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San Onofre Cascading Steam Generator Failures Created By Edison

Imprudent Design And Fabrication Decisions Caused Leaks

This report was completed on April 10th 2012 for Friends of the Earth. On April 11th it was reported that Southern California Edison (Edison) had identified the same type of wear in the tubes of the Unit 2 Replacement Steam Generator as those originally discovered in Unit 3.[1] Edison's findings confirm the original analysis released by Fairewinds in their March 26th report and is confirmed by the evidence reviewed for the report that follows below.

Executive Summary

In Fairewinds Associates March 26, 2012 report entitled *Steam Generator Failures At San Onofre: The Need For A Thorough Root Cause Analysis Requires No Early Restart,* Fairewinds recommended that both San Onofre Unit 2 and Unit 3 remain shut down until the 'root causes' of these twin nuclear power plants' rapid tube failures are understood and repaired, reliability is assured, and radioactive releases are prevented. In its March 23, 2012 letter to the Nuclear Regulatory Commission (NRC), Edison suggests that there are no similarities in the unique and simultaneous problems with each San Onofre reactor's leaking steam generator, therefore restarting Unit 2 is a decision that is separate and apart from any restart considerations for Unit 3. Additionally, in its March 27, 2012 Confirmatory Action Letter, the NRC appears to agree with Edison and develops two separate review and restart procedures for Unit 2 and Unit 3.

Due to the common elements connecting the tube failures in both Units 2 and 3, Fairewinds believes that Units 2 and 3 must be analyzed concurrently. Moreover, in Fairewinds opinion, the most likely common element or 'root cause' of the simultaneous steam generator tube failures at each Unit may be traced to Edison's unwarranted steam generator design changes. San Onofre's original steam generator tubes lasted almost 30-years, and it is probable that replacement steam generators meeting the original design criteria would have lasted for another 30 years.

San Onofre Has Always Been Unique

Originally designed and built by Combustion Engineering (CE), San Onofre's nuclear steam generators are a very unique design that is radically different from all other Pressurized Water Reactor (PWR) designs. The CE design at San Onofre has only two steam generators while all other PWR's of comparable size to San Onofre have four U-Tube Steam Generators. In order to produce as much power as other PWR's from only two steam generators, each steam generator at San Onofre is twice as large as those at similar PWR's with comparable power output.

1 http://sciencedude.ocregister.com/2012/04/11/odd-tube-wear-seen-in-both-onofre-reactors/170292/

Therefore, both the original and the replacement steam generators at San Onofre are some of the largest steam generators that have been designed or manufactured anywhere in the world. NRC spokesperson Victor Dricks agreed when he said, "…this problem is specific to the steam generators at San Onofre… They are virtually a unique design and no other plant in the United States has them."[2]

Extensive Unreviewed Design Changes Were Made To San Onofre's Replacement Steam Generators

Edison decided to replace each San Onofre steam generator due to tube deterioration and degradation that slowly evolved during each Unit's 25-years of operation. Documents reviewed show that the four replacement steam generator specifications are identical to each other and they were purchased together under a single contract with Mitsubishi Heavy Industries (MHI). However, rather than simply rebuild the steam generators to their original design specifications, Edison decided to extensively modify the original San Onofre steam generator design. Furthermore, none of the design modifications were necessary for operation of either San Onofre Unit 2 or 3, and in fact were added by Edison without adequate consideration for their impact upon the reliability or safety of steam generator and the reactor.

A joint report[3] prepared by Edison and (MHI) describes in great detail numerous changes Edison made to the original steam generator design. The evidence reviewed in the Edison/MHI report shows that extensive modifications were made to the original design without the requisite total engineering analysis. Additionally, MHI has only constructed one other replacement steam generator for a CE designed PWR, and that reactor produced one-half the power output created by the San Onofre Units.

Cascading Design Changes By Edison Created Steam Generator Failure

The evidence provided in the Edison/MHI report shows that ***a cascading series of deliberate design changes likely caused the tube failures and tube degradation*** that has shut down San Onofre Units 2 and 3 since January of 2012.

Approximately seven years ago Southern California Edison began the process of replacing San Onofre's original steam generators. Fairewinds believes that two key management decisions created the cascading failure sequence that now exists in San Onofre's steam generators:

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[2] http://www.kpbs.org/news/2012/apr/06/nrc-chair-visit-troubled-san-onofre-nuclear-power-/ Friday, April 6, 2012, KPPS Radio.

[3] *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&EID=af75ecb1-5b23-49be-9dd6-d806f2e9b7b5&skip=&p=36

1. First, a decision was made to change the tube alloy from Inconel 600[4] to Inconel 690[5]. Inconel 600 was the tube alloy in use during the construction of San Onofre and other PWR's. However, many replacement steam generators have been constructed with Inconel 690 that to date appears to have allowed most replacement steam generators to operate longer with less deterioration. Fairewinds believes that if the only fabrication change by Edison/MHI to the San Onofre steam generator had consisted of a tube alloy composition change from Inconel 600 to 690[6], it was most likely that the San Onofre steam generators would have continued to operate successfully well beyond the 40-year license for either Unit.

   Furthermore, a document review of nuclear industry reports reviewing PWR reactor replacement steam generator installations shows that the single composition change from the tube alloy Inconel 600 to 690 appears to be a well established PWR industry fabrication standard, while the addition of almost 400 new tubes to the replacement steam generators created unanalyzed flow and stress design changes that have severely compromised reactor operability for Units 2 and 3.

2. The second key fabrication change supplanted to the San Onofre steam generators by the Edison/MHI team increased the total number of tubes in each steam generator by almost 400 tubes to more than 104% of each generator's original design. Each Original Steam Generator contained 9350 tubes[7] while the Replacement Steam Generators each contain

[4] Inconel 600 is a nickel-chromium super alloy. It is readily weldable and non-magnetic in nature and used in various corrosion resisting applications. The chromium content of the **Inconel 600** provides resistance to weaker oxidizing environments while the high nickel content provides exceptional resistance to chloride stress corrosion cracking and a level of resistance to reducing environments. http://sbecpl.com/products/nickel-alloys/inconel-600/

[5] INCONEL alloy 690 is a high-chromium nickel alloy having excellent resistance to many corrosive aqueous media and high-temperature atmospheres. The alloy's high chromium content gives it excellent resistance to aqueous corrosion by oxidizing acids (especially nitric acid) and salts, and to sulfidation at high-temperatures. In addition to its corrosion resistance, alloy 690 has high strength, good metallurgical stability, and favorable fabrication characteristics. http://www.specialmetals.com/products/inconelalloy690.php

[6] ***Friction Induced Vibrations*, R. Ibrahim, *Encyclopedia of Vibration*, *2001*, Pages 589-596**
http://www.sciencedirect.com/science/article/pii/S0029549303001870
"In the steam generators of nuclear power plants, the flow of cooling water can cause the tubes to vibrate, resulting in fretting wear damage due to contacts between these tubes and their supports. The tubes are made of Inconel 690 and Inconel 600 and the supports are made of STS 304. In this paper, fretting wear tests in water were performed using the materials Inconel 690 and Inconel 600 in contact with STS 304. Fretting tests using a cross-cylinder type set up were conducted under various vibrating amplitudes and applied normal loads in order to measure friction forces and wear volumes. Also, conventional sliding tests using a pin-on-disk type set up were carried out to compare these test results.
In the fretting tests, friction force was found to be strongly dependent on normal load and vibrating amplitude. Coefficients of friction decreased with an increase in the normal load and a decrease in the vibrating amplitude applied. Also, the wear of Inconel 600 and Inconel 690 was predicted using a work rate model. Depending on the normal load and vibrating amplitude applied, distinctively different wear mechanisms and often drastically different wear rates occurred. It was found that the fretting wear coefficients for Inconel 600 and Inconel 690 were 9.3×10^{-15} and 16.2×10^{-15} Pa^{-1}, respectively. This study shows that Inconel 690 can result in lesser friction forces and exhibits less wear resistance than Inconel 600 in room temperature water."

[7] http://www.cpuc.ca.gov/Environment/info/aspen/sanonofre/feir/v1/figs/Fig%20B-4.pdf

9727 tubes[8]. Fairewinds believes it was this management decision to increase the number of tubes that lead in turn to a series of cascading design changes that created the serious problems San Onofre is experiencing in 2012.

Fairewinds believes that Edison's decision to cram an additional 377 tubes into the replacement steam generators was the root cause to the steam generator leaks encountered in 2012. Moreover, Edison's decision to add 377 more tubes to the existing 9,350 tubes rather than perform the like-for like steam generator replacement for which it applied at San Onofre caused a cascading series of replacement steam generator failures.

Cascading Fabrication Changes Following Edison Decision To Dramatically Increase The Number of Tubes

Similar, but smaller, Tubesheet image – prior to drilling for tube insertion

The original San Onofre steam generator contained a *tubesheet*[9], which is a metal disc approximately 13-feet in diameter and slightly less than two feet thick, located near the bottom of the steam generator. Due to the already extremely large size of the CE steam generators, this tubesheet[10] is one of the largest tubesheets ever fabricated after which 18,700 holes (9,350 in-

[8] http://www.nrc.gov/reading-rm/doc-collections/news/2012/12-011.iv.pdf.
[9] Ibid.
[10] A 'tubesheet' divides the steam generator into the primary side and a second side, which 'tubesheet' has an array of holes having U-shaped heat transfer tubes inserted therein, which communicate between the inlet section and outlet section of the primary side of the steam generator. In operation, the heat pressurized fluid passes through the U-shaped heat transfer tubes and is discharged from the outlet section of the primary side of the steam generator to a line, containing a primary coolant pump, back to the reactor in a continuous closed loop. http://www.patentstorm.us/patents/4728486/fulltext.html

hot/9,350 out-cold) were then drilled. This metallic disk [see image] serves as an anchor into which both sides of the U-tubes are inserted. Not only is the tubesheet extraordinarily heavy, but also there can be a pressure difference of approximately 2,000 pounds per square inch (psi) between the radioactive water on one side and non-radioactive water on the other.

In order to support the enormous tubesheet metallic disk, the original steam generator design at San Onofre contained a 'stay cylinder' in the center of the tubesheet that is a support pillar designed to relieve the weight in the middle of the tubesheet.

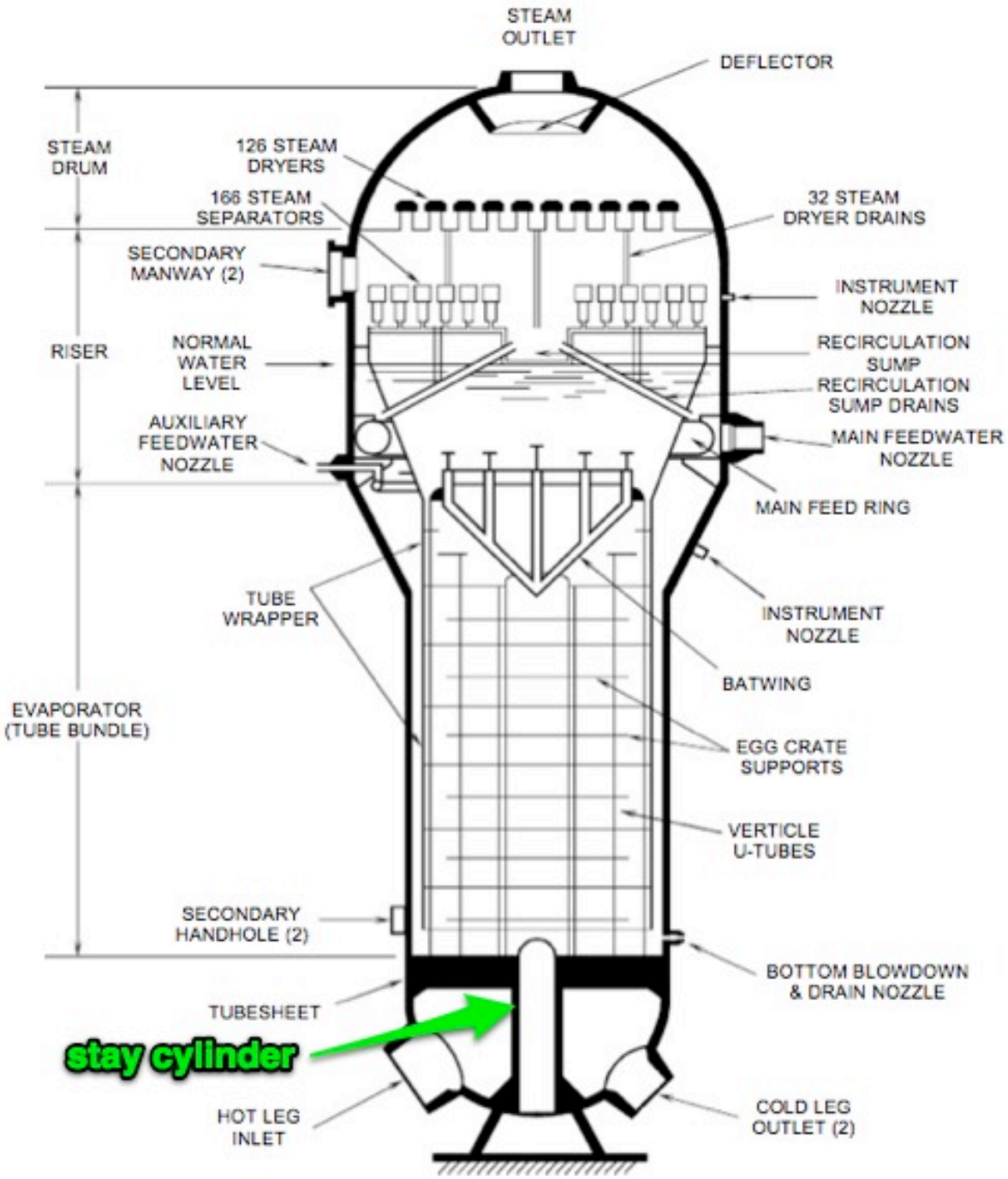
1. When Edison decided to cram in additional steam generator tubes, the fabrication technique created by Edison/MHI for the San Onofre steam generators necessitated the removal of the 'stay cylinder' so that more tube holes could be drilled through the tubesheet. The Edison/MHI decision to add additional tubes and replace this key support pillar was part of the cascading fabrication changes that caused additional stresses and steam generator failure.

2. Removing the stay cylinder required additional cascading fabrication changes. Because the tubesheet was no longer supported in the center by the stay cylinder, Edison/MHI required the fabrication of a thicker tubesheet so that it could bear the additional stress without a stay cylinder. This change in the tubesheet thickness meant yet another design change by reducing the volume of water in the steam generator and changing the flow pattern and also reducing the inspection access area beneath the tubesheet that is required to fit personnel and equipment for tube inspection.

3. Changing the structural loads on the tubesheet have not only affected the reliability of the steam generators but also should have raised a serious safety concern because the tubesheet is the key barrier to keeping radiation inside the containment. Should the tubesheet fail, radiation within the reactor would bypass the containment and pass directly into the environment. Due to the installation of the 'stay cylinder' in the original San Onofre steam generator configuration, a tubesheet failure and subsequent radiation release is considered to be beyond the calculations for a design basis accident at San Onofre. Yet Edison chose to challenge this critical safety barrier and licensing parameter by removing the "stay cylinder" in order to install more, unnecessary tubes.

4. Fabricating more tubes increased nuclear reactor core flow, which was unacceptable because it changed the original design basis safety calculations for cooling the reactor. For that reason Edison welded a flow-restricting ring into the steam generator nozzle in order to reduce the flow of cooling water back into the reactor to the original design parameters, which also changes the flow distribution to the tubes. Thus significant operational changes were also made to the radioactive side of the steam generator as a result of Edison's addition of more steam generator tubes.

Typical Combustion Engineering Steam Generator



5. All of these changes necessitated even more fabrication changes within the steam generator. For example, more tubes meant that the tube supports had to be modified in an attempt to avoid the increased vibration caused by the flow changes induced by the Edison/MHI fabrication changes. The feedwater distribution ring inside the steam generator was also dramatically modified in order to avoid a serious flow induced water hammer.

Conclusions

In Fairewinds' opinion, the vibration between the tubes caused the steam generator leaks and degradation uncovered in January 2012 and was due to the simultaneous implementation of numerous unreviewed fabrication and design changes to the replacement steam generators by Edison/MHI. Almost all of these changes were avoidable if San Onofre's management had not made the decision to cram an additional 377 unnecessary tubes into each steam generator. This Edison decision made seven years earlier was not in the best interests the San Onofre Units and costs to implement these unreviewed changes were not prudent.

Fairewinds believes that if the original steam generators had been replaced with duplicates (*like-for-like*) with the only significant change that of the tube alloy composition from Inconel 600 to 690, it is most likely that the San Onofre steam generators would have continued to operate successfully well beyond the 40-year license for either Unit. However, the extensive unreviewed design and fabrication changes implemented by Edison/MHI to the new San Onofre steam generators are hardly a *like-for-like* change.

The evidence reviewed by Fairewinds shows that the replacement steam generators for Units 2 and 3 have identical specifications and were subject to identical operating conditions. While Unit 2 has experienced more tube degradation and Unit 3 has experienced deeper cracking in fewer tubes, both Units require a concurrent root cause analysis due to their identical specifications and operating conditions.

Friends of the Earth retained Fairewinds Associates (fairewinds.com), a paralegal services and expert witness firm specializing in nuclear engineering and nuclear safety analysis, to conduct this review and issue this report. Arnie Gundersen, MSNE, and chief engineer for Fairewinds Associates authored this report.