Westinghouse Baffle-Former Bolt Predictive Methodology

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Agenda

- Introductions and Opening Remarks
- Background
- Predictive Methodology
  - Basis and Development
  - Sensitivity and Validation
  - Application
- Discussion of Recent Operating Experience
  - Description of Event
  - Results of Westinghouse Investigation
  - Next Steps
- Conclusion and Further Questions

Methodology Development - Overview

- Early development started after first BFB clustering degradation observed at D.C. Cook Unit 2 in 2010
  - Previous modeling efforts focused on empirical projections, usually with dose as a major driver based on EdF experience
  - Clustering pointed to stress as a significant factor
- Shift to considering stress spurred re-evaluation of the IASCC laboratory initiation data
- Recognition of how the degradation rate can vary locally based on stress and dose was the foundation for development of a "semi-empirical" model rather than empirical
- Where to start with developing the model?

Methodology Development – Initial Steps

- Determine the degradation mechanism
  - Concluded that IASCC initiation is the governing mechanism based on failure analyses of degraded bolts
  - Influences the type of reliability distribution to use
  - Limits the supporting laboratory data to use
- Evaluate the laboratory and operating experience data
- Select the reliability distribution model
- Derive form and values for the model parameters and uncertainty and calibrate model

Review of methodology development will include input data used, model form, derivation of parameters, treatment of uncertainty, and calibration

Methodology Development – Input Data

- Data from two sources:
  - Laboratory IASCC initiation testing
  - Industry ultrasonic testing (UT) inspection results for BFBs (including results for visibly degraded bolts)
- Laboratory Data
  - Reliability model selection
  - Validation of model parameters
  - Form and values for stress and dose dependencies
- UT operating experience data
  - Calculation of model parameters
  - Calibration of model based on plant design

Methodology Development – Laboratory Input Data

- Type of test results

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- Material for the results was Type 316SS
  - Material at a mix of cold work levels
  - Data for other material types is very limited
- Most of the available austenitic SS IASCC initiation data is now summarized in MRP-211, revision 1, published in 2017

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Methodology Development – BFB UT Input Data

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- Model built on these inspection results used to date for plant analyses
- Model recently updated with later inspections:

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- Only used UT volumetric data and visibly failed bolts
- Mix of designs and bolt materials (Type 316 and Type 347)
- Lab failure analyses have confirmed IASCC initiation (plants with *)

Model Form – Requirements for BFB Predictions

- Ability to predict clustering that is consistent with operating experience
- Ability to assess the timing and magnitude of stress redistributions
- Must be consistent with observed bolt failure mechanisms
- Statistically based to account for stochastic character of IASCC initiation
- Differentiation based on key variables: stresses, dpa, age, temperature, plant design, bolt design, and bolt material
- Include best available inputs from existing analyses - e.g., finite element modeling, neutronics, and plant-specific operational history
- Capability to analyze bolt replacement while maintaining historical IASCC exposure for bolts left in place

Empirical models are not necessarily suitable for prediction because they are limited to range of variables included in correlation.

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Methodology Development – Model Form

- BFB UT inspection results evaluated using Weibull distribution
- Weibull distribution widely used for reliability and life analyses
  - Provides probability of failure as a function of time in this case
  - Used the two-parameter version of the distribution
  - Has flexibility to represent distributions by changing shape factor
  - Applied in the nuclear industry previously for Alloy 600 degradation

pdf: $$f(t;k,\lambda) = \frac{k}{\lambda^k} t^{k-1} e^{-\left(\frac{t}{\lambda}\right)^k}$$

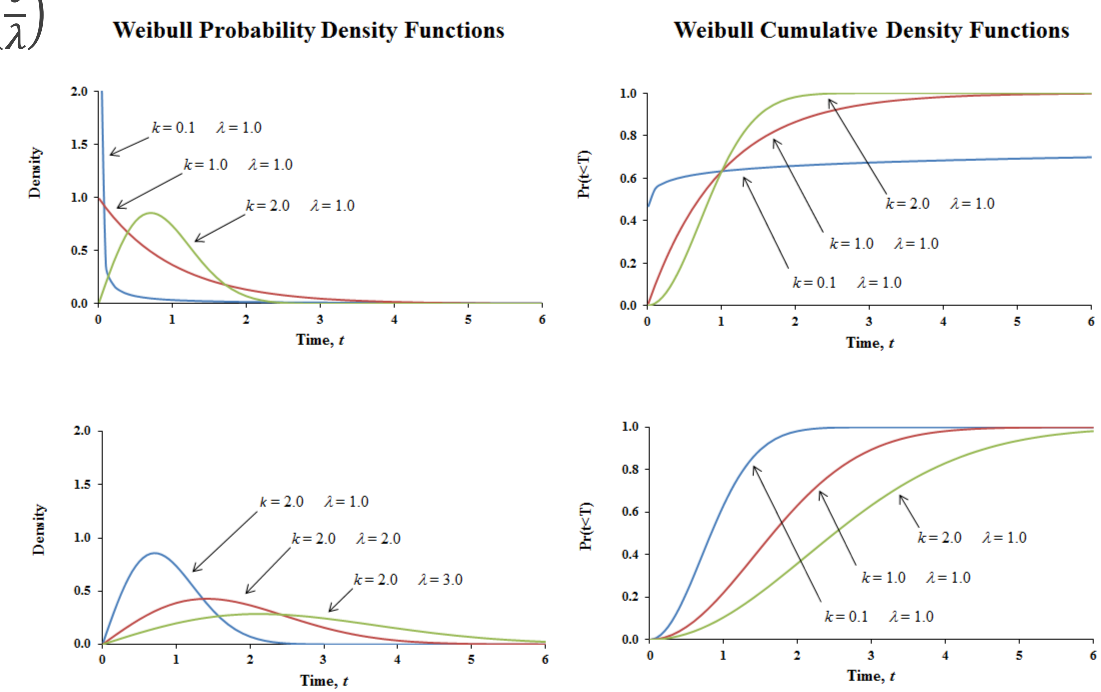
cdf: $$F(t;k,\lambda) = 1 - e^{-\left(\frac{t}{\lambda}\right)^k}$$

t = time

k = Weibull shape parameter

λ = Weibull scale factor

e = natural number.



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Methodology Development – Shape Factor

- Weibull shape factor describes the degradation mechanism (IASCC initiation)
- Shape factor independently developed from both laboratory data and UT inspection data

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- Shape factors from both data sets compared well

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Methodology Development – Lab Data Shape Factor

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Methodology Development – OE Shape Factor

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Methodology Development – Scale Factor Basis

- Shape factor should not vary due to design or operation if IASCC continues as limiting mechanism
- Scale factor/"characteristic life" accounts for design and operation
- Key IASCC variables: stress, dose, temperature, water chemistry, and material

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- Final form of scale factor addresses mechanistic effects of stress and dose directly
- Other effects addressed empirically through calibration to OE

cdf: $$F(t;k,\lambda) = 1 - e^{-\left(\frac{t}{\lambda}\right)^k}$$

λ = Weibull scale factor

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Methodology Development – Scale Factor Form

- Form developed based on lab and OE data
  - Past evaluations of OE supported focus on stress and dose
  - Non-linear regression of lab results determined stress dependence
  - Lab data trends and judgment used to determine dose dependence

Scale Factor: $$\lambda_i = \left. \frac{e^a}{\left(\frac{\sigma_i}{S_y}\right)^b} \middle/ {1-e^{-\left(\frac{t_i \times dpa}{d_0}\right)^c}} \right.$$

Where

- σ_i = applied stress at time step i (from finite element model)
- S_y = yield strength of the material
- dpa = radiation dose rate in displacements per atom per unit time
- t_i = time at step i
- d_0 = adjustment factor used to tune the dose effect
- b = stress exponent from lab data regression analysis
- a = fitting parameter for model calibration

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Methodology Development – Stress Exponent

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Methodology Development – Stress Modeling

- Initial pressure & preload stress for normal operating conditions provided by NRC-approved acceptable bolting pattern (ABPA) methodology*

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* WCAP-15029-P-A

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Methodology Development – Stress Model Example

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Methodology Development – Treatment of Dose

- IASCC does not occur at 0 dpa
  - Threshold of 3 dpa for IASCC is reasonable per MRP-175
  - Many radiation effects saturate by 10 dpa
- Rate of increasing effect between 0 and 10 dpa is unknown
- Several forms to increase radiation effects considered

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Methodology Development – Summary of Inputs

- Multiple inputs are used in the model
  - BFB initial normal operation preload and pressure stress
  - BFB dose history and projections
  - BFB geometry – stress concentration factor under the head
  - Baffle-former assembly geometry
  - Differential pressure distribution across the baffle plates
  - Past inspection results and replacements
  - Coolant temperature
- Uncertainty for these variables is included with the inputs
- Several model parameters developed during model derivation also include uncertainty for the model and certain inputs

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Methodology Development - Uncertainty

- Model parameter uncertainty
  - Weibull shape factor from BFB UT inspection experience
  - Dose threshold
  - Stress relaxation due to neutron radiation
  - Weibull scale factor calibration multiplier

- Input uncertainty
  - Bolt stress from the acceptable bolting pattern analysis
  - Dose at each BFB location
  - BFB stress concentration factor

Methodology Development – Model Uncertainty

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Methodology Development – Input Uncertainty

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Methodology Development - Calibration

- Model built as shown in the previous slides

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Model User Interface

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Model Network Diagram

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Example BFB Prediction Model Outputs (1)

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Example BFB Prediction Model Outputs (2)

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Pattern Evaluation – Predictive Model and ABPAs

- The BFB Predictive Model generates [ ] a,c possible degradation outcomes (patterns) at the end of a specified reinspection interval
- Per PWROG-17071 (update to WCAP-17096), must have a 95% probability of an acceptable pattern at the end of the interval
- Completed plant-specific ABPAs (using the NRC-approved methodology in WCAP-15029-P-A) are a prerequisite for use of the Westinghouse BFB Predictive Model, and are used to assess predicted patterns
- Depending on the level of degradation, various options exist to determine pattern acceptability – from engineering judgement to explicit evaluation

Predictive Model works in conjunction with existing ABPA methodology

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Pattern Evaluation – Acceptable Patterns

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Both approaches use Westinghouse's knowledge and experience in developing acceptable bolting patterns

Pattern Evaluation – Example Checks (Option 2)

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Sensitivity and Validation – Overview

- Model results have been studied and benchmarked to ensure correct data and usage
- Sensitivity studies have evaluated several areas
  - Impact of input variable uncertainty
  - Convergence of the model outputs
- Validation of the model has been supported by comparison to data sets not used in calibration
  - Weibull shape factor comparison to laboratory data already discussed
  - Model projections after inspections and replacements have been compared to follow up inspections at plants
- Sensitivity to population of BFB UT inspection results recently studied in response to operating experience

Sensitivity – Variable Studies

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Sensitivity – Convergence Studies

- Monte Carlo analyses can be dependent on the number of samples simulated
- Evaluated the sensitivity of the key results:
  - Proportion of failed bolts
  - Evaluation of acceptable patterns
- Performing a finite element analysis on each pattern at each time step requires significant time
- Required a balance between convergence and run length

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Sensitivity – Proportion of Failed BFBs Convergence

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Sensitivity – Pattern Analysis Convergence Study

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Validation – Predictions Associated with Initial Calibration Compared to Inspection Results

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Validation – Current Calibration Compared to Inspection Results

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Application of BFB Predictions – Available Outputs

- All results contain a predicted time history – data available for each time step
- Standard outputs:

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- Typical post-processing:

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Predictive Tool in MRP Guidance

- Westinghouse has decades of experience performing Acceptable Baffle-Former Bolting Pattern Analyses (ABPAs) per the NRC-approved guidance in WCAP-15029-P-A
- ABPAs qualify a degraded pattern and historically include a simple and conservative method to account for degradation rate over the next 10 year period (50% margin rule in WCAP-17096-NP-A)
- Possible uses of BFB Predictive Model:

a) Select locations for replacement bolts
   - "Anti-clustering" bolts
   - Pre-emptive replacements

b) Provide input for asset management decisions
   - Projections into extended operation periods
   - Decisions on plant modifications or further bolt replacements

c) Support determination of acceptable re-inspection interval
   - Probability of finding an acceptable pattern with time
   - Consideration of replacement bolts and inspection results

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Spring 2019 Operating Experience

Salem Unit 1 Spring 2019 OE

- Difficulty removing upper internals at Spring 2019 outage
  - Found to be due to thermal shield (TS) support block bolt (TSSBB) impinging on upper core plate
- Upon removal, fuel grid strap damage at two peripheral fuel assemblies was discovered, as well as visual baffle-former bolt damage on neighboring plate
- Follow-up 100% BFB visual exam identified 31 degraded bolts
- Subsequent UT exam identified 196 indications on original bolts, 1 indication on a 2016 replacement bolt, and 3 non-testable bolts
- UT of TSSBBs resulted in 4 bolts with indications
- Subsequent visual exam of TS flexures: 2 flexures with confirmed cracks and 4 flexures with possible/inconclusive indications

Westinghouse BFB Predictive Model Track Record

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Westinghouse Response

- Westinghouse Corrective Action Issue entered and investigation of the Salem predictive model undertaken:
  - No evidence found which would question validity of assumptions and/or underlying mechanics of the model for predicting IASCC initiation
  - Inputs to the predictive model were valid, plant-specific inputs
  - Potential sources of Salem Unit 1 OE identified as
    - Presence of a significant number of false negatives in 2016 UT data
    - Alternate degradation mechanism (possibly related to TS degradation)
- PSEG root cause issued (OE #455142):
  - *"…non-conservative data applied to the Salem Unit 1 plant specific input used in the Westinghouse predictive evaluation…"*
  - Westinghouse does not agree with or endorse this root cause
    - Westinghouse tasked to perform follow-up studies to assess effect of data set used for shape factor (action from the PSEG RCA)
    - Westinghouse also studying the potential connection between the observed thermal shield degradation and the BFBs
  - PSEG recognized that these follow up studies could result in a change to the RCA position by including a future action in the RCA:
    - "*Following completion of failure analysis, engineering evaluations, and Westinghouse limited causal analysis, review Root Cause Evaluation and determine if any changes are necessary to the root and/or contributing causes*"

Results of UT Data Study – PRELIMINARY

- INPO OE Report 455142 pointed to "non-conservative inputs" as a potential cause for discrepancies between predictions and UT results in 2019
  - Specifically the use of all UT inspection data
  - Speculated that only using data obtained under MRP-227 and MRP-228 requirements could provide a different result

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Supports continued validity of the model for prediction of IASCC degradation

Thermal Shield Vibration Investigation (Ongoing)

- How does thermal shield (TS) vibration relate to bolt stresses?
  - Developing dynamic flow-induced vibration (FIV) FEM
  - Includes core barrel, TS, and baffle-former assembly with fluid-coupling in the FEM
  - Benchmarking to 4-loop downflow hot functional test data (modal and forced response)
  - Provides change in baffle bolt, TSSBB, and flexure loads under different scenarios of degradation

Westinghouse Conclusions on Salem Unit 1 OE

- Westinghouse expects that some currently unknown effect has accelerated degradation relative to the predictions
  - Model and inputs have been reviewed and are expected to be applicable to Salem Unit 1
  - UT inspection results did not match the predictions
- Potential examples of effects that could have increased the degradation rate (not a definitive list of all possibilities)
  - Presence of significant numbers of false negatives in the 2016 BFB UT inspection results
  - Degradation mechanism other than IASCC becoming the limiting mechanism
  - Some unknown effect causing higher than expected stress on the BFBs

Further work to investigate possible causes is ongoing

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Questions?

Backup Slides

Methodology Development – Lab Data Filtering Basis

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Validation – Current Calibration Compared to Inspection Results

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Validation – Earlier Calibration Compared to Inspection Results

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