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Application of Probabilistic Methods to Fuel Rod Design Evaluation

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"Advanced Fuel Pellet Materials and
Fuel Rod Designs for Water Cooled Reactors“

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- Introduction
- Evolution of Demands
  - Technical Safety-related Aspects
  - Economical Aspects
  - Ecological Aspects
- Traditional Approaches
  - Principles
  - Basic Questions: Quantification of Conservatism
- Probabilistic Methods
  - Requirements
  - Mathematical Basics
  - Examples
- Conclusions and Outlook

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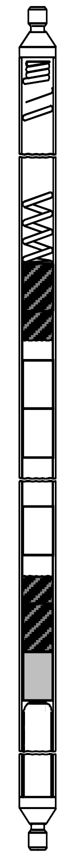
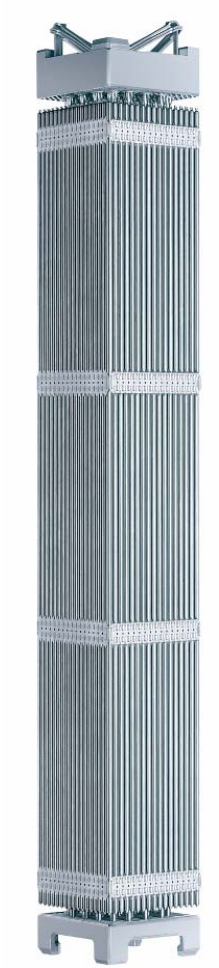
Introduction

- Safety concept of nuclear power plants
  - Relies on a system of multiple barriers
  - Preclude the release of radioactive material
- Fuel rods
  - Gas-tight welded fuel rods
  - First and important barrier of this concept
  - Confine uranium and/or plutonium fuel
  - Confine solid and gaseous radioactive fission products
- Demands on fuel rod design
  - Preclude systematic defects by limitation of temperature, strain, internal pressure, …
  - Proof is performed by applying appropriate codes and methods



Fuel rod (up to ca. 80000 per core)



Fuel assembly (up to ca.840 per core)

Introduction

- Fuel rod design and probabilistic methods – a brief history
  - First-of-a-kind application of probabilistic methods under plant normal operation conditions to cope with advanced demands
  - Developed by the predecessor of today's AREVA NP GmbH, the Siemens AG since late 1980s
  - Applied to licensing issues since 1995
  - Proven to be a very stable, powerful, and flexible tool.
- Probabilistic methods in general
  - Illustration of the potential and benefit
  - Description of fundamental mathematical aspects

Introduction of probabilistic methods in fuel rod design is an excellent demonstration of a successful introduction of an advanced method to cope with new challenges.

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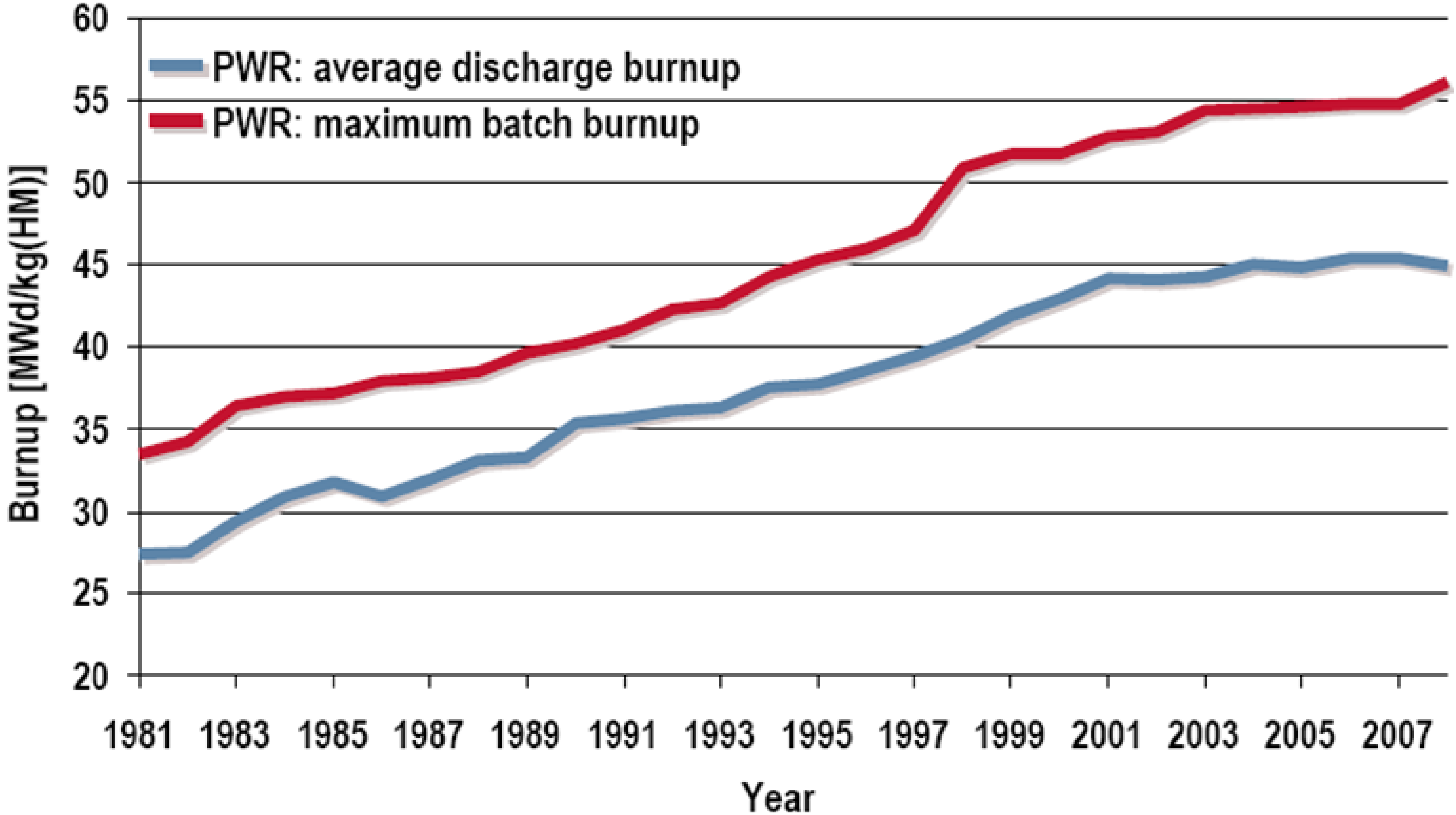
Evolution of Demands

- **Significant drivers for improved methodologies in the nuclear industry**
  - **Economic reasons**
    - Economically optimized plant and fuel utilization of existing nuclear power plants
    - Power uprates of plants (up to 20% in thermal power) → increased power density
    - Increased enrichment approaching and reaching the limit of 5 w/o U235 for commercial LWRs
    - Extended rod burnups up to 75 MWd/kg(HM)
  - **Ecological reasons**
    - Improved fuel utilization reduces reload and discharge batches
    - Decreased amount of spent fuel what can be directly related to the average fuel assembly burnup of discharge batches (see next two slides)

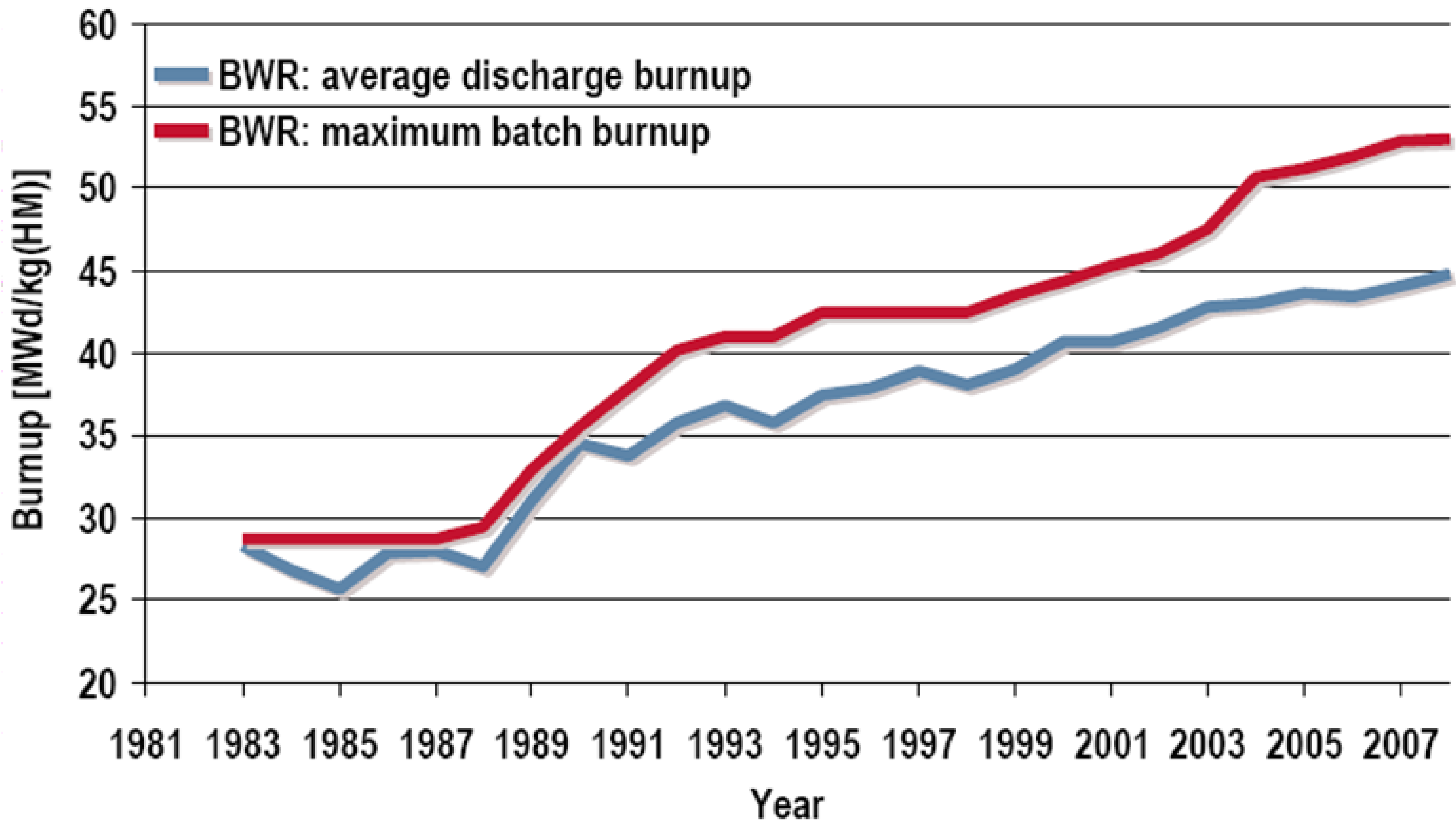
Evolution of Demands

- **PWR:**
  Increase in average and maximum discharge burnup over the last decades



Evolution of Demands

- **BWR:**
  Increase in average and maximum discharge burnup over the last decades



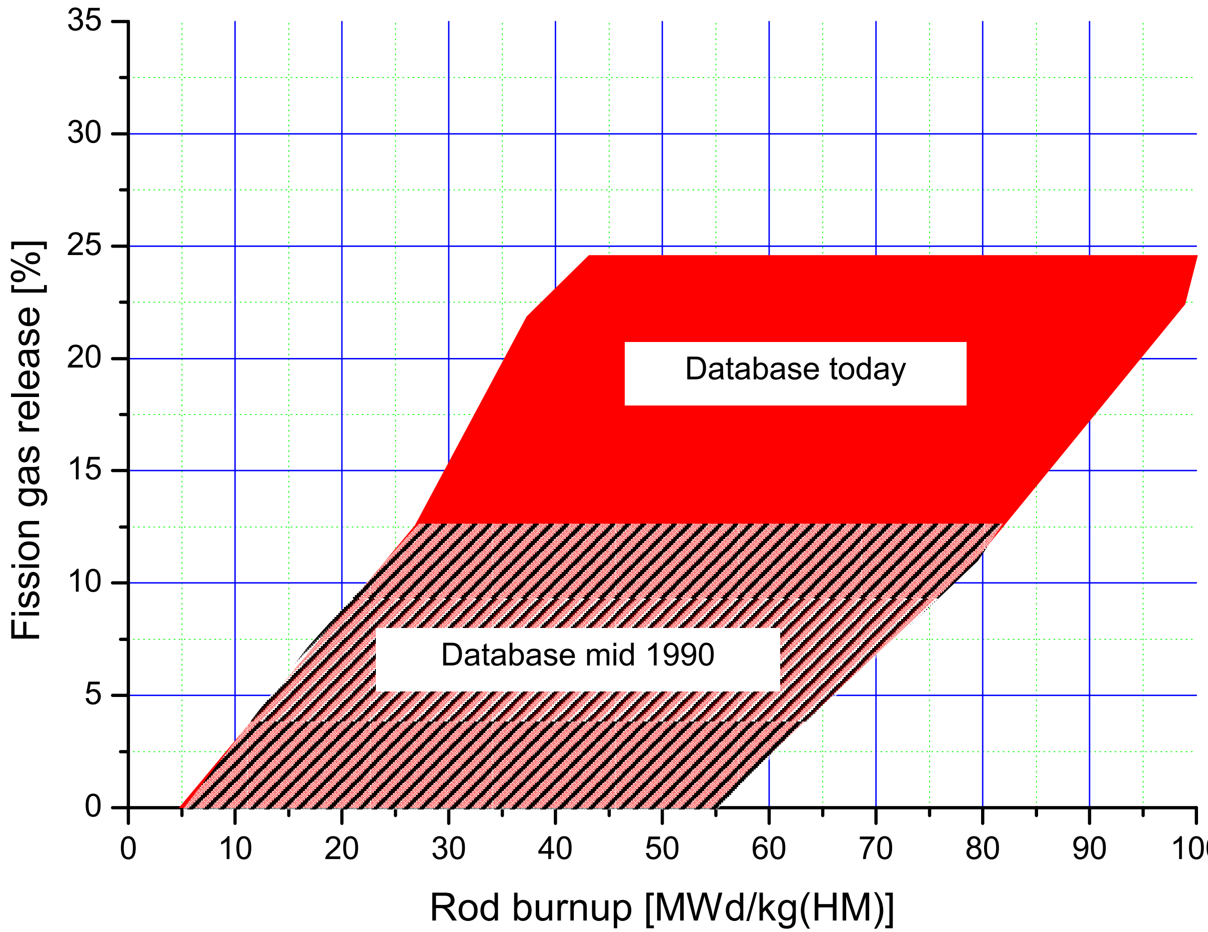
Evolution of Demands

- **Increasing technical challenges in view of economical and ecological demands**
  - **Technical safety-related reasons**
    - High power at high burnup for UO_2 fuel with high enrichment or MOX fuel with high fissile plutonium content
    - New regimes were continuously approached by the lead test assemblies programs accompanied by comprehensive inspection campaigns
      - Pool measurements
      - Post irradiation examination
    - The latest experience for fuel rods is very challenging
      - Not preconceived from established codes and methods
      - Example: fission gas release database for UO_2 rods irradiated in commercial PWRs in the mid 1990s and today (see next slide)

Facing the new challenges all stakeholders of the licensing process were prompted to reflect the potential of the traditional approaches in the light of current and future demands.

Evolution of Demands

- **Schematic range of the fission gas release database for UO_2 rods irradiated in commercial PWRs: comparison between the mid 1990s and today**
- **New challenges, but also a good message**
  - **Generally positive experience with lead test assemblies shows technical feasibility**
  - **To be taken into account in design codes**
  - **Realization of optimized fuel management schemes is possible**



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Traditional Approaches

- **Traditional proofs in the field of nuclear engineering**
  - **Based on a conservative-deterministic approach**
  - **Make use of an unfavorable combination of input parameters with respect to interesting quantities**
  - **Well founded within the frame of the boundary conditions of the past**
  - **Example: Highest fuel temperature in the core is at position of maximum LHGR due to**
    - Low enrichments
      $\rightarrow$ maximum rod burnups below 40 MWd/kg(HM)
      $\rightarrow$ decrease of reactivity led to decreasing rod powers
    - Fuel with low dimensional stability
      $\rightarrow$ open-gap situation
    - Almost no dependencies and interactions between different models
    - Degradation of fuel thermal conductivity is still unknown but also irrelevant due to low power at higher burnups

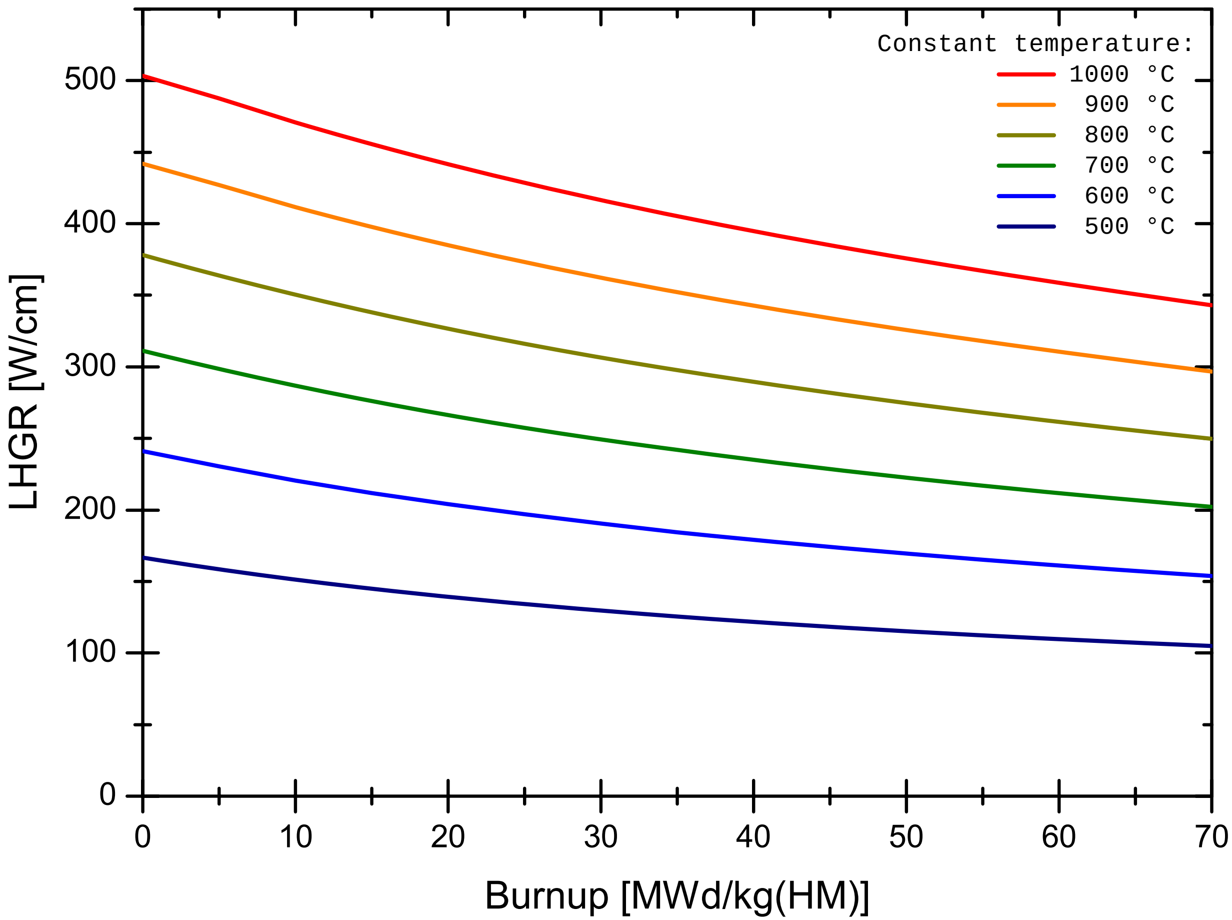
Traditional Approaches

- Boundary conditions of the past are not fulfilled any longer
  - Increased enrichment up to 5 w/o U235 and MOX fuel
  - Burnups up to 70 MWd/kg(HM) and beyond
  - Increased LHGR even in the medium- and high-burnup range
  - Increased knowledge on fuel properties e.g. degradation of fuel thermal conductivity with burnup
- State-of-the-art knowledge
  - Basic sensitivity of fuel temperature on LHGR and irradiation (see next slide)
  - Certain decrease of LHGR has to be assumed to keep the temperature constant with increasing burnup

Originally conservative-deterministic approaches may lack conservatism due to continuously changing boundary conditions.
→ Continuous review of original assumptions is crucial.

Traditional Approaches

- **Necessary decrease of LHGR to keep the average fuel temperature constant with increasing burnup (example for UO_2)**



Traditional Approaches

- **Opposite case can also occur:**
  Existing methods exhibit a degree of conservatism which is not required to comply with the safety guidelines

Existent margins should be exhausted to realize the most economical fuel management with reduced reload batches, and consequently, a reduced number of spent fuel assemblies.

Traditional Approaches

- **Increased mathematical complexity of codes**
  - **Due to recent experience feedback**
  - **Example**
    - Latest fission gas release data
      $\rightarrow$ indicates the well known dependence on burnup
      $\rightarrow$ reveals a pronounced sensitivity on LHGR (or fuel temperature)
    - Effect was not included in the validation database of old fuel rod codes and could not be anticipated either
    - Introducing the temperature sensitivity into a fuel rod code means that the non-linear effect in the fission gas release model of state-of-the-art-codes will be additionally stressed

It has to be reviewed whether simplified approaches relying on error propagation based on linear dependence are still appropriate for fuel rod code models with increased complexity.

Traditional Approaches

- **Example: error propagation based on linear dependence**
  - **Consider two functions**
    - $f_1 : (x_1, x_2) \mapsto 0.5 \cdot x_1 + 0.8 \cdot x_2$
    - $f_2 : (x_1, x_2) \mapsto 0.5 \cdot x_1 + 0.8 \cdot x_2 + x_1 \cdot x_2$
    - depending on two normally distributed ($\mu = 0,\ \sigma = 1/3$) parameters x_1, x_2
  - **Application of error propagation based on linear dependence:**
    - 95%-quantiles of the input parameters yield a 95%-quantile of 0.51 for the resulting distribution for both functions
  - **Direct integration**
    - 95%-quantile is 0.51 for $f_1(x_1, x_2)$ in agreement with error propagation based on linear dependence
    - 95%-quantile is 0.61 for $f_2(x_1, x_2)$ as consequence of non-linear effects

This example shows that the potential of error propagation is limited whenever the model response is governed by nonlinear effect which cannot be properly addressed in this approach.

Traditional Approaches

- **Example: selection of input parameters**
  - **High degree of complexity in fuel rod codes' models**
  - **Which set of input parameters**
    - roughly 10 to 20 for models and geometry
    - state-points defining the power history

  can be still justified to be conservative in all possible cases?
  - **Each result requires an individual set of conservative input parameters**
  - **Are there possible combinations which yield more unfavorable results?**

> **The basic questions to be answered by probabilistic methods are:**
>
> **What is the degree of conservatism of the conservative-deterministic approach?**
>
> **How to achieve a compromise which allows for an appropriate consideration of the combination of economical, ecological and technical safety-related requirements?**

Content

Probabilistic Methods

- Elements of probabilistic methods
  - Fuel rod code and database
  - Treatment of uncertainties
  - Mathematical foundation of methodology
- Results
  - Realistic assessment (“best-estimate scenario”) when omitting the uncertainties
  - Conservative assessment with a well defined degree of conservatism in terms of an appropriate quantile (safety and confidence level)

Probabilistic Methods

- **Requirement for fuel rod codes to be applied for probabilistic methods**
  - **Best-estimate code**
  - **Validated against a comprehensive, representative, reliable database**
    - from pool campaigns and post-irradiation examination
    - encloses all important validation parameters (e.g. temperatures, strains, fission gas release, etc.)
    - fulfills today's and future demands (traditional and modern fuel management schemes, high power densities, high enrichments up to 5 w/o U235, high burnups up to 100 MWd/kg(HM), UO_2, MOX, and UO_2/Gd_2O_3 fuel, modern fuel types
  - **Excellent run-time to be able to perform up to 10^3 … 10^5 calculations in several hours on a Linux cluster or multi-processor workstation**
  - **Excellent numerical stability without any aborts**
  - **Reliable error management to detect numerical problems and warn users if any problems should occur**

Probabilistic Methods

- **Current AREVA NP codes available and licensed for probabilistic methods**
  - **CARO-E3 for PWR and BWR application in Europe (Erlangen market)**
  - **RODEX4 for BWR application in USA**
- **Future AREVA NP code for probabilistic methods:**
  - **COPERNIC3 will replace the current codes**
  - **AREVA NP advanced global fuel rod code for PWR and BWR application**
  - **International experience is accounted for which has been gained with the advanced method for more than 14 years**

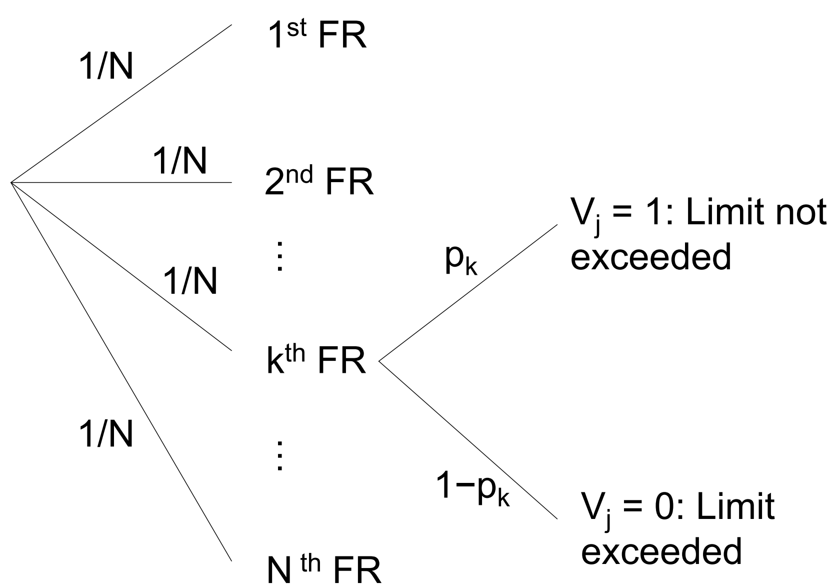
Probabilistic Methods

- Treatment of uncertainties of input parameters
  - **Fabrication uncertainties**
    - Probability distributions derived from an analysis of manufacturing procedures including specifications and processes
    - In most of the cases main input parameters of fuel rod codes as pellet diameter, clad inner and outer diameter are normally distributed.
  - **Model uncertainties**
    - More thorough analysis is required due to model sensitivity
    - Resulting model parameter probability distributions have to map the probability of a code over-prediction or under-prediction.

Probabilistic Methods

- Objective of probabilistic methodologies
  - Perform n simulations
  - Estimate the fraction of fuel rods in a population (e.g. core, reload or discharge batch) not exceeding the given limit
  - The random selection of a fuel rod (FR) is implemented in two steps

1st Step: Select rod 2nd Step: Select parameters



$$p := P(V_j = 1) = \sum_{k=1}^{N} \frac{1}{N} p_k$$

$$P(V_j = 0) = 1 - \sum_{k=1}^{N} \frac{1}{N} p_k = 1 - p$$

Probabilistic Methods

- **Notes related to previous figure**
  - Let us consider the j^{th} simulation (or calculation) ($1 \leq j \leq n$). In the first step one fuel rod (we assume the k^{th} FR) out of N fuel rods in the population is randomly selected. Thus, all rod-specific quantities (power history, materials, input parameter distributions) are uniquely determined. The probability for each rod to be selected is 1/N as we are dealing with a Laplace experiment.
  - In the second step the parameters are randomly selected with respect to the underlying distribution. The randomly chosen parameter combination will yield a value $y \leq y_L$ with probability p_k (fuel rod does not exceed the limit, $V_j = 1$) and a value $y > y_L$ with probability $1-p_k$ (fuel rod exceeds limit, $V_j = 0$). V_j is the random variable describing the result of the j^{th} simulation.

Therefore we can identify $V = V_1 + \dots + V_n$ as a Bernoulli chain with probability p, length n and expected value $E(V) = n \cdot p$.

Probabilistic Methods

- **Statistical evaluation by standard methods (e.g. DIN 53804/Part 4)**
  - **p is estimated from n simulations from v/n**
  - **with the confidence interval $[p_L,1]$ corresponding to the confidence level $(1-\alpha)$**

$$p_L = \frac{v}{v + (n - v + 1)\cdot F_{2(n-v+1),2v;1-\alpha}}$$

  - **$F_{a,b;1-\alpha}$ are the quantiles of the Fisher distribution.**

Two equivalent interpretations:

“The fraction of fuel rods in the population not exceeding the given limit is at least p_L with a confidence level of at least $(1-\alpha)$.”

“The expected value of the number of fuel rods in the core not exceeding the given limit is at least $N\cdot p_L$ with a confidence level of at least $(1-\alpha)$.”

Probabilistic Methods

- **Required number of calculations**

$$n \approx \frac{1}{1-p_L}(n-v+1)\cdot F_{2(n-v+1),\infty;1-\alpha}$$

  - **Depends only on the desired quantile**
  - **Does not depend on the number of input parameters**
    → approach appropriate for a large number of input parameters
    → tedious sensitivity analysis of parameter combinations not necessary
- **No further requirements necessary like**
  - **Linear dependency from input parameters**
  - **Normal distribution of input parameters**
- **Relevance of input parameters and their sensitivity with respect to all different output parameters is inherently mapped onto the resulting distributions**
- **The same set of calculations can be used to analyze all interesting output parameters (e.g. rod internal pressure, strain, temperature) simultaneously.**

Probabilistic Methods

- **Preclusion of systematic fuel rod failures is the crucial objective of verification in fuel rod design**
- **Identification of an appropriate combination of**
  - **Underlying population**
  - **Quantile**
  - **Pertaining criterion**
- **Not only one unique constellation which complies with the requirements**
- **Historical reasons impact licensing boundary conditions which developed differently and this effect can be still observed today**

Probabilistic Methods

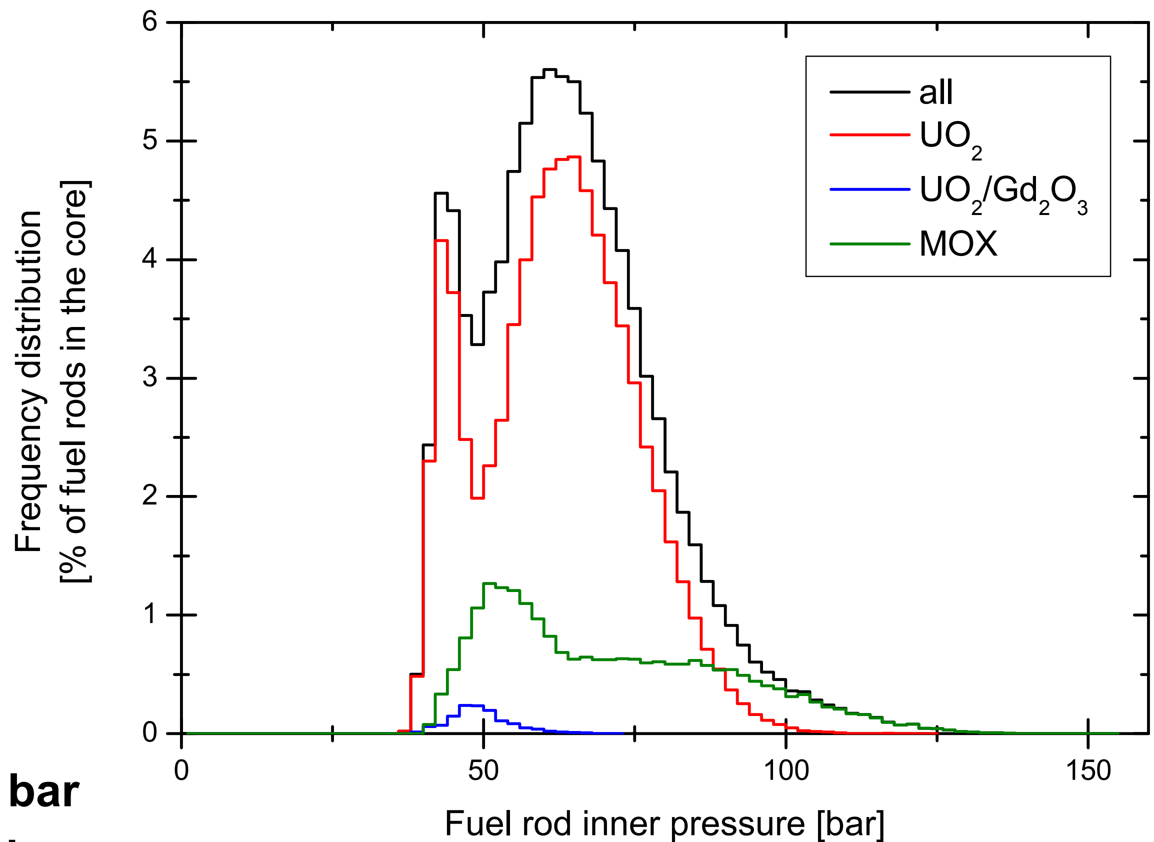
- **Suitable combinations which fulfill the requirement and are established in fuel rod design design licensing with respect to internal pressure in Germany and USA**
  - **Germany**
    - Population: complete core
    - Quantile: 95%/1−1/N (“one-rod quantile”), requires a minimum of 3N calculations
    - Criterion: Preclude rod failure by thermal feedback by limitation of the reopening of the gap due to internal overpressure; criteria derived from rod overpressure experiments
  - **USA**
    - Population: reload batch
    - Quantile: 95%/99.9%, requires a minimum of 2996 calculations
    - Criterion: system pressure plus 55 bar

Probabilistic Methods

- **Mathematically extensions: additional refined statements underline**
  - **That the new approach is consistent and target-oriented to preclude systematic fuel failures**
  - **That the probabilistic approach can be also applied to a mixed core**
    - Usual situation in plants
    - Fuel rods partly treated by new and by traditional methods

Probabilistic Methods

- **Example: German 16x16 PWR, rod internal pressure distribution**
  - **Population: all the rods (UO_2, UO_2/Gd_2O_3, and MOX) contained in the core**
  - **Probabilistic assess-ment performed with CARO-E3**
  - **The total number of calculations: 136110**
  - **Results: number of calculations is suffi-cient to evaluate quantiles up to the one-rod quantile with a confidence level of 95%**
  - **95%/99.9% quantile: 126 bar**
  - **95%/99.9978% quantile: 154 bar**



Probabilistic Methods

- Crucial new information compared to the traditional conservative-deterministic approaches which provide knowledge on extreme values only irrespectively how many fuel rods are in the vicinity of those extremes.

Proof: no risk for systematic fuel rod failure as the majority of fuel rods in the core are far away from calculated maxima.

Content

Conclusions and Outlook

- **Enormous mathematical potential with respect to applicability and information density in the context of nuclear safety**
  - **Best-estimate approach**
    → realistic results
  - **Systematic consideration of uncertainties**
    → result with quantitatively controlled degree of conservatism
  - **Number of calculations**
    - depends on the safety level and confidence level only which are appropriately adapted to the objective of verification
    - does not depend on the number of input parameters or requires linear response or certain input parameter distributions

» Probabilistic methods are an ideal tool to be applied to today's problems with high complexity depending of an increased number of input parameters.

Conclusions and Outlook

- **Probabilistic methods have capability to fulfill all requirements of licensing scenarios**
  - **Well established and have been used as a direct licensing tool in fuel rod design**
    - for many years in Germany, Sweden, Finland, Switzerland, Netherlands, Spain
    - recently approved by NRC in the USA
  - **Available as a benchmark for the traditional methods to prove sufficient margins**
- **Growing relevance is indicated by the extension to other areas**
  - **LOCA**
  - **Hold-down springs**

Probabilistic methods turn out to be the answer how to adequately address economical, ecological, and technical safety-related aspects in nuclear industry and beyond.

Thank you for your attention!

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