Westinghouse Probability Based Simulation Model for Predicting Baffle-Former Bolt Failures (Non-Proprietary)

January 2017

Westinghouse Electric Company
1000 Westinghouse Drive
Cranberry Township, PA 16066

Westinghouse Probability Based Simulation Model for Predicting Baffle-Former Bolt Failures

NRC Meeting

January 10, 2017

Randy Lott
John McFadden
Doug Holderbaum

Westinghouse

Objective of Meeting

- Familiarize NRC Staff with Westinghouse probability-based simulation model for predicting baffle-former bolt failures
  - Anticipate that this model will be used to support multiple utility objectives including:
    - Development of technical basis for revisions to MRP-227-A
    - Optimization of bolt replacement patterns
    - Assessment of degradation in replacement bolts
    - Determination of re-inspection intervals following bolt replacement
  - Do not anticipate submitting model for formal safety evaluation at this time

Westinghouse

Drivers for Development of Bolt Failure Model

- Differentiate plants based on configuration and bolt history
  - 2-Loop, 3-Loop, 4-Loop
  - Upflow versus Downflow
  - Bolt design and bolt material
- Support various specific plant needs
  - Decision making
  - Risk management
  - Operability assessments
  - Bolt replacement pattern design
- Provide technical basis for updates to MRP-227 Inspection & Evaluation guidance

Model must reliably predict bolt performance beyond current OE

Westinghouse

Westinghouse BFB Predictive Methodology - Phenomenological Approach to Explain Bolt Failure OE

- Require a methodology that links probability of bolt failure to relevant input and dynamic parameters

- Approach combines Westinghouse analytical tools with materials data and operating experience to create a dynamic probabilistic prediction of baffle bolt failure distributions with quantified uncertainties
  - Models irradiation assisted stress corrosion cracking (IASCC)
  - Westinghouse uses existing models for estimating relevant input parameters such as bolt stress, temperature, dose, and gamma heating

Westinghouse

Phenomenological approach required to predict bolt response outside current experience base

Background

2005: Westinghouse data and analysis (Conermann, Shogan, Fujimoto, Yonewzama and Yamaguchi, *Env. Deg.*) formed basis for MRP-175 fluence/stress based approach to IASCC
- No data available for long time (>100,000 hrs), low stress (<20ksi) conditions
- Subsequent testing has suggested lower stress thresholds for long time exposures (MRP-211)

2008: Original baffle bolt failure models (MRP-230) attributed IASCC to high stresses at corner bolt locations caused by void swelling due to high local heating and neutron fluence (basis for MRP-227)

2010: Observation of large cluster of failed bolts observed at DC Cook raised concern about apparent bolt interactions
- Westinghouse issued TB-12-05

2012: Westinghouse developed Monte Carlo-based prototype to demonstrate potential for random bolt failures to initiate a cascading failure event

2012-2016: Westinghouse innovation program supports development of baffle-bolt lifetime prediction model

2016: MRP-227-A inspections at Indian Point Unit 2 and Salem Unit 1 revealed clusters of failed bolts
- Westinghouse issued NSAL-16-01

2016: Westinghouse accelerated effort to generate bolt failure model based on experience with Monte Carlo-based prototype

Westinghouse

Critical Characteristics of Defendable Predictions

- Capable of predicting bolt failure patterns that are consistent with OE
  - Differentiation based on key variables: stresses, displacements per atom (dpa), age, temperature, plant design, bolt design, and bolt material
- Able to assess the timing and magnitude of stress redistributions
  - Include best available inputs from existing analyses - e.g., Acceptable Bolting Pattern Analysis (ABPA), Neutronics, and plant-specific operational history
- Consistent with observed bolt failure mechanisms
  - Statistically-based to account for stochastic character of IASCC initiation
- Capable of analyzing both replacement and original bolts
  - Maintain historical IASCC exposure for bolts left in place and reset for new bolts

- **Predictive model requires evaluation of bolt failure mechanisms**
- **Empirical models cannot project behavior beyond current OE**

Westinghouse

Functional Requirement: Consistent with Observed Failure Scenarios

- **Randomly Distributed**
  - Hypothesis: IASCC failure rate governed by stress, temperature, dose, time
  - Key variables: Material, Plant Design, Bolt Design
  - A simple statistics-based empirical (e.g., Weibull Distribution) fit and comparisons between plants can be used in this case.
- **Dose-Related**
  - Hypothesis: IASCC failure rate driven by temperature and stress from high dose rates which causes local acceleration
  - Key variables: Fluence, Gamma Heating, Irradiation Creep, Void Swelling
  - Good correlation with deterministic results from existing MRP aging model (IRRADSS Model): Analysis predicted 60-year stress patterns similar to bolt failure experience in French CP0 plants
- **Clustered**
  - Hypothesis: IASCC failure rate still affected by same parameters as random distribution but local stress increases around groups of adjacent failed bolts due to transfer of primary loads
    - Particular issue for downflow configuration plants due to high baffle plate ΔP

Westinghouse

Emphasis here is on randomly distributed and clustered scenarios

Causes of Clustered Distribution of Failures

- **Option 1**: Failures have a common cause that localizes the effects of IASCC or fatigue
  - Stress anomaly
  - Asymmetric fatigue
  - Local hot spot
  - Bolt source or installation sequence

- **Option 2**: Failure propagates after initial random failures reach a critical level
  - Failures are random until adequate clusters of failed bolts form
  - Probability of failure in neighboring bolts increases with the increased load
  - Group of bolts "cascades" as more and more adjacent bolts fail

Westinghouse

Models Required to Predict Bolt Failure Probability

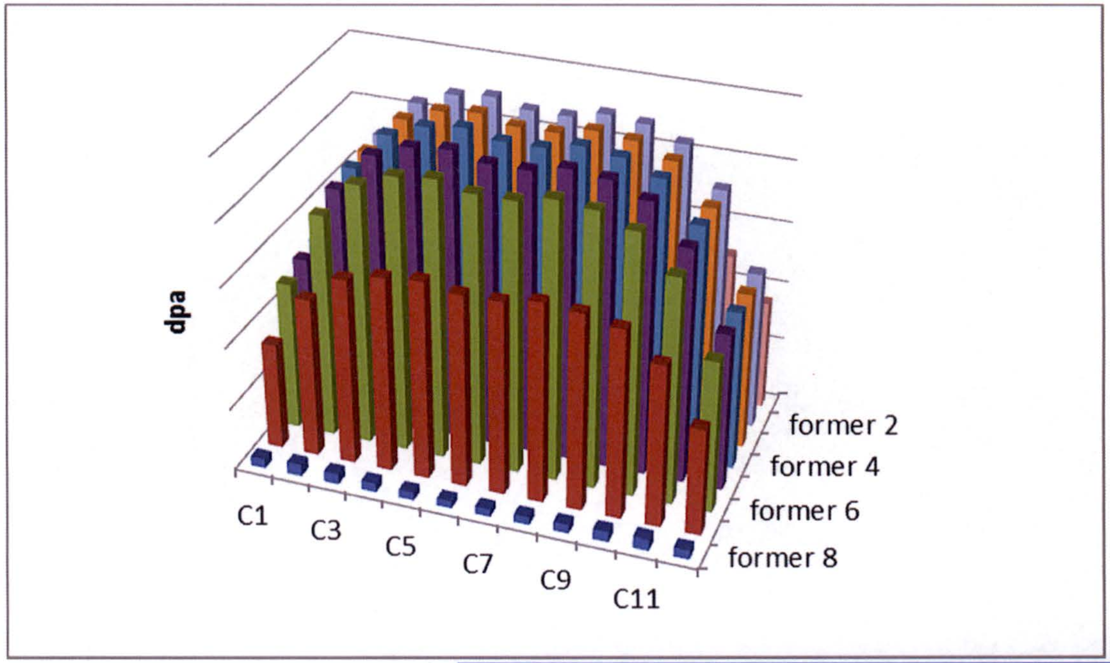
- Fluence Model
  - Maps of dpa rate at each bolt location
- Thermal Model
  - Map of bolt temperatures
- Irradiation Aging Model
  - Embrittlement
  - Creep/Stress Relaxation
  - Void Swelling
- Structural Model
  - Primary Stresses (Pressure and weight)
  - Secondary Stresses (Thermal and pre-stress)
- Bolt Failure Model
  - Probability that individual bolt will fail in time increment Δt
  - Failure rate = $f(\sigma, \phi t$, Temp., Age, material, design)

Multiple inputs required to predict behavior beyond what has already been observed

Westinghouse

Fluence Model

Fluence Map of Large Baffle Plate in Westinghouse 4-Loop Downflow Plant



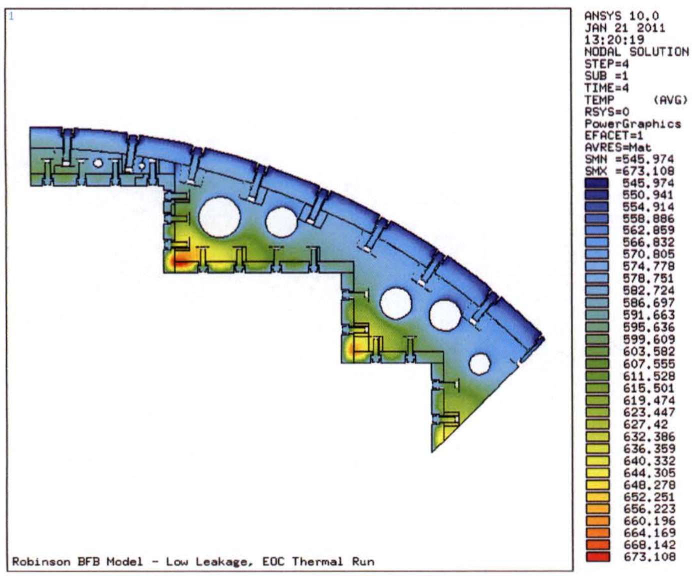
dpa rate at each bolt location

Westinghouse

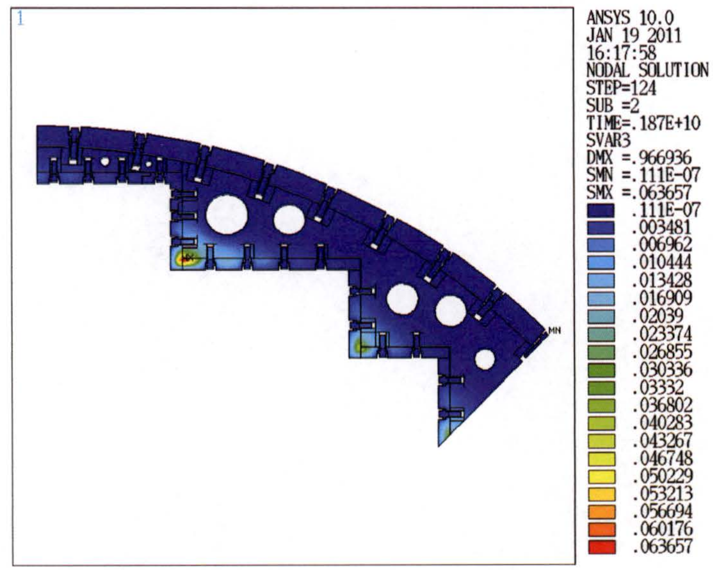
Thermal Model/ Irradiation Aging Model

- Based on MRP-230/232 model

Temperature Distribution for Low-Leakage Core Loading Pattern



Irradiation Growth (VS) Strain Predicted at 60 Years of Operation



Westinghouse

Structural Model

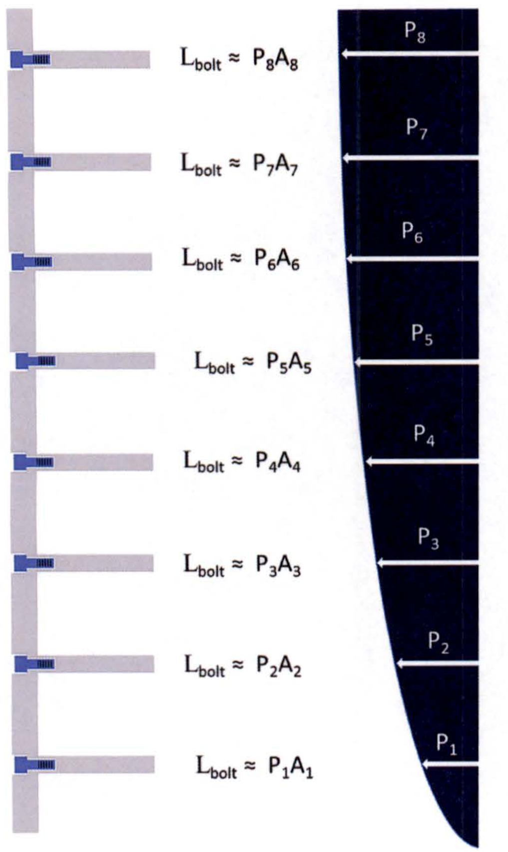
Sources of Stress on the Bolts

- Secondary Stresses
  - Preload – installation torque
  - Thermal – due to gamma heating and heat removal
  - Both are included in the design loads and ABPA modeling
  - Do not transfer to adjacent bolts upon bolt failure
- Primary Stresses
  - Due to dead weight and pressure loads
  - Included in ABPA modeling and addressed in the design (initially small compared to the secondary stresses)
  - Depends on the flow and location in the baffle-former assembly

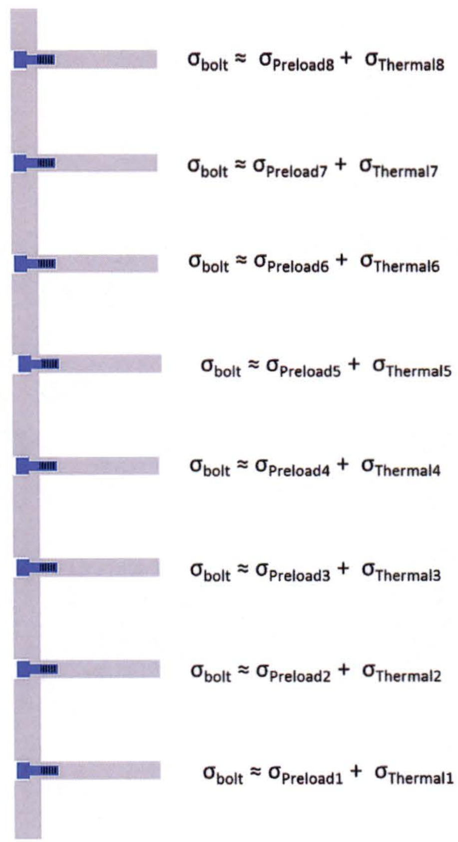
Design information is required to correctly address stress effects

Westinghouse

Stress Redistribution to Adjacent Bolts



Primary Stress (Pressure)



Secondary Stress

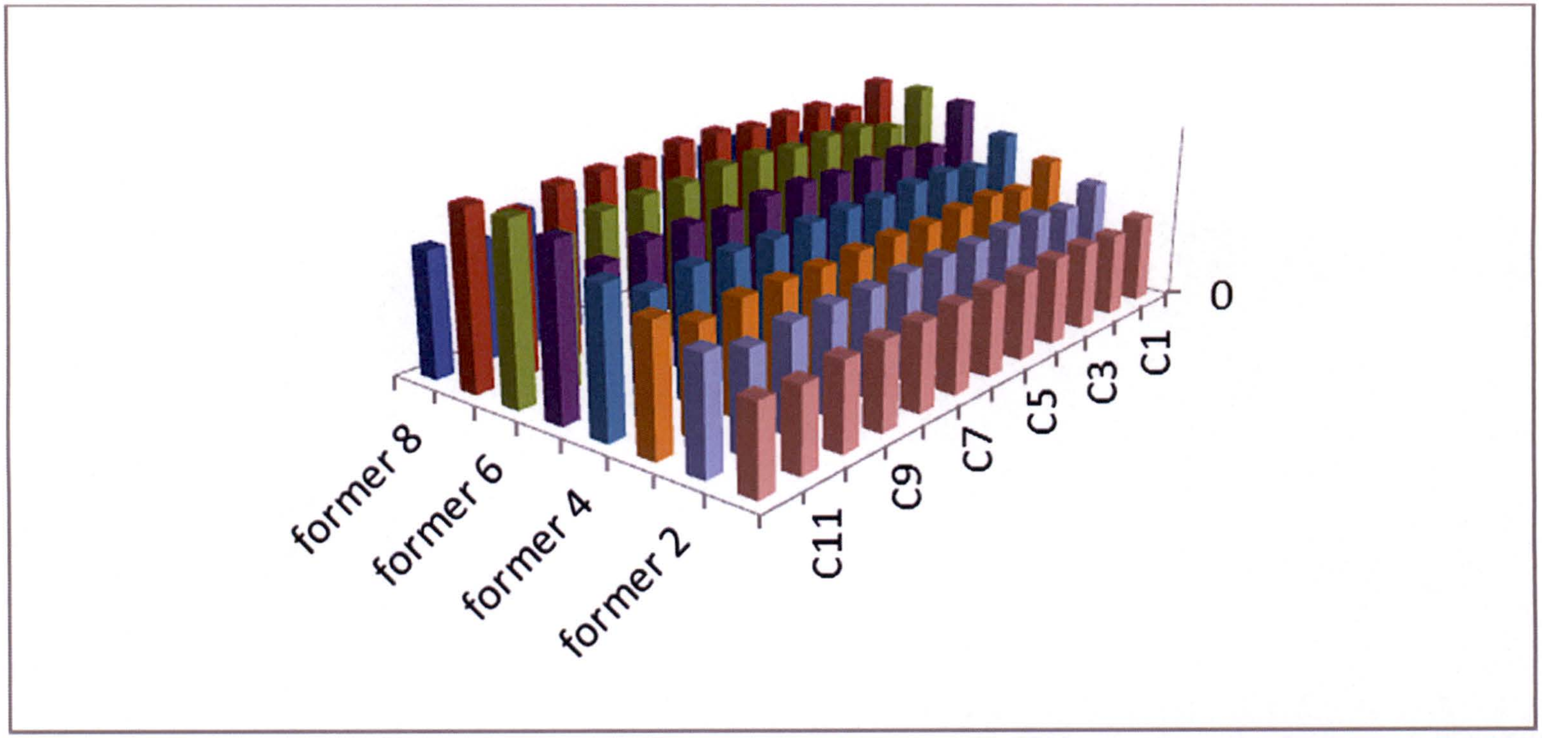
Secondary stresses predominant in early life (bolt preload)

But do not redistribute with failure

Irradiation-Induced Stress Relaxation diminishes secondary stresses over time

Westinghouse

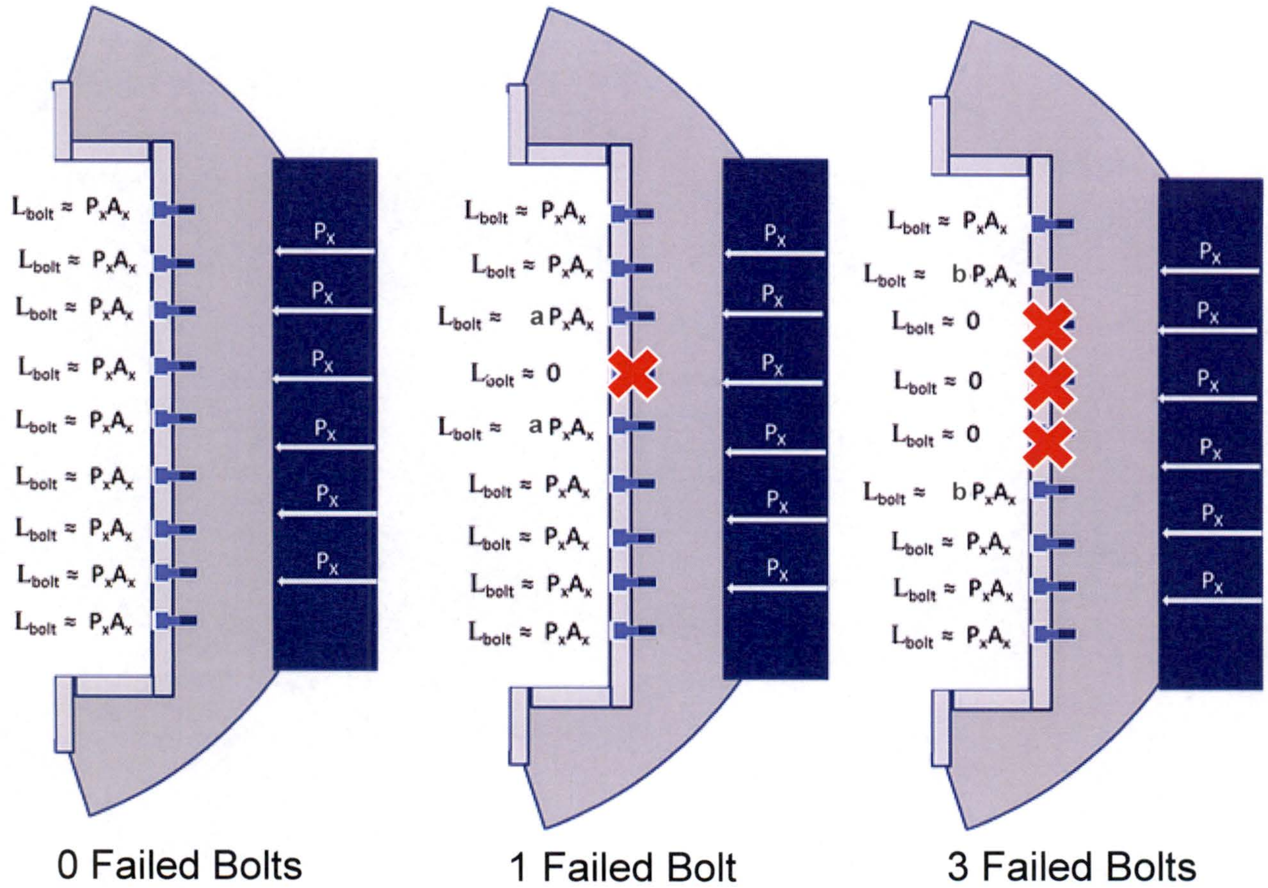
Bolt Axial Stress Distribution for Large Plate in 4-Loop Downflow Plant



Primary membrane stress from ABPA. Assumes 80% preload relaxation, no thermal stress

Westinghouse

Horizontal Primary Stress Variation in Downflow Design
Stress Redistribution to Adjacent Bolts



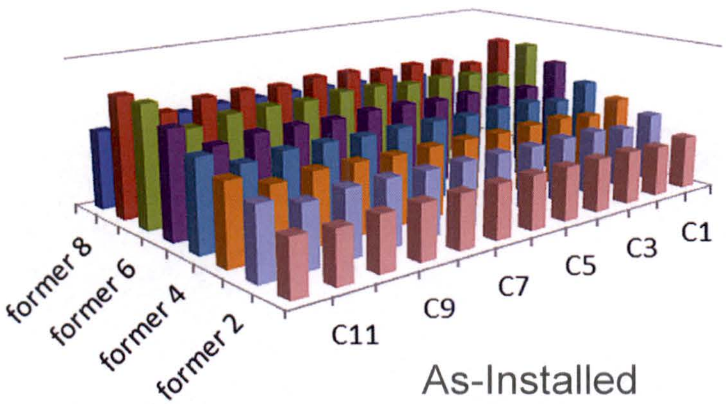
Primary stresses dominate after irradiation stress relaxation occurs.

Stress redistributes as bolts fail.

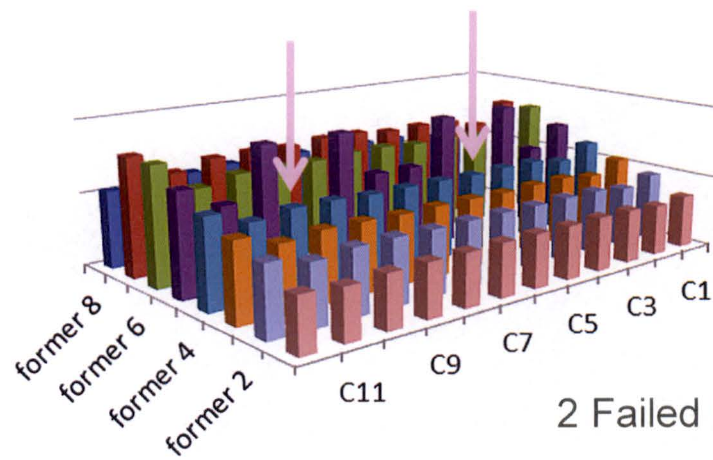
First order approach shown in figure: b > a > 1

Westinghouse

Bolt Load Distribution for Large Plate in 4-Loop Plant Isolated Bolt Failure



As-Installed
80% Relaxation



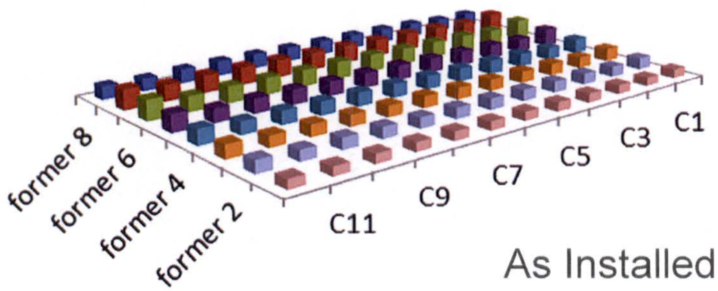
2 Failed Bolts

ABPA Provides Tool for Assessing Bolt Load Re-distribution

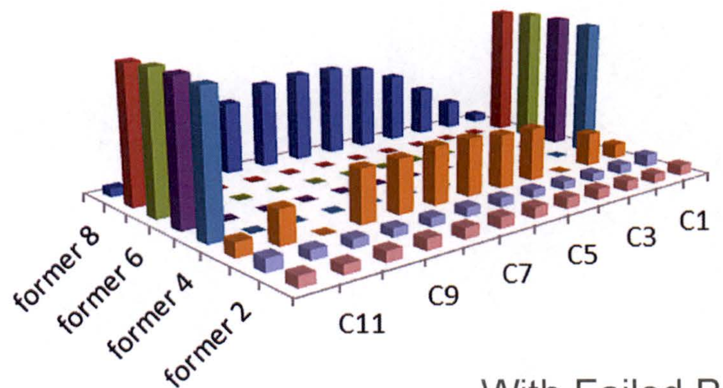
Westinghouse

Bolt Load Distribution for Large Plate in 4-Loop Plant
Clustered Bolt Failure

Re-scaled from previous slide



As Installed

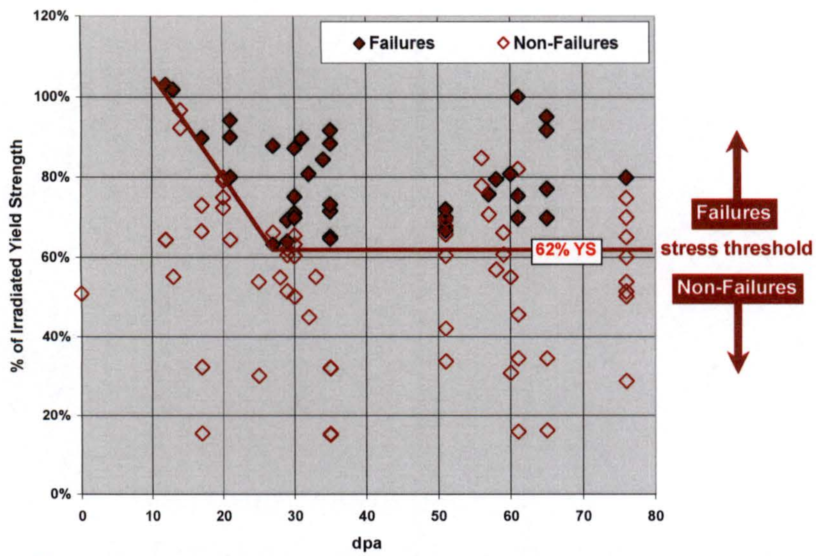


With Failed Bolts

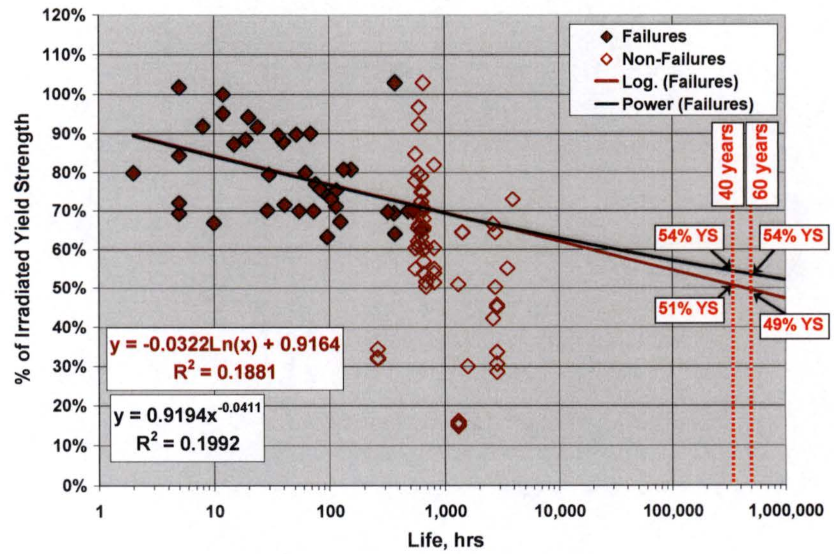
Large clusters grow due to failure of bolts on periphery of cluster

Westinghouse

Existing Bolt Failure Model Based on Laboratory Data



O-Ring test results presented as % of irradiated yield strength versus dpa with apparent stress threshold shown



O-ring test results presented as % of irradiated yield strength versus log life with extrapolation to reactor operating lives and log and power fits provided

Westinghouse

Figures from:
Freyer, P.D., Mager, T.R., and Burke, M.A., "Hot Cell Crack Initiation Testing of Various Heats of Highly Irradiated 316 Stainless Steel Components Obtained from Three Commercial PWRs,"13th International Conference on Environmental Degradation of Materials in Nuclear Power Systems, Whistler, British Columbia, August 19-23, 2007.

Probabilistic Model of IASCC Initiation

- IASCC initiation is a stochastic process
  - Must be analyzed statistically
- Weibull coefficients for bolt failure <u>must be modified</u> to reflect dependence on key variables (stress, dpa, material ...)

Weibull Cumulative Failure Probability

$$F(t) = 1 - \exp\left(-\frac{t^k}{\lambda}\right)$$

t = time (or dose)
k = shape factor
λ = scale factor

- Key variables are changing with time
  - Weibull coefficients are not constant

Strategy for modeling probability of failure for each bolt as a function of time makes Westinghouse simulation model unique

Westinghouse

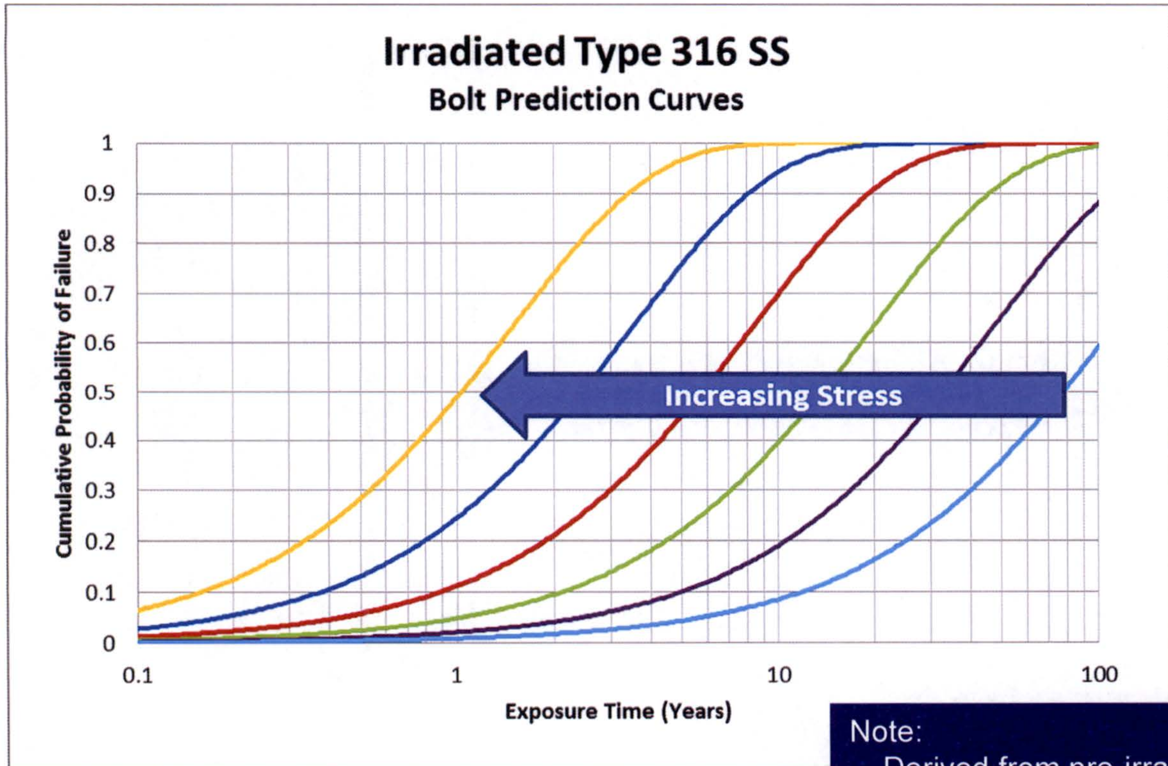
Basis for Westinghouse Bolt Failure Model

- **Goal: Bolt failure rate as function of applied stress, dpa, age,…**
  - Two sources of data available:
    - Laboratory IASCC initiation testing results
    - Baffle bolt inspection operating experience
  - Stress effect determined from laboratory data
    - Test data have a well-known applied stress
    - Data available across a range of stresses
    - Data do require some extrapolation which can be compared to operating experience
  - Weibull Shape factor determined from fitting to both laboratory data and OE and comparing
  - Weibull Scale factor based on baffle bolt inspection results
  - Additional effect of low doses in early life addressed

Must use both sets of data

Westinghouse

Weibull Based Stress Dependent Bolt Failure Model



Note:
- Derived from pre-irradiated specimens.
- Delay added to model for time to reach saturation of irradiation effects.

Westinghouse

Operating Experience Data Considered for Model

a,c

Westinghouse

Simulation Process

a,c

Westinghouse

Example Time-Dependent Bolt Failure Pattern

a,c

Bolt Replacement and New Failures are Simulated

Westinghouse

Illustrative Example of Simulation Results

a,c

Westinghouse

Summary of Westinghouse Model for Baffle-Former Bolt Failures

Predictive approach considers the dynamic and inter-dependent interactions between:

- BFB stresses verified by finite element analysis
  - Dynamic stress re-distribution as bolts break
  - Knowledge of acceptable vs. unacceptable bolting patterns
- Weibull parameters validated by lab test results and OE
  - Lab Data—Weibull shape factor and scale dependence on stress
  - OE—Weibull shape and tuning lab-based scale parameters
- Dose effects on IASCC

[ ] a,c

… to determine a future probability of BFB failure

Westinghouse

Summary

- Westinghouse methodology is based on a mechanistic understanding allowing verified and validated use of:
  - Finite element analysis of the baffle-former assembly
  - Operating experience from PWRs
  - Laboratory test results of IASCC

Westinghouse

Thank You

Westinghouse