

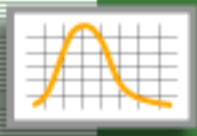
# Probabilistic Assessment: Principles and Methods

3<sup>rd</sup> International Seminar on Probabilistic Methodologies for Nuclear Applications (ISPMNA 2019)  
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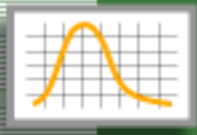
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*The views expressed herein are those of the authors and do not represent official positions of the Canadian Nuclear Safety Commission*

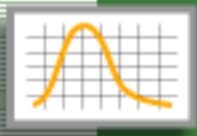


# Presentation Outline

1. Introduction
2. Probabilistic Assessment
3. Reliability Problems
4. Remaining Considerations
5. Closing Remarks
6. Acknowledgements



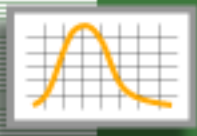
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2. Probabilistic Assessment
3. Reliability Problems
4. Remaining Considerations
5. Closing Remarks
6. Acknowledgements



# Introduction

(1 of 2)

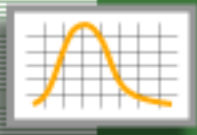
- Fitness-for-service assessments are integral parts of assuring operability of nuclear plant systems and components
  - Deterministic methods have been traditionally used
- Elements of a **deterministic method**
  - A mechanistic method defining the performance requirement
    - Example: Fracture protection, Leak-Before-Break (LBB)
  - A bounding scenario (near “*worst case*”) representing a limiting condition
    - Example: postulated accident, bounding crack
  - Outcome is binary
    - Whether “*pass*” or “*fail*”, or “*safe*” or “*not safe*”
    - Accordingly, mitigating actions may be required



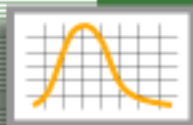
# Introduction

(2 of 2)

- **Limitations** of a deterministic evaluation
  - The “*worst case*” scenario is postulated certain to occur
  - The nearly most unfavorable combination of the variables is postulated certain
- The degree of embedded **conservatism** is unquantified
  - Risk in beyond design basis condition is unknown
- Emergence of probabilistic assessments methods to address these limitations
  - Inspired by a long and successful history of Probabilistic Risk Assessment (PRA)
  - Many standards are being developed to guide the assessment process
- Presentation **objective** is to discuss general principles, methods and elements of a Probabilistic Assessment (PA)

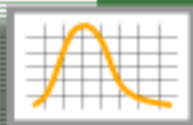


1. Introduction
2. **Probabilistic Assessment**
3. Reliability Problems
4. Remaining Considerations
5. Closing Remarks
6. Acknowledgements



# Probabilistic Assessment

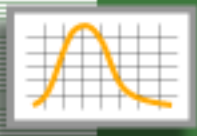
- Typically a starting point is already existing deterministic evaluation method
  - A mechanistic method is the “*backbone*”
  - Adding randomization of the problem variables
    - Involve Monte Carlo simulations
  - Outcome: probability of occurrence of the limiting condition
- **Examples:**
  - Probabilistic Fracture Mechanics (PFM):
    - Leak-Before-Break (LBB) of primary piping system – xLPR
    - Pressurized Thermal Shock (PTS) – FAVOR
  - CANDU reactor or Pressurized Heavy Water Reactor (PHWR) components
    - PFM of pressure tubes, feeder piping
    - Probabilistic Core Assessment (PCA) of pressure tube reactor core



# Probabilistic Assessment Scope

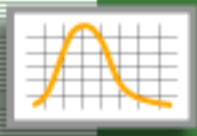
- PA is **NOT** merely an enhancement of a deterministic method with Monte Carlo simulations
- PA is a **conceptual shift** in the paradigm of demonstrating operability
- **The scope of PA can be considerably expanded as compared to a deterministic method**
- Several additional factors to be considered
  - Initiation and propagation of a degradation mechanism
  - Occurrence of a “*limiting condition*” (or accident condition)
  - Operator response under accident condition
  - Role of inspection quality, detection probability and maintenance actions
- **PA is information and resource intensive undertaking**
  - Scope of the PA could be tailored as per the need





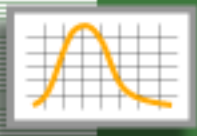
# Guiding Principles

- A consensus view about key guiding principles of probabilistic assessment is needed
  - A rapid emergence of probabilistic approaches could have led to the development of rather piecemeal approaches to satisfy urgent needs
  - Different systems have different procedures with wide differences in the reported outcomes and the reporting requirements
  - Diversity of methods and results may create confusion among the stakeholders



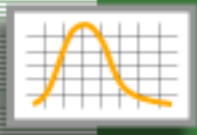
# Fundamental Features

- **Meaningful:** The assessment must be representative of the actual problem and the results must be relevant to the purpose of the assessment
  - The reliability metric must have a meaning to the problem
- **Consistent:** The risk and reliability must be consistently evaluated across Structure Systems and Components (SSC)
  - The principles of risk estimation should be the same for all systems
  - Otherwise, comparison and acceptance standards for risk will be problematic
- **Transparent:** All key assumptions, procedural steps and sources of data must clearly stated and justified
  - To allow scrutiny by independent review and Verification and Validation (V&V) work
  - To inspire confidence by the public and the regulator



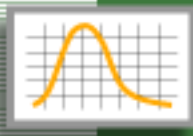
# Major Considerations

- The goal of most probabilistic assessments presumably is to demonstrate that
  - With reference to the limiting condition, the risk in the specified operating interval is less than some acceptable limit
- PA scope is much wider than that of the deterministic assessment
  - Consideration of time
  - Metric of assessment (conditional probability, frequency)
  - Consideration of the uncertainties
  - Overall realism in the assessment
  - Developing probabilistic acceptance criterion
- Foundation of PA: Theory of **Time-Dependent Reliability** Analysis



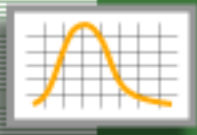
# Consideration of Time

- The most important aspect of PA is the modeling of various time dependent processes
- Various assumptions are implicitly or explicitly introduced in the modeling, which has a great deal of bearing on the final interpretation of the results
- Degradation process
  - The defect is no longer assumed to exist on the component but rather crack initiation and growth processes modelled
- Loading conditions
  - Occurrence of overloading
- Operator response and intervention
- Effect of inspection and maintenance actions

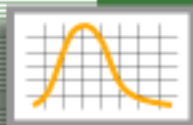


# Modeling and Assumptions of Degradation Process

- The nature of degradation process
  - Flaw initiation as a “*Stationary*” or “*Non-Stationary*” process
  - Homogeneous Poisson Process (HPP) is a stationary process
  - Defects initiate cracking at random without any particular time trend
  - HPP implies that time to initiation is an exponential distribution
- Crack initiation and growth process is independent across component population
  - Crack growth variability can be constant over time, or it can embody temporal variability (i.e., stochastic process)
  - Degradation process can restart after a maintenance followed by a leak detection event
- **Several such assumptions are embedded in PA**
  - They should be carefully examined and technically justified



1. Introduction
2. Probabilistic Assessment
3. **Reliability Problems**
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6. Acknowledgements



# Involved Definitions

- **Reliability**

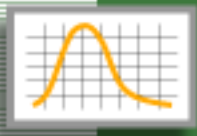
*The probability of a system functioning within **specified limits** for a specified **time** under postulated conditions.*

- **Hazard Rate** (mortality rate)

*Instantaneous probability of “first” failure conditional on survival up to a given age of the system.*

- **Failure Frequency**

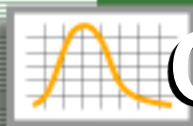
*Expected number of failures in a unit time interval.*



# Reliability Metric

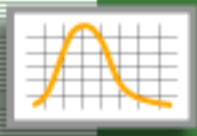
- The next important point is to choose a **reliability metric** that is relevant to the problem
- Reliability theory tells that the metric depends on the type of the problem
  - “*First failure*” (or **Non-repairable**) problem or
  - “**Repairable**” system reliability problem
- In the “first-failure” problem, the **mission reliability** or mission probability of failure is a relevant metric of reliability
  - The probability of failure in the operating interval given that equipment is functioning at the start of the interval
- In the repairable system problem, the **failure frequency** or **unavailability** is a relevant metric
  - The system is repaired or component replaced after each failure





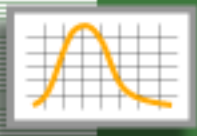
# Classification of Reliability Problems

- The probabilistic assessment should begin with classifying the type of the problem, repairable or non-repairable
  - How do we decide about this?
- Classification depends on
  - Type of performance limit state (serviceability or ultimate)
  - Nature of the failure mode (self-announced or latent)
  - Rate of progression from serviceability to ultimate state
  - Maintainability of the system
- **Performance limit state** means the state (or condition) of the system which divides the system performance into acceptable and non-acceptable domains
  - Introduced in “*structural reliability theory*”



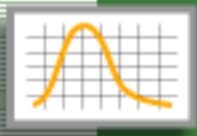
# Types of Limit States

- The **serviceability limit state** indicates a significant deterioration from the original design state
  - Not compromise system safety and functionality in any major way
  - Alarm which prompts to initiate mitigating actions
  - Presence of minor service-induced flaws is an example
- The **ultimate limit state** means a failure that would severely impair the system safety and functionality with potentially severe consequences
  - Rupture in Primary Heat Transport System (PHTS)



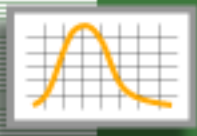
# Progression of Limit States

- In some reactor components, serviceability and ultimate limit states might be closely connected events
  - The **progression** of a serviceability into an ultimate limit state over a period of time
  - Example: flow accelerated corrosion of a feeder pipe bend
    - The wall thickness loss up to a certain limit can be considered as a serviceability limit state
    - Excessive wall thinning can ultimately cause a feeder failure (leak or rupture)
- Hence, the **rate of progression** from a serviceability to an ultimate limit state is an important consideration



# Nature of Failure Mode

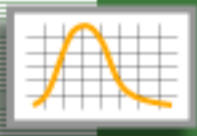
- Two classes of **failure modes** are in the reliability theory:
  - A **self-announced failure** means that the occurrence of a failure is (almost) immediately detected by the operator/user of the equipment
    - A loss of power event is an example
  - A **latent failure**, as the name implies, means the occurrence of a system failure that is not detectable until an inspection is carried out
    - The failure of a **standby** system is a latent failure mode



# Maintainability

(1 of 2)

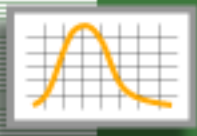
- Maintainability refers to the degree to which a system is **amenable to repair** (or replacement) after a failure, such that its operation can be restored to a safe and functional state
- It should be stressed that maintainability by itself does not determine the type of reliability analysis
  - Repairable vs. non-repairable
- A problem is repairable only if there is an opportunity to repair right after a failure
  - It means that the consequences of failure can be mitigated
- If operating conditions are such that a repair is not possible, then the problem belongs to the non-repairable category



# Maintainability

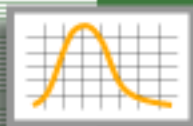
(2 of 2)

- Examples
  - An aircraft engine is designed to have high maintainability
  - A failure to start the engine on the ground is repairable
  - An in-flight engine failure is non-repairable
- In general, the issue of repairable vs. non-repairable problems is not a cut-and-dry situation, rather it depends on several factors that have been discussed



# Repairable vs. Non-Repairable

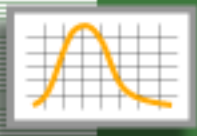
- Some general **guiding principles** are given here
  - It is most appropriate to model an ultimate limit state as a non-repairable reliability problem
  - A latent failure mode is typically in the realm of a non-repairable reliability problem
    - Especially when the mode can progress into an ultimate limit state
    - The probability of failure over the inspection interval is a meaningful reliability measure
  - A self-announced, serviceability limit state can be modelled as a repairable problem provided that the system is maintainable
  - A latent, serviceability limit state of static nature can be modelled as a repairable problem
    - As long as this does not evolve rapidly into an ultimate limit state
- Summarizing, the classification of a reliability problem is very much dependent on **operational considerations**



# Probabilistic Assessment Summary

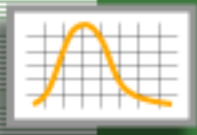
| <b>Conceptual Elements</b>               | <b>Procedural Elements</b>              |
|--|---|
| Purpose of assessment                    | Mechanistic model of performance        |
| Reliability metric                       | Random variables in the problem         |
| Type of reliability problem              | Data and distribution fitting           |
| Type of Limit States of performance      | Reliability calculation method          |
| Failure Mode (Self-Announced vs. Latent) | Uncertainty analysis                    |
| Progression of failure modes             | Final results, reporting and discussion |
| Maintainability                          |   |
| Acceptance criteria                      |   |



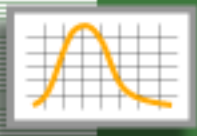


# Conceptual and Procedural Elements

- The conceptual elements are important to
  - Interpretation of numerical results
  - Evaluation of the robustness of the assessment
- The procedural elements are important to an analyst
  - Data collection, statistical analysis, computational methods

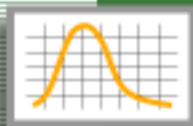


1. Introduction
2. Probabilistic Assessment
3. Reliability Problems
4. **Remaining Considerations**
5. Closing Remarks
6. Acknowledgements



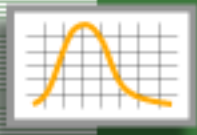
# Realistic Assumptions

- Simulations are commonly used in PA
- Simulation could involve combination of variables which are physically unlikely to take place
  - Random sampling can choose values of the loads and the strength that are physically impossible
- Limitations of a mechanistic model used in the simulation
  - Probabilistic assessment is as good as the underlying mechanistic modelling
  - The model should cover a wide spectrum of all plausible events



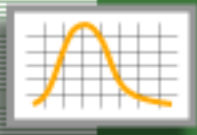
# Uncertainty Analysis

- Separation of epistemic and aleatory uncertainties
  - Include conceptual difficulties
- Computational burden could be challenging
  - Double-loop Monte Carlo simulations are quite intensive
  - Outcome is probability distribution of the reliability metric
  - Selection of adequate measure is debatable
  - Mean value versus some probability bound (50/95 percentiles)
- Prediction interval on the chosen reliability metric must be evaluated
  - Prediction interval is not the same as the confidence interval on the mean value
- Predictive models typically involve epistemic uncertainties

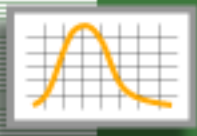


# Acceptance Criteria

- Fully probabilistic criteria
  - The (conditional) probability of failure or failure frequency less than the allowable
- The formulation of acceptance criteria is a raucous process
  - Evaluation of acceptable reliability of SSCs is complex
  - Inter-dependencies and final effect on core damage is difficult to quantify
  - Tradeoff between increasing safety and resource utilization creates conflict

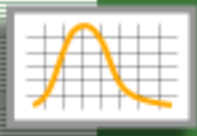


1. Introduction
2. Probabilistic Assessment
3. Reliability Problems
4. Remaining Considerations
5. **Closing Remarks**
6. Acknowledgements



# Closing Remarks

- Probabilistic assessment is not merely a conversion of a deterministic method with Monte Carlo simulation
- Probabilistic assessment is a conceptual shift in the paradigm of demonstrating component or system operability
  - The scope and complexity can be more involved
- Presented broad principles, methods and approaches to improve probabilistic assessments of nuclear plant systems and components



# Acknowledgements

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