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March 15, 2013

E. Roy Hawkens, Chair
Dr. Anthony J. Baratta
Dr. Gary S. Arnold
Atomic Safety and Licensing Board
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Docket: Southern California Edison Company, San Onofre Nuclear Generating Station, Units 2 and 3, Docket Nos. 50-361-CAL & 50-362-CAL

Re: Fifth Notification of Responses to RAIs

Dear Licensing Board Members:

On December 26, 2012, the staff of the Nuclear Regulatory Commission (NRC) issued Requests for Additional Information (RAIs) to Southern California Edison Company (SCE) regarding SCE's October 3, 2012 response to the March 27, 2012 Confirmatory Action Letter for San Onofre Nuclear Generating Station Units 2 and 3. The "Reply Brief of Petitioner Friends of the Earth" (Feb. 13, 2013) and "Natural Resources Defense Council's Amicus Response in Support of Friends of the Earth" (Jan. 18, 2013) both heavily rely upon RAI 32 as a basis for their arguments that SCE needs a license amendment in order to comply with Technical Specification 5.5.2.11, because SCE's operational assessments (OAs) were performed at 70% power rather than 100% power.

On February 25, 2013, SCE submitted its response to RAI 32. The RAI response (page 6) included the following statement:

> As requested in the RAI, SCE will provide an OA that includes an evaluation of steam generator TTW [tube-to-tube wear] for operation up to the RTP [rated thermal power of 100%]. This OA will be provided to the NRC for review by March 15, 2013. In this OA, SCE will supplement the Intertek OA (Enclosure 2, Attachment 6, Appendix C of the CAL Response Letter) which is based on 'traditional' industry guidelines. The OA supplement

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will demonstrate that the Structural Integrity Performance Criteria (SIPC) and the Accident Induced Leakage Performance Criteria (AILPC) are satisfied for 100% Rated Thermal Power (RTP).

SCE has now submitted the OA at 100% power to the NRC staff. The purpose of this letter is to provide notification to the Licensing Board of this OA, which is provided as Enclosure 1.

Respectfully submitted,

Signed (electronically) by Stephen J. Burdick
Stephen J. Burdick

Counsel for Southern California Edison Company

Enclosure

1. Operational Assessment for 100% Power Case Regarding Confirmatory Action Letter Response (TAC No. ME 9727), San Onofre Nuclear Generating Station, Unit 2 (Mar. 14, 2013)

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of	)	
	)	Docket Nos. 50-361-CAL & 50-362-CAL
SOUTHERN CALIFORNIA EDISON COMPANY	)	
	)	
(San Onofre Nuclear Generating Station, Units 2 and 3)	)	March 15, 2013

CERTIFICATE OF SERVICE

I hereby certify that, on this date, a copy of the "Fifth Notification of Responses to RAIs" was filed through the E-Filing system.

Signed (electronically) by Stephen J. Burdick

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Counsel for Southern California Edison Company

BOARD NOTIFICATION ENCLOSURE 1

SOUTHERN CALIFORNIA
EDISON®
An EDISON INTERNATIONAL® Company

Richard J. St. Onge
Director, Nuclear Regulatory Affairs and
Emergency Planning

10 CFR 50.4

March 14, 2013

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Subject: **Docket No. 50-361**
Operational Assessment for 100% Power Case
Regarding Confirmatory Action Letter Response
(TAC No. ME 9727)
San Onofre Nuclear Generating Station, Unit 2

References:

1. Letter from Mr. Elmo E. Collins (USNRC) to Mr. Peter T. Dietrich (SCE), dated March 27, 2012, Confirmatory Action Letter 4-12-001, San Onofre Nuclear Generating Station, Units 2 and 3, Commitments to Address Steam Generator Tube Degradation

2. Letter from Mr. Peter T. Dietrich (SCE) to Mr. Elmo E. Collins (USNRC), dated October 3, 2012, Confirmatory Action Letter – Actions to Address Steam Generator Tube Degradation, San Onofre Nuclear Generating Station, Unit 2

3. Letter from Mr. James R. Hall (USNRC) to Mr. Peter T. Dietrich (SCE), dated December 26, 2012, Request for Additional Information Regarding Response to Confirmatory Action Letter, San Onofre Nuclear Generating Station, Unit 2

4. Letter from Richard J. St. Onge (SCE) to NRC Document Control Desk, dated February 25, 2013, Response to Request for Additional Information (RAI 32) Regarding Confirmatory Action Letter Response, San Onofre Nuclear Generating Station, Unit 2

Dear Sir or Madam,

On March 27, 2012, the Nuclear Regulatory Commission (NRC) issued a Confirmatory Action Letter (CAL) (Reference 1) to Southern California Edison (SCE) describing actions that the NRC and SCE agreed would be completed to address issues identified in the steam generator tubes of San Onofre Nuclear Generating Station (SONGS) Units 2 and 3. In a letter to the NRC dated October 3, 2012 (Reference 2), SCE reported completion of the Unit 2 CAL actions and included a Return to Service Report (RTSR) that provided details of their completion.

By letter dated December 26, 2012 (Reference 3), the NRC issued Requests for Additional Information (RAIs) regarding the CAL response. SCE provided the response to RAI 32 in a letter dated February 25, 2013 (Reference 4). The response to RAI 32 included the following commitment:

P.O. Box 128
San Clemente, CA 92672

SCE will provide an OA that includes an evaluation of steam generator TTW for operation up to the RTP. This OA will be provided to the NRC for review by March 15, 2013. In this OA, SCE will supplement the Intertek OA (Enclosure 2, Attachment 6, Appendix C of the CAL Response Letter) which is based on 'traditional' industry guidelines. The OA supplement will demonstrate that the Structural Integrity Performance Criteria (SIPC) and the Accident Induced Leakage Performance Criteria (AILPC) are satisfied for 100% Rated Thermal Power (RTP).

In accordance with the above commitment, Enclosure 2 of this letter provides Amendment I to the Intertek OA for the 100% power case.

There are no new regulatory commitments contained in this letter. If you have any questions or require additional information, please call me at (949) 368-6240.

Sincerely,

Deborah J. Lindbeck for

Enclosure: As stated

cc: E. E. Collins, Regional Administrator, NRC Region IV
J. R. Hall, NRC Project Manager, SONGS Units 2 and 3
G. G. Warnick, NRC Senior Resident Inspector, SONGS Units 2 and 3
R. E. Lantz, Branch Chief, Division of Reactor Projects, NRC Region IV

ENCLOSURE 1

Amendment I
Operational Assessment for SONGS Unit 2 Steam Generators for Tube-to-Tube Wear Degradation
100% Power Operation Case

Intertek

AES 13018304-2Q-1
Controlled Document I-8
Revision 0
March 2013

Amendment I

OPERATIONAL ASSESSMENT FOR SONGS UNIT 2 STEAM GENERATORS FOR TUBE-TO-TUBE WEAR DEGRADATION 100% POWER OPERATION CASE

Prepared By

Intertek APTECH
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Sunnyvale, California 94086-4831

Supplier Status Stamp

VPL No: 1814-AG117-M0026	Rev No: 0	QC: N/A
☐ DESIGN DOCUMENT ORDER NO. 800918458		
☒ REFERENCE DOCUMENT–INFORMATION ONLY ☐ VIRP IOM MANUAL		
MFG MAY PROCEED: ☐ YES ☐ NO ☒ N/A		
STATUS - A status is required for design documents and is optional for reference documents. Drawings are reviewed and approved for arrangements and conformance to specification only. Approval does not relieve the submitter from the responsibility of adequacy and suitability of design, materials, and/or equipment represented. ☒ 1. **APPROVED** ☐ 2. **APPROVED EXCEPT AS NOTED** - Make changes and resubmit. ☐ 3. **NOT APPROVED** - Correct and resubmit for review. NOT for field use.		
APPROVAL: (PRINT / SIGN / DATE)		
RE: RICHARD A. COE / [signature] / 3/13/13		
FLS: D. Calhoun / [signature] / 3/13/13		
Other:		

SCE DE(123) 5 REV. 3 07/11 REFERENCE: SO123-XXIV-37.8.26

APPROVAL RECORD SHEET

Report No.: AES 13018304-2Q-1 Rev.: 0 Date: March 2013

Report Title: "Amendment I - Operational Assessment for SONGS Unit 2 Steam Generators for Tube-to-Tube Wear Degradation - 100% Power Operation Case"

Originated By:	Project Engineer	3/12/2013 Date
Reviewed By:	Project Engineer	3/12/2013 Date
Approved By:	Project Manager	3/12/2013 Date
Verified By:	Verifier	12 Mar 2013 Date
QA Approved By:	QA Manager	3/12/2013 Date

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EXECUTIVE SUMMARY

The San Onofre Unit 2 (Unit 2) plant has two new steam generators that replaced the original CE-70 design. The replacement steam generators are MHI Model 116TT1 and began operation in Year 2010. The generators have completed one cycle of operation (Cycle 16) with duration of 1.718 years at power (20.6 months). In the first cycle of operation, the Unit 2 tubing has experienced wear degradation at points of contact with anti-vibration bar (AVB) U-bend supports. There were 4348 indications detected at AVB contact points with a maximum Non-Destructive Examination (NDE) depth of 35%TW found during the end-of-cycle (EOC) 16 tube examinations. To a much lesser extent, wear at tube support plates (TSP) was also detected (364 indications) with a maximum NDE depth of 20%TW.

While Unit 2 was in refueling, San Onofre Unit 3 (Unit 3) had a forced outage due to a leak in one of the steam generators after 338 days (0.926 years at power or 11.1 months). The leak was due to tube-to-tube wear (TTW) at freespan locations within the U-bend region. Tube-to-tube wear in Unit 3 was caused by in-plane motion of tubes within a defined region of the bundle. The in-plane motion was due to conditions that created fluid-elastic instability (FEI) of one or more tubes. Subsequent examination of Unit 2 steam generators specifically looking for TTW revealed two indications in steam generator (SG) 2E089. Because of the generic designs of both units, and the nature of the FEI, the possibility of having further initiation and progression of TTW in Unit 2 is addressed.

This report describes the Operational Assessment (OA) performed for the limiting steam generator (SG 2E-089) in Unit 2 for a simulated population of TTW degradation indications under 100% power operation. The original Unit 2 OA was for reduced power operation at 70%. This report is Amendment I to the original OA. A full description of the 70% power OA is given in Ref. 1.

In Ref. 1, a probabilistic model representing the high-wear region of the tube bundle was used to evaluate TTW for the next inspection interval. Calculated tube burst and leakage probabilities

were obtained by Monte Carlo simulation for initiation and growth of TTW. The results for burst and leakage were compared with the structural and leakage performance margin requirements of Nuclear Energy Institute (NEI) 97-06. The performance standards for assessing tube integrity to the required margins are delineated in the Electric Power Research Institute (EPRI) Integrity Assessment Guidelines (Ref. 2). This assessment established the probability of burst for the worst-case tube due to TTW predicted for the defined high-wear region.

The Unit 3 wear behavior was used to establish the initiation and growth of TTW indications in Unit 2 steam generators. An empirical correlation based on a wear index parameter (measure of the state of wear degradation in each tube) provided the method for scaling the Unit 3 wear behavior to Unit 2. Modifications were made to the original OA model to include a revised TTW growth rate distribution that incorporates the estimated initiation times associated with each occurrence of TTW in Unit 3 steam generators.

Two OA analysis cases were evaluated based on the sizing techniques used to define the Unit 3 TTW depths. Case 1 evaluated the situation where voltage based sizing for Eddy Current Testing Examination Sheet (ETSS) 27902.2 was used to establish the TTW depth distributions and the correlated wear rate with wear index. The results for Case 1 indicate that the Structural Integrity Performance Criteria (SIPC) margin requirements are satisfied for an inspection interval length of 0.94 years at 100% power level. For Case 2, where the TTW depths were resized by AREVA using a more realistic calibration standard, the SIPC margins will be met for an inspection interval length of 1.04 years at 100% power level. The plan for Unit 2 is to operate for an inspection interval of 5 months at a 70% power to provide additional margin to the industry requirements for tube integrity.

Tube burst at 3xNOPD (Normal Operating Pressure Differential) is the limiting requirement for inspection interval length. Therefore, the accident-induced leakage requirements will be satisfied provided that burst margins at 3xNOPD are maintained during the inspection interval.

I.1 INTRODUCTION

An Operational Assessment (OA) is a forward-looking evaluation of the steam generator (SG) tube conditions that is used to ensure that the structural integrity and accident leakage performance will not be exceeded during the next inspection interval. The OA projects the condition of SG tubes to the time of the next scheduled inspection outage and determines their acceptability relative to the tube integrity performance criteria.

San Onofre Unit 2 (Unit 2) OA for the next inspection interval is documented in the original OA (Ref. 1). The original OA was completed for 70% power level using operating parameters for temperature, flow, and normal operating pressure differential (NOPD) for the tubes after plugging (Ref. 1). The degradation mechanism evaluated is tube-to-tube wear (TTW). Tube-to-tube wear is caused by in-plane motion of tubes. The in-plane motion is due to conditions that created fluid-elastic instability (FEI).

San Onofre Unit 2 has two new steam generators that replaced the original CE-70 design. The replacement steam generators are MHI Model 116TT1 and began operation in 2010. The generators have completed one cycle of operation (Cycle 16) with duration of 1.718 years at power. In the first cycle of operation, the Unit 2 tubing has experienced wear degradation at anti-vibration bar (AVB) U-bend supports. Wear at tube support plates (TSP) was also detected during the end-of-cycle (EOC) 16 tube examinations. A schematic illustration of the tube supports, AVBs labeled B01 through B12 and TSPs labeled 01C through 07C on the cold-leg side and labeled 01H through 07H on the hot-leg side, is shown in Figure I.1-1.

This report serves as an amendment to the original OA. The analysis in this report performs an OA for 100% power. Similar to the original OA, probabilistic simulation methods were used. These methods establish the tubing structural and leakage margins following standard industry guidelines. These margins are compared with the structural integrity and leakage performance criteria requirements of Nuclear Energy Institute (NEI) 97-06. The performance standards for assessing tube integrity to the required margins are provided in the Electric Power Research Institute (EPRI) Integrity Assessment Guidelines (Ref. 2). This approach established the probability of burst (POB) for the worst-case tube due to TTW.

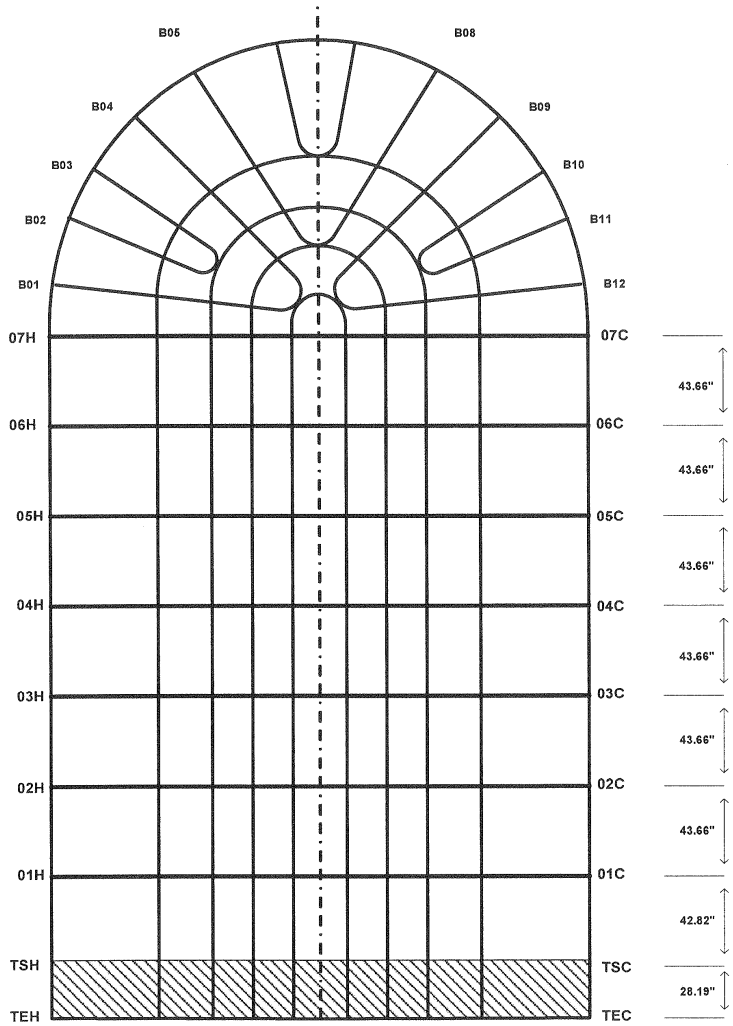

Figure I.1-1 SONGS Steam Generator Tube Support Structure Schematic (Ref. 1)

I.2 STRUCTURAL REQUIREMENTS

An OA projects the condition of the steam generator tubes and establishes the allowable inspection interval over which tube integrity performance criteria will be satisfied. In this OA, the TTW degradation mechanism is evaluated for 100% power operation.

I.2.1 Structural and Leakage Integrity

The structural integrity performance criteria (SIPC) and accident-induced leakage performance criteria (AILPC) applicable to any degradation mechanism including TTW are as follows (Ref. 2):

> **Structural Integrity** — "All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, and cool down and all anticipated transients included in the design specification) and design basis accidents. This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials. Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst or collapse. In the assessment of tube integrity, those loads that do significantly affect burst or collapse shall be determined and assessed in combination with the loads due to pressure with a safety factor of 1.2 on the combined primary loads and 1.0 on axial secondary loads."

> **Accident-Induced Leakage** — "The primary to secondary accident leakage rate for the limiting design basis accident shall not exceed the leakage rate assumed in the accident analysis in terms of total leakage rate for all steam generators and leakage rates for an individual steam generator."

For SONGS, the accident-induced leak rate is 0.5 gallons per minute (gpm) per generator cumulative for all degradation mechanisms.

The acceptance performance standard for structural integrity is (Ref. 2):

> The worst-case degraded tube shall meet the SIPC margin requirements with at least a probability of 0.95 at 50% confidence.

The worst-case degraded tube is established from the estimation of lower extreme values of structural performance parameters (e.g., burst pressure) representative of all degraded tubes in the bundle for a specific degradation mechanism.

The acceptance performance standard for accident leakage integrity is (Ref. 2):

> The probability for satisfying the limit requirements of the AILPC shall be at least 0.95 at 50% confidence.

The analysis technique for assessing the above conditions for TTW is a fully probabilistic assessment of the Unit 2 steam generators.

I.2.2 Assessment Overview

A probabilistic OA involves the analytical evaluation of inspection data in conjunction with a structural (burst) model for comparing the likelihood of tube burst with the SIPC margin requirements. Through-wall leakage probabilities must satisfy the accident-induced leak rate limits. An allowable inspection interval is established by demonstrating the SIPC and AILPC standards will be satisfied for the inspection interval.

For the probabilistic OAs for TTW degradation, the probability of detection (POD), the wear rate, and initiation function for creating new wear indications are explicitly treated by statistical distributions for direct input to the structural model. In addition, distributions for tubing strength and relational uncertainties on the tube burst model are addressed in accordance with industry guidelines.

The OA for TTW is performed with a single-cycle model applied to a defined region where TTW is assumed active. The models for TTW initiation and the determination and assignment of TTW growth rates are critical input variables to the OA.

I.2.3 Probabilistic Model

A Monte Carlo simulation process was used to solve the probabilistic model for TTW. The simulation process is shown in Figure I.2-1, which illustrates one Monte Carlo trial. The probabilistic model includes TTW initiation, growth, and structural integrity analysis for the degraded tubes projected to the next inspection. Tubes that have been preventatively plugged based on wear patterns and other attributes have been removed from the population. This includes Tubes R113 C81 and R111 C81 in SG-2E089 with detected TTW. The population of tubes at the start of the next inspection interval includes inservice tubes that have detected AVB and TSP wear and tubes with No Detectable Degradation (NDD) within the high wear region.

Wear degradation of the steam generator tubing is simulated in the model for the population of indications in the high wear region. The attributes assigned to each degraded tube are the depth and length of the indications, material properties, and the degradation growth rate. These parameters are treated randomly and the calculation of burst pressure is made for each indication in the population.

The major steps in the process are:

1) TTW initiations are predicted based on the wear degradation state. This is accomplished with the total wear index parameter calculated from existing AVB and TSP wear. The initiation of TTW and initial depth is based on total wear index values calculated during operation as a result of further growth of AVB and TSP wear.
2) Attributes are randomly defined for each degraded tube for a single trial representing one inspection interval. These include tube strength properties, the TTW degraded length, and the TTW indication shape factor. The population of degraded tubes at the beginning of the inspection interval contains the tubes with potential undetected TTW.
3) Growth of the TTW degradation for the inspection interval is established by sampling from the Unit 3 wear rate distribution dependent on the total wear index at the time of initiation. The TTW growth model differs from the version used in the original OA (as

discussed in section I.4.8). The size distribution of the TTW degradation is defined in this step.

4) The population of TTW indications is evaluated for burst pressure and leakage at the end of the inspection interval. The degraded tube with the lowest burst pressure is recorded for each trial to establish the distribution of worst case values for comparing with the SIPC margin requirements and acceptance standards. Likewise, the leakage probabilities for each trial are recorded to determine the 95% probability with 50% confidence (95-50) leak rate for comparison with AILPC.

The simulation process generates a record of the results of all trials performed from which overall burst and leakage probabilities are calculated and appropriate distributional information obtained.

The OA methodology is discussed in Sections 3 and 5 of the original OA. The same fully probabilistic modeling approach and numerical algorithm was followed for computing tube burst probabilities for TTW degradation.

I.2.4 Tube Burst Model

TTW indications are characterized by axial volumetric degradation with limited circumferential extent. The burst pressure for TTW is computed from the burst relationship for length and depth dimensions of axial wear given in Ref. 3:

$$P_b = 0.58(S_y + S_u)(t/R_i)\left[1 - \frac{L(d/t)}{L+2t}\right] + 291\,\text{psi} + Z\sigma_B \qquad \text{(I.2-1)}$$

where:

P_b is the estimated burst pressure
S_y is the yield strength
S_u is the ultimate tensile strength
t is the wall thickness
R_i is the tube inner radius

L is the characteristic degradation length

d is the characteristic wear depth

d/t is the fractional normalized depth

Relational uncertainty in Eq. I.2-1 is represented by the standard normal deviate, Z, ($-\infty \leq Z \leq \infty$), and σ_B, the standard error of regression (σ_B = 282 psi). The burst equation, when used with the structural significant dimensions (L_{ST} and d_{ST}), produces consistently conservative burst pressure estimates compared with tube burst data (Ref 3).

I.2.5 Leak Rate Calculation

Leakage predictions for wear-related degradation are subject to large uncertainties. Wear profiles at incipient leakage can vary significantly from simple slits to large holes caused by the blowout of thin membranes. For these situations, absolute leakage rates are not generally computed. Rather, the probability of through-wall penetration is established from projected maximum depths and ligament rupture calculations. A ligament rupture is where the indication pops through the remaining wall without causing tube burst. For TTW, leakage at limiting accident conditions (i.e., main steam line break) will not be controlling on inspection interval length. The depths required for burst at SIPC are much smaller (bounding) than the depths necessary to produce ligament rupture (pop-through) events under accident pressures. SIPC is therefore the controlling criteria.

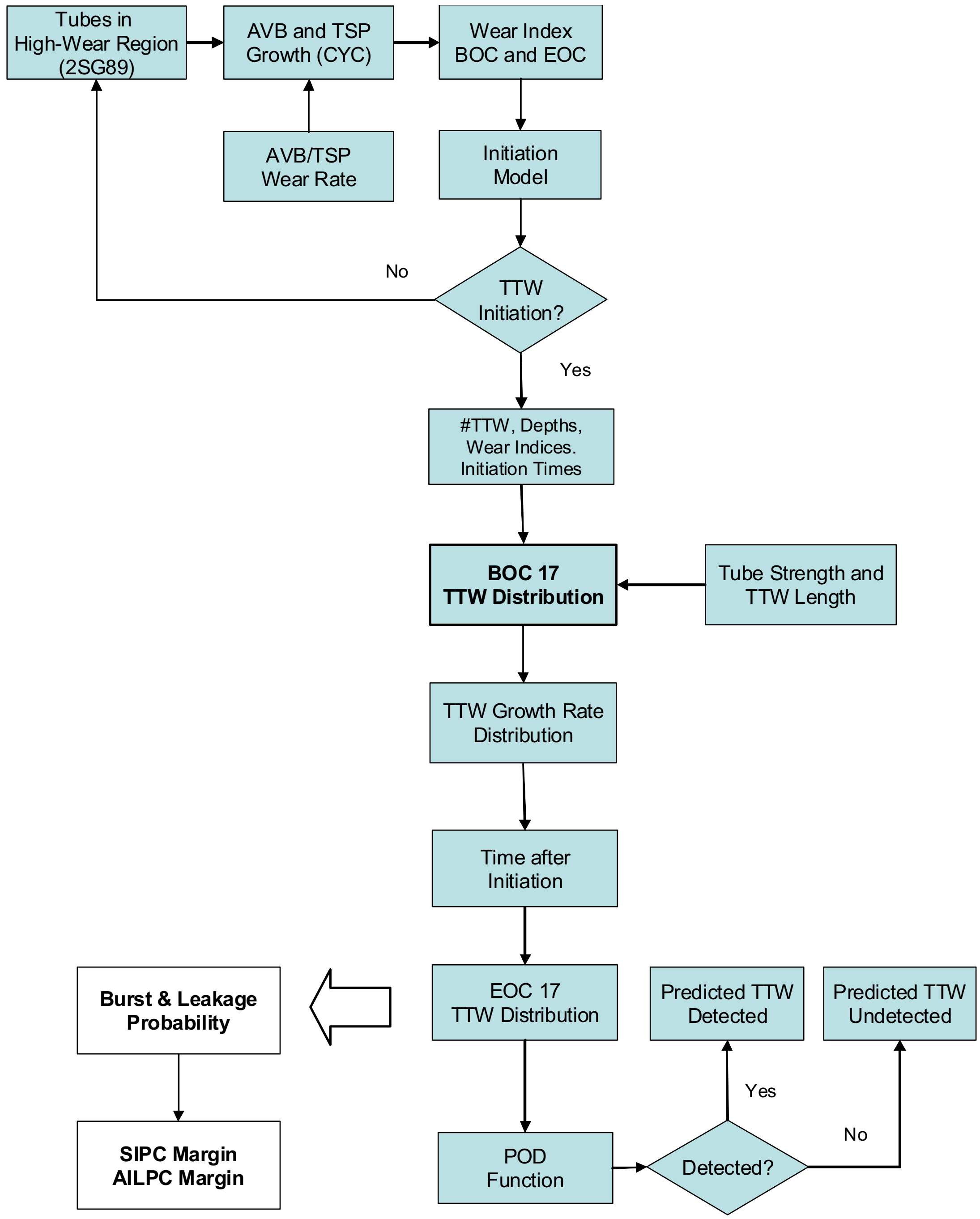

Figure I.2-1 — Operational Assessment Logic Flowchart (One Monte Carlo Trial Illustrated)

I.3 ASSUMPTIONS AND CONDITIONS

The following are the major assumptions and analysis conditions used in this and the original OA model for TTW and input parameters:

1) TTW is analyzed as a stochastic process of independent events based on the state of tube support wear degradation of each individual tube in the high wear region at any point in time during the inspection interval.
2) The critical region for evaluation is assumed as a box area defined by Rows 70 to 140 and Columns 60 to 120. This region bounds the high-wear region in the U-bends.
3) The state of wear degradation at tube supports for a given tube is assumed to be characterized by the summation of NDE depths at AVBs and TSPs wear locations. This is defined as the “wear index” for a degraded tube. This is the same index definition as used in the original OA as described in Ref. 1.
4) The Unit 3 data for TTW is used to define the likelihood of initiating TTW and what will be the TTW growth rate. These data are used to establish the probability of initiation and growth of TTW in Unit 2 through the wear index parameter.
5) The wear rate is based on constant growth on depth rather than constant wear volume basis. This assumption is conservative since wear generally evolves on a constant volume rate basis where the rate of change in depth will decrease as wear progresses.
6) It is assumed at the start of Cycle 17, that any tube within the high wear region can initiate TTW including tubes with no detected support wear at the beginning of the cycle. This is a conservative assumption.

A key analysis condition in the probabilistic model is a measurable amount of AVB and TSP wear precedes tube instability and subsequent tube-to-tube contact.

The assumptions and conditions below are used only in this OA:

1) A variable non-zero initiation-time analysis is used to establish TTW growth rates.
2) The NOPD for Cycle 17 is based on T_{COLD} restoration implementation with 3% plugging.

I.4 ANALYSIS INPUT PARAMETERS

The input parameters for the OA for TTW by fully probabilistic methods are discussed in this section. Much of this information is given in the original OA but is summarized below for completeness.

I.4.1 Tubing Properties

Each Unit 2 steam generator has 9727 tubes. The steam generator tubing has an outside diameter of 0.75 inch and a nominal wall thickness of 0.043 inch. The tube material is Alloy 690 thermally treated (A690 TT). The mechanical properties corrected to a temperature of 650°F were provided by AREVA with the following parameters for $S_y + S_u$:

Tubing Yield plus Ultimate Strength Values (psi)

Parameter	S/G 88	S/G 89
$S_y + S_u$ (mean)	115,361	116,633
$S_y + S_u$ (St. Dev)	2,023	2,504
$S_y + S_u$ (min)	108,700	109,900
$S_y + S_u$ (max)	121,600	123,900

These values were obtained from the certified material test report (CMTR) data sheets for the supplied tubing. A plot of the distribution is shown in Figure I.4-1.

I.4.2 Operating Parameters

Tube pressure differential under normal operating conditions during Cycle 16 was 1430 psi (Ref. 4). The operating conditions assumed for the next cycle of operation for 100% power conditions after plugging are listed below (Ref. 5).

Cycle 17 Operating Parameters

Parameter	100% Power
Thermal power (MWt)/SG	1729
T_{Cold}, (F)	550
RCS pressure, (psia)	2250
Steam pressure, (psia)	926
NOPD, (psi)	1324

Note: NOPD with T_{COLD} restoration implemented at 100% w/3% plugging

Three times normal operating pressure (3xNOPD) for the inspection interval is 3972 psi. For accident conditions, maximum steam line break pressure is assumed at 2560 psi (Ref. 1). The limiting SIPC requirement is 3xNOPD.

I.4.3 Degradation Characterization

Tubes assumed to be susceptible to TTW are located in the high wear region. Wear patterns for AVB and TSP wear were within a region of tubes defined by rows 70 to 140, and columns 60 to 120. The table below shows the nature of degradation within the defined high-wear region.

Summary of Degraded Tubes in the SG 2E-089 Steam Generator High Wear Region at BOC 17 (Ref. 1)

Description (High Wear Region)	SG 2E-089
Total Number of Tubes	2121
Tubes Plugged*	211*
Number of TTW Indications	2
Number of AVB Indications	2537
Number of TSP Indications	90
TSP Indications with No AVB wear	11
BOC Tubes with Wear Degradation	560
BOC NDD Tubes	1350

***Note:** Three additional tubes were preventatively plugged after the original OA. They were conservatively treated as in-service tubes in this analysis for consistency with the original OA.

Previously undetected wear indications at AVB and TSP supports are randomly assigned to the NDD tubes using the cumulative distributions developed from past observed active wear for SG 2E-089 as shown in Figure I.4-2. Depths for these wear indications are defined by the POD performance for the bobbin probe (see Section I.4.6).

The shapes of the TTW indications were determined by line-by-line +Point™ sizing for Unit 3 tubes. The shape factor parameter (F) is defined as the ratio of maximum depth of the indication to the structural average depth of the indication, d_{MAX}/d_{ST}. The shapes were relatively flat (F=1.0) with long structural lengths. The structural lengths (L_{ST}) as determined by the structural-minimum method using the profile data from Unit 3 is shown in Figure I.4-3 (Ref. 1). The cumulative distribution function (CDF) of these data is fitted to a log-normal model.

I.4.4 State Of Degradation – Wear Index

TTW is assumed to initiate when the tube becomes unstable in the in-plane direction under local fluid-elastic conditions. TTW is analyzed as a random process of independent events based on the state of degradation of each individual tube in the high wear region during the inspection interval. This OA uses wear degradation at tube supports (AVBs and TSPs) as a direct indicator of both the likelihood of occurrence and severity of TTW during the inspection interval.

A key assumption in the probabilistic model is that a measurable amount of AVB and TSP wear precedes tube instability and subsequent tube-to-tube contact.

The total wear index is used to define the state of degradation of individual tubes. The total wear index parameter relates the observed AVB and TSP wear states of each tube in the high-wear region to both TTW initiation and growth rate. The same total wear index model used in the original OA is used in this analysis. The total wear index model is based on the summation of AVB and TSP wear depths in a given tube.

$$\text{Total Wear Index} = \text{AVB Wear} + \text{TSP Wear}$$

$$WI = \sum_{i=1}^{12} [\text{AVB depth}]_i + \sum_{j=1}^{14} [\text{TSP depth}]_j \qquad (I.4\text{-}1)$$

where the total wear index is defined in %TW.

This measure was chosen to capture both the total amount of wear as well as the loss of effective support, both of which are assumed to be precursors to in-plane tube instability and the initiation of TTW for a given tube. The total wear index measures the loss of wall thickness due to the vibratory activity of the tube. This loss of wall thickness can adversely affect support effectiveness from changes in tube to support gaps.

I.4.5 Tube Support Distributions

The model considers two cases which assume additional support wear in tubes located in the high wear region:

1) Tubes with no detected wear that may have low level of wear at tube supports
2) Tubes that have detected support wear but may develop additional wear at tube supports during the next inspection interval

The number of affected supports is reflected in the wear index on a tube-by-tube basis. The number of affected tube supports used in this analysis for Unit 2 is shown in Figure I.4-2.

The Unit 2 data shown in Figure I.4-2 for the number of affected wear locations was used to assign wear at support locations in those tubes with no detected wear in the most recent

inspection. All tubes with no detected wear within the high wear region are conservatively assumed to have wear at an assigned number of AVB and TSP locations at the start of the next inspection interval. The number of tube support locations assigned with AVB and TSP wear is determined by sampling from the cumulative distributions derived from Figure I.4-2. On average, each tube with no detected wear is assigned five tube support locations with wear. Wear depths are assigned at these wear locations based on the POD for the bobbin probe as discussed in Section I.4.6.

For tubes in the high wear region with detected support wear, additional support wear locations were assigned. Operating experience (OE) for a similar replacement steam generator provides data on the evolution of tube support wear after two cycles of operation. The number of additional AVB supports that developed wear in the second cycle of operation depends on the number of first cycle detected AVB wear locations in each tube. The OE data were used in the OA to add AVB wear locations at the start of the Cycle 17 inspection interval using a statistical representation. Since the number of TSP wear locations in the OE data did not increase, only the increase AVB wear locations was modeled in the OA. When new AVB wear locations are added to a given tube, wear is assumed to start at the beginning of the inspection interval from an initial zero depth.

Wear from all AVB and TSP supports (including the newly added AVB support locations) are used in the total wear index for the tube.

I.4.6 Probability of Detection

I.4.6.1 Inspected Population

The probability of detection performance of the bobbin probe demonstrates it is capable of reliably detecting AVB wear, TSP wear, and TTW indications in the U-bend region. The probability of detection for eddy current test techniques has been established from industry data and made available through published Examination Technique Specification Sheet s (ETSS). For ETSS 96004.1, Rev. 13, the POD function is shown as a log-logistic function in Figure I.4-4. For comparison, the POD function for +Point^{TM} inspection (ETSS 27902.2) is also plotted in this figure. The log-logistic model for POD and the parameters for the examination techniques used for support and TTW, are given below:

$$POD(h) = \left[\frac{1}{1 + \exp[A + B\, Log(h)]} \right] \qquad (I.4\text{-}2)$$

Probe	ETSS	Intercept (A)	Slope (B)
Bobbin	96004.1	10.61	-11.20
+Point™	27902.2	14.24	-17.22

where h = d/t and is the degradation depth in % TW. The parameters for ETSS 96004.1 were derived from hit-miss ECT data used to establish the ETSS data statistics.

Tubes within the high-wear region that had significant AVB and TSP wear in Unit 2 had received bobbin probe examination. Subsequent to the Unit 3 inspection findings, supplemental +Point™ inspections were performed in Unit 2 to look for TTW with an improved POD. Two TTW indications were found in SG 2E-089 and no indications were detected in SG 2E-088. The most susceptible group of tubes within the high-wear region has been examined with a more sensitive inspection with an improved POD.

I.4.6.2 Undetected Population

The POD function is used to define the population and depth of the undetected AVB, TSP, and TTW indications at the start of the inspection interval.

For the tubes with no detected wear within the high-wear region, wear sites are assigned at AVB and TSP locations that are assumed to develop wear during the inspection interval (discussed in section I.4.5). The wear depths are defined by the bobbin probe POD performance for an assumed threshold level (POD $\le$ 0.05).

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$$Log_{10}(h) = \frac{Ln\left[\frac{1}{RN\,(POD)} - 1\right] - A}{B} \qquad (I.4\text{-}3)$$

where:

h is the wear depth equal to (d/t), expressed as % TW

POD is the assumed threshold level for NDD (POD $\leq$ 0.05)

RN is a randomly selected number between 0 and 1

A and B are constants (intercept and slope) in the log-logistic function for the bobbin probe POD

The wear depths are determined by a random process with equation I.4-3 used for each assigned support wear location in the 1350 tubes without detected wear. The bobbin probe POD is used in this process.

I.4.7 Tube-To-Tube Wear Initiation

The initiation of TTW was established through an empirical model relating the probability of initiation (POI) for TTW to the total wear index parameter. The same POI model developed for the original Unit 2 OA (Ref. 1) is used in this OA (see Figure I.4-5). This model is based on the total wear index value for each tube within the high-wear region. The total wear index parameter relates the observed AVB and TSP wear states of each tube in the high-wear region to the POI function. Further details on the benchmarking process to obtain the POI model parameters for Unit 2 are discussed in Ref. 1.

The Unit 2 initiation model is implemented such that both the POI and the time when initiation occurs can be established. It is possible undetected TTW may exist in some tubes at the start of the inspection interval or may initiate during the inspection interval. The initiation model includes these possibilities, which are illustrated in Figure I.4-6. In the figure, the total wear index for an example tube at BOC and EOC for the Cycle 17 inspection interval is shown. The initiation of TTW is evaluated using a random process. TTW does not initiate when the combination of the EOC total wear index and the random sample produces a value greater than POI curve.

For cases where initiations are predicted to occur during the inspection interval, the point of initiation is determined by the intersection of the random sample with the POI value for the model function as shown by the “X” on the middle dashed line. In this case, initiation is calculated to occur at a wear index between the inspection interval BOC and EOC values. The initiation time is determined by linear interpolation of the total wear index over time. The TTW

indication is assumed to start growing at the time of initiation with an initial depth of zero and at a wear rate determined from the total wear index value at the time of initiation.

The bottom horizontal dashed line in Figure I.4-6 shows the case when initiation was calculated to occur during the prior inspection interval (Cycle 16). In this case, TTW initiation is determined to have occurred during Cycle 16. Because the tube had no detected TTW at EOC 16, the TTW indication is assumed to continue to grow from the beginning of the Cycle 17 inspection interval. The starting depth is determined by a random selection process from the lower 5% detection level of the +Point™ POD curve, with a wear rate determined from the Cycle 17 BOC total wear index value. The time of growth is the inspection interval length.

I.4.8 Degradation Growth Rates

Wear rates for three mechanisms are required for the OA of TTW. The required wear rate distributions are for AVB wear, TSP wear, and TTW. All wear rates are conservatively based on a constant growth in depth.

I.4.8.1 AVB and TSP Growth Models

The AVB and TSP wear rates are used to evaluate the increase in total wear index for each tube during the inspection interval. The increase in total wear index is due to the individual growth in AVB and TSP wear depths. The wear rates for AVB degradation were developed from Unit 2 EOC 16 NDE data (Ref. 1). The distribution of wear depths at each of the 12 AVB and 14 TSP tube intersections for Unit 2 is shown in Figure 4-8 of the original OA (Ref. 1). AVB and TSP wear rates used in this OA are the same as those used in the original OA.

The wear rate distributions for AVB and TSP wear are shown in Figure I.4-7. The AVB wear rate distribution was developed using conservative wear data (AVBs 4 to 9 as discussed in Ref. 1 for Group 3) from both steam generators. The TSP wear rate distribution uses all the data from both steam generators. The two functions are based on a lognormal statistical model for sampling in the simulation.

I.4.8.2 TTW Growth Model

The TTW growth rates for Unit 2 were developed from the TTW wear depth data observed in Unit 3. To establish TTW growth rates for 100% power operation for Unit 2, a variable initiation-time model was used to estimate the time at which TTW began in each affected tube in Unit 3. This approach differs from that used in the original OA (Ref 1) for 70% power where TTW initiation was assumed to occur at beginning of Cycle 16 for Unit 3 (i.e., zero initiation time). The development of the variable initiation-time model is discussed in Ref. 6.

The results of the variable initiation-time model on TTW growth rate is shown in Figure I.4-8. The two OA cases for ETSS 27902.2 sizing and AREVA resizing model of the TTW depths are discussed in the original OA (Ref 1). The TTW growth rates were calculated and the regression lines shown in Figure I.4-8 for the two sizing cases yields the following parameters for 100% power:

Case	Intercept (%TW)	Slope	Error (%TW)
ETSS Sized	30.565	0.0594	13.93
AREVA Resized	23.072	0.06416	14.16

The residuals from the regression analysis are well modeled by a normal distribution over the range of interest for wear index. The relational error for both regression models is normally distributed with a mean of zero and a standard deviation as given in the above table.

I.4.9 Measurement Uncertainty

Measurement uncertainty for sizing of indications is defined in the ETSS for estimating actual (true) structural parameters (depth and length) from NDE wear size data. The 70% and 100% power OA total wear index was based on NDE measured data for both the correlation and predictive models so that adjusting for measurement error was not required.

The need for including measurement uncertainty was assessed for assigning TTW wear depth and growth rates. Initial TTW depths were assigned at beginning of the interval based on

+Point^{TM} POD which has negligible measurement error. Growth applied during the inspection interval was derived from Unit 3 +Point^{TM} depth sizing (ETSS 27902.2) where the systematic error from linear regression is very small. Therefore, sizing uncertainty is not significant for estimating TTW growth rates.

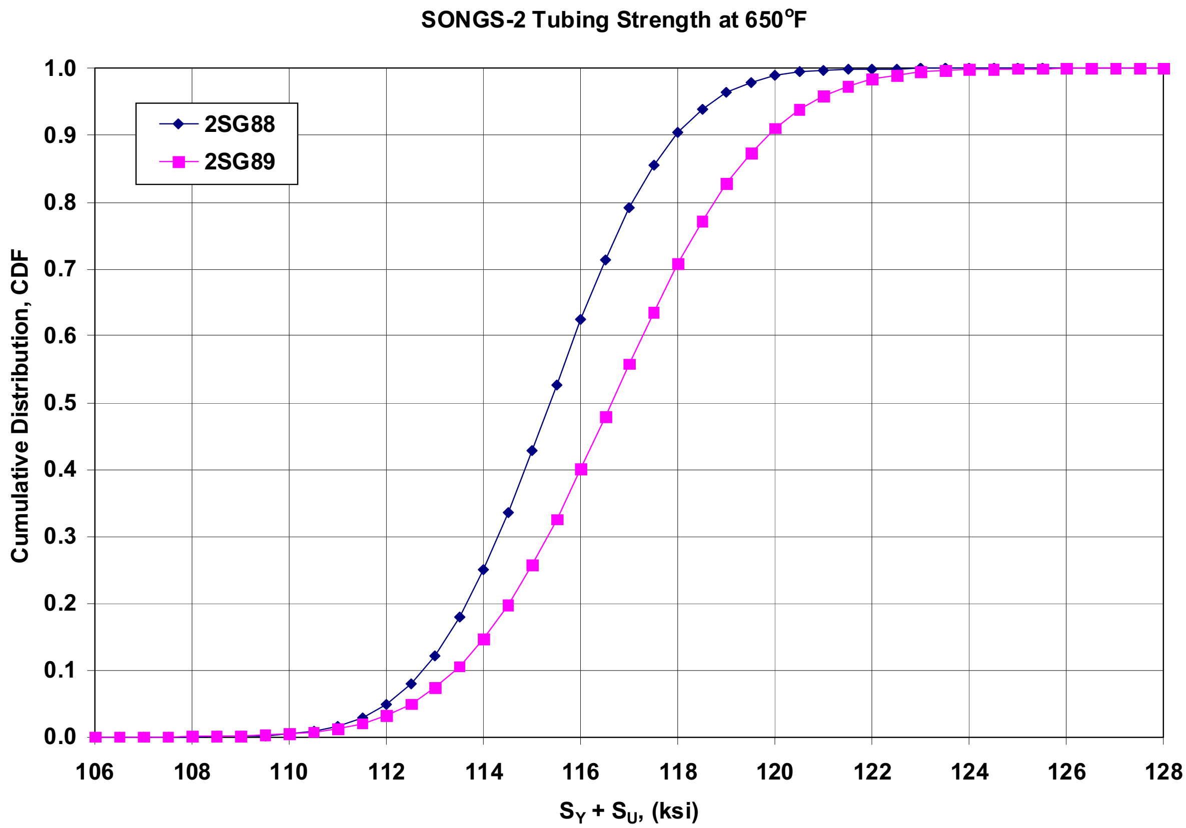
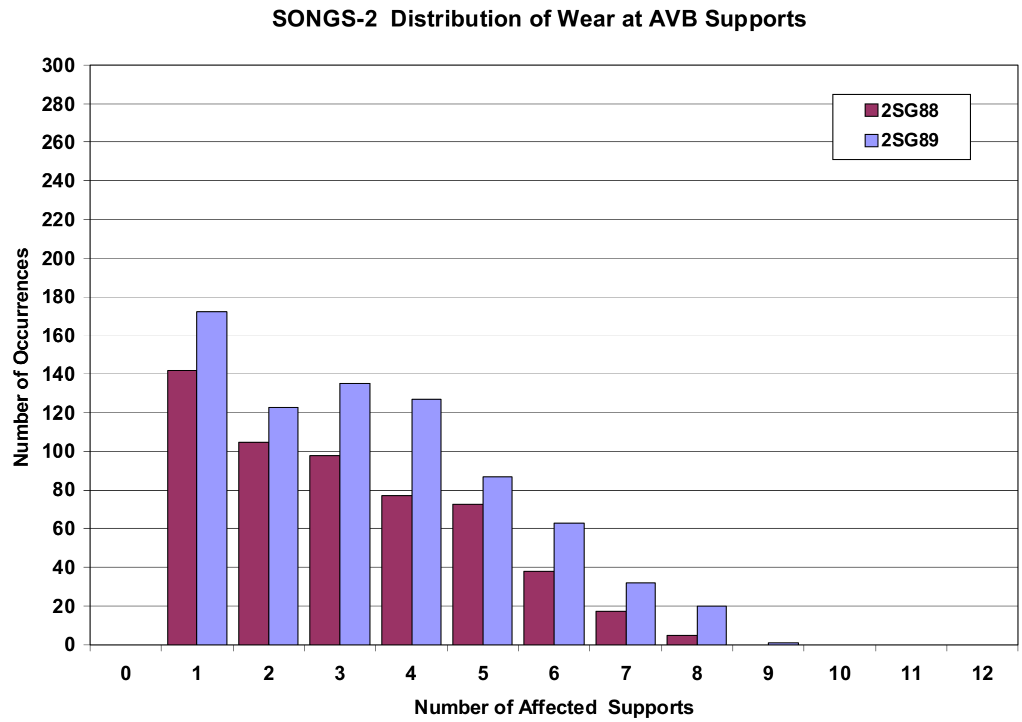


Figure I.4-1 — Distribution of Tubing Strength Properties at 650°F



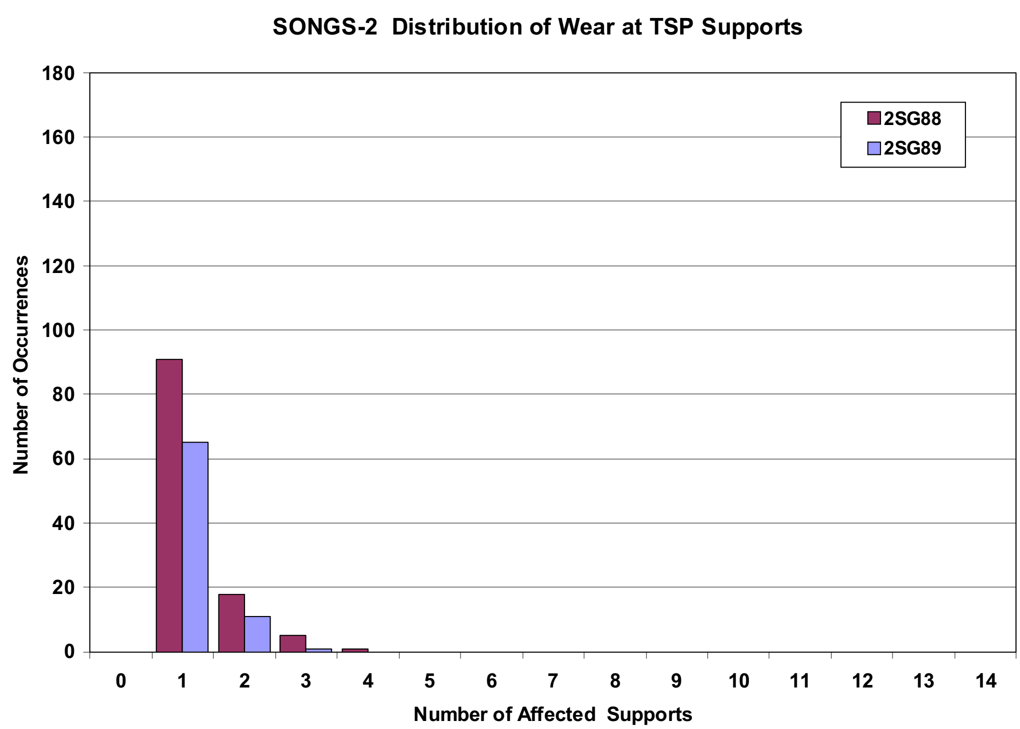


Figure I.4-2 — Support Locations per Tube Exhibiting AVB and TSP Wear in Unit 2

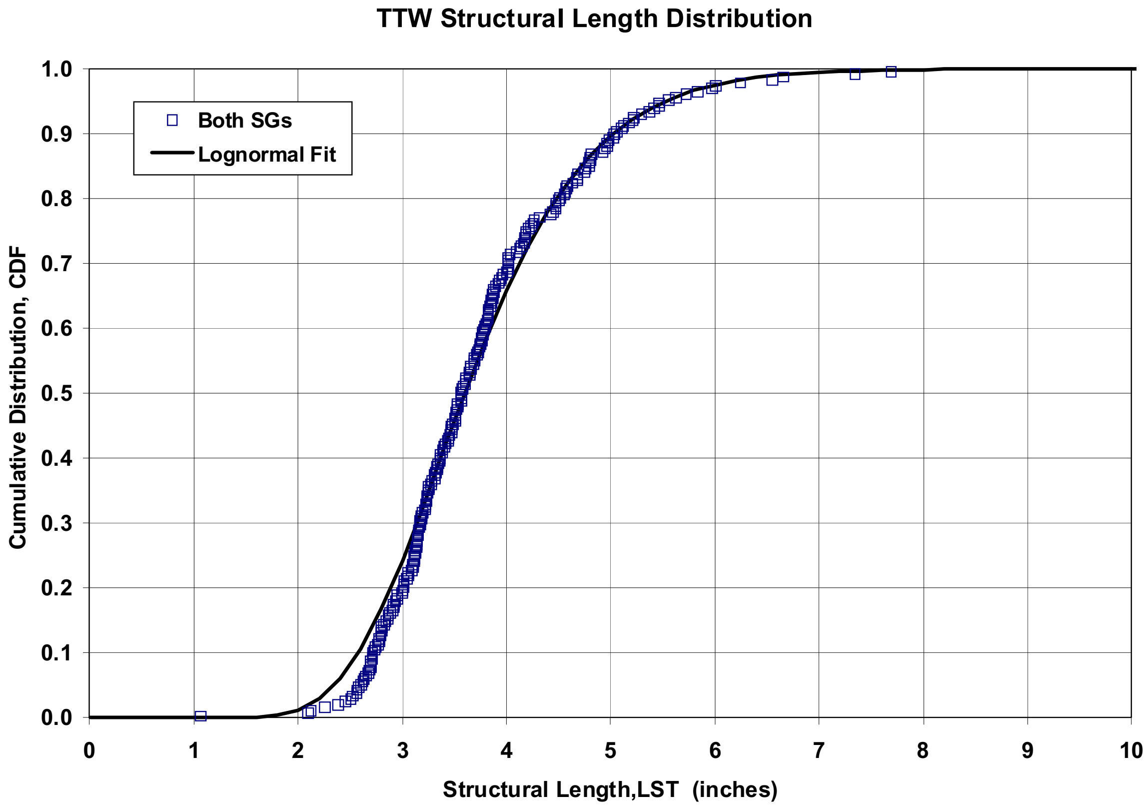


Figure I.4-3 — Structural Length Distribution for TTW in Unit 3

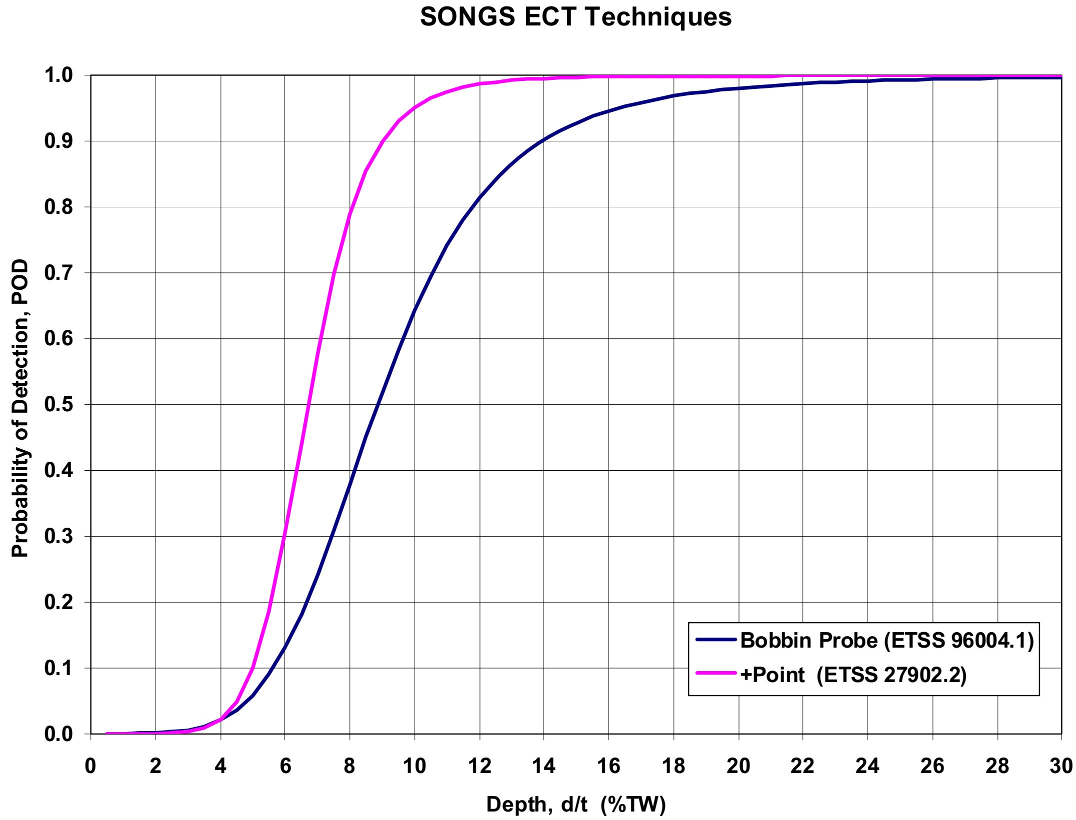


Figure I.4-4— Probability of Detection for Tube Wear

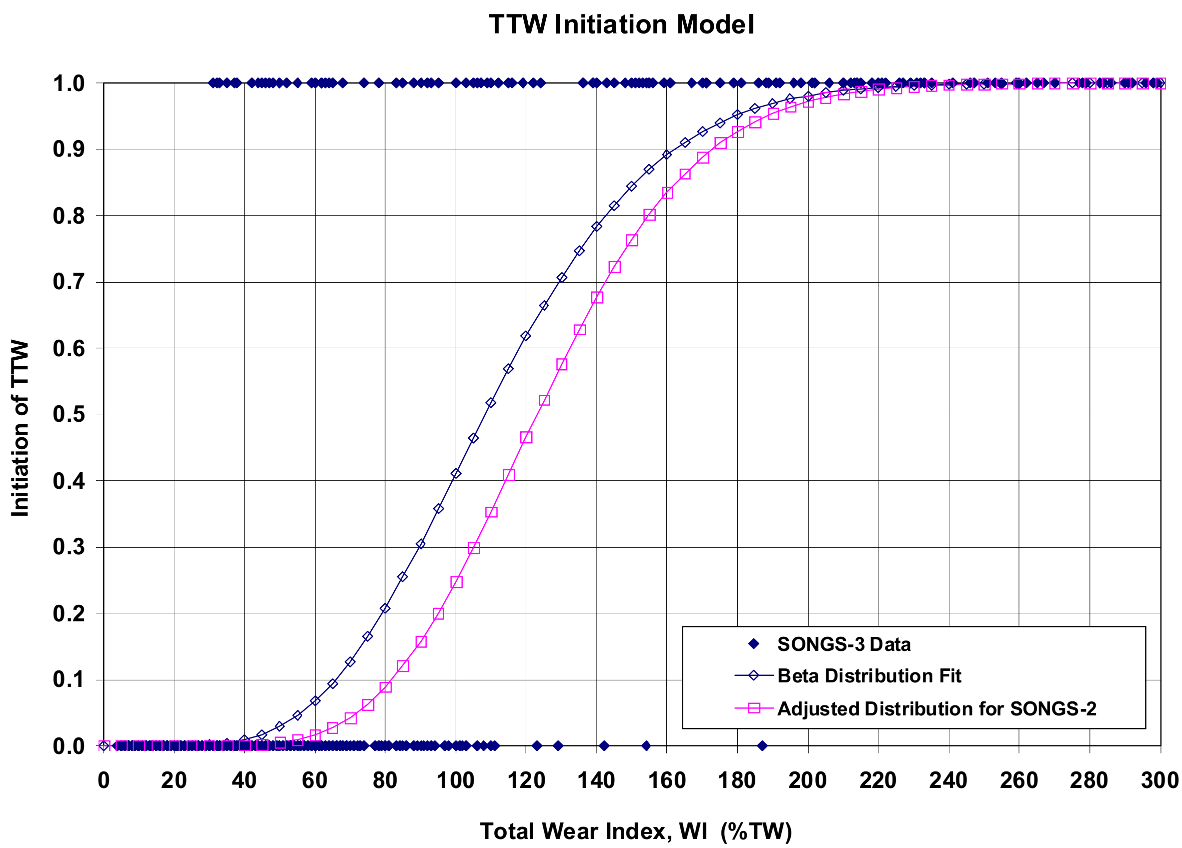


Figure I.4-5— Tube-to-Tube Wear Initiation Model Based on Total Wear Index

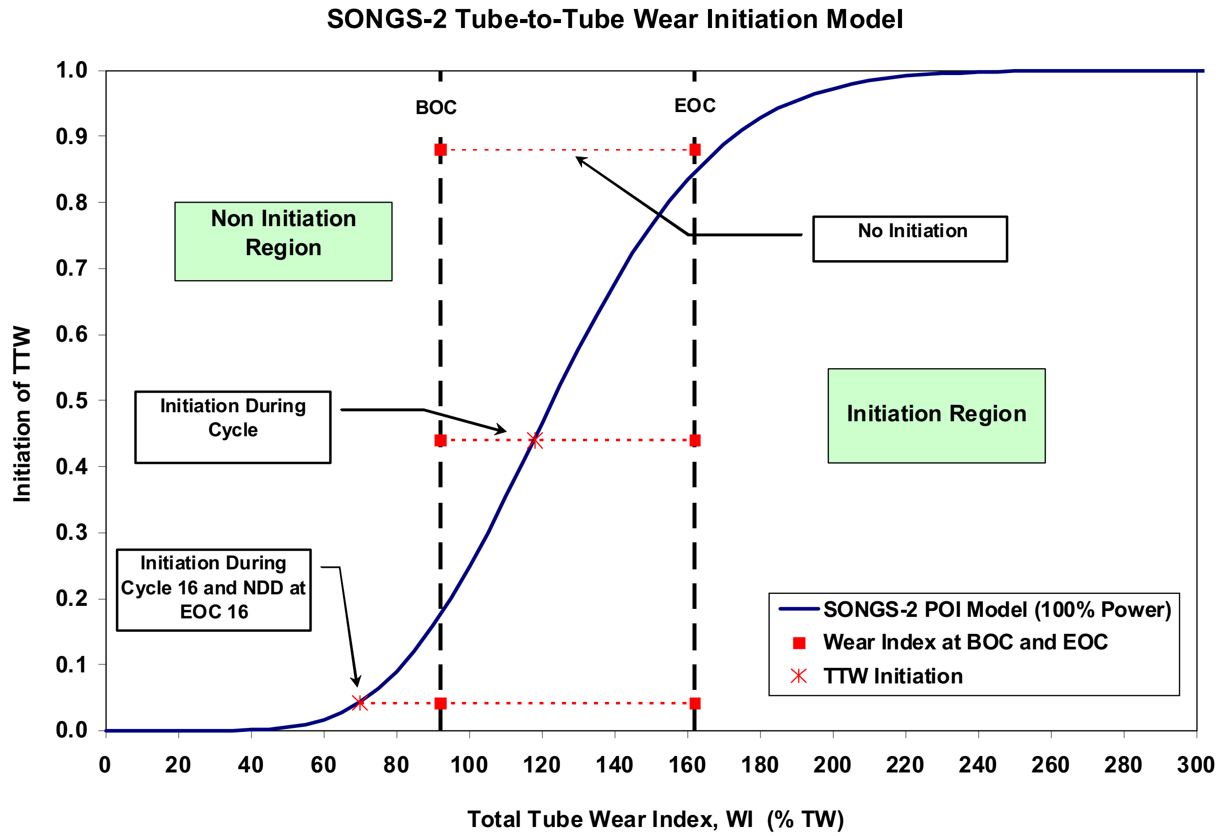
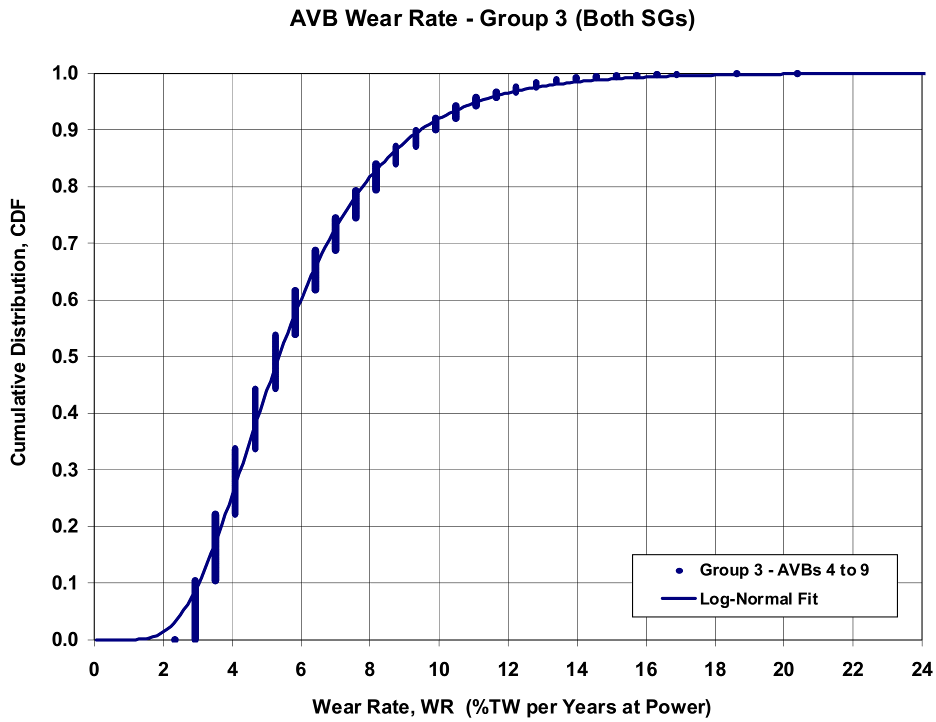


Figure I.4-6 — Illustration of TTW Initiation Model Estimation



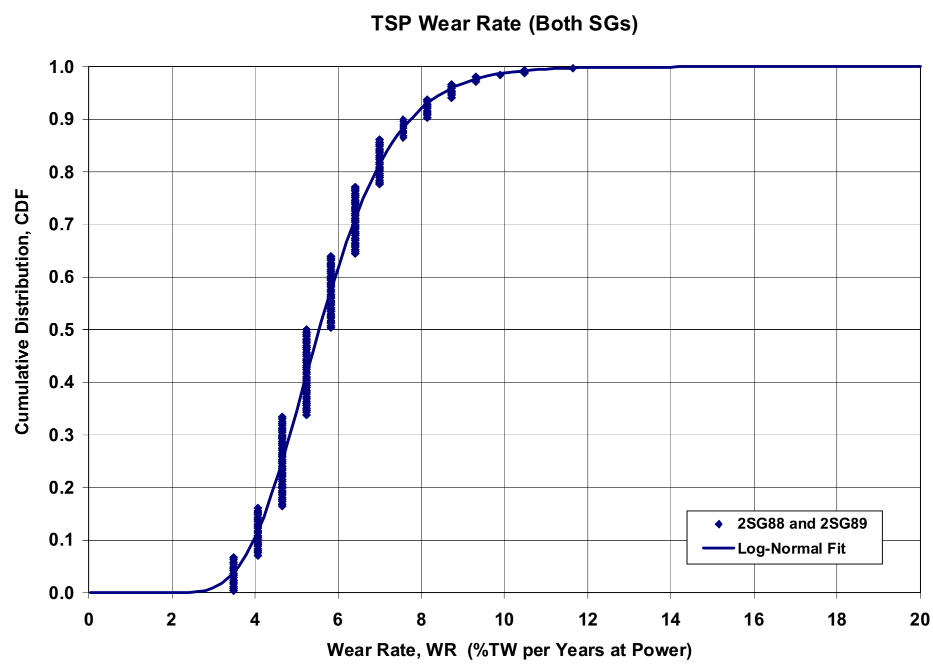
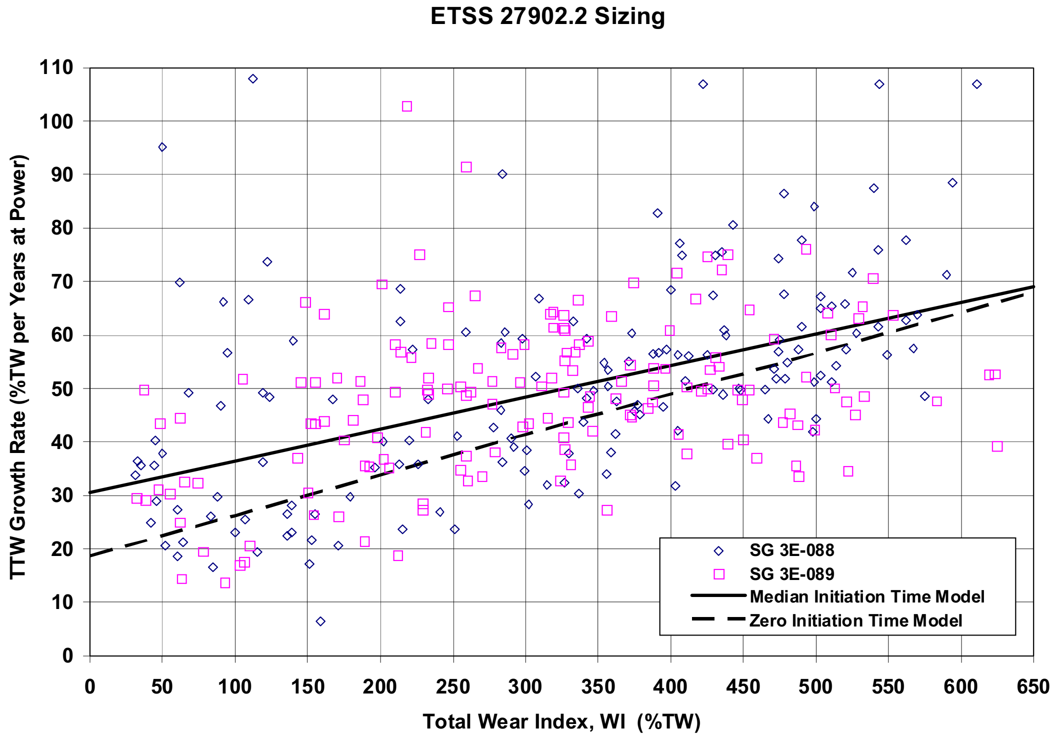


Figure I.4-7 — Wear Rate Distributions for AVB and TSP Wear Mechanisms



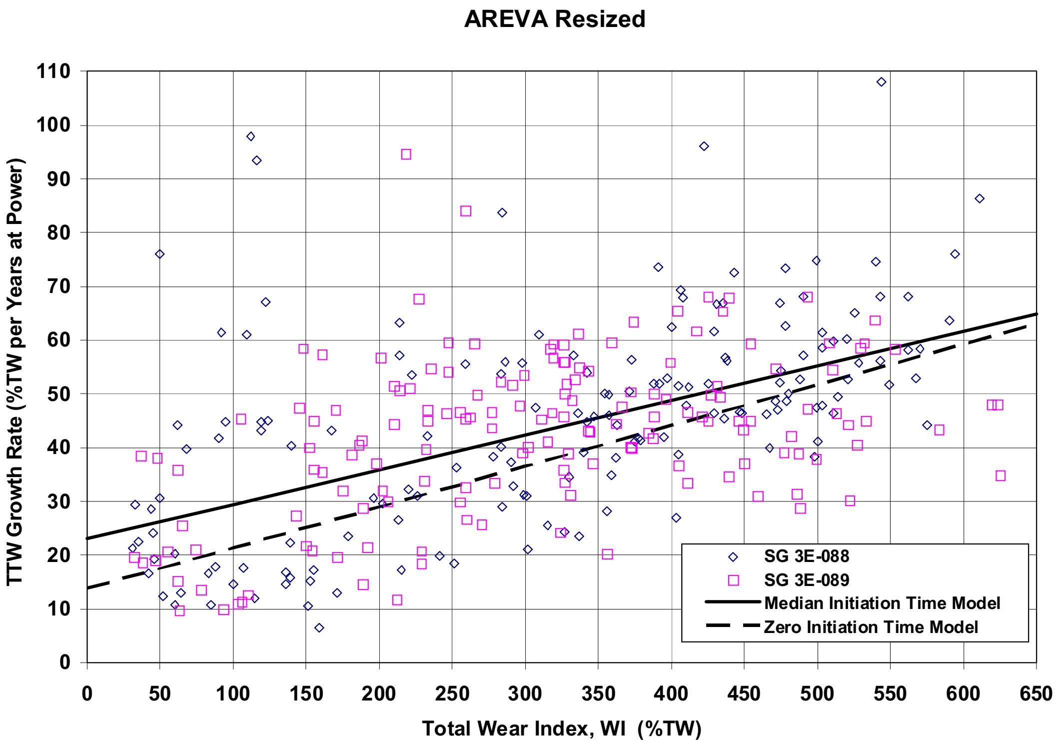


Figure I.4-8 — Tube-to-Tube Wear Rate as a Function of Wear Index

I.5 OPERATIONAL ASSESSMENT

I.5.1 Analysis Cases

The OA for TTW degradation was performed by Monte Carlo simulation with 10,000 trials applied to produce the minimum burst pressure and maximum depth distributions at the completion of the inspection interval. Two cases were evaluated that look at the effect of TTW rate models as described below:

Case 1 – Tube-to-tube wear rate based on the Unit 3 wear depths sized with ETSS 27902.2 (Ref. 1)

Case 2 – Tube-to-tube wear rate based on the Unit 3 wear depths sized with AREVA hybrid voltage model (Ref. 1)

Each case was evaluated for 100% power operation. The planned inspection interval is 5 months.

The NOPD value is 1324 psi and includes 3% plugging and T_{COLD} restoration.

I.5.2 Structural Margin Evaluation

The structural analysis to establish the margins to tube burst was performed for the two analysis cases. The parameters for the input distributions are given in Table I.5-1.

The structural analysis for tube burst was completed for a range of inspection intervals. The POB was determined from the distribution of worst case burst pressures which is compared to the SIPC margin of 3xNOPD. The POB was determined as a function of inspection interval as shown in Figure I.5-1. The performance standard for SIPC margin for the POB for the TTW mechanism is 5%.

The following allowable inspection interval lengths have been computed:

Inspection Interval Lengths at POB = 5%

Analysis Case	Years at 100% Power
Case 1 – ETSS 27902.2 Sizing	0.94
Case 2 – AREVA Resized	1.04

The allowable inspection interval at 100% power is 11 months based on Case 1.

I.5.3 Leakage Evaluation

Due to the long and flat nature of TTW degradation, the tube burst at 3xNOPD is more limiting than the accident-induced leakage criteria. The limiting condition for the inspection interval is based on the SIPC.

Table I.5-1

OPERATIONAL ASSESSMENT INPUT PARAMETERS
TTW FOR Unit 2

Distribution	Type	Parameters	S/G 89 [1]	Basis [2]
Probability of Detection	Log-Logistic	Intercept, A Slope, B	10.61 -11.20	ETSS 96004.1 (Ref. 12)
Probability of Detection	Log-Logistic	Intercept, A Slope, B	14.24 -17.22	ETSS 27902.2 (Ref. 13)
AVB Wear Rate (% TW per Years at Power)	Log Normal	Mean Ln(WR) Std Dev Ln(WR) Max Rate	1.68 0.45 20	Unit 2 (Ref. 6b)
TSP Wear Rate (% TW per Years at Power)	Log Normal	Mean Ln(WR) Std Dev Ln(WR) Max Rate	1.71 0.26 20	Unit 2 (Ref. 6b)
TTW Rate (% TW) [3] ETSS 27902.2	Normal	Intercept Slope Std Dev	30.565 0.0594 13.93	Unit 3 (Ref. 13)
TTW Rate (% TW) [3] AREVA Resized	Normal	Intercept Slope Std Dev	23.072 0.06416 14.16	Unit 3 (Ref. 14)
TTW Initiation Model	Beta	Shape 1 Shape 2	9.839 39.138	Unit 3 (Ref.10a & 16))
Structural Length L_{ST}, (in.)	Log Normal	Mean Ln (L_{ST}) Std Dev Ln (L_{ST})	1.28 0.26	Unit 3 (Ref. 11)
Shape Factor, $F = d_{MAX}/d_{ST}$	Normal	Mean (F) Std Dev (F)	1.00 0.0	Unit 3
Strength, $S_y + S_u$ (psi)	Normal	Mean ($S_y + S_u$) Std Dev ($S_y + S_u$) Min ($S_y + S_u$) Max ($S_y + S_u$)	116,633 2,504 109,900 123,900	Unit 2 CMTR Data SG 2E-089 (Ref. 10b)
Normal Operating Pressure Differential, (psi)	Constant	NOPD at 100%	1325 1305	Unit 2 (Ref. 7 & 9)
Limiting Accident Pressure Differential, (psi)	Constant	LAPD	2560	Unit 2 (Ref. 3)
Inspection Interval Length (Years at Power)	Constant	τ	0.42	SCE RTS Report[4]

Notes

(1) Wear in SG 2E-089 is limiting
(2) Databases for Unit 2 and Unit 3 data and other listed references are from cited references in original OA (Ref. 1)
(3) TTW rates are shown in Figure I.4-8
(4) Return to Service Report (Ref. 8)

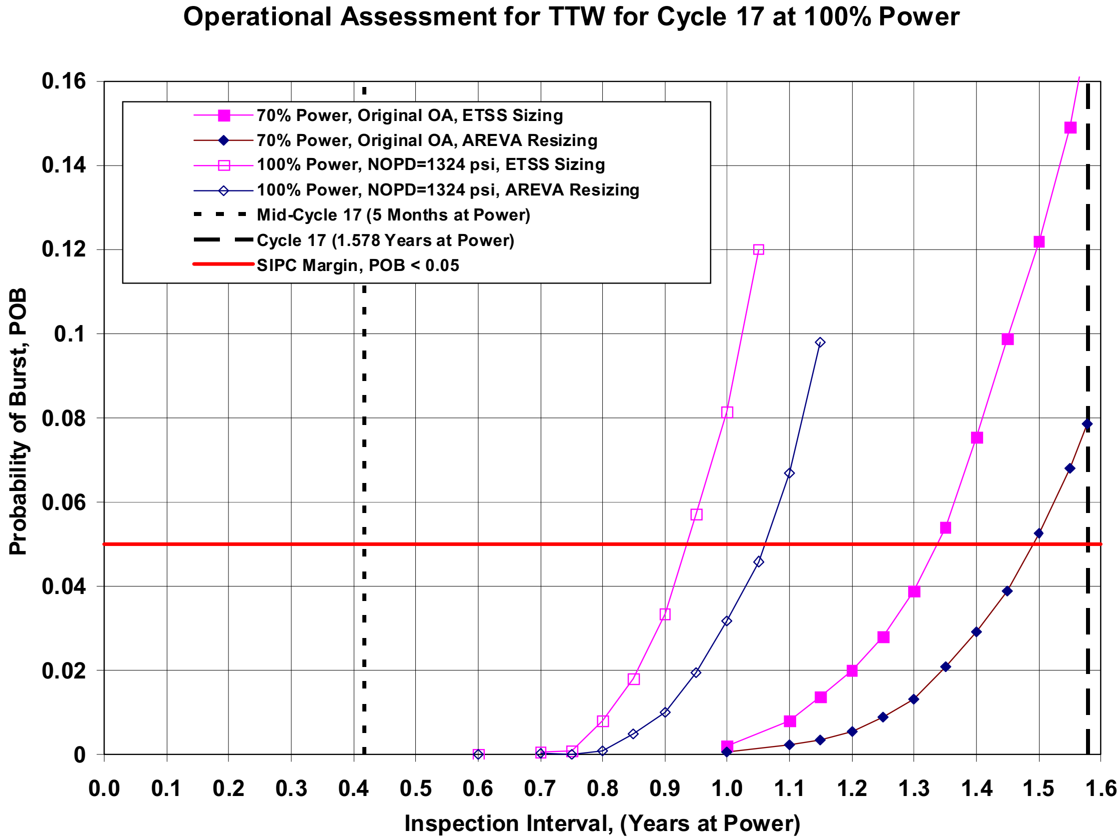


Figure I.5-1 — Probability of Burst at 70% and 100% Power Levels for TTW Growth Rate Models Based on Case 1 - ETSS 27902.2 Sizing and Case 2 - AREVA Resizing Models

I.6 ANALYSIS VERIFICATION AND VALIDATION

A special-purpose computer program called TTWEAR_U2 Revision 1 (R1) was developed to perform the Monte Carlo simulation and required calculations as shown in Figure I.2-1. This program is a revised version of the original program used for the 70% power OA. Verification and validation of TTWEAR_U2 Rev. 1 followed Intertek APTECH Quality Assurance Procedures for computer software and hardware systems as described in Section 3.5 of the original OA report (Ref. 1). The documentation of the verification and validation of TTWEAR_U2 R1 is given in Ref. 7.

I.7 REFERENCES

1. "Operational Assessment for SONGS Unit 2 Steam Generators for Upper Bundle Tube-to-Tube Wear Degradation at End of Cycle 16," Intertek APTECH Report Number AES 12068150-2Q-1, (September 2012).

2. "Steam Generator Integrity Assessment Guidelines, Revision 3," Electric Power Research Institute, Steam Generator Management Program, EPRI Report 1019038, (November 2009)

3. "Steam Generator Degradation Specific Management Flaw Handbook, Revision 1," 1019037, Electric Power Research Institute, Steam Generator Management Program (December 2009)

4. Letter from A. Matheny (SCE) to A. Brown (AREVA), "Numerical Values for the Steam Generator Operational Assessment San Onofre Nuclear Generating Station, Units 2 and 3," (February 8, 2012)

5. "Operating Parameters of Unit-2 RSGs for Various Power Levels after Plugging," MHI L5-04GA602, (January 23, 2013)

6. Calculation-C-8304-3, "initiation Time Model to Determine Tube-to-Tube Wear Rates for Unit 3 – RAI #2," Rev. 2, Intertek Project AES 13018304-2Q, (February 22, 2013)

7. "Verification of Program TTWEAR_U2 R1 for the Operational Assessment for SONGS Unit 2," Calculation No, AES-C-8304-5, Intertek APTECH, (March 2013)

8. Letter from Peter T. Dietrich (SCE) to Elmo E. Collins (NRC), Confirmatory Action Letter-Actions to Address Steam Generator Tube Degradation, San Onofre Nuclear Generating Station, Unit 2, October 3, 2012.

I.8 NOMENCLATURE

Acronym	Description
SG 2E-088	Unit 2 Steam Generator 88
SG 2E-089	Unit 2 Steam Generator 89
SG 3E-088	Unit 3 Steam Generator 88
SG 3E-089	Unit 3 Steam Generator 89
3xNOPD	Three times normal operating pressure differential
95-50	95% probability at 50% confidence
AILPC	Accident Induced Leakage performance Criteria
AVB	Anti-vibration bar
BOC	Beginning of operating cycle
CM	Condition monitoring
CYC	Length of cycle
EOC	End of operating cycle
EPRI	Electric Power Research Institute
ETSS	Examination Technique Specification Sheets
GPM	Gallons per minute
NDD	No degradation detected
NDE	Non destructive examination
NEI	Nuclear Energy Institute
OA	Operational assessment
POB	Probability of burst
POD	Probability of detection
POI	Probability of initiation
QA	Quality assurance
RAI	Request for additional information
RN	Random number
SG	Steam generator

REPORT ACRONYMS (Cont'd)

Acronym	Description
SIPC	Structural Integrity Performance Criteria
SR	Stability ratio
TSP	Tube support plate
TTW	Tube-to-tube wear
TW	Through wall
Unit 2	San Onofre Unit 2 (also SONGS-2)
Unit 3	San Onofre Unit 3 (also SONGS-3)
WI	Total wear index
WR	Wear rate