Remedies for PWR Recirculating Steam Generator Tube Failures

A. S. Amar  
Consultant, Brooklyn NY USA

V. N. Shah  
Idaho National Engineering Laboratory, Idaho Falls, ID USA

INTRODUCTION

Pressurized water reactor (PWR) steam generator tubes form well over one-half of the primary system pressure boundary and have experienced significant aging degradation at some plants (Tatone, 1986). Tube failures have caused contamination of the secondary coolant by the primary coolant, and radiological releases to the environment when atmospheric relief valves were actuated. Degraded steam generator tubes may fail during a severe accident and allow radioactive material to bypass containment. Simultaneous rupture of several tubes may lead to a major plant temperature and pressure transient with potential impact on the structural integrity of various components in the system. Tube leakages result in unscheduled plant outages when the leakage rate exceeds acceptable limits. Finally, repair and replacement associated with steam generators account for much of the personnel radiation exposure (manrems) at PWR plants. Therefore, industry has developed various remedies for steam generator tube aging. This paper evaluates the effectiveness of current remedies used to reduce aging damage to recirculating type steam generator tubes (Shah and MacDonald, 1988). Following topics are discussed: (a) degradation mechanisms, (b) mitigation techniques, (c) repair methods, and (d) conclusions and recommendations.

DEGRADATION MECHANISMS

Table 1 summarizes the degradation processes of recirculating steam generator tubes (Shah and MacDonald, 1987). It identifies the degradation sites, stressors, and mechanisms. Pure water stress corrosion cracking (PWSSC) is the major degradation mechanism acting on the primary side. High residual stresses and absence of grain boundary carbides are preconditions for PWSSC. Thermally treated Inconel 600 resists both PWSSC and secondary side intergranular stress corrosion cracking (IGSSC) because it has grain boundary carbides in its microstructure and no chromium-depleted region (sensitization). IGSSC, intergranular attack (IGA), pitting, denting, and wastage are the corrosion mechanisms acting on the secondary side. Industry has switched almost all PWRs from phosphate chemistry to an all volatile treatment (AVT) to mitigate the wastage problem. In contrast to phosphate chemistry, AVT does not provide a buffering system and the water chemistry must be constantly monitored and corrected. It is difficult to control the water chemistry in the event of chemistry transients.

---

a. Work sponsored by the United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, under DOE Contract No. DE-AC07-76ID01570.
<table>
<thead>
<tr>
<th>Rank</th>
<th>Degradation Site</th>
<th>Stressors</th>
<th>Degradation Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inside surface of U-bends, roll-transition regions and dented tube region</td>
<td>Tube rolling and U-bend stresses, Coriolis phenomenon, denting, grain size, microstructure</td>
<td>PWSCC</td>
</tr>
<tr>
<td>2</td>
<td>Outside surface of hot-leg tubes in the tube-to-tube sheet crevice region</td>
<td>Alkaline environment, presence of SO₄ and CO₃ anions</td>
<td>IGSCC/IGA</td>
</tr>
<tr>
<td>3</td>
<td>Cold-leg side in sludge pile, scale containing copper deposits</td>
<td>Brackish water, chlorides, oxygen, and copper</td>
<td>Pitting</td>
</tr>
<tr>
<td>4</td>
<td>Outside surface of tubing above tube sheet</td>
<td>Phosphate chemistry, chloride concentration, resin leakage from condensate polishers bed</td>
<td>Wastage ( thinning)</td>
</tr>
<tr>
<td>5</td>
<td>Tubes in the tube-support regions</td>
<td>Oxygen, copper oxide, chloride, temperature, pH, crevice conditions</td>
<td>Denting</td>
</tr>
<tr>
<td>6</td>
<td>Contact points between tube and antivibration bar</td>
<td>Flow-induced vibrations</td>
<td>Fretting</td>
</tr>
<tr>
<td>7</td>
<td>Tube dented at upper tube-support</td>
<td>Vibrations due to high recirculation flows, stresses due to denting</td>
<td>High-cycle fatigue</td>
</tr>
<tr>
<td>8</td>
<td>Dented tubes</td>
<td>Thermal transients</td>
<td>Low-cycle fatigue</td>
</tr>
</tbody>
</table>

**MITIGATION TECHNIQUES: PRIMARY SIDE**

We discuss three mitigation techniques for PWSCC: (1) shot or rotopeening, (2) stress relieving, and (3) reducing the hot leg temperature. The highly stressed inside surfaces of the tubes at the tube/tubesheet rolled joint can be shot or rotopeened using the primary side access to the tubing to reduce residual stresses. The peening is done in most tubes only in the rolled-transition region; some tubes are peened over the full length of the tube-sheet. Both shot and rotopeening involve impacting of a high-velocity small-diameter mass on the inside surface, resulting in cold working of a layer of material a few tens of microns deep. This procedure introduces compressive residual stresses that tend to preclude PWSCC. Shot peening involves impacting of high-velocity metallic, ceramic, or glass particles on tube inside surfaces. Owing to concern regarding the spread of contamination from such particles, rotopeening was developed using the impact of shot bonded to fabric in a flapper wheel, and its field application requires remote tooling. Rotopeening may miss impacting some highly stressed surface because of inaccurate positioning of the flapper wheel and, therefore, it is not totally reliable. Currently, the shot peening technique is preferred, since the concern regarding
spread of contamination is addressed. The effectiveness of peening depends entirely on process controls, since there is no postprocess nondestructive field inspection technique that can quantify the benefit.

Stress relieving is a heat treatment used locally to reduce the residual stresses at the apex and the tangent area of the U-bends in the first and second rows. Residual stresses in the excess of yield stress have been measured in these areas of the tubes. Stress relieving is performed by holding the tube bend temperature at 1275°F (690 to 829°C) for 5 to 10 minutes. In situ stress relieving of the critical tube bends has been performed at Sequoyah 1 (Hall and Gahwiller, 1987). U-bend annealing has also been performed at a limited number of new plants (Gorman, 1983). Field performance data are not yet available, and these procedures may not be useful on tubing already cracked. Laboratory studies indicate that the use of in situ stress relief techniques would postpone the time to initiation of PWSCC by at least a factor of 10 (Pement, Economy, and Aspden, 1987).

It is believed that reducing the temperature of the tubing on the hot leg side by about 11°C (20°F) or more will slow down, though not preclude, various thermally activated damage mechanisms (Richards, 1985). This is a temporary mitigation technique that can increase the time between steam generator outages required for inspection. Plant availability is increased, but this benefit is offset by the reduced power during operation.

MITIGATION TECHNIQUES: SECONDARY SIDE

We discuss three mitigation techniques: (1) chemical impurity control, (2) chemical additives that will inhibit corrosion, and (3) periodic cleaning of the secondary side. In-leakage of water through the condenser causes secondary water chemistry transients that result in denting, pitting, IGA, IGSSCC, and excessive sludge formation. Several plants have replaced their admiralty brass condenser tubing with either titanium (sea as well as fresh water sites) or stainless steel tubing (fresh water sites only), to prevent condenser leakage and to minimize the copper content in the secondary water. However, titanium tubes have experienced vibration problems and the leakage has not been completely eliminated. Despite use of titanium condenser tubing, significant quantities of chlorides may still be introduced into the secondary water by the make-up water. Reduced use of make-up water and its chemistry control are needed to control the chloride content. A blowdown recovery system will purify and recycle blowdown water, which is cleaner than the usual supply of make-up water in terms of chlorides and organic impurities.

Various organic acid and ionic impurities can be minimized by ultrafiltration of the feedwater. Several plants purify their condensate by flowing it through condensate polishers. Some utilities are also installing filters between the polishers and the steam generators to trap any resins released from the polishers. Polishers offer the only defense against water chemistry transients for protecting the steam generators from large-scale damage. The copper-bearing alloys (70/30 Cu Ni, 90/10 Cu Ni, brass, etc.) may be removed from the feedwater train to minimize the copper and copper oxide content in the secondary water. These components may be replaced by carbon or stainless steel components, which will reduce the rate of denting and pitting damage. Controlling the dissolved oxygen and eliminating the ingress of air are also important for mitigating these mechanisms.

Since an AVT chemistry involves volatile compounds, constant on-line monitoring and adding of chemicals is needed to replace the evaporated compounds. Some plants are also using corrosion inhibitors such as boric acid and morpholine. Laboratory tests show that boric acid additions prevent denting and IGA and IGSSCC initiation in alkaline environments. A Japanese utility has reported that using boric acid as a neutralizing agent in two plants with full-flow
condensate polishers retarded corrosion without degrading polisher performance (Partridge, 1986). Boric acid additions have also been effective in reducing the carbon steel corrosion and denting at several plants (Partridge and Gorman, 1986).

Several utilities have successfully used secondary-side cleaning methods, such as lancing with a high-pressure water jet and subsequent chemical cleaning that removes residues. Several methods have also been developed to clean tubesheet crevices with hot soaks and tubesheet crevice flushing techniques.

Certain recirculating steam generator designs are susceptible to the high-cycle fatigue damage such as that resulted in tube rupture at the North Anna Unit 1 plant. The fatigue crack was propagated to a double-ended guillotine break in about 12 to 48 hours (USNRC, 1988). Such rapid failures are not detectable by eddy current testing or by tube inspections. One possible way to prevent such failures is to reduce local fluid forces. Flow resistance plates have been installed in the North Anna downcomer to reduce the fluid forces. Fretting damage from flow-induced vibrations can be, and has been, eliminated by changing the point contact design of the antivibration bars to provide a broader region of contact with the tube.

REPAIR METHODS

Sleeving and, recently, nickel plating are used to cover tube defects within the tube sheet and sludge pile. A sleeving operation involves a combination of two or more of the following procedures: (a) rolling, (b) hydraulic expansion, (c) tungsten inert gas welding, (d) explosive welding, and (e) brazing. The hydraulic expansion and explosive welding procedures produce less residual stress than the hard rolling process, but this design resulted in leaks and an all-welded sleeve design is preferred (Hall and Gahwiler, 1987). All sleeving designs are relatively new and there is not much information on long-term field performance of any of these designs. An important concern is that the most sleeve designs create high residual stresses, which may cause new cracks. Residual stresses can be evaluated in the laboratory on mock-up sleeve joints, but cannot be evaluated on field joints. Furthermore, the sleeves provide crevices on the primary side and the long-term impact of these crevices is not known. And finally, it will be difficult to inspect the sleeves for flaws. When a defect on the parent tube grows through the wall, the gap between the parent tube and the sleeve will be filled with stagnant secondary water, which may promote IGSCC or IGA, or both.

Until a few years ago, plugging was the only remedy available for PWR steam generator tubes with unacceptable flaws. In some plants, several hundreds of tubes have been plugged because of denting. Even now, plugging is common for unacceptable degradation above the tubesheet region, since most of the current sleeving techniques can cover only a few inches above the tubesheet and the sludge pile region. Commonly used plugging techniques include welding, explosive forming, and mechanical installation. Plugs installed with explosive forming have leaked in some plants, which is attributed to large plastic strains and residual stresses at plug corners. Mechanical plugs can be installed without welding or explosive forming and can be subsequently removed.

CONCLUSIONS AND RECOMMENDATIONS

Table 2 summarizes the remedies for tube failures in recirculating steam generators. The important conclusions and recommendations are as follows:

1. Highest priority is given to preventing faulted conditions in the secondary water chemistry. Some water chemistry transients can cause large-scale damage in a short time.
### TABLE 2. SUMMARY OF COUNTERMEASURES FOR TUBE FAILURES IN PWR STEAM GENERATORS

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Mitigation of Damage in Existing Tubes</th>
<th>Improvements in New/Replacement Steam Generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary side</td>
<td>Roto/Shot peening to reduce residual tensile stresses. Annealing the U-bends. Control of the denting problem.</td>
<td>Inconel 690 tubes with optimum microstructures and a maximum yield strength of 379 MPa (55 ksi). Minimize/eliminate residual stresses.</td>
</tr>
<tr>
<td>Secondary side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGA/IGSCC</td>
<td>Alkaline impurity control; eliminate acid chlorides; tubesheet crevice flushing, hot soaks, lancing and chemical cleaning; neutralize crevice alkalinity; boric acid additions; tube rolling to eliminate crevices.</td>
<td>Inconel 690 tubes with optimum microstructure, eliminate tubesheet crevices, improved access for lancing and cleaning, increased blowdown capacity. Design flow to avoid sludge accumulation.</td>
</tr>
<tr>
<td>Pitting</td>
<td>Eliminate condenser leakages; preclude ingress of air/oxygen, acid chloride and copper in water.</td>
<td>Titanium or stainless steel condenser tubes, eliminate Cu alloys in feed train, resistant tube materials.</td>
</tr>
<tr>
<td>Denting</td>
<td>Eliminate ingress of air/oxygen, acid chlorides, and copper in water; leak tight condensers; hot soak.</td>
<td>Strict water chemistry controls, stainless steel support structures, design to preclude stagnant water in annuli, titanium condenser tube.</td>
</tr>
<tr>
<td>Wastage</td>
<td>Use of AVT water chemistry; eliminate hideout chemical concentrations; sludge lancing and chemical cleaning; hot soaks; hot blowdown and flushing; preclude resin ingress.</td>
<td>Design flow to preclude hide out and chemical concentrations, minimize sludge formulation. Improved access for cleaning, increased blow down capacity.</td>
</tr>
</tbody>
</table>

2. Condensate polishers may provide the only defense against faulted water chemistry conditions. Filters may be installed between the polishers and steam generators to collect any accidentally released resins.

3. Plant studies have demonstrated that certain chemical additives, i.e. boric acid and morpholine, will reduce IGA, IGSCC, and denting of tubes. Effects of these additives on other plant components need to be assessed.

4. Effectiveness of shot and rotopeening techniques depends upon process controls because no nondestructive examination method is available to measure the residual stresses.
5. Further research is needed to gain a fundamental understanding of the mechanisms causing PWSCC.

6. Efforts to reduce the uncertainties in the NDE results characterizing the damage should be continued.

7. The field performance of the various sleeve designs should be monitored.

8. Plugging is the only remedy when unacceptable flaws are detected in regions away from the tubesheet.

REFERENCES


