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

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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

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- 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

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- 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

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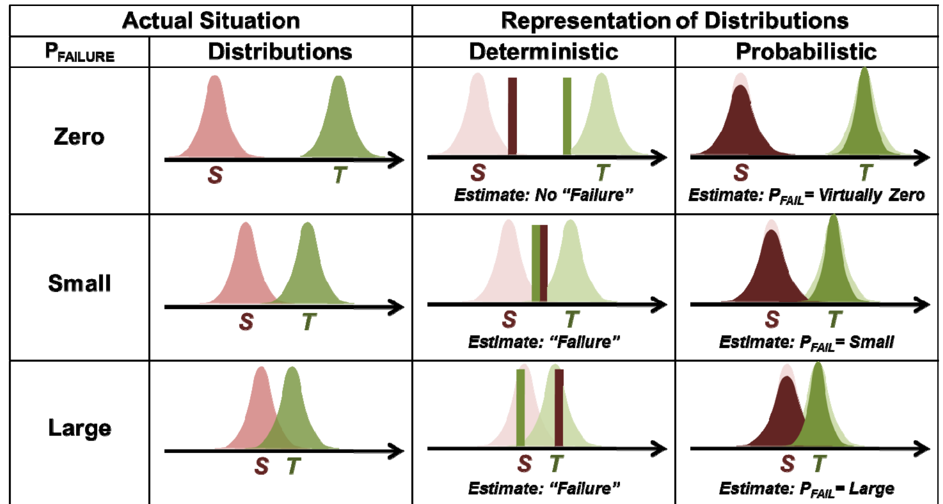
- **K $_{Applied}$ and K $_{Resistance}$ <u>inherently</u> distributed**
- DFM and PFM are fundamentally similar
  – Mathematical abstractions
  – Common goal of representing uncertainties in mathematical form for problem solution
  – Not possible to account for every uncertainty
- PFM analyses will 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



Note: The actual solicitation (S) and failure threshold (T) distributions are also shown, lightly, in the deterministic and probabilistic columns. The difference between the actual distribution and its chosen representation illustrate knowledge uncertainty (i.e. the fact that we do not know the exact actual distribution, and have to chose a distribution that we believe best represents the actual distribution)

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

- 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

- 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

- 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

- 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

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- 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