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FULL BUNDLE PROBABILISTIC ANALYSIS FOR THE EVALUATION OF STEAM GENERATOR TUBE INTEGRITY TO NEI 97-06 REQUIREMENTS

Intertek AIM
R. C. Cipolla (russell.cipolla@intertek.com)
B. W. Woodman
W. K. Cullen

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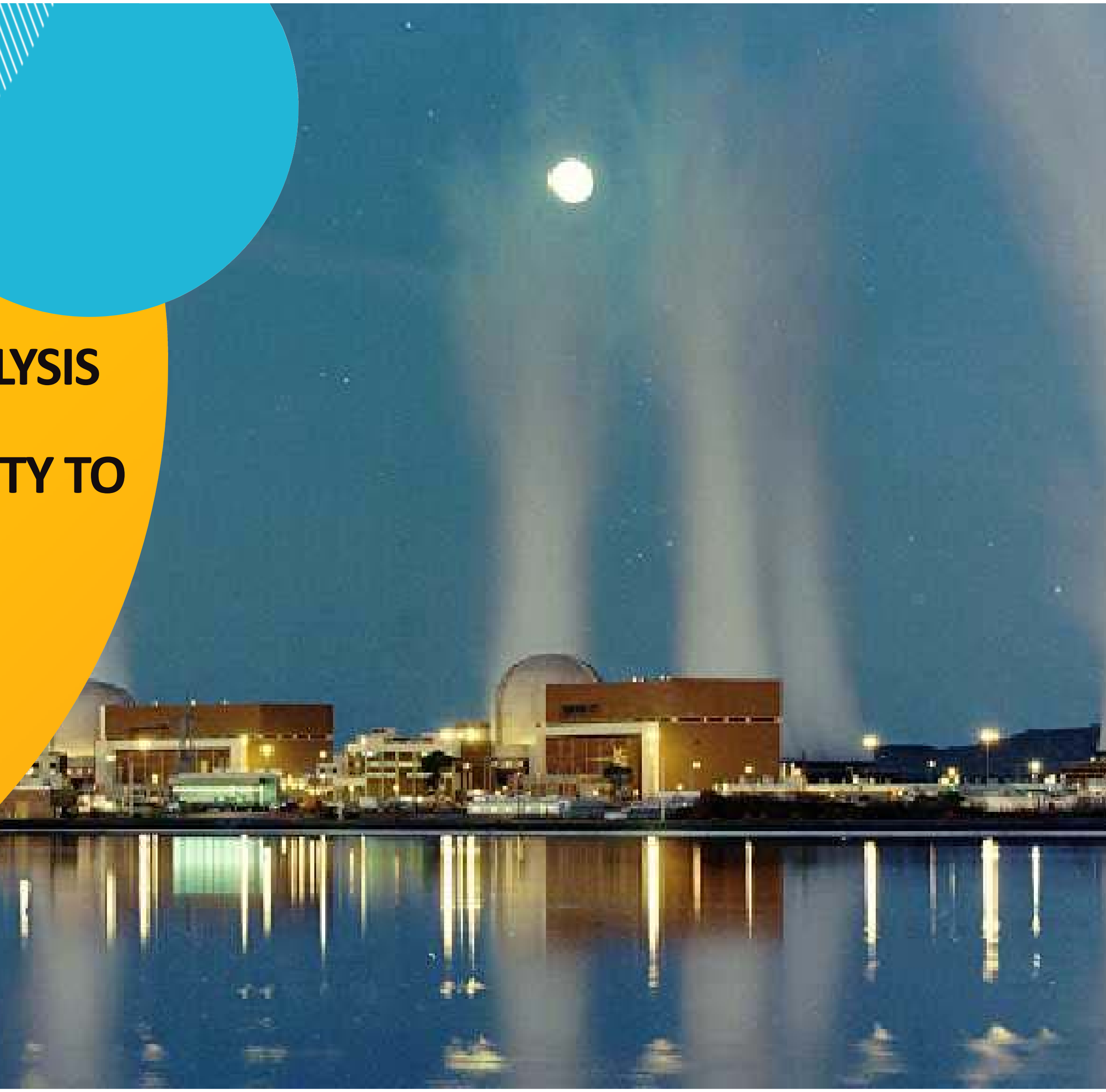

PRESENTATION OUTLINE

1. Introduction
2. Aspects of Tube Integrity
3. Probabilistic Operational Assessments
4. Model Benchmarking
5. Example of Axial ODSCC at Tube Supports
6. Summary and Conclusions

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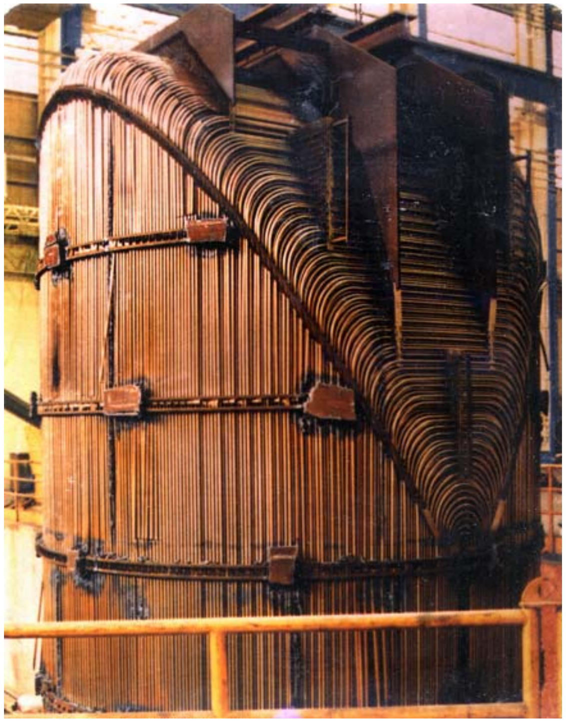
INTRODUCTION

1. INTRODUCTION

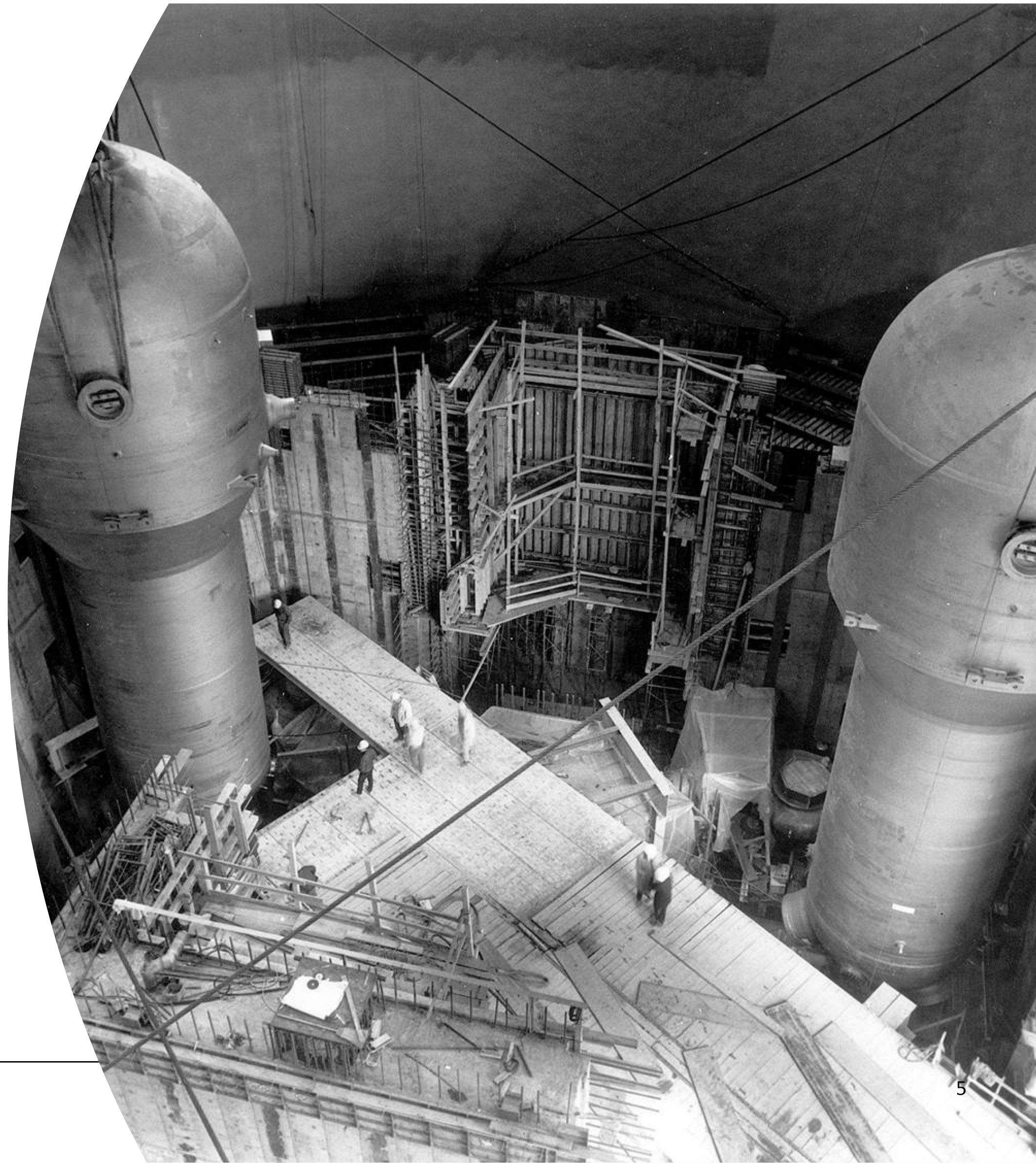
- A significant portion of the reactor coolant pressure boundary is composed of steam generator tubes, whose function is to transfer heat energy from the primary coolant to secondary side of a pressurize water reactor (PWR) power plant.
- The tubing also serves as containment of radioactive water and prevents the release of fission material during postulated accident events.
- Industry document NEI 97-06 establishes a framework for structuring and strengthening existing Steam Generator Programs referred to in steam generator technical specifications.
- All US Licensees have changed their Plant Technical Specifications consistent with NEI 97-06 and its associated regulatory framework.



SG tubing make up a significant portion of the RCPB

1. STEAM GENERATOR TUBE INTEGRITY

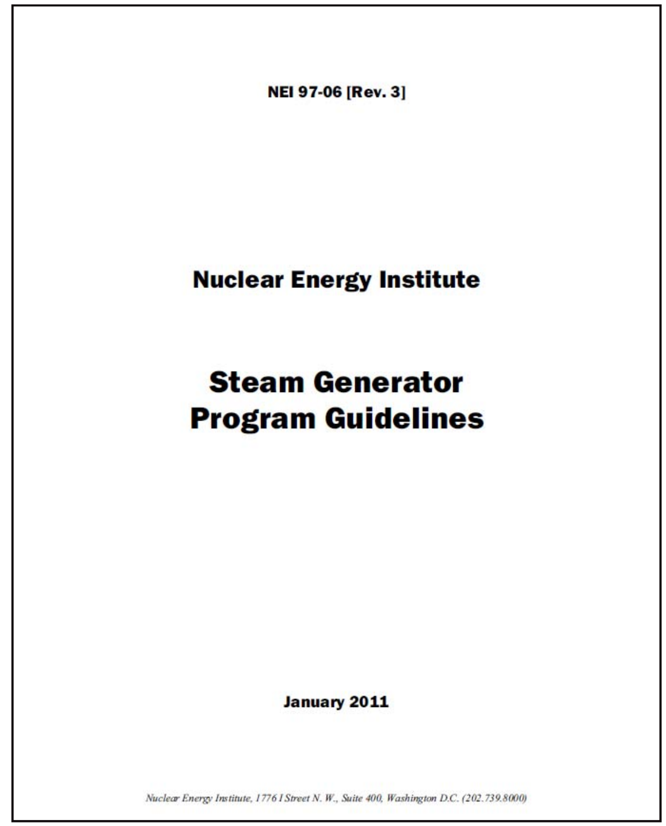
- Tube integrity is maintained under a set of probabilistic acceptance criteria that must be demonstrated on a operating cycle-by-cycle basis
- Objective to prevent excessive leakage resulting in release of radiation to the environment under postulated accident conditions
- Under some circumstances, the assessment for tube integrity requires a fully probabilistic evaluation of the complete tube bundle
- <u>Clear example of the direct application of a probabilistic assessment criteria that govern plant operation</u>



1. REGULATION AND LICENSING BASES

Tube Integrity Requirements

- Title 10 of Code of Federal Regulations Part 50 – General Design Criteria governing the reactor coolant pressure boundary (RCPB)
- US Nuclear Regulatory Commission (NRC) Regulatory Guide 1.121 - Basis for plugging degraded steam generator tubes
- Draft Regulatory Guide DG-1074 – Programmatic framework for tube integrity - deterministic and probabilistic criteria
- Nuclear Energy Institute (NEI) 97-06, Steam Generator Program Guidelines – Framework for improve operability and reliability
- Electric Power Research Institute (EPRI), Steam Generator Management Program - Guidelines and assessment methods (deterministic and probabilistic)
- Plant Technical Specifications – Integrity performance requirements for tube integrity and operational/accident-induced leakage, and allowable inspection intervals


NEI 97-06 [Rev. 3]

Nuclear Energy Institute

Steam Generator Program Guidelines

January 2011

Nuclear Energy Institute, 1776 I Street N. W., Suite 400, Washington D.C. (202.739.8000)

(NRC Adams #ML111310708)

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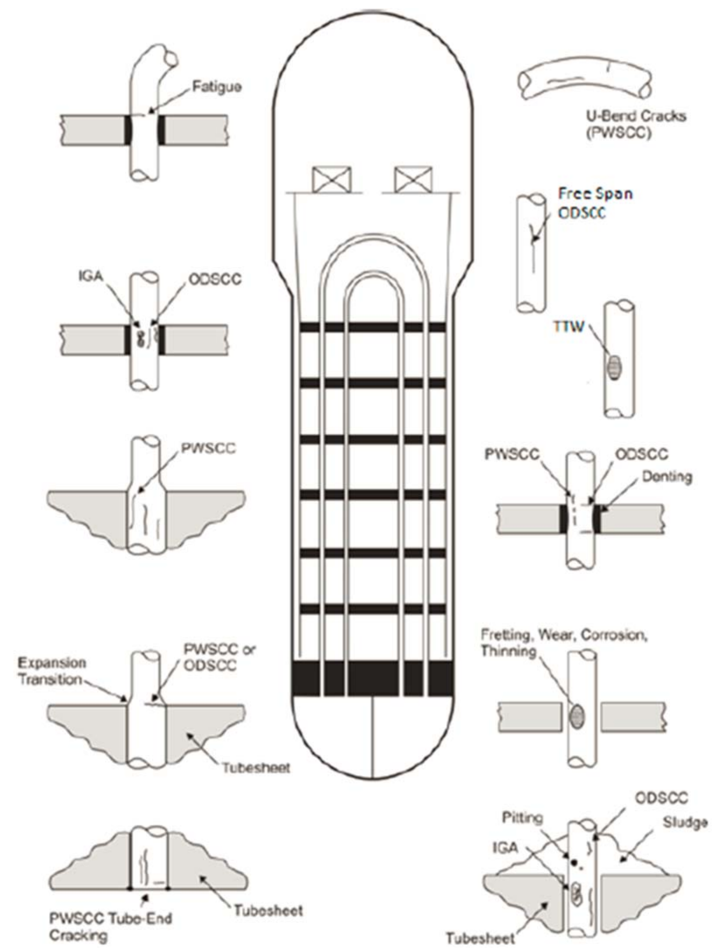
ASPECTS OF TUBE INTEGRITY

2. TUBE INTEGRITY ASSESSMENTS

Degradation Mechanisms

- In general, tube degradation can be categorized as being caused by either **mechanical means** or by **environmental or stress** factors.
- There are many examples of degradation mechanisms that are typically used in integrity assessments and evaluated on an individual basis to the SIPC performance standards.
- These attributes are evaluated collectively to establish the individual degradation mechanisms for integrity assessment purposes.
- Once the degradation mechanisms are defined, calculate the minimum burst pressure for the worst-case tube for each mechanism and compare to the SIPC margin requirements.
- Eddy current test technique is the primarily method used for tube examinations



2. TUBE INTEGRITY ASSESSMENTS

Tube Integrity Criteria Objectives

- Prevention of tube burst/collapse and leakage of degraded tubes
- Maintain ASME Code design margins
- Address important loads affecting tube integrity
- Provide strategies and criteria to evaluate the probability of tube burst or leakage
- Permits analytical evaluations by simplified methods where possible
- Can be verified by in situ pressure testing of SG tubes (experimental verification)
- Establishes the allowable inspection interval

2. TUBE INTEGRITY REQUIREMENTS

General Requirements

- Technical Specifications require that licensees perform periodic in-service inspections of the SG tubing
- Technical Specifications also state the margin requirements for which tube integrity (both burst and leakage) must be satisfied:
    - **Structural Integrity Performance Criterion (SIPC):** defines the margin requirement to prevent tube burst, usually defined as three times normal operating pressure differential under full power steady-state conditions (3xNOPD)
    - **Operational Leakage Performance Criterion (OLPC):** operational primary-to-secondary leakage through any one SG shall be limited to 150 gallons per day.
    - **Accident-Induced Leakage Performance Criterion (AILPC):** primary to secondary accident induced leakage rate for any design basis accident, other than a steam generator tube shall not exceed the leakage rate assumed in the accident analysis (leakage not to exceed 1 gpm)
    - **Performance Acceptance Standards:** defines the conditions under which the SG tubing can be said to meet the SIPC and AILPC margin requirements
- Repair or remove from service all tubes exceeding the tube repair limit.

2. TUBE INTEGRITY CRITERIA AND BASIS

Structural Integrity Performance Criterion (SIPC)

The SIPC provides the margins of safety for tube integrity against tube burst or collapse.

*"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.**"*

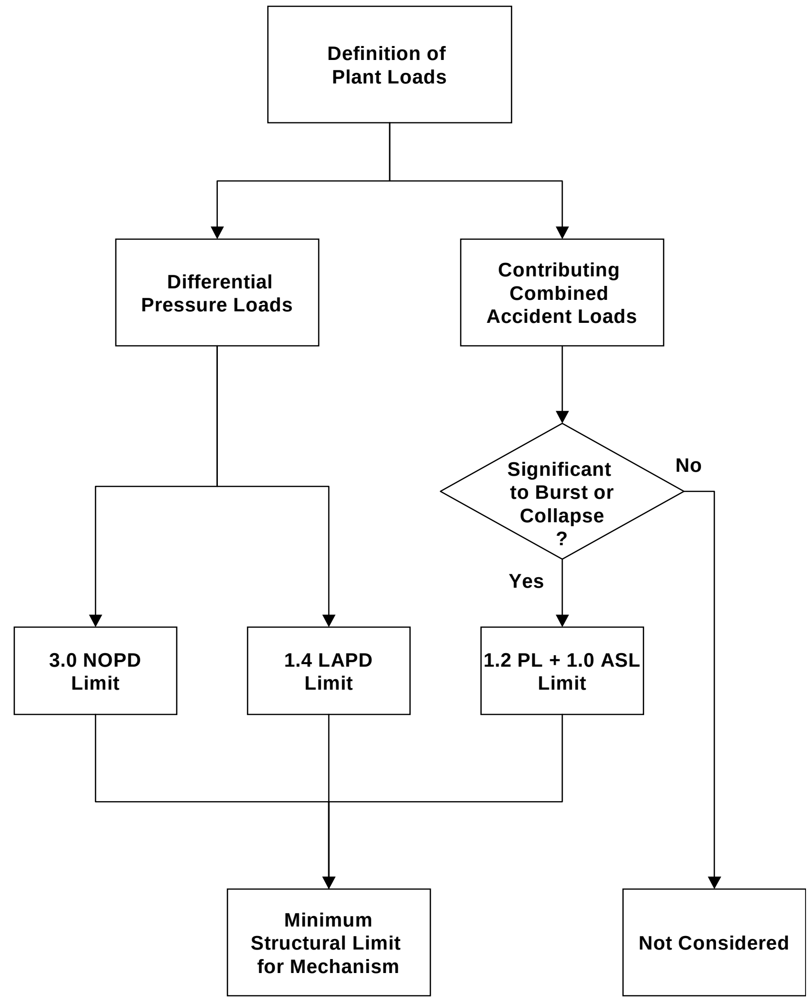
2. TUBE INTEGRITY CRITERIA AND BASIS

SIPC Implementation Logic

Structural limit to satisfy SIPC is minimum limit from three separate margin requirements:

1. 3.0× Normal Operating Pressure Differential (3 × NOPD)
2. 1.4× Limiting Accident Pressure Differential (1.4× LAPD)
3. 1.2× Primary + 1.0× Axial Secondary Loads (1.2× PL + 1.0× ASL)

In most cases, tube integrity is controlled by the 3xNOPD requirement



2. TUBE INTEGRITY REQUIREMENTS

Performance Acceptance Standards

- The acceptance standard for structural integrity:

  The worst-case degraded tube for each existing degradation mechanism shall meet the structural integrity margin requirements with at least a probability of 0.95 at 50% confidence

- The acceptance standard for accident leakage integrity:

  The probability for satisfying the TS limit requirements for accident-induced leakage shall be at least 0.95 at 50% confidence cumulative for all mechanisms

- The worst-case degraded tube for each existing degradation mechanism is established from the estimation of lower extreme values for burst pressure representative of all degraded tubes in the bundle.

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PROBABILISTIC OPERATIONAL ASSESSMENTS

3. OPERATIONAL ASSESSMENTS

What is an Operational Assessment?

- Operational assessment is a forward looking evaluation for tube integrity
- Operational Assessment involves projecting the condition of the SG tubes during plant operation to ensure tube integrity satisfies the tube integrity performance criteria (both structural and leakage integrity)
- Operational Assessment is critical in determining an acceptable inspection interval for tube examinations
- Completed within 90 days following tube examination and plant entering Mode 4

Operational Assessment Process

- All detected (existing) degradation mechanisms shall be evaluated in the OA
- Degradation that have been found at prior inspections but have not been observed at the current inspection shall also be evaluated
- Secondary side inspections results (foreign object search and retrieval, steam drum inspections) should be evaluated if tube integrity can be impacted

3. OPERATIONAL ASSESSMENTS

Why Probabilistic Assessments are Needed?

- Worst case deterministic assessments may not be conservative when evaluating extreme degraded conditions
- Suspect large number of undetected indications - Poor inspection performance
- Large increase in the number of new indications detected at successive inspections - Degradation is accelerating
- Many large depth indications identified - Multiple indications that challenge the SIPC margin requirements
- Consistent under-prediction of the size of the worst detected degraded tube – High uncertainty in degradation growth rates

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3. OPERATIONAL ASSESSMENTS

Integrity Assessment Input and Uncertainty

- A validated burst model based on regression analysis of tube failure data including uncertainty in the prediction of burst pressure for a given extent and mode of degradation,
- Tube material strength information at operating temperature including uncertainty in mechanical strength behavior due to material heat-to-heat variability
- Probability of detection on finding a given size of degradation
- Degradation growth rate distribution for future operation
- Measurement uncertainty for the detected degradation (depth and length) conditional on the NDE technique used for sizing

Other Analysis Conditions

- Nominal tubing dimensions are assumed
- Tube pressures and non-pressure loads are generally assumed at design conditions
- Conservative inspection interval is normally assumed

3. PERFORMANCE ACCEPTANCE STANDARDS

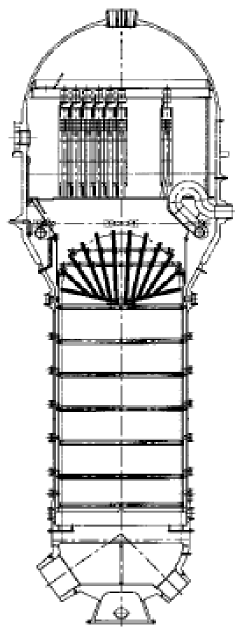
Acceptance Standard for Structural Integrity:

> *"The worst-case degraded tube for each existing degradation mechanism shall meet the SIPC requirements with at least a probability of 0.95 at 50% confidence."*

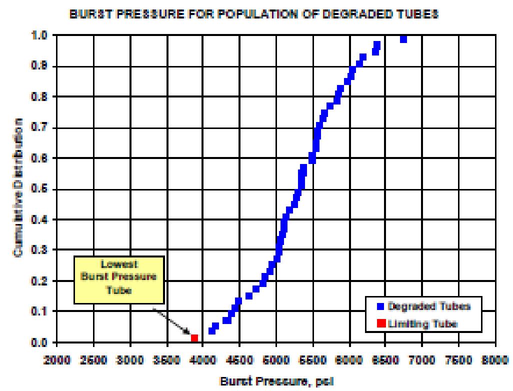
- Project all degradation sites, newly initiated and existing/growing according to probabilistic distributions and cycle length
- Simulate operation with repeated trials via Monte-Carlo methods
- Assemble the distribution for limiting burst pressure, taken from lower extreme value of burst pressure at each trial
- The worst-case degraded tube is established from the estimation of lower extreme values of the burst pressure distribution representative of all degraded tubes in the bundle.

3. MONTE CARLO SIMULATION

Aspects of Monte Carlo simulation to calculate probability of tube burst in accordance with the Performance Standards

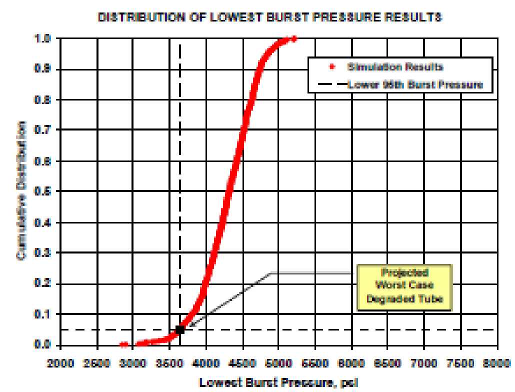


Tube Bundle



One MC Simulation For All Degraded Tubes in the Bundle

After Many Simulations For All Degraded Tubes in the Bundle



Probabilistic Monte Carlo Simulation to Determine Worst-Case Degraded Tube – Full Bundle Analysis

3. MONTE CARLO SIMULATION

Probabilistic Simulation to Determine Worst-Case Degraded Tube – Full Bundle Analysis for a Selected Degradation Mechanism

BOC – Beginning of Cycle

EOC – End of Cycle

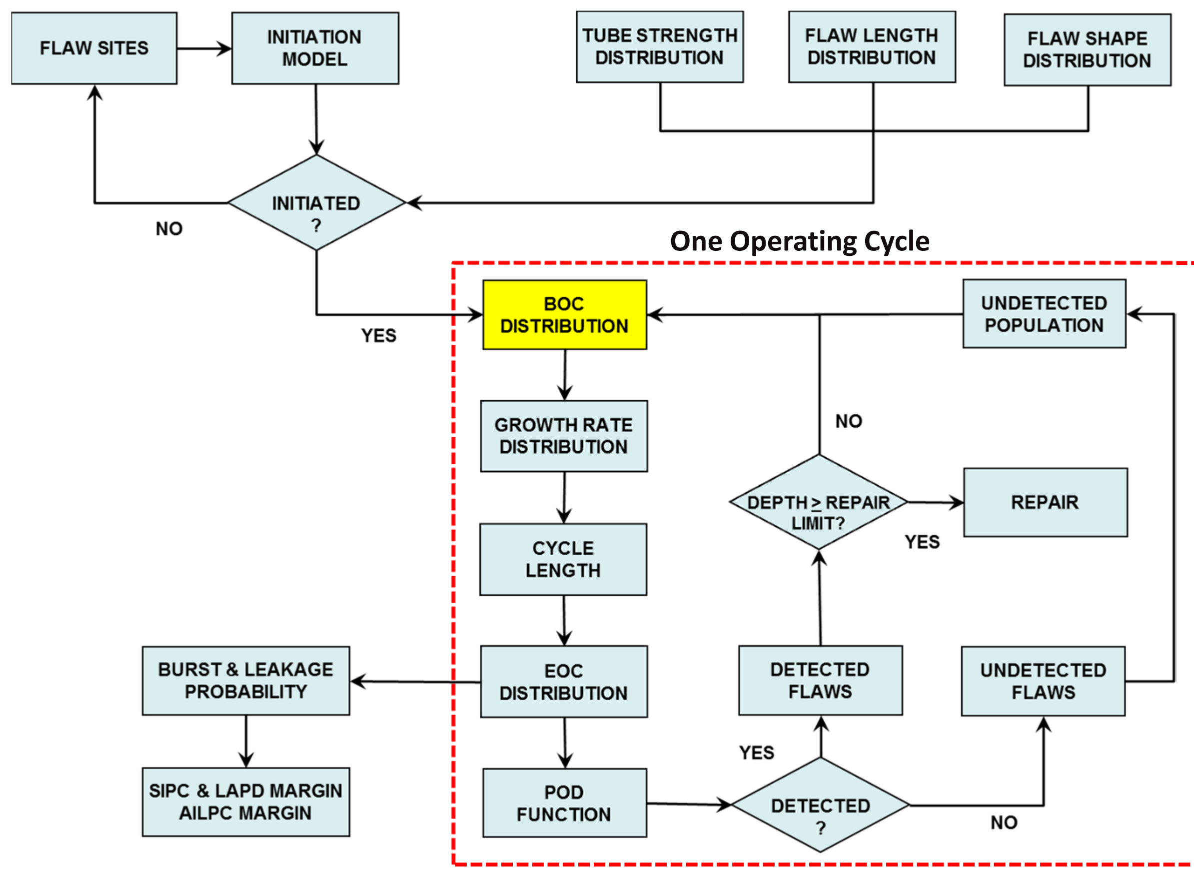
SIPC – 3xNOPD (normal operating pressure differential)

LAPD – 1xMSLB (main steam line break)

AILPC – Accident-Induced Leakage Performance Criteria

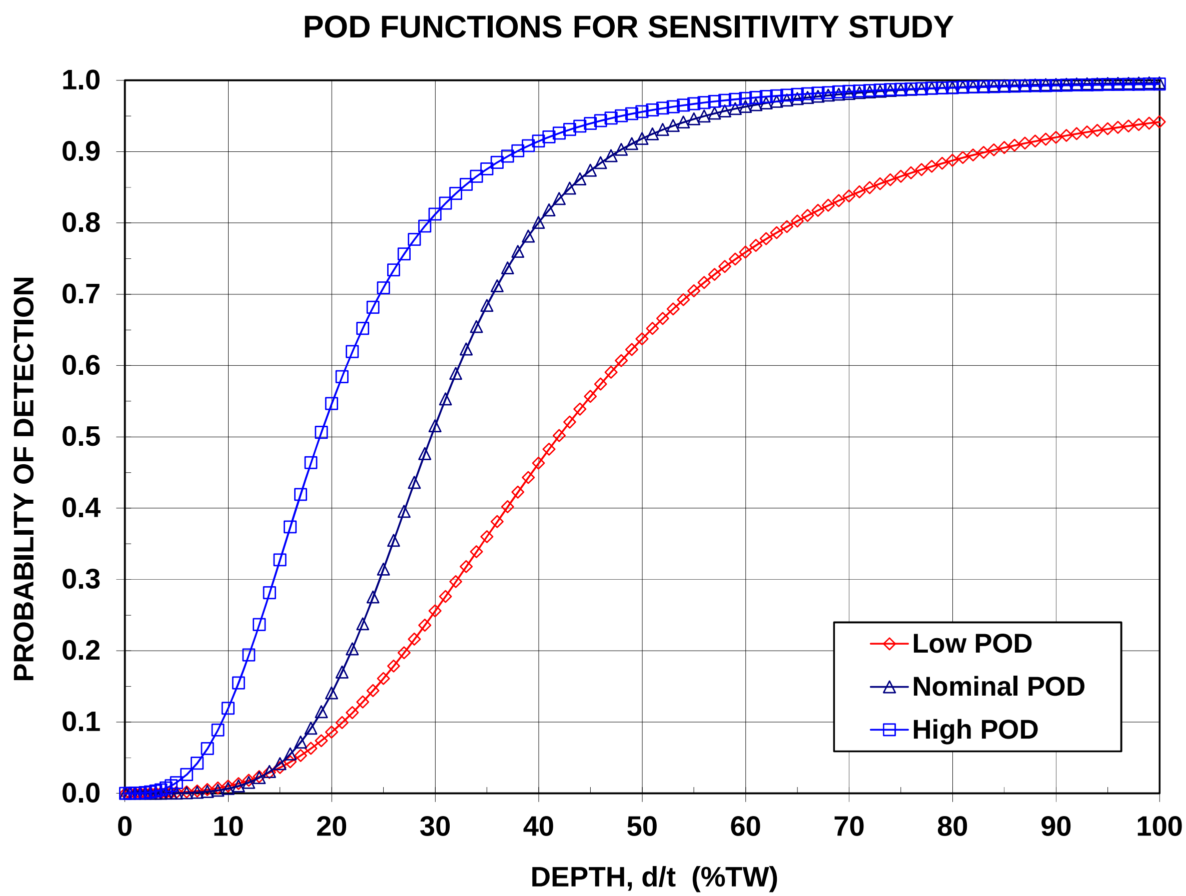
Repair Limit – TS Limit (e.g., 40%TW) or administrative limit

MULTI-CYCLE MODEL LOGIC

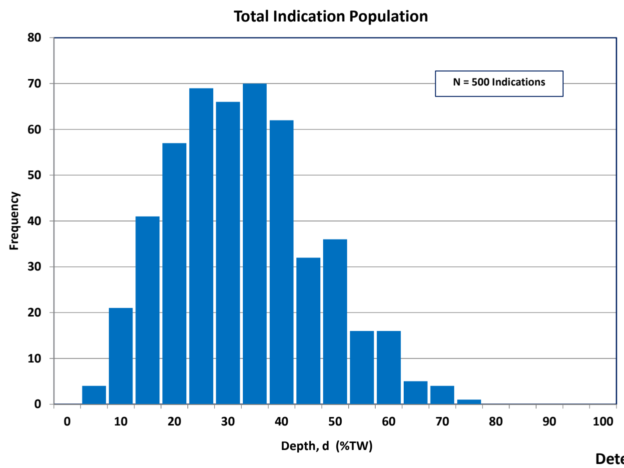


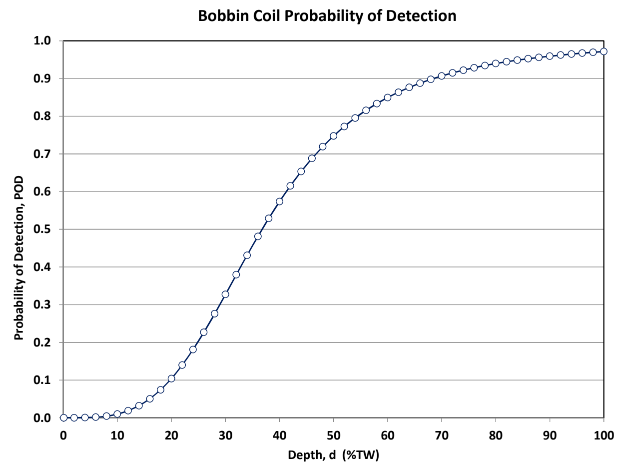
3. PROBABILITY OF DETECTION

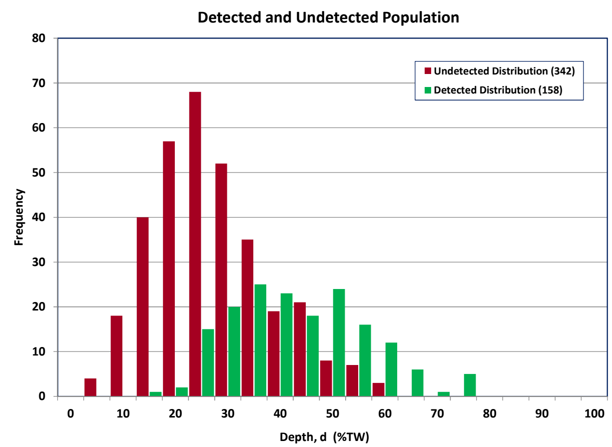
Eddy current technique is the primary examination method. Logistic or log-logistic functions typically are used to represent the POD behavior



3. INSPECTION DETECTION





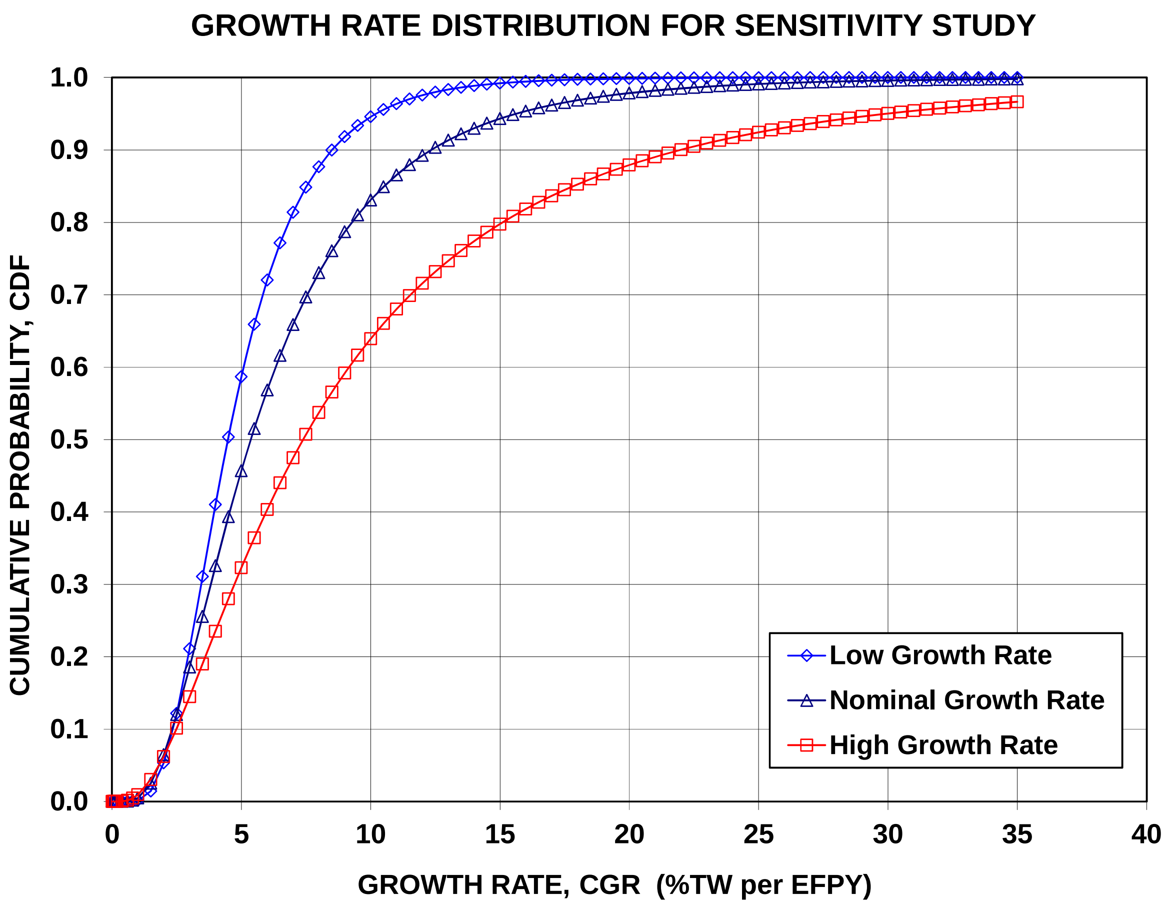


Detection process produces two sub-populations

“detected” and “undetected”

3. AXIAL ODSCC GROWTH RATE MODELS

Growth rate developed from NDE service data. Lognormal distribution is typically used to represent the CGR behavior



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MODEL BENCHMARKING

4. MODEL BENCHMARKING

What is Model Benchmarking?

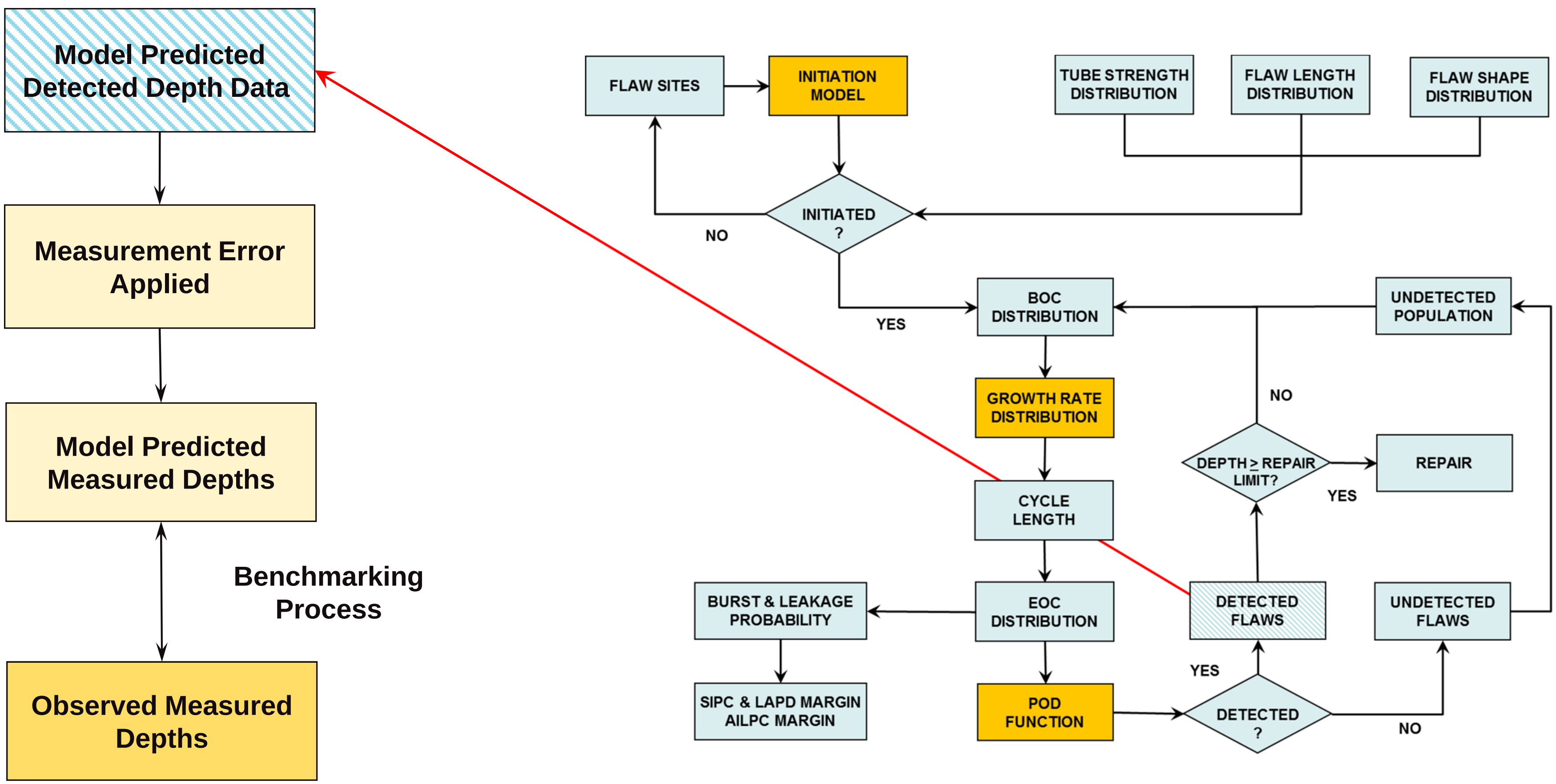
- The benchmarking process is the most critical step in assuring the predictive validity of a steam generator structural integrity model
- Uses a Bayesian approach to establish an accurate model prediction of a future outcome utilizing prior knowledge (i.e., past inspection data)
- The observed depths measured during the NDE inspection form the basis for the model benchmarks
  - *The number and statistical distributions of the measured flaw depths are available for multiple inspections*
  - *In addition, the maximum flaw depth provides the most important structural benchmark*
- Any acceptable simulation model must provide predictions of the above observable quantities to facilitate comparison with the available NDE data

4. BENCHMARKING RESULTS

Operational Assessment Benchmarking

- ➢ Benchmarking model projection results against the current and past outage inspection results
- ➢ Important comparisons are:
  - Predicted versus observed dimensions of the worst case degradation.
  - Predicted versus observed number of indications
  - Projected versus observed distribution of indications depths

4. BENCHMARKING PROCESS



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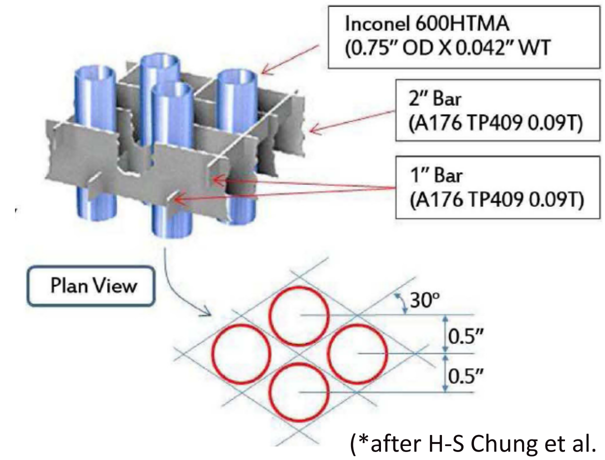
EXAMPLE ASSESSMENT

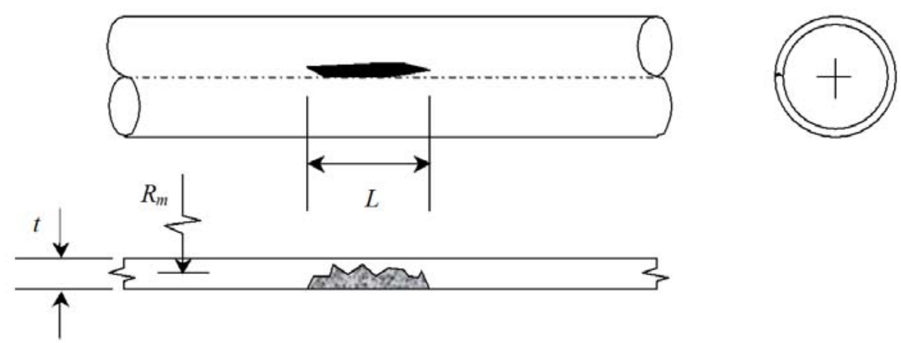
5. EXAMPLE ANALYSIS INPUT

Plant:	Two-Loop, Typical CE Design
Cycles of Data:	Cycles 16, 17, & 18
Cycle Length:	1.26 EFPY
ECT Probe:	Bobbin Coil
Material:	Alloy 600 MA
NOPD:	1240 psi (3xNOPD = 3720 psi)
LAPD:	2560 psi
Mechanism:	Axial ODSCC at Tube Support Plates
Plugging Limit:	Plug on Detection

Objective:	Calculate the Probability of Burst at 3xNOPD at EOC 19



(*after H-S Chung et al. NE&T Aug 2013)



Axial OD Crack Model Geometry

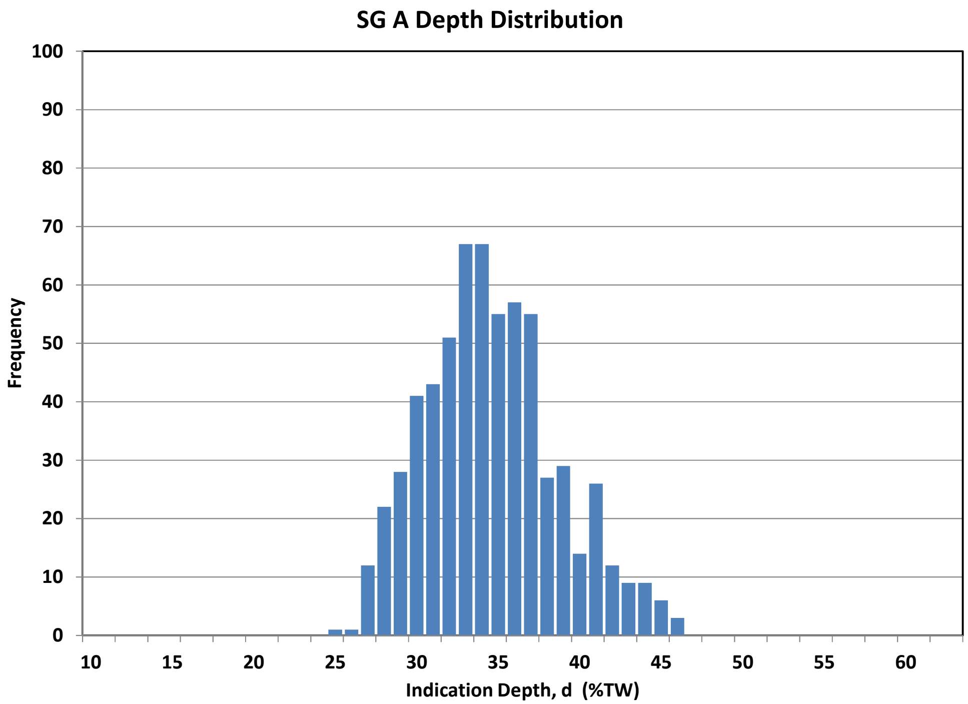
5. OUTAGE DATA

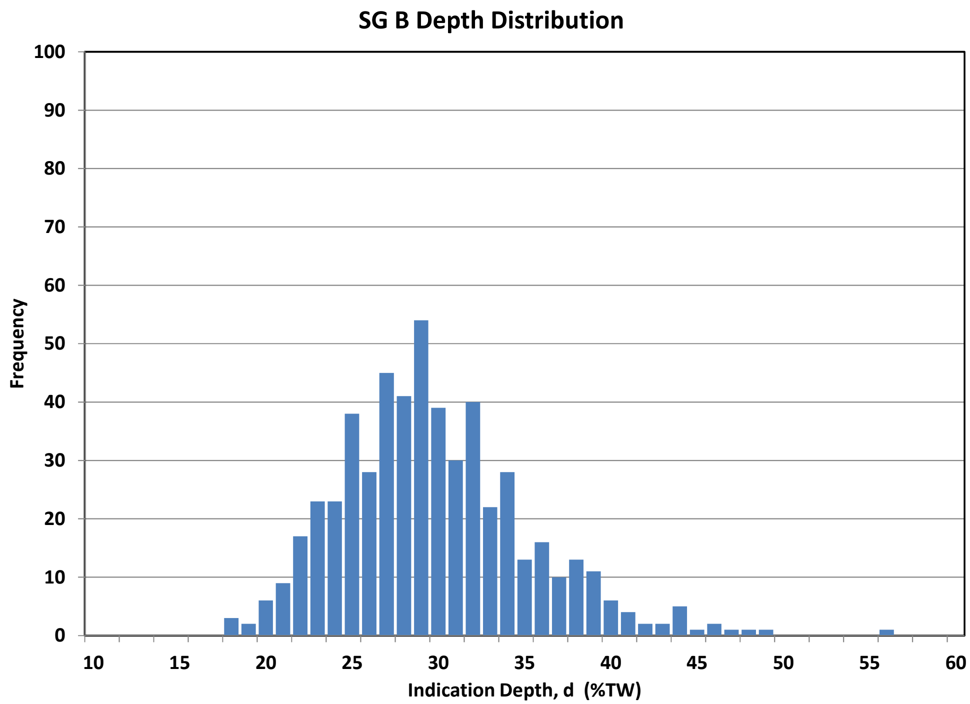
SUMMARY OF INSPECTION DATA FOR AXIAL ODSCC INDICATIONS

Inspection Outage	SG A		SG B	
	DSI	SAI/MAI	DSI	SAI/MAI
Cycle 16	3	1	0	0
Cycle 17	558	27	619	41
Cycle 18*	926	620	828	528

*Chemically cleaning performed

5. Cycle 18 OUTAGE DEPTH DATA





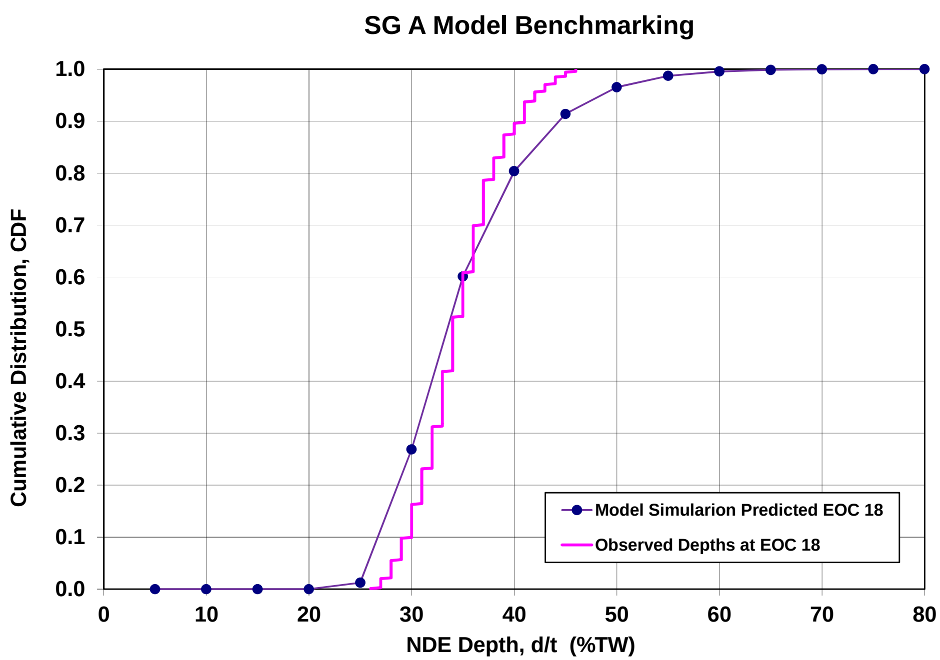
5. EXAMPLE PROBLEM BENCHMARKING

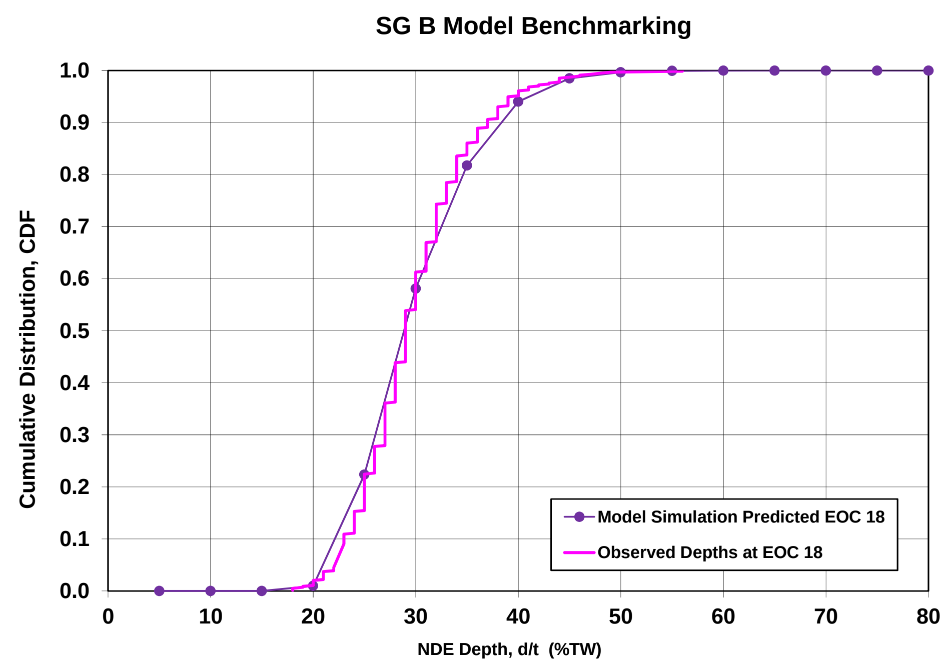
BENCHMARK RESULTS FOR CYCLES 17 AND 18

Benchmark Parameter	SG A		SG B	
	Actual Observed	Model Prediction	Actual Observed	Model Prediction
Number of Detected at EOC 17, N_{DET}	27	35	41	36
Number of Detected at EOC 18, N_{DET}	620	626	528	528
NDE Max Depth at EOC 18, d_{MAX} (%TW)	48% TW	64% TW	56% TW	57% TW

5. EXAMPLE PROBLEM BENCHMARKING

BENCHMARK RESULTS FOR CYCLE 18

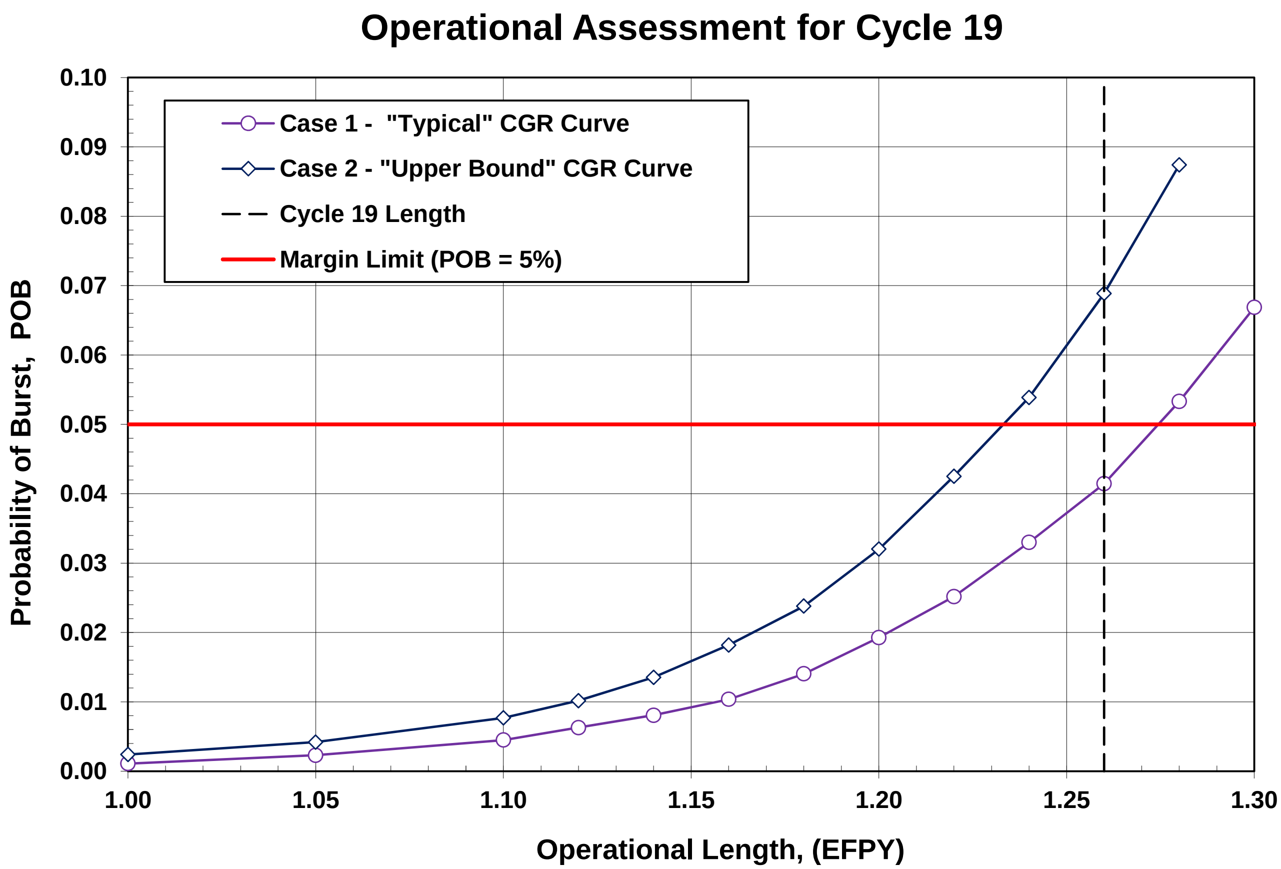




Comparison of Observed with Predicted CDFs

5. PROBABILITY OF TUBE BURST AT MARGIN REQUIREMENTS

For a given inspection technique, POB will be dependent on growth rates and inspection interval in a nonlinear manner



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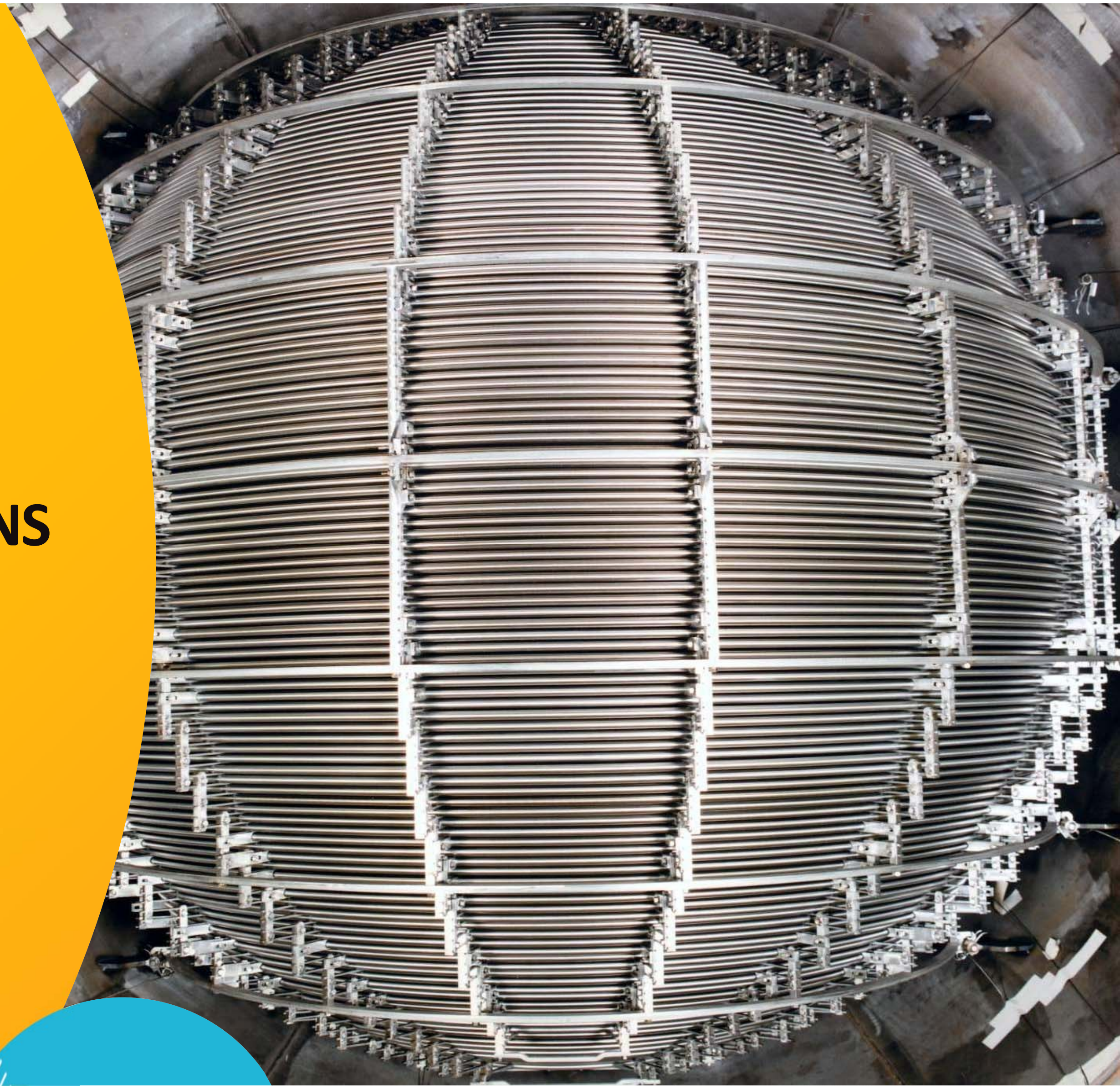
SUMMARY AND CONCLUSIONS



6. SUMMARY AND CONCLUSIONS

- Steam generator tube integrity (burst and leakage) is regulated through NEI 97-06 and the Plant Technical Specifications
- Actual plant operation is controlled by probabilistic acceptance criteria via an Operational Assessment
- Operational Assessments for tube integrity is a practical example where industry accepted probabilistic methodology and criteria are used to:
  - *Evaluate risk of tube degradation and aging rate*
  - *Establish in-service inspection techniques and interval for conducting tube examinations*
  - *Maintain safe plant operation under design-basis and licensing requirements*
- Full bundle assessments can provide useful insight on the sensitivity of tube integrity to key input variables such as system detection performance and degradation growth rates, and operating periods between inspections.

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QUESTIONS?

Russell C. Cipolla, PE

+1 (408) 636-5322

russell.cipolla@intertek.com

intertek.com/aim/engineering