Enclosure 3

TMI Plugged Tube Severance Study

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Non-Proprietary Version

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Three Mile Island Plugged Tube Severance

A Study of Damage Mechanisms

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Topical Report, May 2003

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PRODUCT DESCRIPTION

During Fall 2001 outages, eddy-current inspections at Three Mile Island Unit 1 and Oconee Nuclear Station Unit 1 revealed wear scars on tubes surrounding previously plugged tubes. In both cases, investigations determined that the plugged tubes had severed and impacted neighboring tubes. As a result, the Nuclear Regulatory Commission (NRC) issued Information Notice 2002-02, which did not require a response but did suggest the industry investigate the generic problem of plugged tubes damaging neighboring tubes. EPRI contracted Framatome ANP and Westinghouse Electric Company to assess the issue for once through steam generators (OTSGs) and recirculating steam generators (RSGs), respectively. This report summarizes the results of these studies, which are included in their entirety as appendices A and B.

Results & Findings

A tube taken out of service by plugging can only damage neighboring tubes if either the degradation causing the tube to be plugged continues to grow, or if new degradation is initiated after plugging and grows until it ultimately results in tube failure. Framatome concluded that the only real vulnerability for severance is the growth of circumferential cracks due to high cycle fatigue. For a swollen, plugged tube, any degradation mechanism has the potential to provide an initiating site for failure. Westinghouse concluded that the potential for tube severance is low except for circumferential cracking, either at the top of the tube expansion region less than 0.5 inch below the top of the tubesheet or in the expansion transition region. In addition, tubes that have been plugged for wear may have the potential to sever due to wear that continues after plugging. Both Westinghouse and Framatome have developed stabilization criteria to ensure that tubes susceptible to severance are constrained from motion and do not cause damage to neighboring tubes. As part of this study, both companies reviewed stabilization criteria to ensure that they are conservative in approach.

Challenges & Objectives

The variety of root causes possibly leading to tube severance presented challenges in meeting the primary objective of this study—to determine the known and potential damage mechanisms affecting plugged OTSG and RSG tubes, with emphasis on mechanisms that could result in tube severance and damage to adjacent tubes. Because any plugged tube has a potential for further degradation, the ultimate goal was to develop a utility course of action for avoiding damage to neighboring tubes. One course of action is described in EPRI report TR-107569-V1R5, PWR Steam Generator Examination Guidelines, which requires that tube plugs be inspected as frequently as steam generator tubes.

Applications, Values & Use

No one factor alone is expected to result in failure of a plugged tube. However, when certain factors combine—such as swelling of a plugged tube at a location where high cross flows are present—plugged tube severance becomes a possibility. OTSG plants are including an evaluation of such factors on a plant-specific basis in their upcoming outage plans. For Westinghouse and Combustion Engineering RSGs, an initiative to remove all plugs made from alloy 600 should continue and plugged tubes that remain in service should be inspected for cracking. Furthermore, all tubes with circumferential cracks within the expansion region or within 0.5 inch of the top of tubesheet should be stabilized. Though the root causes of severance of previously plugged tubes can vary between OTSGs and RSGs, it is clear that stabilization may be necessary to avoid future tube severance and consequent damage to neighboring tubes. It is significant to note that no circumferential bursts, cracking, or fatigue failures resulting in tube severance have ever been observed in RSGs. Of less concern in both OTSGs and RSGs is temperature-dependent degradation growth after plugging, since such a tube no longer has hot primary system water flowing through it and therefore assumes the colder secondary temperature. Such findings offer a measure of confidence for utilities as they undertake stabilization analyses.

EPRI Perspective

In a pressurized water reactor, the steam generators serve as the boundary between the primary and secondary sides of the nuclear steam supply system. Within the steam generator shell, the actual primary-to-secondary boundary is the steam generator tubing. In the event of tube failure, the primary reactor coolant can escape from the primary system and enter the secondary side of the system, thereby releasing radioactive materials into the secondary side. The potential for plant shutdown as a result of tube severance and consequent failure of neighboring tubes makes this study particularly important to the operation and maintenance of nuclear power plants.

Approach

Both Framatome and Westinghouse assessed degradation mechanisms that had previously led to tube plugging to determine their potential for causing tube severance. They specifically evaluated three areas: degradation growth after plugging, potential tube severance mechanisms, and mechanisms for damaging neighboring tubes. Finally, they reviewed findings for potential application to other OTSGs and RSGs.

Keywords

Tube Plugging
Tube Severance
Tube Degradation

ABSTRACT

The potential for tube severance and subsequent impact on neighboring tubes at Three Mile Island Unit 1 and Oconee Nuclear Station Unit 1 led the Nuclear Regulatory Commission to issue Information Notice 2002-02. Framatome ANP and Westinghouse have assessed this issue for once-through steam generators (OTSGs) and recirculating steam generators (RSGs), respectively. Their full reports are included as appendices A and B. This Executive Summary provides an overview of the issues at hand as well as the Framatome and Westinghouse studies, with a background section describing events that may have resulted in the severance of previously plugged tubes in OTSGs and RSGs. The Executive Summary then addresses the approach taken in both studies—based on the idea that a tube taken out of service by plugging can only damage neighboring tubes if either the degradation causing the tube to be plugged continues to grow, or if new degradation is initiated after plugging and grows until it ultimately results in tube failure. The Framatome and Westinghouse evaluations of three areas are briefly explained, specifically, degradation growth after plugging, potential tube severance mechanisms, and mechanisms for damaging neighboring tubes. Finally, the Executive Summary presents a review of findings for potential application to other OTSGs and RSGs, particularly in the area of tube stabilization.

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1
TMI TUBE SEVERANCE EXECUTIVE SUMMARY

Introduction

During outages in the fall of 2001, eddy current inspections at Three Mile Island (TMI)-1 and Oconee Nuclear Station (ONS)-1 revealed wear scars on tubes surrounding previously plugged tubes. In both cases, it was determined that the plugged tubes had severed and impacted neighboring tubes. As a result, NRC issued Information Notice IN2002-2, which did not require a response, but did suggest the industry investigate the generic problem of plugged tubes damaging neighboring tubes and identified possible preventive or mitigative actions. EPRI contracted Framatome ANP and Westinghouse to assess the issue for once-through steam generators (OTSGs) and recirculating steam generators (RSGs) respectively. Below is a summary of the results of these studies. The reports are attached as Appendices A and B respectively.

Background

Though both the TMI-1 and ONS-1 events resulted in the severance of previously plugged tubes, the root causes were different.

The TMI-1 tube severance resulted from water ingress into the plugged tube that led to swelling of the tube during heatup, ultimately locking the tube at the tube support plates. Flow-induced vibration of the tube, due to local cross flow, ultimately caused a high cycle fatigue failure at the upper tubesheet allowing the resultant free end of the severed tube to impact its downstream neighbors.

The tube severance at ONS-1 was caused by primary side IGA, most likely due to the presence of contaminants, either from thermocouple instrumentation that had been left in the tube after the first cycle of operation or debris that might have settled into the tube while operating with the top of the tube open and the bottom plugged. Final severance of the tube was ascribed to low stress ductile failure.

There have been previous failures of plugged tubes in RSGs involving tube water ingress, swelling, and burst. Cold water trapped in an enclosed volume like a plugged tube or a closed crevice can lead to very high pressures when it is heated. These pressures can be sufficient to result in plastic deformation of steam generator tubes. This occurred at the Obrigheim Plant in Germany in 1973, when water trapped in a tubesheet crevice produced radially inward buckling of the tube.

Water can be trapped in a plugged tube by leakage between the plug and the tube while they are cold. The seal between the plug and the tube can tighten during heatup, due to differential thermal expansion between the plug and the tube, and prevent outward leakage. This is sometimes referred to as the flow diode effect. Another way that water could be trapped in the tube is by replacing a plug without draining preexisting water from the tube.

Water trapped in plugged tubes has led to swelling and subsequent burst in Ringhals 2 (1984), Salem 1 (1991), Dampierre 2 (1992), Tricastin 1 (1993), Connecticut Yankee (1995) and Indian Point 2 (2000). The failures occurred in tubes that had previously been plugged with Alloy 600 explosively welded plugs, Alloy 690TT rolled plugs, Alloy 600 fusion welded plugs, and with Alloy 600TT mechanical ribbed plugs, including those which have been subsequently plugged with a plug sealing device. There are no reports of swollen tubes that were originally plugged using Alloy 690 TT mechanical plugs with no plug repairs.

It can be concluded, from looking at industry events, that leaking mechanical plugs are not always detected. Therefore, it is possible to have pressurization and swelling caused by a diode effect, which could lead to an axial burst.

It is significant to note that no circumferential bursts, cracking, or fatigue failures resulting in severance of the tube have ever been observed in recirculating steam generators (Appendix B 2.7). Consequently, there has been no damage inflicted upon neighboring tubes by this mechanism.

Approach

Both Framatome and Westinghouse assessed degradation mechanisms for which tubes have previously been plugged to determine the potential for tube severance. A tube that has been taken out of service by plugging can only damage neighboring tubes if either the degradation present at the time of plugging continues to grow or if new degradation is initiated after plugging and grows until it ultimately results in failure (Appendix B 3.4.1).

Degradation Growth After Plugging

A tube that has been plugged no longer has hot primary system water flowing through it; consequently, it assumes the temperature of the secondary side, which is lower than the primary side. This means that temperature dependent degradation growth rates slow significantly and are therefore not of concern for ongoing degradation. These mechanisms include stress corrosion cracking and intergranular attack. Introduction of contaminant material such as a chemistry excursion or contaminant intrusion, which can accelerate corrosion rates, are an exception. This has occurred both on the primary as well as secondary sides of the steam generator.

Mechanisms that are mechanical in nature, such as fretting and wear (AVB or loose parts), vibration and fatigue (both thermal and mechanical) are not strongly affected by temperature and can continue even after plugging.

Both mechanical and thermal fatigue can provide continued growth of degradation that may originally have been initiated by corrosion.

Mechanisms For Damaging Neighboring Tubes

Plugged tubes have generally failed by one of two mechanisms. The first is an axial burst, which generally yields a small "fish mouth" type opening. While the rapid opening of a fishmouth failure can result in an impact with a neighboring tube, as a worst case, such a blow generally would produce only a dent (Appendix B 2.2 and 2.3). From a flow induced vibration (FIV) perspective, the condition of a tube with a fish mouth is considered stable in all flow fields. The second mechanism of tube failure is a tube sever. A single sever of the tube was evaluated in the root cause investigations for the TMI-1 and ONS tube severs as well as in the attached reports for all regions of the OTSGs and RSG.

If a tube experiences a complete sever, depending on where the separation occurs, one or two cantilevered segments could result. Such segments would essentially be fixed at one end and free on the other. If there is sufficient cross-flow and/or turbulence, the segment could potentially become fluid-elastically unstable such that ongoing motion of a tube end with substantial vibration amplitude can wear on the neighboring tubes. If the tube end is constrained to remain within a tube support plate (TSP) or the tubesheet, no contact with neighboring tubes is possible. Framatome uses a conservative criterion (Appendix A 7) of degradation being further than 2 to 3 inches from the secondary face to define when the tube will be captured in the tubesheet and therefore will be unable to contact neighboring tubes. Westinghouse analysis indicates that any crack more than ½ inch below the expansion transition does not represent a potential for tube severance (Appendix B 6.2).

Potential Tube Severance Mechanisms

For a tube to sever into two separate segments, a flaw needs to propagate circumferentially around the tube. The mechanisms that can potentially result in a tube severance are AVB or loose parts wear, fatigue cracking due to FIV, and thermal cycling.

Steam generators were designed to accommodate high cross flows, therefore, FIV is generally not a concern. However, if tubes are locked into the TSPs the damping is decreased and the span is potentially isolated. This may lead to fatigue cracking or, in the worst case, tube instability. Locking at tube support plates can be caused by denting or by swelling of plugged tubes due to the presence of trapped water.

Both Framatome and Westinghouse considered all the mechanisms that have previously led to tubes being plugged to determine the potential for the degradation to ultimately lead to tube severance.

Framatome concluded that the only real vulnerability for severance is the growth of circumferential cracks due to high cycle fatigue. Any degradation mechanism has the potential to

provide an initiating site for failure in a swollen, plugged tube in regions of the SG susceptible to high cycle fatigue,.

Westinghouse concluded that the potential for tube severance is low except for circumferential cracking either at the top of the tube expansion region less than ½ inch below the top of the tubesheet or in the expansion transition region. In addition, tubes that have been plugged for wear may have the potential to sever due to wear that continues after plugging.

Both Westinghouse and Framatome have developed stabilization criteria to ensure that tubes susceptible to severance are constrained from motion and do not cause damage to neighboring tubes. As part of this study, both companies reviewed stabilization criteria to ensure they are conservative.

Recommendations

For all SG designs, utilities should review the cross-functional effects of chemistry excursions and intrusions and loose parts and foreign material on plugged tubes as well as in-service tubes.

Westinghouse/CE (for RSGs)

1. An initiative to remove from service (by deplugging or repairing) all plugs made from Alloy 600 should continue and those that remain in service should be inspected for cracking.

2. Unless the results of a stabilization analysis conclude otherwise, all tubes with circumferential cracks within the expansion transition region or within 0.5" of the top of tubesheet should be stabilized. Analysis must include the effects of the tube being locked at the first tube support plate and the potential for continued growth of degradation.

3. When plugging for AVB wear, analysis should consider post-plugging growth to determine the need to stabilize. For tubes plugged early in life for significant AVB wear and not stabilized, it is recommended that an analysis be performed to determine if tube should be deplugged and stabilized, if adjacent in-service tubes should be plugged, or if bobbin coil monitoring of adjacent in-service tubes is sufficient.

4. Tubes plugged for preheater wear that have been evaluated as part of the preheater wear issue resolution do not have a potential for tube severance; however, in lieu of an analysis to determine the need for stabilization, stabilization is recommended.

Framatome ANP (for OTSGs)

1. For OEM plugged tubes, apply stabilization criteria assuming a volumetric 100% through wall flaw in the upper span. Deplug and stabilize or stabilize and plug downstream flanking tubes as required by stabilization criteria.

2. Plugged tubes with potential for swelling, which includes tubes with repaired plugs or replaced UTS plugs, should be deplugged, inspected, and stabilized or downstream flanking tubes should be stabilized and plugged

3. Tubes plugged in the lower tube end but open in the upper tube end and tube pull locations with an open top end require monitoring of adjacent tubes for wear in the freespan

4. Any indications of wear outside the TSPs in the freespan should be investigated for possible tube-to-tube wear due to a severed tube.

5. If possible, stuck probe debris should be removed at the next outage and the tube dewatered and inspected prior to replugging. Monitoring adjacent tubes for wear in the freespan is an acceptable alternative.

6. Plugged tubes in the lane region that have not been sleeved or stabilized should be deplugged, inspected and stabilized in the top spans or adjacent downstream and flanking tubes should be plugged and stabilized in the top spans. This tube population in the OTSGs is also addressed by plugged tubes that have been repaired (recommendation #2).

APPENDIX A
OTSG PLUGGED TUBE DAMAGE MECHANISMS

ABSTRACT

During recent scheduled outages, inspections of steam generator (SG) tubing at Three Mile Island Unit 1 (TMI-1) and at Oconee Unit 1 (ONS-1) revealed extensive wear on several tubes surrounding a plugged tube. The wear at each plant was found to be the result of a plugged tube that had severed and subsequently contacted adjacent tubes. A root cause investigation was performed in each case and the findings were reviewed for potential implications that apply to the other OTSGs. This volume is intended to provide a summary of the damage mechanisms that may affect OTSG plugged tubes and that could result in tube severance and potential damage to adjacent tubes.

ABBREVIATIONS & ACRONYMS

BWOG	B&W Owner's Group
CAF	Corrosion-Assisted Fatigue
ECT	Eddy-Current Testing
DELTA	Driven Expansion Lightweight Tool Assembly
FDMS	Framatome Data Management System
EFPY	Effective Full-Power Years
FIV	Flow-Induced Vibration
FSM	Fluid-elastic Stability Margin
HCF	High Cycle Fatigue
HFT	Hot Function Test
ID	Inner Diameter
IDIGA	Inner Diameter Intergranular Attack
IGA	Intergranular Attack
IGSCC	Intergranular Stress Corrosion Cracking
LCA	Land Contact Area
LEFM	Leading Edge Flow Meter
LTE	Lower Tube End
LTS	Lower Tubesheet
MBM	Manufacturing Burnish Mark
NOPD	Normal Operating Pressure Differential
NRC	Nuclear Regulatory Commission
OD	Outer Diameter
ODIGA	Outer Diameter Intergranular Attack
OEM	Original Equipment Manufacturer
ODSCC	Outer Diameter Stress Corrosion Cracking
OTSG	Once-Through Steam Generator
PWSCC	Primary Water Stress Corrosion Cracking
RFO	Refueling Outage
RWP	Remote Welded Plug
SCC	Stress Corrosion Cracking

SS	Secondary Side
TSP	Tube Support Plate
TW	Through-Wall
USAR	Updated Safety Analysis Report
UTE	Upper Tube End
UTS	Upper Tubesheet
UTSF	Upper Tubesheet Secondary Face

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1 INTRODUCTION AND BACKGROUND

1.1 Purpose

The purpose of this document is to summarize damage mechanisms affecting plugged tubes in Once-Through Steam Generators (OTSGs). The summary will include the possible consequences of each damage mechanism, the contributing factors for each damage mechanism, and possible cross-functional effects of each factor. Cross-functional effects are factors that occur in combination, such as swelling of a plugged tube at a location where high cross flows exist.

1.2 Background

During recent scheduled outages, inspections of steam generator (SG) tubing at Three Mile Island Unit 1 (TMI-1) and at Oconee Nuclear Station Unit 1 (ONS-1) revealed extensive wear on several tubes surrounding a plugged tube. The wear at each plant was found to be the result of a plugged tube that had severed and subsequently contacted adjacent tubes. A root cause investigation was performed in each case and the findings were reviewed for potential implications that could apply to the other OTSGs.

The severed plugged tube at TMI-1 was caused by swelling of a plugged tube due to trapped water and subsequent high cycle fatigue (HCF) failure at the site of a small area of outer diameter intergranular attack (ODIGA) near the secondary face of the upper tubesheet. Swelling of the tube had changed the flow-induced vibration response of the tube and the tube failed at an area of degradation. The TMI-1 tube severance was the result of an accumulation of a number of factors in which any one single factor would most likely not have caused the event. However, the severed plugged tube at ONS-1 was caused by inner diameter IGA at the lower tubesheet secondary face with final separation due to low stress ductile failure. Thus, the ONS-1 failure was different from the TMI-1 tube failure in that the initiating cause was one predominant factor, ID degradation that was most likely caused by contaminants within the tube.

NRC Information Notice 2002-02 was issued to inform licensees about the findings at TMI-1 without a request for specific action or response (Ref. 29). Supplement 1 of this NRC Information Notice was issued to inform licensees about the ONS-1 findings, also without a specific action or response. However, in response to the findings at TMI-1 and ONS-1, EPRI has sponsored a project to determine the known and potential damage mechanisms affecting plugged tubes that could result in tube severance and potential subsequent damage to adjacent tubes.

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OTSG DESIGN

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Figure 3-1
OTSG General Assembly

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Figure 3-2
Typical OTSG Tube Support Design

4
OTSG TUBE PLUG REPAIR

Steam generator tubing is inspected on a regular basis using qualified eddy-current inspection techniques. Certain types of tube degradation are left in service based on approved alternate repair criteria (ARC) or as allowed by the plant technical specifications. For example, degradation within the tubesheets may be repaired by a mechanical re-roll, based on plant-specific exclusion zones (Ref. 1). However, most tubes are plugged on detection of degradation. After plugs are installed into the tube end openings, they become the pressure boundary. The tube is taken out of service and becomes a passive structure on the secondary side. The two basic plug types are welded plugs and mechanical plugs. Welded plugs include explosive, manual, and remote welded plugs and are designed to be leak tight. Mechanical plugs include rolled and ribbed plugs and are designed to be leak-limiting. As of 2001, more than 22,000 plugs serve as a pressure boundary, with approximately 88% leak-limiting (Ref. 8). Not included in this figure are plugs that no longer serve as the primary pressure boundary, such as violated explosive and welded plugs. Explosive and rolled plugs may be inspected with eddy current. One advantage of the rolled plug is that it can be removed at a later date for inspection of the plugged tube. Due to their geometry, ribbed plugs cannot be inspected with currently available eddy-current techniques. Welded plugs are typically installed at tube pull locations or at tube locations where installation of a rolled plug is not possible.

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A tube that is plugged is taken out of service by plugging both tube ends. Thus, the out-of-service plugged tube does not transfer heat from the primary system. However, secondary fluid may leak into the plugged tube through degraded areas in the tube or the plug joint may allow some primary fluid to leak into the region behind the plug into the tube (i.e. plug leak-by from leak-limiting mechanical plugs). In either of these conditions, there is a potential for the tube to be subjected to internal pressure upon heatup of the plant and/or during operation. A tube with only one end plugged is exposed to the primary system pressure and is considered to be an in-service tube. The effects of plugging one end of the tube are discussed further in this document.

Based on the location of the tube and the type of degradation, plugged tubes may be stabilized. The purpose of stabilization is to prevent a plugged tube from contacting adjacent tubes or becoming a loose part in the SG in the event the tube severs. There are several stabilizer designs, including segmented rods and wire ropes. The stabilizer provides lateral structural support at a potential tube sever location and provides damping and capture properties. Additionally, the stabilizers will provide tube reinforcement and wear allowance. The 80-inch sleeve also acts as a stabilizer (Section 9.5).

5 POTENTIAL FAILURE MODES OF A PLUGGED TUBE

This document addresses damage mechanisms that may affect a plugged tube. The actual plug hardware is outside the scope of this document. As stated previously, a plugged tube is no longer the primary-to-secondary pressure boundary. Therefore, failure of a plugged tube does not result in primary-to-secondary leakage. However, failure of a plugged tube may result in damage to adjacent tubes that are in service, thus challenging the primary-to-secondary pressure boundary. A plugged tube that severs may result in damage to adjacent tubes if the plugged tube contacts them. Contact between tubes creates wear, which could potentially lead to a reduction in wall thickness and potential violation of an in-service tube. A plugged tube that experiences axial burst due to internal pressure from trapped water typically opens in a "fishmouth." Tubes that have significant flaws would likely fail in this manner prior to reaching an internal pressure that could swell the tube.

Based on the principles discussed above, there are two basic potential failure modes for a plugged tube:

- Tensile rupture (tube severance)
- Axial burst

The damage mechanisms and driving forces that lead to failure of a plugged tube are varied and may be cross-functional. This document considers the known damage mechanisms and postulated damage mechanisms that have been identified for the OTSGs, as well as possible contributing factors that may result in actual failure of a plugged tube. Some contributing factors may be related to normal operation of the OTSGs, such as flow-induced vibration, sludge effects, and normal operating tube loads, while other factors may be associated with chemical excursions and/or intrusions. Some contributing factors may also be associated with repair hardware and/or processes, such as in-situ testing, trapped water, and chemical cleaning.

6
DAMAGE MECHANISMS IN OTSG TUBING

As part of the development of steam generator tube integrity programs, comprehensive evaluations of the damage mechanisms that affect the OTSG have been performed. The results of these evaluations are documented in Reference 2, "Generic OTSG Tube Integrity Program" and Reference 3, "BWOG Common Degradation Assessment." These documents are used as a basis for the evaluation of potential damage mechanisms in plugged tubes in the OTSGs.

6.1 Cracking and/or Loss of Metal

The damage mechanisms that may result in cracking or loss of metal in the OTSGs include (Refs. 2 and 3):

- PWSCC (primary water stress corrosion cracking)
- Tube End Cracking
- Groove IGA/Axial IGSCC (groove intergranular attack/axial intergranular stress corrosion cracking)
- Fretting/Wear (Includes loose part damage)
- IGA (volumetric intergranular attack – may initiate on the inner or outer diameter of the tube)
- ODSCC (outer diameter stress corrosion cracking)
- High Cycle Fatigue Cracking (HCF)
- Erosion/Corrosion (impingement)
- Pitting

6.2 Mechanical Distortion

The following damage mechanisms may result in mechanical distortion of the tubes (Refs. 2 and 3). These mechanisms may not have an appreciable effect on the integrity of the tube, but in some cases may provide an initiation site for one of the damage mechanisms listed in Section 6.1. In other cases, these mechanisms may lead to failure in a tube with a relatively minor degradation site.

- Dents/Dings (Includes loose part damage and dents/dings in the tubesheet region of tubes adjacent to explosively plugged tubes)

- MBM (manufacturing burnish marks)
- Twisted Tubes (tubes misaligned from the upper tubesheet to the lower tubesheet; TS hole positions from upper to lower do not match)
- OEM Violated Tubes
- Swollen Plugged Tubes (Trapped Water)
- Effects of in-situ tests, sleeves, stuck probes, etc.

7
EVALUATION OF DAMAGE MECHANISMS

Each of the damage mechanisms and mechanical distortions listed in Sections 6.1 and 6.2 are evaluated for their potential effect on the integrity of plugged tubes. This section considers the effect of the damage mechanism as a lone entity. The cross-functional relationships of these mechanisms and other contributing factors are evaluated in the following sections of this document.

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Figure 7-1
OTSG Damage Mechanisms

7.1 PWSCC

PWSCC at Roll Transitions

PWSCC typically occurs at areas of high residual stress. The most typical location is within the upper tubesheet region of the OTSG tubes at the transition zones of the roll expansion. PWSCC initiates on the inner diameter (ID) and is usually characterized as short, axial cracks confined to the expansion transition zone. PWSCC may also develop in a circumferential orientation or as circumferential cracks between multiple axial cracks. PWSCC that occurs within the tubesheet does not represent a challenge to plugged tubes. If a plugged tube severs due to PWSCC in the tubesheet, the tube ends are contained within the tubesheet and the likelihood of the tube contacting adjacent tubes is not increased. There are no cross-functional effects that would cause PWSCC at the roll transitions to result in damage to an in-service tube.

PWSCC at Dents and Dings

Crack-like indications have been identified at dents and dings in the OTSGs. The cracking is suspected to be due to IGSCC that develops at the localized residual stress on the OD of the OTSG tube at the ding or dent site. The cracking at dents and dings in the OTSGs is typically circumferential in nature. Because of the population of dents and dings in the OTSGs and the

potential for cracking, dents/dings with indications are being tracked in the OTSG Annual Performance Report (Ref. 8).

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A review of the eddy-current data in FDMS on de-plugged OTSG tubes that had dents/dings without flaw indications at the time of plugging showed no initiation of cracks at the dent or ding locations. Since PWSCC is directly related to temperature magnitude, it is reasonable to assume that growth and initiation of new degradation after plugging would be less due to the lower temperatures in plugged tubes. In addition, since the resulting cracking is typically limited to the extent of the dent or ding (Ref. 3), severance of a tube due to PWSCC in dents/dings is unlikely.

In summary, dents and dings are not expected to be a principal failure mechanism in plugged tubes. However, when coupled with swelling of a plugged tube or high cycle fatigue, dents or dings could provide an initiation point for potential failure of a plugged tube.

Dents and dings are discussed further in Section 8.1. Tube swelling due to over-pressurization is discussed in Section 8.5.

7.2 Tube End Cracking

The tube ends of the OTSGs have experienced ID cracking, which is typically axial in nature, but has also appeared as circumferential or a combination of circumferential and axial cracking (Ref. 4). A small number of volumetric indications have also been found in the tube ends. Tube end cracking has been attributed to PWSCC in the heat-affected zone of the tube resulting from the installation of the tube-to-tubesheet weld. If a plugged tube severs due to tube end cracking, the tube ends are contained within the tubesheet and the likelihood of the tube impacting adjacent tubes is not increased. There are no cross-functional effects that would result in a plugged tube severed due to PWSCC at the tube ends, to result in damage to an in-service tube.

7.3 IGSCC/ODSCC

Outer diameter stress corrosion cracking (ODSCC) and intergranular stress corrosion cracking (IGSCC) are pervasive forms of degradation of Alloy 600 tubing. SCC is thought to be the result of oxidation at the grain boundaries of the tube material, which reduces the structural integrity and leak tightness of the tubing. SCC tends to extend throughwall in a very limited width. The crack orientation is dependent on the stress direction and can be either axial or circumferential or a combination thereof. Secondary side (OD) SCC is strongly correlated to the presence of built-in crevices and crevices formed by the deposition of sludge.

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Sludge Pile IGSCC/ODSCC

ODSCC has been associated with dents and the presence of sulfur contaminants in the sludge pile.

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Plugging a tube does not change the dent or contaminant conditions. However, since a plugged tube experiences a lower temperature than an in-service tube, the rate of growth and initiation of new degradation should be less than for an in-service tube.

The presence of IGSCC/ODSCC alone is not expected to result in tube severance unless it is coupled with high cycle fatigue or a change in loading or boundary conditions due to tube swelling. The combined effects of dents, flow-induced vibration, chemical excursions/intrusions, and swelling of a plugged tube are addressed in later sections of this document.

Axial IGSCC (Groove IGA)

Axial IGSCC preferentially attacks the shallow grooves that were formed on the outside of the tubes during insertion into the steam generator during manufacture. IGA develops in these grooves and, in the presence of stresses remaining from fabrication or created during operation, cracks propagate into the tube metal along the grain boundaries. Based on destructive examination of pulled tube samples, the degradation often extends to several feet in length, although the depth of penetration varies along the length of the flaw. Axial IGSCC/Groove IGA is most common in the superheat region of the OTSG and has been associated with chromium oxide deposits and high concentrations of alkaline-forming impurities (Ref. 2).

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7.4 Fretting/Wear

Wear refers to the thinning of a portion of a tube wall caused by the gradual removal of discrete particles from two contacting surfaces in motion. Fretting wear occurs when the mating surfaces are subjected to small amplitude, oscillatory relative motion. In steam generators, vibration induced by high velocity fluid flow may cause fretting of the tubes at the support plate locations.

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Since wear is an OD damage mechanism that is primarily due to secondary side fluid flow, it is reasonable to assume that the damage mechanism may continue to progress and/or that new wear

sites may be initiated after plugging. Plugged tubes may also be susceptible to wear due to loose parts, which is discussed in Section 10.1.

Based on examination of pulled tubes, wear damage is typically more axial in orientation (Ref. 2). Because of the broached tube support plates, wear damage is typically confined to three narrow locations around the tube circumference and is very unlikely to propagate circumferentially. Therefore, failure for this typical type of wear in a plugged tube is highly unlikely, even in the case of over-pressurization of trapped water, since the region of degradation is constrained by the TSP. The mostl likely potential failure mode of atypical (freespan) wear in a plugged tube is axial burst due to over-pressurization of trapped water, which is discussed in Section 8.5.

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7.5 Volumetric ODIGA

Volumetric ODIGA (patch IGA) is defined as three-dimensional intergranular corrosion (IGC) initiating at the grain boundaries on the outside of the tube with no stress corrosion crack-like characteristics. The cross-section of a typical IGA patch has an elliptical or “thumbnail” appearance.

Generic OTSG ODIGA Experience

Secondary side IGA has been found in a large number of PWR steam generators and is strongly correlated with the presence of as-built crevices and crevices formed by the deposition of sludge, such as the secondary side of the lower tubesheets.

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TMI-1 Tube Severance

During the 2001 fall outage at TMI-1, tube B66-130 which had been plugged in 1986 (Ref. 5), was found to be severed at the upper tubesheet secondary face (UTSF). The severance was discovered after eddy-current inspection showed significant wear damage on four adjacent tubes at the upper tubesheet secondary face.

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Summary of Volumetric ODIGA

Review of the data on de-plugged OTSG tubes shows that ODIGA may initiate and/or progress in a plugged tube. While ODIGA has been associated with sulfur deposits, destructive examination has shown that contaminant deposits cannot always be confirmed. ODIGA in the upper spans and freespans of the OTSGs has generally been attributed to a known source of contamination that was due to a unique event for the plant. ODIGA by itself is not expected to result in failure of a plugged tube. However, contributing factors such as swelling due to trapped water and high cycle fatigue may result in severance of the tube at the site of relatively minor ODIGA (< 20% TW). The consequences of swollen tubes, high cycle fatigue, and flow-induced vibration are discussed further in later sections of this document.

7.6 IDIGA

IDIGA Experience at TMI-1

Primary-side IDIGA was detected at TMI-1 in November 1981 after a 30-month cold shutdown period, followed by hot functional testing and two more months of cold shutdown (Ref 2). The IDIGA was attributed to injection of sodium thiosulfate into the primary system. IDIGA is generally associated with chemical intrusions rather than normal operating conditions.

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ONS-1 Tube Severance

During the 2002 refueling outage at ONS-1 (RFO 20), extended wear scars on two tubes in the B-OTSG were identified by eddy-current inspection (Ref. 7). Subsequent inspection showed that tube B78-124 was completely severed at the secondary face of the LTS.

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Summary of IDIGA

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7.7 Corrosion-Assisted Fatigue

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Table 7-1
At Risk Tubes in the Lane/Wedge Tube Region

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7.8 Erosion/Corrosion (Impingement)

Erosion/corrosion refers to loss of metal caused or accelerated by the impingement of a corrosive fluid on a metal surface, resulting in rather specific cavity development in the metal surface (Ref. 2). Impingement attack is associated with high fluid flow that may be accelerated by entrained gas bubbles, or secondary-side solids, or slugs of liquid entrained in the steam flow.

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The conditions that result in erosion most likely exist for short periods of time and are unlikely to reoccur at the same location. Thus, it is unlikely that a plugged tube would fail due to an erosion defect that was present at the time of plugging. Plugging does not change the conditions that result in erosion; therefore, initiation of erosion defects in plugged tubes is possible and may be difficult to predict.

Failure of a plugged tube due to erosion would be highly unlikely unless other contributing factors, such as swelling of the tube, are present. The most likely potential failure mode of a plugged tube due to erosion in a swollen tube is axial tube rupture. Tube swelling due to overpressurization is discussed in detail in Section 8.5.

7.9 Pitting

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7.10 Summary of Damage Mechanisms (Cracking and/or Loss of Metal)

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Table 7-2
Summary of OTSG Damage Mechanisms

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8 EVALUATION OF MECHANICAL DISTORTION

8.1 Dents/Dings

A dent or a ding is a deformity on the tube due to a force strong enough to plastically deform the tube. Dings and dents do not have an appreciable effect on the tube burst pressure in the absence of other damage mechanisms. Therefore, the dent or ding itself is not a damage mechanism that affects the integrity of the tube, though there have been instances where the dent or ding was large enough to prohibit passage of an eddy-current probe. Typically, these deformations are called dings if they are located in the freespan and dents if they are located at a TSP or a tubesheet. However, the designations are not consistent for all the OTSGs.

Dents and dings, in the OTSGs, are generally attributed to loose parts installation practices, or corrosion product build-up at carbon steel support members. Small loose parts or debris that enter the tube from the primary side, or enter the gap between tubes on the secondary side, may cause dents and/or dings, which may have the potential of developing cracks as discussed below.

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As described above and in Section 7.1 and 7.3, cracking has been identified at dent/ding locations. Cracking at dents and dings in the OTSGs is typically circumferential in nature and limited to the extent of the dent/ding. The cracking is suspected to be due to IGSCC that develops as a result of localized residual stress at the dent/ding site.

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8.2 Manufacturing Burnish Marks

Manufacturing burnish marks (MBMs) are shallow volumetric scuffs introduced into the tubes exterior surface during final tube polishing. There are MBMs in all the OTSGs and each indication is evaluated based on the results of previous eddy-current inspections. Any change to the eddy-current signal from a previous inspection would result in the tube being repaired. To date, there has been no evidence that MBMs lead to further degradation (Ref. 2). Therefore, MBMs are not considered a challenge to the integrity of plugged tubes.

8.3 Twisted (Misaligned Tubes)

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8.4 Instrumented Tubes and OEM Violated Tubes

A number of OTSG tubes were plugged prior to service. These tubes include but are not limited to the instrumented tubes at ONS-1 and OEM violated tubes.

Instrumented Tubes

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OEM Plugged Tubes

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8.5 Trapped Water and/or Swollen Tubes

Trapped water by itself does not cause mechanical distortion of the tube; however, increasing the temperature of a sufficient amount of fluid within a tube can result in over-pressurization and tube swelling. Water can end up in a plugged tube by three primary methods. The first method is that water is present in the tube at the time of plugging. This may occur when a leaking plugged tube is replugged or when a plug is installed in the upper tube end after operation with only a bottom plug. Dewatering the tube prior to plugging has not been standard industry practice. Framatome ANP recommends dewatering to a level of at least 280 inches (Ref. 28) below the upper OTSG tube end prior to plugging.

The second method is for water to enter a plugged tube by leakage through tube degradation. In this case, the trapped water is not likely to result in swelling because as the internal pressure increases, the fluid leaks back out of the degradation until the pressure on each side of the tube is equal. In tubes that may have filled with water due to degradation in the upper spans, it is possible that changes in temperature may delay equalization of pressures due to choking of the leakage. As the internal pressure increases, it is most likely that the degradation would open up further, rather than the tube expanding.

The third method is for water to enter a plugged tube by leakage of primary water through or by the plug. Review of the TMI-1 data indicates that this method is the most likely to contribute to swelling of a plugged tube. The three plugged tubes that had failed all had plug repairs that resulted in a tighter leak condition, which trapped any water that may have previously leaked into the plugged tube. Plug types and plugging configurations are discussed further in Section 9.6.

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Water may also be present between a sleeve and the parent tubing. This is a special case that is discussed in Section 9.5.

Trapped Water without Swelling of the Tube

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Based on a review of the de-plugged tube inspections, the presence of trapped water, in the absence of swelling or other contributing factors such as contamination, does not appear to be a significant factor in the initiation and/or growth of degradation in a plugged tube.

Trapped Water with Swelling of the Tube

Review of TMI-1 Swollen Tubes

As described in Section 7.5, the severed plugged tube at TMI-1 that resulted in damage to adjacent tubes was found to be swollen and constrained at the supports, with a severance at the secondary face of the UTS. Bobbin coil inspection of the severed tube B66-130 produced very noisy data that was later determined to be due to the tube being expanded significantly or "swollen" beyond its nominal tube OD of 0.625 inch (Ref. 11). Tube B66-130 was swollen to approximately 0.7 inch OD in the free span (away from the tubesheets and TSP interface areas). Subsequent visual and eddy-current inspection showed 29 tubes that appeared to be swollen due to elevated internal pressure.

Finite element analysis and pressurization tests showed an internal pressure in excess of 10,000 psi was required to swell the OTSG tubes to an ID of 0.69 inch (Ref. 16). The tubes start to yield diametrically at about 6000 psi internal pressure with plastic deformation around 8000 psi internal pressure.

To support FIV analysis for the root cause of the TMI-1 tube severance, damping tests of swollen tubes were performed for support conditions simulating the free span and the 15th and 14th spans (Ref. 12). The tests indicated that expansion of the tube does not significantly affect the damping. Thus, based on the damping tests, it was first thought that a swollen tube should be at least as resistant to flow-induced vibration as the unexpanded tube. However, as the tube

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9 INSPECTION AND REPAIR PROCESS

Inspection and repair processes were reviewed to determine if any of these processes have a potentially negative impact on the integrity of a plugged tube. Included in this assessment are:

- Design BasisTests
- Repair Rolls
- In-situ tests, including pressure effects and localized support probes
- Tube pull
- Sleeves
- Plug Types

9.1 Design Basis Tests

Primary and Secondary Side Hydrotests and Hot Functional Tests were performed on the OTSGs. Primary and Secondary Side Hydrotests are typically performed as shop tests or early field tests

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Hot Functional Tests are conducted prior to core loading, wherein the NSS is tested and qualified for core loading. The testing is conducted over a period of approximately 14 weeks and operating conditions similar to normal and upset conditions occur. These tests do not increase the likelihood of a plugged tube sever nor do they have any significant impact on progression or initiation of any OTSG damage mechanism.

9.2 Repair Rolls

Repair rolls have been qualified to provide a new pressure boundary in the upper and lower tubesheets. PWSCC has been identified in the transition zones in the original rolls and the repair rolls. However, since these locations are within the tubesheets, repair rolls have no impact on the likelihood of a severed plugged tube impacting neighboring tubes. The repair roll qualification includes an exclusion zone at the secondary face of the tubesheet to prevent a potential severed tube from pulling out of the tubesheet.

9.3 In-situ Tests

An in-situ pressure and leak test is performed to test the integrity of degraded tubes in the steam generators. The governing document for in-situ testing is EPRI TR-107620-R1, "Steam Generator In-Situ Pressure Test Guidelines" (Ref. 14). The test procedure includes pressurization to at least three different pressure levels, which include normal operating pressure differential (NOPD), postulated accident (faulted) condition pressure differential, and a proof test differential.

The EPRI Guidelines provide equipment specification requirements and tool qualification guidelines. In-situ pressure testing systems include a remotely installed probe and a pump to supply water. A full tube test allows testing of multiple indications at the same time. A localized test may be required for locked tubes since some of the pressure and load may be reacted through multiple support plates. A localized test is also used to test circumferential indications that require the application of an axial tensile load. In-situ tested tubes are typically removed from service, due to the degradation that led to the testing and the tubes are stabilized based on current stabilization criteria.

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9.4 Tube Pull

In order to confirm degradation and to evaluate the causes of degradation, it is sometimes necessary to remove a sample of a degraded tube for detailed examination and testing. A portion of the tube is normally pulled out through the tubesheet and plugs are installed in the tubesheet to seal the empty tubesheet hole and the other end of the tube. If the severed end of the remaining tube section is in the free span, the tube is evaluated for stability. Input for 50.59 evaluations for an OTSG tube pull (Ref. 18) and a tube pull at TMI-1 (Refs. 19 and 20) address the safety issues involved in removing a tube sample. The stability evaluation performed prior to a tube pull ensures that the severed ends do not present a challenge to adjacent tubes due to cross-flow loads or flow-induced vibration. A tube pull leaves a segment of tube that is open to secondary side fluid. The lower portion of the remaining tube segment may be susceptible to the collection of debris and relatively stagnant fluid. In the UTS and top spans, the remaining segment of the pulled tube is less susceptible to collection of debris and stagnant fluid, but may still be subject to degradation typically found in this region. Based on review of the damage mechanisms in Section 7, a severance in the remaining segment of a pulled tube is unlikely and the stabilization criteria for a pulled tube location are considered sufficient to prevent damage to adjacent in-

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9.5 Sleeves

Repair sleeves are used to keep tubes in service that contain a pluggable eddy-current indication (Ref. 8). A preventative sleeve is typically installed in a tube to prevent high cycle fatigue. The sleeve is installed prior to the initiation of detectable degradation (Section 7.7).

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Based on the review described above, sleeved plugged tubes do not represent any challenge to the integrity of in-service tubes. In addition, a tube that is sleeved with the 80-inch sleeve may be considered as a stabilized in the top span.

9.6 Plug Types and Configurations

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Alloy 690 and Alloy 600 Plug Combinations

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10 OTHER POTENTIAL CONTRIBUTING FACTORS

10.1 Loose Parts and Foreign Material

Loose parts and foreign material have the possibility of affecting plugged tubes in two ways, mechanical distortion and contamination. Loose parts and debris have the capability of causing wear, dents, or dings on the OD of a plugged tube. Tube wear due to loose parts is expected to be similar in a plugged tube as it is for in-service tubes. Therefore, any pattern of unexpected wear or denting for in-service tubes that may indicate a possible loose part should be investigated for damage to neighboring plugged tubes.

Primary-Side Loose Parts

Loose parts and foreign material that are trapped inside a plugged tube would not be expected to cause significant wear, but may result in degradation due to contamination from the material. Such debris may have contributed to the severance of the ONS-1 tube. Evidence of contamination was present, but neither the contaminant nor its source could be identified. Debris is primarily a concern in tubes that have been plugged in the LTS and left open in the UTS, or pulled tubes that have remaining sections that are open at the top, which allows debris to collect in the bottom.

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Secondary-Side Loose Parts

Plugged tubes may also be susceptible to wear due to loose parts on the secondary side. Loose parts may potentially enter the OTSGs from the secondary feedwater system (main and auxiliary). In addition, loose parts may have been left during fabrication or maintenance activities.

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Loose parts from fabrication and early maintenance activities were controlled by FME (foreign material exclusion). Significant loose parts associated with original fabrication would have been identified by ECT wear indications during early OTSG inspections. The OTSG operating experience over the past 20-30 years has not identified any significant wear indications from loose parts. Periodic inspections and maintenance of the secondary side are performed with strict FME requirements to prevent items from entering the OTSGs. Therefore, loose parts due to fabrication and maintenance are unlikely.

Periodic secondary-side inspections, water-lancing, and ECT are performed, and have detected a limited number of small loose parts (e.g. wire and small nails), which had produced no appreciable wear indications. Even if a small part were left in the OTSG, the resulting wear would be unlikely to result in severance of a plugged tube.

10.2 Chemistry Excursions and Intrusions

During the course of a plant's operating life, chemical excursions and/or intrusions may occur.

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The occurrence of a chemical excursion or intrusion that appears to contribute to degradation of in-service tubes should also be reviewed for possible degradation of plugged tubes.

10.3 Normal Operation

The root cause review for the TMI-1 severed tube included a review of TMI-1 operation over the last two cycles and found that there were no appreciable variations from normal operation of the OTSGs. Therefore, the in-service and plugged non-swollen tubes did not experience any loading conditions that were in excess of those considered in the current plugging limits.

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10.4 Flow-Induced Vibration

For a normal OTSG tube, every span is affected by flow-induced vibration (FIV) due to various flows in the steam generator. Each span vibrates and energy dissipation is distributed across a number of spans

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A tube that severs may vibrate with amplitudes that are greater than a normal tube and thus, impact neighboring tubes, resulting in wear. A tube that severs in an area of high cross flow is also susceptible to instability, which results in large amplitudes and high stresses at the point of restraint as well as wear on neighboring tubes. Stabilization criteria have been developed to ensure that tubes with degradation susceptible to severance and/or instability are stabilized to

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ONS-1

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TMI-1

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Fluid-Elastic Stability Margin

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Summary of FIV Effects

As discussed above, flow-induced vibration effects were not the primary cause of the tube severance for either the TMI or ONS-1 plugged tube failures. In the case of the TMI-1 tube, swelling was the major factor in promoting failure by fatigue due to FIV. In the case of the ONS-1 tube, new degradation was the primary cause of the plugged tube severance with no influence from FIV. However, in each case flow-induced vibration of the severed plugged tube resulted in damage to the neighboring tubes.

In summary, flow induced vibration of plugged tubes is not a concern by itself because stabilization criteria define tubes that are susceptible to severance and requires that these tubes be stabilized at the time that they are plugged. However, FIV is a potential concern if accompanied by other contributing factors, such as tube swelling or severance by an unforeseen mechanism.

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10.5 Effects of Tube Plugging and Power Uprates

After years of operation, variations in tube plugging patterns and power uprates cause some differences in the thermal-hydraulic conditions between OTSGs. These changes can affect the responses of the steam generator tubes, both plugged and non-plugged.

Tube Plugging

The number of tubes plugged, and the pattern of tube plugging, has an effect on the overall conditions in the OTSGs and specific parameters that affect individual plugged tubes. A typical plugged tube is subjected to secondary side temperature and pressure.

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Power Uprates

A power uprate typically involves only minor changes in temperatures and pressures. However, these minor changes can result in changes in the normal steady state tube loads, which could affect the stability of both plugged and in-service tubes. In addition, the increased flows associated with power uprates also affect the stability of the tubes. Stability margins associated with flow-induced vibration decrease with increased mass flow rates. Therefore, power uprates may impact OTSG stabilization criteria and it is recommended that all tubes be addressed prior to changes in power output.

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The tube FIV analysis and stabilization requirements for each potential uprate, including "Caldon uprates," must be reviewed to ensure that no changes are required. All installed hardware has been evaluated for each of the power uprates at the OTSG plants.

11 SUMMARY

Recent inspections of OTSGs identified plugged tubes that had severed and caused wear on adjacent in-service tubes. In each case, the severance of the plugged tubes was identified by freespan wear on adjacent tubes and were addressed before failure of an in-service tube occurred. However, performance criteria were not met since two of the wear indications were greater than 60% TW. Thus, it is important that the utilities and analysts continue to recognize and investigate wear patterns located outside a TSP as these indications may represent wear due to a severed plugged tube.

In response to these findings, a review was performed to evaluate potential damage mechanisms for plugged tubes. This review included damage mechanisms, mechanical distortion, inspection and repair processes, and other potential contributing factors.

11.1 Damage Mechanisms

- PWSCC (primary water stress corrosion cracking)
- Tube End Cracking
- Groove IGA/Axial IGSCC (groove intergranular attack/axial intergranular stress corrosion cracking)
- Fretting/Wear (Includes loose part damage)
- IGA (volumetric intergranular attack – may initiate on the inner or outer diameter of the tube)
- ODSCC (outer diameter stress corrosion cracking)
- High Cycle Fatigue Cracking
- Erosion/Corrosion (impingement)
- Pitting

Review of the degradation mechanisms that are known to occur in the OTSGs did not reveal any mechanism caused by normal operation of the steam generator that is likely to progress to failure in a plugged tube except for circumferential cracks due to high cycle fatigue, which has been addressed by preventative sleeving and stabilization criteria. OTSG plugged tubes that have not been stabilized and may be susceptible to CAF have been identified (See Table 7-1).

However, in a swollen plugged tube, any degradation mechanism has the potential to be the initiating site for failure of the tube by axial burst or sever.

IDIGA, which was the cause of the plugged tube sever at ONS-1, is the result of contamination due to chemical intrusion or foreign material and typically has not been associated with normal operation. Upon review, the ONS-1 sever due to IDIGA is considered to be a unique event that was most likely due to contamination from debris that entered the tube when it was plugged in the lower end while open in the top.

11.2 Mechanical Distortion and Inspection and Repair Processes

- Dents/Dings (Includes loose part damage)
- MBM (manufacturing burnish marks)
- Twisted Tubes (tubes misaligned from the upper tubesheet to the lower tubesheet; TS hole positions from upper to lower do not match)
- OEM Violated Tubes and instrumented tubes
- Swollen Plugged Tubes (Trapped Water)
- Effects of in-situ tests, sleeves, repair rolls, tube pulls, stuck probes, etc.

There is no evidence that MBMs present any challenge to the integrity of a plugged tube. Twisted tubes are applicable to only one OTSG plant and review of these tubes revealed no factors that are likely to result in a plugged tube sever. There is no evidence that instrumentation alone is a risk factor for a plugged tube sever. Sleeves and repair rolls also present no challenge to the integrity of a plugged tube.

While, OEM plugged tubes are not considered to present a high risk for tube sever, the possibility of violation of these tubes with volumetric holes should be considered by applying the current stabilization criteria to an assumed volumetric flaw as discussed in Section 8.4.

Subsequent eddy-current data from tubes that were plugged with dents and/or dings shows no evidence that cracks are likely to develop at the site of the dents or dings. In the event that a crack does develop, it is unlikely to result in a tube sever since the crack is typically limited to the extent of the dent or ding.

The effects of in-situ tests that have the potential to increase the likelihood of severing a plugged tube are addressed by the current stabilization criteria.

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Therefore, Framatome ANP recommends that stuck probes that are considered to contain potentially harmful corrosive constituents be removed as soon as reasonably possible and/or adjacent tubes monitored for signs of freespan wear.

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11.3 Other Potential Contributing Factors

- Loose parts and foreign materials
- Chemistry excursions and intrusions
- Normal operation, including design basis tests, effects of tubesheet bow, heatup rates, and power uprates
- Flow-Induced Vibration
- Plug types and plugging configurations

There are no factors associated with normal operation that are considered to directly challenge the integrity of a plugged tube. Flow-induced vibration is a factor that must be considered in conjunction with the effects of swelling due to over-pressurization. Flow induced vibration of plugged tubes is not a concern by itself because stabilization criteria define tubes that are susceptible to being severed, and requires that these tubes are stabilized when they are plugged. Therefore, in the absence of other contributory factors, such as over-pressurization of a plugged tube, the current OTSG stabilization criteria are considered a reliable means to prevent damage to in-service tubes from plugged tubes.

Secondary-side loose parts have the potential to produce wear. However, the spray plates on the main feedwater nozzles, infrequent use of the auxiliary feedwater system, and FME requirements for maintenance and repair activities prevent the entry of large loose parts into the steam generator. Wear from small loose parts is typically negligible. Thus, wear due to secondary-side loose parts in the OTSGs is not expected to result in a tube sever or axial rupture of a plugged OTSG tube.

Foreign material and contamination were implicated in the severance of theONS-1 tube. IDIGA at the site of the severance was most likely due to debris and contaminants that collected in the tube during the time when the tube was open at the top end and plugged at the bottom. In the same manner, chemistry excursions and intrusions may have the potential to result in degradation in a plugged tube, especially in a tube that is open at the top end and plugged at the bottom at the time of the event.

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12 CONCLUSIONS AND RECOMMENDATIONS

No one factor alone is expected to result in failure of a plugged tube. However, when certain factors are combined, there is a potential for severing a plugged tube in the OTSGs. The OTSG plants are including an evaluation of these factors on a plant-specific basis in the upcoming outage plans.

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APPENDIX B
WESTINGHOUSE / CE DESIGN STEAM GENERATOR PLUGGED TUBE DAMAGE MECHANISMS

ABSTRACT

During the 14th refueling outage at the Three Mile Island Unit 1 (TMI) nuclear power plant four steam generator tubes were found with wear scars as a result of being abraded by an adjacent plugged tube which had severed. NRC Information Notice 2002-02 [Reference 1] was issued to present information about the incident and about the finding of root cause evaluations. While NRC IN 2002-02 did not require specific actions from plant operators, it was suggested that the industry review the history of plugged tube failure mechanisms and investigate the potential for tube severance and consequential damage to adjacent tubes.

This report is written to present the results of the review of plugged tube failures, the evaluation of the potential for burst tubes to damage adjacent tubes, and an evaluation of analytical methods used to prevent such events. This report addresses both Westinghouse Electric and Combustion Engineering recirculating steam generators. This includes generators designed and manufactured by, or for, these companies.

Section 2.0 provides a review of industry burst steam generator tube events and a general overview, and more detailed discussions of plant specific events in order to facilitate comprehension of tube degradation events. Section 3.0 discusses the various tube degradation mechanisms that have resulted in tube plugging. Section 4.0 addresses the analytical techniques that are employed to mitigate the effects of tube degradation mechanisms. Section 5.0 provides a ranking of the degradation mechanisms by potential for tube burst, conclusions are summarized in Section 6.

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LIST OF FIGURES

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1 INTRODUCTION

In a Pressurized Water Reactor system, the steam generator serves as the boundary between the Primary and Secondary sides of the Nuclear Steam Supply System (NSSS). Within the steam generator shell, the actual primary-to-secondary boundary is the steam generator (heat exchanger) tubing. In the event of tube failure (burst) the primary reactor coolant can escape from the primary system (steam generator tubing) and enter the secondary side of the system, thereby releasing radioactive materials into the secondary side.

There have been a number of potential causes for tube bursts that have been identified over the years. Potential causes include tube corrosion, fatigue failures, loose part interaction and wear, and overpressure due to the "Diode" or "Obrigheim" effect. The Diode effect is applicable to only those steam generator tubes that have been previously isolated by the installation of "plugs" in the open ends of the tubes. In the Diode effect, primary fluid is postulated to enter the plugged tube past the tube to plug seal at cold RCS conditions. The primary leak path is isolated as the RCS temperature rises. If sufficient primary water has entered the tube, the thermal expansion characteristics of the entrapped water cause an internal pressurization that can result in failure (burst) of the tube. The Diode effect refers to the one way flow through a crack or flaw in the plug, or past a less than optimum plug to tube seal.

This report addresses the potential for a plugged tube to axially separate and to damage adjacent steam generator tubes.

1.1 Steam Generator Design

There are a variety of models of Westinghouse and Combustion Engineering steam generators currently in operation. Tables 1-1 and 1-2 provide a list of operating plants that were originally equipped with Westinghouse or Combustion Engineering steam generator types. The steam generator models are identified for each plant, along with any steam generator replacements that have been installed. Steam generator models are principally differentiated by component materials, feedwater designs, moisture separator designs, and heat transfer areas. All Westinghouse and Combustion Engineering models however share the same basic architecture, a vertical u-tube heat exchanger with secondary side feedwater recirculation.

A typical Westinghouse steam generator is shown in Figure 1-1. Figure 1-2 shows a typical Combustion Engineering steam generator.

Table 1-1
Westinghouse Steam Generator Models (in operation)

Plant	Model (Original)	No. of Loops	Model (Replacement)	Plant	Model (Original)	No. of Loops	Model (Replacement)
Almaraz 1	D3	3	*Siemens*	Korean Nucl. Plant 5	F	3	
Almaraz 2	D3	3	*Siemens*	Korean Nucl. Plant 6	F	3	
Alvin Vogtle 1	F	4		Korean Nucl. Plant 7	F	3	
Alvin Vogtle 2	F	4		Korean Nucl. Plant 8	F	3	
Angra 1	D3	2		KORI 1	51	2	Delta 60
Asco 1 (FESCA)	D3	3	*Siemens*	KORI 2	F	2	
Asco 2 (FESCA)	D3	3	*Siemens*	Krsko	D4	2	*Siemens*
Beaver Valley 1	51	3	54F**	Maanshan 1	F	3	
Beaver Valley 2	51M	3		Maanshan 2	F	3	
Beznau 1	33	2	*Fram 33/*	McGuire 1	D2	4	*BWI*
Beznau 2	33	2	*Fram 33/*	McGuire 2	D3	4	*BWI*
Braidwood 1	D4	4	*BWI*	Mihama 1	33	2	35F (CE)
Braidwood 2	D5	4		Mihama 2	44	2	*MHI 46F*
Byron 1	D4	4	*BWI*	Millstone 3	F	4	
Byron 2	D5	4		North Anna 1	51	3	54F
Callaway 1 (SNUPPS 1)	F	4	*FTI*	North Anna 2	51	3	54F
Catawba 1	D3	4	*BWI*	OHI 1	51A	4	*MHI 52FA*
Catawba 2	D5	4		OHI 2	51A	4	*MHI 54FA*
Comanche Peak 1	D4	4		Point Beach 1	44	2	44F
Comanche Peak 2	D5	4		Point Beach 2	44	2	Delta47
D. C. Cook 1	51	4	*BWI-51R*	Prairie Island 1	51	2	*FTI*
D. C. Cook 2	51	4	54F	Prairie Island 2	51	2	*FTI*
Diablo Canyon 1	51	4		Qinshan 1	Delta 60	4	
Diablo Canyon 2	51	4		Qinshan 2	Delta 60	4	
Doel 1	44	2		R.E. Ginna	44	2	BWI
Doel 2	44	2	*MHI***	Ringhals 2	51C	3	*KWU*
Doel 4	E1	3	*Fram 79/*	Ringhals 3	D3	3	*KWU*
H. B. Robinson 2	44	3	44F	Ringhals 4	D3	3	
Indian Point 2	44	3	44F	Salem 1	51	4	F
Indian Point 3	44	3	44F	Salem 2	51	4	**
Jose Cabrera - Zorita	24	1		Seabrook 1	F	4	
Joseph Farley 1	51	3	54F	Sequoyah 1	51	4	W/CE
Joseph Farley 2	51	3	54F	Sequoyah 2	51	4	
Kewaunee	51	2	54F	Shearon Harris 1	D4	3	Delta75
Sizewell B	F (690)	4		Turkey Point 3	44	3	44F

Plant	Model (Original)	No. of Loops	Model (Replacement)	Plant	Model (Original)	No. of Loops	Model (Replacement)
South Texas 1	E2	4	Delta 94	Turkey Point 4	44	3	44F
South Texas 2	E2	4	Delta 94	Vandellos 2	F	3	
Surry 1	51	3	51F	Virgil C. Summer 1	D3	3	Delta75
Surry 2	51	3	51F	Watts Bar 1	D3	4	W/CE**
Takahama 1	51	3	*MHI 54FA*	Watts Bar 2	D3	4	
Tihange 1	51	3	*MHI 51F*	Wolf Creek (SNUPPS 2)	F	4	
Tihange 3	E1	3	*Fram 79/*				

** Indicates Replacement Steam Generators to be installed within 5 years

Replacement models shown in Italics are not addressed by this report

Table 1-2
Combustion Engineering Models

Plant	Model	Loop	Model (Replacement)	Notes
Palisades	Early	2	CE	
Fort Calhoun	CE67	2		Pre-67
Calvert Cliffs 1	CE67	2	*BWI*	2570 Mwt
Calvert Cliffs 2	CE67	2	*BWI*	2570 Mwt
Millstone 2	CE67	2	*BWI*	2570 Mwt
St. Lucie 1	CE67	2	*BWI*	2570 Mwt
San Onofre 2 (SONGS 2)	CE70	2		3410 Mwt
San Onofre 3 (SONGS 3)	CE70	2		3410 Mwt
Arkansas Nuclear 2	CE70	2	Delta 109	2570 Mwt
Waterford 3	CE70	2		3410 Mwt
St. Lucie 2	CE70	2		2570 Mwt
Palo Verde 1	CE80	2	System 80+ **	CE80 denotes System 80 design
Palo Verde 2	CE80	2	System 80+ **	
Palo Verde 3	CE80	2	System 80+ **	System 80 design
Yong Gwang 3	CE80	2		System 80 design
Yong Gwang 4	CE80	2		System 80 design
Yong Gwang 5	CE80	2		System 80 design
Yong Gwang 6	CE80#	2		System 80 design
Ulchin 3	CE80	2		System 80 design
Ulchin 4	CE80	2		System 80 design
Ulchin 5	CE80#	2		System 80 design
Ulchin 6	CE80#	2		System 80 design

These Units have not started initial service

** Indicates Replacement Steam Generators to be installed within 5 years

Replacement models shown in Italics are not addressed by this report

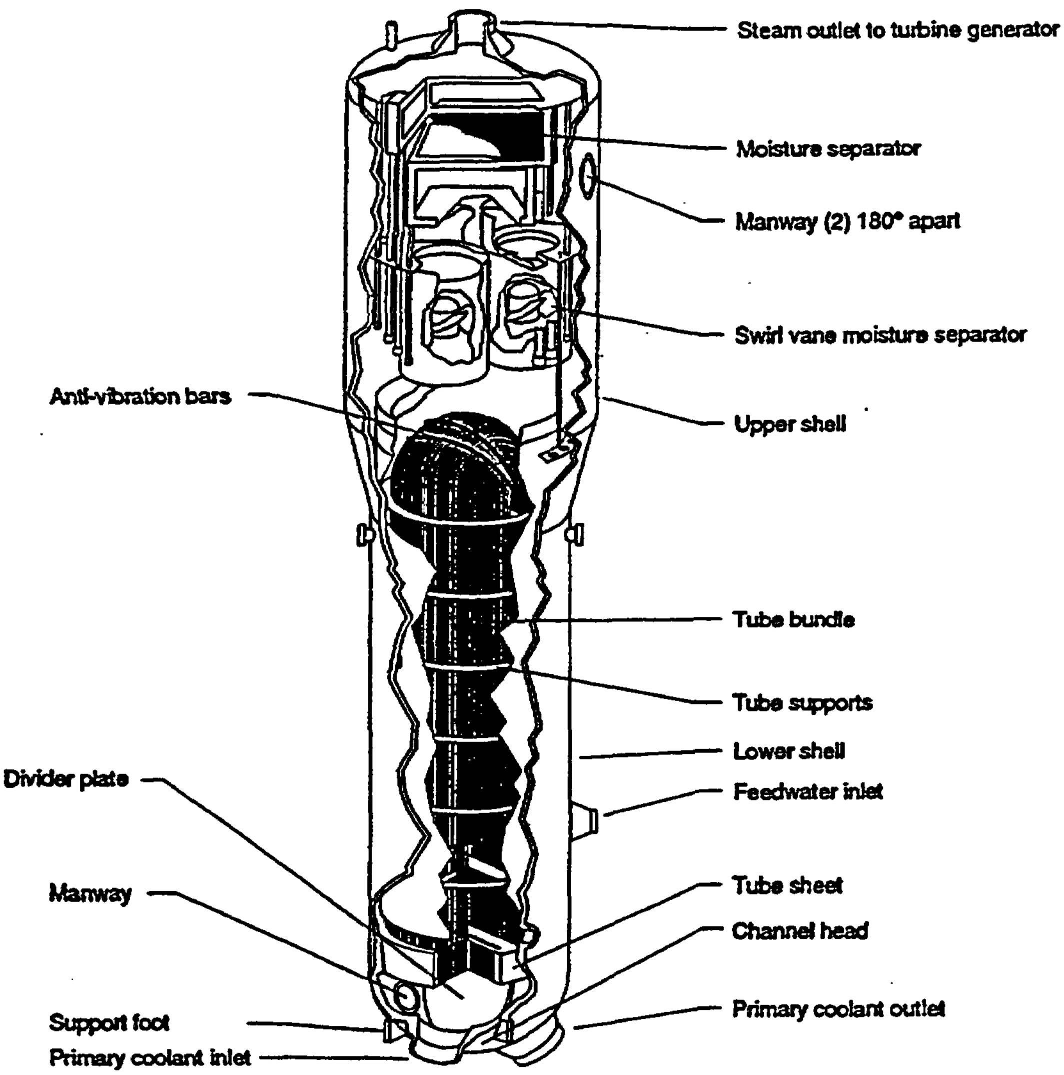

Figure 1-1
Typical Westinghouse Recirculating Steam Generator

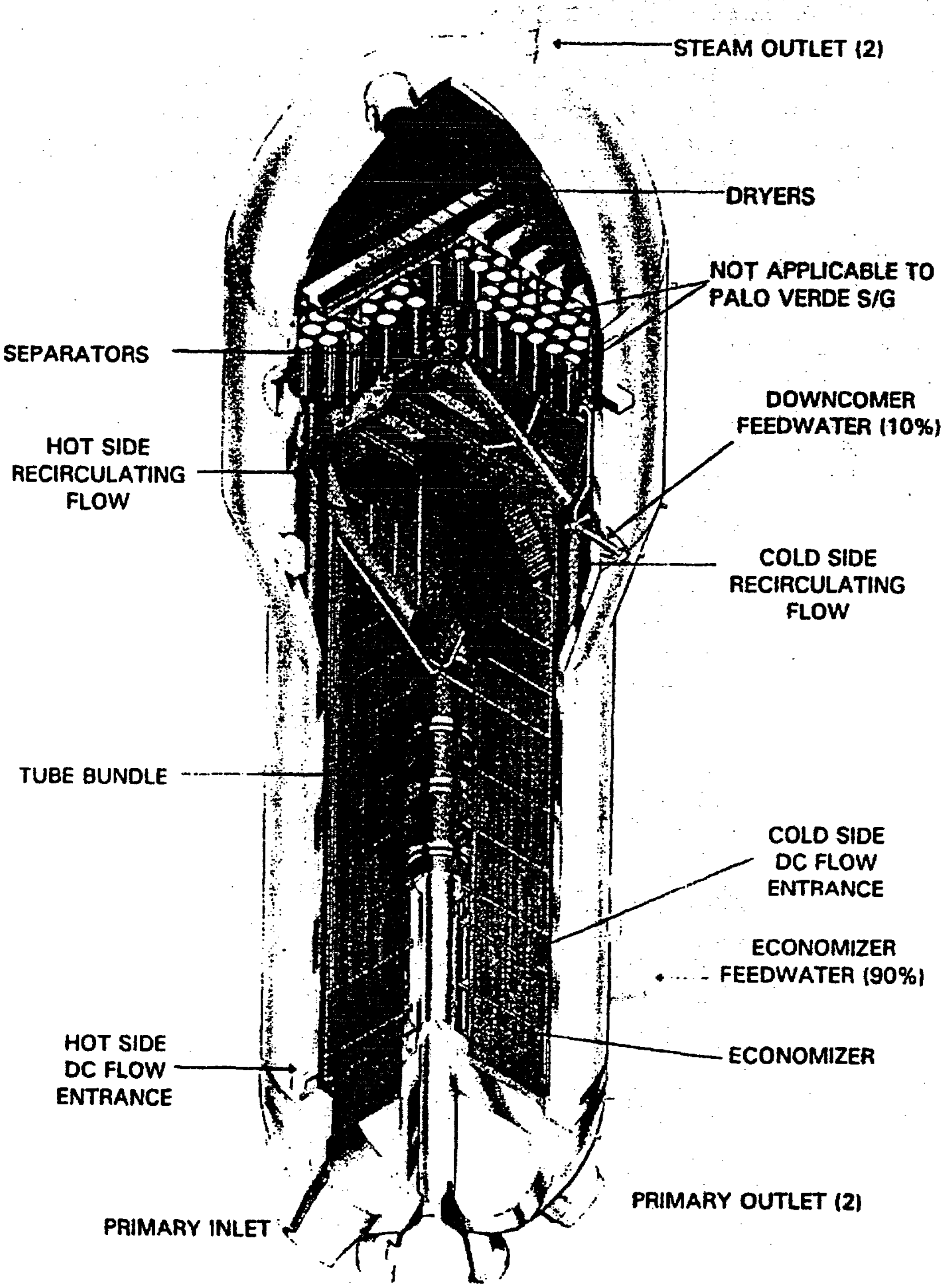

Figure 1-2
Typical Combustion Engineering Recirculating Steam Generator

1.2 Steam Generator Tube Plug Design

A number of different tube plug designs have been installed in Westinghouse and Combustion Engineering Steam Generators. Table 1-3 provides a listing of the plug types that have been provided by both companies. In addition to the Westinghouse and Combustion Engineering plug types, other vendors have supplied plugs to the industry. Those designs are not included in this report.

Table 1-3
Steam Generator Tube Plugs

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Sentinel Plugs

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Roll Plugs

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Weld Plugs

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Identifying Leaking Plugs

Leaking plugs are not normally identified during plant operation. To identify leaking plugs, a plug inspection must be performed to assess the integrity of the plug-to-tube joint. Plug

inspection is essentially always a remote visual (video) inspection. Of particular interest is the potential for a leak path from the channelhead to the tube above the plug.

Boric acid deposits at the bottom of the tubesheet and around a plug are normal, as such deposits alone are not indicative of a leaking plug. The amount of a deposit around a plug depends on a variety of parameters such as the type of plug, for example, mechanical plug versus weld plug, drain rate from within the plug, leak path between the plug and the tube if any, the timing of the manway opening relative to the timing of the video inspection, etc. Therefore, the amount of boric acid deposited around a particular plug is not an appropriate acceptance criterion for the plug.

For a plug assessment the analyst reviews the video data of each plug and documents the observations. In particular, the amount of deposit and the surface wetness around the plug are noted. Depending on the timing of the video inspection, a small amount of wetness can be expected around normal plugs and hence such a condition is acceptable. However, excessive wetness or dripping is unacceptable.

If excessive wetness is noted, the video inspection may be repeated after at least 24 hours subsequent to the initial inspection. If wetness does not appear in the subsequent inspection, the plug joint is considered to be leak tight. However, if the wetness persists, leaktightness of the plug becomes suspect and further assessment of the plug is warranted.

Summary

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2
INDUSTRY EXPERIENCE

In order to understand the potential damage that can result from steam generator plugged tube burst, it is necessary to review the history of plugged tube bursts and the analyses and evaluations that have been performed to investigate the mechanisms that caused these events. Since the November 2001 TMI tube severance is the catalyst which precipitated this program, this event is discussed first. A general discussion of tube swelling events is presented, followed by discussion of failure events at specific plants. The plant specific discussions are intended to illustrate and to better understand tube degradation mechanisms.

2.1 TMI Event Description & Root Cause

During the 14th refueling outage at the Three Mile Island Unit 1 (TMI) nuclear power plant, four steam generator (SG) tubes were found with wear scars as a result of being abraded by a neighboring plugged tube which had become severed at the bottom of the upper tubesheet during operation. TMI-1 uses a Once Through Steam Generator (OTSG) design which differs significantly from the Westinghouse and Combustion Engineering recirculating steam generators discussed in this report. The tube burst event at TMI has been thoroughly studied and several conclusions have been reached. Although the thermal hydraulic conditions and architecture of the OTSG differ significantly from the Westinghouse / Combustion Engineering steam generators, the mechanisms acting to cause the TMI failure must be examined to understand their applicability to the Westinghouse and Combustion Engineering type generators, and as such are discussed herein.

The root cause of the severance of the affected tube was reported to be a sequence of:

1. swelling of the plugged tube (which had no throughwall degradation) which led to
2. increased axial stress at the upper tubesheet and tube support plate (TSP) intersections,
3. the tube became more susceptible to flow induced vibration (FIV), the combination of which led to
4. a subsequent circumferential fatigue failure [References 17 and 18].

The swelling of the affected tube was concluded to have been caused by the thermal expansion of water that had entered the tube past a plug which was installed in 1986. In 1997 this plug was replaced with an alloy 690TT plug which resulted in water being trapped within the tube. The subsequent increase in temperature to operating conditions causes swelling if the tube is full or nearly full because the thermal expansion of water is greater than that of the tube material.

The NRC staff requested the support of the Nuclear Energy Institute (NEI) "in organizing technical and management meetings between the nuclear industry, including the pressurized water reactor (PWR) owner's groups, and the Nuclear Regulatory Commission (NRC)." These meetings would serve to facilitate discussions on what actions, if any, the industry plans on taking in response to the TMI-1 experience," Reference 19. In subsequent discussions with the NRC staff, Reference 20, representatives from NEI, EPRI, the utilities, and nuclear plant supplier engineering organizations argued that:

1) The TMI issue is not an immediate problem for the entire nuclear power industry,

2) Plants should continue to operate, and

3) There is sufficient time for the performance of a thorough evaluation of the TMI issue to determine its applicability, if any, to the remaining operating plants.

In this report information is provided to substantiate the position that the TMI type of failure can not occur in the Westinghouse / Combustion Engineering recirculating steam generators.

2.2 Overview of other Foreign & Domestic Tube Swelling events

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2.3 Review of the Ginna Tube Burst Event

In early 1982 a tube burst event occurred in the "B" steam generator at the Ginna plant. The burst tube was removed from the generator and evaluated. It was determined at that time that the tube severed at the top of tubesheet as the result of wear due to an impacting loose part.

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2.4 Fatigue Induced Tube Bursts

Several instances of tube burst or leakage have occurred during operating experience. Although the initial occurrence of these events did not occur in plugged tubes, the mechanism of occurrence is independent of whether the tubes were plugged or not. Therefore, if the conditions for a fatigue induced tube separation existed in a tube that had previously been plugged for another reason, tube separation of the plugged tube could occur and lead to propagation of damage to adjacent tubes.

2.4.1 North Anna Tube Fatigue

In 1987, a circumferential tube separation occurred at North Anna. This event led to the NRC issuing bulletin 88-02 that describes the conditions leading up to the tube rupture, and required certain utilities to take action.

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2.4.2 Mihama Tube Fatigue

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2.4.3 Indian Point 3 Long Row Tube Fatigue

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2.5 Review of French Data on Plugs Removed from Swollen Tubes

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2.6 Evaluation of the Bruce Plant Tube Burst

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Figures 1 and 3 from Reference 2

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2.6.1 Scenario of Events Resulting in the Failure of the Bruce Steam Generator Tube

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2.6.2 Results of the Review of the Bruce Event

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2.7 Summary of Industry Burst Event Review

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3
EVALUATION OF TUBE DEGRADATION MECHANISMS RESULTING IN PLUGGED TUBES

There are a number of mechanisms such as corrosion, wear and fatigue that have required plugging of tubes. This section evaluates the potential of tubes, plugged as a result of these damage mechanisms, to result in a tube severance, giving rise to a potential risk for damage to adjacent active tubes.

3.1 Tube Sheet Expansion Region Axial Cracking

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3.2 Tube Sheet Expansion Region Circumferential Cracking

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3.3 Expansion Transition Axial Cracking

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3.4 Expansion Transition Circumferential Cracking

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3.4.1 Assessment of Continuing Corrosion Degradation after Plugging

An assessment was made of the corrosion contribution to circumferential crack extension following tube plugging at various steam generator models. The corrosion growth estimate is based on changes that occur as a result of tube plugging.

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3.5 Freespan and Sludge Pile Axial Cracking

Freespan and sludge pile axial cracking is the degradation mode least likely to result in tube separation. Axial cracks in the freespan and the sludge pile will quickly vent, should significant internal pressurization occur due to a postulated flow diode.

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In summary, axial cracking within the sludge pile or freespan region can lead to a swelling event, however, this condition would result in an axial failure at the location of the preexisting degradation, thus relieving the internal pressurization. Consequently, tube separation cannot occur due to a postulated flow diode event.

3.6 Tube Support Plate Axial Cracking

Axial degradation at tube support plates has been associated with crevice packing due to TSP corrosion and/or deposit formation due to precipitation. Should an internal pressurization condition be present due to a postulated flow diode, the crevice packing materials would prevent displacement of the tube OD, and thus, the crack is constrained. Therefore, the crack would not be expected to vent the internal pressure unless it were located at the edge of the TSP.

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In summary, for axial cracking at the TSPs, tube swelling may occur for a postulated flow diode effect, however, axial tube burst in the freespan would occur before axial tube separation (circumferential tube burst). Consequently, axial cracking at the tube support plates is not a concern with respect to tube separation.

3.7 Axial Fatigue Due to Locked TSP Condition

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3.8 Flow Induced Vibration and Tube Fatigue

The requisite condition for a plugged tube to cause damage to neighboring tubes is that its vibration amplitude must be large enough for contact with the neighboring tubes to occur. This can happen when the plugged tube becomes severed, as did the tube in the TMI SG. Severed tubes would be expected to be fluidelastically unstable and to exhibit large vibration amplitudes. For a tube to experience fatigue damage sufficient to sever, it must have a combination of reduced damping and environmental conditions conducive to inducing fluidelastic instability of sufficient amplitude. Axial cracking would not be expected from flow induced vibration because the fatigue damage is caused by the alternating bending stress.

There are two significant flow field excitation mechanisms that affect the tubes in RSGs, turbulence and fluidelastic instability. Other mechanisms such as vortex shedding are not significant. In the absence of a significant pre-existing circumferential crack, turbulence excitation in SGs is not sufficient to result in tube fatigue crack initiation or tube severance.

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There are two regions in recirculating steam generators (RSG) that would be considered most susceptible to fluidelastic excitation, the U-bend region where the velocities are highest and at the top of the tubesheet where there is significant cross-flow and the density is greatest. In addition, the preheater region on the cold leg side of the steam generator for preheat style SGs would also be considered susceptible because of the cross-flow velocities and high fluid density. The potential for tube severance to occur in these regions is discussed in the following sections.

3.8.1 Top of the Tubesheet Region

The maximum cross-flow velocity coupled with the highest fluid density generally occurs at the top surface of the tubesheet and along the tube lane, the space between the straight length portions of the tubes with the smallest U-bend radius. There has never been any evidence of flow induced cracking or fatigue of the tubes due to cross-flow at the top of the tubesheet, in spite of the locked tube conditions.

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3.8.2 U-Bend Region

Damage resulting from flow induced vibration of tubes in the U-bend region was the subject of a significant engineering investigation in 1987 as the result of a tube burst at the North Anna plant. In that case the tube had become locked at the top TSP, which resulted in a significant reduction in vibration damping, and a local region of high velocity flow had been created by non-uniform anti-vibration bar (AVB) penetrations as described in NRC Bulletin 88-02, Reference 22 (see section 2.4.1).

Only the SGs considered susceptible to the conditions for the North Anna tube rupture were analyzed. Thus, in general, the SGs with stainless steel support plates or broached support plates were not analyzed, since these were not considered to have significant potential for tube locking at the support plates.

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The design of the upper bundle supports in CE SGs was analyzed for the North Anna type U-bend failure event following the issuance of Reference 22. It has been determined that the design differences provide greater in-plane and out-of-plane tube support and that the SR of the tubes is less than unity for this condition regardless of the boundary condition at the top tube support. In summary, no failures were predicted and none have occurred in the operation of the CE design RSG.

In later steam generator designs, replacing carbon steel support plates with stainless steel, and changing from drilled to broached holes, eliminated tube denting, removing one of the prerequisites for tube fatigue. For the later replacement SGs, updates in AVB design and steam generator manufacturing techniques have assured the alignment of the AVBs, eliminating the other identified prerequisites for high tube fatigue. Improvements in tube materials have also resulted in increased fatigue strength in new generator tubes.

In conclusion, identifying and removing susceptible tubes from service, and implementing design changes which eliminate the prerequisites for high fatigue stresses, have removed tube fatigue as a possible failure mechanism for both plugged and active tubes in Westinghouse and Combustion Engineering generators. Tubes that were identified as susceptible to fatigue failure had cable tube dampers installed to damp out vibrations as a result of 88-02 evaluations.

3.8.3 Preheater Wear

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3.9 Antivibration Bar/ Structure Wear

Fretting/wear/thinning degradation has been identified as a problem since the early 1970's and includes wear/fretting in both Westinghouse and Combustion Engineering steam generators. Anti-vibration bars (AVBs), i.e., vertical strap, and diagonal supports in CE steam generators, are used in the U-Bend regions of steam generator tube bundles to stiffen the tubes and limit vibration amplitudes. Possible insufficient restraint between the AVB and tubes, or secondary-side flow causing the diagonal supports to move are just some of the mechanisms that can contribute to wear at the AVB/tube interfaces. This is mostly an issue in early model steam generator designs. More recent modifications, which have included the replacement of AVBs in existing steam generators, and re-design of the u-bend region to tighten tolerances between the tubes and AVBs and provide lower wear material couples in replacement steam generator designs, have practically eliminated the incidence of AVB wear.

Tube wear/fretting at AVBs/diagonal supports is primarily the result of flow induced vibration effects. The wear/fretting process has been identified to occur in some plants principally in peripheral regions of the tube bundle, while other plants have experienced random AVB wear/fretting degradation. A slow process, wear at AVBs can be monitored and remedial actions taken once the wear depth reaches Tech Spec limits (typically 40% through-wall wear depth).

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3.10 Loose Parts Wear

Foreign objects (i.e., Loose Parts) are known to be able to wear through the walls of tubes and generate both leaks and bursts. It has been established through operational history that foreign object induced tube wear has produced at least two tube bursts and numerous cases of leakage. One such event that occurred at the Ginna Unit in 1982 involved both severance of a plugged tube and a subsequent active tube burst at least partially attributed to wall loss from the whip

action of a plugged tube severed by sustained interaction with a foreign object. This burst was discussed above in Section 2.3.

The potential for loose part induced tube wear to sever a tube that contacts a neighboring tube has been considered in loose part analyses performed by Westinghouse. The potential for loose parts to wear tubes can be addressed for both active tubes, and for tubes removed from service via plugging. Depending upon circumstance, the particular analysis will address either continued wear due to the object as a result of the inability to retrieve the object, or the potential for additional degradation (see Section 4.3) to occur at the degradation site even after the object is removed.

3.10.1 Object Removed From S/G (Without Tube Degradation)

A common plant situation involves secondary side loose parts that are observed by FOSAR and/or eddy current and are then removed by FOSAR, with no tube damage being identified. Visual inspection equipment used for state of the art FOSARs performs quite well, and it is very common to obtain very clear pictures of the inner regions of the S/Gs. As a result, even the smallest objects can be found and can usually be removed. In addition, during FOSAR, a visual examination of the tubes in conjunction with eddy current inspection, are generally sufficient to determine that loose part induced tube wear has not occurred.

3.10.2 Unretrieved Object Inside S/G (With Tube Degradation - Inactive Tube - Ginna Scenario)

On January 25, 1982 a tube burst occurred at the Ginna power station. During the subsequent root cause investigation it was determined that a large wear scar, approximately 6 inches long with a "fish mouth" opening was present on the burst tube. This wear scar was a result of repeated contact by previously plugged neighboring tubes that were in a severed or cantilevered condition.

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As a result of the Ginna and other loose part events, the US-NRC issued Information Notice no 83-24, [Reference 43]. Later, Generic Letter 85-02, [Reference 44] was issued. This was followed by Information Notice No. 88-06, [Reference 45]. All of these documents proyided information regarding the potential for foreign object to affect tube Integrity and also to encourage utilities to keep foreign material out of the S/Gs.

In response to the recommendations and guidance issued by the US NRC, utilities have developed effective FME practices and continue to regularly perform FOSAR in regions of the

generator most susceptible to loose part induced tube wear.

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3.10.4 Object Removed From Inside S/G With Tube Degradation - Active or Inactive Tube

For the condition where a secondary side foreign object has degraded a tube (including degradation resulting from a burst), there are several options available to address the off-nominal condition of the tube. It has been determined that most utilities prefer to install stabilizers in the tubes affected or degraded by the object to preclude the potential for interaction of the degraded tube with any neighboring tubes.

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3.10.5 Potential for a Tube Burst or Severance Due to Loose Parts

As a result of previous operational experience it has been established that there is a potential that loose part induced tube degradation can result in a significant tube leak or burst. However, various industry actions have been performed to mitigate this potential, including application of

appropriate secondary side S/G inspection methods in conjunction with appropriate analytical methods.

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4 ANALYSIS METHODS FOR STABILIZATION

Section 3 summarized the degradation mechanisms for which tubes are plugged, and evaluated their potential to pose a future risk to adjacent active tubes due to severance of the plugged tube. Tubes with a known potential for severance are normally stabilized, regardless of the degradation mechanism. Stabilization is performed by introducing cable stabilizers into the tube. Once the stabilizer is in-place, if the tube were to sever, its motion would be constrained and it would not pose a threat to adjacent tubes. However, there are several types of degradation that have either been routinely analyzed with regard to the need for stabilization (e.g., circumferential cracks) and have been plugged but not stabilized, or have been routinely plugged without consideration of stabilization (e.g., AVB wear). This section discusses analytical methods that are employed to determine when tube stabilization is necessary.

4.1 Analysis Methods for Circumferential Cracking

Tubes with circumferential cracks can experience additional crack propagation after being removed from service. Depending upon the specific characteristics of the crack, it may be possible that a sufficient crack propagation can occur and that a severed tube could be produced. Conservative estimates of the level of additional crack growth that could occur over a given period of time can be made for many of such cases. Before any estimates can be made, the morphology of the crack must be established so that proper estimates of the stress near the crack tip can be made. With these estimates, the degree of susceptibility to tube severance can be determined and a decision made regarding the need to stabilize the affected tube. The following describes the types of crack morphologies generally considered in recent tube stabilization evaluations.

4.1.1 Circumferential Crack Morphologies

Various types of circumferential crack morphologies can exist depending upon the crack initiation mechanism. Primary water stress corrosion cracks are ID originated. Roll transition cracking or cracking associated with dented tube support plates can be ID or OD initiated. In practice it has been observed that the actual morphology of the crack in tubes with circumferential cracking is not a crack where there is clear separation of the tube material along the entire fracture surface. Instead it has been generally found that small ligaments separating portions of the circumferential crack are present. These ligaments provide additional strength margin.

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Crack Location Considerations

Analysis of the potential for additional crack propagation is greatly influenced by the location of the crack along the length of the tube.

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4.1.2 Crack Propagation Mechanisms

Tubes with circumferential cracks can experience additional crack growth even after removal from service via plugging. Any methods that are developed to define stabilization criteria have

addressed, and should continue to address, not only the individual crack growth mechanisms, but also the effects of the interaction between the different mechanisms. The following describes the types of analysis performed that address the individual mechanisms. The combined effects of these mechanisms are considered in a subsequent section

Thermal Cycling / Load-Follow

The general characteristics of a plugged tube would change as a result of a change in the bulk temperature of the tube material.

To define stabilization criteria for tubes with circumferential cracking, an evaluation is necessary to determine the circumferential extent of sound tubing required to ensure that the tubes can withstand the cyclic "load follow" type axial loadings, and the resultant circumferential crack growth which a plugged tube could experience.

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tubes. The crack tip stress intensity is then calculated for an enveloping temperature difference between the plugged and active tubes.

The following assumptions are made to determine the axial stresses in the plugged tube:

1) All tubes are locked at the support plates.

2) The temperature of the plugged tube is the same as the secondary side fluid temperature.

3) The largest temperature difference associated with any given event is typically used to envelope all other thermal conditions. The only exception to this is certain upset events with a small number of occurrences but a much larger thermal stress. These events are considered on an individual basis.

Based on the above, the crack growth due to thermal cycling of the steam generator can be determined.

Flow Induced Vibration (FIV)

The potential for flow induced vibration (FIV) loadings to propagate pre-existing circumferential tube cracks must also be determined. The response of tubes with various size circumferential cracks is evaluated using a combination of linear elastic fracture mechanics and existing computer codes.

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4.1.3 Stabilization Criteria Development

The potential interaction of each of the individual crack growth mechanisms must be considered in order to determine if excessive crack growth can occur in plugged tubes. Any stabilization analysis must consider the interaction of mechanically induced crack propagation resulting from thermal mismatch loadings (load follow type loadings), flow induced vibration loadings and additional potential corrosion induced growth.

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Figure 4-1
Typical Tube Stabilization Map

4.1.4 Identification of Conservatisms

Criteria developed to determine the need to stabilize tubes have been developed using models with various degrees of conservatism in the calculation or the initial assumptions used to develop the model. The following is a list of the types of conservatisms typically included in the analysis models.

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4.1.5 Historical Review of Application of Stabilization Criteria

The stabilization approach described above has been applied at both domestic and foreign utilities since the late 1980's. As a result, there is a relatively large database that can be examined in regard to the applicability of the criteria. Table 4-1 contains a summary of data obtained during the time period of January 1990 through December 1999. This period of time was selected to obtain a representative sample of the use of the stabilization criteria using readily available data. The data in the table do not represent the entire industry experience, but are sufficient to show that this approach has been generally accepted.

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Table 4-1
Summary of Tube Stabilization Criteria Applications
(For Outages Occurring 1990 Through 1999)

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4.1.6 Conclusion

Operating plant data has demonstrated that the circumferential crack stabilization analyses are successful in determining when stabilizers are required for circumferential cracks. The analysis techniques are very conservative, and, at the same time, have eliminated excessive conservatism in the stabilization criteria. Tubes with circumferential cracks that have been evaluated using the

techniques described above do not pose a potential for severance of plugged steam generator tubes in either Westinghouse or Combustion Engineering steam generators.

4.2 Analysis Methods for AVB Wear

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4.3 Analyses for Foreign Objects

Analyses have been performed to determine the proper course of action following a foreign object (i.e., loose part) initiated event where either a leak/burst occurred, or where significant tube wear was noted on a particular tube, but leakage had not yet developed. In many of these cases the proper and most expedient course of action is to plug and stabilize the affected tubes. This is generally considered to be the most prudent action since a properly designed tube stabilizer will prevent even a severed tube from contacting an adjacent neighboring tube.

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4.4 Analyses for Preheater Wear

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Both of these methods have been used to estimate the rate of tube wear for various boundary conditions and flow rates. Through these evaluations it was determined that the tube boundary conditions, (as defined through various parameters such as: baffle plate, shift, tubesheet bow, etc.) could greatly affect the amount of time required to wear a tube down to a minimally acceptable tube wall thickness.

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5
REPLACEMENT STEAM GENERATOR DESIGN – TUBE DEGRADATION SUSCEPTIBILITY

An extensive amount of analyses, tests, and inspections have been performed on operating Westinghouse and Combustion Engineering steam generators. This work has allowed Westinghouse to understand the various tube degradation mechanisms that have affected steam generators. Westinghouse and Combustion engineering have taken the experience gained over the last three decades of generator operation to improve generator designs, materials, and operating and maintenance practices. Each successive generator model has incorporated new designs and materials in order to minimize all known tube degradation mechanisms. This section provides a discussion on replacement generator designs and improvements that have minimized the potential for tube rupture and/or severance.

5.1 Replacement Steam Generator Susceptibility for Continuing Degradation of Plugged Tubes

The relevant operating experience for Replacement Steam Generators manufactured by Westinghouse is derived from those units with design features similar to those of the Model F SG and the Delta series SGs. These plants utilize Alloy 690 TT or Alloy 600 TT tubing.

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Alloy 690 TT has been the material of choice for the replacement SG tubing since 1988, because of its superior corrosion resistance compared to Alloy 600 TT, as demonstrated in laboratory testing of potential candidate tube materials. Based on the test data summarized in Reference 36, Alloy 690 was found to be highly resistant to primary water stress corrosion cracking (PWSCC), and was superior to all other candidate materials tested for corrosion except in one or two extremely aggressive corrosive environments. To date only wear-related degradation mechanisms related to loose parts or foreign objects have been reported for the Alloy 690 TT plants. While the total operating experience with Alloy 690 is limited, approaching 450 plant operating years, compared to that of Alloy 600, it has been essentially flawless to date.

The corrosion-free experience of the Westinghouse replacement SGs renders the likelihood of corrosion related tube plugging very low. Since no features have been added to the replacement SG designs that would lead to additional degradation mechanisms beyond those noted for the first generation SGs, the potential for a tube severance in the replacement steam generators is significantly lower than for the original SGs. However, if it is postulated that specific corrosion degradation mechanisms may occur in the replacement SG, the categorization and ranking of corrosion related degradation mechanisms vis-a-vis tube severance is the same as for the first generation SGs.

Table 5-1
Westinghouse Replacement Steam Generators

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5.2 Steam Generator Tube Wear

As in the original SGs, there are two regions in replacement steam generators that would be considered most susceptible to fluidelastic excitation: The U-bend where the velocities are highest and the top of the tubesheet where there is significant cross-flow and the density is

greatest. Replacement RSGs have been manufactured to reduce susceptibility to all forms of degradation including fluidelastic interactions.

5.3 U-Bend Region

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Significant AVB wear in the replacement RSGs with Alloy 690 TT tubes is extremely unlikely. The first replacement SGs (Turkey Point 3 and 4; Surry 1and 2; Point Beach 1 and Robinson 2) have experienced very little wear at AVBs. The design and manufacturing of the U-bend region and AVB supports was modified from the first generation SG AVB design to eliminate the potential for wear, to the degree practicable. AVB wear was determined to be due to fluid induced tube vibration causing the tubes to impact on the adjacent AVBs. The key parameter for the fluidelastic vibration of the tubes was determined to be the length of the unsupported span of tubing, which by implication demonstrates the effectiveness of the AVBs in supporting the tubes.

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The operating experience for the improved AVB design has been flawless. The initial data points for the effectiveness of the design were derived from first generation SGs that had been modified with replacement AVBs, which developed the improved AVB design philosophy. Very few AVB indications were reported after field replacement of AVBs in the first generation SGs. Factory implementation of the revised design philosophy permitted even better controls on

the remaining AVB/tube gaps than the field replacement. Thus, the second class of replacement SGs are expected to be virtually free from AVB wear over extended operating intervals.

5.4 Top of Tubesheet Vibration

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5.5 Preheater Design Recirculation SGs

The Westinghouse preheater or counter-flow design SGs were subject to flow induced vibration degradation in the early 1980's. Remedial actions were preformed for generators of that type (discussed in Section 3.8). Design features affecting flow characteristics and tube support configurations have been incorporated in new designs to mitigate tube vibration. Note that these features are based on design configurations which have been proven successful in operating steam generators.

5.6 Replacement SGs Conclusions

- Replacement pre-heater SGs designed by Westinghouse incorporate changes in tube supports and flow characteristics in order to mitigate any preheater degradation mechanisms.
- The use of stainless steel TSPs in replacement SGs eliminates the linear corrosion that affected carbon steel TSPs, thereby eliminating corrosion induced tube lockup related to denting at the lower TSPs.
- Replacement SGs remain susceptible to the incidence of loose parts or foreign object wear at the top of the tubesheet.
- Replacement SGs may be remotely susceptible to OD corrosion mechanisms such as SCC, thinning and pitting.
- Circumferential ODSCC and wear are mechanisms that have the potential to produce severance of a plugged tube. Accordingly, the analytical measures employed for the original steam generators are applicable to replacement steam generators, notwithstanding the benefits of their improved materials and design.

6 CONCLUSIONS

This section summarizes, and ranks the degradation mechanisms on the basis of the potential to result in tube failure and/or severance.

6.1 Ranking of Degradation Mechanisms Potential for Tube Severance

This report has identified, and discussed the steam generator tube degradation mechanisms that are applicable to Westinghouse and Combustion Engineering steam generators. Based on operating generator experience, tube testing programs, and analytical evaluations, it is possible to rank these various mechanisms based on potential for causing tube severance in previously plugged tubes. The mechanisms are ranked as High Potential, Medium Potential, and Low Potential. The rankings are summarized on Table 6-1.

6.2 Conclusions

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Table 6-1
Potential for Plugged Tube Severance – All Westinghouse and CE Steam Generators

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