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Advances in Fuel Modeling and Design/Licensing Methodologies by Improved Knowledge and Uncertainty Quantification–AREVA Contribution

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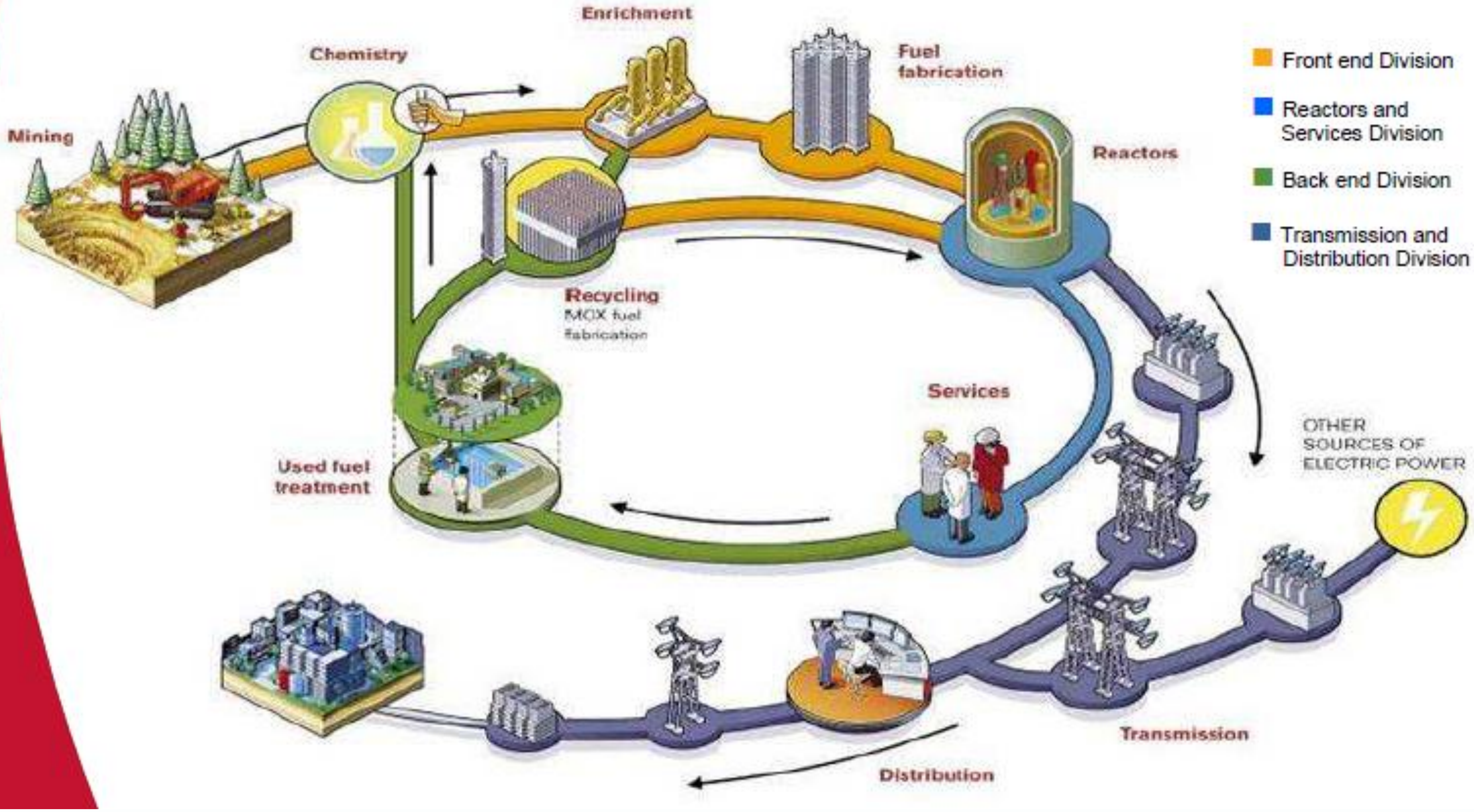
Energy, our core business



- 🟧 Front end Division
- 🟦 Reactors and Services Division
- 🟩 Back end Division
- 🟦 Transmission and Distribution Division

AREVA NP: A matrix structure

	Plants	Services	Fuel	Components
FRA				
GER				 Sales only
USA				 Sales only

AREVA NP worldwide

☐ *14.000 employees worldwide*

● Engineering ● Manufacturing ● Service ● Offices

General features of licensing analyses and methodologies

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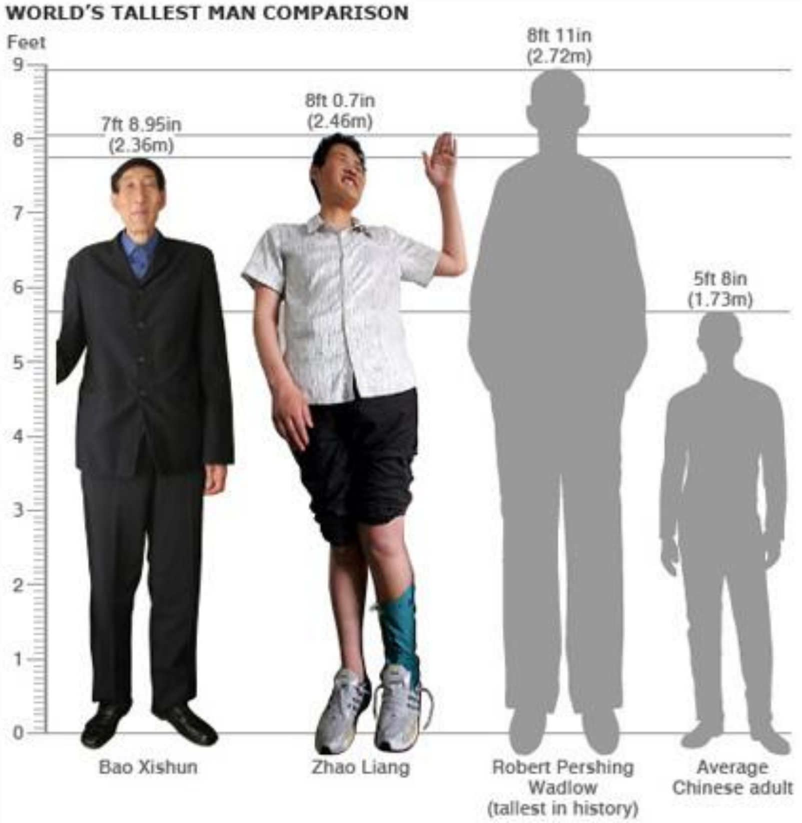
- Licensing criteria have margin to actual failure thresholds, either as stipulated by the NRC or proposed by licensees and approved by the NRC.
- Quantifying the licensing criteria analysis depends on the amount and depth of the body of knowledge with regards to fuel behavior.
- The magnitude of the engineering safety margin of licensing criteria to actual failure limits is correlated with the knowledge depth – move towards informed decision based methods from bounding conservative.
- Initially, deterministic/bounding methodology was used for fuel licensing, because:
  - Limited knowledge of fuel behavior
  - Limited experimental database

Deterministic/bounding methodologies

- There are two type of unknowns:
  - Known unknowns – burnup degradation of fuel thermal conductivity before 1990's, as no reliable data were available to support modeling
  - Unknown unknowns – such as HBU, although early indications were available from plate fuels
- In order to cope with limitations in knowledge and/or lack of data, models in fuel codes were biased conservatively and conservative/bounding assumptions were also made in methodology.
- The basis for deterministic/bounding approach is to identify the most limiting case and analyze it with the worst combination of inputs and biased models – i.e., we are looking for the extreme, but in many cases overly conservative, see illustration next page.

In many cases, the worst case scenario led to overly conservative assumptions, as in the right-hand side illustration



Worst case – did we always get it right?

- Even with very good insights into all aspects of fuel behavior, the nonlinear system and complex dependencies on power history, it is questionable that all assumptions made in deterministic methods were bounding.
- As an example, let's consider the usual assumption of employing an envelope power history, that allegedly defines an operating domain which can be used (as an ergodic property !?!) entirely.
- However, FGR e.g., is greatly affected by power variations (notably power ramps); is therefore such a steady-state power envelope always bounding ?
- In addition, especially in BWR's, axial power profile is varying with irradiation in a complex way.
- Past bounding methodologies imposed arbitrary power transients through the power envelope, to address above issue.

Implementation of realistic analyses and methodologies

Need for realistic methodologies

- System is nonlinear and interdependencies exist between inputs – difficult to select & justify worst-case combination
- Power histories are complex, variations both in average power as well as axial power profile
- The extreme case might be an isolated outlier, and there is no information about the bulk of the fuel rods in the core – it is important to know whether there are several rods close to the limiting one, in which case the risk of any of them exceeding the limit becomes higher
- The philosophy of the licensing analysis is to limit to the maximum extent possible the risk of exceeding the limit – no systematic trend
- The reactor cooling system can deal with one or a few failures but no more – the deterministic/bounding analysis can be either not capturing the real extreme, or be overly conservative.

Hybrid methodologies with simplified statistical method

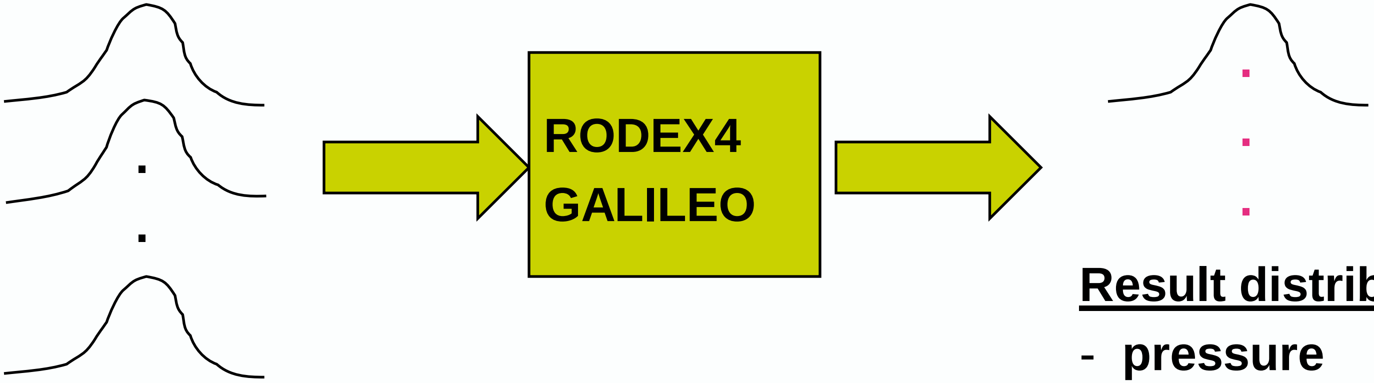
- **Typically, the power history is considered as the power envelope, with caveats as pointed out before.**
- **A linear uncertainty propagation approximation, commonly known as SRSQ, was used in the past, neglecting also the cross-terms, i.e., assuming no correlation (covariance) between parameters.**
- **Also, the SRSQ method relies on sensitivity coefficients estimated at nominal, one at a time, parameters.**
- **Although, studies were performed to justify the SRSQ approach, no theoretical basis to extend it to wider ranges, farther away from nominal values.**
- **A method that allows the synergy of various input parameters is desirable: *<u>the non-parametric, order statistics is applicable to any distribution and for any number of inputs.</u>***

Realistic fuel thermal-mechanical methodology as approved for RODEX4

Realistic RODEX4 BWR Methodology – extended to GALILEO and PWR

- Based on best-estimate code and a methodology that evaluates uncertainty propagation for the outputs of interest based on quantified inputs' uncertainties.
- Statistical statement to show compliance with licensing criteria: the expected specific quantile (99.9 %) of the fuel rods is estimated for a reload batch and it is shown that it lies below the SAFDL.
- Uses realistic power histories (MB2, ARCADIA calculated) and modified by calculational core simulator uncertainty and operational flexibility allowance uncertainty.
- Accounts for channel bow impact on fuel rod powers.
- The non-parametric order statistics method is used to estimate the desired quantile, which then is shown to be less than the criterion

Realistic Fuel Rod Methodology for LWR's Evaluation Process – uncertainty propagation through the code



Input:

Projected operation

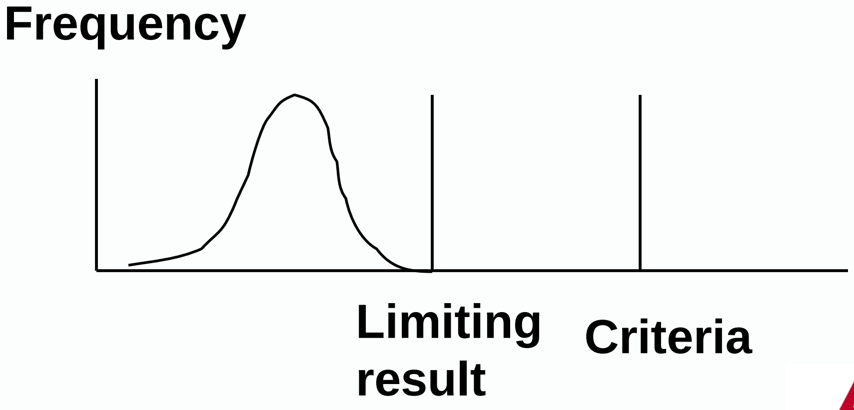
- scenarios

Parameter distributions:

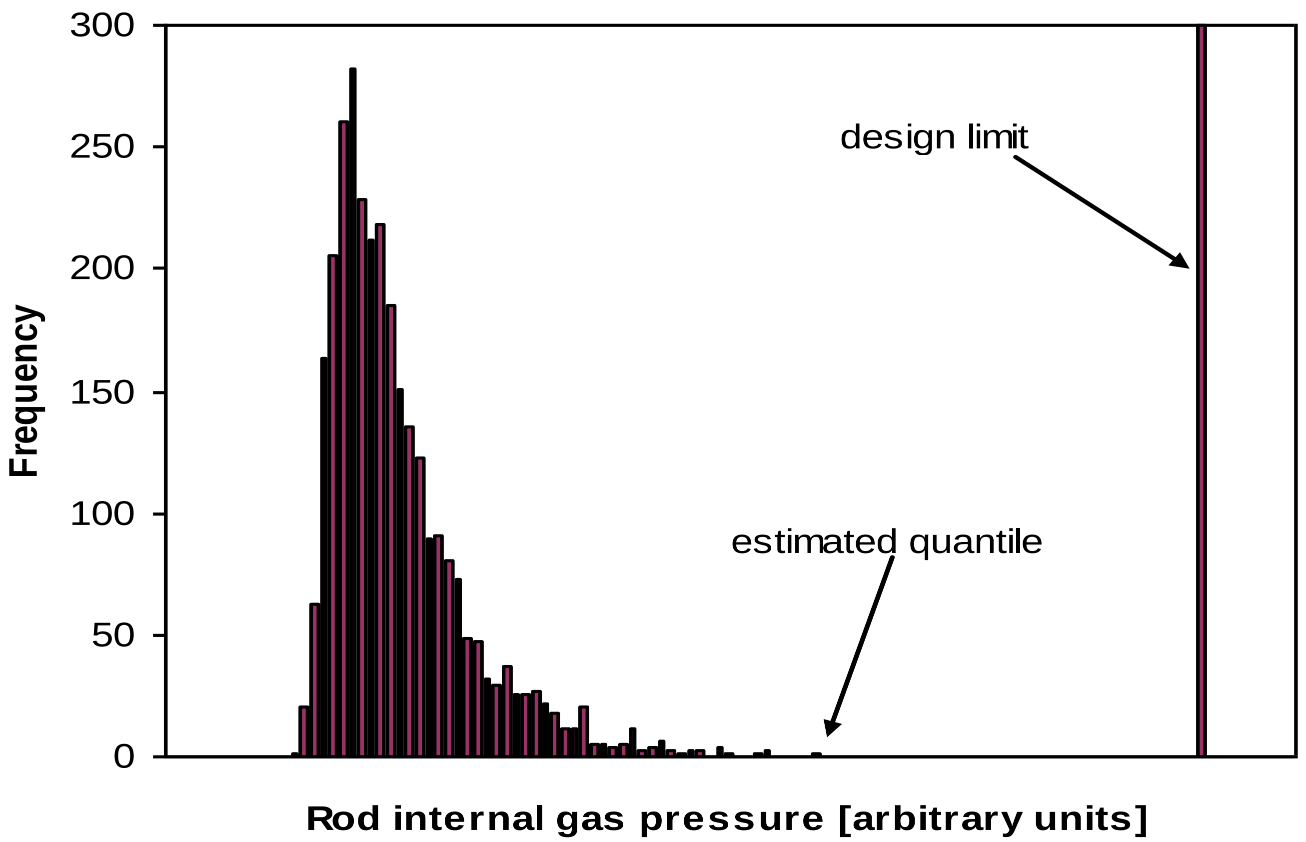
- operational parameters
- fabrication parameters
- model parameters

Result distributions:

- pressure
- strain
- corrosion, etc.



BWR 6 -maximum internal gas pressure criterion



Choice of method to be used in order to arrive at the final statement

- **Direct Monte Carlo calculations with the full set of power histories – too computationally expensive**
- **Statistical method used to evaluate the various distributions required by the final statement is the “non-parametric order statistics”**
- **This is particularly suited to estimate quantiles of populations with an unknown distribution function.**
- **Let the p-th population quantile be denoted by q_p. Then, q_p is defined in terms of the cumulative distribution function, $F_X(x)$, of the population as the real number which satisfies the equation:**

$$F_X(q_p) = p$$

Method to Estimate the upper bound 99.9 Percentile

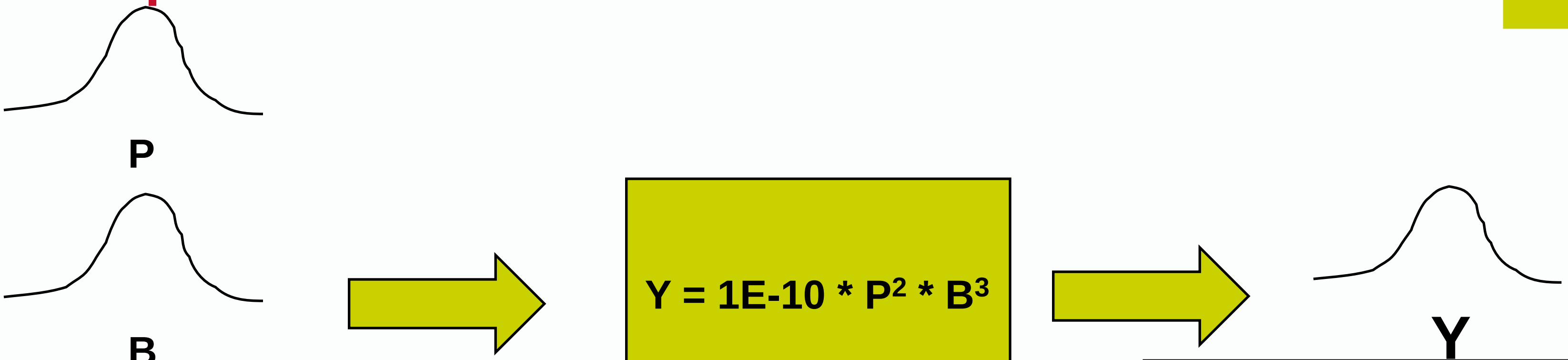
- **direct way**
  - **sample a multi-variate input vector for all fuel rods**
  - **count how many fuel rods exceeded the threshold for each sample event**
  - **the expected number can be estimated as the sample average.**
- **Indirect way**
  - **use the link between the distribution of all possible values from all fuel rods, called the overall distribution, and the distribution of the fraction of fuel rods not exceeding the threshold:**
- **“The expected fuel rod fraction, p, of all rods, that do not exceed the threshold q is equal to the p-quantile, q_p, of the overall pressure distribution.“**

Verification/Validation of the statistical methodology

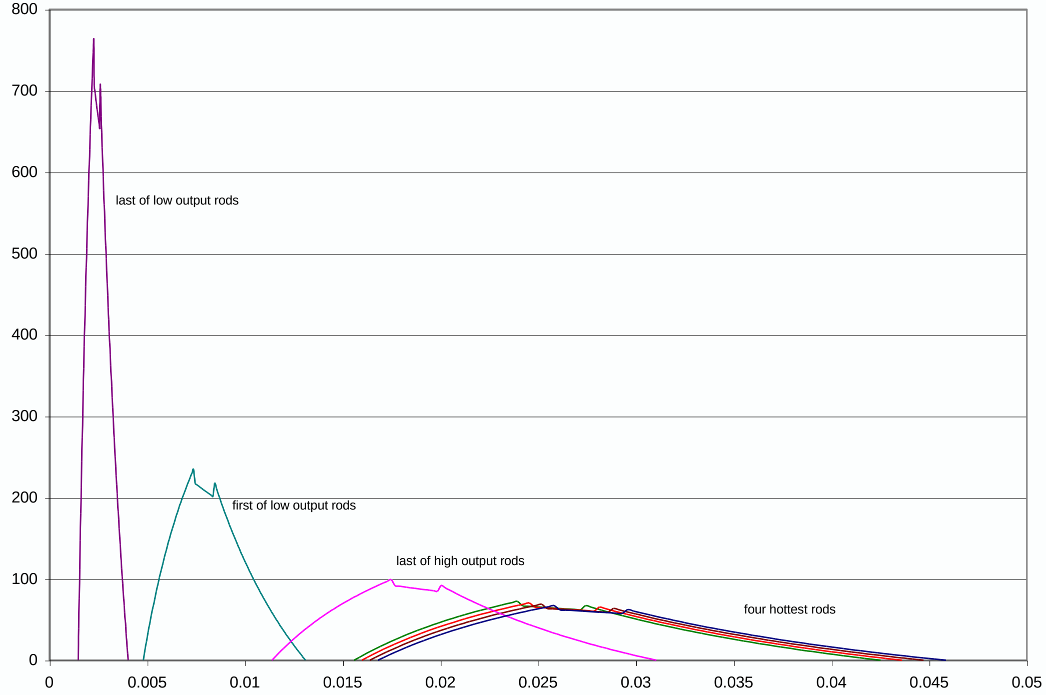
Verification/Validation of the statistical methodology

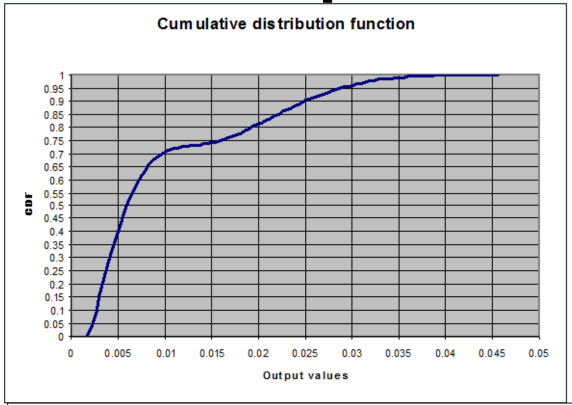
- **A simplified example was developed in order to validate the methodology and its implementation**
- **In the simplified example the code is replaced by a simple response function**
- **The conservatism of the minimum number of samples of the order statistics was studied and proven.**

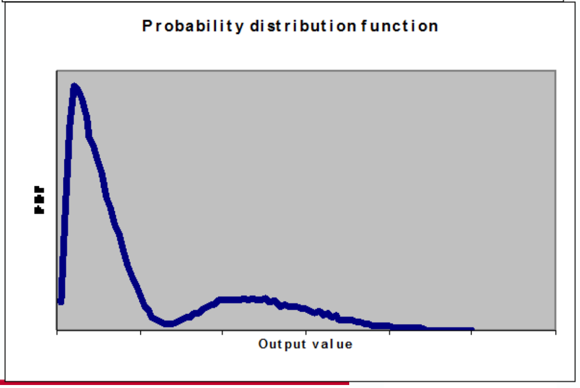
Simplified methodology example: 590 “rods”, 95 % quantile with 95% confidence limit; transfer function with 2 independent variables



$Y = 1E\text{-}10 * P^2 * B^3$



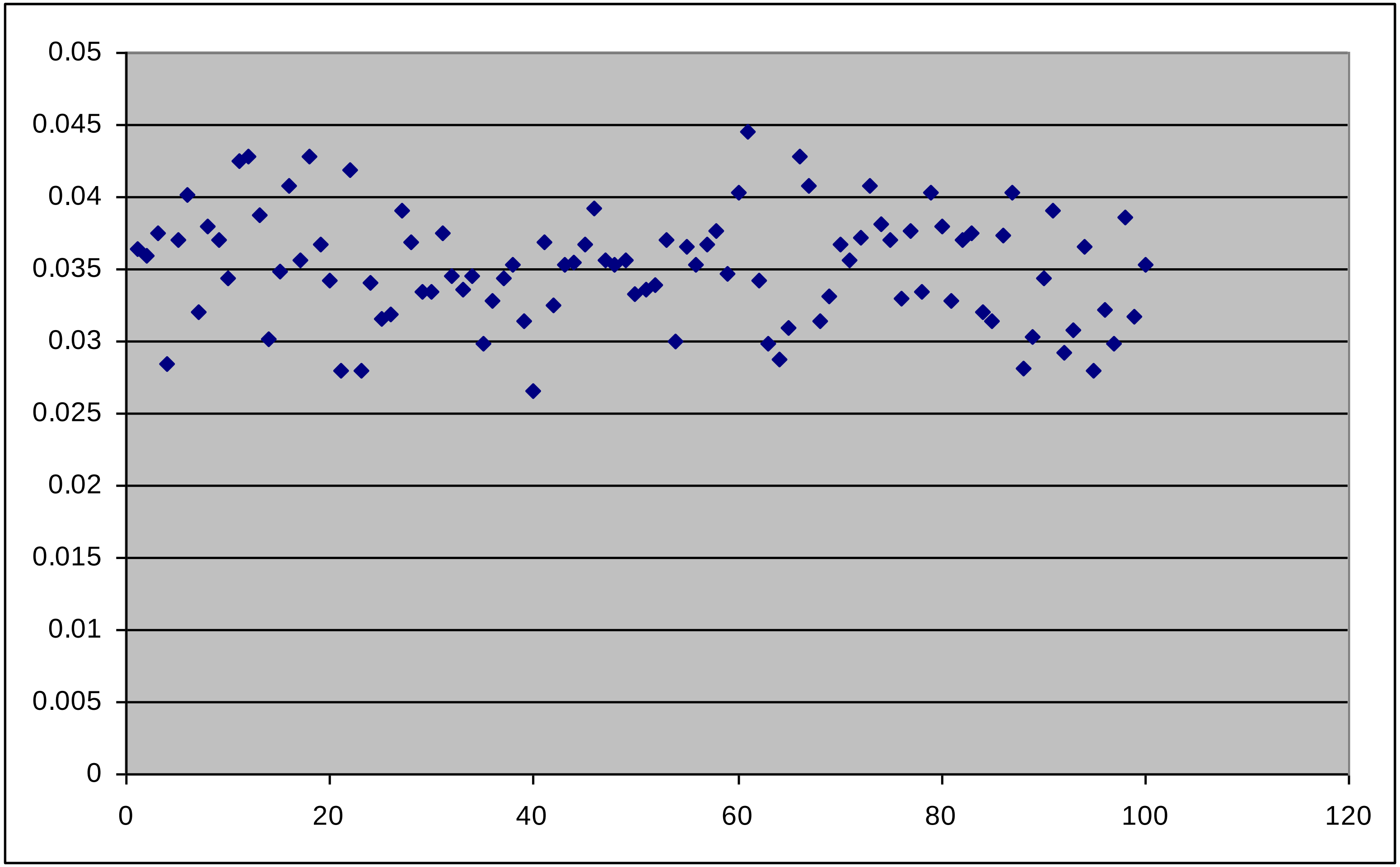




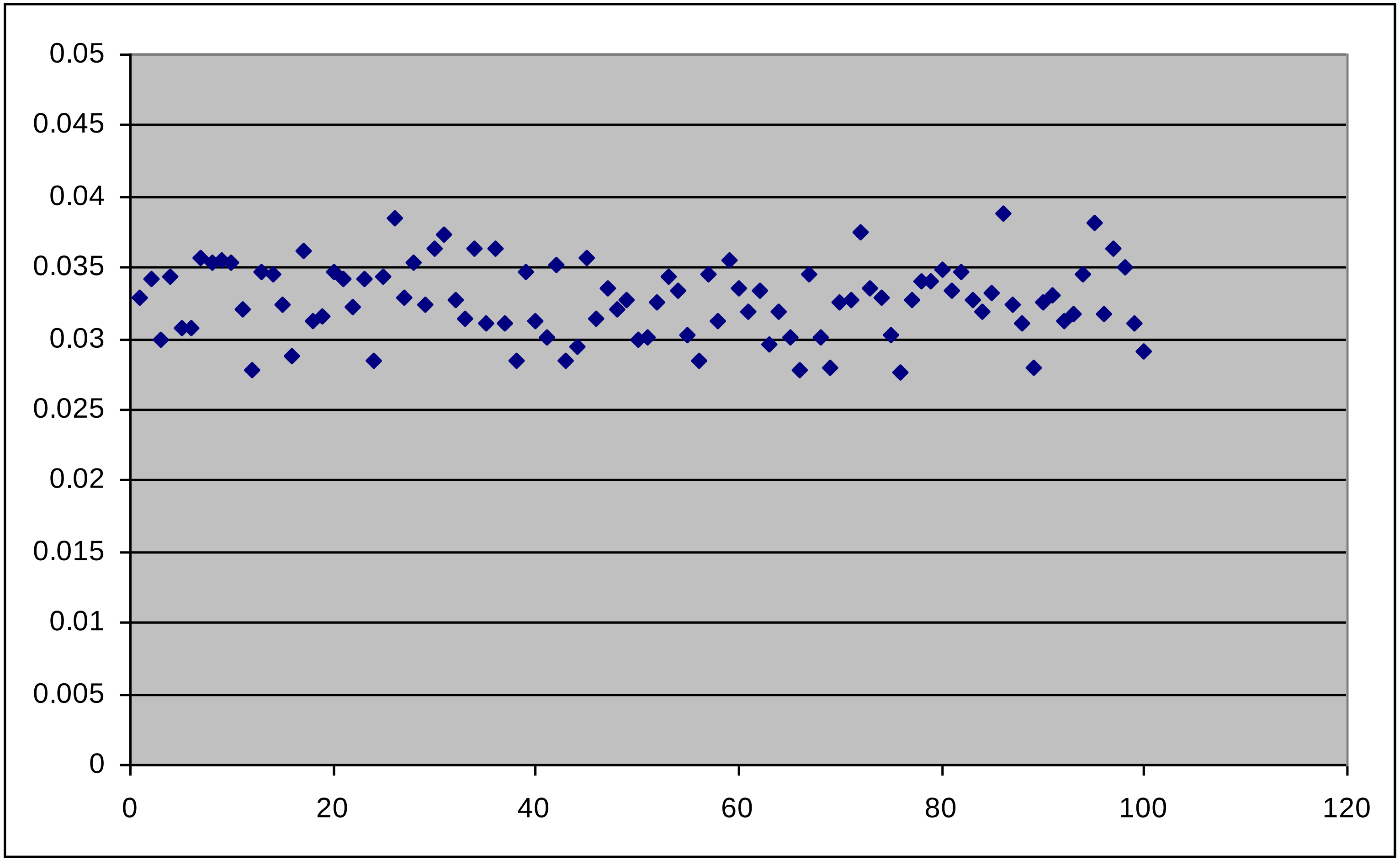
Sampling the power histories and conservatism of small-size samples

- **The non-parametric order statistics is applied to estimate the 95/95 quantile.**
- **The minimum number of runs is 59, for which the largest value of the 59 calculations is the estimate of the 95/95 quantile**
- **If more runs are performed, the second largest, or the third largest, etc. can be used as an estimate.**
- **The accuracy of the estimate increases with the number of runs, but the lower-size samples provide a conservative estimate (i.e. greater than the theoretical value).**
- **The following figures illustrate the conservatism of minimum sample size.**

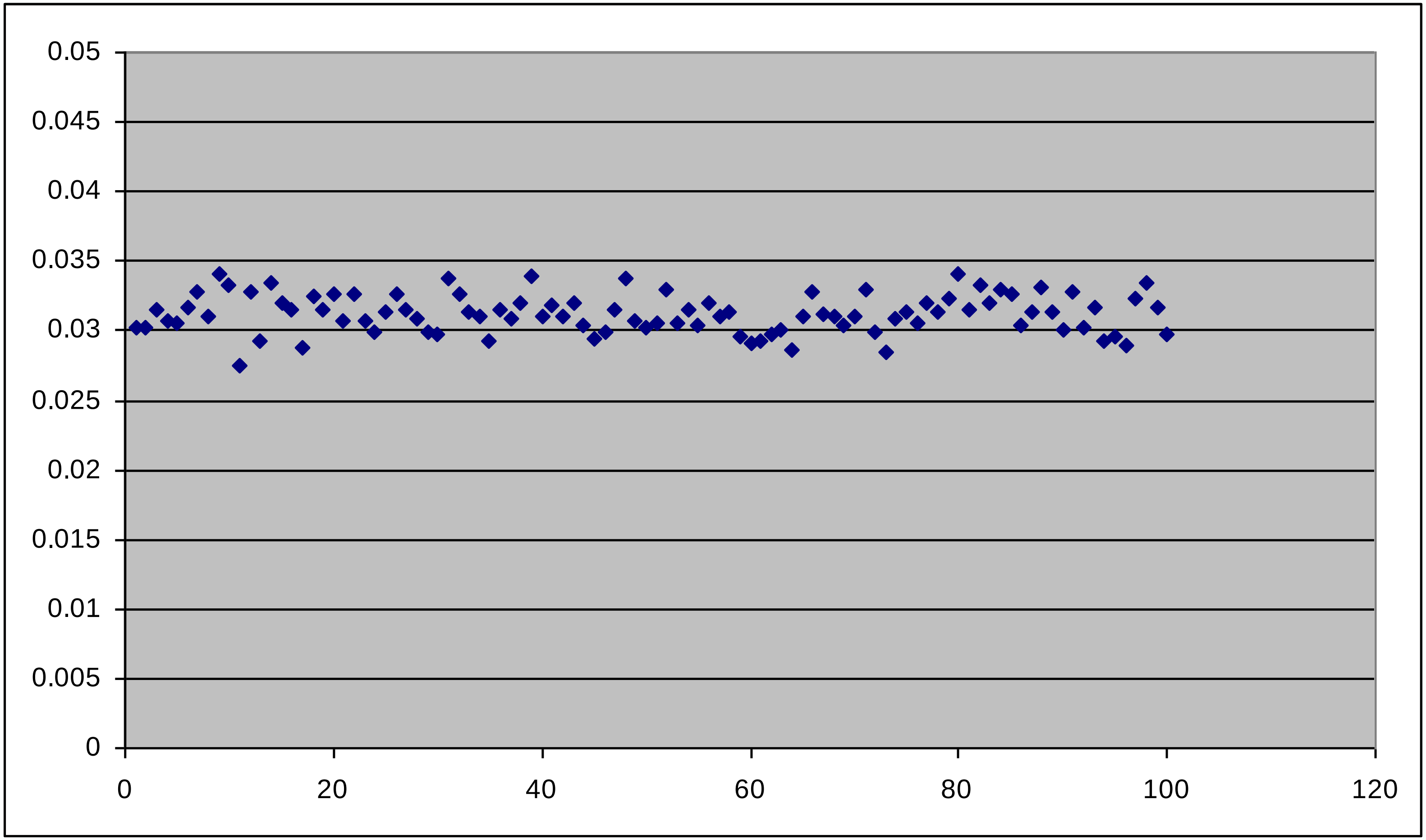
59 runs, 95/95 estimate



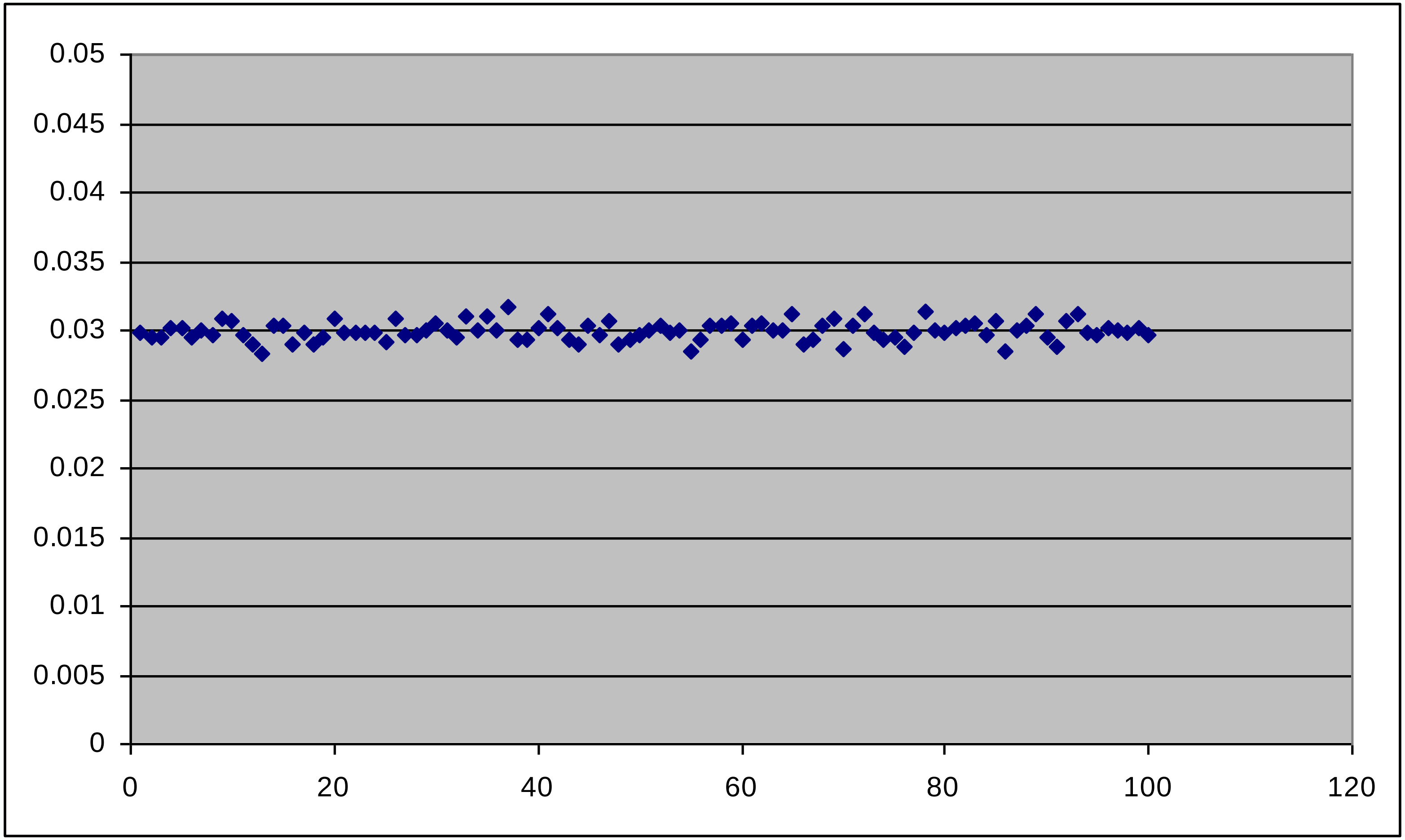
133 runs, 95/95 estimate



314 Runs, 95/95 estimate



1200 runs, 95/95 estimate

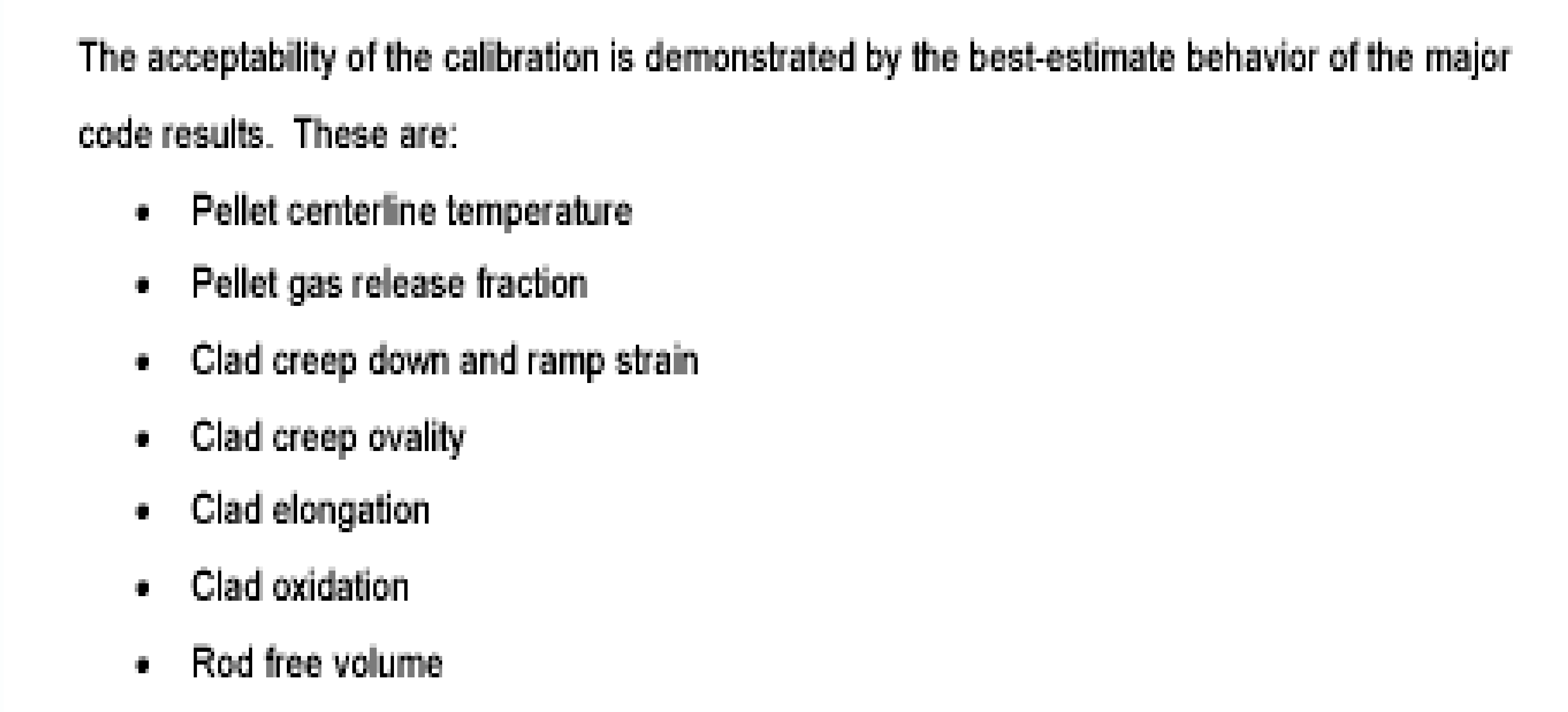


Fuel Codes

Salient features of RODEX4

- State-of-the-art best-estimate fuel code
- Mechanistic modeling of processes and especially of feedbacks between thermal and mechanical phenomena – most mechanistic code available
- This allows a realistic, best-estimate of the pellet-to-cladding gap, without any empirical relocation model.
- Then, the gap statistics from the steady-state runs forms the basis for the fast AOO methodology (physically based).
- Comprehensive treatment of uncertainties
- Comprehensive benchmarking database covering BWR and PWR data and conditions
- MOX models included in the code but not benchmarked for MOX

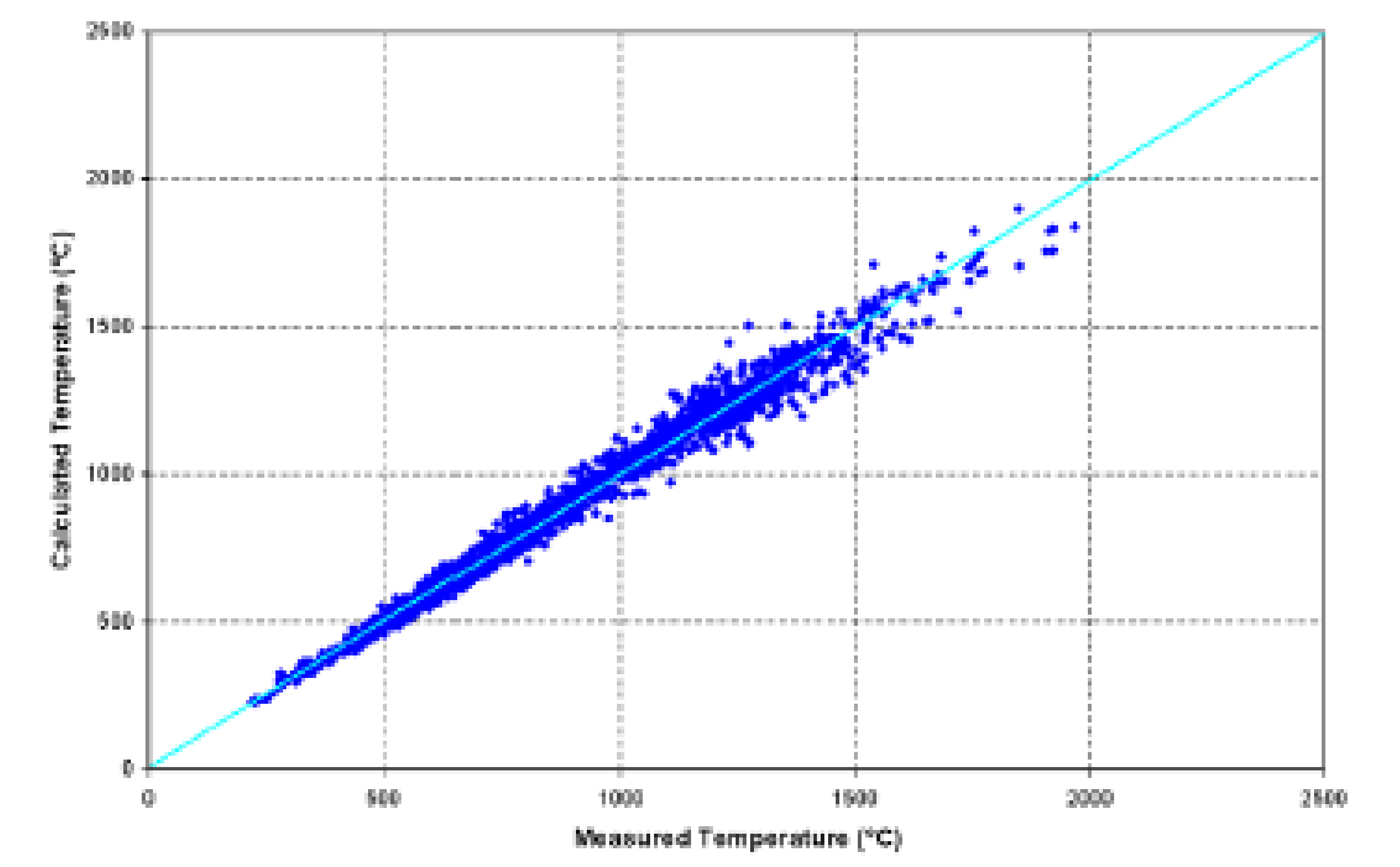
Validation measures



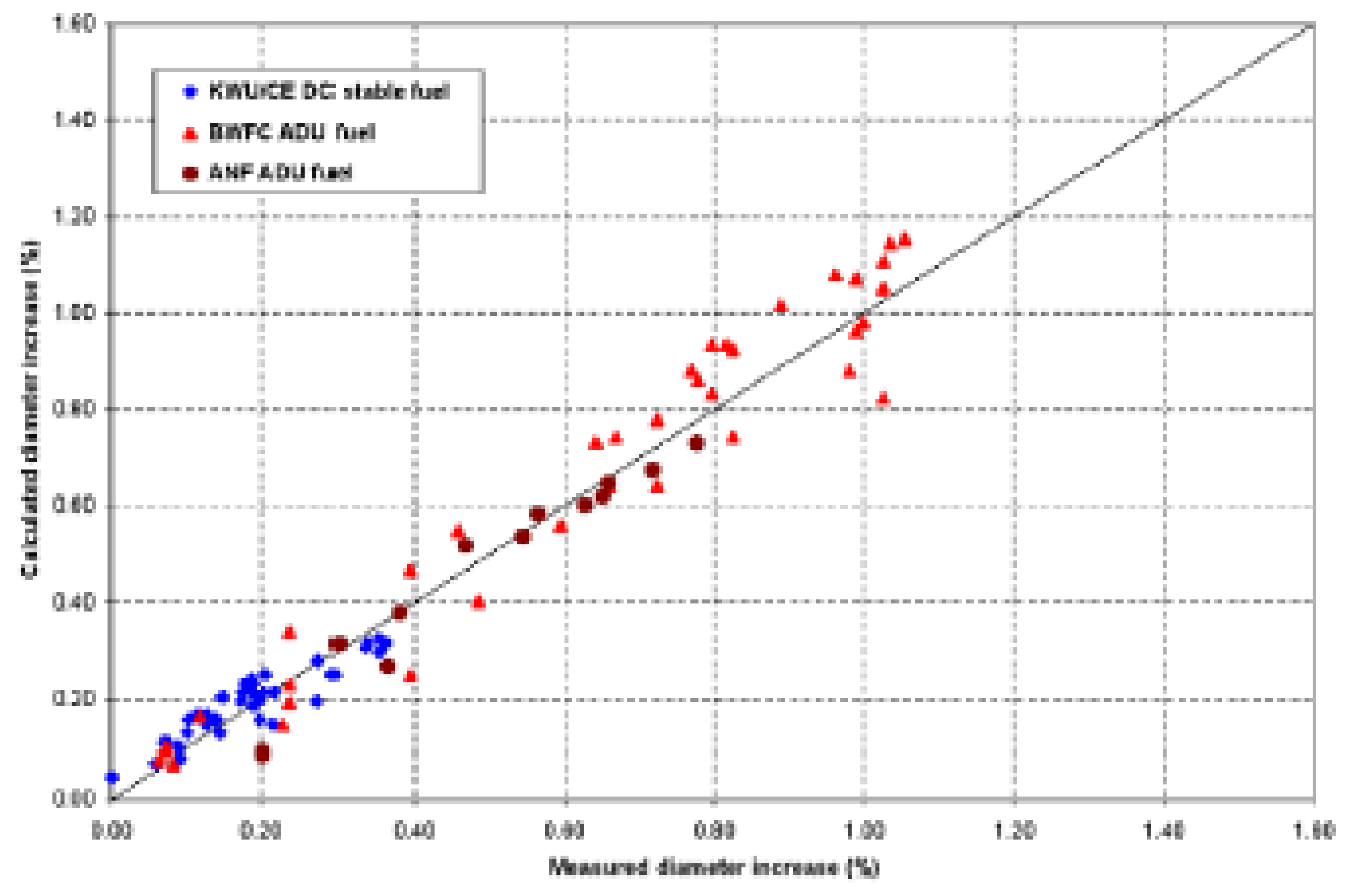
The acceptability of the calibration is demonstrated by the best-estimate behavior of the major code results. These are:

- Pellet centerline temperature
- Pellet gas release fraction
- Clad creep down and ramp strain
- Clad creep ovality
- Clad elongation
- Clad oxidation
- Rod free volume

Temperature benchmarking

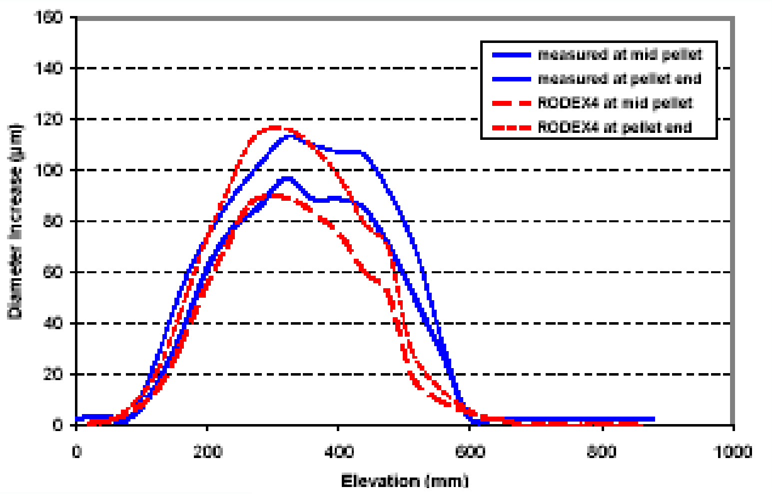


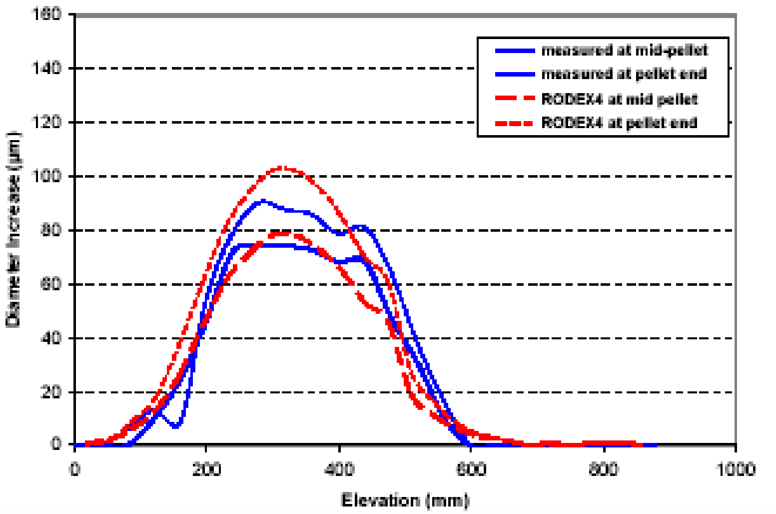
Strain increment during power ramps

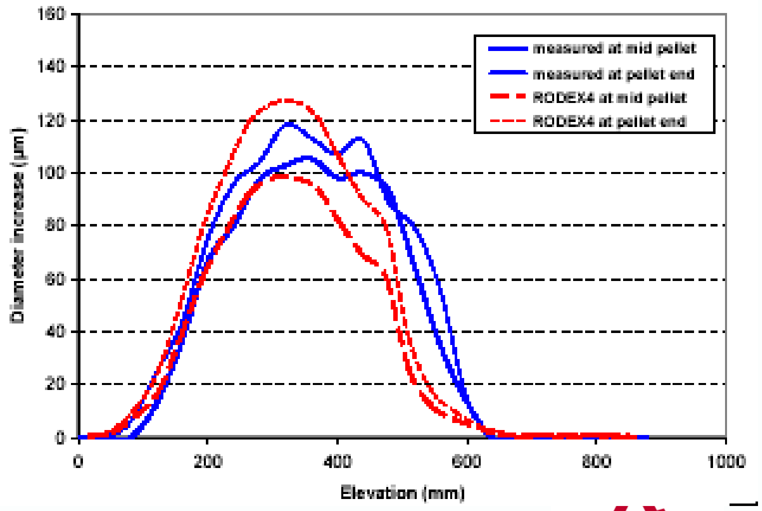


AREVA proprietary

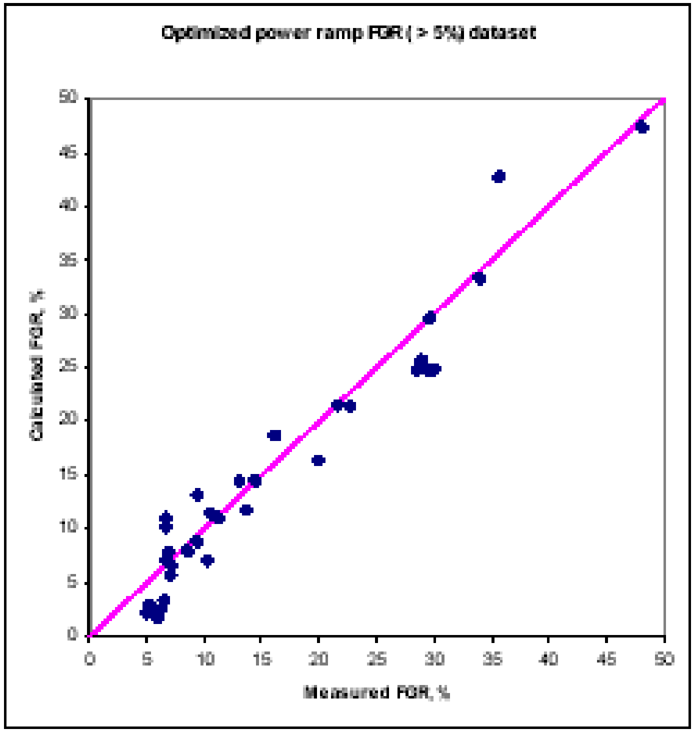
High-burnup power ramp – 1% strain increment



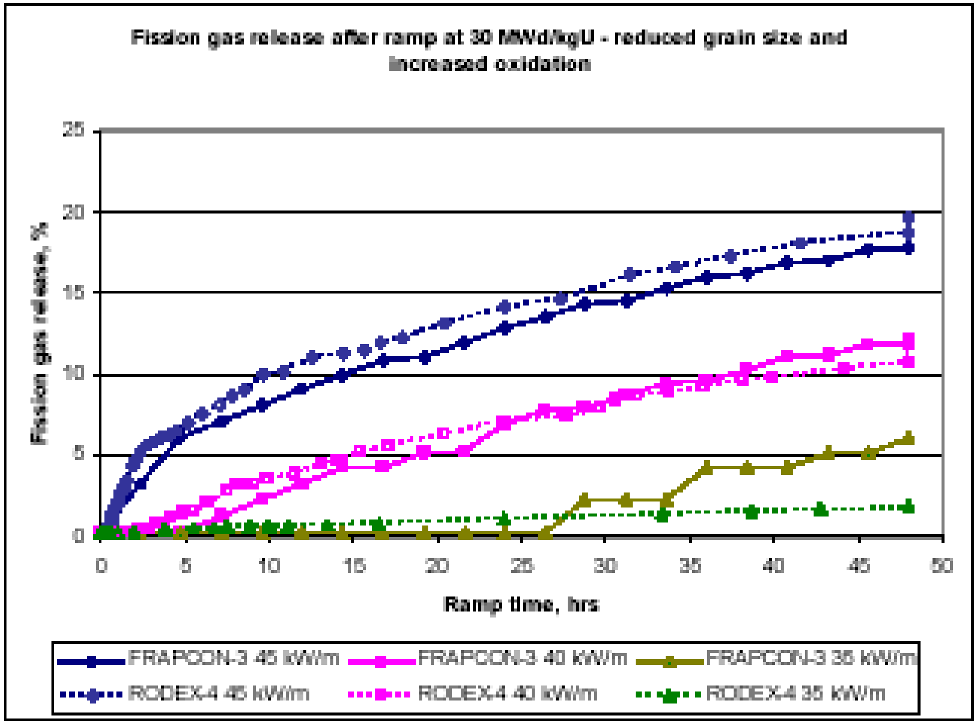




Fission gas release during power ramps

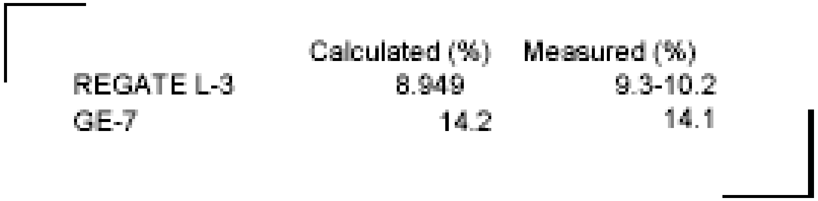


Optimized power ramp FGR (> 5%) dataset



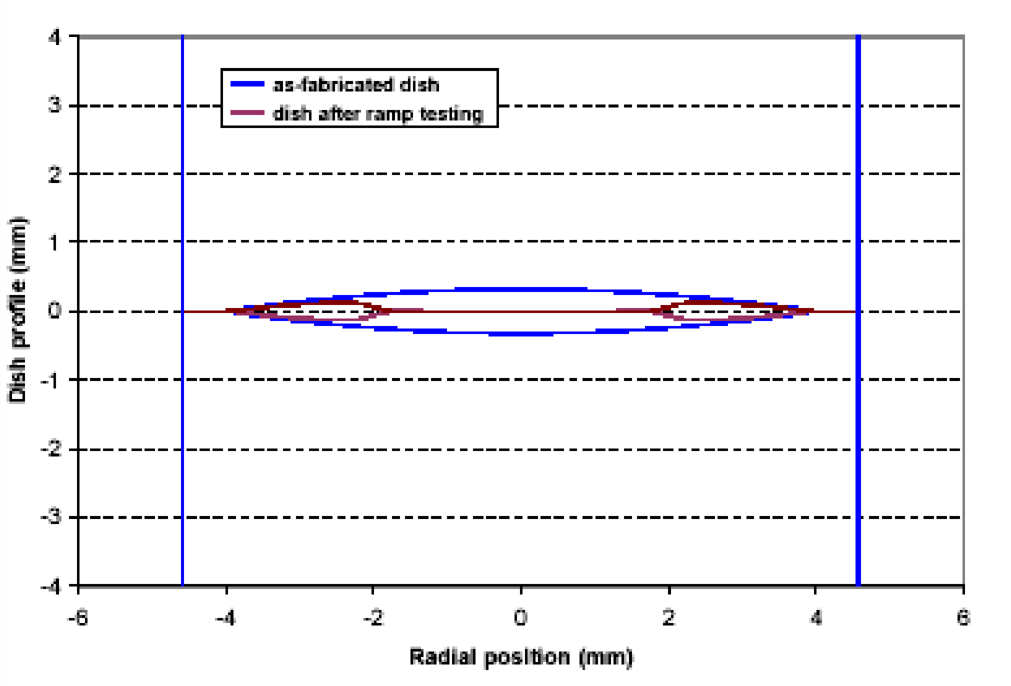
Fission gas release after ramp at 30 MWd/kgU - reduced grain size and increased oxidation

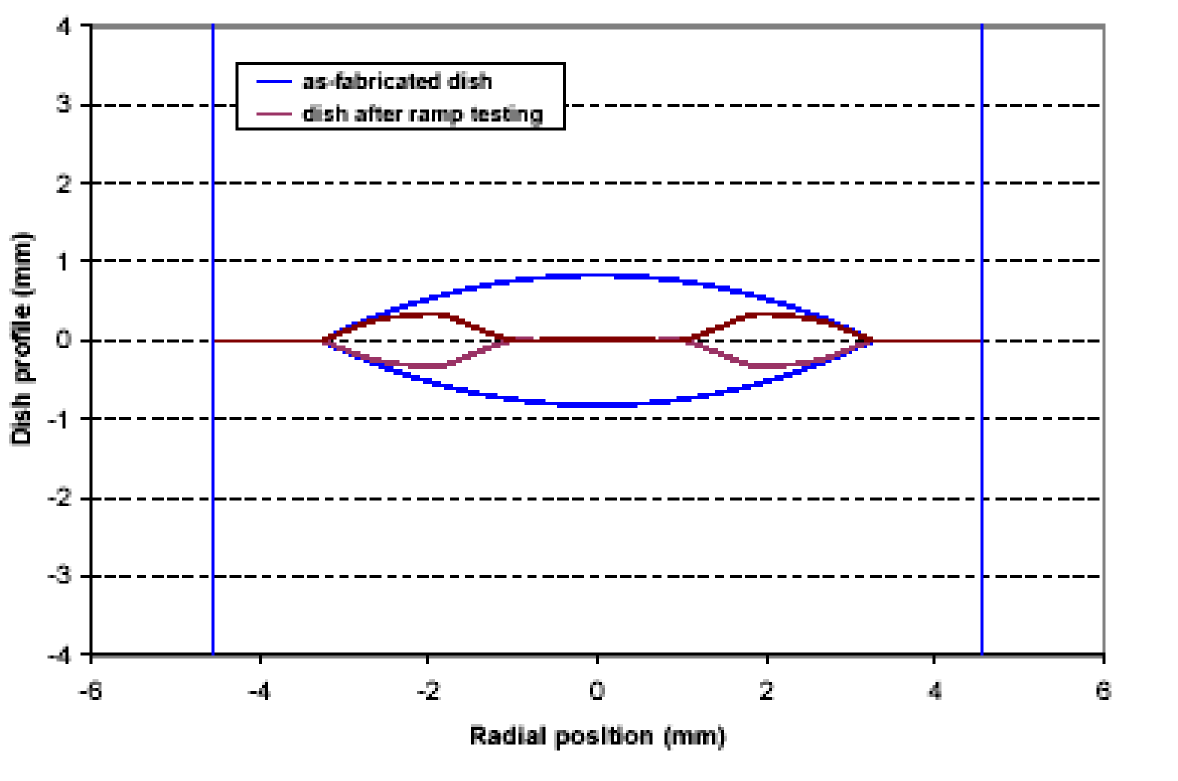
Table 4.2 Simulation of short hold time transient FGR

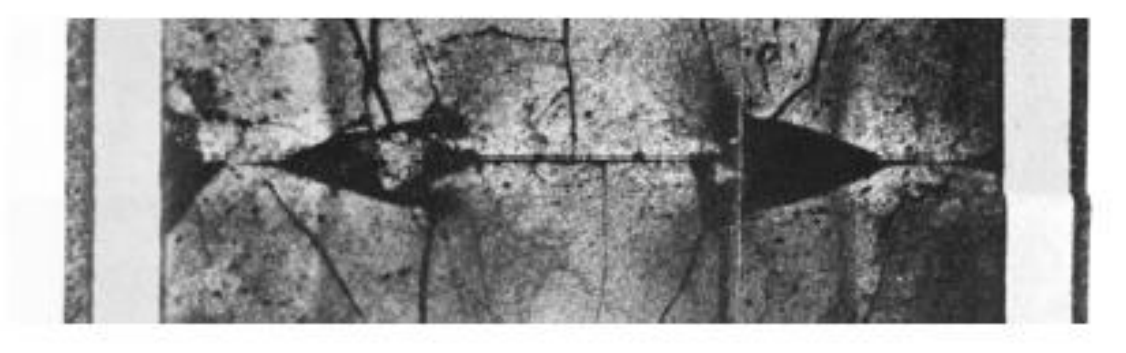


	Calculated (%)	Measured (%)
REGATE L-3	8.949	9.3-10.2
GE-7	14.2	14.1

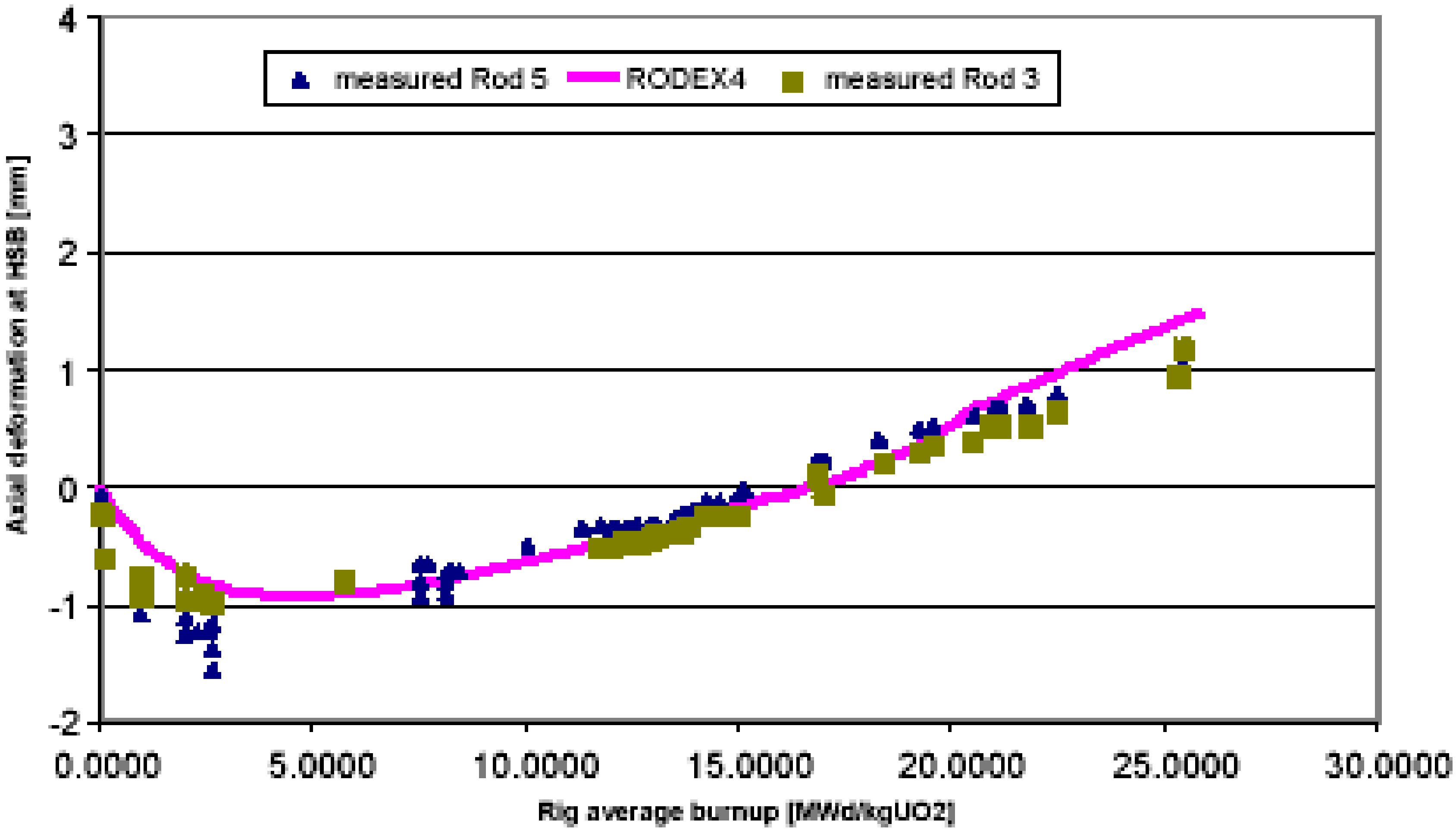
Pellet dish filling during power ramps



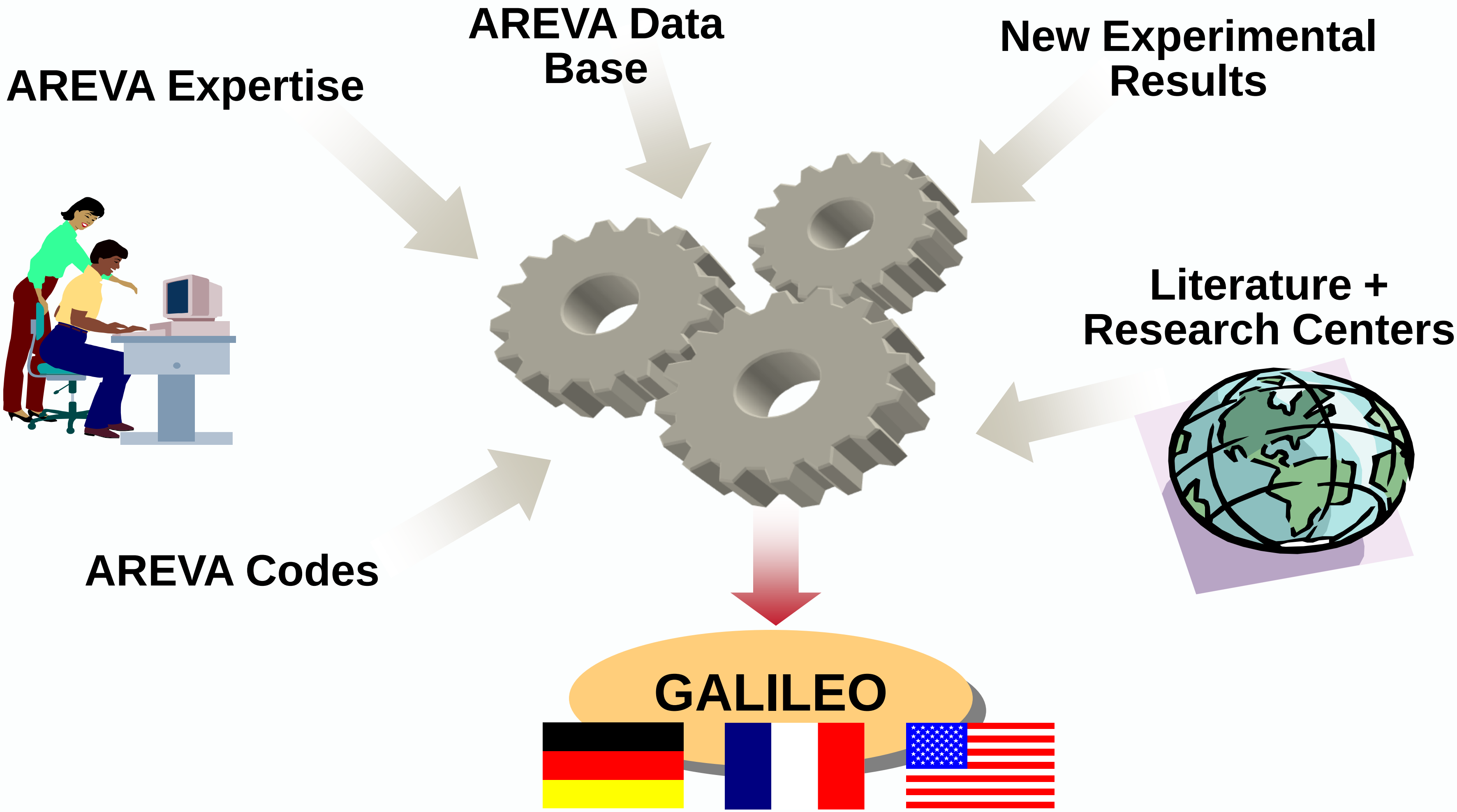

as-fabricated dish
dish after ramp testing
Dish profile (mm)
4
3
2
1
0
-1
-2
-3
-4
-6
-4
-2
0
2
4
6
Radial position (mm)



Pellet stack densification and solid swelling



The new AREVA Global Fuel Code GALILEO



AREVA Expertise

AREVA Data Base

New Experimental Results

Literature + Research Centers

AREVA Codes

GALILEO

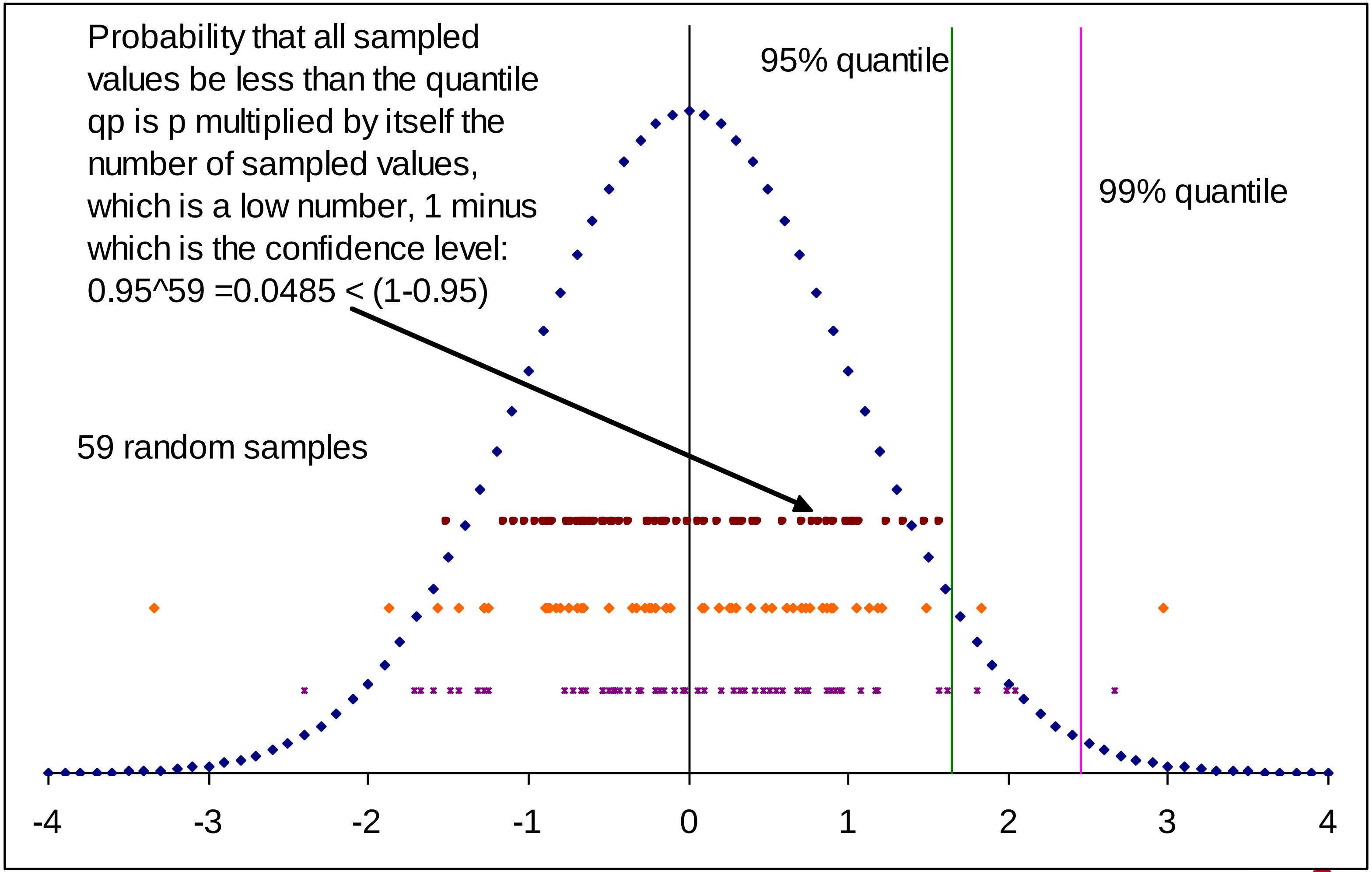
Code Applicability Domain

Reactor type	**PWR and BWR**
Operation type	**Steady-state and AOO conditions**
Fuel type	**UO_2, UO_2-Gd_2O_3 and MOX**
Fuel rod burnup	**UO2: up to 75 GWd/tM** **UO_2-Gd_2O_3 and MOX: up to 65 GWd/tM**
Cladding type	**Zy-4, M5, Zy-2 CWSR and Zy-2 RX**
Fuel temperature	**Up to fuel melting**

Backup Slides

Proof of the global probabilistic statement used in the realistic methodology

Non-parametric order statistics: minimum number of runs



Probability that all sampled values be less than the quantile qp is p multiplied by itself the number of sampled values, which is a low number, 1 minus which is the confidence level: 0.95^59 =0.0485 < (1-0.95)

95% quantile

99% quantile

59 random samples

Proof of the global statistical statement: part 1

- Each of the “m” fuel rods can be considered as a random variable which has two possible outcomes: not exceeding the upper bound limit with probability p_i, or exceeding the limit with probability $(1-p_i)$.
- Then the expected value of any of the rods exceeding the upper bound limit can be calculated as:

$$E(X) = (1/m)\sum_{j=1}^{m} p_j$$

Proof of the global statistical statement: part 2

- On the other hand, the quantile, q_p, of the overall pressure distribution associated to p, can be calculated by using:
  - the probability of choosing any of the fuel rods is 1/m because all fuel rods are equally probable and
  - for any fuel rod the probability of having the output value less than q_p is $P(i)=p_i$.
- Then the desired probability corresponding to the q_p quantile can be calculated and the same result is obtained as for the fraction of fuel rods exceeding the upper bound limit, and thus the statement is proved.