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Overview of Draft Technical Letter Report on "Important Aspects of Probabilistic Fracture Mechanics (PFM) Analyses"

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Public Meeting
Development of Guidance for Probabilistic Fracture Mechanics (PFM)
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Background

- First deliverable of the PFM Regulatory Guide development project
- GOALS
  - Create a technical report within a relatively short period of time to highlight what NRC views as important concepts for PFM regulatory applications
  - Means to communicate NRC's initial thoughts on PFM, prior to the development of a Regulatory Guide and supporting NUREG
  - Means to generate discussion and obtain feedback

Technical Letter Report Outline

1. Introduction: motivation and objectives
2. Definition of PFM, including similarities and differences with deterministic analyses
3. Analysis models
4. Analysis inputs
5. Uncertainty framework
6. Analysis outputs

Important Definitions

- Accuracy and Precision
- Aleatory Uncertainty
- Epistemic Uncertainty
- Probabilistic Fracture Mechanics
- Probabilistic Risk Assessment
- Realization
- Sensitivity Analysis
- Sensitivity Study
- Stability Analysis
- Uncertainty Analysis
- Uncertainty Propagation
- Validation and Verification

1- Introduction: Motivation for Increased Confidence in PFM and Primary Objective

- Regulating the use of structural nuclear materials:
  - Before 1995: deterministic approaches (safety factors, margins, conservatisms…)
  - Since PRA policy statement in 1995: towards risk-informed and performance-based regulations
- Fracture behavior at heart of safety of nuclear structures
  - Consensus Codes and Standards typically deterministic conservative approaches to bound uncertainties
  - PFM can complement deterministic analyses and quantify uncertainties
- PFM pros and cons:
  - Direct representation of uncertainties through the use of best-estimate models and distributed inputs
  - Permits determination of the direct impact of uncertainties on the results, identification of problem drivers
  - Often more complex, requires more data to construct distributions, more time consuming
- NRC experiences with PFM regulatory reviews overall challenging
  - Some successes (risk-informed inservice inspection, elimination of vessel weld inspections)
  - Many difficulties: input choice justification, 'black-box' tools, insufficient V&V, sensitivity analyses & studies

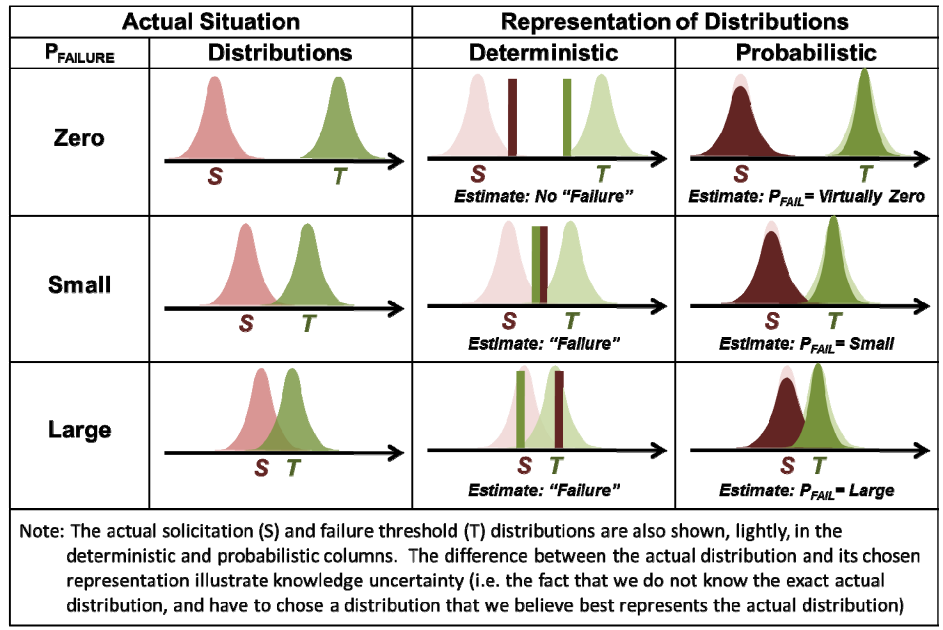
➢ **Primary objective: develop a methodology that is sufficiently general to be suitable to guide the development and/or critique of any PFM analysis, and that also effectively and logically manages the level of detail and breadth of scope that PFM analyses can take on**

2- Definition of a PFM Analysis: Generalities on Fracture Mechanics

- Basic principle: is $K_{Applied}$ [≤ or >] $K_{Resistance}$?
  - $K \sim \sigma\sqrt{a}$
- Six variables comprise the most important aspects of any DFM or PFM analysis
  - K, σ, a, and component geometry are common to any fracture mechanics analysis
  - Environment and time also required to completely understand, characterize, and evaluate virtually any fracture mechanics analysis
- Human interaction (inspection) is considered as a measure to confirm the validity of the fracture mechanics model
- Repair or mitigation is considered as a measure to change some or all key variables
- Accurate representation of interdependences in the DFM or PFM model is key to the development of a model that reasonably approximates reality
- Multiple time and spatial scales may need to be modeled

2- Definition of a PFM Analysis: Deterministic vs. Probabilistic

- **$K_{Applied}$ and $K_{Resistance}$ <u>inherently</u> distributed**
- DFM and PFM are fundamentally similar
  - Mathematical abstractions
  - Common goal of representing uncertainties in mathematical form for problem solution
  - Not possible to account for every uncertainty
- PFM analyses will represent most, but not necessarily all, uncertainties as important distributed quantities
- Both PFM and DFM use specific metrics to quantify results
- Use of DFM or PFM methods does not represent an either-or choice
- DFM and PFM methods can, and have, been used as complementary parts of a safety case
- Failure *probability* is one possible numeric outcome of a PFM analysis: impediment to the acceptance of PFM techniques



2- Definition of a PFM Analysis: Considerations on Use of PFM

- Reasons for shift from deterministic to probabilistic approaches in regulating component integrity
  - PRA policy statement in 1995
  - Factors unanticipated in the design phase, and/or not addressed by Codes and Standards
    - New degradation mechanisms or deficiencies discovered after design and construction: cost benefit analysis
    - PFM ideally suited to calculate perform risk assessment, required by backfit rule
    - Unanticipated service occurrences not covered by Codes and Standards cannot easily be accounted for in standard deterministic demonstrations
    - PFM potentially more adaptable
    - DFM and PFM require continuous updating
  - Use of structures beyond their design, or licensed, lifetimes
    - Application of large safety factors may become impracticable
    - PFM can better quantify the risks associated with operation of NPPs beyond the initial licensed life
- Other benefits
  - Rigor of process needed to build models can revealed deficiencies previously overlooked
  - Force analysts to be more critical of data used to develop models or inputs

3- Models for PFM Analyses: Model Selection

- Collection of deterministic models linked in a probabilistic framework
- Considerations for model selection
  - Best-available representation
  - Engineering judgement
  - Accuracy and precision vs. mathematical/computational feasibility
  - Documentation of choices, proper justification, discussion of model uncertainties/biases
- Different 'types' of models
  - Mathematically derived models with various degrees of theoretical underpinning
  - Empirical models that rely only on data fitting (lab vs. field data)
    - Importance of data quality and relevancy
    - Statistical characterization of model uncertainties and biases
  - Computational models
- Model validity considerations
  - Applicability bounds: underlying data, expert judgement, physical limits of system
  - Importance of documentation
  - How does the code/model deal with sampled inputs that are out of bounds?

3- Models for PFM Analyses: Gaining Confidence in Models

- Heavy reliance on documentation of models and on V&V activities

- Model V&V
  - Verification: QA process by which the coded model is verified to meet the defined software requirements, i.e. the mathematics of the model are correctly coded
    - Independent verification
  - Validation: QA process to assess degree to which the chosen model represents the physical system
    - Does the model predict expected values, trends, and actual data?

- Documentation of model uncertainties
  - Simplifying assumptions, scatter in dataset used to create model, lack of data, simplified models for computational reasons
  - Identification of sources of uncertainty, qualification/quantification of uncertainty
  - Assurance that limitations of PFM code are understood and accounted for

- Consideration of alternative models
  - Potential sensitivity studies
  - Strengthen argument for choice of a particular model

4- Inputs for PFM Analyses: Uncertainty Type, Distributions, Bounds

- Input uncertainty classification: constant vs. random

- Random inputs are usually represented by mathematical distributions
  - Sampling based methods use probability distributions
  - Multitude of distribution types
  - Continuous or discrete distributions
  - Other non-sampling based methods exist

- Construction of input distributions
  - Availability and pedigree of data
  - Distribution type and fitting distribution parameters
  - Distribution bounds, skewness, kurtosis
  - Goodness-of-fit tests, engineering judgement

- Input bounds
  - Many engineering applications require bounds to remain within physical reality
  - May choose bounds to limits inputs to a model's domain of applicability
  - Important to exercise caution and justify choice input bounds
    - Different models may have different validity domains
    - True physical bounds not always well known

4- Inputs for PFM Analyses: Assumptions, Conservatisms, Dependencies

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- Justification of input assumptions (technical basis for inputs)
  - Need stronger technical bases for most influential inputs
  - May not need very strong basis for less influential inputs
  - Scrutinize important input distribution tails for low probability events (sensitivity studies)
  - If large impact of distribution tails, may need more data, expert elicitation, more refined statistics…

- Conservatisms in inputs and models may not be appropriate in PFM
  - Looking for best-estimate with quantified uncertainty
  - Should attempt to quantify know conservatisms, and understand their impact
  - Conservatism could be applied on final criteria instead of inputs or models

- Input variables usually assumed to be independent
  - Known variable dependencies should be modeled
  - Avoid underestimation of input variable importance (sensitivity analysis)

5- Uncertainty Characterization: Aleatory and Epistemic

- Definitions
  - Aleatory Uncertainty: (perceived) natural, unpredictable variation in the performance of the system under study over which there is little control, or inherent randomness in the future
  - Epistemic Uncertainty: due to a lack of knowledge about the behavior of the system that is conceptually resolvable

- Most inputs contain both types of uncertainty, characterization is not absolute

- Aleatory and epistemic uncertainties can sometimes be separated
  - Typical means of separation: double nested loop
  - Can provide additional insights: confidence intervals on quantities of interest
  - Potentially higher computational cost
  - Not all codes have the capability to separate aleatory and epistemic uncertainty

- Sensitivity studies consisting of changing the uncertainty characterization can be helpful to remove some of the most influential variables from the sensitivity analysis
  - Gain insights on second-order importance of inputs

5- Uncertainty Characterization: Representation and Propagation

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- Choice of random variables often responsibility of experts
  - Need capture major sources of uncertainty
  - Need to have proper representation of uncertainty (distributions)
  - Potentially need to separate epistemic from aleatory uncertainty

- Context of analysis (specific plant system versus generalization) may have important impact on choice of distributions and output uncertainty

- Several possible probabilistic frameworks to represent and propagate uncertainty
  - First/Second Order Reliability Method good for well defined response surfaces
  - Sampling based techniques are more general but more ‘expensive’
    - Sample random variables at each realization
    - Simulate the system for each sample
    - Collect results of independent realizations and combine into probability distributions of possible outcomes

- Many Monte Carlo sampling techniques
  - Simple Random
  - Latin Hypercube
  - Importance Sampling
  - Adaptive Sampling

5- PFM Framework/Code: Verification and Validation

- High confidence in PFM software and analyses requires verification and validation
  - Verification establishes the correspondence between the PFM computer code and its specifications
  - Validation establishes whether the PFM code is fit for its intended purpose
- Quality Assurance (QA) requirement of 10CFR50 Appendix B
  - Documented requirements for the PFM software, including development, procurement, maintenance, testing and configuration management
  - Criteria for QA plans: ASME NQA-1 or NUREG/BR-0167
- V&V of both deterministic sub-models and probabilistic framework is required
  - Validation can be done against data, analytical solutions, or output from another validated tool (e.g. FEA)
  - Validation required for each output, and for overall solution
  - Validation may be application-specific
  - Graded approach useful (most important quantities require higher degree of validation)
  - For low probability events with scarce data, sensitivity studies and study of trends is useful
- QA and V&V extent can vary based on…
  - Application permanence in time, safety significance
  - Scale and complexity of code and models
  - Pre-verified software vs. one-time-use
  - Novel code vs. accepted consensus
- Other factors that increase confidence: peer-review, detailed documentation, availability of source code, benchmarking

6- PFM Outputs: Convergence and Uncertainty Analysis

- Reliable, realistic PFM results require more than a single PFM analysis with a given PFM code
  - Should conduct multiple runs to demonstrate that solution is converged, uncertainties are properly represented, and parameters driving the problem have been sufficiently characterized

- Convergence is often a matter of perspective, linked to confidence in decisionmaking
  - Need to define a target threshold value or range for pass/fail criterion
  - A solution is considered converged enough if the uncertainty is low enough that it does not change the conclusion that could be drawn from the analysis
  - Acceptable level of uncertainty decreases when getting closer to the threshold value
  - Mean may converge fast, 99^{th} percentile no so fast…

- Temporal, spatial, and statistical converge need to be demonstrated
  - Temporal and spatial: time stepping and discretization
  - Statistical: stability analysis: changes in sample size, random seed, sampling technique, etc.

- With convergence achieved, uncertainty analysis on outputs of interest can be performed
  - Construct distributions of outputs/quantities of interest (QoI)
  - Many possible representations (probability vs. time, distribution of spatial location, horsetail plot of all realizations, PDF or CDF of a QoI, etc.)
  - QoI may be mean or percentile

6- PFM Outputs: Sensitivity Analysis

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- Sensitivity analyses: understanding the relationship between problem input and output uncertainties
  - Useful to identify drivers of the problem being analyzed
  - Important in developing sampling options which provide converged results
- Two main categories of sensitivity analyses:
  - Graphical qualitative methods: scatterplots
    - Can deal with any set of arbitrarily-distributed input and output variables
    - Direct qualitative visual indication of sensitivity
    - Identification of good candidates for importance sampling
  - Quantitative ‘variance-explained’ methods: regression analysis
    - Several methods should be combined to eliminate false positives
    - Goal: show that the final results are comprehensive, well supported, and well documented
    - Common methods: linear, rank, quadratic, or Gaussian regression; regression trees, and multivariate adaptive regression splines (MARS)

6- PFM Outputs: Sensitivity Studies

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- Sensitivity studies: exploring the specific influence of important parameters and analyzing specific scenarios of interest
  - Useful to better understand the physics of a problem
  - Used to perform "what if" analyses, to revisit some assumptions, and to investigate alternative scenarios in support of the defense in depth
- Two main categories of sensitivity analyses:
  - Deterministic sensitivity studies
    - Change one or more constant parameters that could influence the output one-at-a-time (alternative scenarios)
    - Usually focus on the physics of the system
    - Build confidence on the theoretical aspect of the analysis
  - Probabilistic sensitivity studies
    - Change one or more random input distributions: shift median, change uncertainty (kurtosis), change focus (skewness)
    - Change uncertainty classification between aleatory and epistemic
    - Focuses on the changes in probabilities of occurrence associated with each change

6- PFM Outputs: Problem Drivers and Confidence Demonstration

- Sensitivity analyses and studies should be performed to identify the drivers of the problem, and revisit the uncertainty of those drivers, to gain confidence in PFM conclusions
  - Important to ensure that the distributions for problem drivers are representative
  - Just as important to study the consequences if these distributions are not representative

- The parts of a given input distribution that drive the answer to a problem should be identified and sufficiently sampled
  - Role of importance sampling if distribution tails are important

- When confidence cannot be gained in the chosen distribution for a given parameter that drives the problem, several alternatives can be explored
  - Expert elicitation
  - Additional data collection

Future Work

- This Technical Letter Report is only the first step in the PFM Regulatory Guidance development project

- Next phase:
  - Development of a Draft Guide on PFM
  - Development of a detailed technical basis NUREG document

- In parallel: pilot study to test the Draft Guidance
  - Identify deficiencies and areas that need improvement
  - Lessons-learned will be incorporated in final Draft Guide document, and the technical basis NUREG will be revised accordingly