Extremely Low Probability of Rupture (xLPR):

PIB Vertical Slice Review – Treatement of Uncertainty

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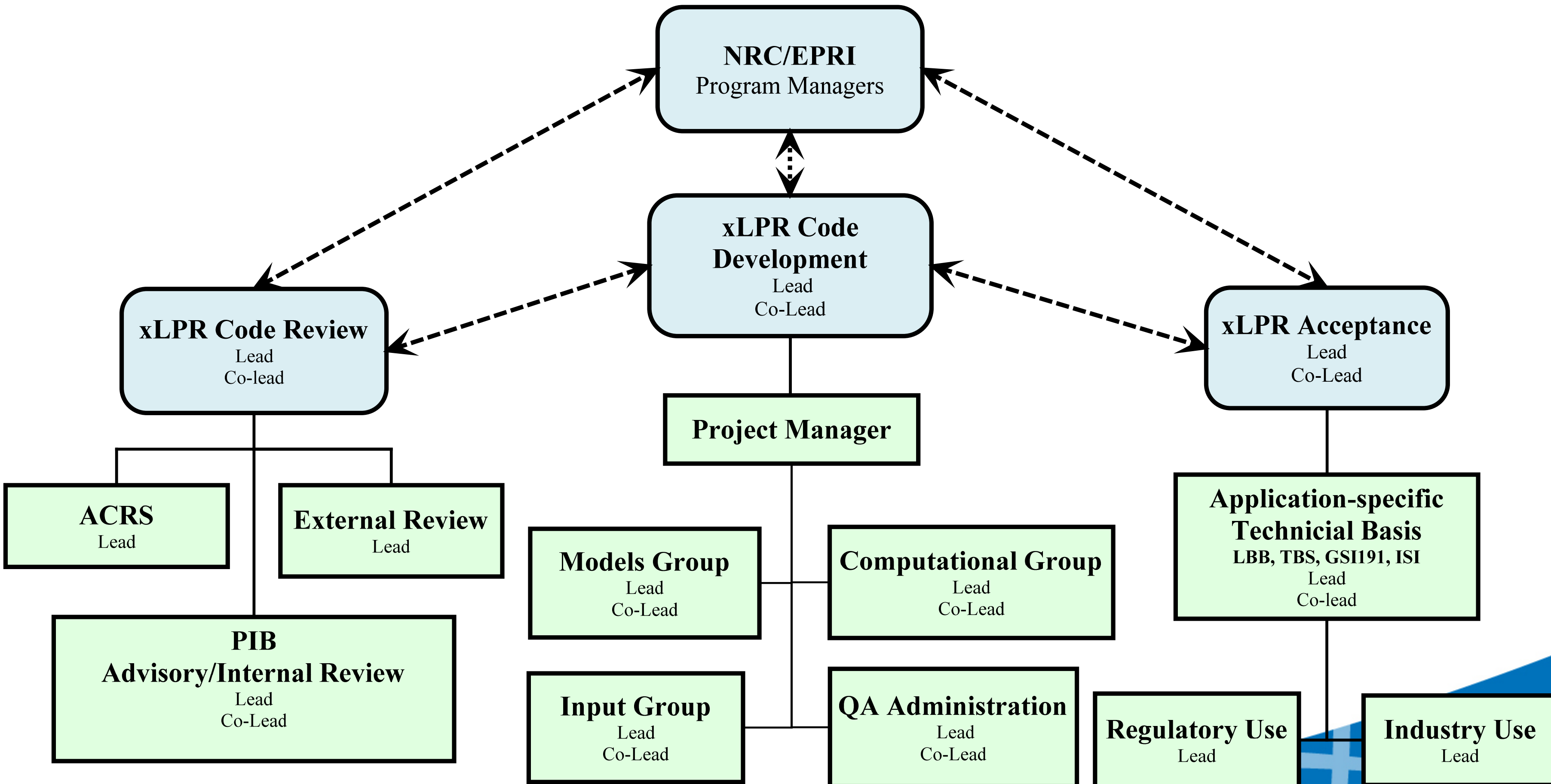
Protecting People and the Environment

Presentation Outline

- Program Integration Board – Overview
- Treatment of Uncertainty in xLPR
- Vertical Slice Review (VSR) Objective & Approach
- Vertical Slice Review Questions
- Initial VSR Responses and Example Results
- VSR Schedule and Use of Results

Program Integration Board – Overview

xLPR Program Management



PIB Roles and Responsibilities

- PIB objective: Provide review, oversight, and independent advice related to the xLPR Project
  - Technical Review and Assessment
    - *Vertical Slice Review*
  - Issue Review and Resolution
  - Project Management Assessment

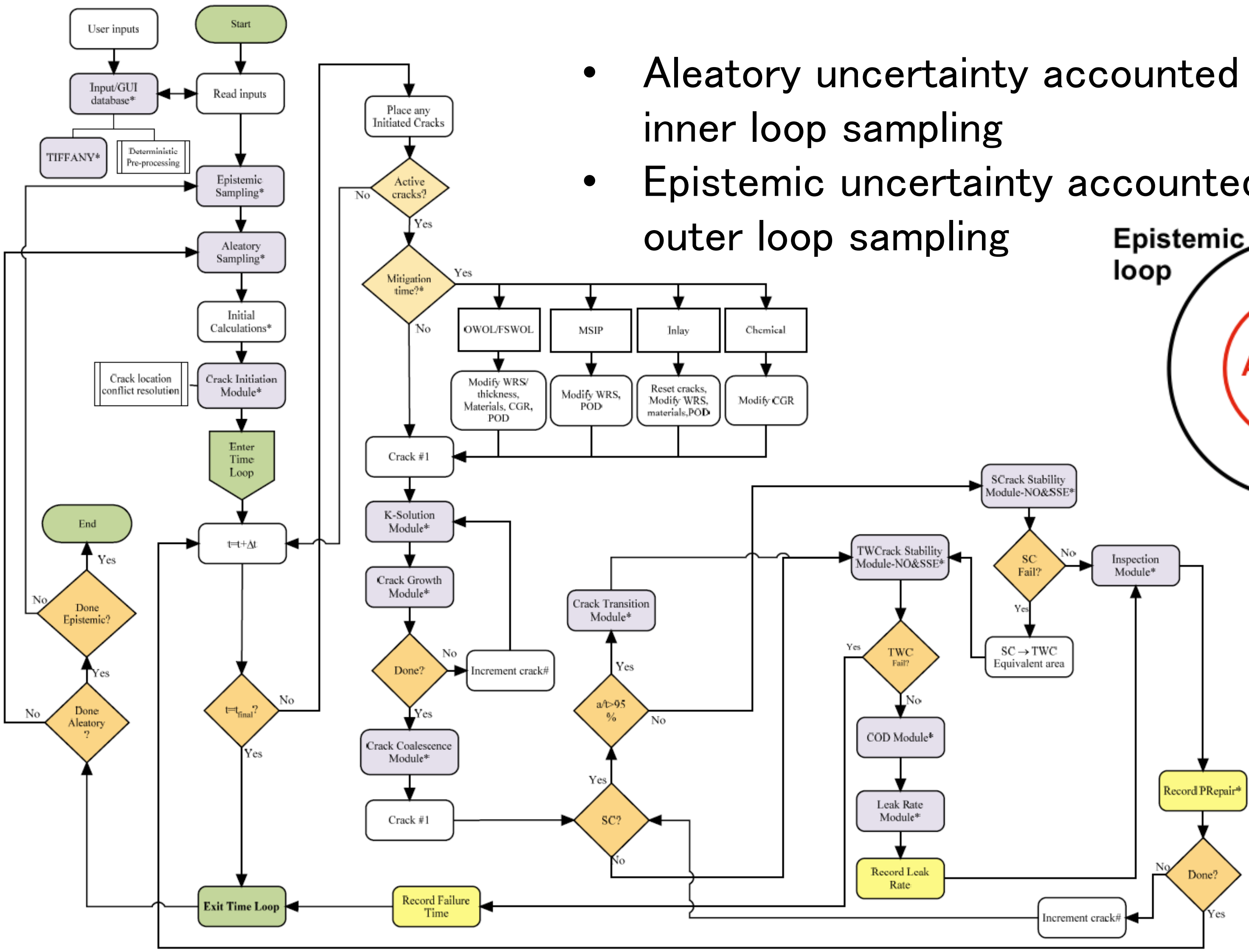
- Vertical Slice Review (VSR)
  - Address a specific technical area or issue and drill down to review the underlying basis and implementation
  - Planned at the discretion of the xLPR code development leads or the PIB lead
  - Treatment of uncertainty identified both by PIB members and code development leads as important cross-cutting issue appropriate for a vertical slice review

Treatment of Uncertainty in xLPR

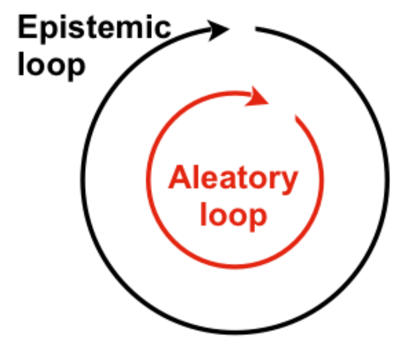
Treatment of Uncertainty

- All input variables and model parameters are subject to uncertainty
- Quantitative uncertainty characterization
  - Epistemic
    - Can be decreased through greater knowledge or data
    - Ex: Uncertainty in surface stress in crack initiation, direct model #1 (i.e., initiation time inversely proportional to surface stress).
  - Aleatory
    - Cannot be decreased further with more information
      - Ex: yield strength distribution for Ramburg-Osgood type constitutive model
    - May not be captured in current model
      - Ex: Effect of variation in level of cold work on PWSCC crack growth rate (not modeled)
- All xLPR participants were provided information on uncertainty estimation and classification
- Excel spreadsheet developed to characterize uncertainty associated with large (> 10 points), small, and no amounts of test data

Treatment of Uncertainty



- Aleatory uncertainty accounted for in the inner loop sampling
- Epistemic uncertainty accounted for in the outer loop sampling



Treatment of Uncertainty

- Model uncertainty - Uncertainty between models and their implementation within the framework and reality
- Examples of model uncertainty in xLPR V2.0
  - Modeling of cracks as straight and planar
  - Consideration of design basis transients instead of actual transients for fatigue
  - Use of elastic stress intensity factor (K) to govern crack growth
  - Idealization of materials as homogeneous, isotropic with sharp interfaces between materials
  - Treatment of crack coalescence using simplified rules
  - Discretization of piping segments
  - Independence of cyclic fatigue and stress corrosion cracking
- Intent is to identify all model uncertainties and qualitatively assess their impact
  - Are uncertainties conservative or unconservative with respect to factors promoting pipe rupture?
  - What is the level of the model uncertainty (high, medium, low)?

Vertical Slice Review – Objectives and Approach

Vertical Slice Review Objectives

- Provide an overview of the treatment and documentation of input, parameter, and model uncertainties and the classification of these uncertainties as either aleatory or epistemic by each group and subgroup within the xLPR Project Team.
- The review addresses
  - Process used to identify and characterize uncertainty
  - Consistency of uncertainty treatment across xLPR groups and subgroups
  - Basis for estimating uncertainties for input variables and model parameters
  - Basis for characterizing uncertainties as epistemic or aleatory for input variables and model parameters
  - Identification of biases resulting from assigning uncertainties for the input values, parameters
  - Truncation of uncertainty distributions
  - Assessment of model uncertainty relative to field behavior
  - Basis for deterministic (constant) parameters and inputs

Vertical Slice Review Approach

- Develop an initial set of questions which satisfy vertical slice objectives and can also support final documentation of technical basis for model validation report
- Provide initial questions to each project team group lead or subgroup lead, as appropriate
  - Inputs group
  - Computational group
  - Models group and subgroups
- Review initial responses to determine if the responses adequately address all the topics in the vertical slice questionnaire
- Iterate with each group lead so that the final responses are adequate and as consistent as possible among the various groups

Vertical Slice Review Questions

Vertical Slice Review Questions

1. Provide basis of and process used to assign and document uncertainties associated with the input values, parameters to the computational model(s), and the overall uncertainty of the model(s)
   a. Describe the process used to identify, classify and document uncertainties
   b. List uncertain quantities, the associated distribution developed for each quantity, and the basis for the distribution
   c. Describe the assignment and basis of correlation between variable uncertainties
   d. Identify basis for the aleatory and epistemic classification
   e. Discuss apportionment of uncertainties to avoid double-counting uncertainties
   f. Describe the methods for uncertainty propagation and any supporting sensitivity analysis
   g. Describe the physical basis for truncating or bounding distributions

- Address above questions for uncertainties associated with both **common/shared** and **unique** input variables or model parameters

Vertical Slice Review Questions

2. Basis, approach, and documentation used to address model uncertainties (both aleatory and epistemic) associated with the computational models developed
   – Assess whether uncertainties were treated quantitatively, qualitatively, or as a mixture of both

3. Basis (e.g. through sensitivity analyses) for determining if the uncertainties utilized (input, parameter, and model) provide a conservative or non-conservative output and documentation of this basis

4. Basis for deciding that a quantity is a constant value and documentation of basis

Sample Responses

- Sample responses appropriate for most questions include:
  - Same as Version 1 and the basis for applicability in Version 2 is the following,
  - Engineering judgment of experts, as documented in the following,
  - From xLPR Excel Uncertainty Worksheet,
  - The following alternate statistical analysis of data or
  - Other (explain).
- For basis of constants, sample responses include:
  - Same as used in Version 1 and the basis for applicability in Version 2 is the following,
  - Insufficient data available to quantify uncertainty,
  - Judged to be less than +/- 10% using Excel Uncertainty Worksheet,
  - All model uncertainties combined in one coefficient, or
  - Other (explain)
- Excel spreadsheet provided for completing responses

Initial VSR Responses and Example Results

Initial VSR Responses

- Initial responses provided for the following modules
  - Fatigue crack initiation
  - PWSCC crack initiation
  - Fatigue crack growth
  - PWSCC crack growth
  - K solutions
  - Crack transition
  - Crack coalescence
  - Crack stability, both through-wall and surface crack
  - Crack opening displacement (circumferential and axial)
  - Weld residual stress
- Awaiting responses for the following modules
  - Leak rate
  - In-service inspection
  - Tiffany (develops fatigue transient changes in stress and K solutions)
- Awaiting responses from the following groups
  - Inputs
  - Computational (framework considerations)

Initial VSR Responses

- Content, quality and completeness of initial responses varies greatly
  - Fatigue/PWSCC initiation , fatigue/PWSCC crack growth, and coalescence responses are most complete and have highest quality
  - Some iteration has occurred on virtually all of the initial responses
  - All responses have a unique structure which complicates the PIB review
- Questions are challenging and require thoughtfulness and rigor to complete
- Response timeliness and content has suffered due to competing, higher priority demands
  - Model coding
  - Model testing, verification and validation (V&V)
  - Development of inputs for implementation and example problems
  - Final completion of documentation needed for coding, testing and V&V
- Expect much of this information to be more fully developed as part of model validation reporting

Example VSR Response: PWSCC Crack Growth

- Developed different structure and organization for response to provide requested information
- Organization of document
  - Description/justification of deterministic inputs
  - Description of physical parameter uncertainties and how these are considered during model parameter estimation
  - Description of model parameter uncertainties
  - Discussion of correlation
  - Discussion of documentation and validation

PWSCC Crack Growth: Deterministic Inputs

- Many inputs can be varied but are fixed during any single realization
  - User defined
  - Defined by computational framework (including TIFFANY)
  - Hardwired into coding
- Inputs (user defined)
  - Material group
  - Mechanism type flag (i.e., PWSCC, fatigue or both)
  - PWSCC reference temperature
  - Crack growth rate model parameters (other distributions used for scaling)
    - Power-law constant
    - Power-law exponent
    - Threshold stress intensity factor

PWSCC Crack Growth: Non-Deterministic Physical Inputs

- Inputs that represent uncertainty in physical plant conditions
  - Reflects component-to-component variability, temporal variability, spatial variability, and/or randomness
- Variables used as part of model
- Evaluated to ensure that uncertainties are not double-counted in remaining portion of the model
- Inputs (user defined)
  - Operating stress intensity factor (uncertainties due to load)
  - Operating temperature (uncertainty in future operating periods)
  - Hydrogen concentration (uncertainty due to transients and controls)
  - Duration of integration time step (uncertainty in capacity factor)

PWSCC Crack Growth: Model Parameter Uncertainty

- Intended to account for uncertainty not captured elsewhere
- May result from unmodeled effects, inappropriate model forms, or randomness.
- Recognizes ongoing expert panel to revise A600 and develop A690 disposition curves
- Example parameters
  - Component-to-component CGR variation factor
  - Within-component CGR variation factor
  - Thermal activation energy
  - CGR improvement factor

PWSCC Crack Growth: Component-to-Component CGR Variation Factor

- Value that is sampled for each contiguous material group (e.g., each weld) that is used to scale the PWSCC CGR prediction for cracks in that material group
- Uncertainty reflects variability in growth susceptibility from weld to weld or from heat to heat (base material)
- Heat-to-heat (A600) and weld-to-weld (A82/182/132) variations are based on regression analyses in MRP-55 and 115
- A600 and A82/182/132 distributions are log-normal with log-μ = 0.00 and log-σ = 1.016 (A600), or log-σ = 0.5892 (weld without hydrogen).
- Characterize uncertainty as epistemic
- Truncate so CGRs are not significantly outside of recorded data

PWSCC Crack Growth: Within-Component CGR Variation Factor

- Value that is sampled for each circumferential subunit in each contiguous material group (e.g., each weld) that is used to scale the PWSCC CGR prediction for cracks in that material group
- Uncertainty reflects variability in growth susceptibility within welds or within heats (base material)
- Heat-to-heat (A600) and weld-to-weld (A82/182/132) variations are based on regression analyses in MRP-335r1 and MRP-307
- A600 and A82/182/132 distributions are log-normal with log-μ = 0.00 and log-σ = 0.5695 (A600), or log-σ = 0.4807 (weld without hydrogen).
- Characterize uncertainty as aleatory
- Truncate so CGRs are not significantly outside of recorded data.

PWSCC Crack Growth: Thermal Activation Energy

- Defines the sensitivity of CGR to temperature variation via the Arrhenius equation.
- Uncertainty is believed to predominantly reflect heat-to-heat or weld-to-weld variation in temperature sensitivity
- A600 and A82/182/132 mean values developed by expert panel consensus while variability developed based on published results
- A600 and A82/182/132 distributions are normal with $\mu = 130$ KJ/mol and $\sigma = 5$ KJ/mol (A600) and $\sigma = 20$ KJ/mol (welds)
- May have double-counting with component-to-component and within-component variation factors
- Characterize uncertainty as epistemic
- No truncation recommended

PWSCC Crack Growth: CGR Improvement Factor

- Quantity used to scale the CGR model prediction, usually to credit improved PWSCC resistance of a certain alloy without altering other model trends
- Uncertainty represents heat-to-heat variability, within-heat variability, and/or lack of knowledge about the relative improvement
- MRP-115 recommends a deterministic improvement factor among welds; uncertainty could be used in A690 improvement factor
- Recommended improvement factor of A82 vs. A182/132 is 2.6
- A690 and A52/152 factors are under development
- Characterize A690 & A52/152 uncertainty as epistemic
- No truncation recommended at this time (1.0 may be justified)

PWSCC Crack Growth: Correlation

- Only recommended correlations are for hydrogen model parameter uncertainties among Alloys 82/182/132
- Inter-dependencies: changes to certain parameters should be done together (e.g., CGR model for a material)
- No correlation between PWSCC growth and fatigue growth (also treated as separable and independent)
- PWSCC initiation and growth uncertainties can be correlated

PWSCC Crack Growth: Documentation & Validation

- Treatment of uncertainty, is captured in xLPR-SRD-CGR, *xLPR Software Requirements Description for PWSCC and Fatigue Crack Growth Rate Module*, Version 3.1, 2014
- Rigorous independent validation of the growth models is ongoing
- Rigorous model validation will be documented in the Module Validation Report (MVR)

Vertical Slice Review: Remaining Tasks, Schedule, and Use of Results

Remaining VSR Tasks and Schedule

- Remaining tasks
  - Receive remaining initial responses
  - Review and iterate responses
  - Determine summary report structure
  - Draft summary report
- Schedule
  - Receive remaining initial responses
    - Estimates have been provided by most groups
    - Targeting end of the year
  - Complete draft report within 2 months of receiving final responses
  - Coordinate final responses with schedule for model validation report, if needed
  - Schedule has been flexible to ensure that coding, input development, module testing, and V&V remain highest priorities

Use of VSR Results

- Questionnaire has been valuable to identify uncertainty considerations that need to be incorporated into software requirements description and model validation reports
- Responses should provide basis for summary of uncertainty treatment in the validation reports
- Higher quality responses can be used to improve responses of all groups and improve consistency
- Remaining gaps and inconsistencies can be documented and addressed, either for implementation in V2.0 or later versions
  - Basis for uncertainty in current version is known and provides starting point for future development of xLPR