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Progress in Uncertainty Analyses Methods
Safety analysis of nuclear reactor steam supply systems

- Performed by **computer simulation** using complex system codes
- Margins to acceptance criteria are determined by
  - **conservative** evaluation model calculations
  - “**best estimate**” code plus **conservative initial and boundary conditions**
  - “**best estimate**” **calculations** supplemented by **uncertainty analysis** of code results
Regulation of deterministic safety analysis

- IAEA Safety Guide “Safety Assessment and Verification for Nuclear Power Plants” No. NS-G-1.2 (2001), 4.6: **Use more sophisticated tools and methods as they become available**

- IAEA Safety Guide No. NS-G-1.2 (2001), 4.90:
  Combination of BE computer code and realistic assumptions on initial and boundary conditions $\Rightarrow$ **uncertainties should be statistically combined.**

The calculated results shall not exceed the acceptance criteria with a **specified high probability.**
Regulation in USA

- **USA** Code of Federal Regulations 10 CFR 50.46 (Acceptance criteria for emergency core cooling systems) allows the use of **BE codes** instead of conservative code models
  - **Uncertainties** have to be identified and assessed so that the uncertainty in the calculated results can be estimated
  - High level of probability that acceptance criteria would not be exceeded
  - “High level of probability” in Reg. Guide 1.157 “Best Estimate Calculations of Emergency Core Cooling System Performance”: **95% or more**
Illustration of Margins

- Safety Limit

- Acceptance Criterion (Regulatory Requirement)

- Margin to Acceptance Criterion

- Actual Safety Margin

- Upper Limit of Calculated Uncertainty Range

- Calculated Uncertainty Range

- Real Value
Uncertainty analysis, GRS method

\[ y = f(P_i, t) \]

Set of time functions
Minimum, Medium, Maximum

Relevant function
Number of code calculations – Wilks’ formula

- Minimum number of code runs to calculate limits which are not to be exceeded with 95% probability (95% percentile):

<table>
<thead>
<tr>
<th>One-sided tolerance limit</th>
<th>Two-sided tolerance limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 at 99% confidence level, 59 at 95% confidence level, 45 at 90% confidence level, 32 at 80% confidence level, 14 at 50% confidence level.</td>
<td>130 at 99% confidence level, 93 at 95% confidence level, 77 at 90% confidence level, 59 at 80% confidence level, 34 at 50% confidence level.</td>
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Comparison with more than 1 acceptance criterion (1)

- Controversial international discussion
- A. Wald extended Wilks‘ concept to several output variables
- Shortcomings:
  - Requires considerably increased number of code runs
  - Depends on numbering of the output variables, i.e. on the order in which the output variables are treated and extreme values are omitted
    => e.g. 1-sided upper tolerance limit:
    1st variable is PCT, run with highest PCT eliminated for next output variable,
    2nd variable evaluated without that eliminated run,
    run with highest value of 2nd variable eliminated, etc.
Comparison with more than 1 acceptance criterion (2)

- Slightly modified concept proposed by GRS:
  - No consideration of joint tolerance limits for the multiple outputs of interest
  - Consideration of the statistical confidence limit (e.g. of at least 95%) for the probability of "satisfying all acceptance criteria for all output parameters"

- Advantages:
  - In the one-dimensional case of one single output parameter the concept is equivalent to the known concept of one-sided upper tolerance limit
  - Minimum number of calculation runs is the same for the “multi-dimensional” case, independent of output parameters and criteria involved, and consequently independent from interrelationships between the output parameters and criteria
Best estimate analysis including uncertainty analysis

- **Used in licensing** up to now in:
  - USA
  - Netherlands
  - Brazil
  - Korea
  - Lithuania

- **Significant activities** for use in licensing in:
  - Canada
  - Czech Republic
  - France (e.g. IRSN; Extended Statistical Method 3D by EDF)
  - Hungary
  - Russia
  - Slovak Republic
  - Spain
  - Ukraine
  - Germany (e.g. AREVA, GRS; RSK recommendation, draft revisions of regulation by BMU and KTA Safety Standards)
Uncertainty analysis for German Reference PWR
Up-rated power 4000 MW thermal, maximum clad temperature
OECD BEMUSE results, LOFT L2-5 experiment: 9 from 10 participants used static method, first proposed by GRS

1st PCT: Uncertainty bounds ordered by increasing band width
Main reasons for different results

- Quality of the reference calculation
- Uncertainties of the input parameters

Procedures to obtain distributions for input uncertainties:
  - Expert elicitation
  - “Bayesian prediction” procedure
  - Vinai procedure
  - “CIRCE” Procedure of CEA
  - Parameter fitting for uncertain models (PARFUM) procedure
  - Random Fuzzy (RAFU) by IRSN
Data used for quantification of uncertainties

- Results obtained during code validation, envelop results from separate effects and integral tests
  - Relevant and available experimental data should be used
  - Scaling effects considered by large scale experiments, like UPTF
- Data uncertainties from documentation (geometry, bypass flow paths, decay heat)
- Fuel data from fabrication tolerances
Example for influence of input uncertainty:
Film boiling heat transfer coefficient

Uniform distribution, nominal value: 1.0

Histogram distribution, range from 0.15 to 6.5, nominal value: 1.0
LOFT L2-5 peak clad temperature of hot rod in a hot channel, comparison of data and CATHARE V2.5 mod 6.1 calculation
Best estimate and uncertainty values, LOFT L2-5 experiment

On the left of the diagrams

BE 5%  
[BE 5% min, BE 5% max]

On the right of the diagrams

BE 95%  
[BE 95% min, BE 95% max]
Results of comparing different distributions of heat transfer coefficient and number of uncertain input parameters

- No significant effect of number of parameters
- The 3 most influential parameters are:
  - Liquid wall friction
  - Vapour-wall heat transfer (forced convection)
  - Film boiling (Berenson/ Bryce correlation)
- Uncertainty range of calculated peak clad temperature is highly dependent on distribution of uncertain input parameters
Random Fuzzy (RAFU) Method by IRSN

- Provides a methodology which does not need to specify one unique probability distribution for an uncertain parameter
- Based on Dempster-Shafer theory => unified framework for probability and possibility
- A possibility distribution contains a set of probability density functions
- Consideration of
  - Compensation due to independence of input uncertainties or
  - Accumulation due to dependencies of input uncertainties
- Computational cost reduction by optimised sampling
Quantification of knowledge: Sampling distributions

Probability distribution

Possibility distribution
Complementary cumulative density functions of the 3 most influential uncertain parameters

Confidence level

95% - Percentile

Dempster-Shafer approach

Statistic treatment

Dempster-Shafer approach

Uncertainty compensation

Uncertainty accumulation

Dempster-Shafer

Statistic

Dempster-Shafer

Statistic

PCT
Results of comparison between Depster-Shafer approach and statistic approach

- Triangular distribution of fuzzy variables leads to a difference of 100 K of the 95th percentile of first PCT
- Differences between uncertainty accumulation and classical uncertainty compensation leads to difference of 30 K for the 95th percentile
Summary

- Statistic uncertainty analysis method is used for safety analyses in licensing applications in several countries.
- Significant activities in other countries to introduce the statistic method in licensing.
- High requirements in determining uncertain input parameters.
- Alternative approach for quantifying input uncertainties when only incomplete knowledge is available.
  => RAFU method
  => provides an interval instead of one value for the percentile.