures.				
Aspect 11. Procedure compliance H.4(b)	Sufficient - MHI's corrective action program governed the design process. Additionally the design section decisions were made pursuant to decision making procedures.				

Safety Culture Area, Component, Aspect	Root Cause 1		Root Cause 2	Contributing Cause 1	Contributing Cause 2	Contributing Cause 3
Aspect 12. Supervision and management oversight H.4(c)	Sufficient -MHI's SG design activities were reviewed and confirmed by the design section at design review and technical review meetings.	X	Not sufficient - The need for a FIV analysis of retainer bar was not detected in the design review process.			
Area 2. Problem Identification and Resolution (P)						
Component 5. Corrective Action Program						
Aspect 13. Risk-based identification threshold P.1(a)	Sufficient - MHI's corrective action program governed the design process.					
Aspect 14. Trending program P.1(b)	Sufficient - MHI's corrective action program includes trend based assessments.					
Aspect 15. Cause evaluations P.1(c)	Sufficient - MHI's corrective action program includes Root Cause and apparent cause assessments.					
Aspect 16. Corrective actions P.1(d)	Sufficient - No unresolved corrective actions were at issue.					
Aspect 17. Alternative processes P.1(e)	Sufficient - MHI has alternative programs in addition to its regular reporting program.					
Component 6. Operating Experience						
Aspect 18. Systematic process P.2(a)	Sufficient - MHI investigated operating experience with U-bend tube degradation using INPO, NRC and NPE data bases, and communicated internally in a timely manner.					
Aspect 19. Process changes P.2(b)	Sufficient - MHI conducted benchmarking and concluded that the SONGS RSG was designed to minimize the potential for tube wear by providing more support points with shorter spans in the U-bend region along with effective zero tube-to-AVB gaps during SG operation.					
Component 7. Self- and Independent Assessments						
Aspect 20. Nature of assessments P.3(a)	Sufficient - MHI periodically and appropriately conducted self-assessments.					

Safety Culture Area, Component, Aspect	Root Cause 1	Root Cause 2	Contributing Cause 1	Contributing Cause 2	Contributing Cause 3
Aspect 21. Tracking and trending P.3(b)	Sufficient - MHI periodically and appropriately conducted self-assessment.				
Aspect 22. Coordination and communication P.3(c)	Sufficient - MHI coordinated and communicated result from self-assessment to affect personnel and took appropriate corrective actions.				
Area 3. Safety Conscious Work Environment (S)					
Component 8. Environment for Raising Concerns					
Aspect 23. Free and open information exchange S.1(a)	Sufficient - The SG design team and AVB design team encouraged discussions of safety issues and openly exchanged information on design alternatives				
Aspect 24. Alternate processes S.1(b)	Sufficient - MHI has alternative programs for raising safety concerns in confidence.				
Component 9. Preventing, Detecting, and Mitigating Perceptions of Retaliation					
Aspect 25. Training S.2(a)	Sufficient - There were no claims of harassment by SG team members.				
Aspect 26. Investigation S.2(b)	Sufficient - There were no claims of retaliation by SG team members.				
Aspect 27. Chilling effect S.2(c)	Sufficient - MHI appropriately considers chilling effect. No disciplinary actions were taken.				
Area 4. Other Safety Culture Components (O)					
Component 10 .Accountability					
Aspect 28. Alignment of safety and rewards O.1(a)	Sufficient - Accountability for SG design decisions was clearly understood within MHI.				
Aspect 29. Reinforcement O.1(b)	Sufficient - Management reinforced safety standards.				
Aspect 30. Safety focus O.1(c)	Sufficient - MHI demonstrated safety focus, review of meeting minutes indicates focus of SG design team was to come up with design with appropriate margin which demonstrated focus on safety.				

Safety Culture Area, Component, Aspect	Root Cause 1	Root Cause 2	Contributing Cause 1	Contributing Cause 2	Contributing Cause 3
Component 11. Continuous learning environment					
Aspect 31. Training and knowledge O.2(a)	Sufficient - SG design team was trained on SG design continuously.				
Aspect 32. Internal and external learning O.2(b)	Sufficient - SG design team was trained on SG design continuously and transfer of knowledge was provided by internal experts, however the issue of effective AVB to contact force was not known within the industry so training could not be effective.				
Component12. Organizational change management					
Aspect 33. Organizational change management O.3	Sufficient - MHI management used systematic process and evaluated of impacts of decisions when organization was changed.				
Component13. Safety policies					
Aspect 34. Raising concernsO.4(a)	Sufficient - MHI has appropriate policies which required reinforce to raise safety concern.				
Aspect 35. Safety policy training O.4(b)	Sufficient - MHI has appropriate policy training to raise individual safety concern.				
Aspect 36. Decisions consistent with safetypriorityO.4(c)	Sufficient - Decisions related to SG design were consistent with MHI policies.				
Aspect 37. Top management commitment O.4(d)	Sufficient - Top management communicated need for safe SG design as issue of effective AVB to contact force was not known within the industry so management communication could not be effective.				

Cause-effect analysis for the tube to tube wear



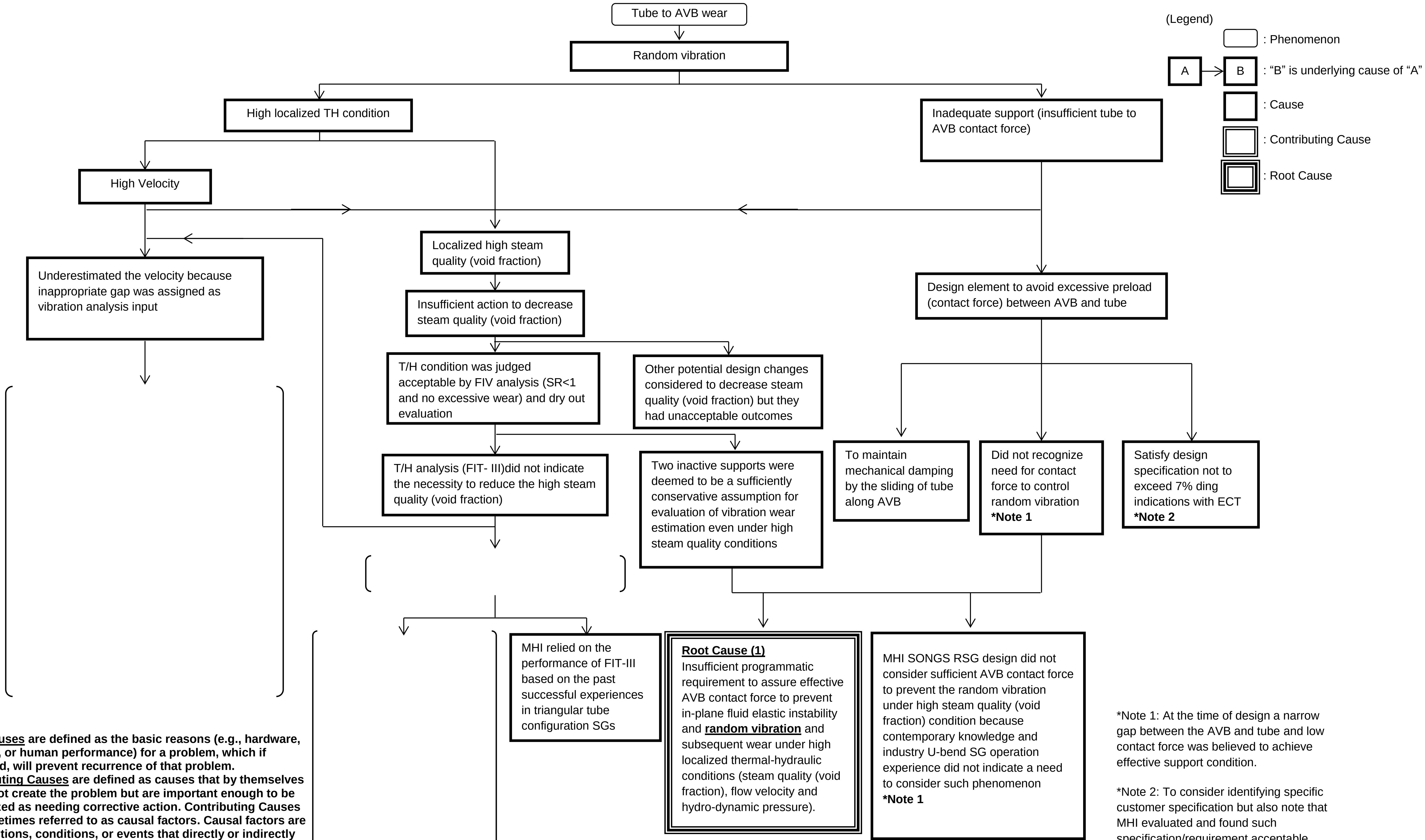
*Note 1: Each SG on unit 3 had about 160 tubes with TTW. Only 2 tubes in one unit 2 SG had TTW. This difference was caused by manufacturing and fabrication improvements implemented for unit 3. These improvements resulted in lower tube to AVB contact force in unit 3 SGs when compared to unit 2 SGs.

*Note 2: At the time of design a narrow gap between the AVB and tube was believed to achieve effective support condition.

*Note 3: To consider identifying specific customer specification but also note that MHI evaluated and found such specification/requirement acceptable based on experiences.

<u>Root Causes</u> are defined as the basic reasons (e.g., hardware, process, or human performance) for a problem, which if corrected, will prevent recurrence of that problem.
<u>Contributing Causes</u> are defined as causes that by themselves would not create the problem but are important enough to be recognized as needing corrective action. Contributing Causes are sometimes referred to as causal factors. Causal factors are those actions, conditions, or events that directly or indirectly influence the outcome of a situation or problem.

Cause-effect analysis for the tube to AVB wear

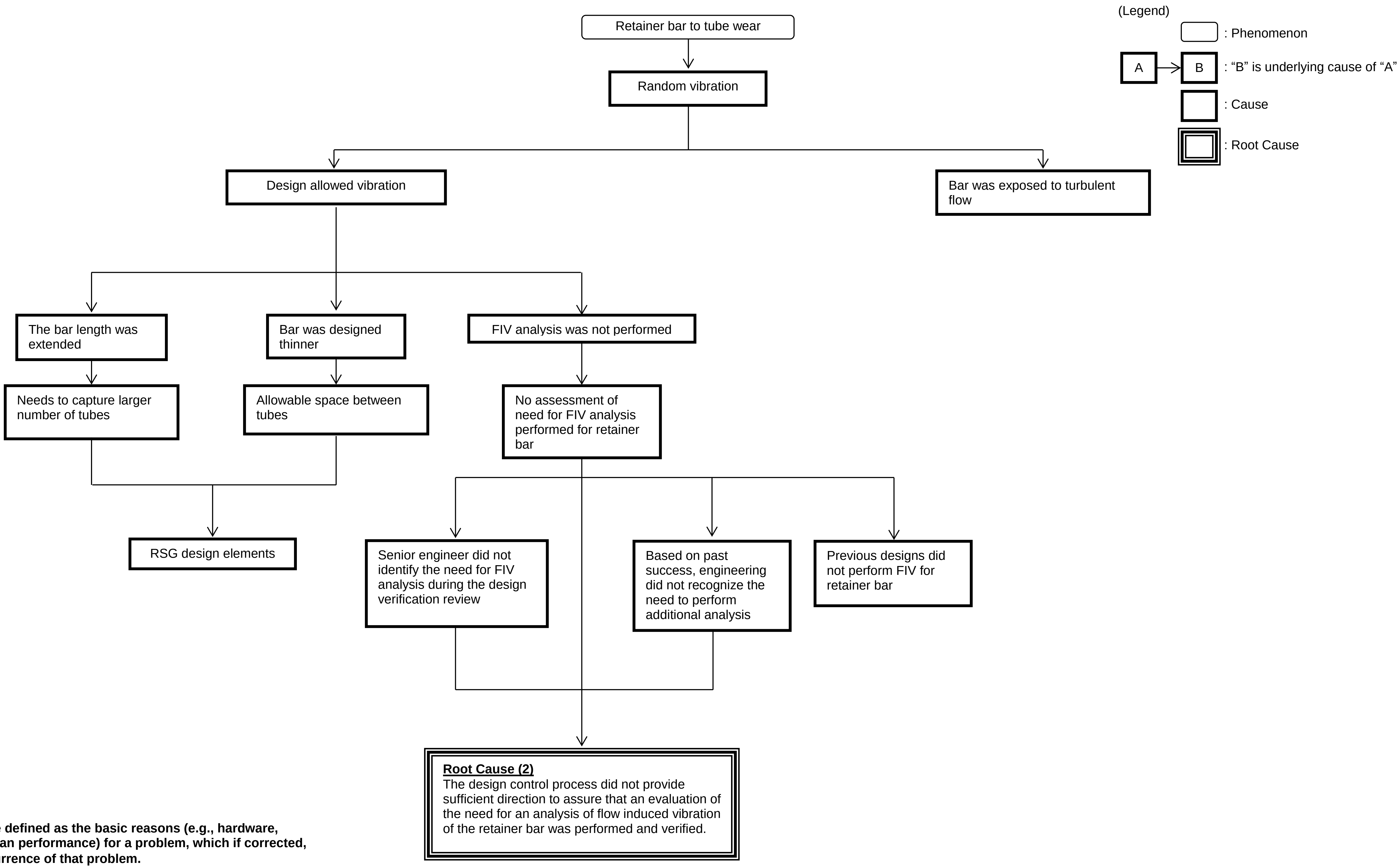


<u>Root Causes</u> are defined as the basic reasons (e.g., hardware, process, or human performance) for a problem, which if corrected, will prevent recurrence of that problem. <u>Contributing Causes</u> are defined as causes that by themselves would not create the problem but are important enough to be recognized as needing corrective action. Contributing Causes are sometimes referred to as causal factors. Causal factors are those actions, conditions, or events that directly or indirectly influence the outcome of a situation or problem.

*Note 1: At the time of design a narrow gap between the AVB and tube and low contact force was believed to achieve effective support condition.

*Note 2: To consider identifying specific customer specification but also note that MHI evaluated and found such specification/requirement acceptable based on experiences.

Cause-effect analysis for the retainer bar to tube wear



Root Causes are defined as the basic reasons (e.g., hardware, process, or human performance) for a problem, which if corrected, will prevent recurrence of that problem.

Barrier analysis

A barrier analysis for the SONGS RSGs was performed with respect to the items listed below.

- Design
- Fabrication
- Post Installation testing/monitoring
- Post Operational Inspection

The barrier analysis was developed to assess the barriers at each of the major stages of the steam generator replacement program. The two primary barriers assessed at each stage included training/ qualification of personnel and procedures. As shown in the Barrier analysis table, procedures and training / qualification were lacking for the three wear mechanisms evaluated (tube to tube, retainer bar to tube, and tube to AVB). There were no issues identified with the fabrication process so there were no failed barriers. The results of the barrier analysis support the cause-effect analysis.

Consequence	Barrier			Outcome	Evaluation
Tube to Tube wear	Design	Training / Qualification	In-plane FEI	Not Effective	The design section procedure did not contain guidance on in-plane FEI. As a result, training programs did not cover the phenomenon of in-plane FEI. This will be addressed with CA 1 in the Corrective action matrix.
			TH model FIV analysis	Not Effective	
		Procedures	In-plane FEI	Not Effective	Analyses were not performed because there was no consideration of this phenomenon mentioned in the procedure. This will be addressed with CAPR 1 in the Corrective action matrix.
			TH model FIV analysis	Not Effective	FIT-III predicted a lower velocity due to use of inappropriate gap value. This will be addressed with CA 3 in the Corrective action matrix.
		Supervision	In-plane FEI	Not Effective	Supervisors used same procedures and received the same training as design engineers. Every 3 months, an Executive Oversight Meeting was held. Deputy Head of MHI and Department Managers participated. However, there were no questions related to in-plane FEI because it was not considered under MHI procedure or industry practice. This will be addressed with CAPR 1 and CA 1 in the Corrective action matrix.
			TH model FIV analysis	Potentially Not Effective	FIT-III output indicated higher steam quality (void fraction) than previous SG designs. However, the senior engineer did not consider the potential adverse effects of the higher steam quality (void fraction). This will be addressed with CA 1in the Corrective action matrix.

Retainer to tube bar wear	Design	Training	Required Analyses	Not Effective	Necessary analyses for each component were selected based on engineering judgment and past success. Training was insufficient. This will be addressed with CAPR2in the Corrective action matrix.
		Procedures	Required Analyses	Not Effective	There was no requirement to confirm the consideration of a FIV analysis for changes made to a component in the flow stream. This will be addressed with CA 2in the Corrective action matrix.
		Supervision		Not Effective	Based on past successful experience, engineering did not recognize the need to perform additional analysis for the retainer bars. The senior engineer did not identify the need for FIV analysis during the design verification review. This will be addressed with CA 2in the Corrective action matrix.
Tube to AVB wear	Design	Training	Contact force under high steam quality	Not Effective	SG design training does not discuss contact force as a control mechanism to address vibration related wear under high steam quality (void fraction) condition. This will be addressed with CA 1in the Corrective action matrix.
		Procedures	Contact force under high steam quality	Not Effective	SG design procedures do not mention AVB contact force as a control mechanism to address vibration related wear under high steam quality (void fraction) condition. This will be addressed with CAPR1in the Corrective action matrix.
Consequence all		Fabrication		Not applicable	The SGs were fabricated as intended. For unit 2 it was done using the normal fabrication process. For unit 3 it required divider plate failure repair. There were no causes identified associated with fabrication deviation from the design.

Change analysis

For the SONGS RSGs, a change analysis was performed in two stages. The first stage compared the SONGS SG design to previous MHI SG designs for the triangular tube configuration. MHI had previously performed three steam generator designs using a triangular tube configuration. The second stage compared the SONGS RSGs to the previous SONGS SG design (Combustion Engineering type design). Only the most significant changes are included in this analysis.

The change analysis results are set out below.

(1) Differences between SONGS RSGs and previous MHI SG triangular design.--

[ ]

The SONGS RSGs have:

- [ ] circulation ratio
- [ ] maximum flow velocity
- [ ] average flow velocity
- [ ] P/D ratio
- [ ] out-of-plane FEI stability ratio
- Largest U bundle radius
- Specified AVB twist[ ] [ ]
- [ ]range of G-value (tube diameter, out-of-plane)
- Highest steam quality (void fraction)
- Thinnest and longest retainer bar
- [ ] nominal tube-to-AVB gap (0.002” cold / 0.000” hot)
- [ ] variation in tube-to-AVB gap (3 sigma[ ])

(2) Differences between SONGS RSGs and the previous SONGS OSG design. --

[ ]

- Increase in tube bundle heat transfer surface area (11%)
- Increase in number of tubes (5%)

- Removal of stay cylinder
- Change from lattice bars to trefoil broached tube support plates
- Change in tube support configuration in U region
- Change from CE to MHI moisture separators
- Power level / operating temperature / tube plugging margin

(3) Identification of the changes from previous SG designs led to the recognition that the RSG design deserved close scrutiny. MHI considered the changes in the SONGS design from previous steam generator designs and compared the basic design parameters of the SONGs RSGs (e.g., heat transfer area, circulation ratio, steam pressure, etc.) with other steam generator designs. Further, as part of the development of the SONGS RSG design, MHI conducted a detailed comparison between its proposed AVB support for the tubes in the U-bend region and that of a comparison plant of similar design. A special AVB team was formed and included industry experts to conduct an extensive design review process in 2005 / 2006 to optimize the U-bend design and address the technical issues. The team concluded that the SONGS design was significantly more conservative than previous designs in addressing U-bend tube vibration and wear.
Also MHI and SCE recognized that the SONGS RSG steam quality (void fraction) was high and MHI performed feasibility studies of different methods to decrease it. Several design adjustments were made to reduce the steam quality (void fraction) but the effects were small. Design measures to reduce the steam quality (void fraction) by a greater amount were considered, but these changes had unacceptable consequences and MHI and SCE agreed not to implement them. It was concluded that the final design was optimal based on the overall RSG design requirements and constraints. These included physical and other constraints on the RSG design in order to assure compliance with the provisions of 10 C.F.R. §50.59. Thus, MHI did compare the SONGs RSG design with previous steam generator designs, and in particular did a detailed evaluation of different options of the AVB design taking into account other large steam generator designs.

Comparison between SONGS RSG Design and Previous MHI Designs

Operating Conditions	SCE RSG U2	SCE RSG U3	Comparison to other MHI design	Potential Cause	Evaluation
Pressure (ata) *1	58.9	←	[		]
Steam Flow (kg/h)	3.44E+06	←			
FW Temperature (℃)	228	←			
S/G Level (mm)*2	1612	←			
Circulation Ratio (-) *5	3.3	←	[	]	[ ] the high steam quality (void fraction) with lower tube damping, which in combination with other factors can lead to tube vibration.
Maximum Flow Velocity (m/s) *5	[ ]	←			The high flow velocity provides the large dynamic pressure to the tube, which in combination with other factors can lead to tube vibration.
Average Flow velocity (m/s) *5	[ ]	←			The high flow velocity provides the large dynamic pressure to the tube, which in combination with other factors can lead to tube vibration.
P/D Ratio (-)	1.33	←	[		]

Operating Conditions	SCE RSG U2	SCE RSG U3	Comparison to other MHI design	Potential Cause	Evaluation
Stability Ratio (highest) (-) (Where) *5		←			stability ratio of out- of- plane FEI
U-bend Radius (mm)		←	Largest		The large bending radius gives
AVB Thickness (mm)		←			
AVB width (mm)		←			
AVB twist (mm)		←			
G-Values (mm)		←			
Nominal span between AVBs (mm)		←			

Operating Conditions	SCE RSG U2	SCE RSG U3	Comparison to other MHI design	Potential Cause	Evaluation
Natural Frequency (Hz) (tubes of Concern) *4		←			.
Steam Quality (Void Fraction) (-) *5	0.9 (0.996)	←	Highest	Y	The high steam quality (void fraction) gives the low tube damping, which in combination with other factors can lead to tube vibration.
AVB design *3	Solid type	←			
Retainer bar dimension		←	Thinnest	Y	The thinnest and longest retainer bar gives a low frequency, so FIV of retainer bar may result.
		←	Longest		

*1 This parameter shows secondary pressure.
*2 The distance between the U-bend top to water level.
*3 This parameter shows RSG AVB.
*4 The lowest natural frequency of tube is provided
*5 Circulation ratio is obtained from SSPC code, and Max. flow vel., Avg. flow vel., stability ratio, and steam quality (void fraction) are obtained ATHOS code.

Comparison between SONGS RSG and Previous SONGS (CE) SG (OSG) Design*1,2

Design Element	OSG Specification	RSG Specification	Potential Cause	Evaluation
Number of Tubes	9350	9727		
Channel Head and Tubesheet Configuration	Stay cylinder to support tubesheet, floating divider plate	Thick welded structural divider plate		
Tube Support Configuration (U-Bend Section)	Batwing assembly, diagonal and vertical strips with interlocking horizontal strips between tubes, lattice bars attached to structural members (shroud) external to the tube bundle	Floating structure consisting of 6 V-shaped anti-vibration bars (AVBs) with 12 support points, retaining bars, bridges, and retainer bars		
Tube Support Configuration (Straight Section)	Lattice bars (egg crates) positioned by tie rods and wedge-welded to the shroud after alignment with tubesheet, shroud is active part of radial load path, 2-inch line contact on 2 sides, 1-inch line contact on 2 sides	7 trefoil broached tube support plates (TSPs) positioned by stay rods, radial load path at all TSPs		

*1 This analysis focused on mechanical differences because T/H conditions were expected to be similar.
*2 Five design elements listed above were obtained from MPR report 'Original Steam Generator and Replacement Steam Generator Design Feature/Change Evaluation'.

RCA charter

Title: Root Cause Analysis Report for tube wear identified in the Unit 2 and Unit 3 Steam Generators of San Onofre Nuclear Generating Station

Management Sponsor:

Team:

Problem Statement:

(1) Requirement

No Primary-to-Secondary Leakage due to Defects in any of the RSG Units for the duration of the Warranty Period. (per 17.2.3 of General T&C with EMS)

(2) Deviation

Unit 3 SG-B (SCE SG088) experienced tube leakage during operation and failure of eight tubes during in-situ pressure testing. (Both due to Defects)

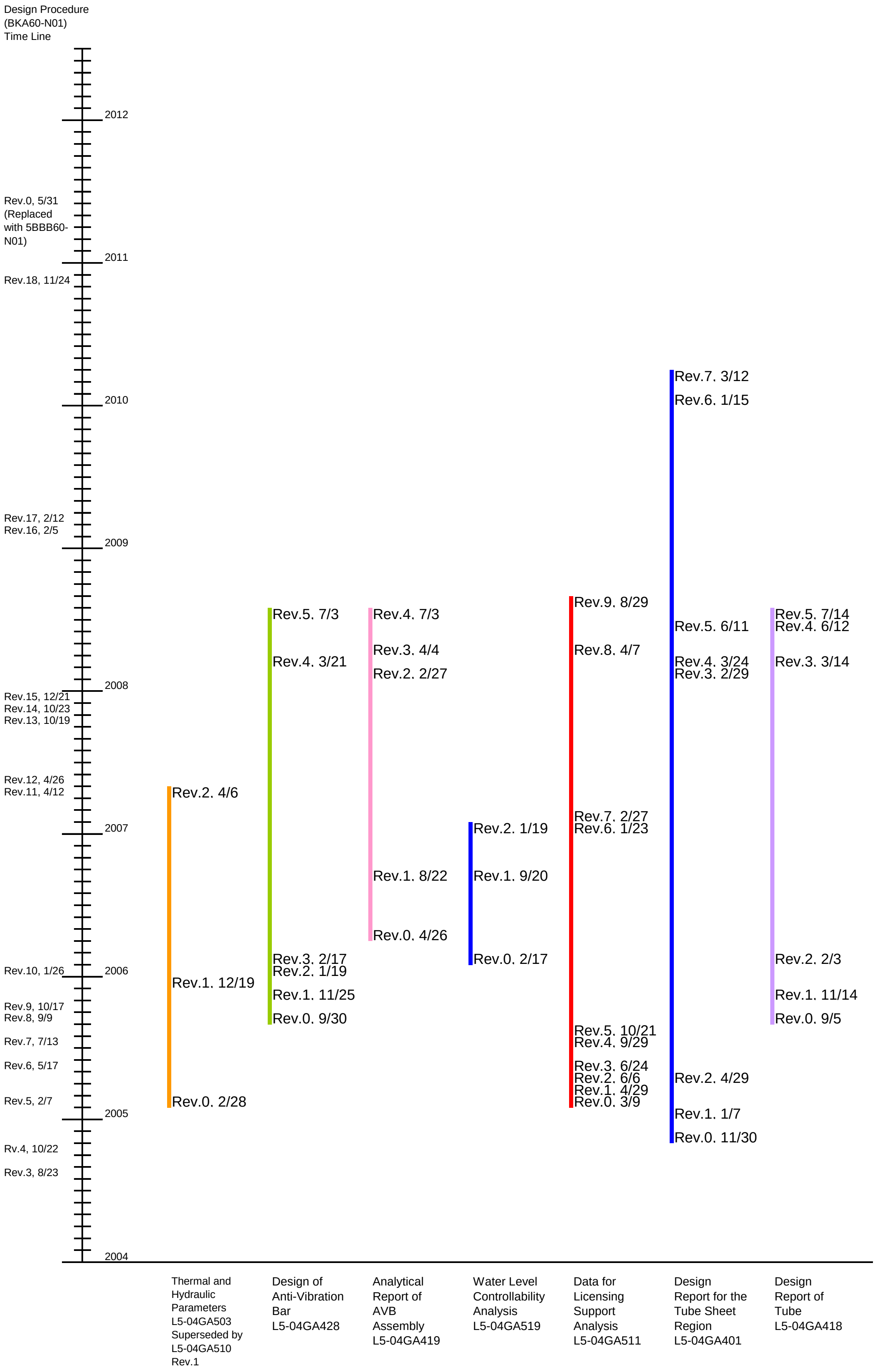
(3) Consequences (For MHI)

- 10CFR21 Report required

Timeline and Deliverables:

- RCA Team Assigned : March 23, 2012
- Problem Statement committed : March 23, 2012
- Prepare begun: March 26, 2012
- DRAFT Cause-effect analysis : April13, 2012
- DRAFT RCA Summary : July5, 2012
- Review RCA Summary : July7, 2012
- DRAFT RCA Report : July20, 2012
- Review Revised RCA Summary : August30, 2012
- Review RCA report: September 6 and 11, 2012
- RCA Due Date: October12, 2012

Time line


Design Procedure (BKA60-N01) Time Line
2012
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Rev.16, 2/5
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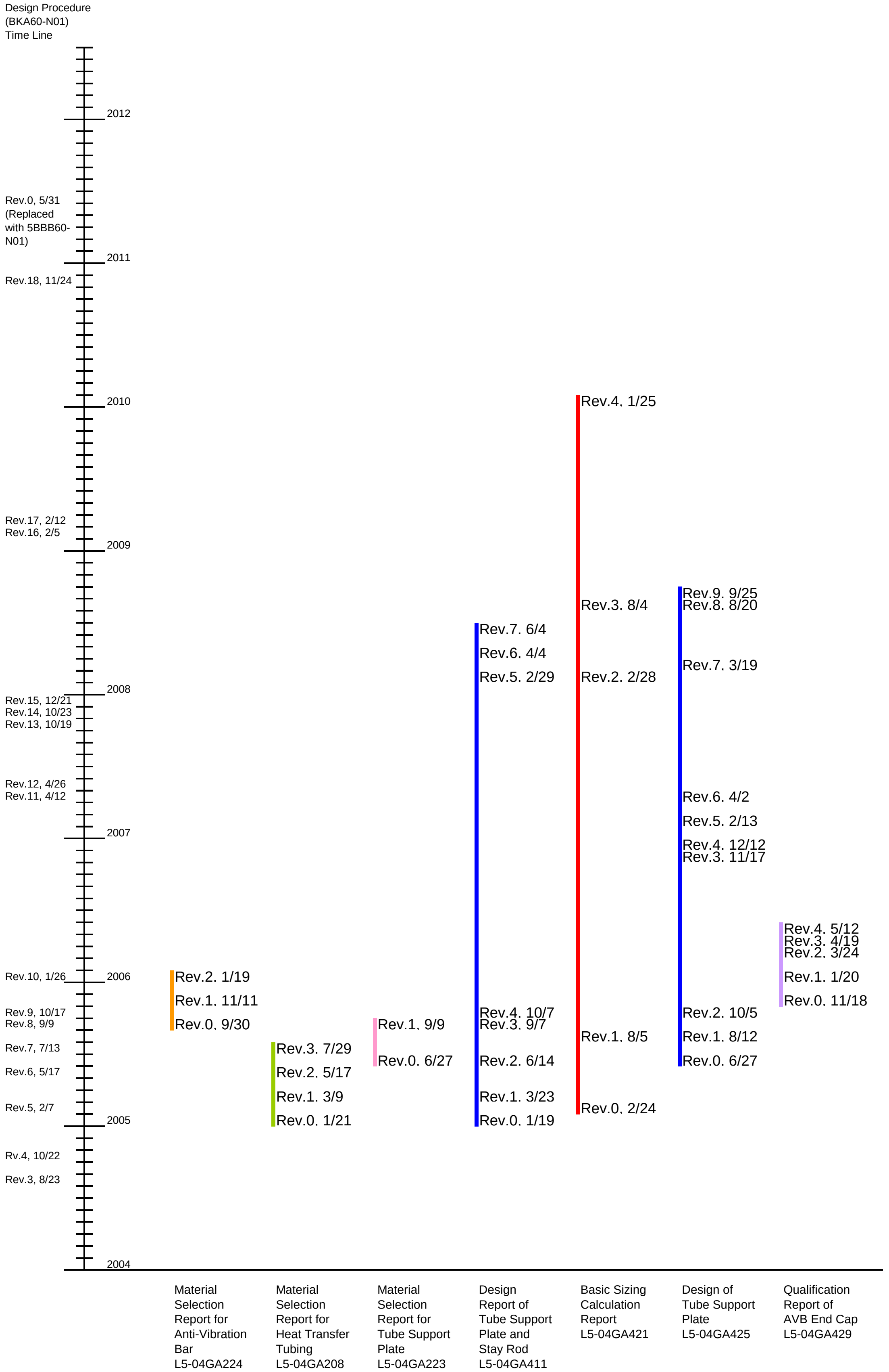
Thermal and Hydraulic Parameters L5-04GA503 Superseded by L5-04GA510 Rev.1
Design of Anti-Vibration Bar L5-04GA428
Analytical Report of AVB Assembly L5-04GA419
Water Level Controllability Analysis L5-04GA519
Data for Licensing Support Analysis L5-04GA511
Design Report for the Tube Sheet Region L5-04GA401
Design Report of Tube L5-04GA418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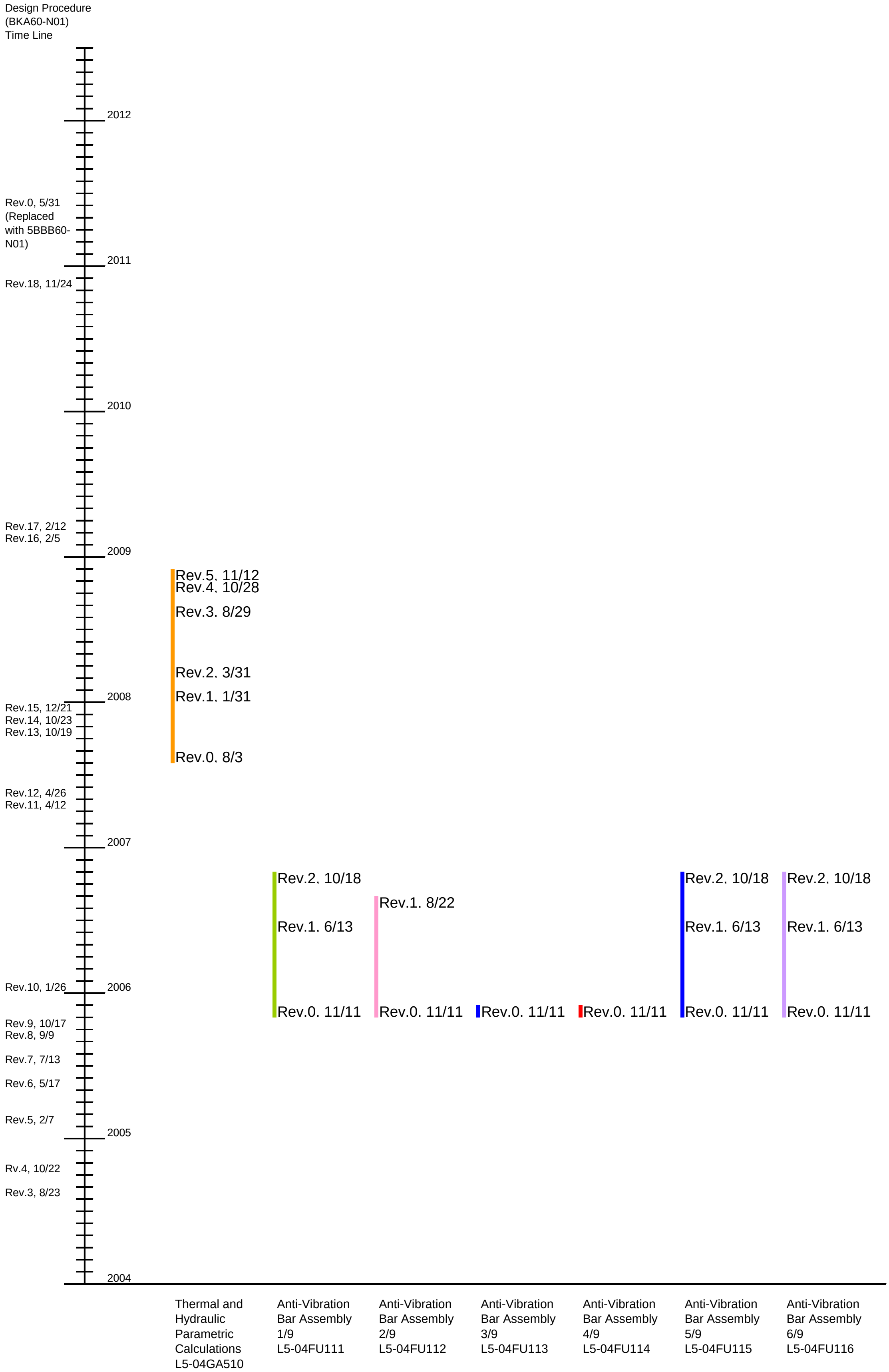
Material Selection Report for Anti-Vibration Bar L5-04GA224
Material Selection Report for Heat Transfer Tubing L5-04GA208
Material Selection Report for Tube Support Plate L5-04GA223
Design Report of Tube Support Plate and Stay Rod L5-04GA411
Basic Sizing Calculation Report L5-04GA421
Design of Tube Support Plate L5-04GA425
Qualification Report of AVB End Cap L5-04GA429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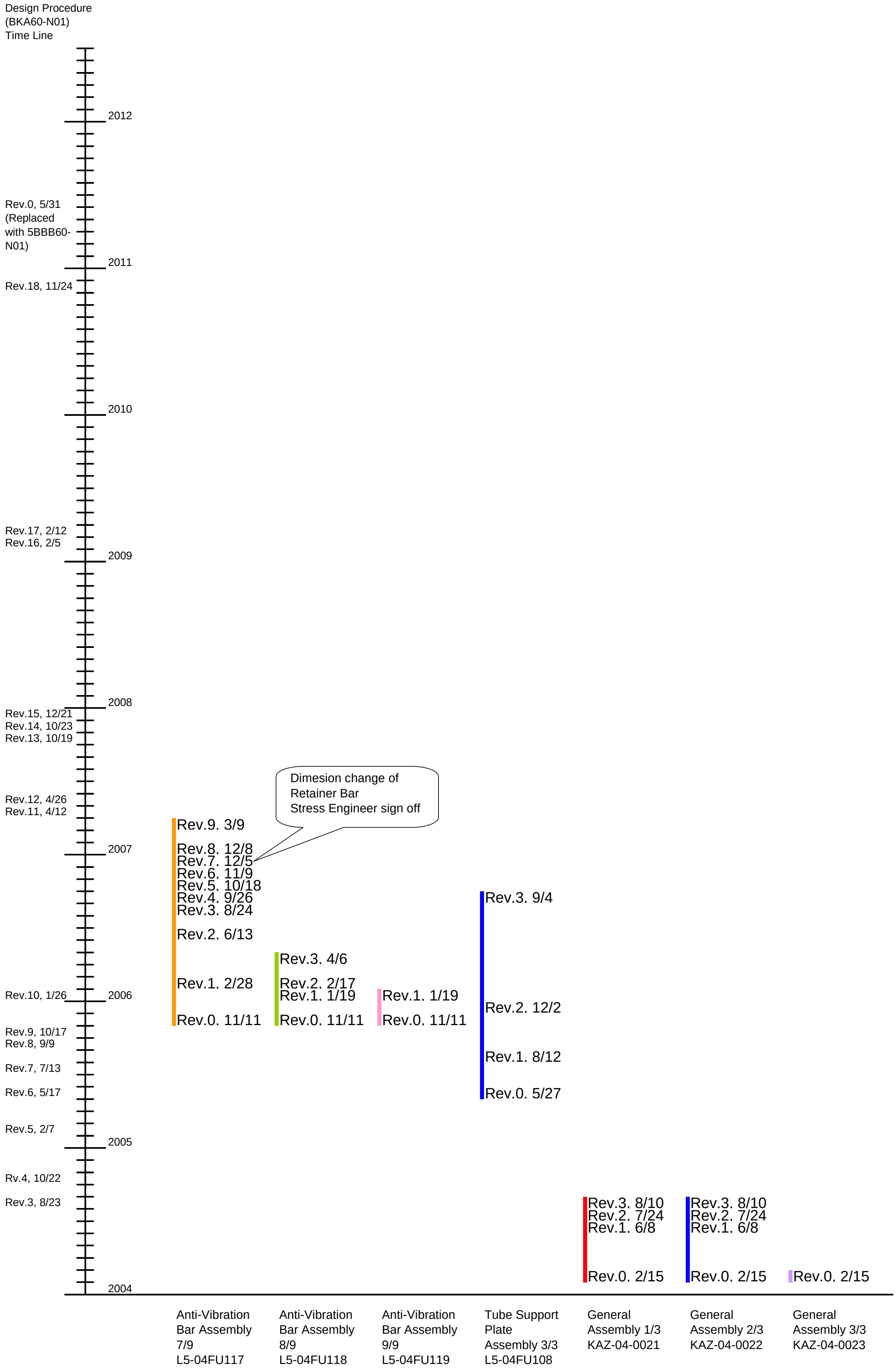
Thermal and Hydraulic Parametric Calculations L5-04GA510
Anti-Vibration Bar Assembly 1/9 L5-04FU111
Anti-Vibration Bar Assembly 2/9 L5-04FU112
Anti-Vibration Bar Assembly 3/9 L5-04FU113
Anti-Vibration Bar Assembly 4/9 L5-04FU114
Anti-Vibration Bar Assembly 5/9 L5-04FU115
Anti-Vibration Bar Assembly 6/9 L5-04FU116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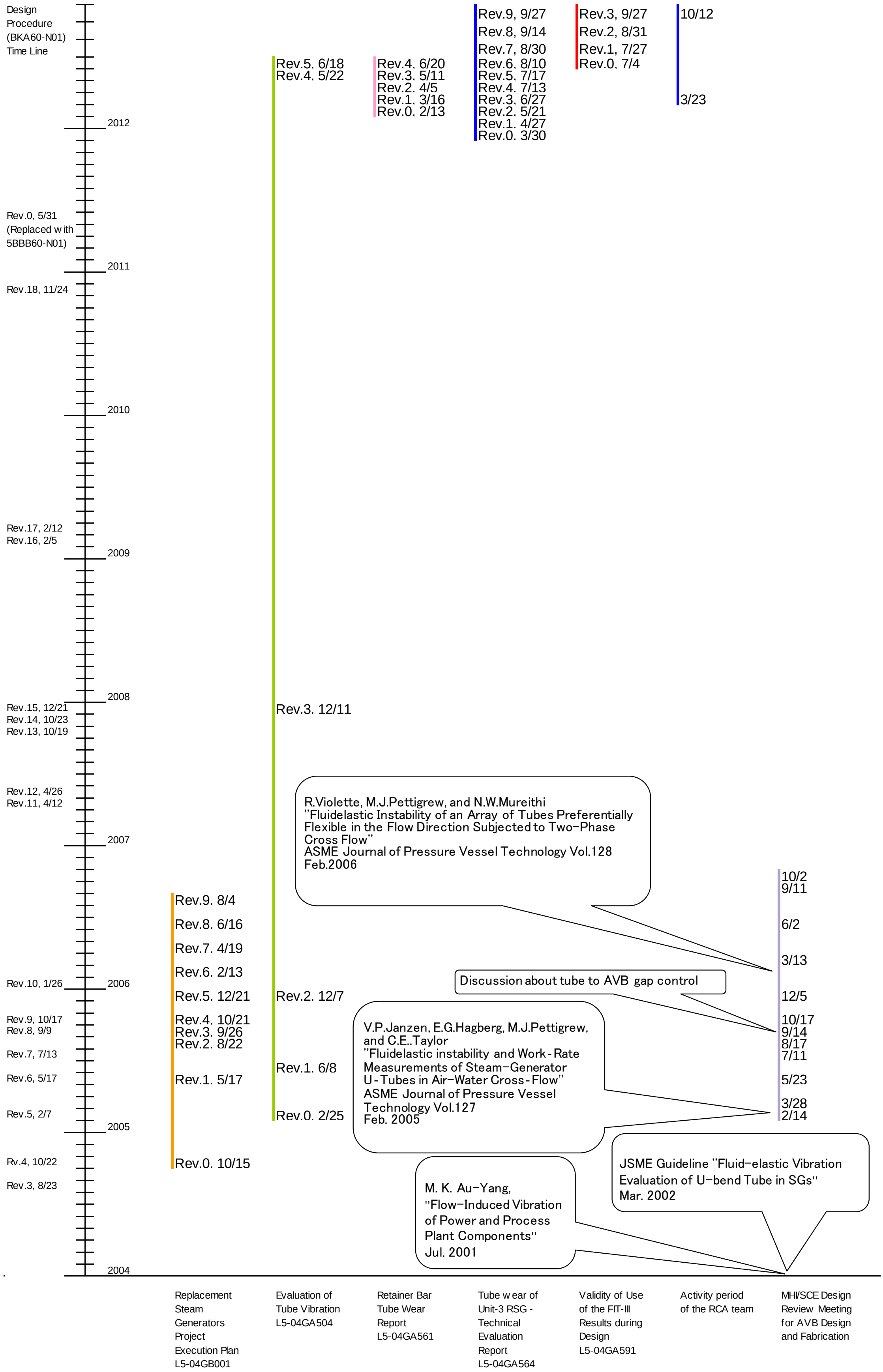
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San Onofre Nuclear Generating Station, Units 2 & 3
REPLACEMENT STEAM GENERATORS

Supplemental Technical Evaluation Report

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0	Initial issue	See cover sheet			

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)

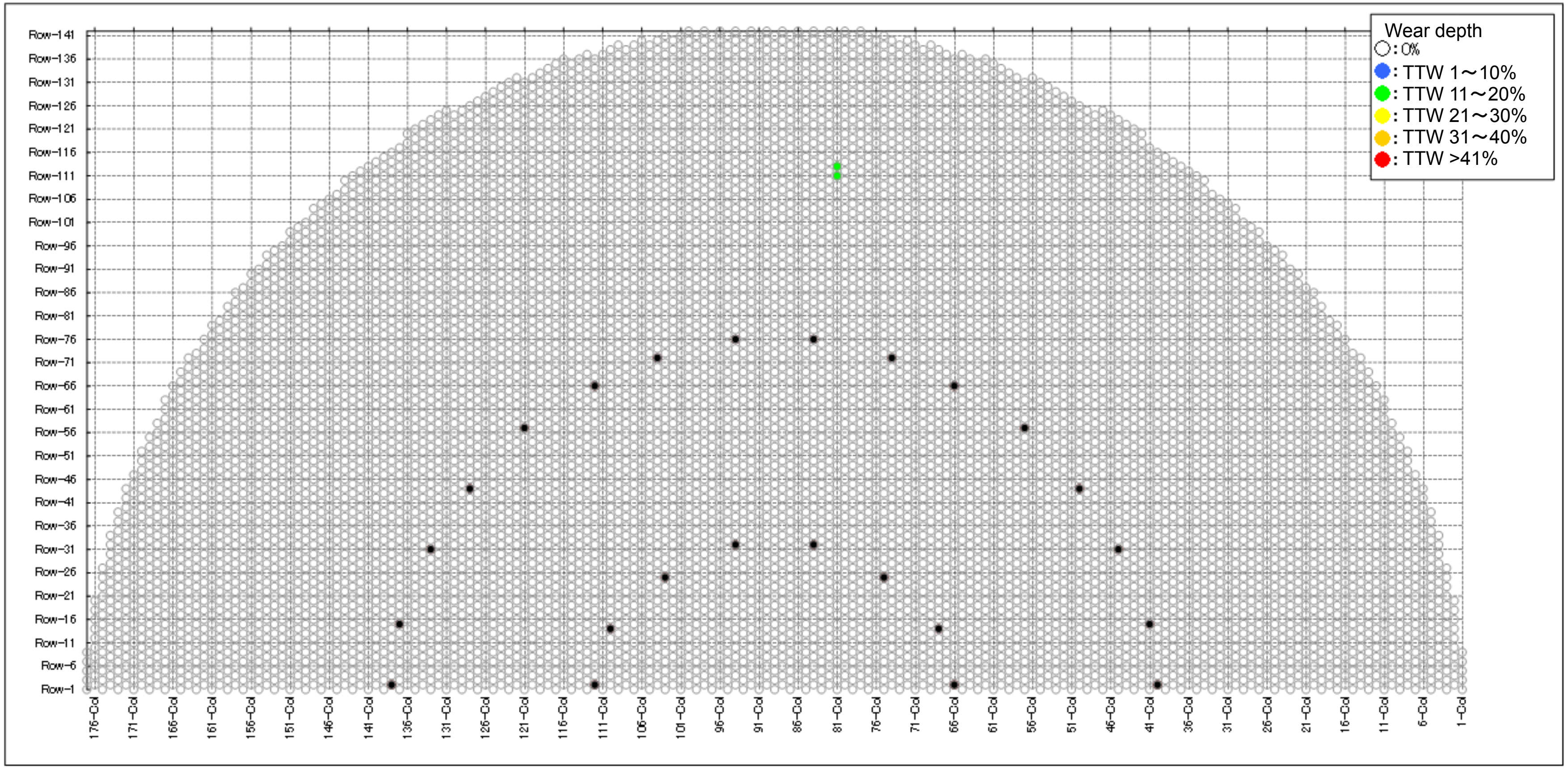


Fig 2.1-1 (1/2) Unit 2 Tubes with TTW indications

2B-SG (Unit 2 E088)

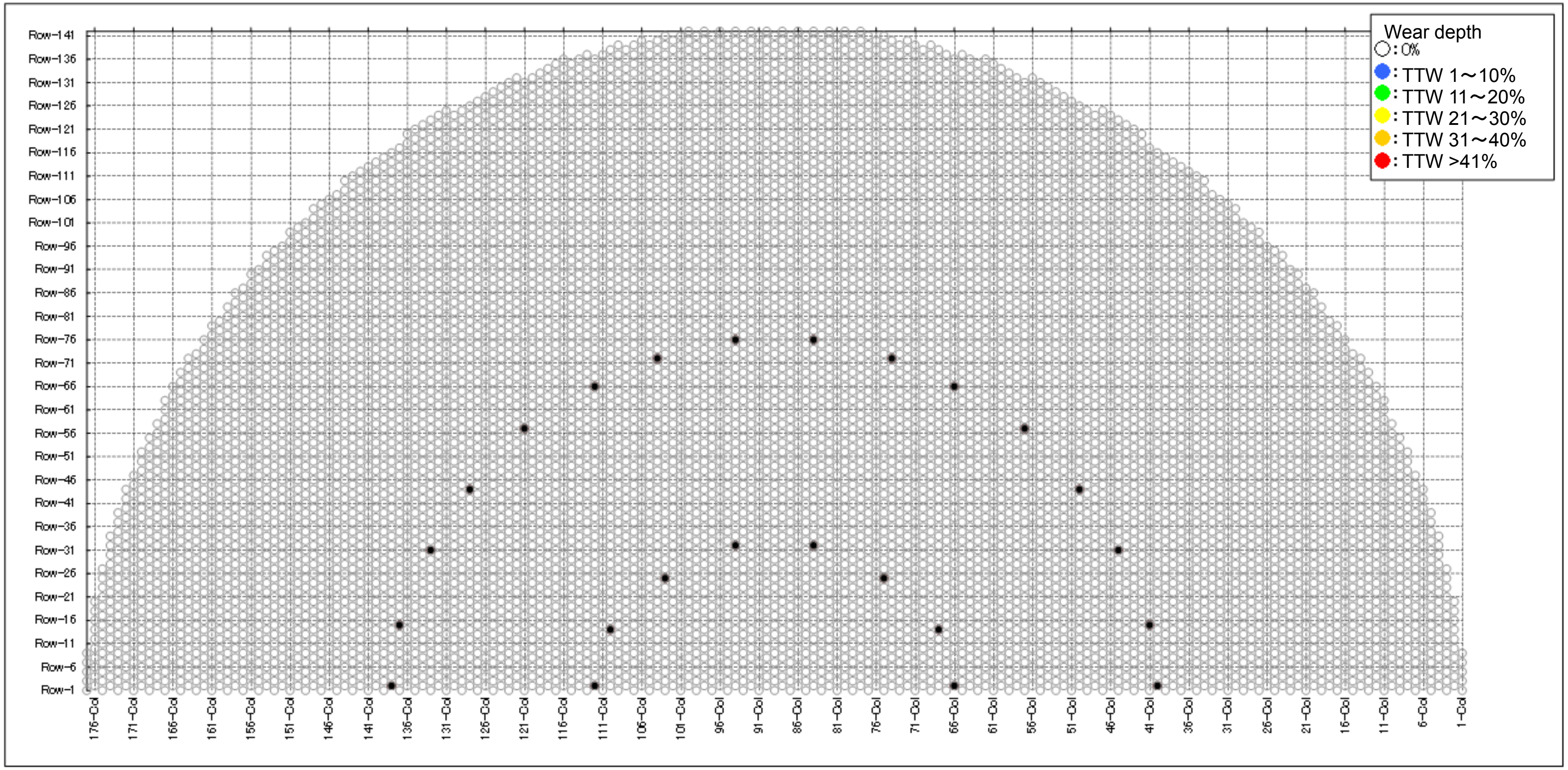


Fig 2.1-1 (2/2) Unit 2 Tubes with TTW indications

3A-SG (Unit 3 E089)

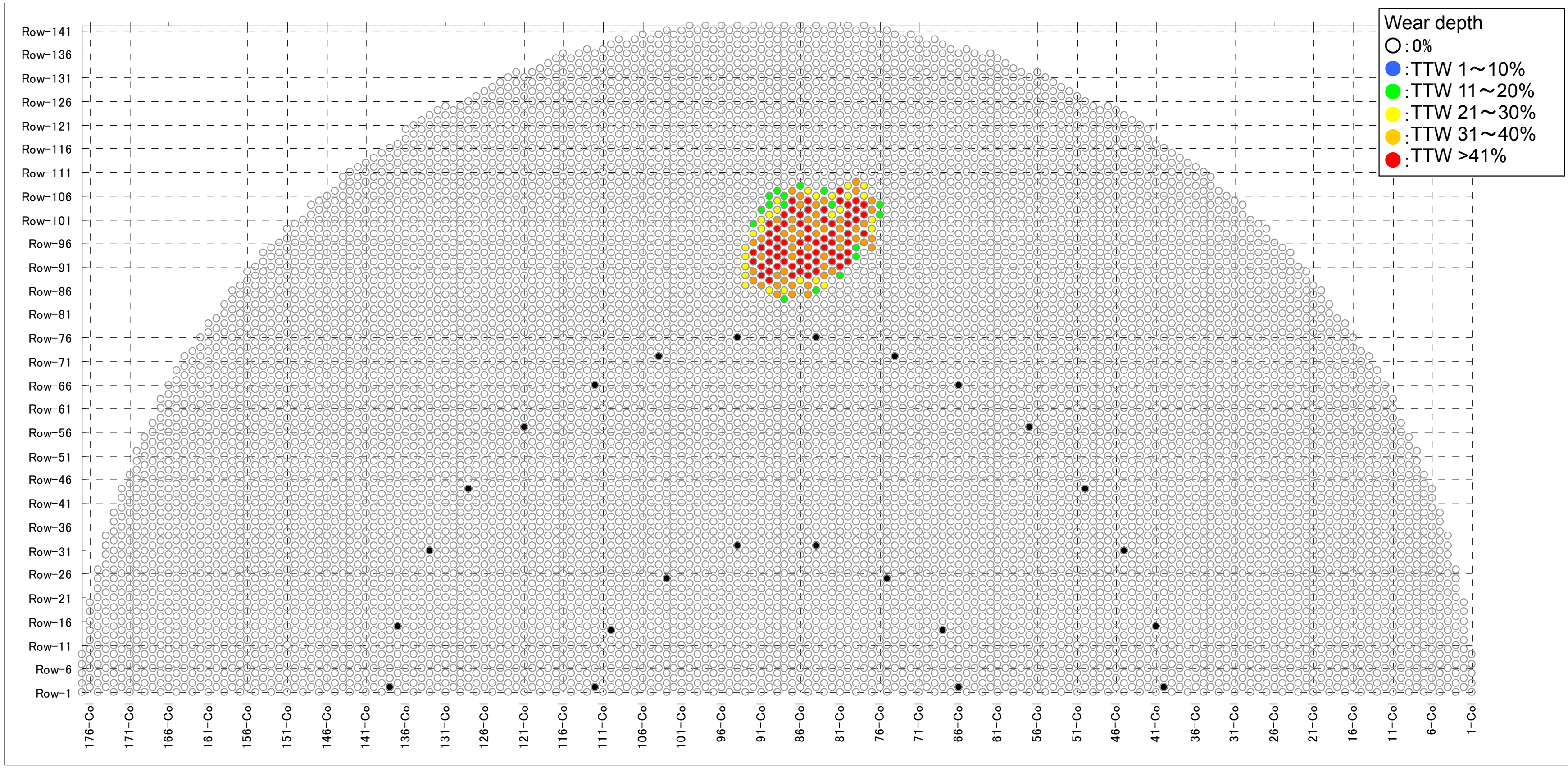


Fig 2.1-2 (1/2) Unit 3 Tubes with TTW indications

3B-SG (Unit 3 E088)

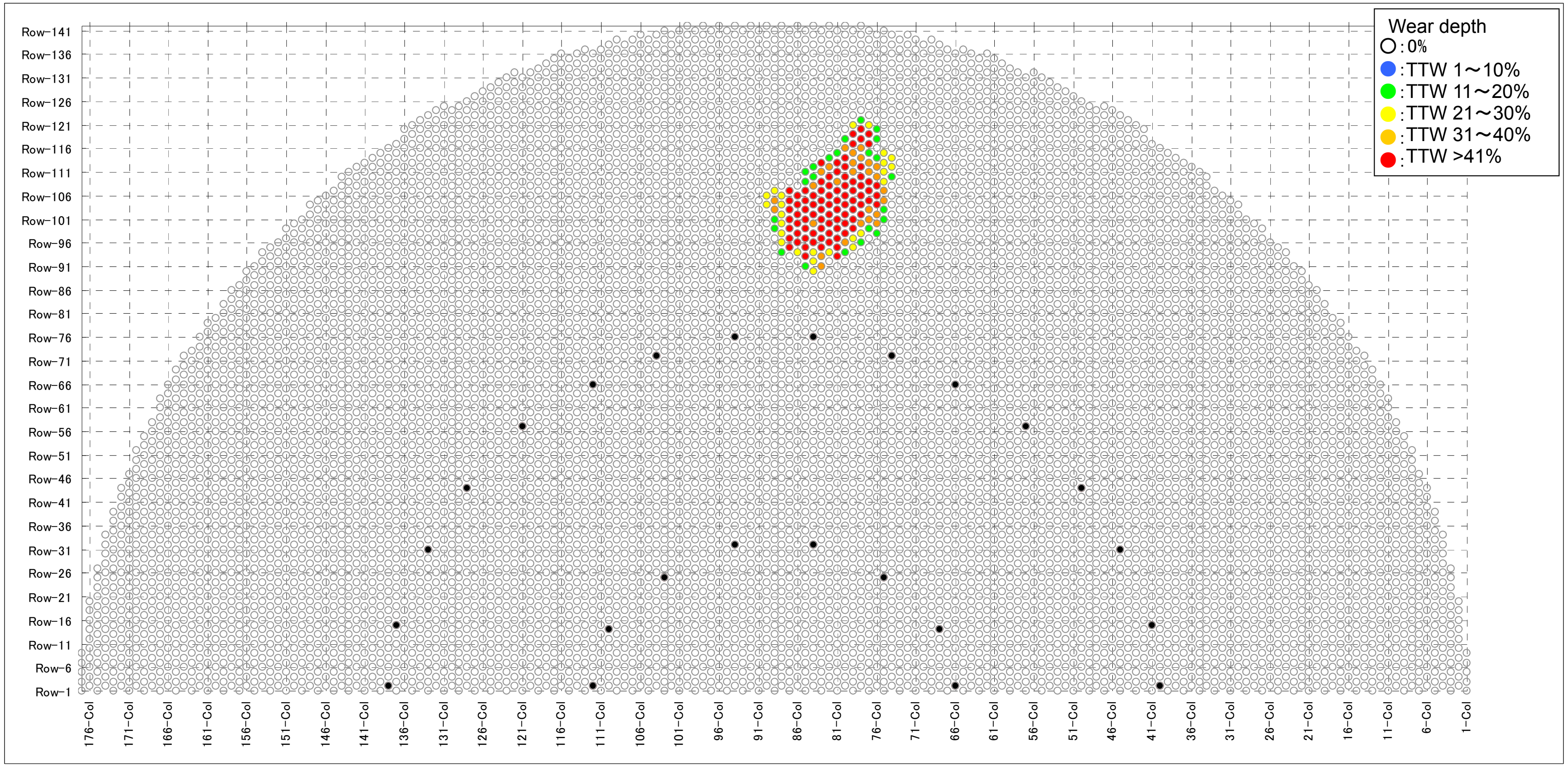


Fig 2.1-2 (2/2) Unit 3 Tubes with TTW indications

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.

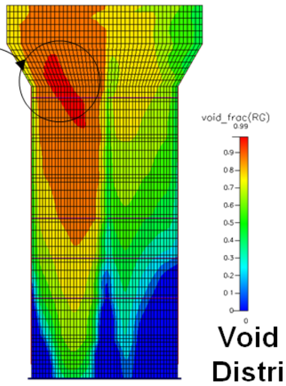
Characteristics of SONGS RSG

【Thermal Hydraulics】

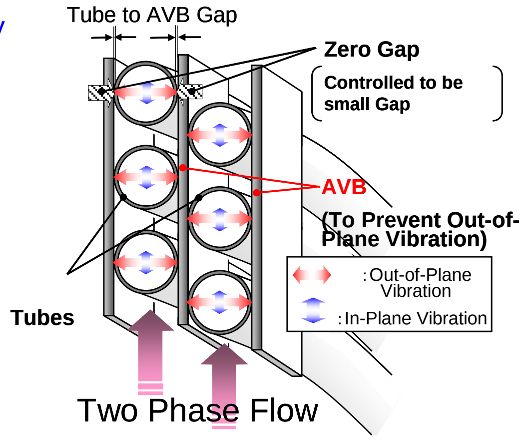
- ✓ Design with High Steam Quality in U-Bend (max 0.9)

【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



Void Fraction Distribution in 100% Output



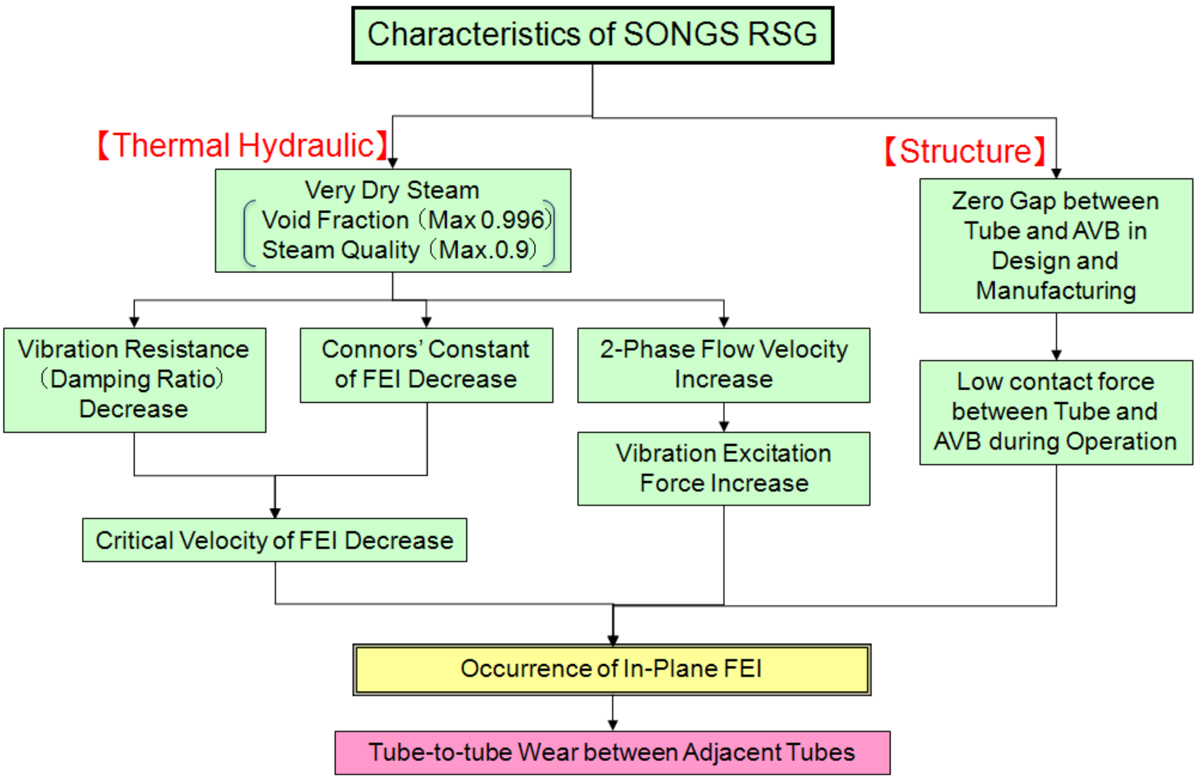


Fig. 2.2-1 Type 1 Wear (TTW) In-Plane Mechanism

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”.

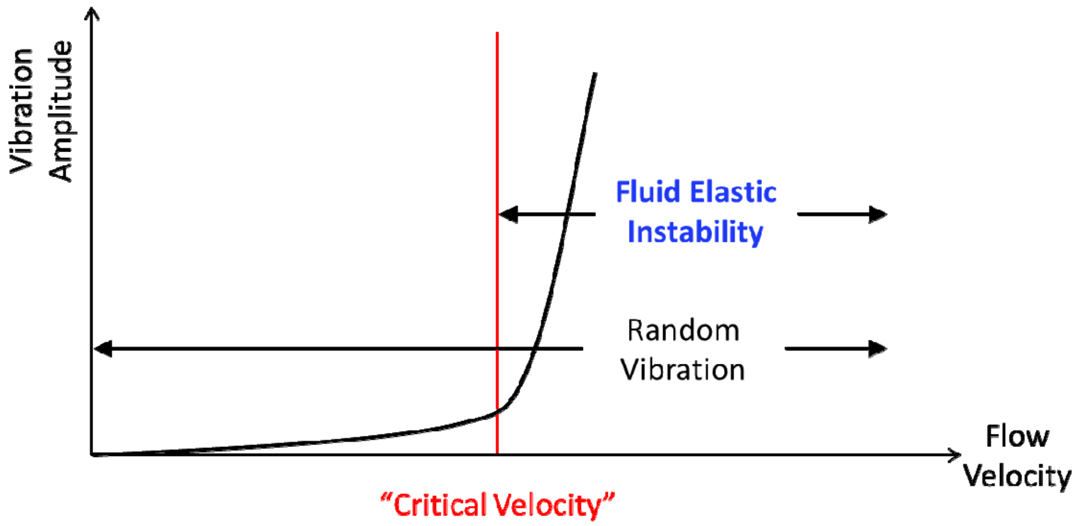


Figure 2.3-1 Relation between Vibration Amplitude and Flow Velocity

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 1.33. 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).

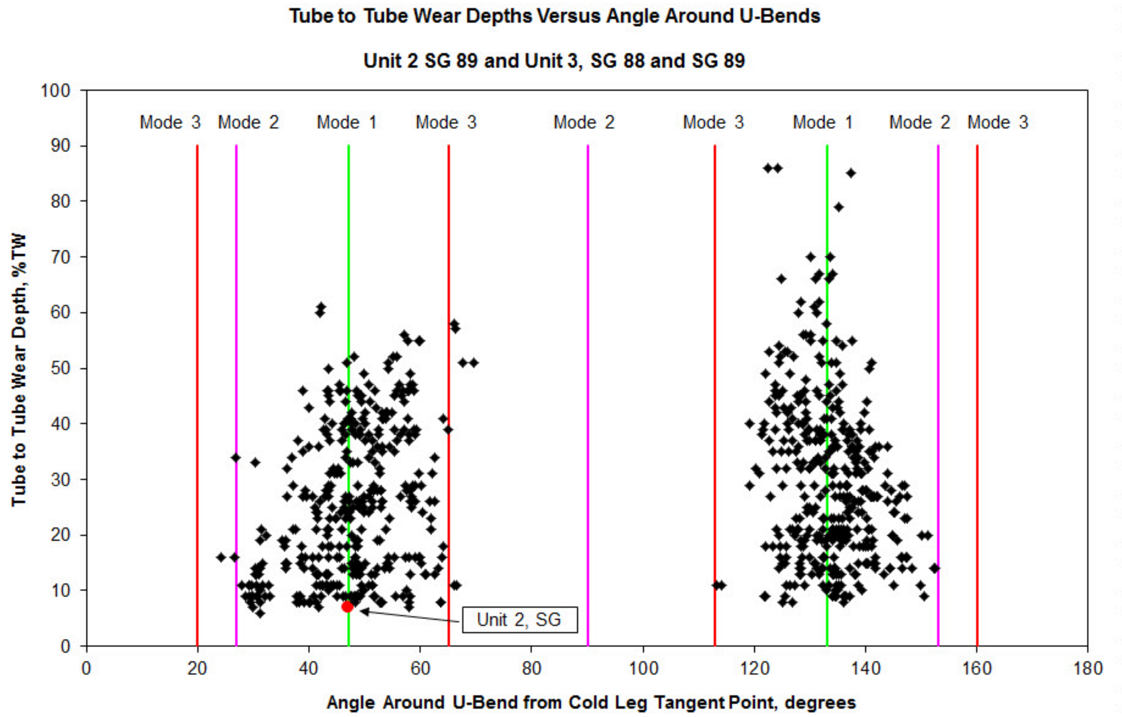


Fig. 2.3.3-1 Location of deepest wear along the length of each TTW wear scar

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).

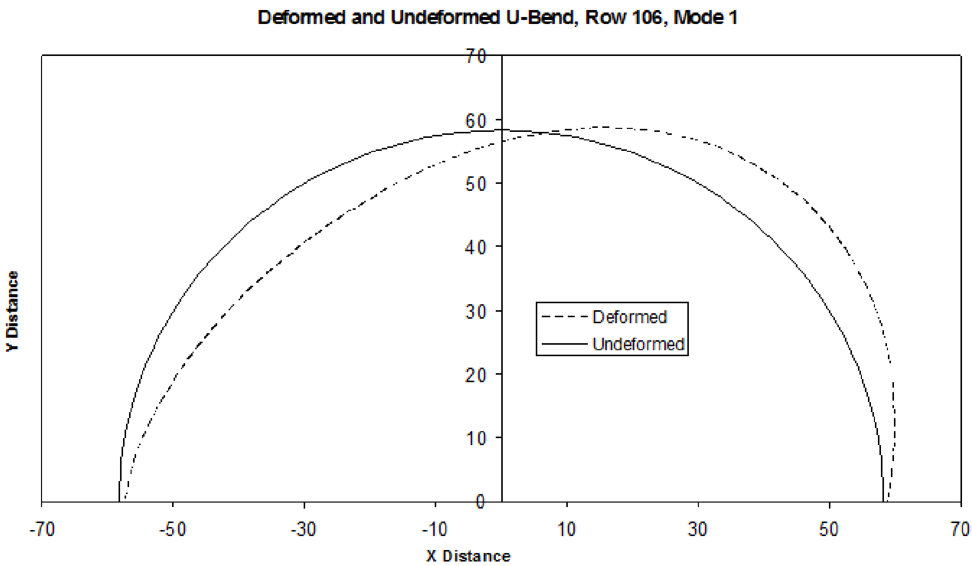


Fig.2.3.3-2 The large amplitude deformation of a U-tube in the first in-plane mode

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).

Manufacturing Tolerances

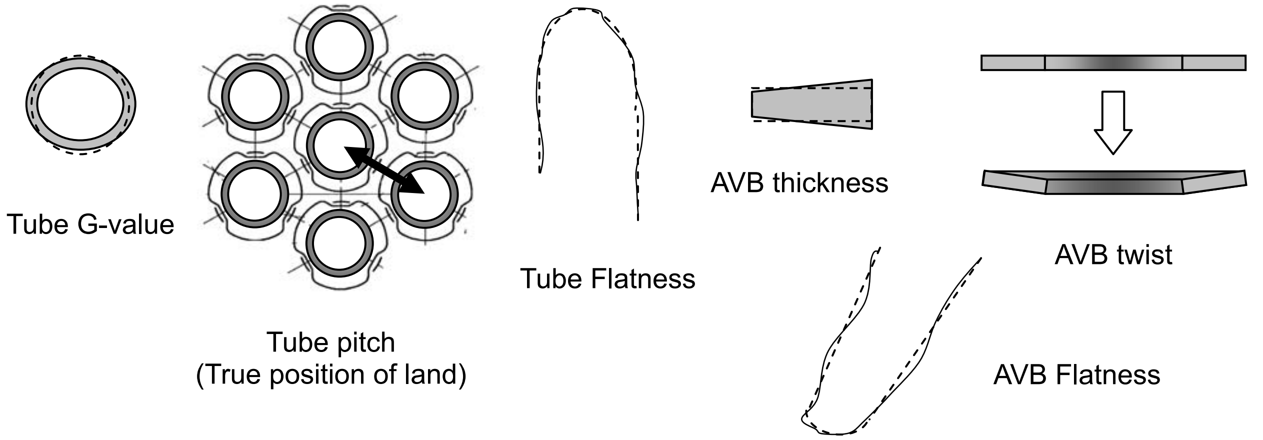


Fig.2.3.3-3 Contact Force Simulation with Manufacturing Tolerances

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 99.6% (0.4% of the volume is occupied by saturated liquid water). The highest void fraction calculated using ATHOS for prior MHI-designed SGs is 98%. 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.

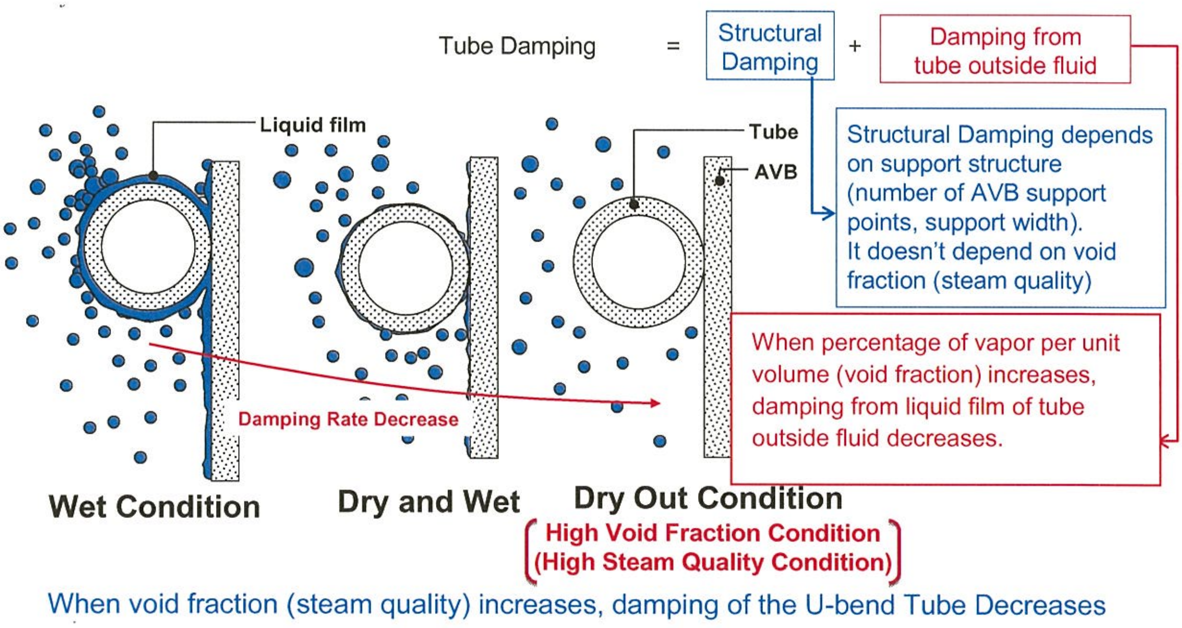


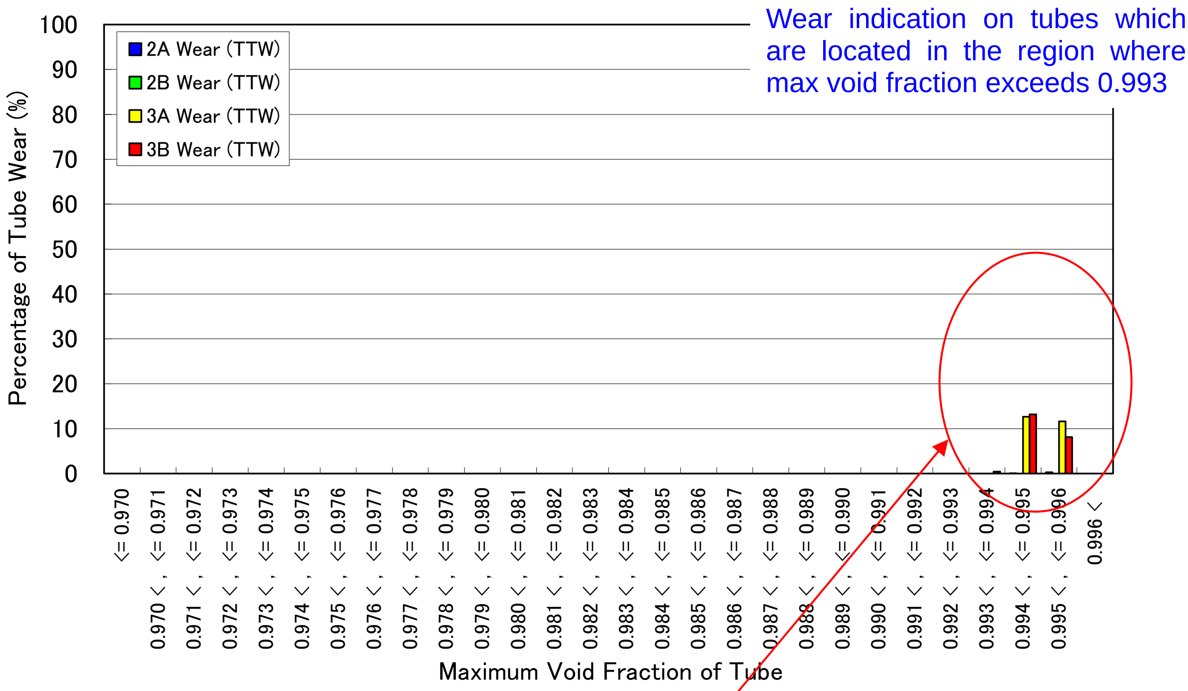
Fig 2.3.4-2 Relation between Steam Quality (Void Fraction) and Damping

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 0.996. 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.



Strong correlation between the number of tubes with wear and void fraction (steam quality)

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).

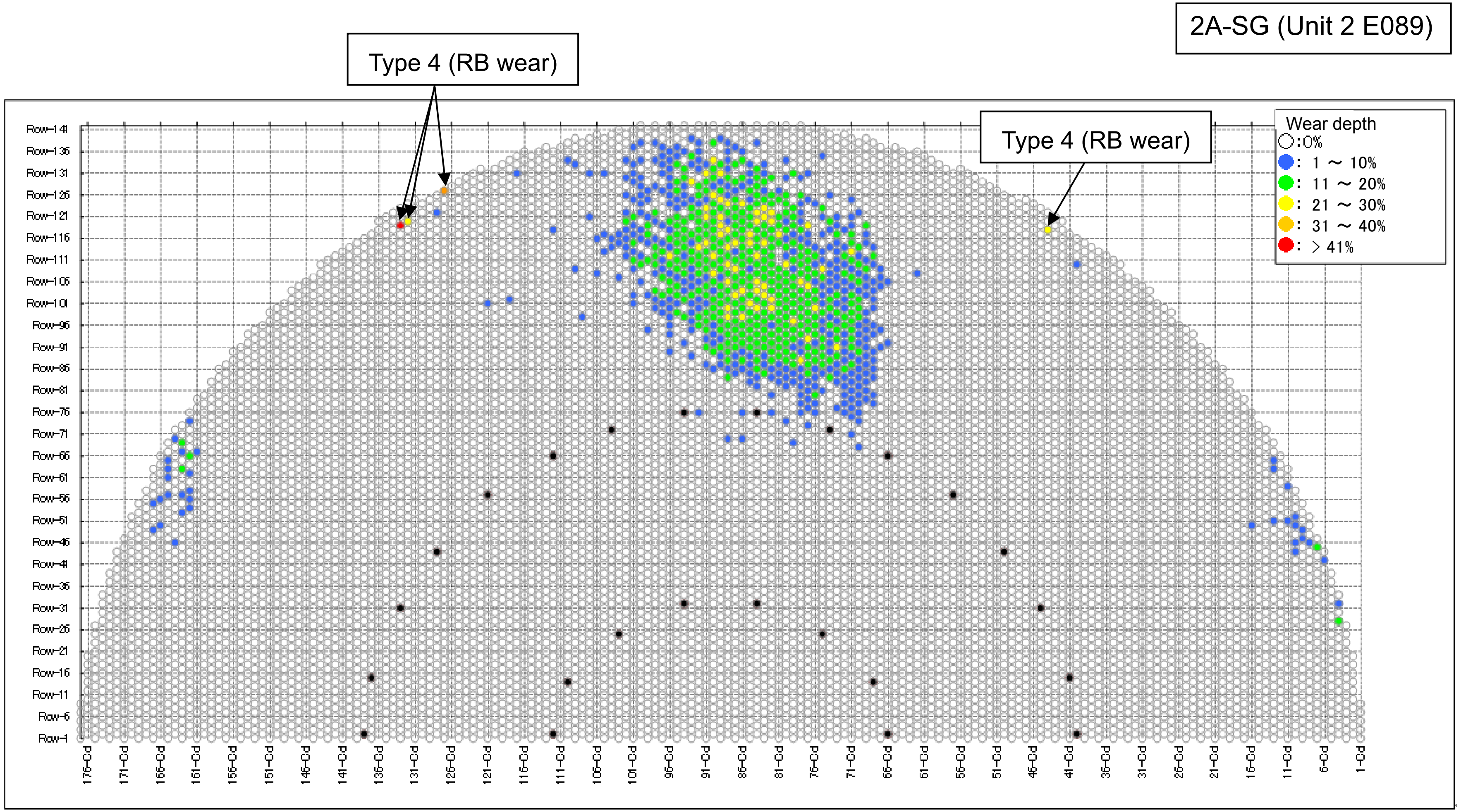


Fig 3.1-1 (1/2) All Unit 2 U-bend tube indications

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

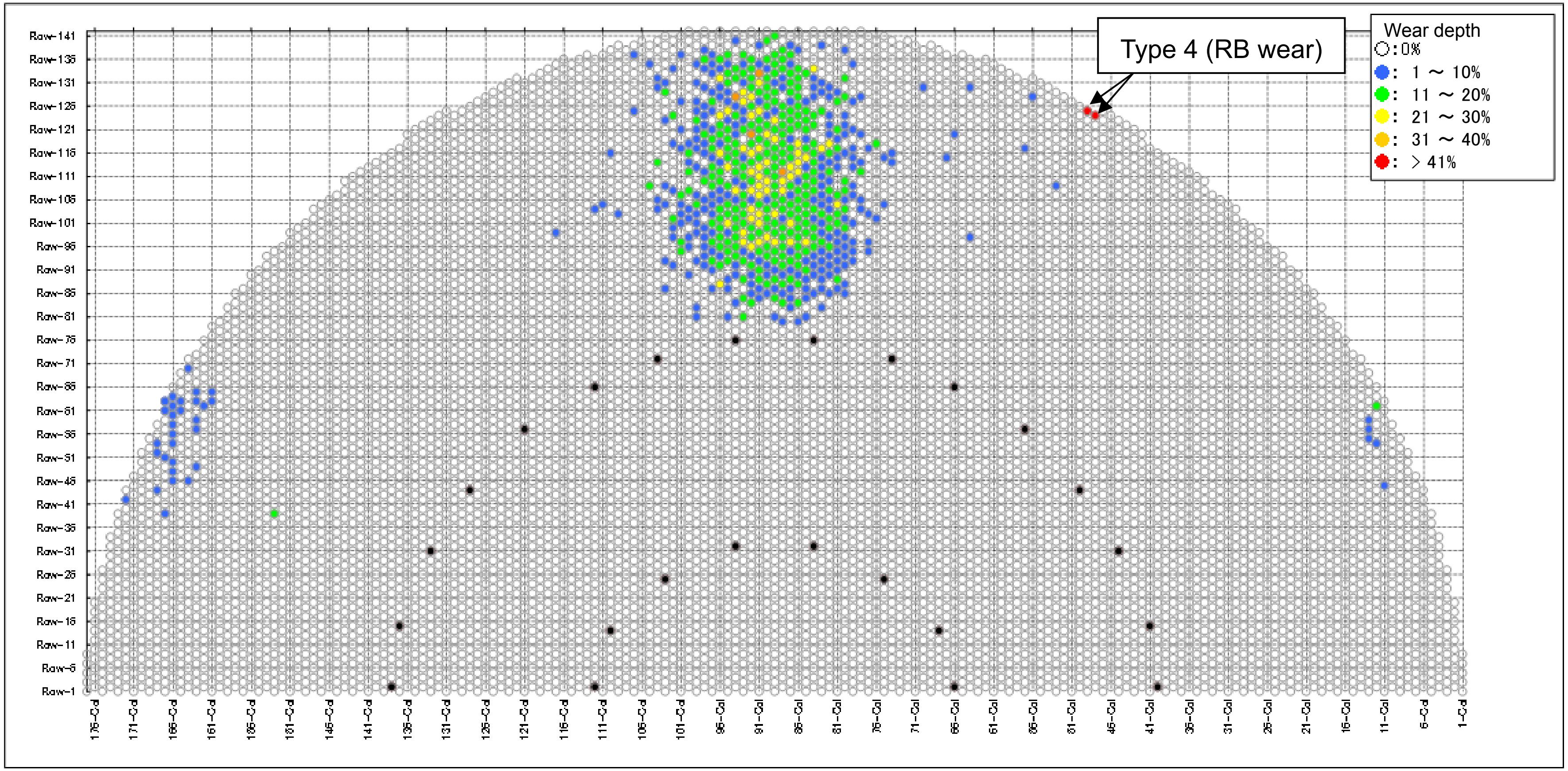


Fig 3.1-1 (2/2) All Unit 2 U-bend tube indications

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

3A-SG (Unit 3 E089)

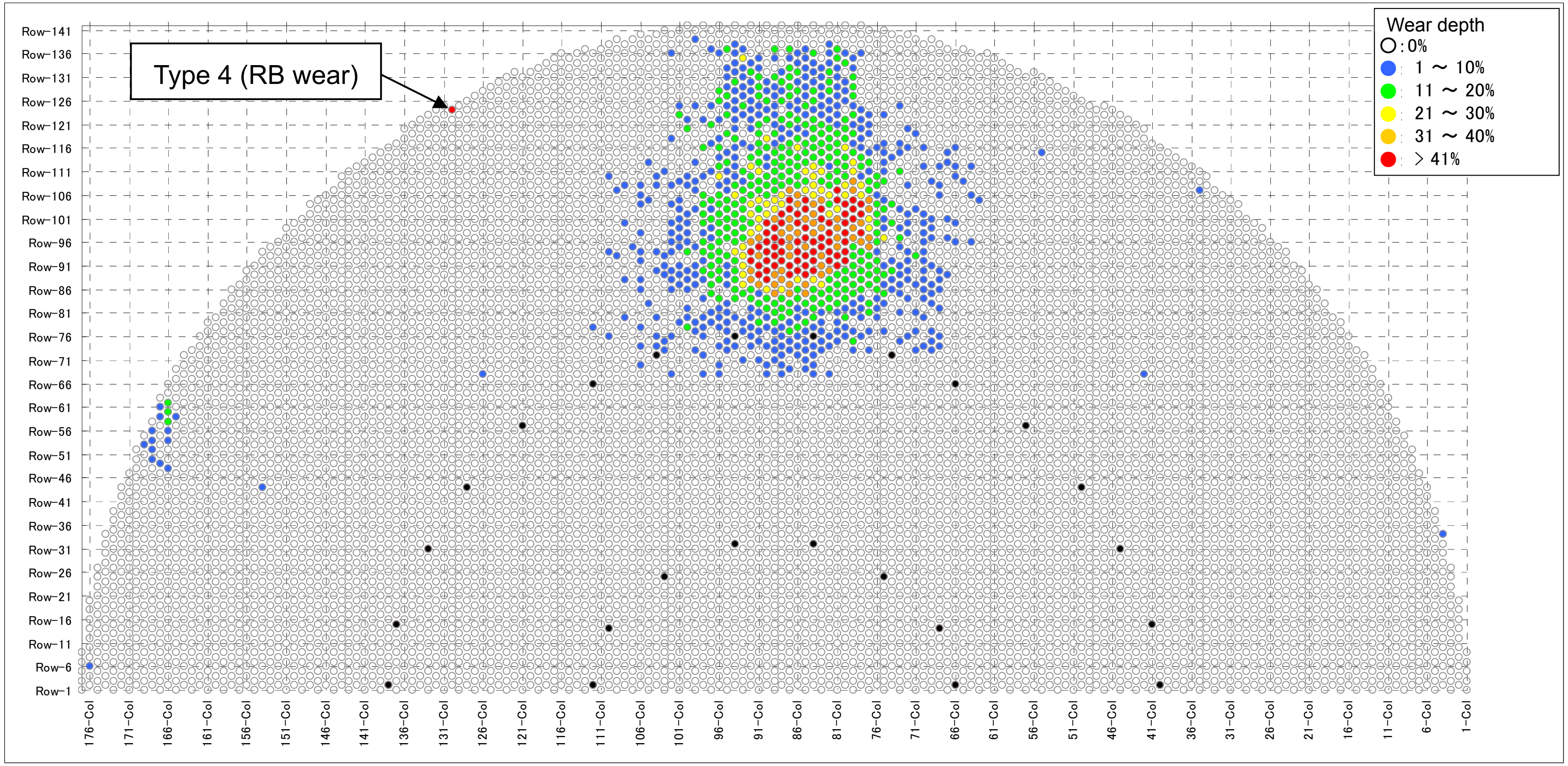


Fig 3.1-2 (1/2) All Unit 3 U-bend tube indications

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

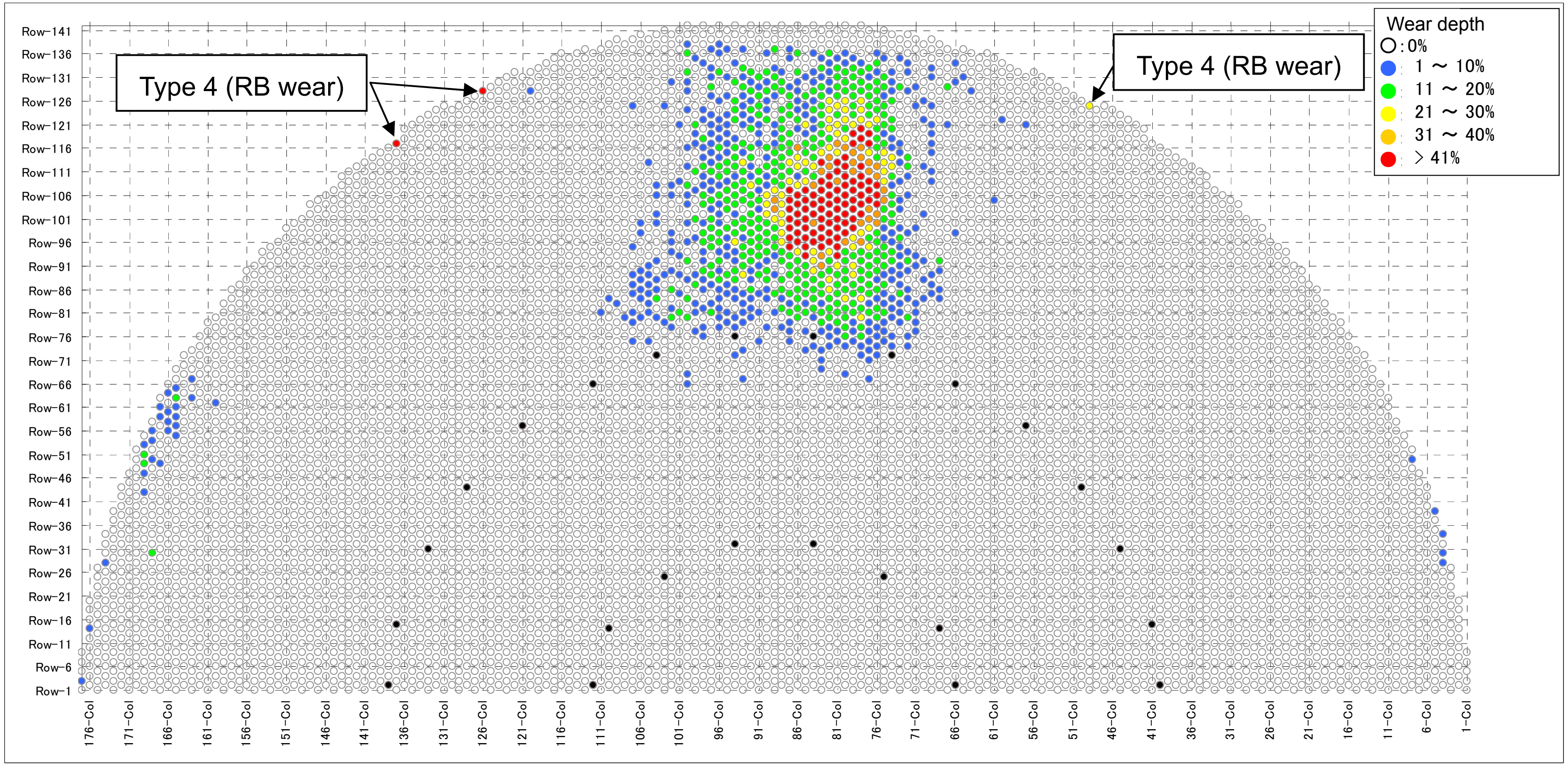
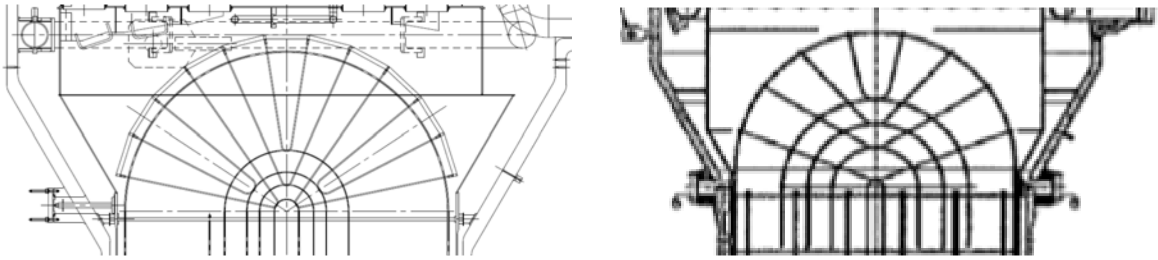


Fig 3.1-2 (2/2) All Unit 2 U-bend tube indications

(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.



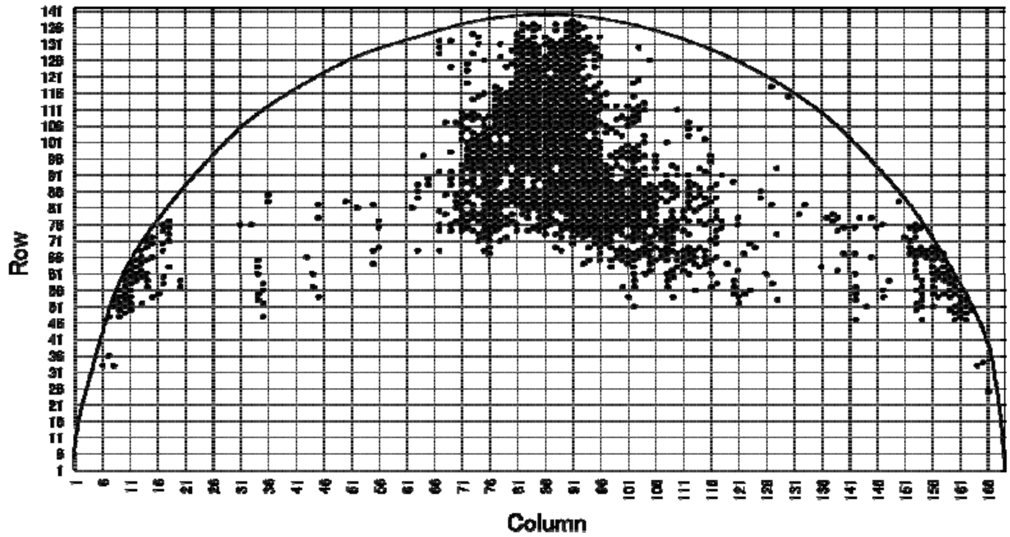
(a) SONGS (12AVB design) (b) Plant-A (8 AVB design)

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

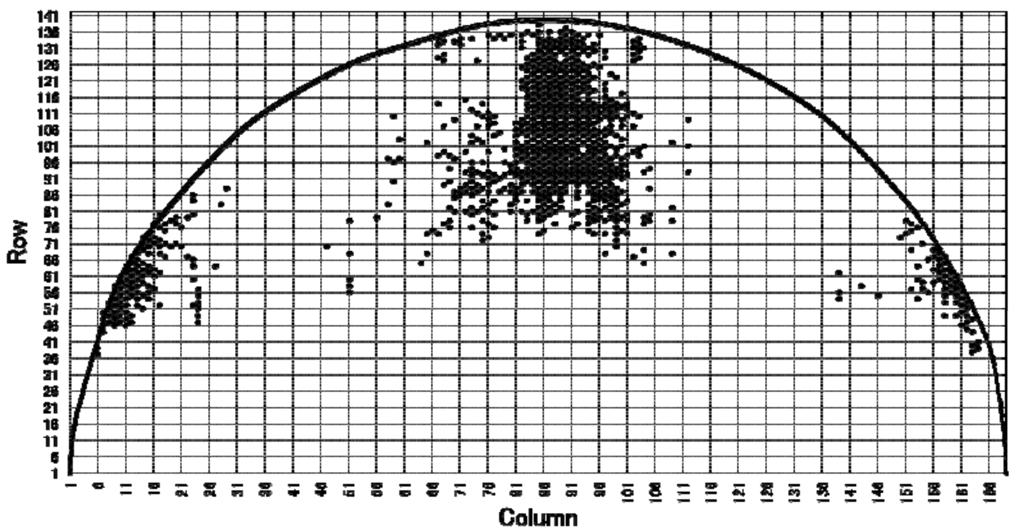
The Plant-A inspection results show a wear pattern with many tubes in the center of the U-bend that have tube-to-AVB wear similar to that found in the SONGS steam generators. Figure 3.2.1-2 shows the tubes with tube-to-AVB wear identified at Plant-A during the first inspection following installation 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).

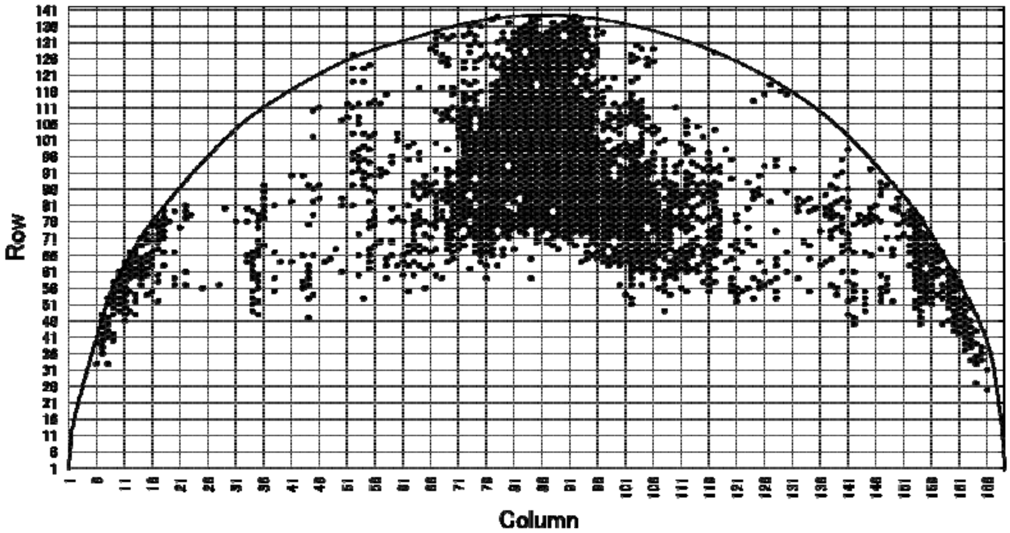


(a) 2A-SG

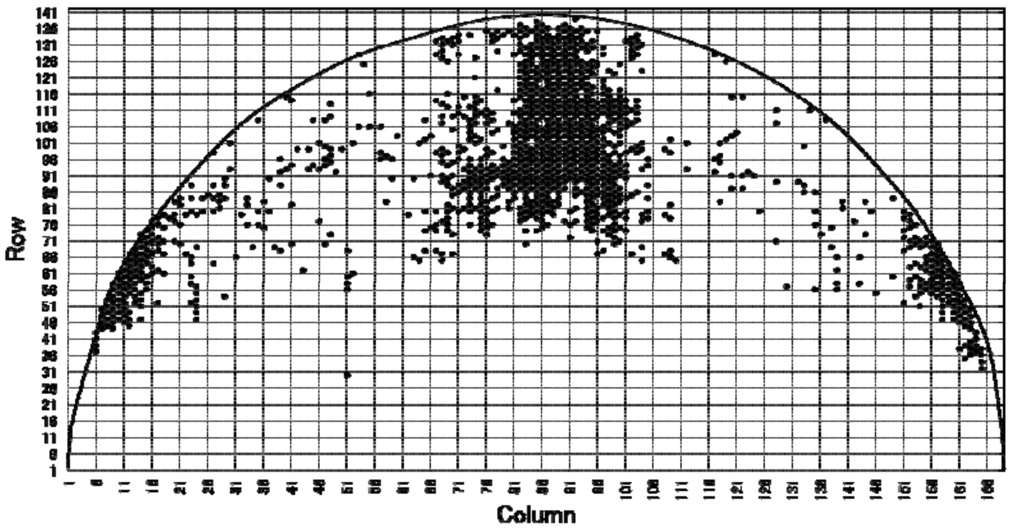


(b) 2B-SG

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

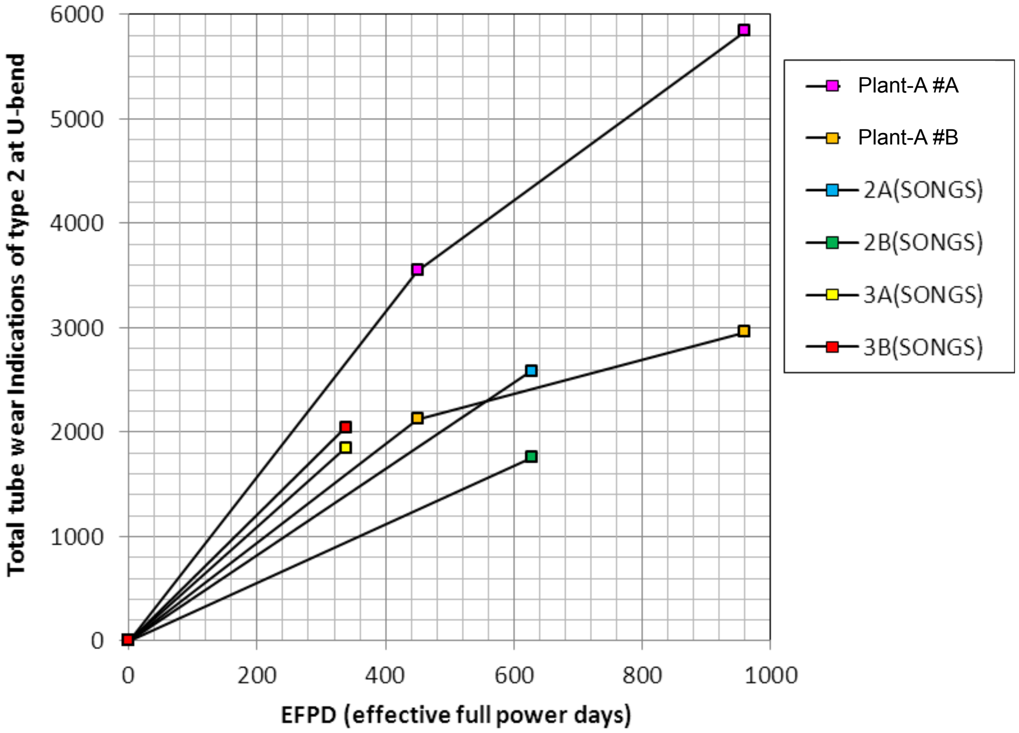


(a) 2A-SG



(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)

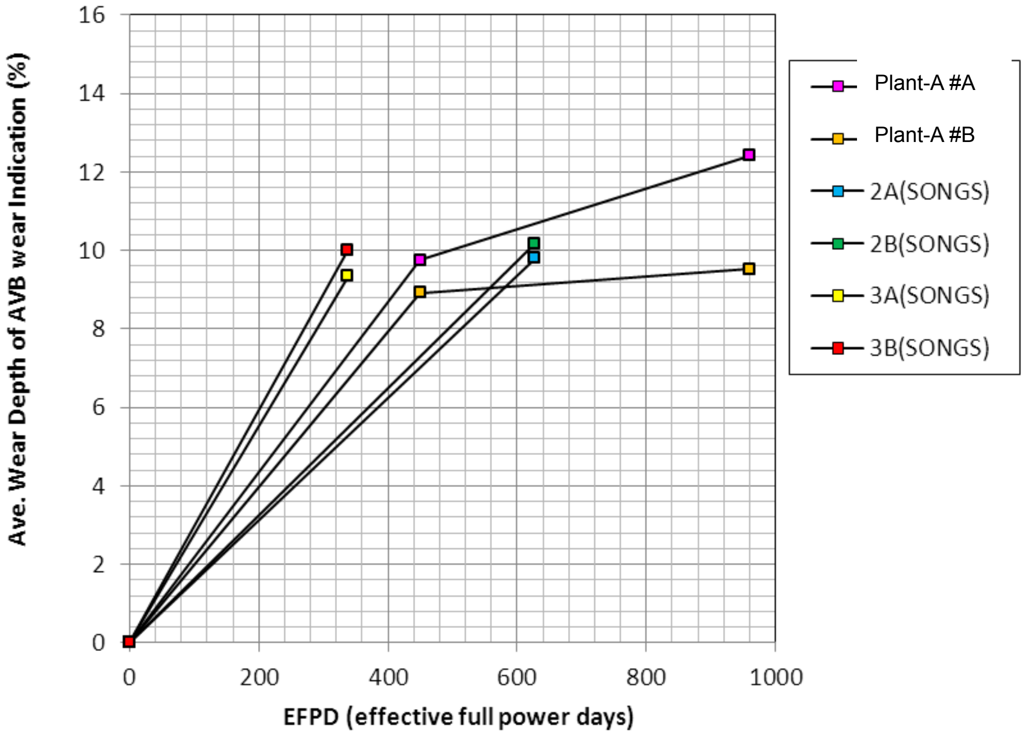


Fig.3.2.1-5 Average Tube-to-AVB Wear Rate
(based on information from NRC ADAMS ML11270A015 and ML093230226)

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.

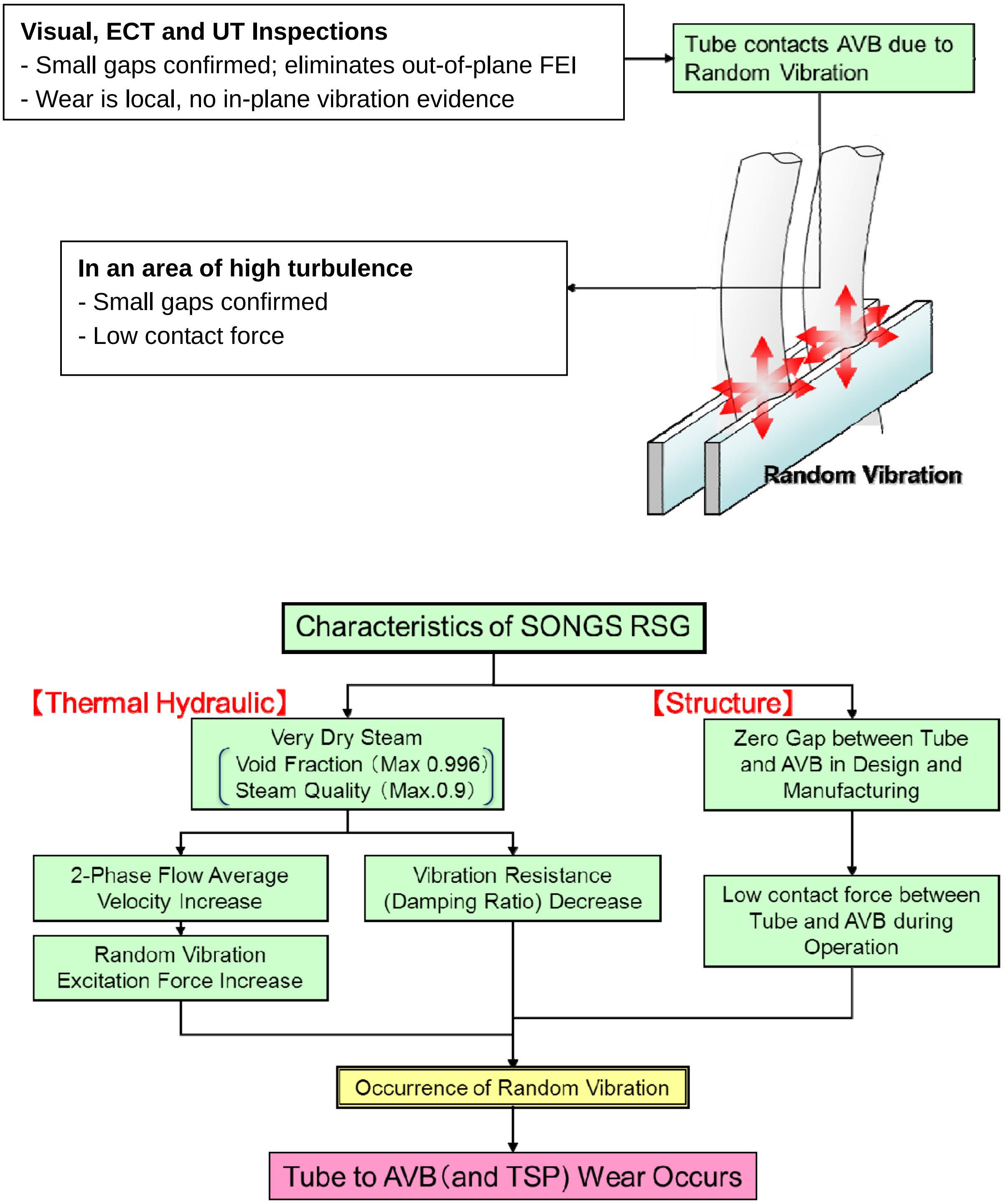


Fig.3.3-1 Type 2 Wear (AVB wear) Mechanism

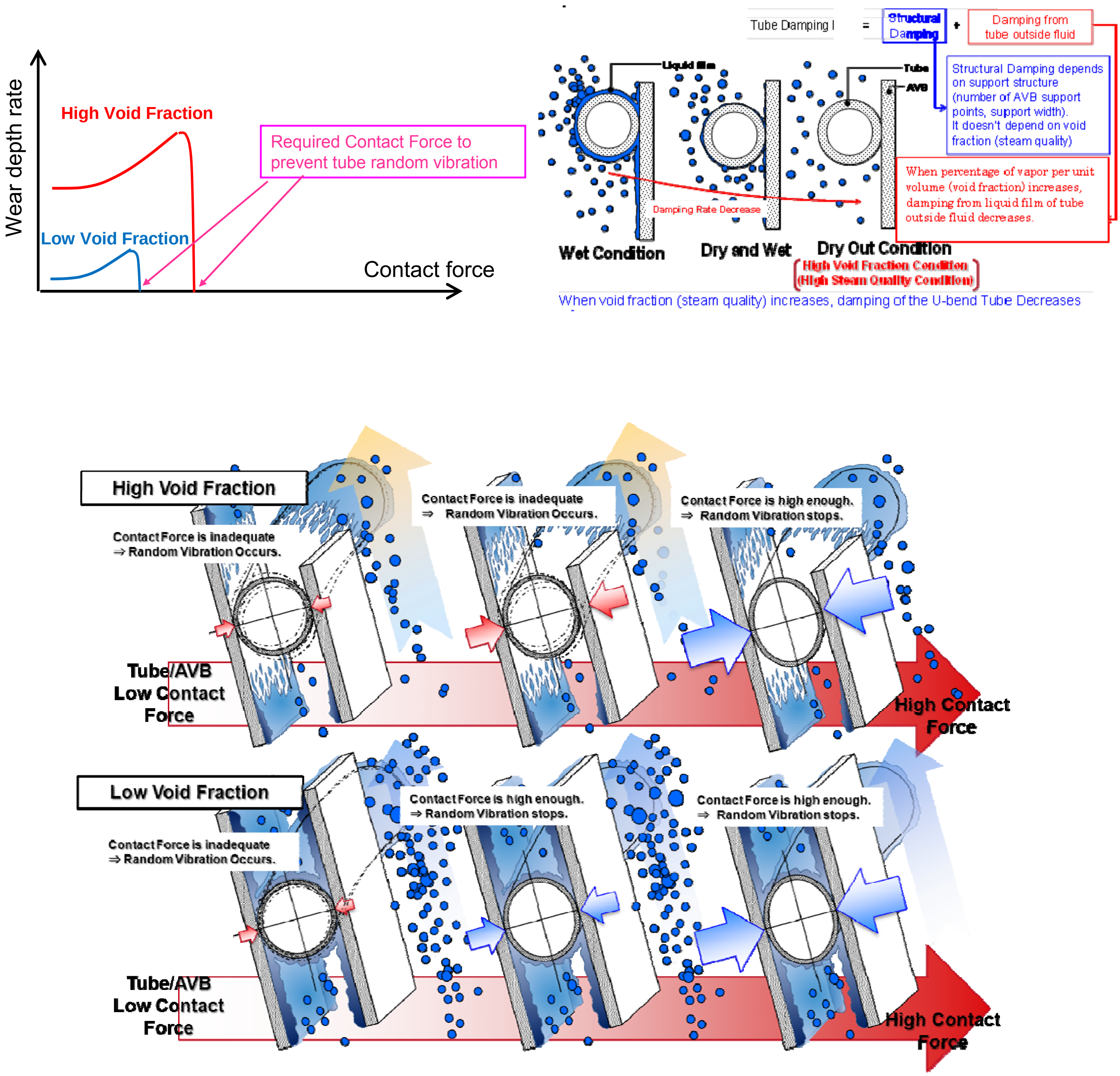


Fig.3.3-2 Contact force sufficient to prevent random tube vibration

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.

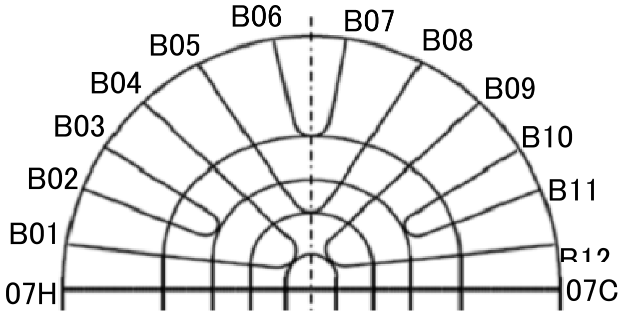
Scenario #1: In-plane FEI in Unit 3 had no precursor

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

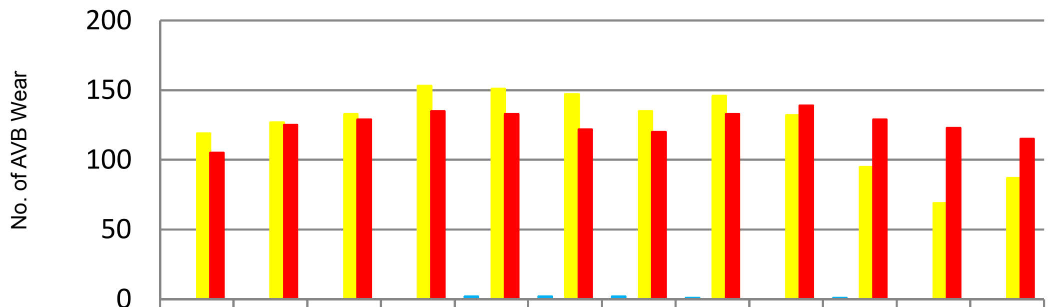
The first scenario is more likely supported based on the investigation below (See Fig.3.5-1 and Fig.3.5-2):

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.

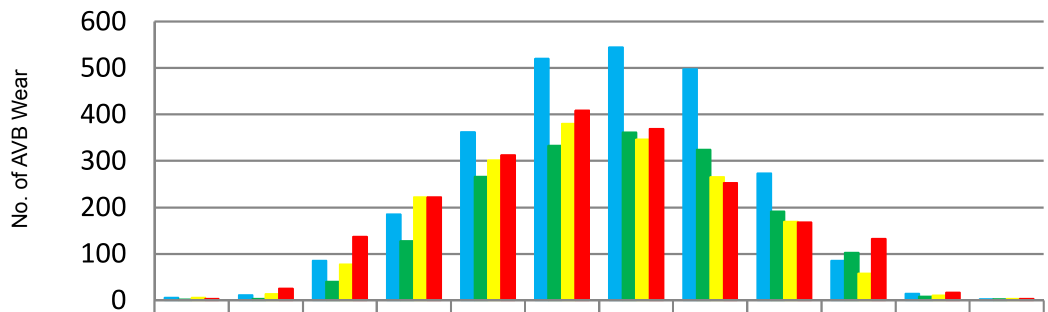


Number of TTW Tube with AVB wear



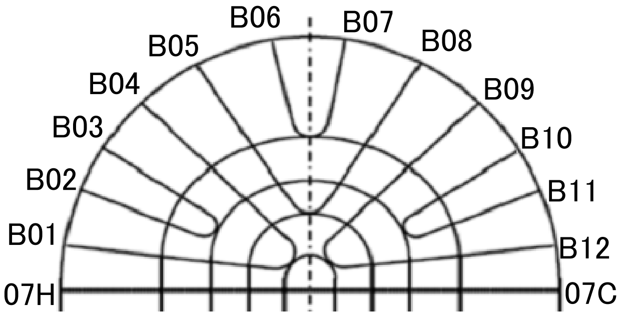
	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A TTW	0	0	0	0	2	2	2	1	0	1	0	0
2B TTW	0	0	0	0	0	0	0	0	0	0	0	0
3A TTW	119	127	133	153	151	147	135	146	132	95	69	87
3B TTW	105	125	129	135	133	122	120	133	139	129	123	115

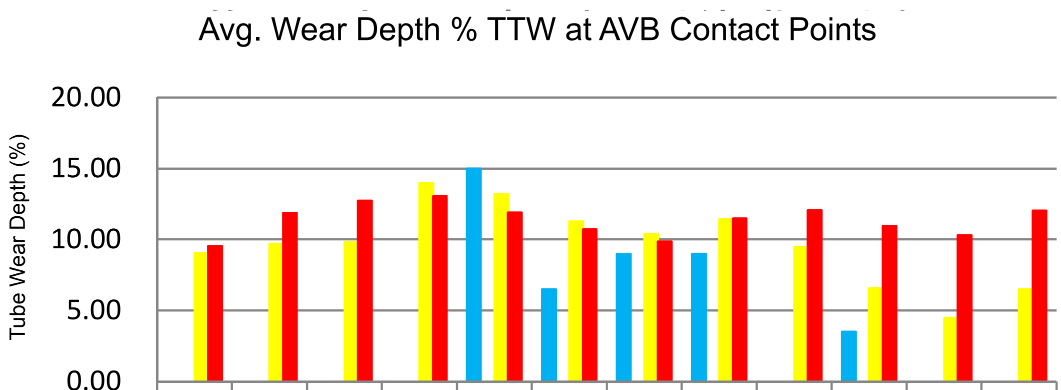
Number of Tube to AVB Wear Tubes (excluding TTW tubes)



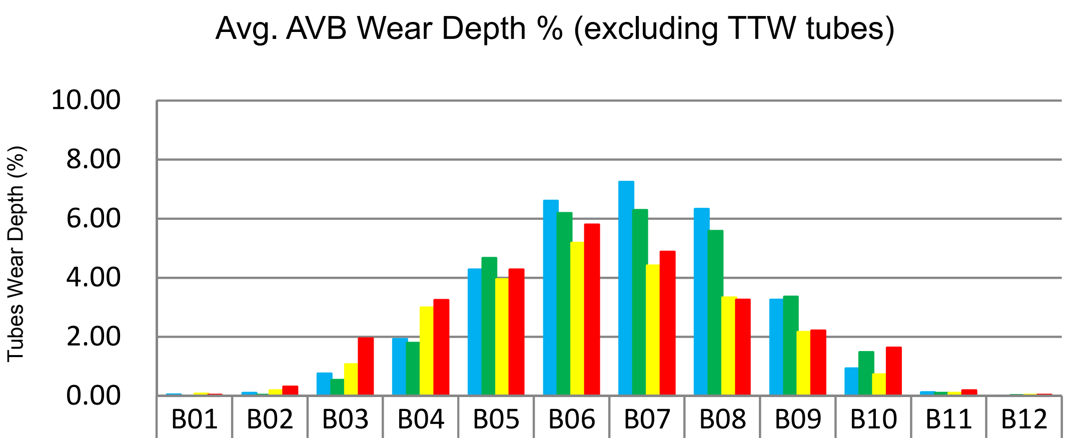
	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
2A AVB	5	11	85	185	362	520	544	497	273	85	14	2
2B AVB	1	3	40	127	266	333	361	324	191	102	8	2
3A AVB	5	13	77	222	301	380	346	265	169	57	10	3
3B AVB	3	25	137	222	312	408	369	252	167	132	16	3

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.

<u>Tube and AVB Fabrication and U-bend Assembly</u>

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 A New Paradigm

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^{o} (hot leg side) and 135^{o} (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

[11] ASME Press, New York," Flow Induced Vibration in Power and Process Plant Components", Au-Yang, M. K

[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

[15] MHI report, "Experimental Study on Impact/Fretting Wear Evaluation of S/G Tube and Tube-Support", 2507637A, June 1987

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.

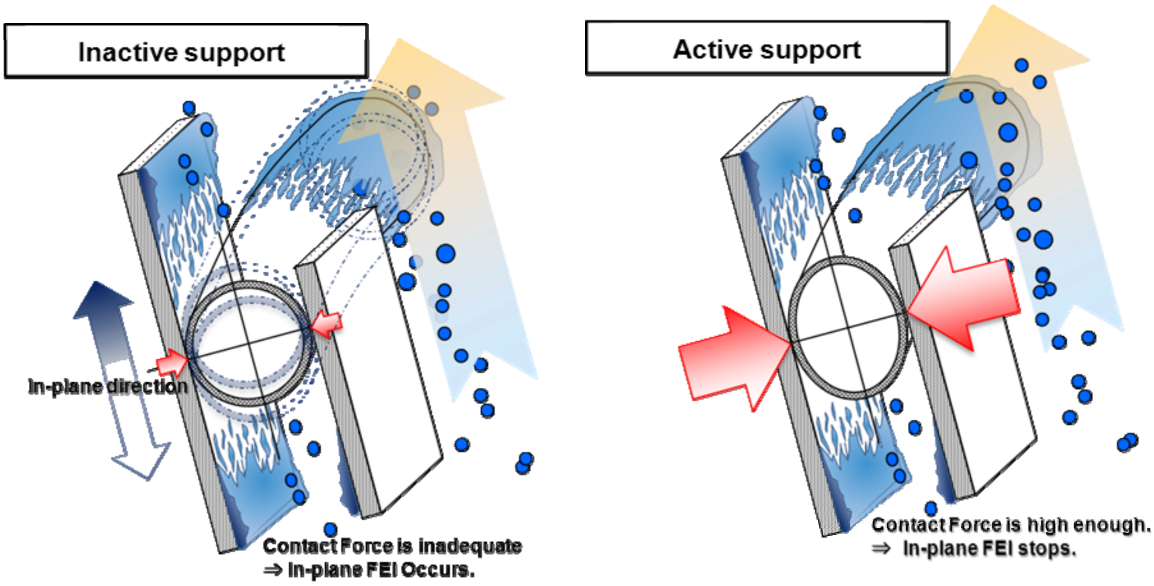


Fig. A2-1 Correlation between Number of inactive supports and Critical velocity

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.

SOUTHERN CALIFORNIA
EDISON®
An EDISON INTERNATIONAL® Company

Dwight E. Nunn
Vice President

November 30, 2004

Mr. Akira Sawa
General Manager
Mitsubishi Heavy Industries, LTD
Kobe Shipyard & Machinery Works
1-1, Wadasaki-Cho 1-Chome
Hyogo-Ku
Kobe 652-8585
Japan

Dear Mr. Sawa:

Subject: Replacement Steam Generators
San Onofre Nuclear Generating Station, Units 2 & 3

Since I was unable to participate in the Replacement Steam Generator contract signing in September due to emergent problems at our facility, let me now express my appreciation for Mitsubishi Heavy Industries' willingness to partner with us on providing the replacement steam generators for San Onofre. This is an extremely important undertaking, not just for San Onofre, but for the entire Southern California Edison Company. Our detailed and exhaustive evaluation convinced us that Mitsubishi Heavy Industries was the best match for our needs.

This will be one of the largest steam generators ever built for the United States and represents a significant increase in size from those that Mitsubishi Heavy Industries has built in the past. It will require Mitsubishi Heavy Industries to evolve a new design beyond that which they currently have available. Such design evolutions require a careful, well thought approach that fully evaluates the risks inherent in creating a new and significantly larger steam generator. Such design evolutions tend to challenge the capability of existing models and engineering tools used for proven steam generator designs. Success in developing a new and larger steam generator design requires a full understanding of the risks inherent in this process and putting in place measures to manage these risks. Understanding the difficulty in transitioning from the standard Mitsubishi Heavy Industries steam generator design to a new and larger two-loop design, San Onofre has made it a goal to partner with Mitsubishi Heavy Industries and maintain a close relationship with your engineering and fabrication organization to assist them in this design evolution. To this end we are performing detailed, intrusive evaluations of your design documentation and your approach to design evolution on this job. A recent example of successful cooperation between our engineers is the design of the feedwater distribution system. San Onofre's concern with potential water hammer as a result of the design of the distribution ring has been address by Mitsubishi Heavy Industries by utilizing the J-tube design. Prudent questioning by San Onofre followed by an exhaustive evaluation by Mitsubishi Heavy Industries led to a design revision to address a potential risk to the success of the project. However, we recognize that we are not designers of steam generators and there are limitations to the assistance we can provide. Notwithstanding this fact and after working with your organization for almost two months, we have some observations that we'd like to share with you.

P.O. Box 128
San Clemente, CA 92674-0128
949-368-1480
Fax 949-368-1490

- A detailed and accurate calculation of Reactor Coolant System flow is critical to ensure the steam generators are designed to within limits required to satisfy our existing licensing basis of 106% of the original flow rate (as required by our Purchase Order). Failure to meet this requirement would have significant impact on the operation of San Onofre including a potential inability to operate the units. We understand that Mitsubishi Heavy Industries is currently in discussions with Westinghouse to develop a detailed loop model to perform this analysis. We support Mitsubishi Heavy Industries' sensitivity to the significance of this issue and the prudent course of action they are undertaking.

- Anti-Vibration Bar design (and installation) is by far one of the most challenging tasks that will face Mitsubishi Heavy Industries and San Onofre; in fact, it is in our opinion the single most significant task facing the industry for steam generators of our size today. Since the San Onofre steam generators are one of the largest steam generators ever built and large steam generators appear more susceptible to wear (in fact, our current steam generators have experienced a high percentage of plugged tubes due to wear), it is a paramount concern of ours that we ensure a reliable support design. We consider this engineering challenge perhaps the most critical issue at this time. Recent industry experience with Anti Vibration Bar supports has demonstrated the difficulty in developing a successful design (the recent experience at a United State's plant emphasized this point when more that 180 tubes were found to have wear indications after only one cycle of operations, some of these indications were up to 20% through wall). Our discussions with Mitsubishi Heavy Industries to date have not resulted in a plan that will successfully address this industry concern. Both San Onofre and Mitsubishi Heavy Industries are having difficulty in formulating such a plan.

- San Onofre is located in a high seismic zone. As Mitsubishi Heavy Industries is aware this creates significant design challenges, especially in light of the fact that the San Onofre steam generators are among the largest ever built in the United States and are the largest ever built by Mitsubishi Heavy Industries. We have been working very closely with your staff to assist them in any manner we can in this design effort. As part of this seismic design effort, Mitsubishi Heavy Industries developing a stick mass spring model for the new steam generators. In addition, Mitsubishi Heavy Industries is developing some localized three-dimensional models of the new steam generators to benchmark the stick model. However, these models aren't ready for use at this time and the design effort must proceed to meet the 2008 delivery date for the steam generators for Unit 2. Consequently, the design of the new steam generators is currently proceeding using the existing steam generator seismic response based on a like-for-like replacement concept (although the old and new steam generators will be similar in many respects they aren't like-for-like replacements). Should there be a significant difference in the seismic response of the old and new steam generators, changes in the steam generator design may be necessary. Therefore, it is imperative that adequate margin be provided in the replacement steam generator design to accommodate this possibility while simultaneously expediting the necessary new analysis (procurement of major components is currently in progress and purchase of new forging can't be accommodated in the schedule should it become necessary). The development of an accurate stick model, using conservative assumption and subsequent validation of this stick model using results from the three dimensional models is essential to minimize the risk of any future design modification after the major forgings are procured and/or machined.

- The San Onofre steam generator moisture separator assembly will be the largest Mitsubishi Heavy Industries has ever designed. The configuration of the moisture separators and dryers and their ability to achieve the required performance remains a concern for San Onofre. Scaling up an existing design is not necessarily a linear task and if not performed correctly may result in unsatisfactory performance at San Onofre. Mitsubishi Heavy Industries is encouraged to consider using all available resources (such as being done with respect to the Reactor Coolant System flow analysis) in the design the steam generators to ensure acceptable performance.

Based upon these observations, I am concerned that there is the potential that design flaws could be inadvertently introduced into the steam generator design that will lead to unacceptable consequences (e.g., tube wear and eventually tube plugging). This would be a disastrous outcome for both of us and a result each of our companies desire to avoid. In evaluating this concern, it would appear that one way to avoid this outcome is to ensure that relevant experience in designing larger sized steam generators be utilized. It is my understanding the Mitsubishi Heavy Industries is considering the use of Westinghouse in several areas related to scaling up of your current steam generator design (as noted above). I applaud your effort in this regard and endorse your attempt to draw upon the expertise of other individuals and company's to improve the likelihood of a successful outcome for this project. I would encourage you to continue to draw upon those resources available to you to produce a design that will represent a Mitsubishi Heavy Industries steam generator capable of meeting not just San Onofre's, but the world's needs.

Should you have any questions or desire further discussion on this matter, I can be reached at (949) 368-1480. I look forward to visiting your facility again in the near future.

Sincerely,

Dwight E. Nunn
Vice President

cc: Y. Nishi
J. E. Hutter
H. Kaguchi
H. Hirano
M. Ida
M. A. Wharton
R. L. Park

Non-Proprietary Version

Technical Meeting Report
for the meetings during the week of March 28, 2005

Abstract

Meetings were conducted in Japan between Edison, MHI and ( ) with the main goal of finalizing the Tubing Specification. Other technical topics were discussed as time permitted. This Report summarizes the meeting topics, discussions, and agreements reached during the week of March 28 through April 1, 2005. Since several topics relating to the Tube Specification were repeated during the week, the official record of final agreements will ultimately be the changes to the revised Tube Specification and the revised Edison Comment sheet which will be supplied to Edison shortly.

Document List

The following documents were used during these meetings. Documents that have not been issued to Edison by other means are attached to this Report.

Item	Title or Subject
A	Technical Discussion Meeting Agenda of the week of March 28, 2005 (Rev.6)
B	Attendance Diagram(3/28/05)
C	Edison-MHI-( )Meeting at( )on March 28, 2005
D	(MHI) Technical Discussion Material in the week of March 28, 2005 – Part 1
E	(MHI) Technical Discussion Material in the week of March 28, 2005 – Part 2
F	Reply to Edison Comment for Purchase Specification L5-04FZ041(0)-M3
G	Reply to Edison Comment for PPQ (not discussed)
H	( )'s proposal on G value tolerance including G value actual Data
I	Attendance Diagram (3/30/05)
J	The Work Scope and the Methodology of the water Level Controllability Study for the Replacement Steam Generators
K	SG Performance for SONGS Units 2 & 3 Replacement Steam Generators
L	Figure (Blockade ratio vs Dumping factor)
M	Fabrication sequence and technique of Tubesheet cladding
N	Outline of Consumable Control for SONGS RSG
O	Justification of Laser beam OD measurement method
P	Analysis of Tube Support Plate
Q	Technical Meeting on Channel Head Design Presentation
R	Analysis for Upper Head and Upper Shell (includes Steam Nozzle)
S	SONGS RSG Tube Specification Open Items Resolution Schedule
T	Position Paper on Tube Ovality and U-bend Tube Flatness

March 28, 2005 Meeting

The meeting was conducted at the offices of( ) in ( ], Japan. In the morning( ) provided MHI and Edison personnel an overview of the tube fabrication process, which included a shop tour. After lunch, MHI and Edison conducted a private meeting to discuss Edison comments on the MHI tube specification. Following is a summary of these discussions. These topics were re-discussed during the remainder of the week, so some of these notes may not be the final point of resolution.

Attendees

( )

Afternoon Technical Discussion

( ) presented the first 10-slides of a MHI handout describing MHI's design basis for the U-bend support system. The purpose of this presentation was to prompt a discussion of the U-bend gap control issue which has direct bearing on the tube sizing requirements.

Comment #1 (( )) "MHI has experience with small SGs and the SONGS RSGs have large U-bends, therefore the prior MHI experience is invalid."

Comment #2 (( )) on the Tubed Heat Exchanger Manufacturer's Association (TEMA) design standards which recommends a tube-to-support clearance of( ]" for heat exchangers with tubes in cross-flow – "that's not applicable because heat exchangers are small and the SONGS RSGs are large."

The MHI presentation emphasized the influence of the tube diameter on U-bend gap control, especially within a single column. The variations in thickness of AVB bars and / or the variations in tube spacing (pitch) were not addressed in detail during the presentation. This prompted the following two action items.

Action Item #1: "MHI to provide actual values for AVB thickness, G-values, and pitch variations (design value with tolerance)."

Action Item #2: "MHI to demonstrate the influence of pitch variation on gap control for AVB design."

Two U-bend Assembly Strategies: MHI described two cases or approaches being considered for U-bend gap control. The first was to assemble the bundle "cold" without leaving space for tube expansion due to pressure and temperature. This approach assumes the operational expansion of U-bend components will not overload individual tubes, but will just cause the assembly to spread apart slightly. Such a design approach would reduce the average tube-to-AVB gaps within the bundle by approximately [ ]" / tube pitch. The second approach is to assemble the bundle "cold" with extra clearance (conventional approach) to allow space for the operational expansion of the U-bend components so there is no "flowering" of the U-bend and, on average, no significant tube clamping forces.

It is the first case that lead MHI to the conclude that (a) the variations in AVB thickness and pitch are secondary influences on tube-to-AVB gap control and (b) that such an approach requires assurance that the U-bend can indeed expand (i.e. is not constrained by either the top TSP or the AVB retaining bar structure).

The Tube-to-AVB Gap Influence on Tube Support [ ] stated that ideal tube support is achieved when the tube is in contact at each of its tube supports. Where the structure must be designed with clearances between tubes and supports, this ideal support condition can still be achieved by one-sided tube support (i.e. the tube is located so the tube-to-support clearance is all on one side of the tube).

Furthermore, when a tube is placed between two AVBs, it is the smaller gap that determines the effectiveness of the tube support. This means the worst-case (i.e. largest possible gap) is when the tube is equidistant from its supports. So, for a U-tube delta-G value of [ ]" the maximum gap used to determine the effectiveness of the support and used in the tube wear calculation is half of the total gap ([ ]").

U-bend Delta-G Value: During the presentation, it was stated that the delta-G value has two major components. The first is the variation in tube diameter over the entire tube length (i.e. the straight tube diameter variation) and the second is the change in tube diameter caused by the U-tube bending process. This led to the awareness that tighter control of the tube diameter at the straight length stage may be a good way to reduce the U-bend delta-G-value.

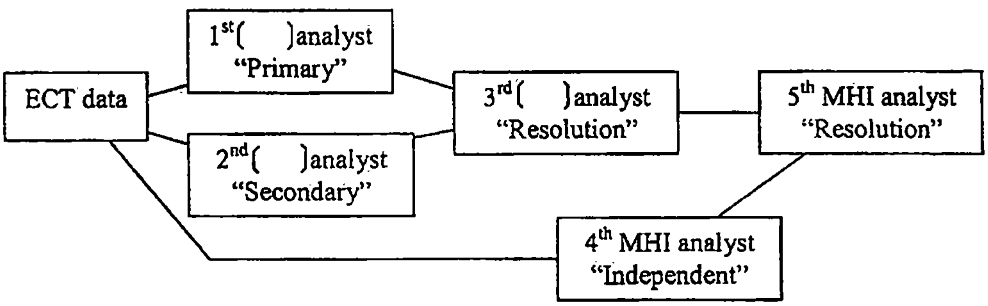
Summary of the U-bend Delta-G Value Issue: Edison is pressuring MHI to minimize the U-tube delta-G value – but admittedly does not know how small it can be. The value in the current MHI tube specification is [ ]" which is larger than the [ ]" value typical of [ ] tubing specifications (according to Edison). [ ] has reported values from the [ ] tube bundles that are within [ ]", although the [ ] tube specification had a larger allowable delta-G value. MHI agrees that the smaller the U-tube delta-G value, the greater the assurance that the tubes will be supported by "active" supports, but has not determined how to specify it without impact on the tube fabrication schedule and/or cost. Edison and MHI agree that neither schedule delay nor increase in tube cost is desired.

Discussion of MHI Responses to Edison Comments

Following are notes of the first review of the MHI responses to the Edison comments on the Tubing Specification. These notes do not necessarily represent the final actions for these items.

L5-04FZ041(0)-M3 Item number	Action (3/28/05 meeting)
3.a Tube Material Supplement S1	Edison & MHI agreed that the ASME Code rules are to be followed. MHI will rewrite the response to say "Supplement S1 for SB-163 will be followed." MHI will discuss the application of S1 for SG tubing with their ANI and will report the result to Edison.
3.b.	Edison accepted MHI's answer; but MHI will shorten the response and will eliminate the sentence "We will submit SDR"
4, 5, 6, 7, 8, 9	Edison accepted MHI's responses without discussion.
10 Roughness standard	MHI will revise the response stating the JIS standard is used. Edison requested this standard be supplied in English.
11.a Words "laps, scratches, stains & discoloration"	MHI will revise the response and will include these words in the Tube Spec.
11.b	Edison accepted the MHI response
12. Largest U-bend size for stress relief	Edison accepted the MHI response. In addition, Edison asked MHI to supply data on U-bend residual stresses for tubes larger than row-13 (this was discussed further in later meetings).
13. Uses of industrial water (for rinsing or cleaning)	Edison is seeking clarification of use of industrial water. MHI will check with( )and will add the information to the response (this was discussed further in later meetings).
14.	Edison accepted the MHI response.
15.	Edison showed MHI that the CDS 7.1.8 last paragraph says that "all tubes" will have special dimensional measurements. CDS Section 9 of the Purchase Order lists measurement of all the U-tubes at the AVB contact regions. MHI admitted they had misread this section of the CDS (this was discussed further in later meetings).
16.	The CDS requires measurement of % wall reduction after bending at the joint between straight and bend. MHI will measure t at this location but cannot measure t at the same location prior to bending. (this was discussed further in later meetings).

L5-04FZ041(0)-M3 Item number	Action (3/28/05 meeting)
18.	Edison asked for an integrated discussion of why ovality requirement is not more consistent with the G-Value requirement. MHI answered that ovality is based on a separate criteria relating to tube stress and tube collapse. It is not as limiting as the G-Value. Edison asked for[ ] ovality[ ] data to compare with the G-Value (this item was discussed further in later meetings).
19.	Edison thinks the U-bend flatness requirement in the Tube Specification is high. MHI agreed to provide a position paper describing the basis for the flatness value (this item was discussed further in later meetings).
20.	[ ]needs to tell MHI & Edison if they can use the[ ] notch width (this item was discussed further in later meetings).
23.	CDS Table 3.11-1 requires MHI to perform an independent analysis and resolution of tube ECT. This means MHI independently analyzes the ECT data, without knowing the [ ]answers. When complete the[ ]and MHI results are to be compared. An independent MHI analyst "resolves" and differences (this item was discussed further in later meetings).



L5-04FZ041(0)-M3 Item number	Action (3/28/05 meeting)
26.	Edison requested a copy of the acceptance standards for Vessel & Physical examinations including standard and discoloration. MHI will ask[ ].
29.	Room temperature stress-strain curves – Edison would like all data they can get – no extra work intended. MHI will ask [ ](this item was discussed further in later meetings).
30.	Edison requested the[ ]NDE reference standards be shipped to Edison for use on Pre-Service NDE. Also requested were as-built drawings of the reference standard.
31.	Edison commented that a catalog of defects (acceptable / unacceptable) should be prepared by[ ]from historic data.
36.	Figure 11.b. S/N ratio for tubes – (1) How is the whole bundle average S/N ratio determined? (2) How is the calculation performed? (3) Which is the tube with the "worst" S/N ratio? (refer to CDS 7.1.6) (this item was discussed further in later meetings)
37.	Edison asked MHI to see if[ ]can meet 5% ding requirement rather than 8% - that way MHI would have 5% margin in their factory rather than only 2% (this item was discussed further in later meetings).
38.	The CDS figure 3B-1 limits MBMs to 10/SG. EDISON suggested MHI lower the ding number being 10% and increase the MBM # from 10 total/SG to something reasonable. A small Number of MBMs is desired but leaving scratches that aren't buffed to avoid MBMs is not desired either. The goal of the suggestion is "No schedule or commercial impact".[ ]reminded us that the acceptance levels were part of this too. MHI / [ ]were asked to propose a better balance of these criteria (this item was discussed further in later meetings).

March 29, 2005 at the [ ] Offices

(Private meeting between MHI and Edison)

Prior to the meeting [ ] explained his view of the [ ] RSG tube wear and how it applies to the SONGS RSGs. He said as gaps clog up the tube damping is reduced. At [ ] the OSGs had a lot of sludge build-up which produced water level instability. [ ] says when you wear at supports the gaps open up and tube frequency goes down. [ ] says the T/H modeling is the root cause of the [ ] – not tube support gaps. The SONGS OSGs had tube wear problems so they don't see why the RSGs will be different. They suggest a comparative analysis of the OSG and RSG. MHI should ask Edison to provide a typical ATHOS analysis with flow conditions on the OSG tube with the most well understood wear. With this information MHI may be able to perform comparative analysis. [ ] thinks the tube wear is not fluid elastic instability but rather due to "energy" input – he may mean turbulence, but this was unclear.

The discussion of the Tube Specification and the Edison Comments continued from the previous day. These notes are not the final record, as further discussions were held later in the week. The final record will be reflected in the revised Tube Specification and the revised Edison Comment document.

L5-04FZ041(0)-M3 Item number	Action (3/29/05)
40, 41, 42, 43	Edison accepted MHIs responses.
44.	Edison requests (1) proof of accuracy of laser tube measurement (2) does not accept laser. The CDS requires UT. A negotiating point being used by EDISON to pressure MHI (this item was discussed further in later meetings).
45.a & b.	Edison clarified their intent – (1) CDS page 3-65, 3.11.2.3-.2 ECT (a) PPQ, (2) page 3B-23, 10.3(a) – all "finished" PPQ tubes (some are split before final processing) should be examined by bobbin coil – all tubes in straight form prior to bending and for the bent tubes, a second inspection after bending (this item was discussed further in later meetings).
45.c.	Answer accepted. Edison will do data analysis for S/N for information.
46.	Addressed by actions on #45.
47.	For the PPQ, report analysis results without regard to ECT voltage flow chart. Report everything that is above the noise level of the tube. [ ] wants a minimum criterion. MHI proposed and Edison agreed that the [ ] analyst would determine what is called and reported (this item was discussed further in later meetings).
48, 49, 50, 51, 52, 53	Edison Accepted the MHI responses.

L5-04FZ041(0)-M3 Item number	Action (3/29/05)
54.	Edison needs the ECT analysis to be based on the Edison CDS figure 3B-1. (1) Remove the first "gate" based on the maximum noise level. (2) The wall loss criteria is based on phase rotation and theoretically could be zero voltage wall loss signal and be rejectable (MHI thinks 'zero' should be a small value, but not zero). (3) NQS criteria will be based on PPQ and agreed criteria / method prior to production. Also and action plan for how to resolve (for instance rotating coil). (4) MHI wants / needs to consult ECT experts to clarify the NQS and wall loss criteria – but other than that they (1) understand the Edison requirement to remove the( )VPP box and (2) will remove it (these topics were discussed further in later meetings).
56.	Covered in discussion #54.
57.	MHI will delete comment beyond sentence #1.
58.	TBD tomorrow – MHI / Edison (this item was discussed further in later meetings).
59.	Accepted item b is "minimum" (this item was discussed further in later meetings).
60.	Edison promised to give information to MHI (today) (this item was discussed further in later meetings).
61.	Discuss with( )later today (this item was discussed further in later meetings).
62 & 63	Accepted.
64.	Similar to #18 – discuss with( )(this item was discussed further in later meetings).
65.	Accepted.
69.	(a) See #23, MHI will change answer replacing "record" with "acquired raw data". (b) See #45.
72.	Discuss with( )(this item was discussed further in later meetings).
73.	Accepted.

March 29, 2005 at 11:45 AM

After private discussions between MHI and Edison were competed,( )returned to the meeting and all of the Edison comments and MHI responses found in L5-04FZ041(0)-M3 were discussed again.( )provided some new information and some item responses were revised again. This record is not complete and not final. The official changes will be seen in the revised Tube Specification and the revised Edison Comment document.

L5-04FZ041(0)-M3 Item number	Action (3/29/05 part 2)
7.	( ) will put ( )°F in their specification. MHI's spec doesn't include it.
10.	The JIS roughness specification B0651 (in English) will be provided by MHI /( ) to Edison.
12.	( ) showed residual stress data measured by strain gauge & sectioning showing tensile values for R = 316mm (~13") to R=60" ( ) to ( ) MPa (( ) to ( ) Ksi). MHI will provide Row-1 alloy 600 residual stress data tomorrow (this item was discussed further in later meetings).

After lunch ( ) presented Delta-G Value data and proposed the following...

For R1-13 (R < 12") Delta-G ≤ ( ) mil (( ) mm)
For R14-142 (R > 12") Delta-G ≤ ( ) mil (( ) mm)

Edison took a few moments to consider this proposal. Edison asked if MHI was pleased and accepted the ( ) proposal. MHI said yes. Edison asked MHI if they could design a U-bend with adequate vibration and wear margin based on these values. MHI said yes.

(a) ( ) proposed to measure the G-Value for every tube at the apex using a Go / No-Go gauge – 9727 tubes
(b) ( ) proposed 1-tube in each row measured at all AVB intersections – actual measurement by micrometer (142 rows, 1 to 12 AVB locations).
(c) ( ) proposed for 5% of each row to measure G-Value at the apex by micrometer measurement (5% of 9727 = 486 tubes)

Edison asked "what dimension will MHI design to?" Answer: data comes after design so must use max (or min) value as design basis. ( ) data may be used as part of the design basis. Edison stated that the CDS requires ~60,000 measurements where ( ) proposes ~1500 measurements. Edison concluded "thank you for your proposal – we will discuss with MHI" (this item was discussed further in later meetings).

The meeting proceeded until all items on the Edison Comment sheet had been re-discussed. Final agreements will be captured in the revised Tube Specification and the revised Edison Comment document.

Non-Proprietary Version

Following is a table summarizing the technical Open Items on the Tubing Specification.

SONGS RSG Tube Specification Open Items Resolution Schedule

<table>
<tr><th>Comment No.</th><th>EDISON Comment</th><th>MHI Proposal</th><th>Resolution Schedule</th><th>Critical Item</th></tr>
<tr><td rowspan="3">13</td><td rowspan="3">a). Specify the stage of manufacturing where industrial water may be used for rinsing, e.g., prior to final cold drawing.
b). If industrial water is used after cold drawing the method of cleaning after that needs to be clarified.</td><td>MHI will propose an alternative tube ID cleaning procedure for Edison review prior to PPQ.</td><td>The alternative cleaning procedure (April 28, 2005)</td><td rowspan="3">- PPQ
- Cleaning for production tubes</td></tr>
<tr><td>MHI will verify the procedure during PPQ.</td><td>Verification for the procedure (≤ Dec. 2005)</td></tr>
<tr><td>MHI will develop a contingency plan.</td><td>if necessary</td></tr>
<tr><td>15</td><td>The delta G dimension of[ ]inch appears to be excessive compared to current industry practice. Please provide the basis for the delta G max number. Please confirm that that the delta G max relates to the entire RSG.

Measuring 2pcs per row is not acceptable. CDS para 7.1.8 which says" Special dimensional inspection of all tubes shall be performed to verify compliance with dimensional requirements at AVB locations".

Note: CDS requires dimensional inspection.
It does not mean measurement.</td><td>MHI will negotiate with[ ]about measurement frequency for G value.
1. Agree to confirm every tube G-Value is in specified band (GO-NOGO)
2. Practical proposal ([ ] tubes/day)
(1) 100% GO/NO GO check at Apex.
(2) ?% measurement at Apex.
(3) ? tube/Row/SG. All AVB locations.
3. Verify the procedure during PPQ</td><td>The alternative delta G measurement procedure (April 28, 2005)</td><td>PPQ</td></tr>
</table>

Comment No.	EDISON Comment	MHI Proposal	Resolution Schedule	Critical Item
16, 61	Note 2 is a deviation from CDS and is not acceptable.	PPQ : All bent tubes in the PPQ will be measured (0, 45, 90, 135, 180 degrees).	Done	PPQ
		Production : Measurement frequency will be negotiated with ( )	MHI will negotiate with ( ) by Apr. 28, 2005	
18	Edison has previously expressed concerns over the potential problems with this level of ovality and AVB gaps. This concern has not been resolved. It has been reported that ( ) has achieved significantly lower levels of ovality on a recent project. Edison would like to know what ( ) can achieve and how the AVB concern is resolved.	MHI provided a position paper on April 1, 2005.	Done. See notes from 4-1-05 later in week.	N/A
19	a). The flatness tolerances appear to be too high. b). Clarify how they will affect AVB gaps.	MHI provided a position paper on April 1, 2005.	Done. See notes from 4-1-05 later in week.	N/A
37	a). It is not clear to Edison how so many dings could be produced during tubing production. b). Edison requires that MHI withhold ( )% dings for other conditions that may arise during tube installation at MHI. c) Edison has additional requirement for the number of MBM and Ding.	MHI agrees to have no gate at top of the ECT chart.	N/A	N/A
		Total acceptable indications and tube numbers for Ding and MBM comply with the Edison specification.	Later	N/A
		Edison and MHI ECT Level 3s will discuss detailed criteria.	in April 2005	Production
38	Clarify how zero MBMs can be produced.	Same as #37	Same as #37	Same as #37
44	Laser beam method contradicts CDS.	MHI provided data for the laser beam method.	Done. See notes from 4-1-05 later in week.	PPQ
56	Any proposed amplitude threshold is unacceptable for wall loss type indications. This shall apply to both the straight and bent sections of the tube.	Same as #37	Same as #37	Same as #37

Non-Proprietary Version

Comment No.	EDISON Comment	MHI Proposal	Resolution Schedule	Critical Item
58	The issue is not clear, in particular the language "The tolerance in inch unit is larger than ones in metric unit, to avoid the permissible tolerance to cross between metric unit (actual fabricated dimension) and inch unit (just translated dimension). We think that the Code requires a tolerance of + or -( ) inch and ( ) violates Code, and that for Code purposes, inch units must be used.	MHI agrees with Edison comment. MHI will revise the specification.	By April 28, 2005	N/A

March 30, 2005 Meeting

Confirmation of the Tube Spec. Open Item

MHI and Edison confirmed the Tube Spec. Open Item, and MHI explained the MHI's proposal. After that, Edison showed the Edison's position for each Open Items. Finally, MHI was made to explain Resolution Schedule for Tube Spec. Open Items on April 1, 2005. (This Resolution schedule is shown the last page.)

Water Level Controllability

( )presented the work scope and the methodology of the Water Level Controllability Study for SONGS RSG. This presentation was based on the experience of Japanese SG water level controllability analysis. Therefore, MHI and Edison discussed with reliability of the Code, because MHI didn't have experience of the large SG such as SONGS RSG.

Action:

- For OSG of water level control (6/E)
 (1) MHI to check what is needed. (4/7)
 (2) MHI to issue letter which requests what is needed for Analysis and Verification.
 (3) Edison to provide Plant data for calc. condition. (4/17)
 (OSG water level analysis if available.)
- For RSG Analysis (8/E)
 (4) Operating Parameter Study to be performed based on parameter range specified in Spec.

March 31, 2005, Thursday Technical Meeting

Two meetings were arranged for the morning. One related to the Eddy Current Testing requirements involving an Edison NDE expert by telephone that began around 9:15 AM. The main meeting began at 9:40 AM. Prior to the meeting( )had a discussion about Edison Status classification of documents.

Water Level Stability

( )began with a discussion of the SG design process for setting wrapper annulus. This explanation, though accurate, was not complete enough for Edison to understand the sizing procedure to set the dimensions of each part (i.e. outermost tube location, TSP rim width, wedge space, wrapper thickness, lower shell OD & ID, annulus width).

Due to short time,( )moved directly to a presentation of the water level stability. ( )asked what causes or initiates instability. The answer was this is a steam generator "only" analysis and instability is begun by an arbitrary analytical assumption – not particularly real. The analysis determines if such a perturbation damps out (stable) or grows (instability).

A table showing SG damping factor Vs. downcomer annulus was presented. A 4" annulus had a damping factor of( ) and the current( )" annulus has a damping factor of( ). The typical acceptance limit is "more negative than ( )".

( ) offered his insights into this issue. He asked for comparison with other SG models. A slide showing sludge clogging of TSPs vs. stability was presented. Edison asked "what can be done to improve the design or make it better than other SGs"? None of the options were good ones. Edison repeated their concern that the RSG design may not be "optimum" because MHI is buying parts without having completed the design. Edison doesn't understand that the design process requires iterative optimizations of smaller and smaller magnitude and that most of the design choices were set during the proposal stage (which included significant design optimization). MHI needs to make more visible when and how key design trade-offs have been made.

In the CDS there is a requirement for a circulation ratio of 3.5. The reduction in downcomer annulus adds stability margin and reduces the circulation ratio to a value of 3.4.

<u>Action</u>: ( ) asked MHI to add to their "assumptions" sections in their reports explanations & reasons why certain assumptions are "appropriate" or "conservative" – not just a list of assumptions.

<u>Action</u>: ( ) noticed that the feedwater temperature of 442°F was used in the stability analysis. He commented that the RSG must be designed for a range of operating conditions (for example, T_{hot} between 598°F and 611°F). MHI needs to include in their analyses consideration of such ranges. Edison asked if there is a "Design Input document" for this project." MHI answered "yes" and committed to bring it to next week's meeting. The MHI / Edison team needs to establish a set of analytical parameters to be used for all the analyses, so that the results cover an operating window.

10:45 AM

Tubesheet Cladding Manufacturing

( ) made a comment that the tubesheet clad thickness of( )" (( )") (which is in the CDS) is too small. He mentioned a code requirement that the distance from the bottom of a weld repair zone may not come closer than ( )" (( )") of the clad-to-base metal interface. He recommends a larger clad thickness to avoid potential code violation due to tube-to-tubesheet weld repair or future material removal to accommodate certain tube plug types.

This was followed with a question about the MHI tube plugging procedure that may be applied. MHI answered that they use a non-welded mechanical tube plug when needed. MHI responded that they will use a two layer process which is thick. They believe the thickness value will be greater than the ( )" value. ( ) commented that the weld qualification for the tube-to-tubesheet weld should be based on the( )" minimum value to confirm that the code ( )" limit will not be violated.

Edison asked about [ ] clad issues. [ ] described long indications between clad layers that did not violate the [ ]" flat bottom hole criteria. MHI explained their analysis of the issue is not entirely conclusive; but their opinion is that the grinding of the 1st weld pass prior to the 2nd weld pass produced a variable contour that caused this condition. They intend to spend more time training the welders to spend adequate time grinding this interface to achieve a specific contour. MHI also emphasized that this weld indication is not common and was not present on the other [ ] tubesheet.

Another issue was tubesheet uniform thickness and its relationship to tubesheet joint crevice depth. Edison would like the MHI primary-to-secondary face parallelism requirement to be [ ]" rather than [ ]". MHI desires that the two surfaces be exactly parallel; but achieving exact parallelism is not as easy as changing the tolerance on the drawing. If the thickness varies more than desired, then the hydraulic expansion mandrel lengths can be adjusted for separate zones of the tubesheet.

Consumable Material Control

The next presentation was about the control of consumable materials. It appeared that MHI is complying with all the CDS requirements. Approval of their documents is needed ahead of the tubesheet cladding operations.

Measure of Tube OD by Laser

The laser beam method is similar to the UT process. The accuracy is reported as [ ]". Comparison with micrometer measurement was made and reported. The variation was within [ ]mm ([ ]") and includes the error in measuring with a micrometer. This measurement is made for two orthogonal diameters (top-to-bottom, side-to-side) as the tube moves by the measuring station.

<u>Action</u>:
(1) MHI to confirm what is the basis of data population.
(2) MHI to confirm which tube is rotated or not during the measurement.
(3) MHI to confirm of the definition of subtracts.

Tube Support Plate Presentation

MHI is soon to procure the TSP material and needs to set the TSP thickness. The TSP material will arrive in the factory in late summer. Drilling and broaching are scheduled to begin in September 2005. The purpose of the discussion was to discuss the basis for the TSP thickness. Other TSP details will be addressed at later meetings.

- TSP diameter is [ ]"
- TSP thickness is [ ]" ([ ]mm)
- 19,454 broached holes
- TSP has 20 vertical edge supports and 49 stay rods (the one at the center may be deleted)

- The top 2 TSPs have lateral support wedge groups around 100% of the TSP periphery. Lower TSPs have spaced lateral edge supports (highest lateral loads occur at the top 2 TSPs).

A discussion of TSP flow area and broached hole shape occurred next.( )said that thickness should be set based on out-of-plane displacement.

MHI is using NF-3220 for out-of-plane loads, NF-3280 for in-plane loads. NF-3280 apparently has a 10% reduction allowable for TSP crushing (this may be incomplete, see presentation).( )pressed MHI for E* and v* values from the in-plane and out-of-plane testing. He was of the opinion that it should match the values of the Code. MHI did not agree. The values are contained in the TSP design basis document. Since the holes are not circular, the code values do not apply (and they are non-mandatory).

MHI showed a new stayrod arrangement, with them shifted the inward, away from the wrapper edge to better accommodate differential vertical thermal expansion of supports. This accommodates rapid addition of cold water for cooling down the SG to shorten outage time.

MHI showed that there is margin for in-plane and out-of-plane Faulted loadings. Later in the project( )will supply actual loads for SLB and seismic and this analysis will be repeated. MHI expects more margin in the final design.

<u>Action</u>:
(1) MHI to compare the stiffness between test results and E* based on App. A8000.
(2) MHI to revise the report to change the design input 830 to 900.

Channel Head

( )presented the status of the channel head design with the goal of gaining Edison permission to proceed with( )pouring of the rough dimensions only.

<u>Action</u>: The primary inlet and outlet nozzle minimum thicknesses should match the thicknesses of the connecting RCS piping.

( )pouring is to begin soon.( )will begin rough machining ~1 month after pouring. The dimensions need to be checked.

<u>Action</u>: It is possible that there is a mid-loop operation requirement at SONGS relating to the channel head spill-over elevations. MHI will determine the distance from the RSG support skirt interface elevation to the hotleg & coldleg spillover elevations. Edison will determine the same for the OSG and will confirm the RSG channel head spillover elevations are acceptable – or will provide a new dimension requirement to MHI by mid-April 2005.

3:50 PM

Upper Head and Upper Shell

( ) presented information with the goal of releasing ( ) for rough supply of these components. In discussing the steam nozzle there were a few action items recalled from last meeting whose response was uncertain.

The least structural margin was at the interface between the nozzle ID and the venturi section (( )). MHI stated that this value was large, but this was based on the modeling itself. Therefore, MHI explained that there was no problem for actual value, obtained agreement from Edison.

Conclusion

At 4:20 PM the MHI presentations were concluded and the action items during the meeting were summarized.

Friday, April 1, 2005 Meeting

9:10 AM

( ) began with a summary of the day's agenda. The Edison team had an afternoon flight so adjournment was scheduled for lunch time.

( ) reminded the team that daylight savings time begins on April 3 in the USA (not in Japan) so the weekly videoconference times will be changed to 4 PM PDT and 7 PM EDT. 8 AM JST will be not changed.

( ) led a discussion of the Open Items from the Tube Specification meetings. Following is a summary of these Open Items.

Comment	Discussion	Resolution
13	Edison wants the tube ID cleaning process to be proven before using it on the PPQ tubes.	MHI understands and will discuss with( ).
	Edison commented that PPQ procedure may contain the PPQ tube cleaning procedure and that the whole document approval may be delayed until the cleaning process is approved.	Edison thought that the PPQ Plan could be approved while putting a "hold" on the cleaning section.

MHI Tentative PPQ / tube cleaning verification Schedule

- Develop tube cleaning procedure – End of April 2005
- PPQ melting – Beginning of June 2005
- PPQ tube cleaning verification test – End of August 2005
- PPQ meeting to review PPQ results – Beginning of December 2005
- Production melting – January 1, 2006
- Production tube cleaning – End of April 2006

Comment	Discussion	Resolution
	Edison is concerned that waiting until the end of April to approve the Tube Specification conflicts with( )'s schedule indicating that they need an approved Spec by April 8.	MHI believes the( )April 8 date can be moved.
15	Edison said that specifications cannot be approved with "holds" on subsections. This differs from a drawing with "ballooned holds" that are allowed.	MHI will need to restructure the Tube Spec PPQ documents to allow Edison to approve them without "holds" within documents. They will minimize the "breaking out" of subsections, but may do it to allow melting to proceed.
	Edison said that whatever is agreed on G-Value measurement, the PPQ can only enlarge the sample, they do not want to use what is learned to "optimize" the process if "optimize" involves making fewer measurements.	
37, 38 & 56	Edison repeated that this item is the most important item. They implied they would trade other CDS items in exchange.	MHI needs time to consider how to go forward.
	MHI says they will comply with the CDS ding & MBM requirements (for now). Edison wants to change the CDS in this regard.	This will be "revisited" when the whole set of tube requirements are renegotiated.

11:00 AM

Tube Ovality and Flatness Discussion

( )presented the MHI position on Ovality explaining why the existing G-Value and Ovality limits are specified. Next he presented information about tube flatness. In conclusion MHI will refine the calculations, to discuss the Row 1 to 10 process limitations with( ), and to revise the design criteria. The flatness issue must be resolved as part of the Tube Specification approval.

Primary Nozzle Interface Dimension

The primary nozzle as-clad ID is the same as the as-clad ID of the primary piping. However, the RSG CDS requires the cladding thickness to be greater than that of the pipe. Edison stated a desire that the nozzle and pipe have identical base metal IDs & ODs and

Non-Proprietary Version

that the cladding can be blended from one thickness to the other. MHI agreed to change the design drawings and supporting structural analyses.

Edison will not have a contract with the RSG installer until August 2005 and advised that MHI interaction with the installer is not expected until December 2005. Edison should be reminded to include( ) work scope for revision of external support interfaces in the Installer's scope of work.

The meetings concluded a 12:13 PM Friday, April 1, 2005.

SOUTHERN CALIFORNIA EDISON®
An EDISON INTERNATIONAL® Company

San Onofre Nuclear Generating Station Units 2 & 3

STEAM GENERATOR REPLACEMENT PROJECT OVERVIEW

June 7, 2006

SONGS SGR TEAM

Agenda

- Background
- Schedule
- Current Status
- Licensing
- Replacement Steam Generators
- Transportation
- Implementation
- Disposal of Original Steam Generators
- Q&A

SONGS SGR TEAM

SONGS Background

- **Started SONGS 2 & 3 Construction: 1974**
- **Commercial Operation: August 1983 - Unit 2**
  April 1984 - Unit 3

- **Licensed to Operate: Until 2022**
- **Nuclear Steam System Supplier: Combustion Engineering**
- **Architect/Engineer: Bechtel**
- **Turbine Supplier: English Electric**
- **Unit Output: 1,150 Megawatts each**
- **ABB-CE Steam Generator, Model 3410, two S/G per unit**
- **I-600 MA Tubing**

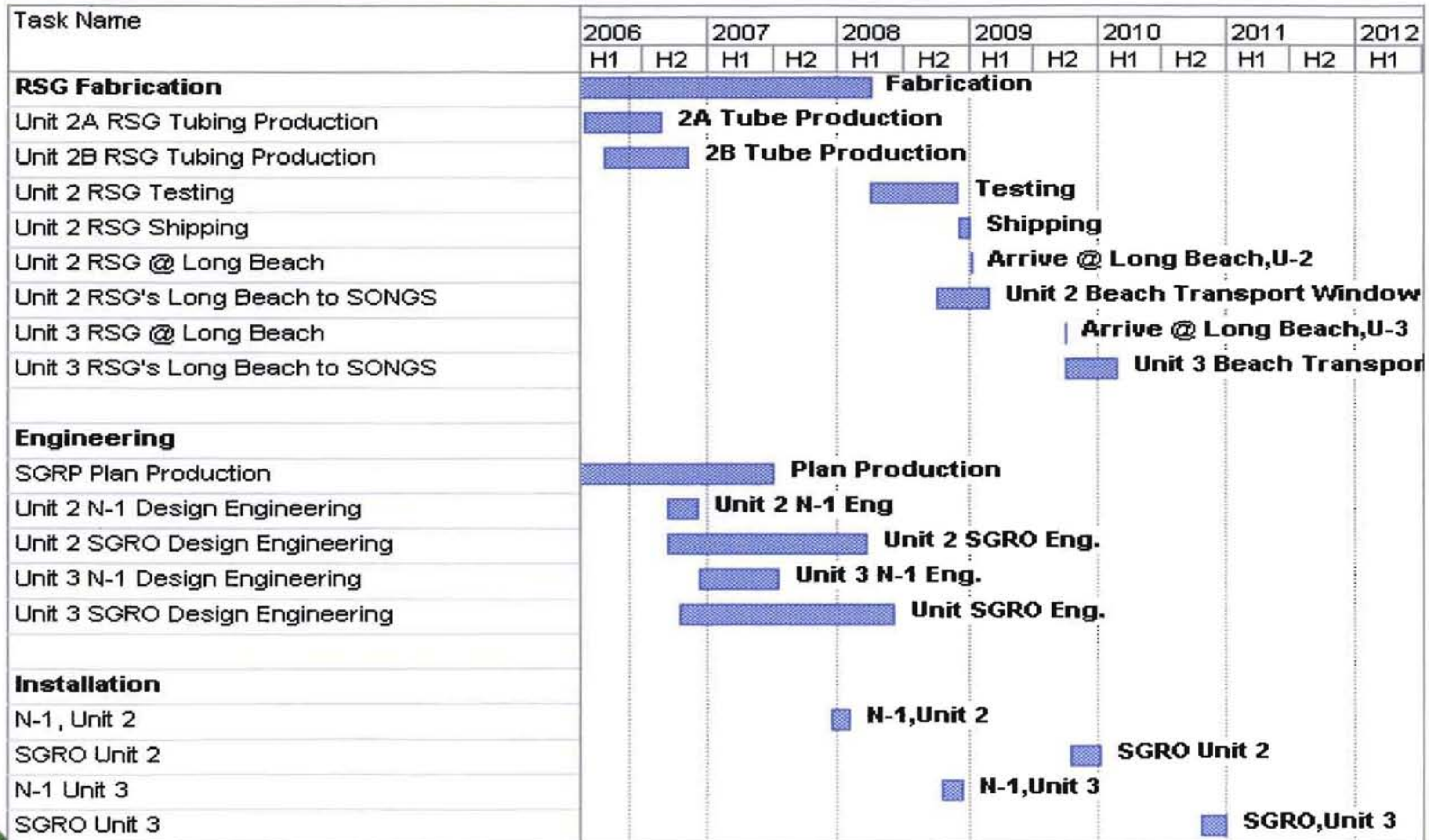
SONGS TEAM

Unit 2 Tube Plugging Projections

- Current Plugging Values
  - Unit 2: 13.5% Effective Plugging (Includes Sleeves)
  - Unit 3: 7.6% Plugging (No Sleeves)
- SG Inspections Before Cycle 16 Steam Generator Replacement Outage (SGRO)
  - Unit 2: Cycle 15
  - Unit 3: Cycle 14 & 15
- Plugging Limit is 21.4%
- Do Not Expect to Reach Plugging Limit

SONGS SGR TEAM

Schedule for SONGS Steam Generator Replacement



SONGS SGR TEAM

Benchmarking

- **Plant Benchmarking**
- **Fabricator Benchmarking**
- **Loan Employees**
- **Future Benchmarking Plans**

Palo Verde RSG Transport

➢ Recently Completed SGRO

- Palo Verde 1 & 2
- Beaver Valley 1
- ANO
- Callaway

➢ Future SGRO

- Ft. Calhoun
- Watts Bar
- Comanche Peak
- Palo Verde 3

SONGS SGR TEAM

Current Status

- CPUC Application for Steam Generator Replacement Project (SGRP) Submitted February 2004
- Estimated Cost at $680m (2004 $)
- CPUC Decision December 2005
- EIX Board Accepted CPUC Decision March 2006

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Licensing

- Will Be Implemented Under 10CFR 50.59
- No Power Uprate
- Associated Technical Specification Changes
  - Identification 2007

SONGS
TEAM

Replacement Steam Generators (RSG) Fabrication

Mitsubishi Heavy Industries Kobe, Japan

- Contract Award September 28, 2004

2A Primary

2A Secondary

RSG 2ATube Sheet

SONGS TEAM


Mitsubishi Heavy Industries, Kobe, Japan
MHI
RSG Fabrication Facility
Engineering Offices

Oversight

- Design Reviews
- Technical Meetings (SONGS, Kobe)
- SCE Resident Personnel @ Kobe
- Special Engineering Visits
- Readiness Reviews
- Independent Inspections
- Audits

SONGS 2B Channel Head

SONGS
TEAM

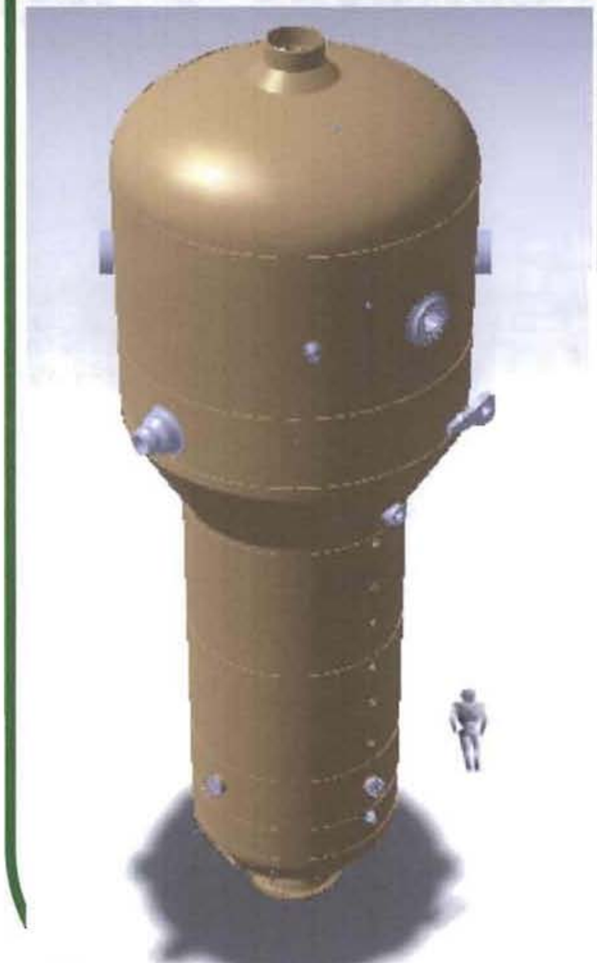
Some Key Design Improvements

- Larger Surface Area
- Alloy 690 Thermally Treated Tubing
- Improved AVB Design
- Integral Steam Nozzle
- Improved Material for Tube Supports
- Forged Shell

S/G 3A Lower and Middle Shell
S/G 2A Balance Ring, Extension Ring, & Tubesheet

SONGS TEAM

Replacement Steam Generators

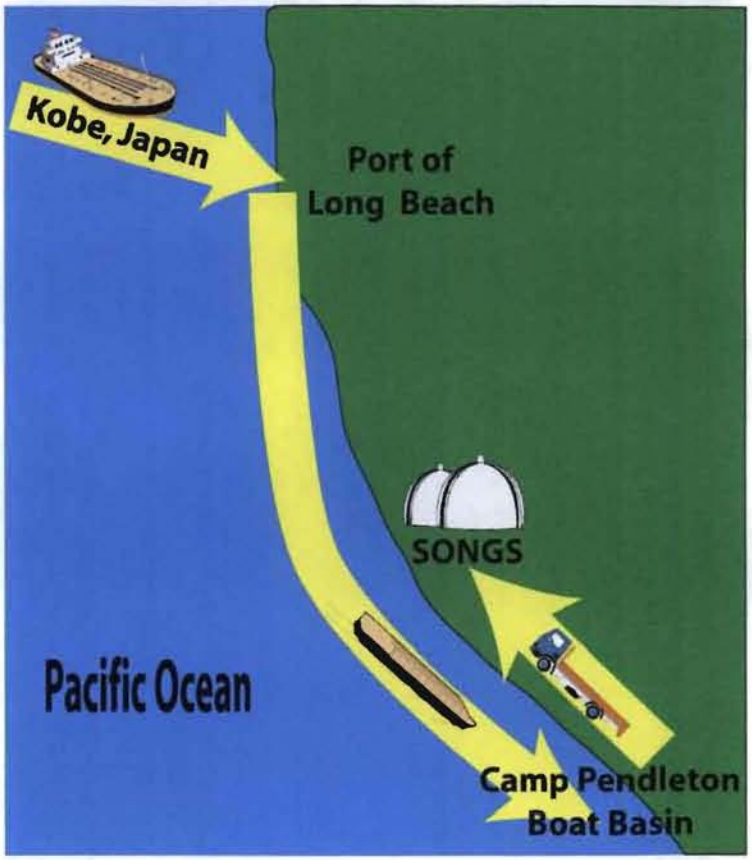


	Original	RSG
Weight	620 tons	643.6 Tons
Height	65'6"	65'6"
Upper Section Diameter	22 feet	22 feet
Tubes	9,350 per SG	9,727 per SG
	¾ inch diameter	

SONGS SGR TEAM

RSG Transportation to SONGS

- Heavy Lift Cargo Ship from Japan to Port of Long Beach
- Ocean Barge from Long Beach to Camp Pendleton
- Heavy Transport Vehicle from Camp Pendleton to SONGS



SONGS SGR TEAM

Key Implementation Considerations
Compact Site/Space Limitations

Key Implementation Considerations
Containment Penetration

- 28' x 28' Opening
- 33.5' Above Ground Level
- Over Equipment Hatch
- 4 ft Thick, Reinforced Wall
- 100 Cubic Yards Concrete
- Approximately 50 Tendons Will Be Removed

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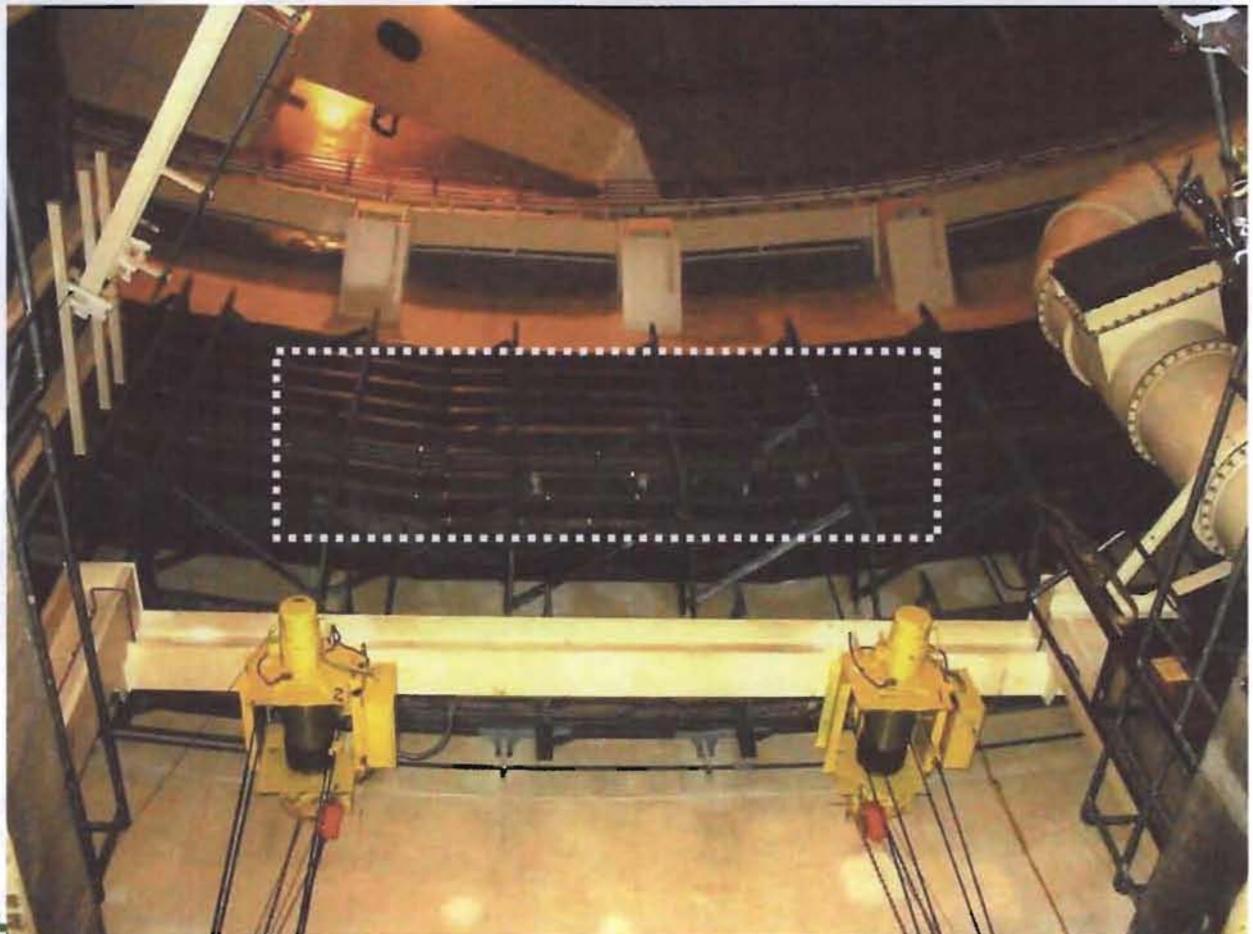
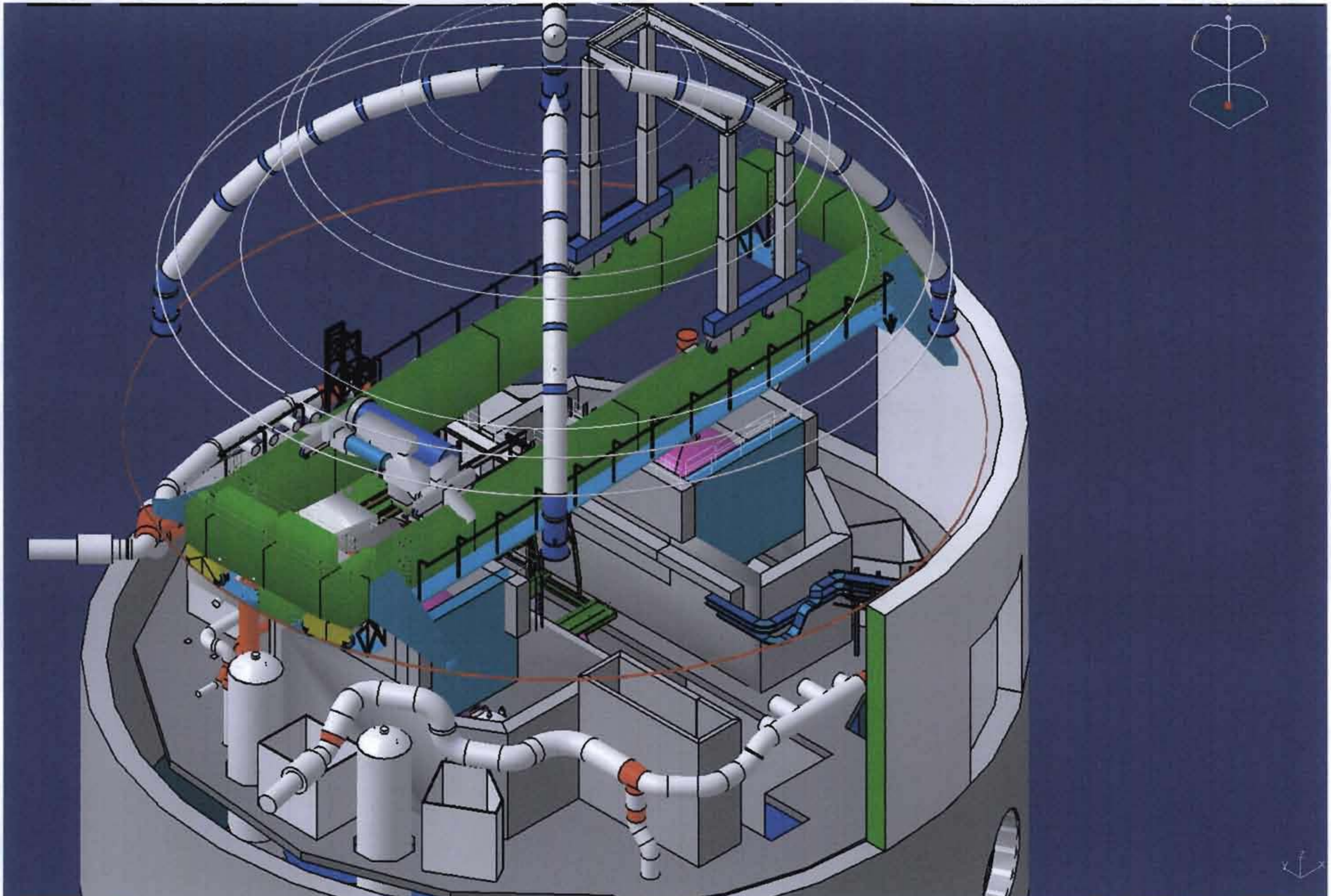
Key Implementation Considerations
Containment Tendon Design

Rancho Seco Tendon Validation Test

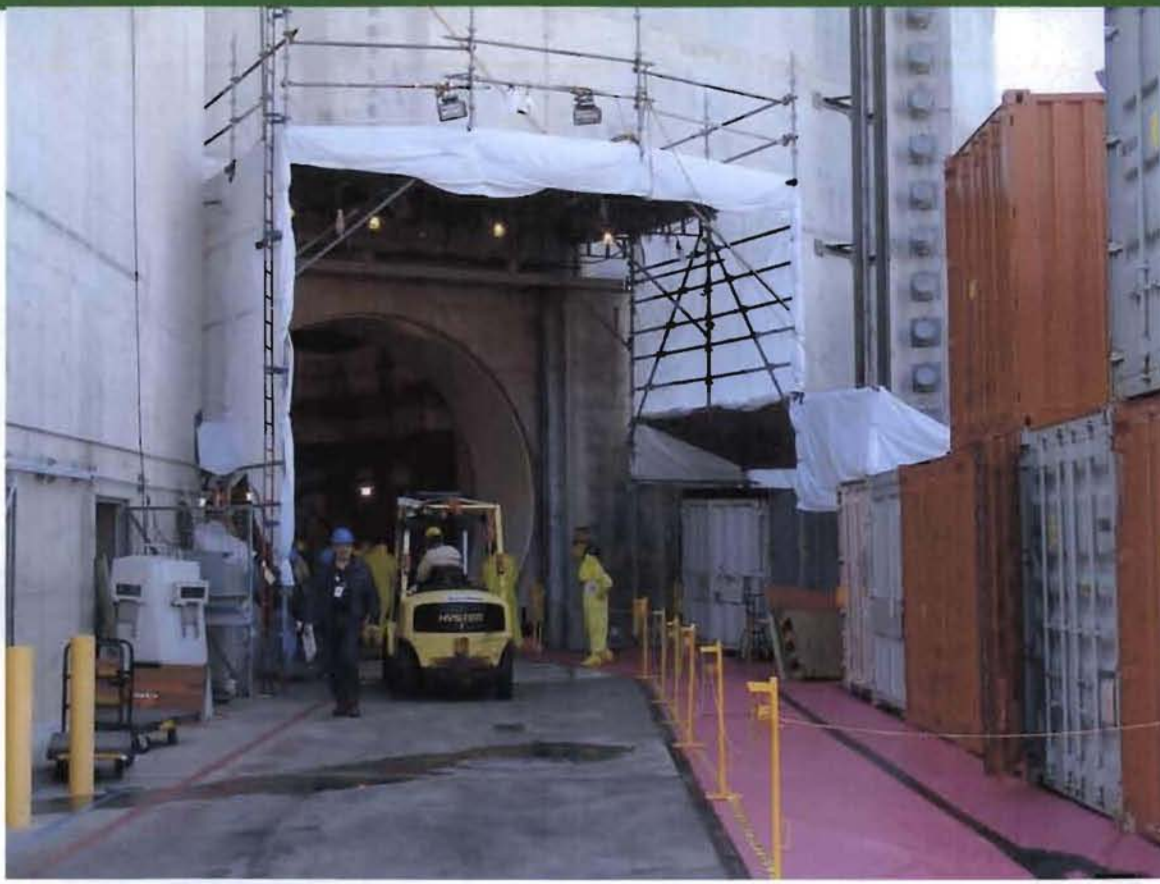
Key Implementation Considerations
Containment Interferences



Cable Trays Affected by Containment Breach



Key Implementation Considerations
Installation Contractor



Equipment hatch during a normal refueling outage

Bechtel
Awarded Installation Contract December 2005

Original SONGS AE

Current Maintenance Contractor for SONGS

Significant SGR Experience

Early Project Involvement

SONGS SGR TEAM

Original Steam Generator Disposal

- Disposal of OSG's Offsite Is Required Due to SONGS Compact Site
  - OSG's Large Size Requires Segmentation to Facilitate Shipping
  - Disposal at Energy Solutions, LLC, (formerly Envirocare of Utah, LLC) Planned

Q & A