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# STRUCTURAL INTEGRITY CRITERIA AND PERFORMANCE ACCEPTANCE STANDARDS FOR FULLY PROBABILISTIC ASSESSMENTS OF STEAM GENERATOR TUBING

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# PRESENTATION OUTLINE

# 1

# INTRODUCTION

# 1. INTRODUCTION

## Historical Background

- In the late 1980s and early 1990s, there were several tube leak events detected during operation.
- PVNGS-2 tube rupture in March 1993 was a first time occurrence of axial freespan outside diameter stress corrosion cracking (ODSCC) leading to a large leak (240 gpm).
- IN No. 94-62 issued by US NRC to inform the industry of tube leaks and ruptures (Braidwood-1, PVNGS-2, ANO-2, McGuire-1, Indian Point-3, North Anna-1).
- These tube rupture/leak events led to more advancements in tube integrity assessments.
- In particular, the intensive work performed at Palo Verde became the background for performing tube integrity and leakage assessments on a periodic basis
- Such evaluations are known as Operational Assessments

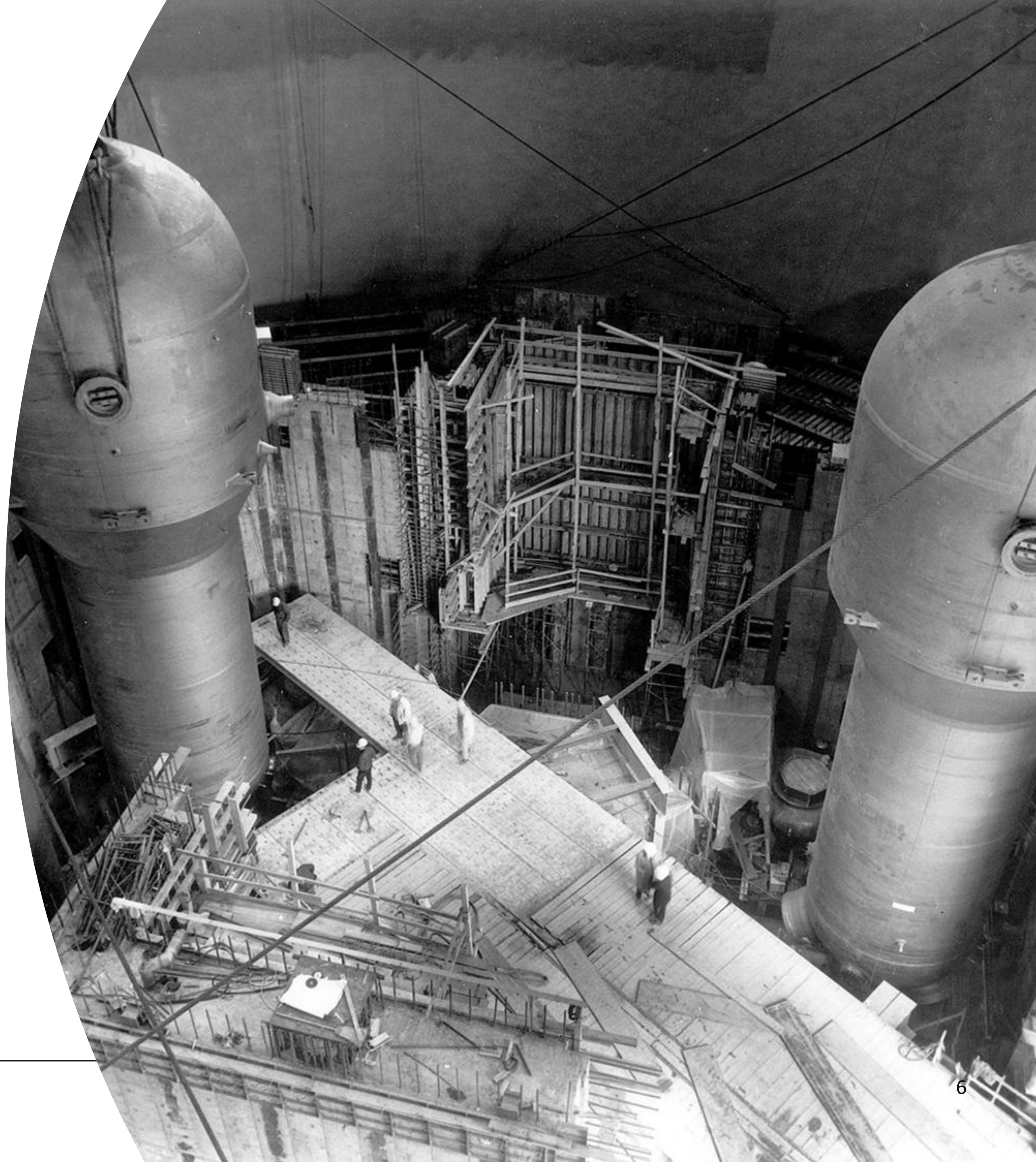
# 1. INTRODUCTION

## Lessons Learned

- Alloy 600 mill-annealed (MA) tubing has suffered significant service-induced degradation
- Many Alloy 600 MA steam generators have been replaced due to various forms of corrosion degradation
- Present tubing material of choice in the US is Alloy 690 thermally-treated
- Maintaining tube integrity is critical and controls many aspects of steam generator management
    - *Inspection strategies and techniques (primary and secondary side)*
    - *Secondary side maintenance*
    - *Chemistry controls and chemical cleaning*
    - *Cycle length determination*
- Tube integrity performance criteria are now part of the Plant Technical Specifications (TS) in the US

# 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
- Clear example of the direct application of a probabilistic assessment criteria that govern plant operation



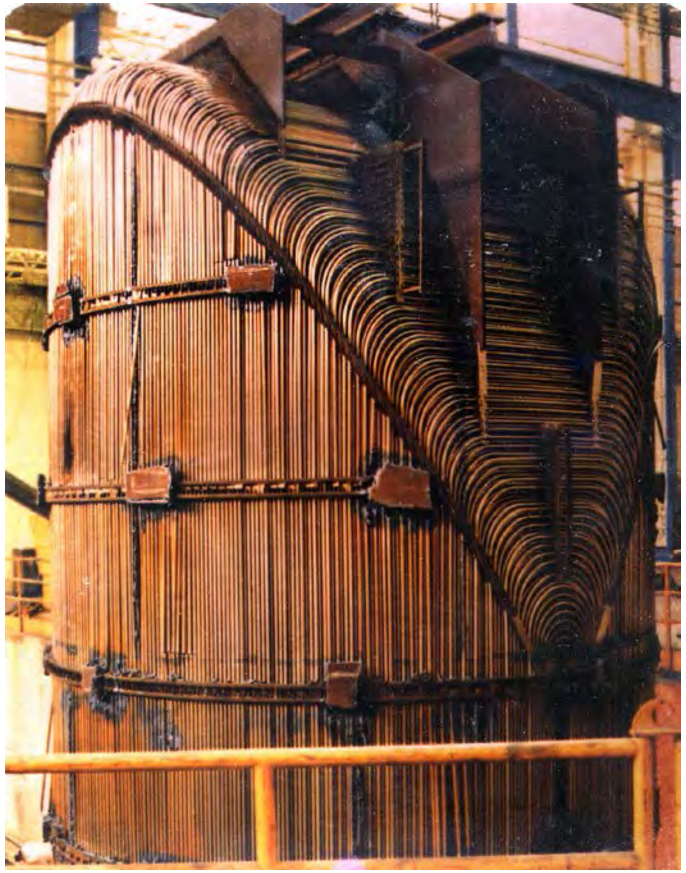
# 2

# OVERVIEW OF INDUSTRY REQUIREMENTS

# 2. REGULATION AND LICENSING BASES

## Tube Integrity Requirements

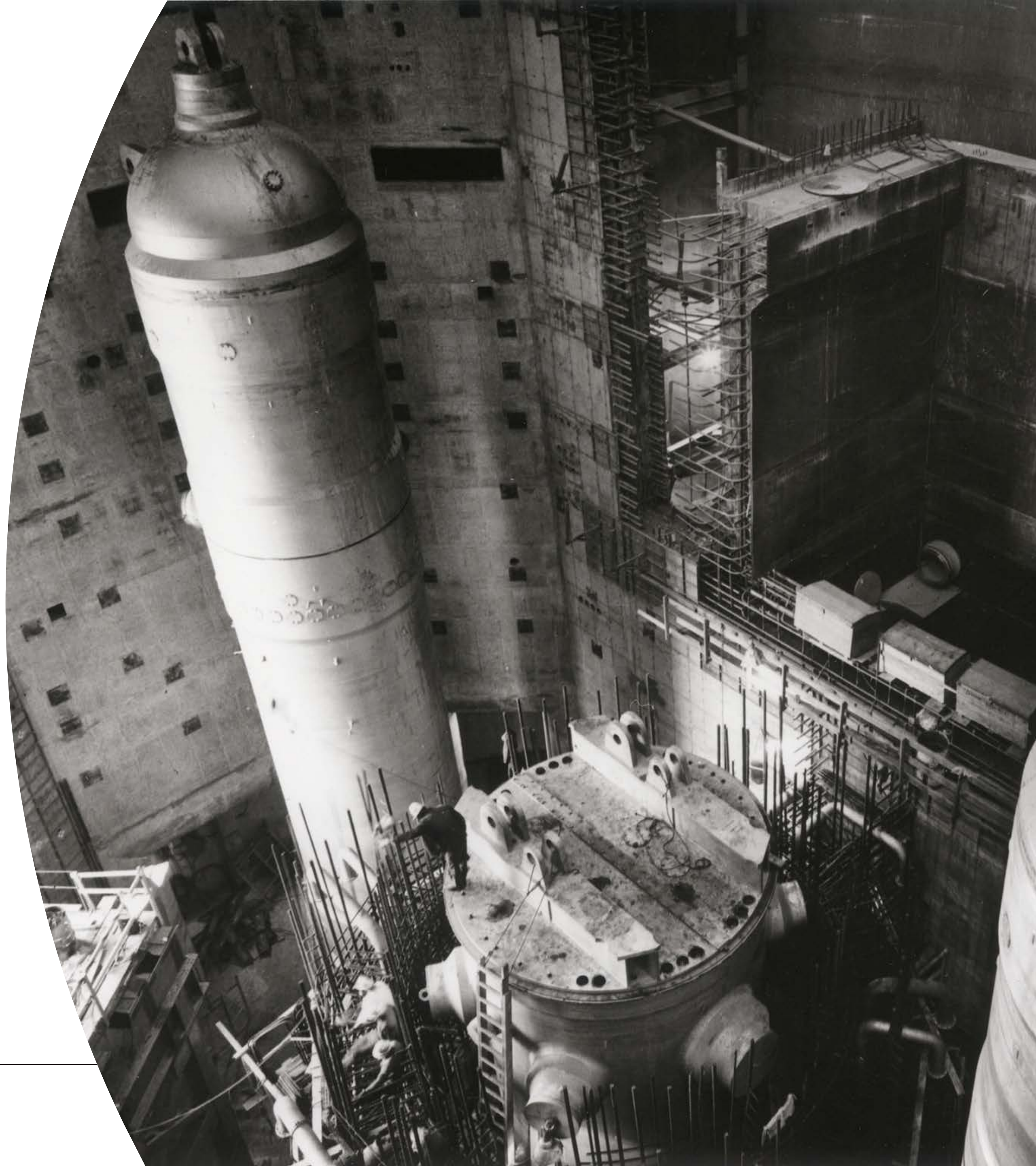
- Title 10 of Code of Federal Regulations Part 50 – General Design Criteria governing the reactor coolant pressure boundary (RCPB)
- US Nuclear Regulatory Commission (NRC) Regulatory Guide 1.121 - Basis for plugging degraded steam generator tubes
- Draft Regulatory Guide DG-1074 – Programmatic framework 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



**SG tubing make up a significant portion of the RCPB**

# 2. ONGOING INDUSTRY EFFORTS

1. US NRC Nuclear Reactor Regulation (NRR) - Chemical, Corrosion, and Steam Generator Branch
2. Nuclear Energy Institute (NEI)
3. EPRI Steam Generator Management Program (SGMP)
4. EPRI Institute of Nuclear Power Operations (INPO)
5. NRC/SGMP Task Force Meetings
6. EPRI SGMP Workshops on NDE and tube integrity methodologies
    - Periodic updates to industry guidelines
    - Publish interim guidelines as needed
7. Operating experience shared through website databases and INPO audits



# 2. TUBE INTEGRITY REQUIREMENTS

## General Requirements

- Technical Specifications require that licensees perform periodic in-service inspections of the SG tubing
- Repair or remove from service all tubes exceeding the tube repair limit.
- 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 rupture, 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

# 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.

# 3

# ASPECTS OF TUBE INTEGRITY ASSESSMENTS

# 3. TUBE INTEGRITY ASSESSMENTS

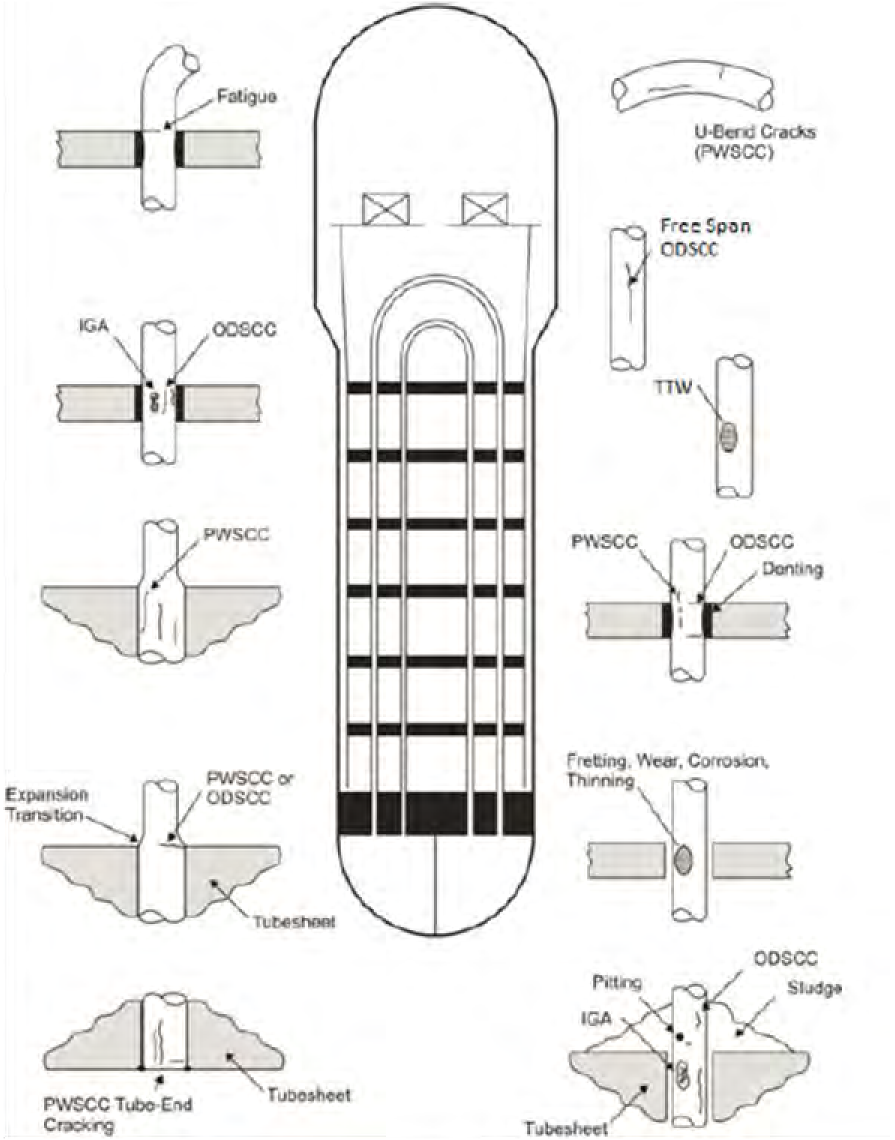
## Tube Integrity Criteria Objectives

- Prevention of tube burst/collapse 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)

# 3. 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.



# 3. OPERATIONAL ASSESSMENT

## 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 to the time of the next scheduled inspection outage and determining their acceptability relative to the tube integrity performance criteria (both structural and leakage integrity)
- Completed within 90 days following tube examination and plant entering Mode 4

## Operational Assessment Process

- All detected 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 POD
- Large increase in the number of new indications detected at successive inspections - Mechanism is accelerating
- Many large depth indications identified - Multiple indications that challenge the SIPC margins
- Consistent under-prediction of the size of the worst detected degraded tube – High uncertainty in 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

4

# STRUCTURAL INTEGRITY PERFORMANCE CRITERION

# 4. 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****."*

# 4. TUBE INTEGRITY CRITERIA AND BASIS

## Structural Integrity Performance Criterion

SHALL cover full range of normal operating conditions

- Startup
- Operation in Power Range
- Anticipated Transients
- Hot standby
- Cooldown

## Safety Factors:

- **3.0×** Normal Operating Pressure Differential (NOPD)
- **1.4×** Design Basis Limiting Accident Pressure Differential (LAPD)

## Design Basis Contributed Loads Require Additional Safety Factors

- **1.2×** Combined primary loads (PL)
- **1.0×** Axial secondary loads (ASL)

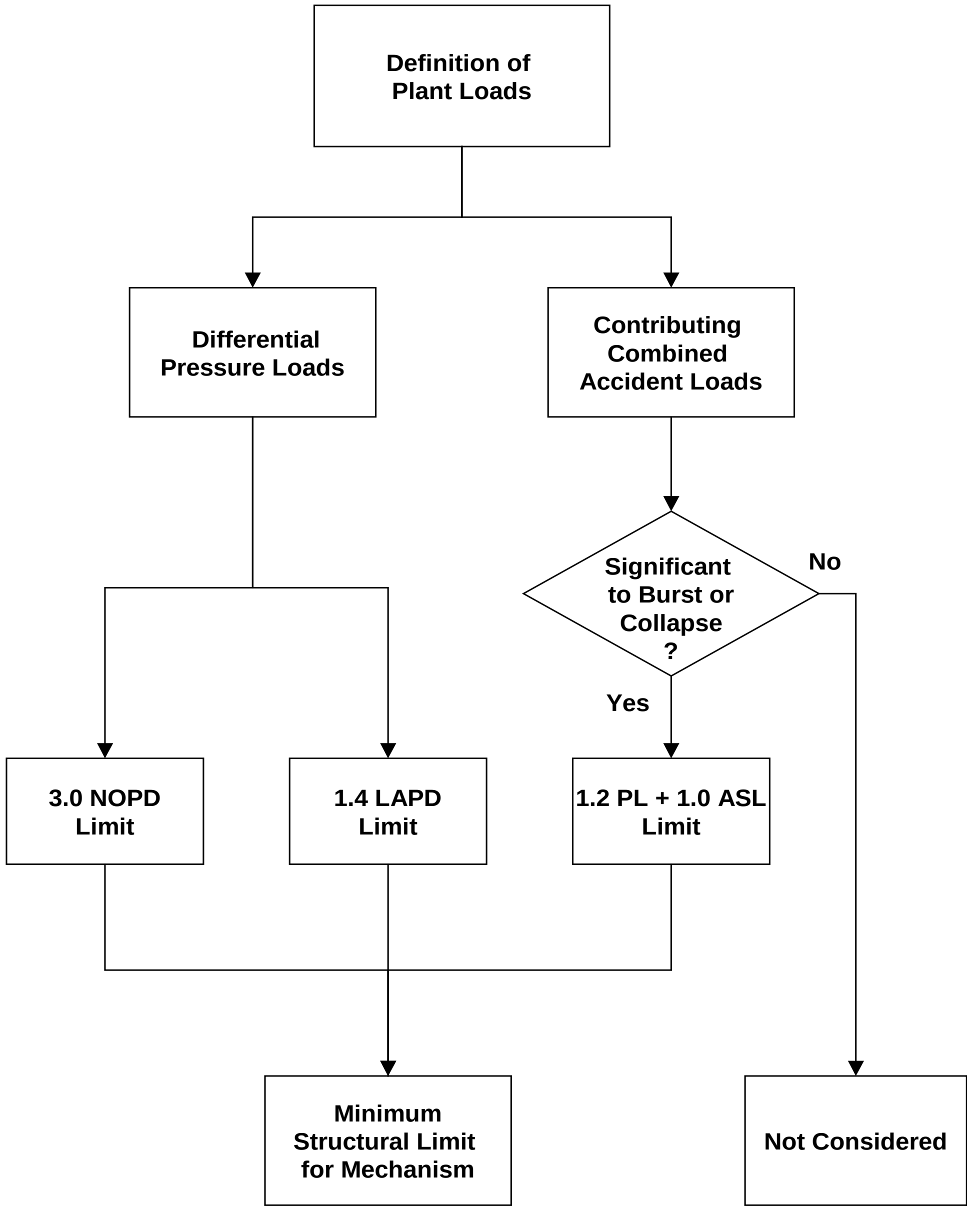
# 4. TUBE INTEGRITY CRITERIA AND BASIS

## 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



# 4. TUBE INTEGRITY CRITERIA AND BASIS

## Basis from NRC Regulatory Guide 1.121

### Normal Operating Pressure Loads

- Safety factor of 3.0 on tube pressure differential (3×NOPD) for full power steady state operation is derived from the allowable limit of primary membrane stress:

$$P_m = S_u/3$$

- No yielding during normal operating conditions will be satisfied by meeting 3×NOPD requirement

### Design Basis Accidents – Membrane Pressure Loads

- Safety factor of 1.4 on limiting accident pressure differential for design basis accidents
- Safety factor of 1.4 follows from Code allowable limit for primary membrane stress:

$$P_m < 0.7 \times S_u$$

- Non-pressure primary membrane loads are not significant based on EPRI Industry Impact Study findings

# 4. TUBE INTEGRITY CRITERIA AND BASIS

## Basis For Safety Factors For Accident Loads

### Section III Nonmandatory Appendix F – Level D Service Limits

- Determination of the 1.2 safety factor (SF) is derived from an equivalency comparison between the load that would be permitted by the Appendix F collapse method and the collapse load determined by standard industry methods for tube integrity.
- Appendix F Subsections F-1331.1(c)2 and F-1341.3 define the allowable stress as 90% of the calculated collapse load.
- For Alloy 600/690, safety factors (based on typical as-measured properties) may range from 1.12 to 1.17
- Since typical safety factors are < 1.20, this is conservative

- Statement of equivalency

$$SF = \frac{\text{Calculated Collapse Load}}{90\%\ \text{Design Accident Load}} = \frac{\sigma_{Flow}}{0.9\,\sigma_{AppF}}$$

where

$\sigma_{Flow} = (\sigma_y + \sigma_u)/2$

$\sigma_{AppF} = 2.3S_m$ or $0.7\sigma_u$ (whichever is smaller)

$S_m$ = design stress intensity

$\sigma_y = k\,\sigma_u$

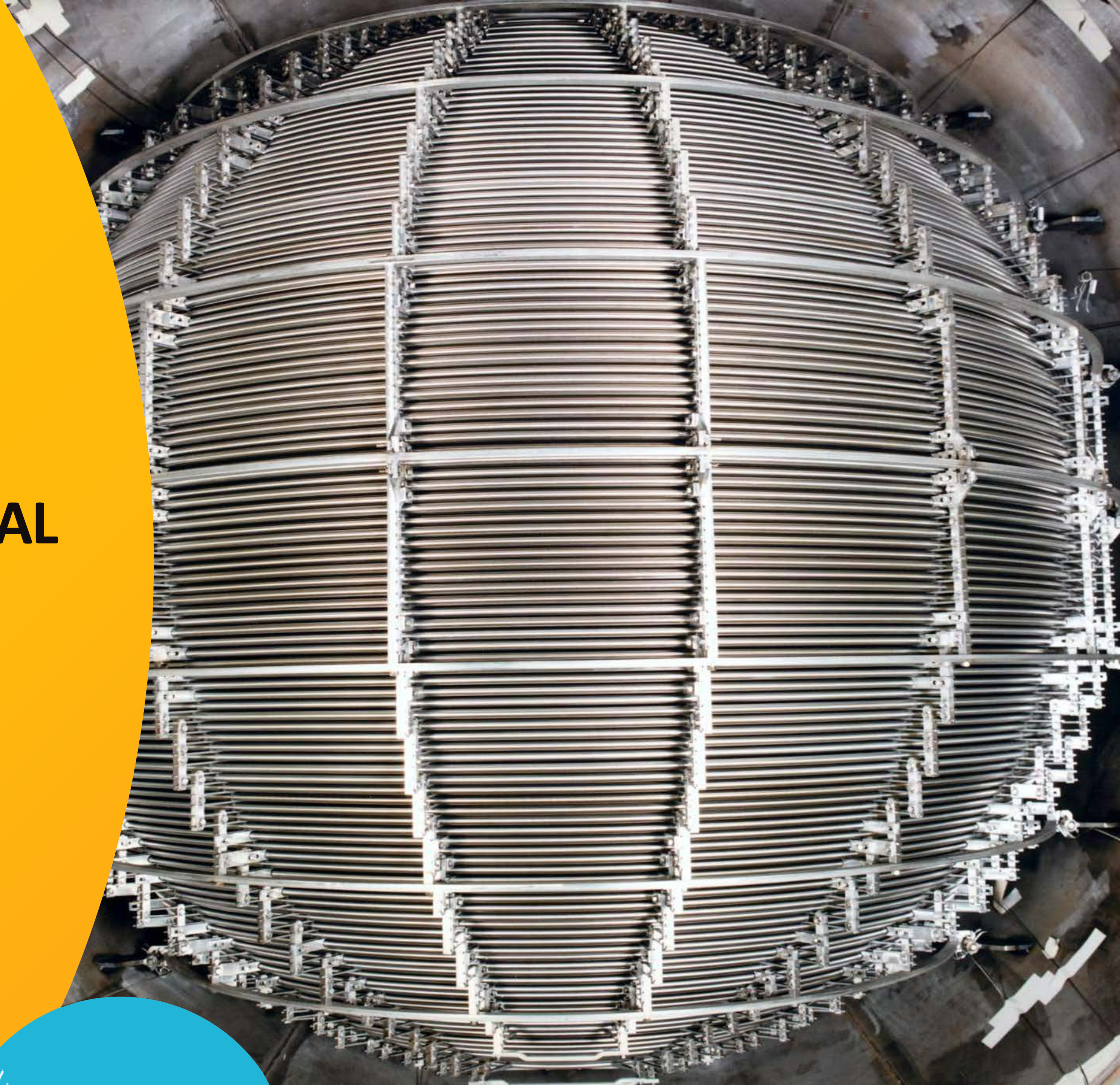
# 4. TUBE INTEGRITY CRITERIA AND BASIS

| A600 Tubing | @ Temp (ksi) | | | $\sigma_{Flow}$ (ksi) | $\sigma_{AppF}$ (ksi) | SF |
|---|---|---|---|---|---|---|
| | $\sigma_y$ | $\sigma_u$ | $S_m$ | | | |
| 7/8" × 0.050" MA | 41.89 | 95.67 | 31.9 | 68.78 | 66.97 | **1.14** |
| 7/8" × 0.050" TT | 39.91 | 94.77 | 31.6 | 67.34 | 66.34 | **1.13** |
| 3/4" × 0.043" MA | 45.78 | 97.35 | 32.5 | 71.57 | 68.15 | **1.17** |
| 3/4" × 0.043" TT | 41.50 | 95.87 | 32.0 | 68.69 | 67.11 | **1.14** |
| 3/4" × 0.042" MA | 36.49 | 94.65 | 27.6 | 65.57 | 63.48 | **1.15** |
| 3/4" × 0.042" MA | 35.44 | 93.67 | 26.8 | 64.56 | 61.64 | **1.16** |
| 3/4" × 0.042" MA | 40.00 | 97.62 | 30.3 | 68.81 | 68.33 | **1.12** |
| 3/4" × 0.042" MA | 40.76 | 97.63 | 30.9 | 69.20 | 68.34 | **1.12** |
| 3/4" × 0.042" MA | 42.81 | 97.73 | 32.4 | 70.27 | 68.41 | **1.14** |
| 3/4" × 0.042" MA | 43.04 | 97.53 | 32.5 | 70.29 | 68.27 | **1.14** |
| 3/4" × 0.048" MA | 39.88 | 92.62 | 30.2 | 66.25 | 64.83 | **1.14** |
| 3/4" × 0.042" MA | 36.72 | 88.15 | 27.8 | 62.44 | 61.71 | **1.12** |
| 3/4" × 0.048" MA | 40.69 | 92.95 | 30.8 | 66.82 | 65.07 | **1.14** |
| 3/4" × 0.048" MA | 40.55 | 92.18 | 30.7 | 66.37 | 64.53 | **1.14** |
| 5/8" × 0.037" MA | 41.98 | 94.61 | 31.5 | 68.30 | 66.23 | **1.15** |
| 5/8" × 0.037" MA | 40.60 | 93.90 | 31.3 | 67.25 | 65.73 | **1.14** |

$$SF = \frac{\text{Calculated Collapse Load}}{90\%\ \text{Design Accident Load}} = \frac{\sigma_{Flow}}{0.9\,\sigma_{AppF}}$$

# 5

# PERFORMANCE ACCEPTANCE STANDARDS FOR OPERATIONAL ASSESSMENTS



# 5. PERFORMANCE ACCEPTANCE STANDARDS

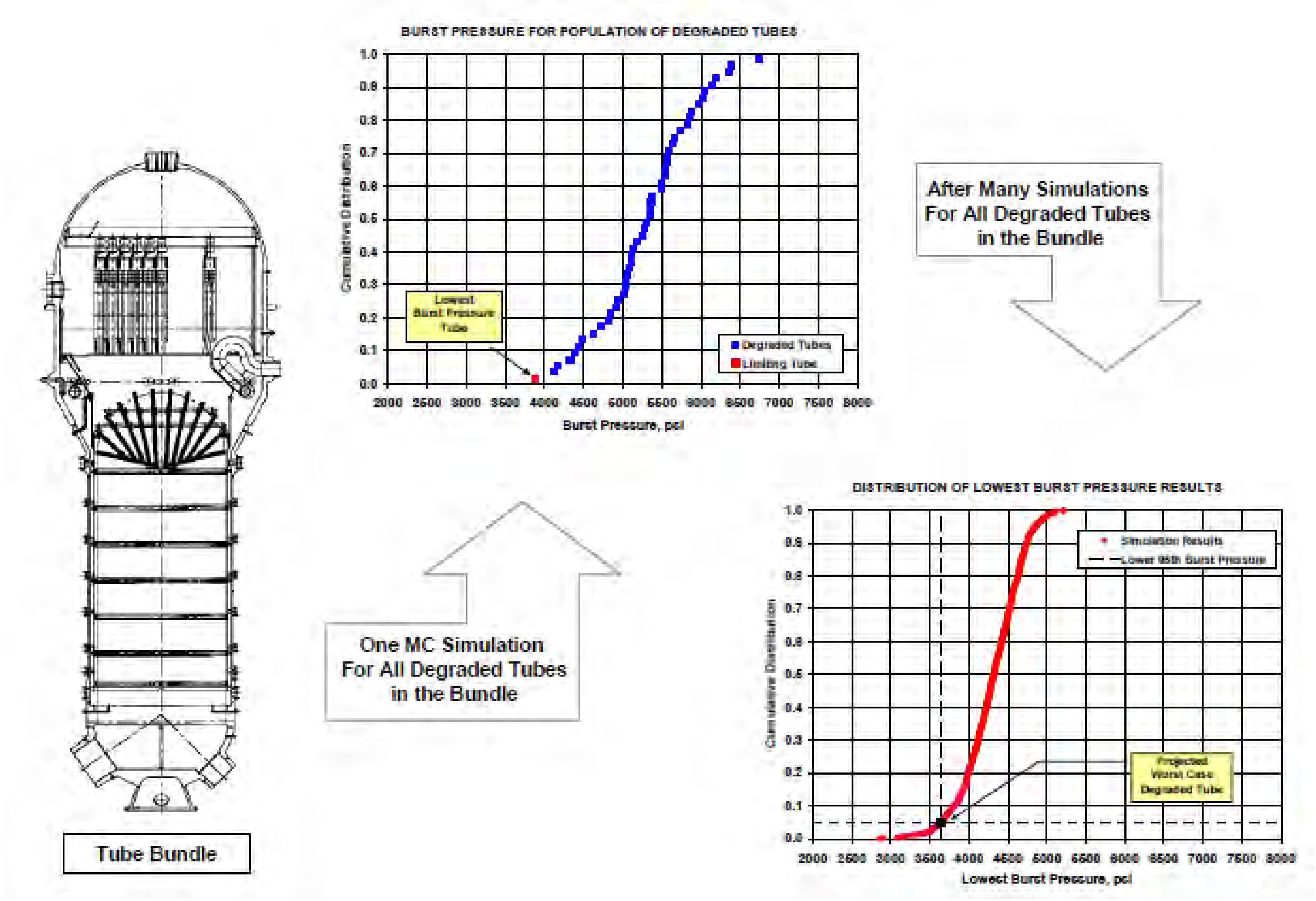
**Acceptance Standard for Structural Integrity:**

*"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 simulation 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.

# 5. MONTE CARLO SIMULATION

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




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

# 5. PERFORMANCE ACCEPTANCE STANDARDS

## How was the 95/50 Performance Standard Established?

- Figure of Merit selected from NRC DG-1074
  - *Frequency of tube bursts under normal operating conditions should not exceed 2.5 x $10^{-3}$ per reactor-year.*
  - *Conditional POB of one or more tubes under postulated accidents conditions should not exceed 2.5 x $10^{-2}$ for all mechanisms in a SG*
  - ***Conditional POB of one or more tubes under postulated accidents conditions should not exceed 1 x $10^{-2}$ for any one mechanism (flaw type)***
- Comparative calculations were performed in a sensitivity study to determine the POB value for satisfying the SIPC margin requirement (3xNOPD) to gibe reasonable assurance that the conditional probability of 0.01 for main steam line break (1xMSLB) will also be met

# 5. PERFORMANCE ACCEPTANCE STANDARDS

## Sensitivity Study

- Use the Operational Assessment logic to establish an acceptance level
- Select a challenging degradation mechanism – Axial Freespan ODSCC
- Select range of distributions (POD, growth rate, and flaw length)

## Input Distribution Models

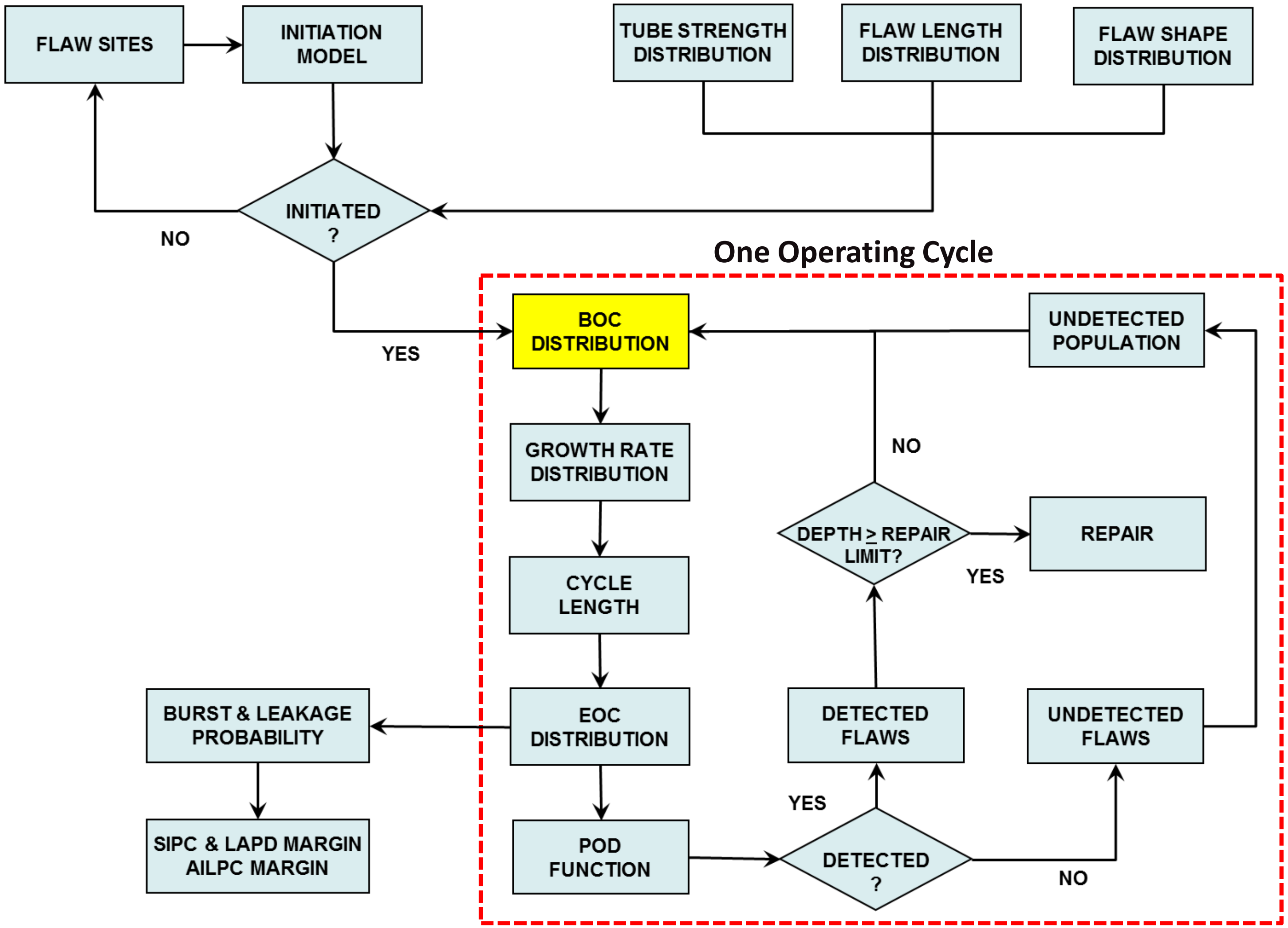
- Initiation Function – Weibull
- Probability of Detection – Log-logistic
- Growth Rate – Lognormal
- Flaw Length - Lognormal
- Measurement Uncertainty – Gaussian (Normal)
- All other model uncertainties - Normal distributions

# 5. MONTE CARLO SIMULATION STUDY

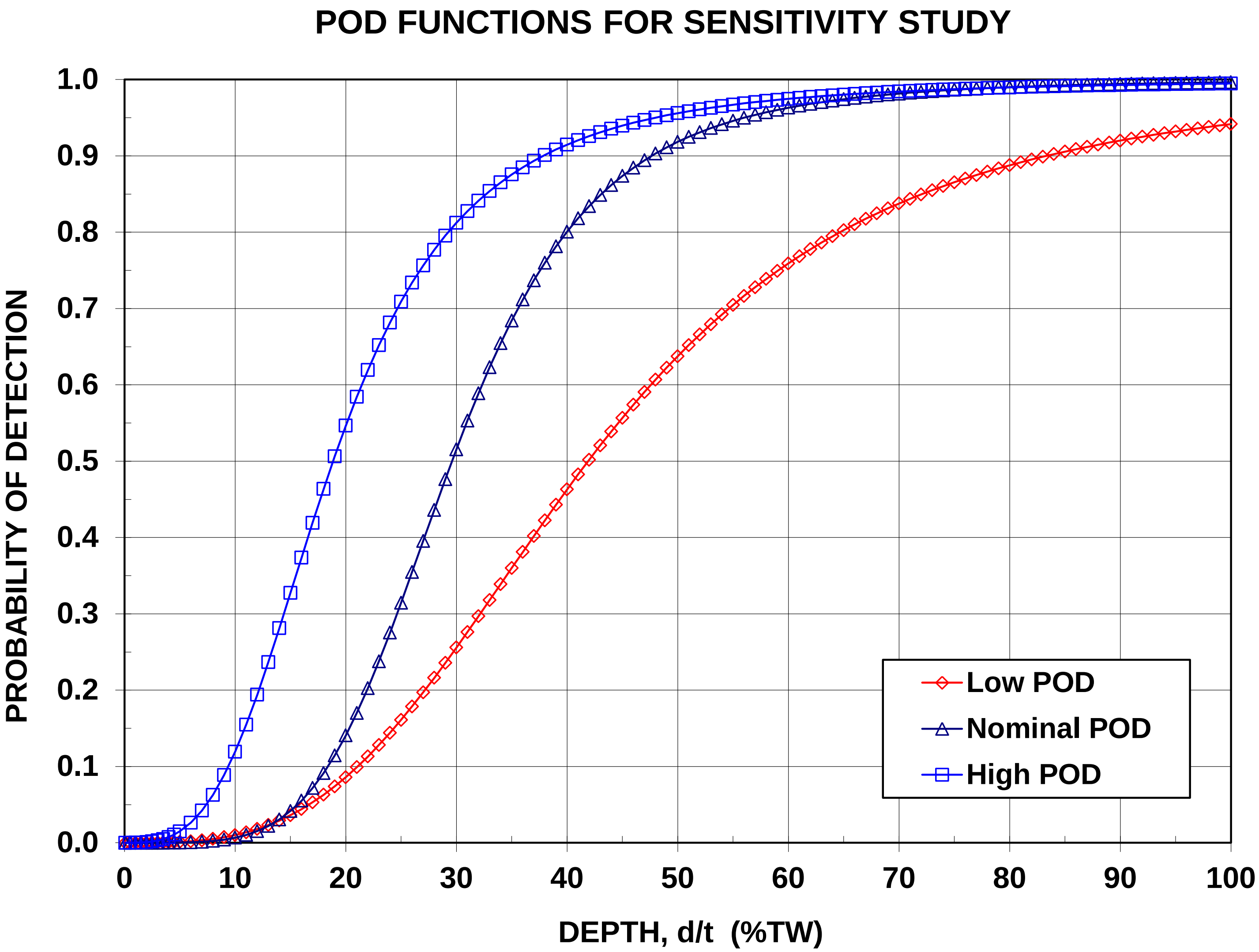
**Probabilistic Simulation to Determine Worst-Case Degraded Tube – Full Bundle Analysis for Axial Freespan ODSCC**

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)
Simulated 10 Operating Cycles
Number of Trials = 10,000
Total Cases = 27

## MULTI-CYCLE MODEL LOGIC



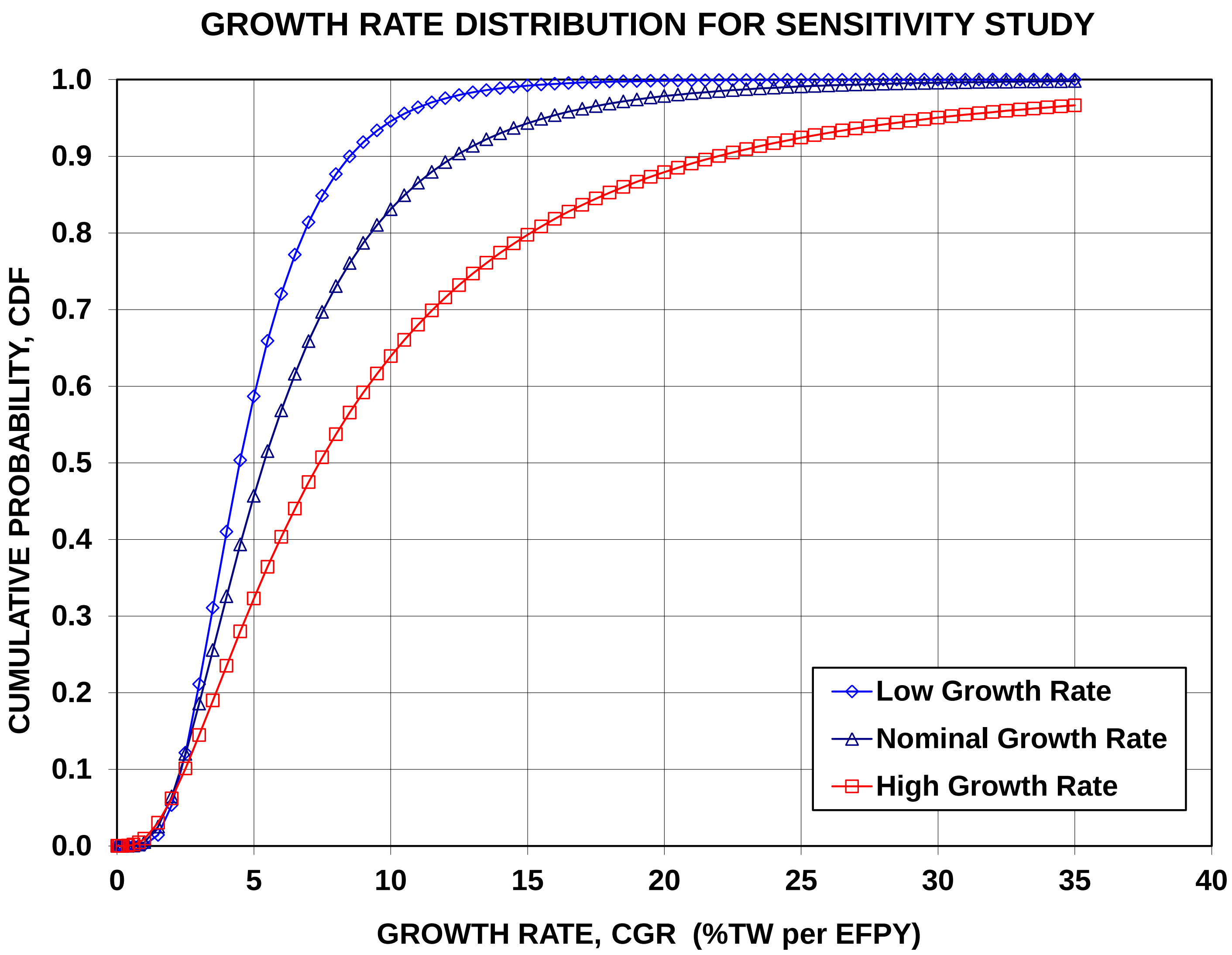
# 5. PROBABILITY OF DETECTION




Eddy current test techniques are the primary examination methods. Logistic or log-logistic functions typically are used to represent the POD behavior

# 5. AXIAL ODSCC GROWTH RATE MODELS

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



# 5. BURST PRESSURE FOR WORST TUBE

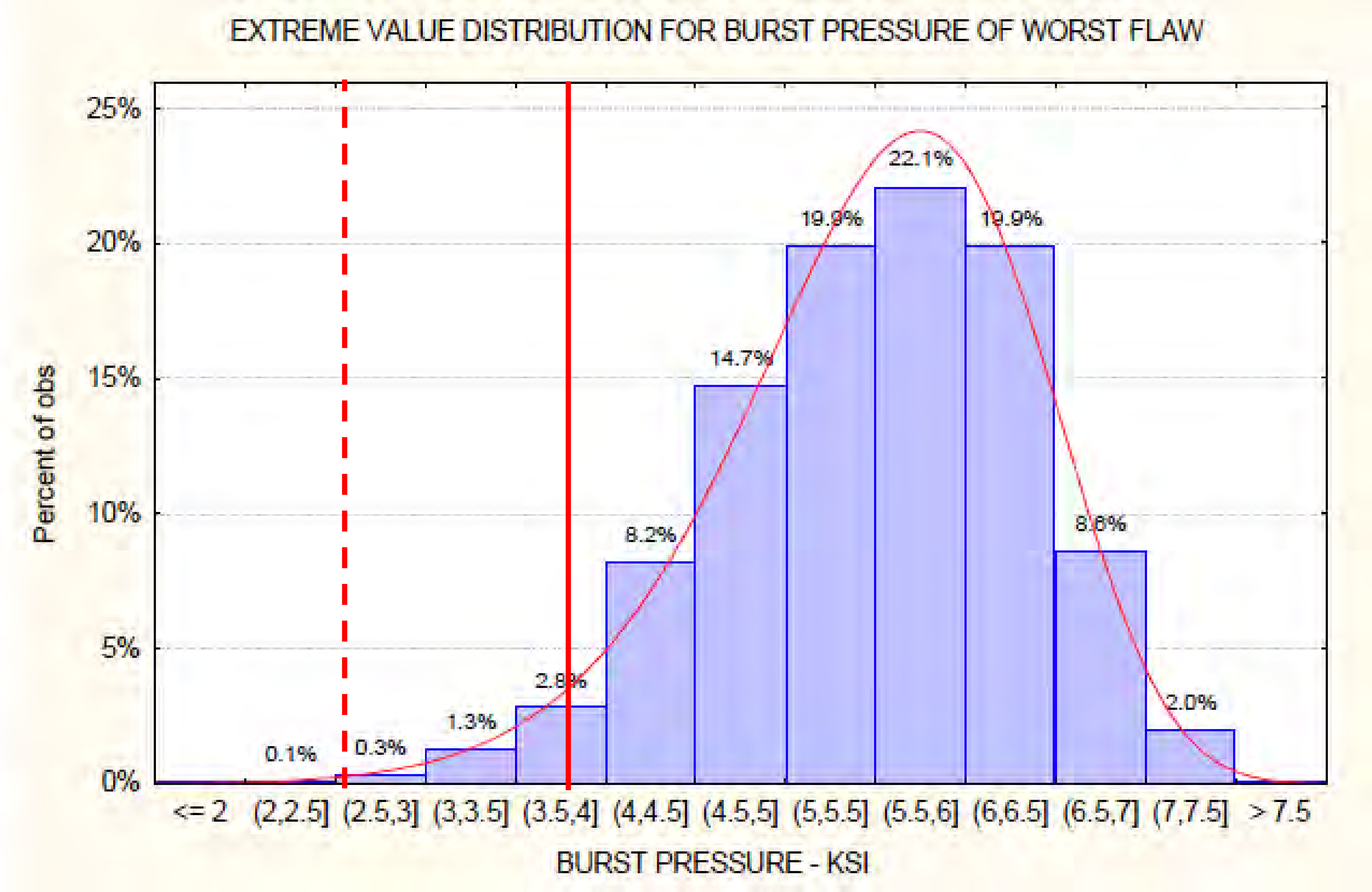
**EXAMPLE ASSESSMENT**

SIPC Margin = 3,800 psi
LAPD Margin = 2,500 psi

POB = Area under one-sided left tail of PDF

SIPC margin is met if POB < 5%
LAPD margin is met if POB < 1%

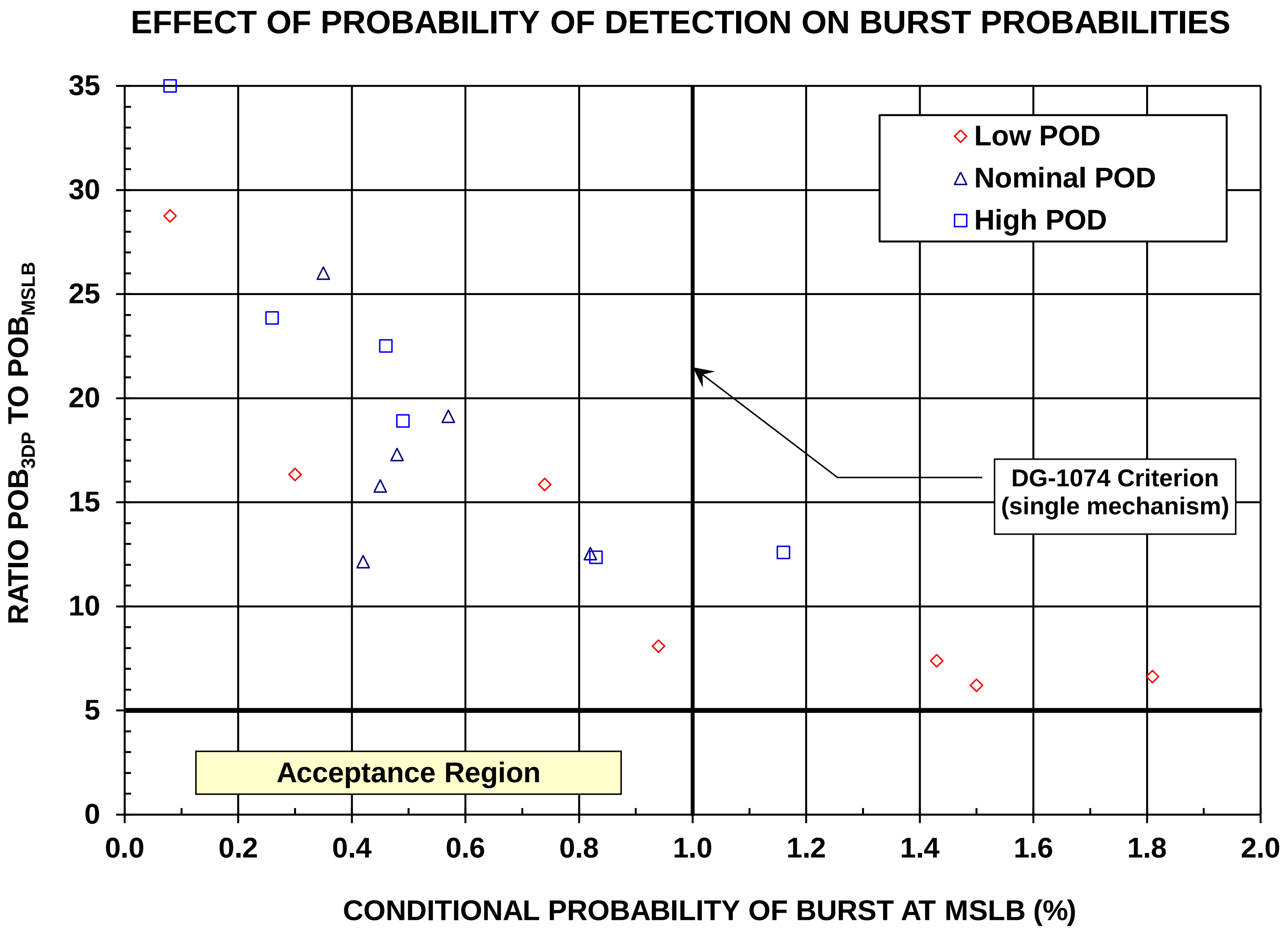
Typically use a median ranked CDF to determine POB or use a nonparametric analysis of the Monte Carlo results




**Probability Density Function (PDF)**

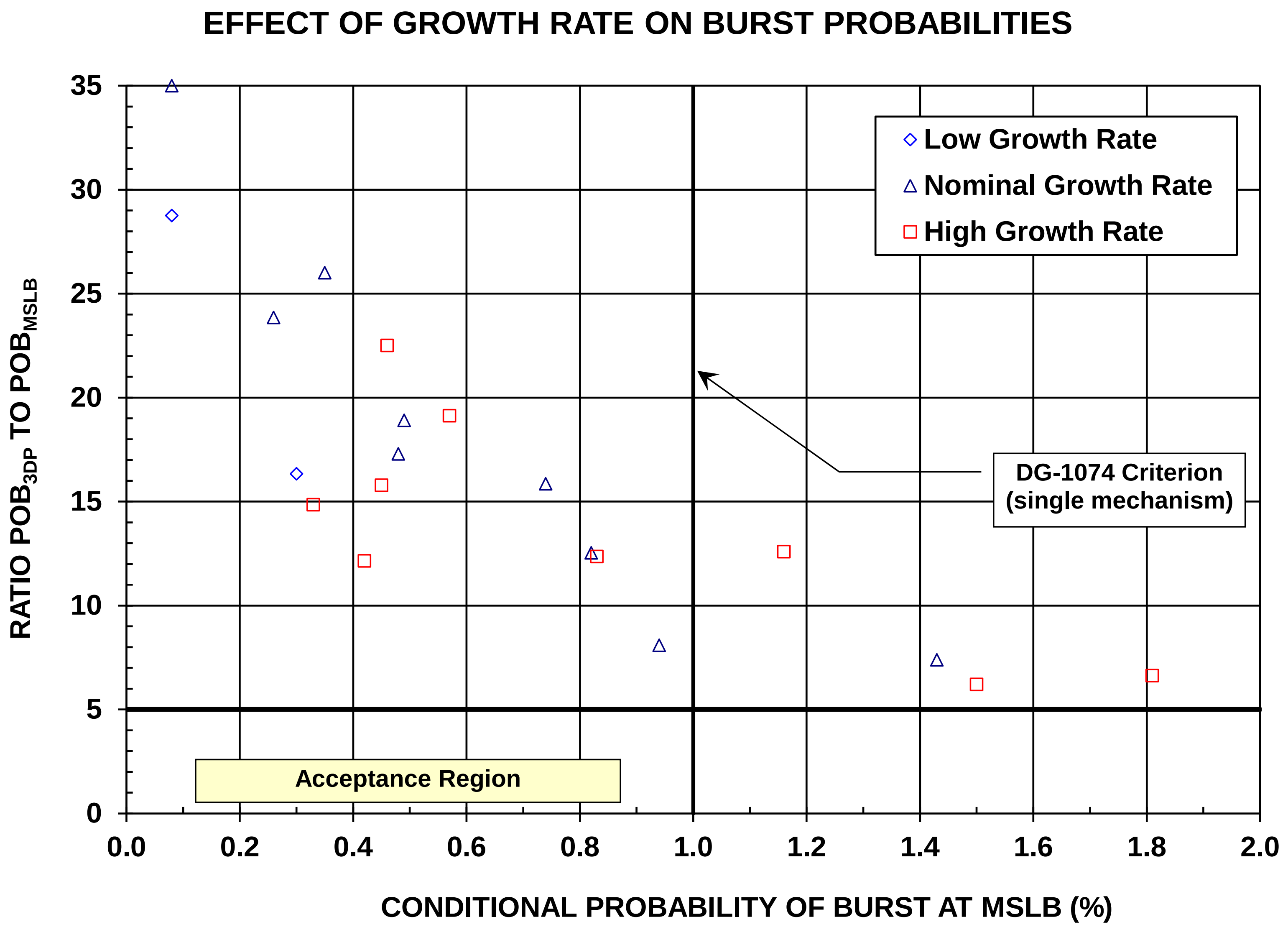
# 5. RESULTS FOR POD SENSITIVITY

Low Probability of Detection (POD) performance is the most challenging to the probability of tube burst.



# 5. RESULTS FOR GROWTH RATE SENSITIVITY

High growth rates or nominal growth rates with low POD are the most challenging to the probability of tube burst under accident conditions



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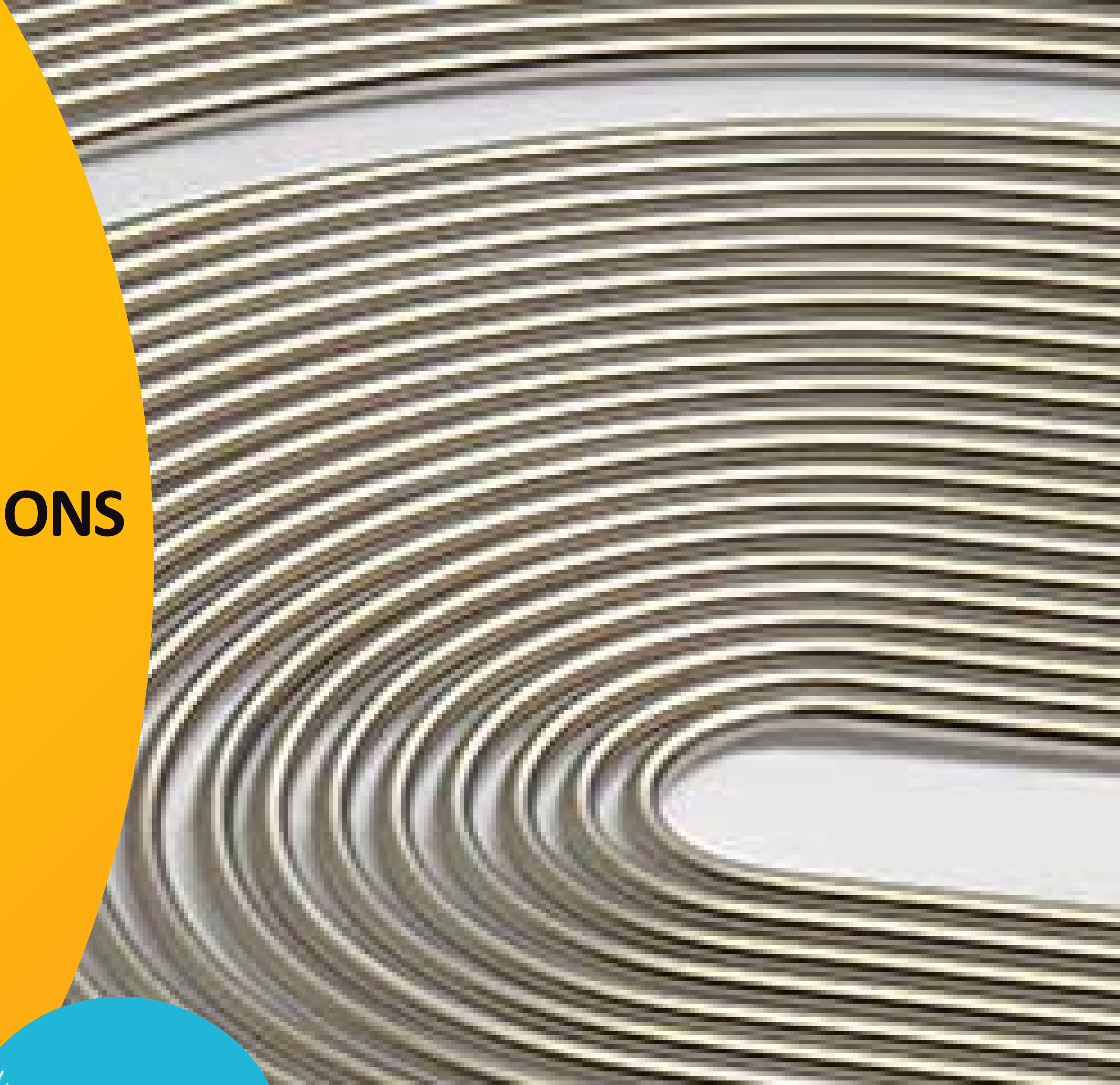
# SUMMARY AND CONCLUSIONS



# 6. SUMMARY AND CONCLUSIONS

- Tube integrity (burst and leakage) is regulated through US Plant Technical Specifications
- The basis for the Structural Integrity Performance Criterion (SIPC) is the ASME Section III Code as outlined in US NRC RG 1.121
- The Performance Acceptance Standards for meeting the SIPC margin requirement follow from US NRC DG-1074 where the conditional probability of burst (POB) for one or more SG tubes is not to exceed $1 \times 10^{-2}$ under design-basis accident events
- Comparative calculations among fully probabilistic POB projections show that meeting POB < 0.05 at SIPC margin requirement for the worst-case degraded tube will also satisfy the POB of 0.01 for postulated accident conditions (main steam line break concurrent with a safe shutdown event)
- Operational Assessment for tube integrity is a prime example where industry accepted probabilistic methodology and performance acceptance 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

# ACKNOWLEDGEMENTS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