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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**

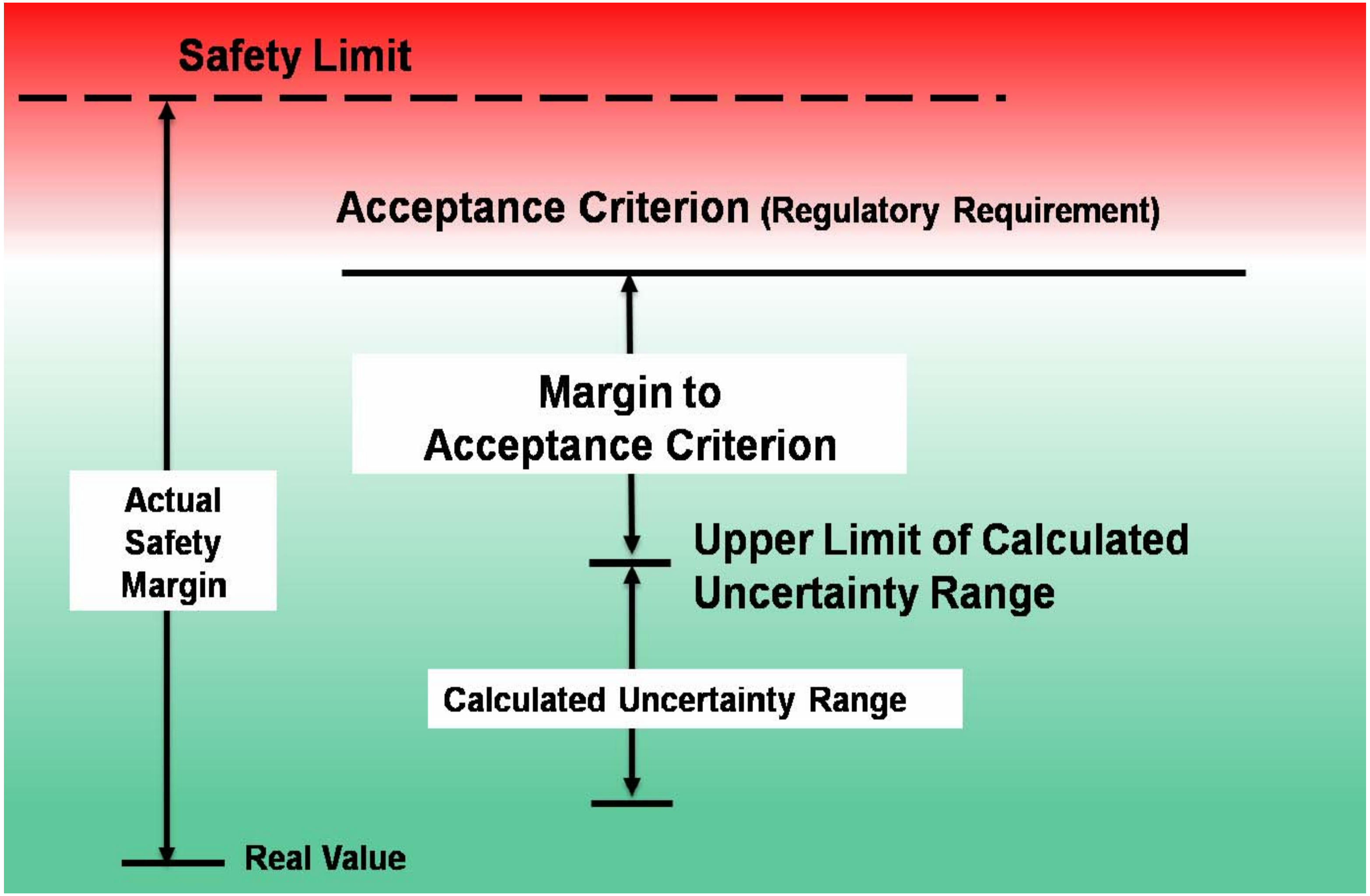
- **IAEA Safety Guide** No. NS-G-1.2 (2001), 4.90:
  Combination of BE computer code and realistic assumptions on initial and boundary conditions => **uncertainties should be statistically combined.**

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

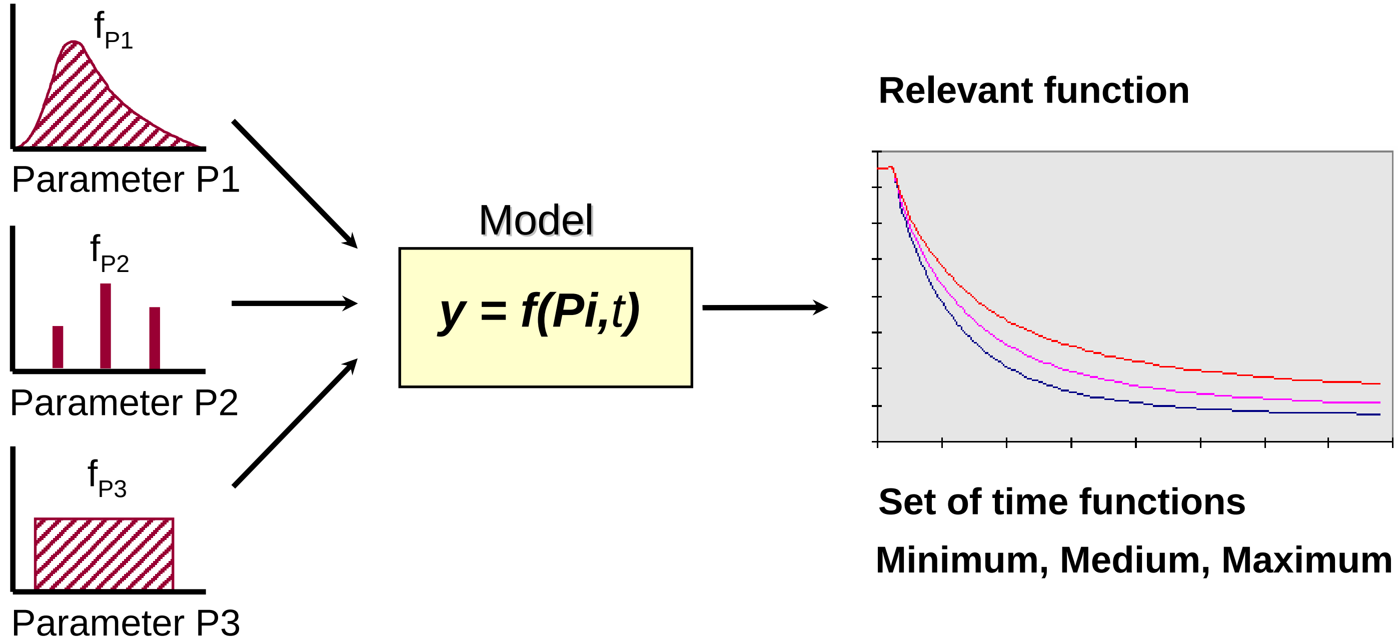
Regulation in USA

- **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



Uncertainty analysis, GRS method



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):

One-sided tolerance limit	Two-sided tolerance limit
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.	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.

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.

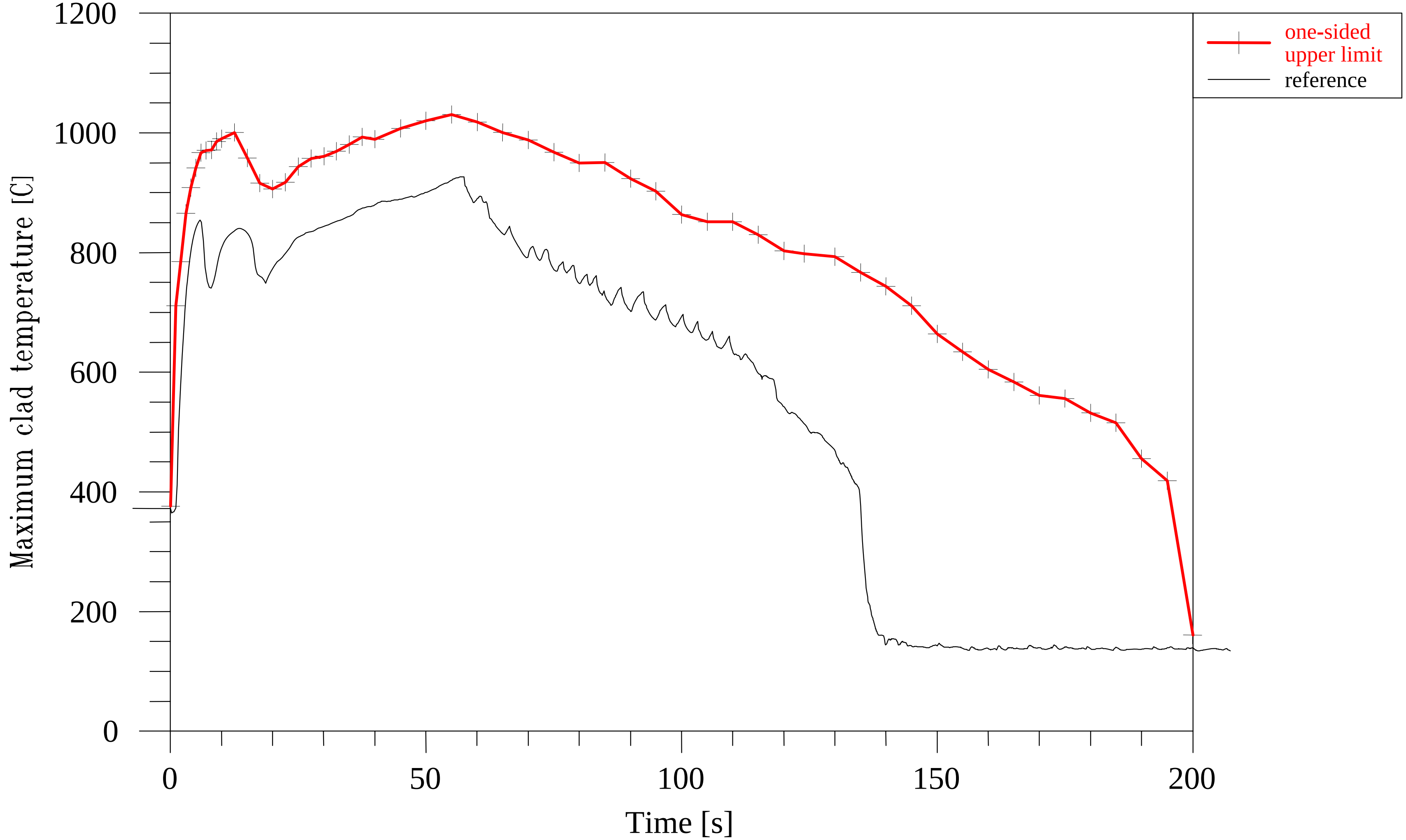
Comparison with more than 1 acceptance criterion (2)

- 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

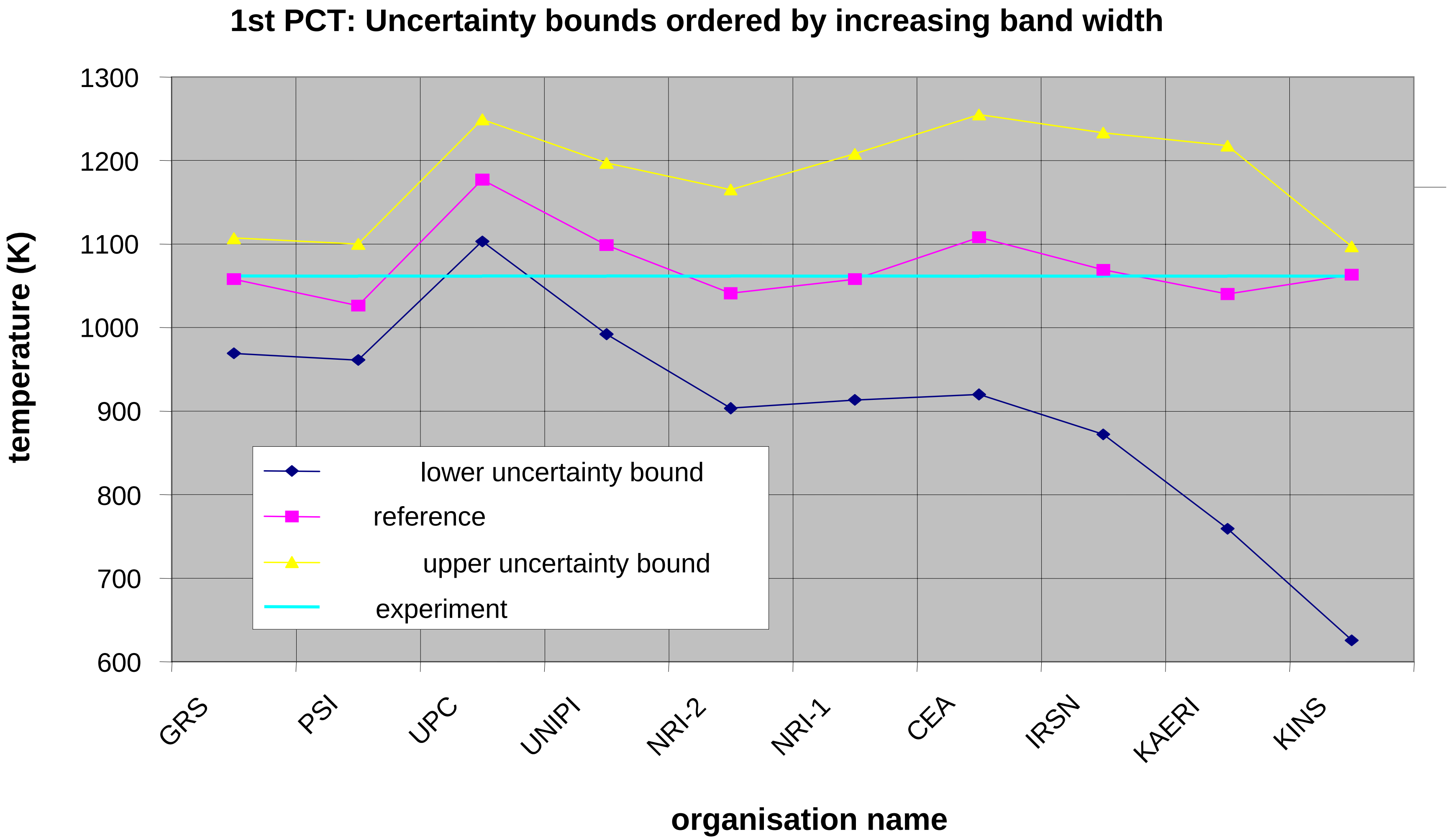
Best estimate analysis including uncertainty analysis

- **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



Main reasons for different results

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

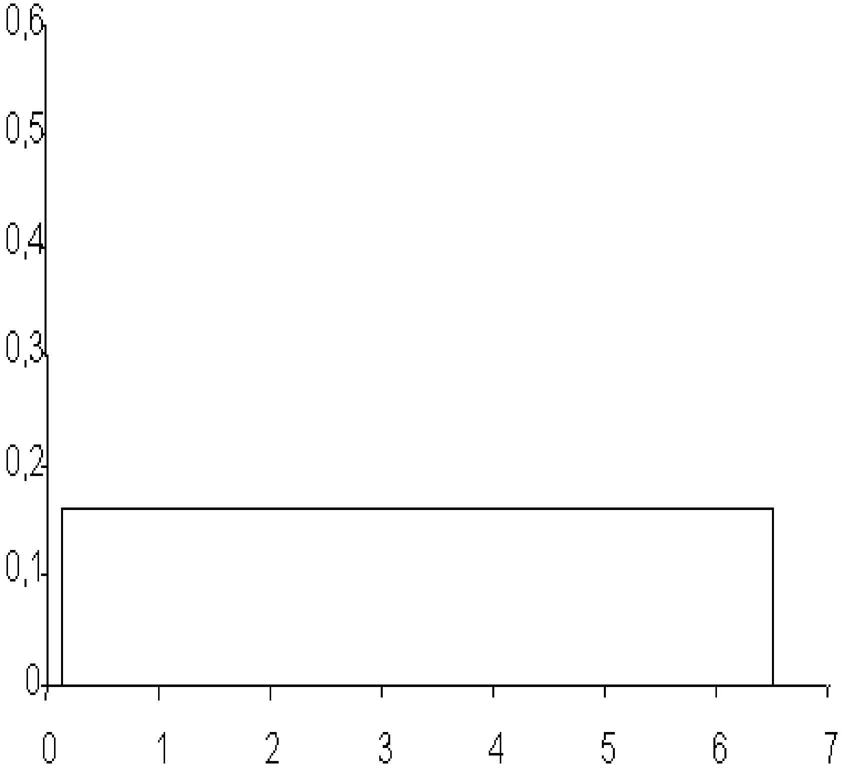
- Procedures to obtain distributions for input uncertainties:
  - Expert elicitation
  - “Bayesian prediction” procedure
  - Vinai procedure
  - “CIRCE” Procedure of CEA
  - **Par**ameter **f**itting for **u**ncertain **m**odels (PARFUM) procedure
  - **Ra**ndom **Fu**zzy (RAFU) by IRSN

Data used for quantification of uncertainties

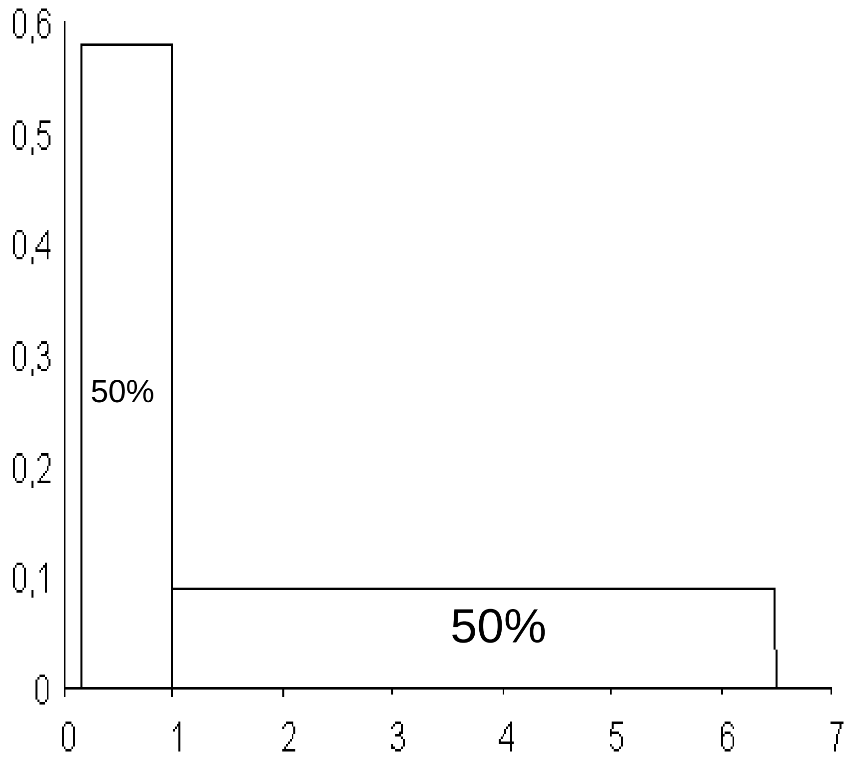
- Results obtained during code validation, envelop results from separate effects and integral tests
  - Relevant and available experimental data should be used
  - Scaling effects considered by large scale experiments, like UPTF
- Data uncertainties from documentation (geometry, bypass flow paths, decay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

Example for influence of input uncertainty: Film boiling heat transfer coefficient

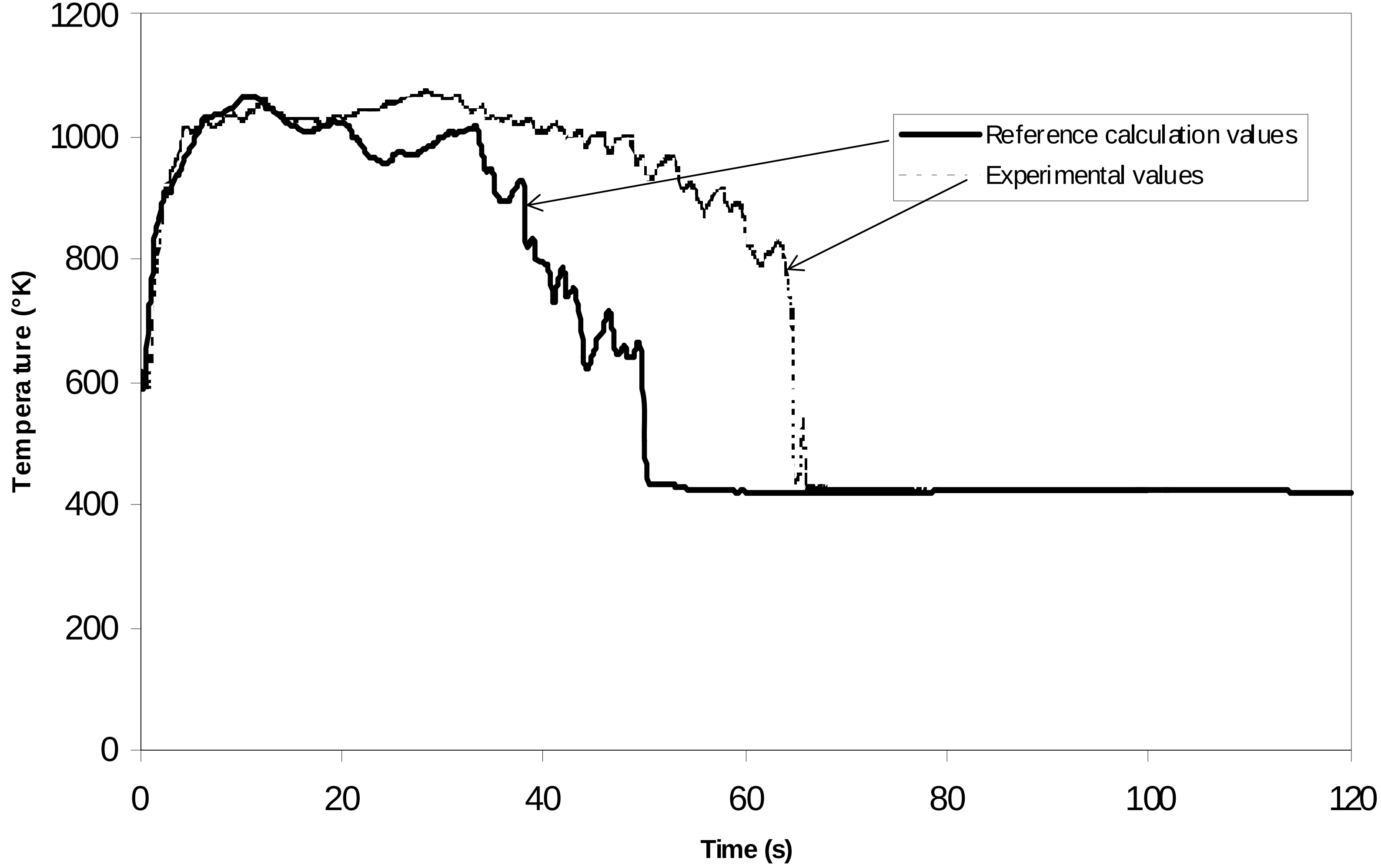
Uniform distribution,
nominal value: 1.0



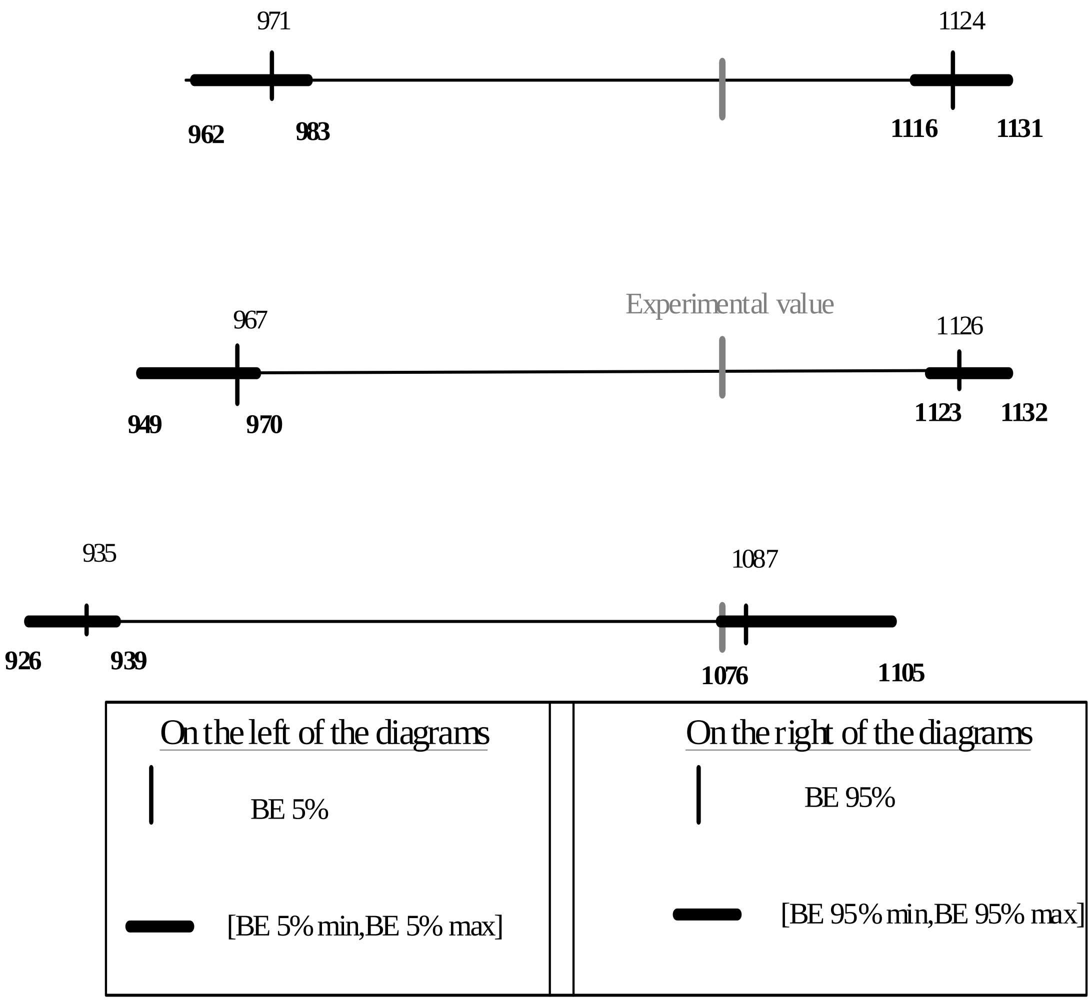
Histogram distribution,
range from 0.15 to 6.5, nominal value: 1.0



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



3 parameters, histogram distribution

27 parameters, histogram distribution

27 parameters, uniform distribution

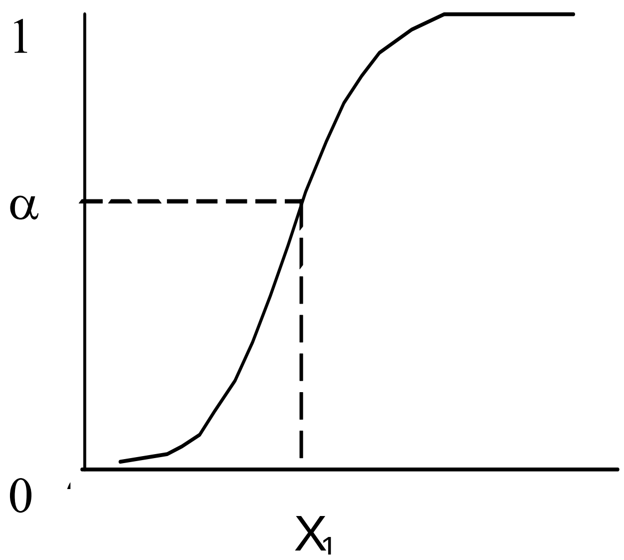
Results of comparing different distributions of heat transfer coefficient and number of uncertain input parameters

- 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

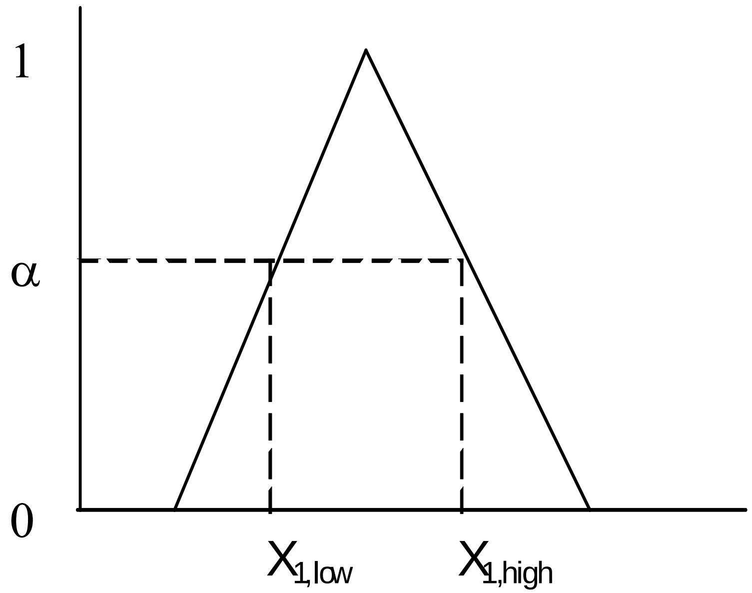
Random Fuzzy (RAFU) Method by IRSN

- 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

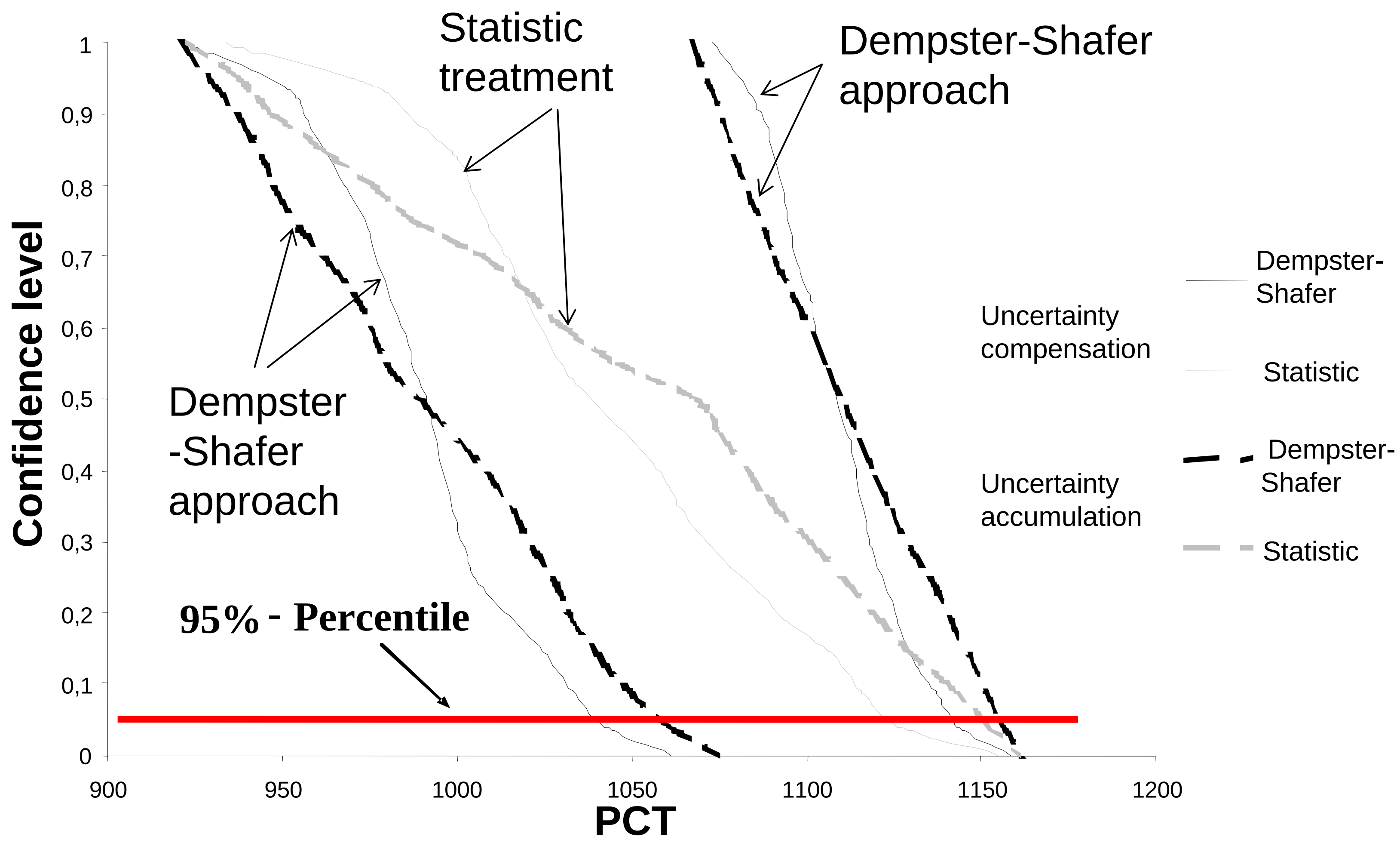


Probability distribution



Possibility distribution

Complementary cumulative density functions of the 3 most influential uncertain parameters



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