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Implementation of External Event Modeling in Advanced PSA Studies

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Current approach to Nuclear Safety

- **Complementary use of PRA and more "classical" deterministic principles in risk-informed approach**

- **PSA or (PRA) has evolved over many years, and in various jurisdictions, as a useful *tool* to evaluate NPP risk and support risk-informed decision making**
  - **e.g., providing insights on design vulnerabilities**
- **By means of PSA, established safety goals have been quantitatively analyzed as one method of demonstrating reactor safety**

- **Probabilistic Risk Analysis**
  - **Comprehensive treatment of operating states**
  - **Comprehensive treatment of internal and external hazards**

Introduction

- Lessons learned from Fukushima event for PSA
- Gaps in PSA state of practice, e.g.
- PSA for extreme external events
- Site-wide risk
  - Multiple units
  - Spent fuel pools
- Extended accident scenarios
  - Long-term station blackout
  - Loss of ultimate heat sink
- Performance assessment of passive systems to mitigate the consequences of events initiated by external hazards
- The role of operator under extreme harsh conditions (human reliability)

Introduction cont'd

- Relevant factors pertinent to PSA studies
- PSA for external events
  - Dependencies between certain classes of hazards
  - Dependencies between seismic events and tsunamis
  - Modeling in PSA framework
- Implementation of PSA models to incorporate the hazards combination
- Requirement to consider correlated hazards as emphasized by Fukushima accident, e.g.
  - Combination of extreme hazards, between seismic events and tsunamis
  - External hazard-induced initiating events, e.g. tsunami induced flooding
- Simplifying assumption of independence to be avoided
- Models suitable to describe the correlation mechanisms

Correlation mechanisms

- Common Cause Initiators, like e.g.
  - Seismic hazard and tsunami, as events sharing the same source of origin
  - Strong winds and heavy rain, as phenomenological correlated events
  - Seismic hazards and seismically induced fire, as induced hazards

- Not site-specific analysis
- "Technology neutral framework"

- Frequency assessment of correlated hazards
  - Available site-specific information
  - Uncertainties

Combination of hazards approach

- **Easiest and "uncomplicated" way to assess the frequency of two or more external events occurring simultaneously**
  - **independent events**
  - **overall frequency as the product of the single frequencies**

- **Single frequencies actually not suitable to be chosen independently of each other, e.g. because of synergism between different events**
  - **Synergistic effects trigger an accident sequence with the potential to challenge the system performance and safety at a more severe degree and extent**

- **Implementation of the initiating event quantification process**
- **Interaction between the frequencies of the single events**

Combination of hazards approach cont'd

- **Dependent external events**
- **Joint pdf (probability distribution function) of single frequencies**
- **Simple case of two dependent events with frequencies x_1 and x_2 and distributions $f(x_1)$ and $f(x_2)$**

  $f(x_1, x_2) \neq f(x_1)*f(x_2)$

  $f(x_1, x_2, \ldots, x_n) \neq f(x_1)*f(x_2)*\ldots*f(x_n)$ for n events

- **Application of the conditional probability concept to include the dependencies between the events**
  - **marginal distributions relative to the conditioning and conditioned events**

Conditional probability: Recalls

- **Conditional** probabilitiy for events A and B

$$P(A/B) = \frac{P(AB)}{P(B)}$$

- **Conditional** probability **density function**

$$f(y/x) = \frac{f(x,y)}{f_x(x)}$$

- **Marginal** density f_x

$$f_x(x) = \int_{-\infty}^{\infty} f(x,y)dy$$

- **Conditional** probability

$$F(y/x) = P(y < Y / x = X) = \int_{-\infty}^{Y} f(y/x)dy$$

Illustrative example

- **Exemplary application for combination of two events, e.g earthquake and tsunami**

Normal pdfs $f(x) = (1/\sigma\sqrt{2\pi})\exp - ((x-\mu)^2/2\sigma^2)$

Standard form N(0,1) $f(t) = (1/\sqrt{2\pi})\exp - (t^2/2) \qquad t = (x-\mu)/\sigma$

Parameter	Range (a-b, 1/year)	Characteristics (1/year)
x_1	3-7 E-1	μ =5.0E-1 σ =1.0E-1
x_2	2-6 E-1	μ =4.0E-1 σ =1.0E-1

Parameter characteristics

2σ range corresponding roughly to 95% of confidence interval

Bivariate normal distribution

- **Joint probability distribution of two normal random variables x and y (standard form): general expression**

$$f(x,y) = (1/2\pi(1-\rho^2)^{1/2})$$
$$\times \exp -((x^2 + y^2 - 2\rho xy)/2(1-\rho^2))$$

$\rho = \sigma_{12}/(\sigma_1\sigma_2)$ **correlation coefficient**

σ_{12} **= COV** **covariance**

ρ **= 0** **bivariate distribution of uncorrelated normal variables**

Bivariate normal distribution cont'd

- **Bivariate distribution of correlated normal variables ($\rho \neq 0$)**
  - **Average matrix**

$$\begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}$$

  - **Variance-covariance matrix**

$$\begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{21} & \sigma_2^2 \end{bmatrix} \qquad \sigma_{12} = \sigma_{21} = \mathrm{COV}(x, y)$$

$$\begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix} = \begin{bmatrix} 5^{*} \\ 4^{**} \end{bmatrix}$$

* read as 5.0E-1
** read as 4.0E-1

$$\begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{21} & \sigma_2^2 \end{bmatrix} = \begin{bmatrix} 1^{*} & 0{,}9^{**} \\ 0{,}9^{**} & 1^{*} \end{bmatrix}$$

*read as 1.0E-2
**read as 0.9E-2

$\rho = 0{,}9$

$COV = 0{,}9\ E\text{-}2$

Bivariate normal distribution cont'd

- $P = \int \int f(x,y)$
- **Numerical integration techniques required**

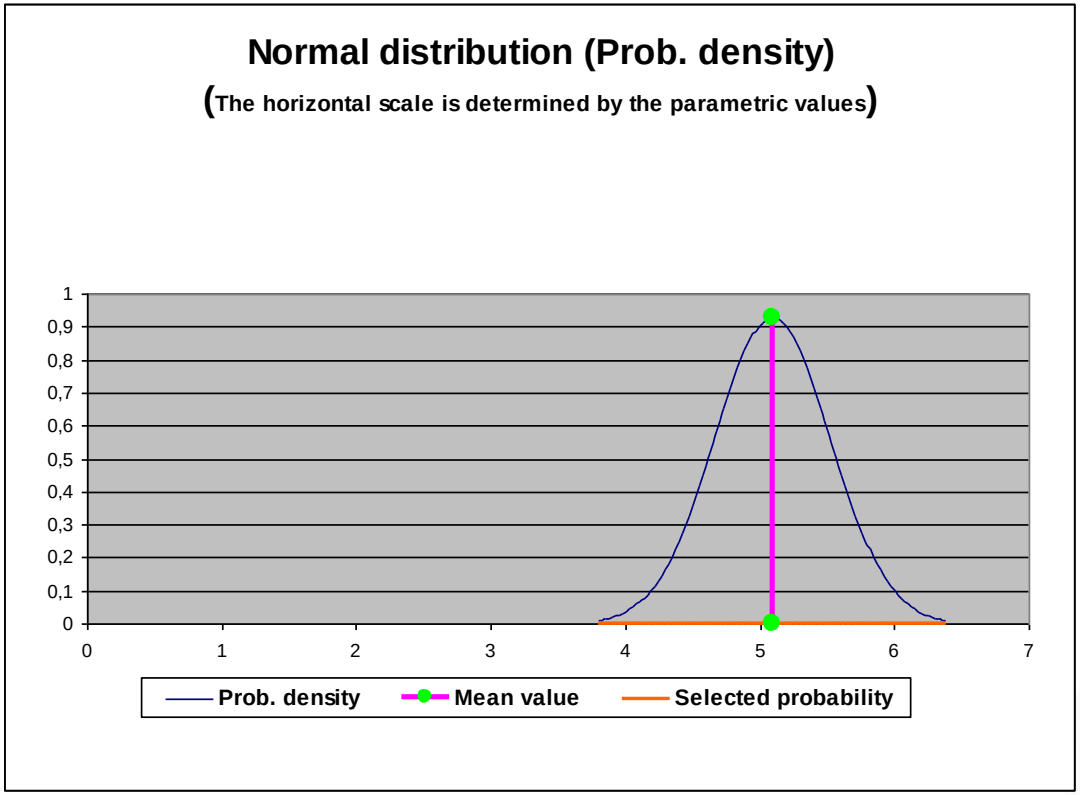
- **Conditional distribution of y, given x = X**
  - **normal distribution**

$$f(y/x=X) = Nor\ (\mu_y + \rho(\sigma_y / \sigma_x)(x - \mu_x), \sigma^2_y(1 - \rho^2))$$

- **Probability of the correlated events (*y* and *x*), given a certain frequency value for one of them, let' s say *x***

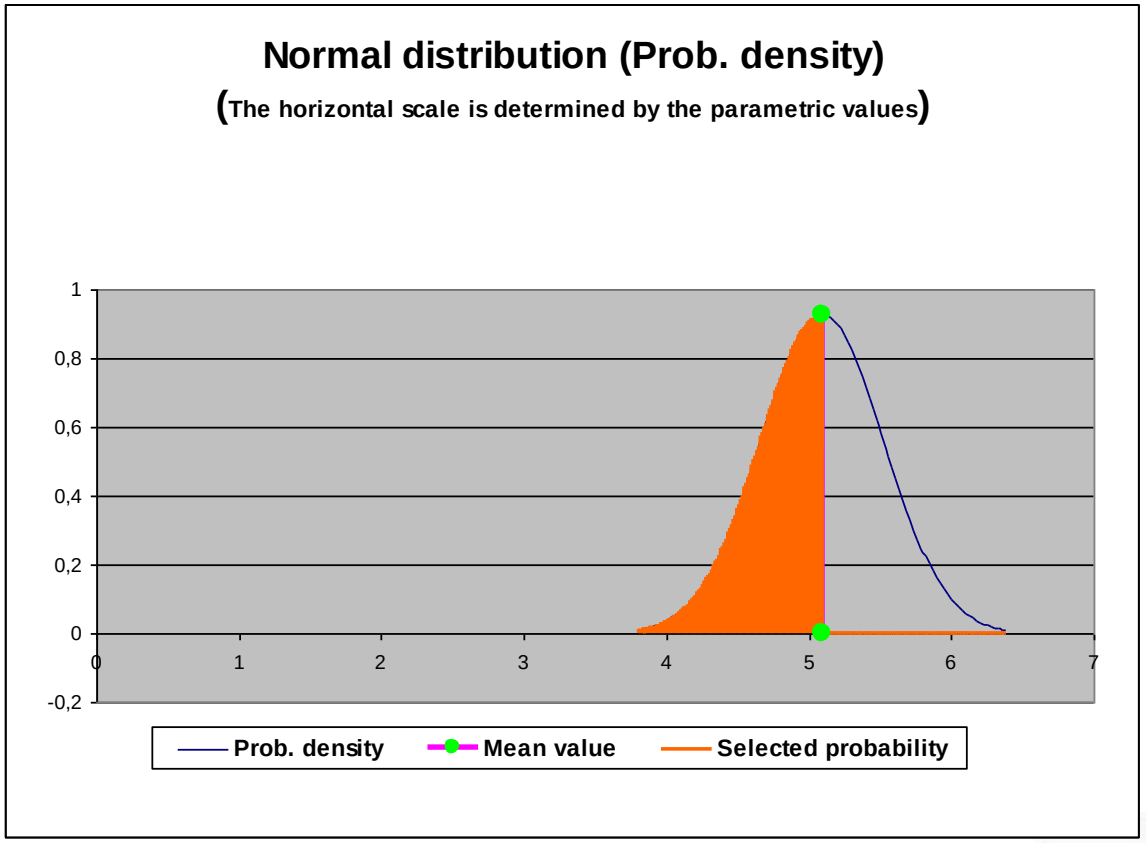
Illustrative example results

- **Correlated external events probability distribution, upon one single external event frequency assuming a value of 4.1E-1/year**
- **E** *(y/x=* 4,1*E-1/year) = **5,09E-1/year**
- **σ** *(y/x=* 4,1*E-1/year) = **0,43E-1/year**
- **f** (*y/x*=4,1*E-1/year) = **Nor (5,09*E-1/year, 0,43*E-1/year)**



Illustrative example results cont'd

- **Probability of both events, with frequency 5.1E-1/year and 4.1E-1/year**
- $P(y \leq 5{,}1 \text{ *E-1} / x = 4{,}1\text{*E-1}) = \Phi(0{,}023) = 0.5$



Discussion

- **Approach relevance**
  - **Induced accidents, as e.g. external hazard induced initiating events, as earthquake-induced fire or tsunami-induced flooding**

- **Inclusion of more external events, by multivariate (normal) distributions**

- **Whole probabilistic safety analysis**
  - **External events PSA models for safety systems to assure critical functions in case of**
    - **Loss of AC power to safety equipments**
    - **Loss of cooling capability**
  - **Conditional probability as a measure of the protection systems availability**

Conclusions

- **Risk associated to the correlation of hazards underestimated by many PSA teams**
- **Lack of scientific understanding of the correlation of hazards with other hazards or events**
- **Lack of site specific data on which estimations for those correlations could be based**
- **Correlated or simultaneous events perceived as very unlikely**
- **Dismissed in the screening process as minor contributors for core damage**

Conclusions cont'd

- **Models to address the combination of correlated external events in a PSA framework**
  - **Joint pdf of event frequencies**

- **Dependence between the marginal distributions**
  - **Correlation coefficient**
  - **Conditional distribution**

- **Exploratory study**
  - **PSA issue as emerging from Fukushima accident**
  - **Results are shown for illustrative purposes**
    - **Generic numerical values**
    - **No site-specific data for statistical inference**

Thank you for your attention!