

SAN ONOFRE'S STEAM GENERATOR FAILURES COULD HAVE BEEN PREVENTED

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San Onofre's Steam Generator Failures Could Have Been Prevented

Summary

Southern California Edison's four replacement steam generators at their San Onofre Nuclear Generating Station failed in less than two years of operation, while the original equipment operated for 28 years. Fairewinds has been analyzing the data in order to determine how such an expensive investment could fail so quickly.

In June of 2006 Edison informed the NRC that the replacement steam generators to be manufactured by Mitsubishi would be fabricated to the same design specifications as the original San Onofre Combustion Engineering (CE) steam generators. According to Nuclear Engineering International, Edison has admitted that this was a strategic decision to avoid a more thorough license amendment and review process.¹

At SONGS, the major premise of the steam generator replacement project was that it would be implemented under the IOCFR50.59 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.²

Fairewinds finds that there are numerous changes to the San Onofre steam generators that are not *like-for-like* or "*in-kind*".

Furthermore, the facts reviewed by Fairewinds makes it clear that if Edison had informed the NRC that the new steam generators were not *like-for-like*, the more thorough NRC licensing review process would have likely identified the design problems before the steam generators were manufactured.

Finally, Fairewinds finds that tube plugging is not the solution to the vibration problem³ and that the damaged steam generators will still require major modifications with repair and outage time that could last more than 18 months if Edison and Mitsubishi are even able to repair these faulty designed steam generators. However, Fairewinds finds that the safest long-term action is the replacement of the San Onofre steam generators.

Analysis

The requirements for the process by which nuclear power plant operators and licensees may make changes to their facilities and procedures as delineated in the safety analysis report and without prior NRC approval are limited by specific regulations detailed in The Nuclear Regulatory Commission's *10 CFR Part 50, Domestic Licensing of Production and Utilization Facilities, Section 50.59, Changes, Tests and Experiments*.

The implementing procedures for the 10 CFR 50.59 regulations have eight criteria that are important for nuclear power plant safety. (These eight criteria are provided in Table 1, footnote A below.)

These implementing procedures created for 10 CFR. 50.59 require that the license be amended unless none of these eight criteria are triggered by any change made by Edison at San Onofre. If a single criterion is met, then the regulation requires that the licensee pursue a license amendment process.

By claiming that the steam generator replacements were a *like-for-like* design and fabrication, Edison avoided the more rigorous license amendment process. From the evidence reviewed, it appears that the NRC accepted Edison's statement and documents without further independent analysis. In the analysis detailed below, Fairewinds identified 39 separate safety issues that failed to meet the NRC 50.59 criteria. Any one of these 39 separate safety issues should have triggered the license amendment review process by which the NRC would have been notified of the proposed significant design and fabrication changes.

As the NRC guidelines state:

“(c)(1) A licensee may make changes in the facility as described in the final safety analysis report (as updated), make changes in the procedures as described in the final safety analysis report (as 1.187-A-1 updated), and conduct tests or experiments not described in the final safety analysis report (as updated) without obtaining a license amendment pursuant to § 50.90 only if: (i) A change to the technical specifications incorporated in the license is not required, and **(ii) The change, test, or experiment does not meet any of the criteria in paragraph (c)(2) of this section.**”⁴ [Emphasis Added]

In its previous reports, Fairewinds identified at least eight modifications to the original steam generators at San Onofre.

Table 1 below was designed to compare the eight major design modifications that Fairewinds identified in its analysis with the eight criteria the NRC applies to the license review process in order to determine whether or not a new license amendment process is required. The major design changes are located at the top of the table, and the NRC Criteria are listed in the left hand column of table. The term SSC stands for Systems, Structures and Components. A green *No* means that the *like-for-like* criteria were indeed met and that no license amendment was required. A red *Yes* means that Edison should have applied for a license amendment.

Table 1 shows that 7 out of 8 of the major design changes to the original steam generators meet a total of 39 of the NRC's 50.59 criteria requiring amendment to the license.

Table 1
Steam Generator Design Changes Identified By Fairewinds
Compared With The NRC's Like-For-Like Criteria

50:59 Criteria (A)	(B) Remove stay cylinder	Change tube sheet	Tube alloy change	Add tubes	Change tube support	Add flow restrictor	Additional water volume	Feed water distribution ring
i – Accident Frequency Increase	Yes (1)	Yes (1)	No	Yes (3,4)	Yes (3,4,8)	No	No	No
ii – Increase in SSC Malfunction occurrence	Yes (1)	Yes (1)	No	Yes (3,4)	Yes (3,4,8)	No	No	No
iii - Accident consequent increase	Yes (1)	Yes (1)	No	Yes (3,4)	Yes (3,4,8)	Yes (2)	Yes (2,5,6)	No
iv - Increase in SSC consequence of malfunction	Yes (1)	Yes (1)	No	Yes (3,4)	Yes (3,4,8)	Yes (2)	Yes (2,5,6)	No
v - Create unanalysed accident	Yes (1)	Yes (1)	No	No	No	Yes (2)	Yes (2,5,6)	Yes (3,7,8)
vi – Create new malfunction	Yes (1)	Yes (1)	No	No	Yes (3,8)	Yes (2)	No	Yes (3,7,8)
vii – Alter fission product barrier	Yes (1)	Yes (1)	No	Yes (3)	No	No	No	No
viii – Change design basis evaluation method	Yes (2)	Yes (2)	No	Yes (2)	Yes (2,8)	Yes (2)	Yes (2,5,6)	No

Table Footnotes

A - The criteria listed in the left column in the table above refers to the criteria as laid out in the NRC Guidelines⁵ which states as follows:

“(2) A licensee shall obtain a license amendment pursuant to § 50.90 prior to implementing a proposed change, test, or experiment if the change, test, or experiment would:

- (i) Result in more than a minimal increase in the frequency of occurrence of an accident previously evaluated in the final safety analysis report (as updated);
- (ii) Result in more than a minimal increase in the likelihood of occurrence of a malfunction of a structure, system, or component (SSC) important to safety previously evaluated in the final safety analysis report (as updated);
- (iii) Result in more than a minimal increase in the consequences of an accident previously evaluated in the final safety analysis report (as updated);
- (iv) Result in more than a minimal increase in the consequences of a malfunction of an SSC important to safety previously evaluated in the final safety analysis report (as updated);
- (v) Create a possibility for an accident of a different type than any previously evaluated in the final safety analysis report (as updated);
- (vi) Create a possibility for a malfunction of an SSC important to safety with a different result than

- any previously evaluated in the final safety analysis report (as updated);
 - (vii) Result in a design basis limit for a fission product barrier as described in the FSAR (as updated) being exceeded or altered; or
 - (viii) Result in a departure from a method of evaluation described in the FSAR (as updated) used in establishing the design bases or in the safety analyses.”
- B – The horizontal axis contains a list of design changes made by Edison and whether they meet or have not met the criteria as set out in 10 CFR 50.59.
- 1 – The Steam Generator Replacement Project modified the tube sheets and stay cylinder that are a containment barrier – The NRC was not informed nor did it specifically approve these changes to the containment barrier as they were apparently not addressed under Edison's analysis for the 10 CFR 50.59 process;
 - 2 – The Mitsubishi thermo hydraulic code is inadequate to assess flow inside the Steam Generators that dramatically affect the ability to cool the nuclear reactor core in the event of an accident;
 - 3 – The Steam Generator Replacement Project increases the consequences of a steam line break accident;
 - 4 – The Steam Generator Replacement Project has already proven to increase the frequency of tube failure;
 - 5 – The Steam Generator Replacement Project changed the volume of primary coolant because more tubes were added, which changes the Final Safety Analysis Report;
 - 6 – The Steam Generator Replacement Project changed the flow rate of primary coolant, which changes the Final Safety Analysis Report;
 - 7 – The Steam Generator Replacement Project changed the potential for water hammer. Given that the Mitsubishi thermo hydraulic code is inadequate, the potential for water hammer is increased;
 - 8 – The Steam Generator Replacement Project created steam binding at top of steam generator. The steam generator is designed to remove heat in the event of an accident and its role has been compromised.

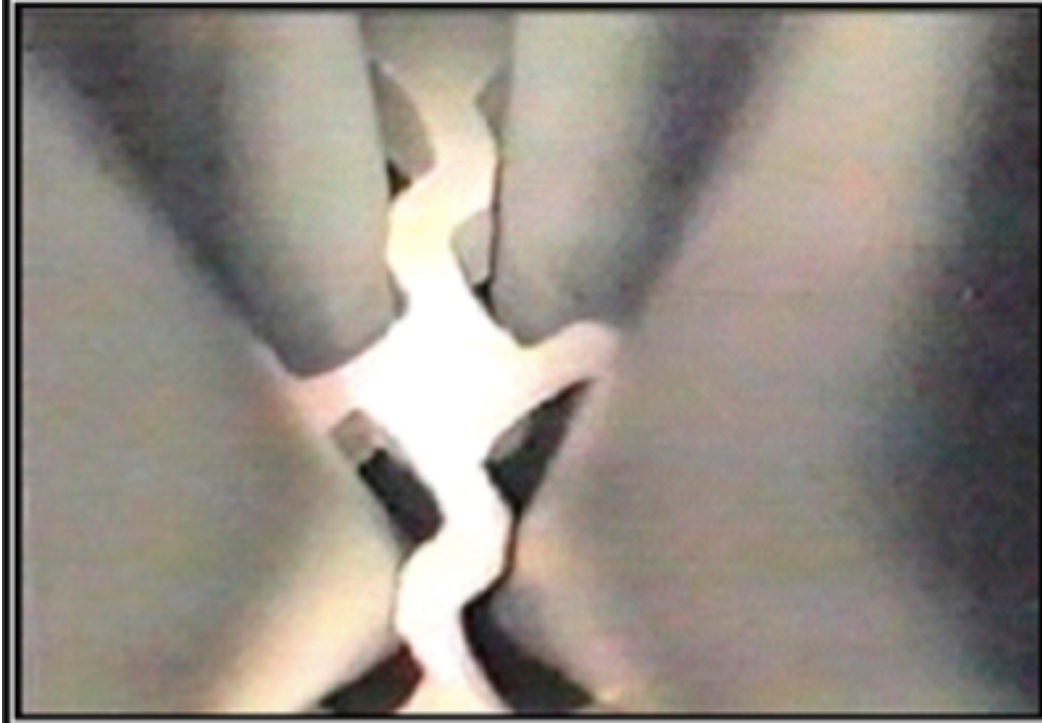
Ramifications Of Edison’s Decision To Avoid The License Amendment Process

Edison’s strategic goal was to avoid the process of license amendment according to the January 2012 article in Nuclear Engineering International NEI Magazine⁶. Had Edison notified the NRC that the new steam generators at San Onofre were not a *like-for-like* replacement, a more thorough review through the license amendment process would have been required. Given that scenario, it is likely that the requisite and thorough NRC review would have identified the design and fabrication inadequacies that appear to have caused the San Onofre steam generator tube failure.

More specifically, Fairewinds believes that the NRC would have identified the inadequacy of the Mitsubishi Heavy Industry computer code applied to validate the tube design and vibration pattern prior to fabrication. Mitsubishi’s computer code was simply not capable of analyzing Combustion Engineering (CE) designs like San Onofre and was only qualified for Westinghouse designs that are not similar to the original CE steam generator design. In NRC licensing jargon, the Mitsubishi design codes were not benchmarked for the CE Design⁷.

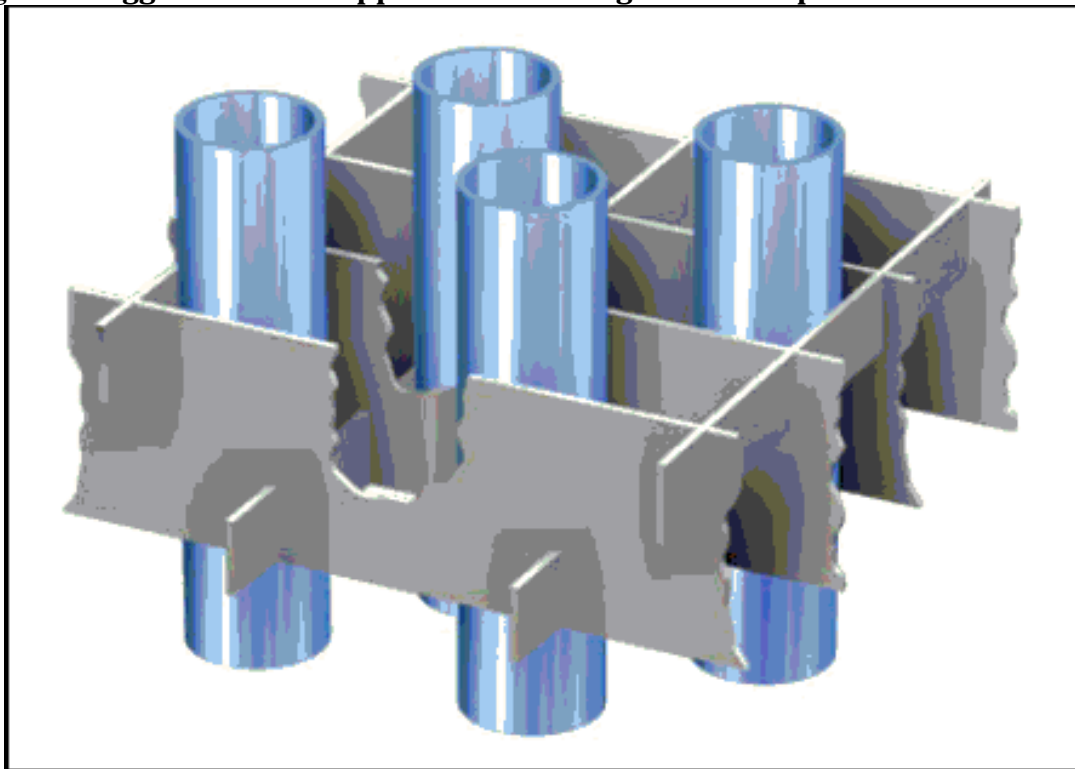
While Mitsubishi Heavy Industry has been supplying steam generators for many years in Japan, it did so under a specific license from Westinghouse for Westinghouse nuclear reactors. Although Mitsubishi made several incremental changes to the Westinghouse design, such as switching to alloy 690 tubing and the use of stainless steel broached plate tube supports, Mitsubishi has had very little experience with the tight tube pitch and the egg crate design used in the original CE design for San Onofre.

Figure 1: Broached Tube Support Plate - Designed To Keep Tubes From Rattling



Broached (quatrefoil and trefoil) tube support plates (TSPs)⁸

Figure 2: Eggcrate Tube Support Plate - Designed To Keep Tubes From Rattling



Horizontal Tube Supports (Eggcrate)⁹

The original steam generators designed and manufactured by CE for San Onofre were successfully operated 28 years. Moreover the original steam generators had a triangular tube pitch pattern, very closely packed U-tubes, and unique egg-crate tube supports that kept the tubes from vibrating and colliding. The pitch to diameter ratio of tubes in the original CE generators is dramatically different from any of the Westinghouse generators fabricated by Mitsubishi. Moreover, an NRC licensing review would have identified the fact that the Mitsubishi computer design code, which is based upon Westinghouse models, was not appropriate for design changes to the San Onofre replacement steam generators originally designed by CE.

Another problem with the San Onofre steam generators is that Edison and Mitsubishi made a very significant design change that magnified the San Onofre steam generator stresses and vibrations by removing the main structural pillar called the stay cylinder in order to fit an additional 400 tubes into the unique and already tightly packed design. Furthermore, this design is also bigger than anything Mitsubishi Heavy Industries (MHI) had ever fabricated or designed. The NRC license amendment review process would likely have identified these and other problems.

The Actual Steam Generator Problem

As water moves vertically up in a steam generator, the water content reduces as more steam is created. When the volume of steam is much greater than water then the flow resistance of the water/steam mixture passing through the tube supports accounts for one third of the total resistance at the top of the steam generator. Therefore to avoid vibration at the top of the tubes, Mitsubishi needed to specifically analyze the type of tube support to use in this unique application.

The flow resistance of the Mitsubishi broached plate is *much higher* than that of the original Combustion Engineering egg crate design because the tubes are so tightly packed in the original CE San Onofre steam generators. By reviewing the documents thus far produced, it appears that due to Mitsubishi's fabrication experience with broached plates, both Edison and Mitsubishi missed this key difference in the design and fabrication of the new San Onofre steam generators.

Not only is Mitsubishi unfamiliar with the tightly packed CE design, but also Edison's engineers created so many untested variables to the new fabrication that this new design had a significantly increased risk of failure. As a result of the very tight pitch to diameter ratios used in the original CE steam generators, Mitsubishi fabricated a broached plate design that allows almost no water to reach the top of the steam generator.

The maximum quality of the water/steam mixture at the top of the steam generator in the U-Bend region should be approximately 40 to 50 percent, i.e. half water and half steam. With the Mitsubishi design the top of the U-tubes are almost dry in some regions.¹⁰ Without liquid in the mixture, there is no damping¹¹ against vibration, and therefore a severe fluid-elastic instability developed.

In response to the Edison/Mitsubishi steam generator changes, the top of the new steam generator is starved for water therefore making tube vibration inevitable. Furthermore, the problem appears to be exacerbated by Mitsubishi's three-dimensional thermal-hydraulic analysis determining how the steam and water mix at the top of the tubes that has been benchmarked against the Westinghouse but not the Combustion Engineering design.

The real problem in the replacement steam generators at San Onofre is that too much steam and too little water is causing the tubes to vibrate violently in the U-bend region. The tubes are quickly wearing themselves thin enough to completely fail pressure tests. Even if the new tubes are actively not leaking or have not ruptured, the tubes in the Mitsubishi fabrication are at risk of bursting in a main steam line accident scenario and spewing radiation into the air.

This Tube Damage Cannot Be Repaired

Edison claims that the proximate cause of these U-tube failures at San Onofre is high vibration, and it has embarked upon a process of plugging some of these damaged tubes in hopes of quickly restarting one or both units. Fairewinds believes that this damage is occurring on the outside of the tubes where they collide with each other, while access to the tubes for repair and/or plugging can only be conducted from inside the tubes. Space limitations due to the tight fit of the 9,700 tubes (19,400 holes in the tube sheet) in each steam generator have made it impossible to access the outside of the U-tubes for inspection where the wear is actually occurring.

Presently, the Edison approach is to plug tubes in the most heavily damaged zone of each steam generator. Plugging the tubes only eliminates the radioactive water inside the tubes, but it does not eliminate the vibration, so the plugged tubes will continue to vibrate and damage adjacent tubes. More than 500 tubes have already been plugged in Unit 2 and more than 800 tubes have been plugged in Unit 3.¹² The number of plugged tubes is still considerably smaller than the number of tubes already ascertained as damaged in both steam generators. To date, Edison has not provided adequate data to compare damaged tubes to plugged tubes.

Initially, in March 2012, Edison claimed that as part of the Electric Power Research Institute's (EPRI) criteria used in the in-situ pressure testing of the Steam Generators, it was required to plug about one dozen tubes in the San Onofre steam generators. However, in May 2012, Edison announced it had plugged 1300 tubes, more than one hundred times the number of tubes required by the EPRI criteria. According to the industry steam generator experts interviewed by Fairewinds, Edison did not plug these additional tubes because they had failed, but rather Edison needed to plug these particular tubes because they would likely fail during a main steam line break accident.

If a steam line break accident were to occur, the depressurization of the steam generator caused by the steam line break coupled with the lack of water at the top of the steam generators would cause cascading tube failures, involving hundreds of tubes. The cascading tube failures would pop like popcorn and the cascading failures would cause excessive offsite radiation exposures. In an attempt to avoid a severe steam line break accident Edison prophylactically plugged additional tubes.

Fairewinds investigation has found that plugging the tubes is not a sure solution, because it fails to deal with the root causes of a failed design and it relies upon the incorrectly applied Mitsubishi 3-Dimensional steam analysis to determine which tubes should be plugged. Realistically, the 3-D steam analysis is not accurate enough to apply to such important safety-related determinations. To make such mathematical risk 3-D analysis, a very large margin of error must be applied, and that has not been done. For example, if the 3-D steam analysis determines that plugging 100 tubes is a solution, then plugging ten times that number might be the appropriate solution due to the mathematical errors in the 3-D analysis being applied by Edison and Mitsubishi.

Fairewinds concludes that plugging the tubes will never solve the underlying problem because vibration is the result not the root cause of the steam generator problems at San Onofre. The actual problem is a variety of design changes that have caused too much steam and too little water at the top of the steam generators. Plugging tubes cannot repair these design changes created and that are causing the tubes to collide with each other.

The tubes that Edison has already plugged on the inside will continue to vibrate because they are being pushed by steam and water from the outside. Therefore Fairewinds concludes that Edison's solution of plugging the inside of the tubes will not lessen the risk of an accident or stop the ongoing vibrational damage that is occurring to the inaccessible outside of the San Onofre steam generator tubes.

Options For Continued Operation Of The San Onofre Reactors

Complete Replacement

The ongoing plugging of the tubes will not eliminate the vibrational failure mechanism causing tube failures. Over time, the damaged tubes that are plugged will in turn damage more tubes. Therefore, Fairewinds believes that the only sure solution to this significant safety issue is to once again cut open the reactor containment and install new steam generators that replicate the original CE design.

Due to the significant risk of a steam generator tube rupture accident in such a highly populated and vulnerable area, both San Onofre Unit 2 and Unit 3 should remain shut down until such a significant safety threat can be mitigated with the fabrication of new *like-for-like* steam generators adhering to the original CE design. If all the appropriate steps are taken in design and fabrication of new CE replica steam generators, and the proper procedures are taken to repair and reseal the San Onofre containment coupled with requisite NRC oversight, Fairewinds estimates that the entire process might take Edison approximately four years and cost in excess of \$800,000,000, not including replacement power while the Units remain shut down.

Repair In Place

While technically this would be an extremely challenging repair process, it may be possible to cut the steam generators apart while still inside the containment. Such a process would take approximately 18 months to make repairs and then weld the steam generators back together again without cutting the containment open. Cutting the top off the steam generators would allow construction personnel access so that additional supports could be inserted into the U-tube region. Smaller replacement packages would fit through the existing equipment hatch and the containment would not be compromised another time. The cost for these repairs would be less than completely redesigning and manufacturing new steam generators and replacement power costs would be less. However, it is still reasonable to estimate that this cost would exceed \$400,000,000 without replacement power, not including replacement power while the Units remain shut down.

There are two possible alternatives, both of which would require an additional analysis of the overall steam generator flow patterns to ensure that no new problems are created in the process of attempting to mitigate the damage from these design flaws and fabrication errors. The two alternatives are:

1. Because too much steam and too little water in the U-bend region cause the vibration problems, it might be possible to reduce the steam/water mixture qualities in the U-bend area by changing the internal structures to divert some of the internal recirculating flow into the U-bend region.
2. Another possible solution would require replacing the steam-water separators. The Mitsubishi separators require a water level that is quite low in the steam drum, and cannot be raised. Changing the separators to a different design may allow more water to reach the top of the tubes and thereby stop the tube vibration and wear.

Power Reduction

Reducing power does not provide a remedy for the underlying structural problems that are creating the vibration that has damaged and will continue to damage tubes deep inside the San Onofre steam generator. Edison has suggested that plugging tubes and operating at indeterminate reduced power levels for the remainder of the life of the plant may be a *solution* to the San Onofre tube vibration problem. Unfortunately this course of action would leave San Onofre operating with a significant safety risk if the NRC were to allow the reactors to restart.

The concept of reducing the power output from the San Onofre reactors will not change either the inside steam generator tube water temperature or the steam temperatures outside of the tubes. Reducing the power output will also not change the 2200-pound per square inch pressure within the tubes or the 1,000-pound pressure outside the tubes. Operating at reduced power will not prevent previously damaged tube supports and plugged tubes from vibrating and damaging surrounding tubes and tube supports, and it will worsen the existing damage.

More importantly, Fairewinds concern is that operating the San Onofre reactors at a lower power and flow rate might actually create a resonate frequency within the steam generators at which some of the tubes will vibrate as bad or worse than they did originally.

Because the plugged tubes are now filled with air their weight has changed, and therefore the plugged tubes will vibrate with a different amplitude and frequency. The inaccuracies in the Edison and Mitsubishi computer code do not allow Edison and Mitsubishi to conduct a resonant frequency analysis proving that such a problem will not occur.

It is impossible to determine exactly what is happening inside an operating steam generator. For example, at Millstone 2, a smaller CE reactor, the steam generator tube supports began to disintegrate due to vibration, and there was no method to alert the operations staff that such deterioration was occurring. This challenging problem was finally detected when the Millstone 2 was shut down for a refueling, and small cameras meant to inspect the steam generator found rubble on the tube sheet at the base of the tubes.

Historical evidence from other operating nuclear reactors that have attempted to mitigate vibrational damage by using power reductions rather than solving the resonant frequency issues have in fact compromised other nuclear safety related components by operating at reduced power.

- In 2002 the Exelon Quad Cities Nuclear Power Plant in Illinois operated its Unit 2 reactor at reduced power in order to eliminate vibrationally induced damage causing high moisture carryover in its steam dryer. While the power reduction temporarily reduced moisture carryover, the problem reoccurred and a shutdown was ordered causing an extended unplanned outage. Vibrationally induced severe cracking was discovered in the steam dryer and repaired. Following an analysis and subsequent repairs, Exelon claimed to have rectified the Quad Cities Unit 2 problems only to be forced in 2003 to once again attempt operation at a reduced power level when vibrationally induced steam dryer moisture carryover became excessive. Following this second attempt to operate the reactor at a reduced power level, pieces of the dryer as large as a man broke off and damaged nuclear power safety related components, and a second unplanned extended outage ensued. Once again, vibration was determined to be the cause of the gross failure and another unplanned and forced outage. Finally, following years of analysis and two damaged steam dryers, Quad Cities made major piping modifications that are alleged to have eliminated harmonic frequencies, prevented further component damage, and allowed Unit 2 to eventually return to full power production.¹³
- A second example of a failed attempt to reduce power to solve vibrationally induced resonance frequency problems occurred at the Susquehanna nuclear plant in Pennsylvania. During the mid 1990s, a vibrationally induced failure in the jet pump sensing lines occurred at Susquehanna. This failure was attributed to the vane passing frequency from the recirculation pumps causing harmonic vibration of the lines. Like Quad Cities, Susquehanna attempted to implement a power reduction in order to minimize the harmonic vibrations. Unfortunately, the resonant vibration issues continued to damage systems after the power was reduced thereby forcing an unplanned outage and extensive modifications and repairs.¹⁴

Conclusion

In conclusion, the NRC has stated that nuclear power plants like San Onofre cannot risk compromising critical safety systems and possible radiological contamination in an effort to return to operation before a thorough root cause analysis, modifications, and subsequent repairs are adequately reviewed by the NRC and implemented. Historical evidence has proven that power reductions do not solve underlying and serious degradation problems, resonance frequency issues. Rather, power reductions can significantly increase the risk of unplanned, forced outages during times of peak demand and can cause significant risk to public health in the event of a single tube rupture or a series of ruptures if the main steam line were to break.

Finally, if a steam-line accident were to occur, vibrationally induced tube damage at San Onofre could cause an inordinate amount of radioactivity to be released outside of the containment system compromising public health and safety in one of the most heavily populated areas in the entire United States.

Note:

This report represents the opinion of Fairewinds. Industry insiders, who have had lengthy careers in steam generator design, fabrication, and operation, and who have chosen to remain anonymous, have assisted Fairewinds with research for this report, but are not responsible for its content.

Endnotes

¹ Improving Like-For-Like Replacement Steam Generators by Boguslaw Olech of Southern California Edison and Tomouki Inoue of Mitsubishi Heavy Industries, Nuclear Engineering International, January 2012, page 36-38. <http://edition.pagesuite-professional.co.uk/launch.aspx?referral=other&pnum=36&refresh=K0s3a21GRq61%20&EID=af75ecb1-5b23-49be-9dd6-d806f2e9b7b5&skip=&p=36>

² Ibid.

³ Vibration source: March 27, 2012, Confirmatory Action Letter – San Onofre Nuclear Generating Station, Units 2 And 3, Commitments To Address Steam Generator Tube Degradation

⁴ See, 1.187-A-1, *ibid*, <http://pbadupws.nrc.gov/docs/ML0037/ML003759710.pdf>

⁵ Ibid.

⁶ Improving Like-For-Like Replacement Steam Generators by Boguslaw Olech of Southern California Edison and Tomouki Inoue of Mitsubishi Heavy Industries, Nuclear Engineering International, January 2012, page 39. This article was based on a paper published at ICAPP 2011, 2-5 May 2011, Nice, France, paper 11330. Boguslaw Olech, P.E., South California Edison Company, 14300 Mesa Rd., San Clemente, CA 92674, USA, Email: bob.olech@sce.com.

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⁷ This statement is based upon Fairewinds analysis and confirmed by two independent industry steam generator experts who wish to remain anonymous.

⁸ http://westinghousenuclear.com/Products_&_Services/docs/flysheets/NS-ES-0073.pdf

⁹ Figure 13-7 http://www.kntc.re.kr/openlec/nuc/NPRT/module2/module2_6/2_6.htm

¹⁰ With the Mitsubishi design the top of the U-tubes are almost dry in some regions. Fairewinds research and four independent industry experts, who wish to remain anonymous, substantiate this statement.

¹¹ Damping [**dam**-ping] *noun Physics*.

1. a decreasing of the amplitude of an electrical or mechanical wave.
2. an energy-absorbing mechanism or resistance circuit causing this decrease.
3. a reduction in the amplitude of an oscillation or vibration as a result of energy being dissipated as heat.

<http://dictionary.reference.com/browse/damping?s=t>

¹² http://www.songscommunity.com/docs/SONGS19_CALFactSheet_050712.pdf

¹³ <http://pbadupws.nrc.gov/docs/ML0609/ML060960338.pdf>

¹⁴ <http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1995/in95016.html>