Steam Generator Degradation and Its Impact on Continued Operation of Pressurized Water Reactors in the United States

by

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Introduction

Nuclear power is the second largest source for electricity generation in the United States, accounting for more than one-fifth of total utility-generated electricity in 1994. Currently, 109 nuclear units are licensed in the United States, representing a total capacity of 99 gigawatts electric.[1] Of the 109 units, 72 are pressurized light-water reactors (PWR) and 37 are boiling-water reactors (BWR).[2] Since nuclear power began to be widely used for commercial purposes in the 1960's, unit operators have experienced a variety of problems with major components. Although many of the problems have diminished considerably, those associated with PWR steam generators persist. As of December 31, 1994, 35 steam generators had been replaced in 12 of the 72 operating PWR's, and 3 units had been shut down prematurely, due primarily (or partially) to degradation of their steam generators: Portland General Electric's Trojan unit, located in Prescott, Oregon, in 1992; Southern California Edison's San Onofre 1, located in San Clemente, CA, in 1992; and Sacramento Municipal Utility District's Rancho Seco unit in 1989.

In the coming years, operators of PWR's in the United States with degraded steam generators will have to decide whether to make annual repairs (with eventual derating likely), replace the generators, or shut the plants down prematurely. To understand the issues and decisions utility managers face, this article examines problems encountered at steam generators over the past few decades and identifies some of the remedies that utility operators and the nuclear community have employed, including operational changes, maintenance, repairs, and steam generator replacement. The technical, regulatory, and financial factors associated with steam generator maintenance and replacement are also identified. In addition, a list of 23 units are identified as potential candidates for steam generator replacement or shutdown.

Pressurized Light-Water Reactor

In a PWR, heated water is carried out of the reactor core by the primary loop to the steam generator, where the heat is transferred to the secondary loop (Figure FE1). The pressure in the reactor and the primary loop is about 2,250 pounds per square inch, which permits the water to be heated to a temperature of 600° F without boiling.[3] Tubes containing primary-loop water, which is radioactive, heat up the secondary-loop water and convert it into steam. This process cools the primary-loop water somewhat, to about 550° F. The primary-loop water is then pumped through the reactor again, reheating the water and starting the cycle over.

In the secondary loop, meanwhile, steam leaves the steam generator at a temperature of about 500° F and at a pressure well below that of the primary loop. It exits at the top of the steam generator through moisture separators, steam dryers, and other systems, and is then piped to a turbine generator, where it expands and spins a turbine to generate electricity. The steam leaving the turbine, which is now lower in pressure than when it leaves the steam generator, is converted back into water in the condenser and returned to the steam generator to begin the secondary cycle again. U.S. PWR's have two, three, or four steam generators and are called two-loop, three-loop, or four-loop units, respectively. Generally, the plants with larger capacities have more loops in order to accommodate a larger total heat transfer surface area while limiting the size of each

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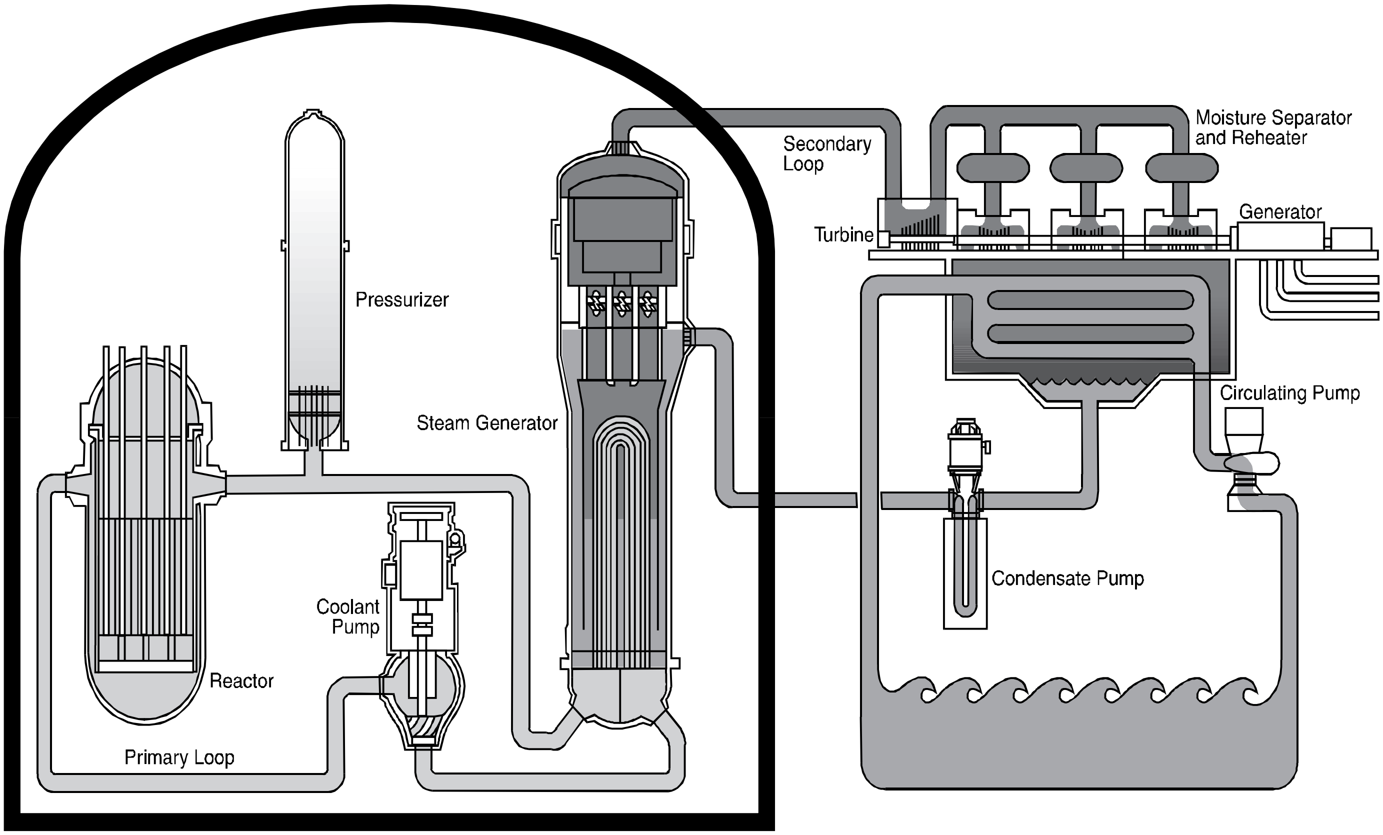
[1] Energy Information Administration, Form EIA-860, "Annual Generator Report."

[2] Two types of reactors operate in the United States: PWR's and BWR's. Only PWR's have steam generators.

[3] "The Nuclear Power Plant," a brochure published by B&W Nuclear Technologies, Lynchburg, Virginia, p. 2.

Figure FE1. Nuclear Steam Supply System
(U-bend Design Steam Generator)



CONTAINMENT HATCH

Source: Westinghouse Corporation.

steam generator. Three vendors have provided steam generators for existing U.S. reactors—Babcock & Wilcox, Combustion Engineering, and Westinghouse. All 7 Babcock & Wilcox units and 14 of the 15 Combustion Engineering units are two-loop reactors (one Combustion Engineering unit is a three-loop reactor), while the 50 Westinghouse units range from two to four loops.[4]

The capacity, shape, and features of a steam generator depend mostly on the manufacturer. In a once-through design, for instance, the primary-side water enters the steam generator at the top, flows through the generator in unbent tubes, and exits at the bottom (Figure FE2). In the U-bend design, the primary-side water enters at the bottom of the steam generator, flows through tubes that bend in an inverted "U" approximately in the middle of the steam generator, and returns to exit at the bottom of the steam generator (Figure FE3). All Babcock & Wilcox steam generators are of the "once-through" design rather than the recirculating or "U-bend" design used by Combustion Engineering and Westinghouse steam generators.

The number of tubes in the steam generator varies by manufacturer, unit capacity, and type of design. Westinghouse units contain about 3,200 to 5,600 tubes per steam generator, Combustion Engineering uses 5,000 to 11,000 tubes per steam generator, and Babcock & Wilcox uses 15,500 tubes in each of its steam generators. The Babcock & Wilcox steam generators require more tubes than the Westinghouse or Combustion Engineering units because the once-through design with straight tubing provides less surface area per tube for a given tube shell length than does the U-bend design. The diameter of each tube ranges from 19 to 25 millimeters. Water from the reactor pressure vessel enters the steam generator through the "hot leg" pipe,

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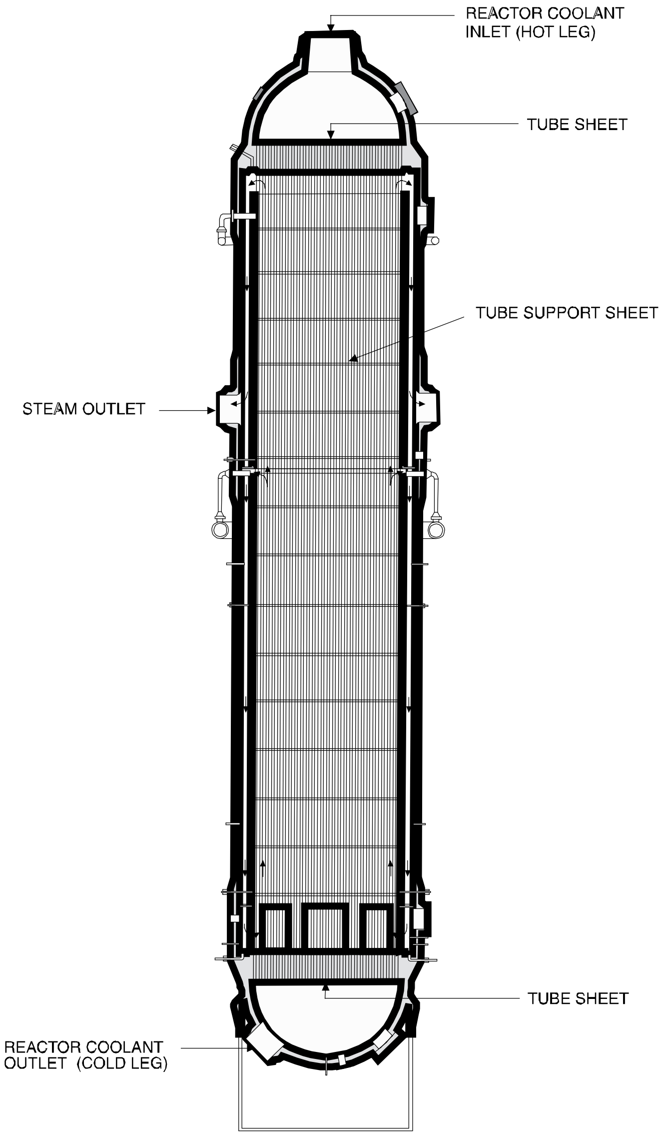
[4] Energy Information Administration, *World Nuclear Outlook 1994*, DOE/EIA-0436(94) (Washington, DC, December 1994), pp. 90-92.

Figure FE2. Once-Through Steam Generator



Source: Babcock & Wilcox Company.

Figure FE3. U-Bend Steam Generator

Source: Westinghouse Corporation.

circulates under pressure through the tubes, and exits through the “cold leg” pipe. A typical steam generator weighs 250 to 400 metric tons and exceeds 15 meters in length and 6 meters in diameter.

Types of Failure and Degradation Issues

In the 1970’s, tube wastage was the earliest problem many utilities reported at a number of units (Table FE1). The Electric Power Research Institute (EPRI) formed the first of two Steam Generator Owner Groups to address the wastage problem and an emerging problem: widespread tube denting.[5] By the end of 1982, the cause and remedies for denting were much better understood, and that problem had dramatically decreased. By 1979, stress corrosion cracking and apparent fatigue cracking had begun to be reported at a number of operating units.

The issues associated with steam generator degradation have had a significant impact on nuclear power plant operation. As a result, utilities with degrading steam

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[5] Electric Power Research Institute, “Steam Generator Progress Report (Revision 10),” EPRI Research Project RP3580-06, Final Report, November 1994, p. 1-1.

Table FE1. Steam Generator Degradation Definition

Type of Degradation	Definition
Denting	The physical deformation of the Inconel Alloy 600 tubes as they pass through the support plate. Caused by a buildup of corrosive material in the space between the tube and the plate.
Fatigue cracking	Caused by tube vibration.
Fretting	The wearing of tubes in their supports due to flow induced vibration.
Intergranular attack/stress-corrosion cracking (outside diameter)	Caused when tube material is attacked by chemical impurities from the secondary-loop water. It occurs primarily within tube sheet crevices and other areas where impurities concentrate.
Pitting	The result of local breakdown in the protective film on the tube. Active corrosion occurs at the site of breakdown.
Stress-corrosion cracking (inside diameter)	Cracking of steam generator tubes occurring at the tangent point and apex of U-bend tubes, at the tube sheet roll transition, and in tube dents. It occurs when Inconel Alloy 600 tubing is exposed to primary-loop water.
Tube wear	A thinning of tubes caused by contact with support structures either as the tubes vibrate or as feedwater entering the vessel impinges on the tube bundle at that location.
Wastage	A general corrosion caused by chemical attack from acid phosphate residues in areas of low water flow.

generators must make a tradeoff between either (1) continued operation with high operation and maintenance costs, high worker radiation exposures, increased risks of forced outage from tube ruptures, derating the plant, or (2) replacement.[6]

Currently, the most common form of failure is intergranular attack / stress-corrosion cracking. This form of failure now accounts for 60 to 80 percent of all tube defects requiring plugging. Fretting and pitting combine to account for another 15 to 20 percent of all tube defects. The remaining failures are attributed to mechanical damage, wastage, denting, and fatigue cracking.[7]

Initially, the problems were thought to be isolated incidents resulting mainly from defects in manufacturing, poor operations, poor water chemistry, and other factors. Over time, however, a pattern of failures began to emerge, suggesting common factors and common failure modes. The physical factors most often responsible for these failures, and the typical corrective actions, are as follows:

- **Tube alloys**—The most common factor in tube defects has been the tube alloy most widely used in original steam generators both in the United States and throughout the world, Inconel 600 mill-annealed, a thin nickel alloy material that has proven susceptible to many forms of cracking, pitting, denting, and other types of degradation. Replacement steam generators manufactured by Westinghouse, Babcock & Wilcox, as well as foreign manufacturers Framatome and Mitsubishi now use thermally treated Inconel 690. The Inconel 690 thermally treated tube has proven to be 9 to 10 times more resistant to secondary-loop cracking than Inconel 600 mill-annealed.[8]

- **Tube sheet design and alloys**—The tube bundles connect to a tube sheet on each end of the tubes. The tube sheet separates the primary-loop water from the secondary-loop water. Both the tube sheet connection and the exterior of the tubes at the connection tend to accumulate sludge, crack from vibration, and show excessive fatigue

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[6] Derating is the lowering of the electrical output capacity of a plant.

[7] Benjamin L. Dow and Robert C. Thomas, "SG Status: Worldwide Statistics Reviewed," *Nuclear Engineering International,* January 1995, p. 18.

[8] As explained by Joseph Eastwood, a Virginia Power Company representative, on March 14, 1995.

cracking. Replacement tubes in more modern steam generators use different tube sheet designs, tube sheet materials, and tube/tube sheet attachments to reduce these problems.

- **Tube support plate designs and alloys**—The tube bundles are supported above the tube sheet by tube support plates and antivibration bars. Tube support connections tend to accumulate corrosive sludge, crack, and fret. Improved designs and materials that permit better venting of steam around the tube supports and minimize formation of corrosive sludge in crevices have improved steam generator performance.

- **Small-radius U-bends**—In "U-bend" steam generators, the tubes nearest the center of the tube bundle have the smallest radius U-bends. During manufacture and operation, small-radius U-bends are subject to greater stress than large-radius U-bends or the unbent portion of the tubes. Recent designs enlarge the small-radius U-bends and rely on improved or additional antivibration bars.

The once-through steam generators have experienced fewer problems than the U-bend design. The reason once-through steam generators have been able to control the degradation phenomenon is that Babcock & Wilcox, the manufacturer of the once-through design, incorporated flow openings around the tube support plate (a known corrosion area) and fabricated their tubes differently. Instead of Inconel 600 mill-annealed, Babcock & Wilcox tubes were Inconel 600 sensitized.[9] Currently, these design and technological improvements have been incorporated in the U-bend design steam generators.

Maintenance and Repair

Several strategies have been developed to minimize degradation problems and prolong steam generator life. Water chemistry improvements and chemical cleaning have been used to reduce the number of failures and limit the need for plugging or sleeving. Plugging and sleeving tubes remain, however, the most common remedial actions taken by utility operators.

- **Water Chemistry Improvements**—Tube defects and failures occur for various reasons, particularly when the secondary-loop water contains impurities or particles that lodge in crevices or create sludge or when the water is excessively basic/acidic or excessively oxidizing/reducing. Changes in secondary water chemistry over the years have included substituting all-volatile treatment[10] for phosphate treatment to reduce sludge. Improved water chemistry has helped somewhat but has not arrested the widespread degradation of Inconel 600 mill-annealed tubes.

- **Cleaning**—Accumulations of sludge and corrosion products on the outside of the tubes, especially at the connections with the tube sheet and the tube support plates, are responsible for several types of tube degradation, including stress corrosion cracking and intergranular attack. Mechanical cleaning methods, such as water lancing,[11] are used to reduce deposits and slow tube degradation. Steam generators have been cleaned at six U.S. units (Table FE2).

- **Plugging**—As of December 1993, approximately 38,000 tubes, or 0.9 percent of all the tubes in operating steam generators in the United States, have been plugged. In general, 15 to 20 percent of the tubes may be plugged before replacement or derating is required.[12] Excessive steam generator plugging hinders coolant flow, which may require significant power reduction. In general, plugging is an operator's initial response to degrading tubes. Steam generators are designed to have an excess number of tubes; therefore, tubes are generally plugged when they degrade. Once a number of tubes degrade, the operator may decide to sleeve tubes (see below), including those that were initially plugged. New steam generators have an even higher excess of tubes. From 1987 to 1991, in units throughout the world, the location of the defects requiring plugging varied considerably (Table FE3).

- **Sleeving**—Sleeving is used only for steam generator tubes with cracks penetrating no more than 40 percent of the tube wall; more serious cracking requires the tube to be plugged. A short tube, or "sleeve," is inserted into the base tube to bridge the degraded area. The sleeve is then welded inside the tube to isolate the degraded section of the tube. The sleeve effectively seals the leak from the secondary-loop water. This technique is usually limited to the portion of the tubes near the

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[9] Mill-annealed and sensitive refer to two different types of fabrication methods.

[10] All-volatile treatment uses chemicals that do not form solids that can lodge in the steam generator cracks and crevices.

[11] Water lancing is a high-pressure cleaning treatment.

[12] Steven E. Kuehn, "A New Round of Steam Generator Replacements Begins," *Power Engineering*, July 1992, pp. 39-43.

Table FE2. Steam Generator Chemical Cleaning in the United States

Unit	Utility	First Year of Operation	Year Cleaned	Amount of Corrosion Removed (Pounds[a])	Amount of Corrosion Removed (Kg[a])	Steam Generator Manufacturer
Millstone 2	Northeast Nuclear Energy Co.	1975	1985	567	258	CE
Maine Yankee	Maine Yankee Atomic Power Co.	1973	1987	2,381	1,082	CE
Oconee 1	Duke Power Co.	1973	1987	6,648	3,022	B&W
Oconee 2	Duke Power Co.	1973	1988	8,909	4,050	B&W
Arkansas 1	Arkansas Power & Light Co.	1974	1990	10,040	4,564	B&W
Three Mile Island	GPU Nuclear Power Co.	1974	1991	6,540	2,973	B&W

[a] Amount of corrosion products removed from the steam generator.

B&W=Babcock & Wilcox Co.

CE=Combustion Engineering Corp.

Note: The conversion factor used by the Electric Power Research Institute is 1 kg = 2.2 pounds, which is not exactly the same conversion factor used by EIA.

Source: Electric Power Research Institute, “Steam Generator Progress Report (Revision 10),” EPRI Research Project RP3580-06, Final Report, November 1994.

Table FE3. Location of Defects Requiring Tube Plugging at Units Throughout the World
(Percent of Tubes Plugged)

Location of Defect	Year 1987	1988	1989	1990	1991
Within Tube Sheet	43	40	19	26	18
Above Tube Sheet	14	16	37	34	15
U-bend	9	11	9	2	5
Anti-vibration Bar	--	2	3	13	2
Tube Support Plates	14	20	17	18	50
Other	2	1	1	1	1
Undetermined	18	17	15	6	9

--=Not applicable.

Note: The sum of component percentages may not add to 100 percent due to independent rounding.

Source: L.M. Stippan and R.L. Tupping, “Tube Plugging: Looking Behind the Trends,” *Nuclear Engineering International*, January, 1995, p. 21.

tube sheet. Although sleeving is more expensive than plugging, and the water flowing through the tube is slightly affected, the tube remains in service. In the United States, sleeving has been done in almost two dozen operating PWR’s.

- **Improvements**—The low-pressure steam leaving the turbine-generator is converted back into water in the condenser before being returned to the steam generator. The condenser is a heat exchanger (much like a steam generator) where cooling water (from a river, a pond, the sea, or other sources) converts the steam in the secondary-loop back to water. Leaks or degraded condenser tubes can contaminate the secondary-loop water that circulates through the steam generator and lead to steam generator tube degradation. Improved condenser materials (e.g., titanium tubes), better leak detection devices, and better water chemistry minimize condenser-related problems and associated steam generator problems.

Even with condenser improvements,[13] water chemistry improvements, inspection and cleaning programs, operational changes, and other actions, problems at steam generators are continuing. Recently, there have been reports of circumferential cracks[14] near the tube sheet that went undetected in standard inspections, but were found using more sophisticated tube inspection equipment. Although circumferential cracks are not a new phenomenon, new tube inspection devices have shown that the cracks may be more numerous than initially thought. EPRI reports that 28 plants have reported finding circumferential cracks near the top of the tube sheet since 1987.

In 1994, circumferential cracks were discovered in more than half the tubes at the top of the tube sheet in the steam generators at the Maine Yankee nuclear plant. The utility, Maine Yankee Atomic Power Company, is considering sleeving all 17,109 tubes in the three-loop reactor. The repair is estimated to cost $64 million, not including the cost of replacement power. Due to the industry's latest findings, the Nuclear Regulatory Commission is asking each PWR operator to prove that, like Maine Yankee, it is adequately inspecting its steam generators for these cracks. Working to address these problems are the individual utilities and vendors and several industry groups, such as the Steam Generator Replacement Group, the EPRI Steam Generator Strategic Management Project (successor to the EPRI Steam Generator Owners Group), the Westinghouse Owners Group, and the Combustion Engineering Owners Group.

Steam Generator Replacement

When a utility decides to replace its steam generators, it must go through extensive planning efforts that include examining the extent of damage to the steam generators, estimating the length of time required to replace the steam generators, deciding whether a partial or complete steam generator replacement is needed, and determining the cost associated with replacement. A total of 12 U.S. units have replaced steam generators (Table FE4), all of which are of the U-bend design.

Two techniques have been utilized to replace steam generators: the pipe-cut and channel-head-cut methods. In the pipe-cut method, the entire steam generator is removed from the reactor coolant system by cutting the hot and cold leg primary piping adjacent to the channel head of the steam generator. Replacement steam generators or replacement portions are installed by reconnecting the primary piping to complete the repair operation. If the reactor containment hatch is large enough, the entire steam generator assembly can be removed intact (after disconnecting the feedwater and steam nozzle) and replaced. This not only shortens replacement time and lowers worker exposure, but also reduces costs as compared to cutting a hole in the containment hatch.

In the channel-head-cut technique, the steam generator is separated by cutting the channel head just below the tube sheet. This leaves the lower primary piping in place and simplifies fitting the steam generator back into place. The upper portion of the steam generator can be replaced in its entirety or the upper part of the steam generator can be cut and refurbished in the containment building.

Both steam generator outage time and worker radiation exposure (person-rem per steam generator) during steam generator replacement have dropped considerably (Table FE4). The most recent replacement, at South Carolina Electric & Gas Company's Summer unit, took 38 days from the time the reactor coolant system piping was severed until the secondary-side piping was pressurized to 1,500 pounds for testing. The world record for a steam generator replacement, set in France in 1994 at Gravelines Unit 1, is 37 days.[15] During steam generator replacements, as well as other operational activities (e.g., refueling and maintenance), the NRC requires each utility to keep exposure "as low as reasonably achievable." Total worker exposure for the Summer replacement was 33 person-rem. The lowest worker exposure rate in the United States was 24 person-rem at North Anna 1, the replacement prior to the Summer unit replacement.

The only significant deviation from the downward trend in outage duration and worker exposure was the replacement at the Millstone 2 unit, located in Waterford, CT. The Millstone 2 situation was unusual in that one of the cold leg pipes shifted as it was being

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[13] The condenser is the unit where raw cooling water condenses the steam leaving the turbine. Improper condenser materials can introduce contaminants, minerals, chemicals or other materials into the steam generator.

[14] Circumferential propagating cracks are cracks occuring around the perimeter of the tube in contrast to axial cracks, which propagate lengthwise on the tube.

[15] "SCE&G Sets U.S. Steam Generator Replacement Record at Summer," *Nucleonics Week*, December 1, 1994, pp. 1-2.

Table FE4. Steam Generator Replacements in the United States

Unit Name	Utility	First Year of Operation	SG Manu-fac-turer	Net Capacity (MWe)	Year Replaced	Length of Outage[a] (Days)	Replacement	Num-ber of SG's	Worker Exposure (person-rem)	Cost[b] (million dollars)
Surry 2	Virginia Electric Power Co.	1972	WEST	781	1979	303	Lower section	3	214	94
Surry 1	Virginia Electric Power Co.	1973	WEST	781	1980	209	Lower section	3	176	94
Turkey Point 3 . .	Florida Power & Light Co.	1972	WEST	666	1981	210	Lower section without channel head	3	215	90
Turkey Point 4 . .	Florida Power & Light Co.	1973	WEST	666	1982	183	Lower section without channel head	3	131	90
Point Beach 1 . . .	Wisconsin Electric Power Corp.	1970	WEST	492	1983	117	Lower section	2	59	47
Robinson 2	Carolina Power & Light Corp.	1970	WEST	683	1984	225	Lower section without channel head	3	121	85
Cook 2	Indiana/ Michigan Power Co.	1977	WEST	1,060	1988	202	Lower section	4	56	112
Indian Point 3 . . .	Power Authority of the State of N.Y.	1976	WEST	980	1989	105	Entire SG	4	54	120
Palisades	Consumer Power Co.	1972	CE	755	1990	121	Entire SG	3	49	100
Millstone 2	Northeast Nuclear Energy Co.	1975	CE	873	1992	192	Lower section	3	70	190
North Anna 1 . . .	Virginia Electric Power Co.	1978	WEST	900	1993	51	Lower section	3	24	125
Summer	South Carolina Electric & Gas Co.	1982	WEST	885	1994	38	Entire SG	3	33	153

[a] Outage represents only days spent to replace steam generator.

[b] Nominal cost excludes replacement power cost.

CE=Combustion Engineering Corp.

SG=Steam generator

WEST=Westinghouse Corp.

Sources: Electric Power Research Institute, "Steam Generator Progress Report (Revision 10)," EPRI Research Project RP3580-06, Final Report, November 1994; **Net Capacity and Year of Operation**—Energy Information Administration, *World Nuclear Outlook 1994*, DOE/EIA-0436(94) (Washington, DC, December 1994), pp. 90-92.

cut. The shift, which occurred despite pipe restraints, relieved stresses the pipe developed during original installation and operations. Because of the shift, the Northeast Nuclear Energy Company conducted an extensive examination and analysis of pipe stress and alignment. Analyzing and realigning the pipes added 41 days to the process. Additional welding and radiographic inspections took another 12 days.

Costs and Benefits of Steam Generator Replacement

Replacement Costs

Replacement of a steam generator is an economic decision. A steam generator with excessive tube degradation creates extra costs for reasons such as:

- Tube inspections and leakage monitoring
- Maintenance and repair (e.g., plugging and sleeving)
- Water chemistry control
- Condenser inspection, maintenance, and monitoring
- Occupational radiation exposure
- Power derating due to plugging
- Potential for forced outages due to tube leaks or ruptures.

An analysis of one case showed that, compared to continuing with the existing equipment, installing a new steam generator would reduce annual steam generator repair costs by $3.4 million.[16] As maintenance costs increase and derating becomes more likely, the economics of steam generator replacement becomes more attractive.

The cost to replace the steam generator varies significantly depending on factors such as:

- The number of generators replaced at one time
- Whether the replacement is partial or total
- Whether the equipment hatch is large enough to accommodate the entire unit
- The amount of free space in the containment area to position the unit and the type of containment facility where the steam generator is located
- The number of pipes that must be cut and the number of cuts
- The requirements for radiation shielding
- The requirements for pipe support
- Any potential pipe shifting problems (such as at Millstone 2).

The cost of a steam generator is $12 million to $20 million.[17] The cost to replace a steam generator is substantially more. Complete replacement at a three-loop PWR in the United States over the past 2 years cost between $125 million and $153 million (Table FE4), or about $139 per kilowatt (kW) to $170 per kW for a typical 900 MWe unit. South Carolina Electric & Gas Co. (SCE&G) spent an estimated $153 million to replace three steam generators at the 885 MWe Summer unit.[18]

Ten U.S. units are planning to replace steam generators, according to formal announcements or reports concerning placement of steam generator orders (Table FE5). Florida Power & Light expects to spend about $170 million, excluding replacement power costs, to replace two steam generators at St. Lucie 1 in 1997.[19] Duke Power expects to spend $437 million, excluding replacement power costs, to replace steam generators at three four-loop units (McGuire 1 and 2 and Catawba 1) between 1995 and 1997.[20] The expected cost to replace the steam generators at the three-loop North Anna 2 unit is $140 million.[21]

Whether replacement power costs are added to the steam generator replacement cost depends on whether the replacement occurs during an outage already required for a refueling or maintenance outage. Ordinarily, the steam generator replacement coincides with a normal refueling or maintenance outage. If the replacement is carried out during a scheduled outage, the steam generator replacement activity is charged only for the time it adds to the outage. Steam generator replacement times in the United States have been dropping sharply over the past 2 years and are now less than 2 months (Table FE4).

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[16] Rochester Gas and Electric Corp., “1992 Integrated Resource Plan,” June, 1992, Appendix D, p. 5. The analysis concerns the Robert Ginna plant in Rochester, New York, which is scheduled for a steam generator replacement in 1996.

[17] H. Hennicke, “The Steam Generator Replacement Comes of Age,” *Nuclear Engineering International,* July 1991, pp. 23-26.

[18] “SCE&G Set U.S. Steam Generator Replacement Record at Summer,” *Nucleonics Week*, December 1, 1994, p.2, and “SCE&G Returns Summer to Service After Replacing Steam Generators,” *Nucleonics Week*, December 22, 1994, p. 3.

[19] “DE&S Steam Generator Replacement Team Gets Foothold in Growing Market,” *Nucleonics Week,* October 27, 1994, p. 7.

[20] “Duke Power Readies for Successive Steam Generator Change-Outs,” *Nucleonics Week,* October 27, 1994, p. 6.

[21] “Duke Power Readies for Successive Steam Generator Change-Outs,” *Nucleonics Week,* October 27, 1994, p. 6.

Table FE5. Planned Steam Generator Replacements in the United States

Plant	Utility	SG Alloy	SG Manufac-turer	Loops	Net Capacity[a] (MWe)	First Year of Opera-tion	Total Tubes	Total Plug-ged	Per-cent Plug-ged	Total Sleeved[b]	Projected Year of Replace-ment	Projected Cost (million dollars)
North Anna 2	Virginia Electric Power Co.	I-600 MA	WEST	3	887	1980	10,164	1,332	13.1	0	1995	140
Ginna	Rochester Gas & Electric Corp.	I-600 MA	WEST	2	470	1969	6,520	483	7.4	1,953	1996	115
Catawba 1	Duke Power Co.	I-600 MA	WEST	4	1,129	1985	18,696	1,480	7.9	183	1996	437[c]
McGuire 1	Duke Power Co.	I-600 MA	WEST	4	1,129	1987	18,696	1,819	9.7	841	1996/1997	NA
McGuire 2	Duke Power Co.	I-600 MA	WEST	4	1,129	1983	18,696	1,387	7.4	615	1996/1997	NA
Point Beach 2	Wisconsin Electric Power Co.	I-600 MA	WEST	2	482	1973	6,520	622	9.5	3,895	1996/1997	120
St. Lucie 1	Florida Power & Light Co.	I-600 MA	CE	2	839	1976	17,038	1,818	10.7	0	1997	170
Zion 1	Commonwealth Edison Co.	I-600 MA	WEST	4	1,040	1973	13,552	948	7.0	806	2001	NA
Braidwood 1	Commonwealth Edison Co.	I-600 MA	WEST	4	1,090	1987	18,696	333	1.8	0	1998	470[d]
Byron 1	Commonwealth Edison Co.	I-600 MA	WEST	4	1,120	1985	18,696	847	4.5	0	1999	NA

[a] Energy Information Administration (EIA), Form EIA-860, "Annual Electric Generator Report."

[b] A tube can be sleeved more than once, and plugged tubes may have been sleeved.

[c] $437 million is the cost to replace the steam generators at Catawba 1, McGuire 1, and McGuire 2.

[d] $470 million is the cost to replace the steam generators at Braidwood 1 and Byron 1.

CE=Combustion Engineering Corp.
NA=Not available.
I-600 MA=Inconel 600 mill-annealed
SG=Steam Generator
WEST=Westinghouse Corp.

Sources: Electric Power Research Institute, "Steam Generator Progress Report (Revision 10)," EPRI Research Project RP3580-06, Final Report, November 1994; **Net Capacity and Year of Operation**—Energy Information Administration, *World Nuclear Outlook 1994*, DOE/EIA-0436(94) (Washington, DC, December 1994), pp. 90-92.

The cost of replacement power depends on many factors, including the amount of power that must be replaced, the region of the United States supplying the replacement power, the time of year, and the length of the replacement outage. In most of the United States, the cost of economy energy is roughly $20 to $30 per megawatthour (MWh).[22] [23] The cost could, however, be less if the utility has a significant amount of low-cost baseload surplus energy. Short-term firm power would be available for no more than about $40 per MWh.[24] The output from an 900 MWe nuclear power plant at 100 percent capacity factor is 657,000 MWh per month. At $40 per MWh, replacing the output from the plant would be about $26 million per month. Taking into account the availability of economy energy at $20 per MWh, and short-term firm power at $40 per MWh, the amount of nuclear output to be replaced, and the duration of the replacement, replacement power costs

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[22] Economy energy is energy produced and supplied from a more economical source in a system, substituted for that being produced or capable of being produced by a less economical source in another system.

[23] "Utility Reports Show Sharp Decline for February in Florida Economy Market," *Power Markets Week,* April 10, 1995, p. 5.

[24] Federal Energy Regulatory Commission (FERC) Form 1 (1993), "Annual Report of Major Electric Utilities, Licensees, and Others," was used to calculate short-term firm purchase power.

are likely to range from $13 million to no more than $30 million. If the replacement coincides with a regularly scheduled outage, steam generator replacement power costs and, therefore, total steam generator costs, could be appreciably lower.

Replacement Benefits

In general, there are four benefits to replacing a nuclear steam generator. The first benefit is avoiding, or at least substantially reducing, the problems associated with tube degradation outlined earlier. The savings from eliminating repeated tube plugging, extra maintenance and inspection work, and so forth can be millions of dollars per year. The savings from avoiding a forced outage due to a tube rupture are difficult to quantify but could certainly amount to tens of millions of dollars, depending on when in the operating cycle the rupture occurred; for example, if a tube ruptures immediately before a refueling outage the utility would be able to conduct maintenance and repairs on the steam generator during the refueling outage. Tube ruptures also prompt intense scrutiny by the NRC and probably additional attention from State regulators and the public. Thus, avoiding tube ruptures is of considerable value beyond the direct costs of the forced outage.

The second benefit is that the increased heat transfer surface may allow an uprating in the electric output of the unit.[25] [26] At the Summer station, SCE&G plans an uprate of approximately 50 MWe (about 5 percent) following the 1996 refueling outage.[27] The increased number of tubes and the increased heat transfer surface also expand the margin for future plugging, if necessary.

The value of an uprating depends on the remaining expected life of the generating unit. For example, the value of a 50 MWe uprate of a good-performance plant, that has 20 years of remaining life, is probably worth tens of millions of dollars.

The third benefit is reduced occupational exposure after replacement.[28] Prolonged operation with degraded steam generators will ultimately increase radiation exposure and extend refueling outages due to the increasing need for extensive tube inspection and repair.

The fourth benefit is deferred decommissioning. Premature shutdown creates two major decommissioning problems. First, the decommissioning trust will not have had the time to accumulate the full amount needed to pay for decommissioning. If a plant is shut down 10 years prematurely, the decommissioning trust is likely to lack at least three-quarters of its decommissioning total.[29] Second, decommissioning requires extensive planning many years in advance of actual decommissioning activity. Planning includes onsite activities, waste disposal preparations, licensing, settlement of State regulatory issues, replacement power planning, and the like. Deferring these activities and conducting the planning on a non-emergency basis has significant value to a utility.

Finally, owners considering steam generator replacement will find the job easier to justify if they are also considering license renewal, as a long license term provides a lower per kWh cost for the replacement.

Outlook

Units with original steam generators incorporating the Inconel 600 mill-annealed alloy tubing are almost certain to face degradation problems. In 1993, the NRC found “no end in sight” to steam generator tube cracking problems at plants operating with original steam generators.[30] There are 23 U.S. units that could be candidates for steam generator replacement in the future (Table FE6). These 23 units are those units whose percentage of plugged tubes range from 2 to 16 percent, suggesting the unit has some degree of degradation in its steam generators. Utilities are continuing to make necessary adjustments to their systems to prolong steam generator life. For example, the Arizona Public Service Company, the operator of the Palo Verde nuclear plant in Wintersburg, Arizona, has made several adjustments to its plant and believes that its steam generator may in fact last the full 40-year license period. The company attributes its positive results both to reducing the reactor hot leg temperature by 10° F, which increases moisture in the upper, outer region of the steam generator, and to cleaning the steam generators.[31]

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[25] In the United States, nuclear units are limited to a certain thermal rating, not an electrical rating.

[26] “Utility Reports Show Sharp Decline for February in Florida Economy Market,” *Power Markets Week*, April 10, 1995, p. 5.

[27] “SCE&G Returns Summer to Service After Replacing Steam Generators,” *Nucleonics Week*, December 22, 1994, p. 3.

[28] L. D’Ascenzo, P. Livolsi, and T. Lazo, “Comparing Exposures During Replacements,” *Nuclear Engineering International*, February 1995, p. 102.

[29] NRC Dockets 50-321 and 50-366; NRC Nuclear Decommissioning Financing Plan; *Plant Hatch Units 1 and 2* (July 30, 1992).

[30] “Steam Generator Cracking Woes Multiplying, NRC Report Says,” *Nucleonics Week*, July 15, 1993, pp. 6-7.

[31] “Steam Generators May Last Entire License Period,” *Nuclear News*, February 1995, p. 26.

Table FE6. Reactors With Greater Than 2 Percent Tubes Plugged, No Steam Generator Replacements and No Planned Replacements

Plant	Utility	Net Capacity[a] (MWe)	First Year of Operation	SG Manufac-turer	Loops	SG Alloy	Total Tubes	Total Plugged Tubes	Percent Plugged	Total Sleeved[b] Tubes
Zion 2	Commonwealth Edison Co.	1,040	1973	WEST	4	I-600 MA	13,552	552	3.9	252
Arkansas Nuclear 1	Arkansas Power & Light Co.	836	1974	B&W	2	I-600 S	31,062	676	2.2	978
Oconee 1	Duke Power Co.	846	1973	B&W	2	I-600 S	31,062	1,266	4.1	475
Oconee 3	Duke Power Co.	846	1974	B&W	2	I-600 S	31,062	622	2.0	247
Three Mile Island 1	GPU Nuclear Corp.	786	1974	B&W	2	I-600 S	31,062	1,641	5.3	502
Joseph Farley 1	Alabama Power Co.	815	1977	WEST	3	I-600 MA	10,164	358	3.5	136
Joseph Farley 2	Alabama Power Co.	825	1981	WEST	3	I-600 MA	10,164	710	7.0	275
Arkansas Nuclear 2	Arkansas Power & Light Co.	858	1978	CE	2	I-600 MA	16,822	417	2.5	444
Palo Verde 2	Arizona Public Service Co.	1,270	1986	CE	2	I-600 MA	22,024	558	2.5	0
San Onofre 2	Southern California Edison Co.	1,070	1982	CE	2	I-600 MA	18,700	646	3.5	0
San Onofre 3	Southern California Edison Co.	1,070	1983	CE	2	I-600 MA	18,700	614	3.3	0
St. Lucie 2	Florida Power & Light Co.	839	1983	CE	2	I-600 MA	16,822	467	2.8	0
Waterford 3	Louisiana Power & Light Co.	1,075	1985	CE	2	I-600 MA	18,700	518	2.8	0
Beaver Valley 1	Duquesne Light Co.	810	1976	WEST	3	I-600 MA	10,164	1,620	15.9	0
Haddam Neck	Connecticut Yankee Atomic Power Co.	560	1967	WEST	4	I-600 MA	15,176	1,228	8.1	0
Donald Cook 1	Indiana/ Michigan Power Co.	1,000	1974	WEST	4	I-600 MA	13,552	952	7.0	1,840
Indian Point. 2	Consolidated Edison Co.	931	1973	WEST	3	I-600 MA	9,786	1,131	11.6	0
Kewaunee	Wisconsin Public Service Corp.	522	1973	WEST	2	I-600 MA	6,776	517	7.6	4,274
Prairie Island 1	Northern States Power Co.	510	1974	WEST	2	I-600 MA	6,776	193	2.8	319
Prairie Island 2	Northern States Power Co.	505	1974	WEST	2	I-600 MA	6,776	249	3.7	0
Salem 1	Public Service Electric & Gas Co.	1,106	1976	WEST	4	I-600 MA	13,552	508	3.7	0
Salem 2	Public Service Electric & Gas Co.	1,106	1981	WEST	4	I-600 MA	13,552	478	3.5	0
Sequoyah 2	Tennessee Valley Authority	1,106	1981	WEST	4	I-600 MA	13,552	434	3.2	0

[a] Energy Information Administration (EIA), Form EIA-860, “Annual Electric Generator Report.”
[b] A tube may be sleeved more than once, and plugged tubes may have been sleeved.
B&W=Babcock and Wilcox Co.
CE=Combustion Engineering Co.
WEST=Westinghouse Corp.
I-600 MA=Inconel 600 mill-annealed.
I-600 S= Inconel 600 sensitized.
SG=Steam Generator.

Sources: Electric Power Research Institute, “Steam Generator Progress Report (Revision 10),” EPRI Research Project RP3580-06, Final Report, November 1994.

Summary

In the final analysis, utility managers must decide whether to maintain existing steam generators or replace them. This is a difficult decision, one that must be based on technical and cost analyses and license terms. Steam generator problems contributed to the premature shutdown of the Trojan nuclear unit and, to a lesser extent, to the shutdowns of the Rancho Seco and San Onofre units. Additional premature shutdowns are not out of the question. Maintenance methods now make it possible to extend life or postpone replacement for longer periods than before.

Overall, the prospect for continued operation of PWR's in the United States is good, but the prospect for long-term operation of original steam generators with Inconel 600 mill-annealed tubing is poor. Steam generator problems rank second, behind refueling outages, as the most significant contributor to lost electricity generation. The only exceptions are likely to be those reactors that recently began operation, where the lessons learned in such areas as water chemistry, tubing material, tube support plate material, and tube support plate design and attachment were incorporated from the very beginning of unit operation.