DE LA RECHERCHE À L'INDUSTRIE

"BEST ESTIMATE PLUS UNCERTAINTY" SAFETY STUDIES AT THE CONCEPTUAL DESIGN PHASE OF THE ASTRID DEMONSTRATOR

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Advanced simulation in support to GIF reactor design studies – Contribution of HPC and UQ

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- Best Estimate Plus Uncertainty (BEPU) Analysis
- Application of BEPU analysis to ASTRID demonstrator
- Some issues of the BEPU analysis

BEST ESTIMATE PLUS UNCERTAINTY (BEPU) ANALYSIS

BEPU VERSUS CONSERVATIVE METHODS IN SAFETY ANALYSIS

Conservative method

- Context : licensing calculations used conservative method owing to the difficulty of modeling complicated physical phenomena with limited computer capacity and a lack of adequate data.
- Use of conservative codes with conservative input data,
- No insurance that combination of conservatism give the most conservative response
- No realistic evaluation of the safety margin

Realistic approach with taking account uncertainties (BEPU)

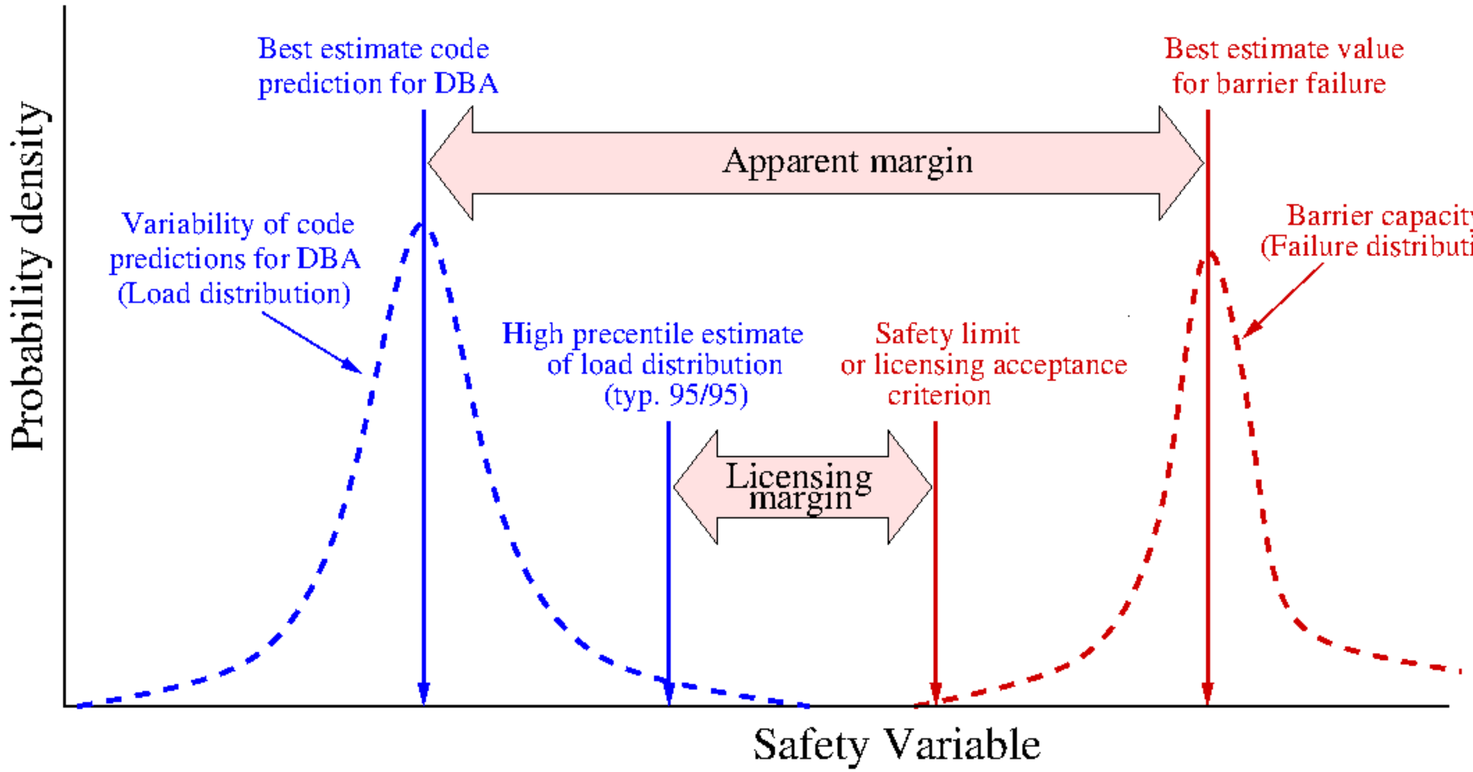
- Context: as more experimental data have become available, and with advances in code development
- Use of realistic calculation codes (*B-E = best-estimate*)
- Evaluation of uncertainties
- Realistic evaluation of the safety margin
- Enable the identification of the important contributors

VARIOUS OPTIONS FOR COMBINATION OF A COMPUTER CODE AND INPUT DATA

Option	Computer code	Availability of systems	I&B conditions
1) Conservative	Conservative	Conservative assumptions	Conservative input data
2) Combined	Best estimate	Conservative assumptions	Conservative input data
3) Best estimate (BEPU)	Best estimate	Conservative assumptions	Realistic plus U; partly most unfavourable cond.
4) Risk informed	Best estimate	Derived from PSA	Realistic plus U

Reference*: Deterministic Safety Analysis for Nuclear Power plants, Specific Safety Guide, n° SSG2*, IAEA Safety Standards, Vienna, 2009

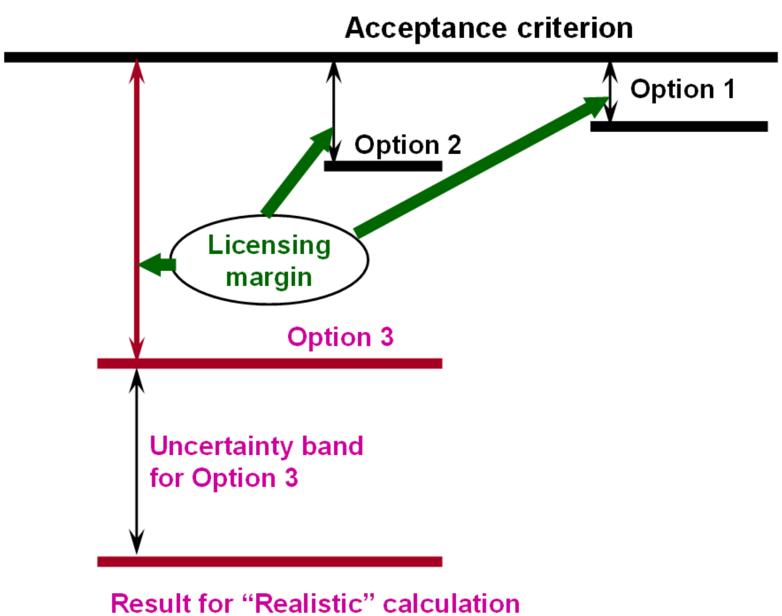
PRINCIPLE OF THE BEPU ANALYSIS

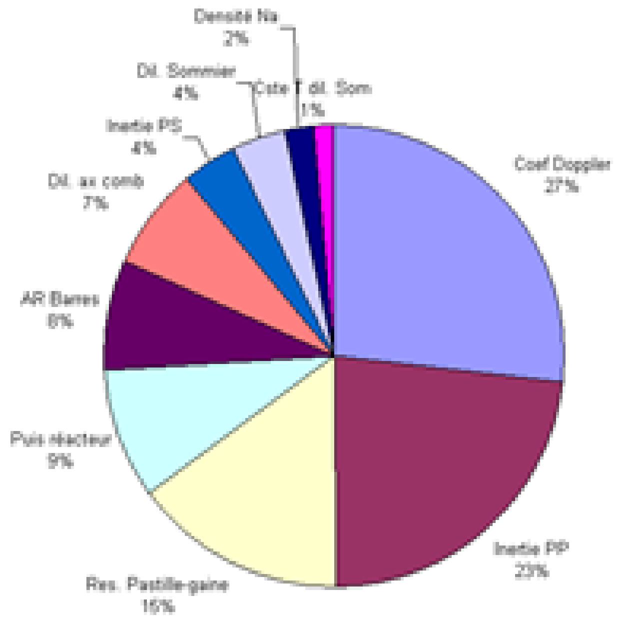


It must be verified that a high percentile of the load distribution (typically 95%, covered with a high confidence level, typically 95%) **is less than the acceptance criterion**

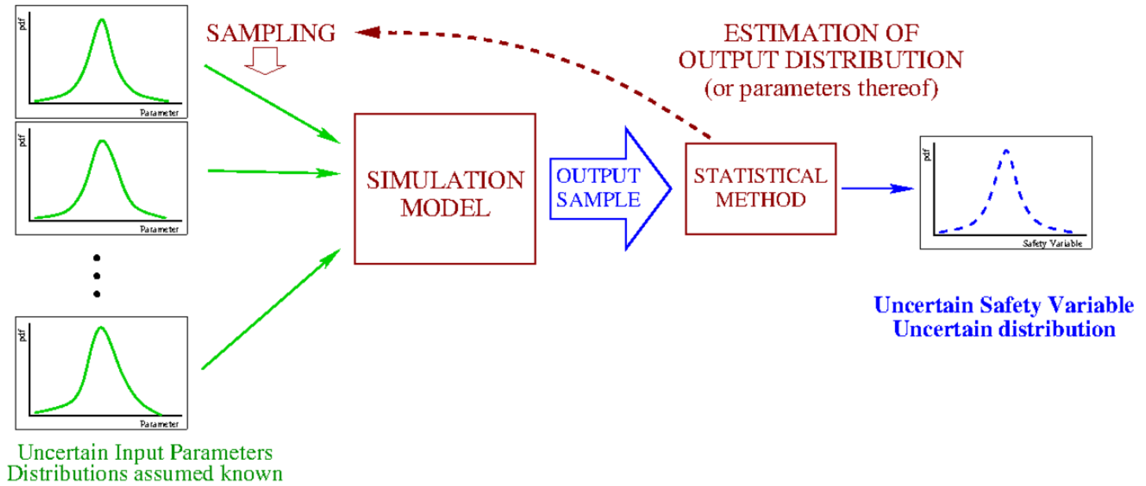
OBJECTIVES OF THE BEPU ANALYSIS AT THE DESIGN PHASE

- **Evaluate the safety margin** by a realistic evaluation taking into account the uncertainties
- **Quantify the contribution of each input uncertainty to the uncertainty of the safety margin** → Guide the research for reducing the uncertainties of the biggest contributors by complementary tests or calculations or, if this reduction is not possible, in limiting their impact through design changes





IMPLEMENTATION OF THE BEPU ANALYSIS



- **Identification and quantification** of the uncertainties of the input parameters
- **Uncertainties propagation**: Monte-Carlo simulation
- **Percentile evaluation with a high confidence level**
  - Wilks method
  - Bootstrap method
- **Sensitivity analysis**

EVALUATION OF THE PERCENTILE $M_{95,95}$

Wilks method

- For an ordered sample of size N: $M_{(1)}, \ldots, M_{(N)}$ of the random variable M following an unknown probability distribution, **the probability P that the value $M_{(N-1+r)}$** (where r is the order) **represents the percentile α% with a confidence level equal to β%**
- Noting $M_{\alpha,\beta}$ this percentile, it follows that: $\text{Prob}\,[\,\text{Prob}\,(M \le M_{\alpha,\beta}) = \alpha\,] \ge \beta$
- Number of simulations N and order r are linked by: $1 - \sum_{i=N-r+1}^{N} C_N^i \alpha^i (1-\alpha)^{N-i} \ge \beta$
- **For evaluating $M_{95,95}$** : 59 calculations necessary at order 1, 93 at order 2, 124 at order 3 …

Bootstrap method

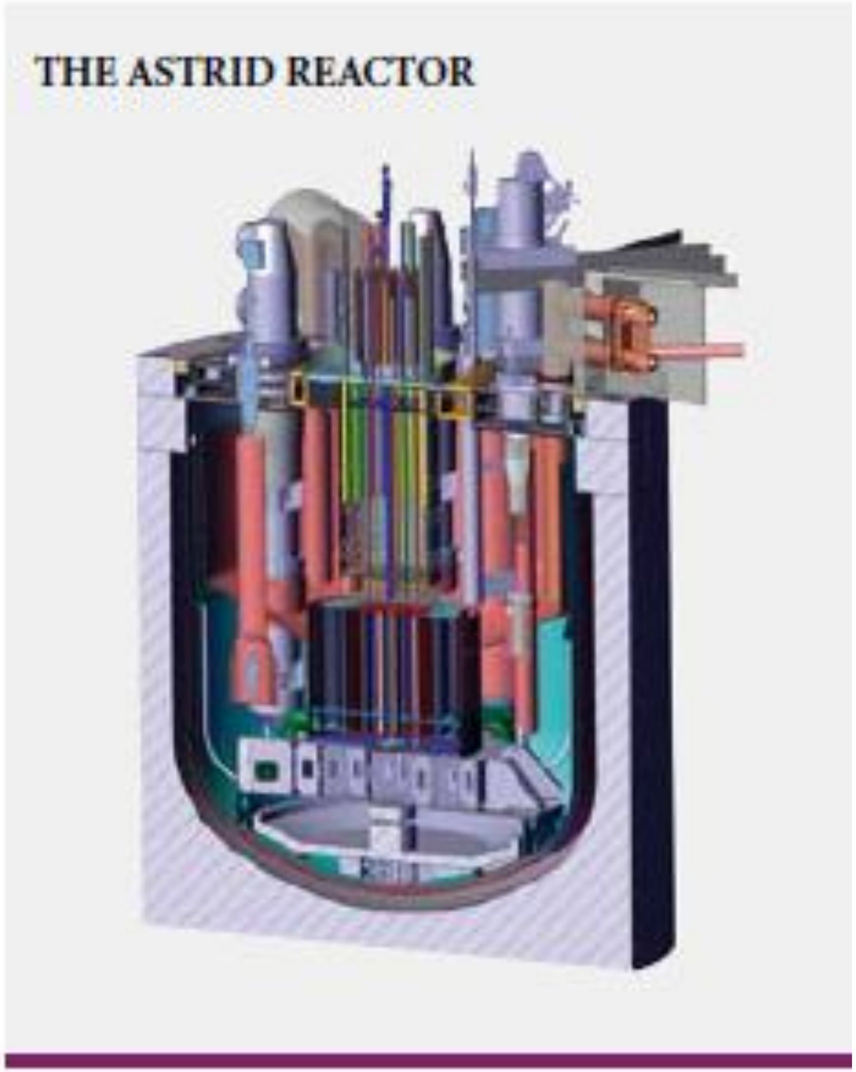
- Generates a large number of samples (called **replicas**), by random selection with replacement, from an original simulation sample of size N
- From the set of replicas created by bootstrap, **various statistical estimation are performed** as if these replicas were samples coming from the original

						Mean
Original sample	2	3	4	6	9	4.8
Replica 1	2	2	4	6	6	4
Replica 2	3	4	6	9	9	6.2
Replica 3	2	3	4	6	6	4.2
	Mean					4.8
	Standard-deviation					1.22

- In particular: **evaluation of the α-percentile of each replica** and deduce, from the set of replicas, $M_{\alpha,\beta}$, the α-percentile of the response M with a confidence level β

APPLICATION OF BEPU ANALYSIS TO ASTRID DEMONSTRATOR

Advanced Sodium Technological Reactor for Industrial Demonstration



- GEN IV SFR Demonstrator
- 600 MWe
- Pool type
- Enhanced safety features : Innovative core design (CFV concept) proposed with the objective to minimize sodium void effect on the reactivity
- Allow testing of new fuels and structural materials
- Improved and robust safety demonstration

CONTEXT OF THE BEPU ANALYSIS (1/2)

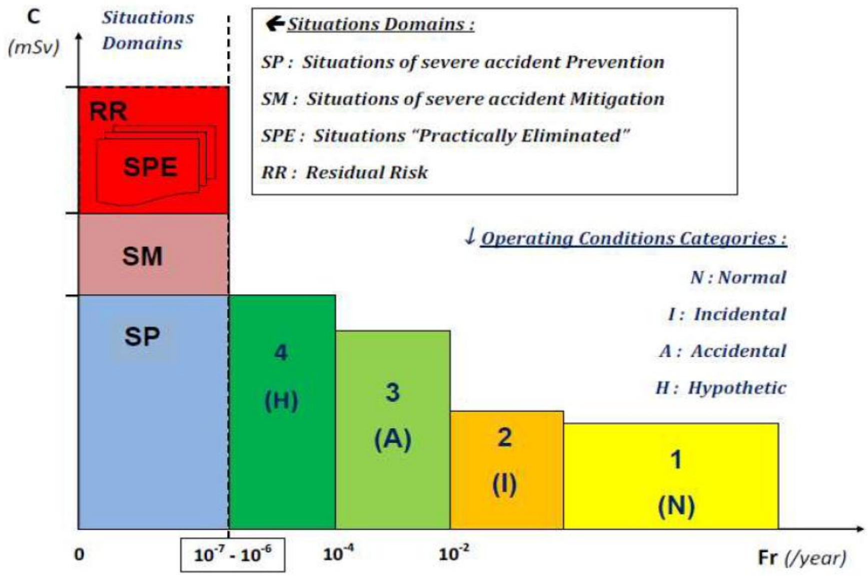
- **Design objective** is to have a natural behavior of the core favorable for transients of unprotected loss of flow and loss of heat sink

- **Target criteria for the design:** no sodium boiling for transient of Unprotected LOss of Flow due to a Station Blackout (ULOF/SBO):
  - loss of the primary flow (loss of the primary pumps)
  - loss of heat sink (loss of the secondary pumps)
  - no scram.

- **Margin = gap between the maximal temperature of the sodium at core exit and the boiling temperature of sodium.**

CONTEXT OF THE BEPU ANALYSIS (2/2)

- **ULOF/SBO transient** belongs to the accidental category "situation of prevention of severe accidents" (SP) having a very low frequency of occurrence (less than 10^{-7}) ,
- **For these SP situations**, **the safety demonstration is** no more **based** on a deterministic demonstration with conservative assumptions on models and parameters but **on a BEPU approach**
- The **probabilistic criterion** has been fixed: percentile $\mathbf{M_{5,95}}$ margin to sodium boiling, which has a probability 95% to be exceeded, obtained with a confidence level of 95%.



Risk diagram

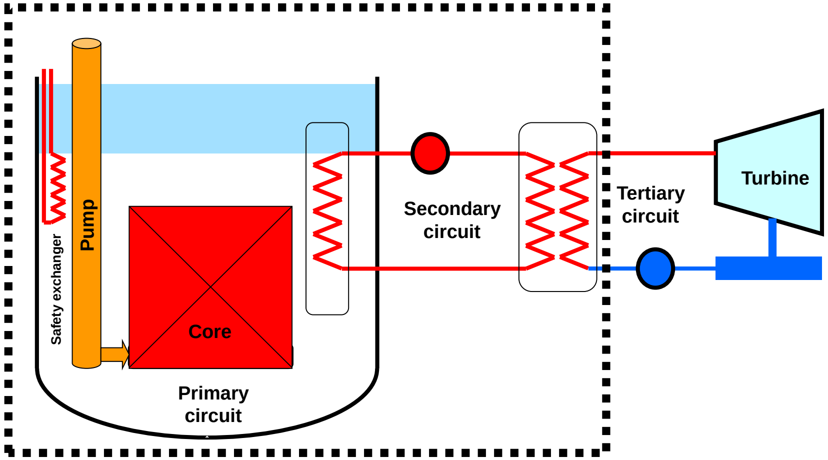
From: P. Lo Pinto *et al*., Preliminary safety orientations of ASTRID, Proceedings of ICAPP'13, Jeju Island, Korea, 1'-18 April 2013.

« BEST-ESTIMATE » CALCULATION WITH CATHARE2

The ULOF/SBO accident sequence is simulated with the CATHARE2 code:

Model includes :
- the core,
- the entire primary system,
- the secondary circuits,
- boundary conditions at the

secondary of the steam generators.



During the entire conceptual design phase, work focused on improving the modelling:
- modelling of the core and fuel pins based on GERMINAL calculations,
- modelling of the secondary circuit,
- reducing some bias (large volumes considered as isotherm) by comparison with CFD calculations
- primary pumps characteristics (information from the manufacturer)
- …

UNCERTAIN PARAMETERS

Type of parameter	Parameter	Uncertainty range at + or – 2σ
Reactor	Nominal reactor power	+ or – 3%
	Residual power	+ or – 15%
	Emptying time of steam generator	+ or – 35%
Pumps	Primary pumps inertia	+ or – 20%
	Pump friction	+ or – 50%
	Secondary pumps inertia	+ or – 20 %
	Fallback speed of primary pumps	18% - 20% of nominal speed
	Battery duration for primary pumps fallback	+ or – 50%
Reactivity (coefficients)	Axial dilatation of fuel	+ or – 25%
	Doppler	+ or – 15%
	Axial dilatation of clad	+ or – 20%
	Radial dilatation of clad	+ or – 20%
	Axial dilatation of hexagonal tubes	+ or – 20%
	Radial dilatation of hexagonal tubes	+ or – 20%
	Sodium density	+ or – 20%
	Diagrid dilatation	+ or – 20%
	Control rods anti-reactivity	+ or – 20%
Thermal	Diagrid dilatation time constant	+ or – 50%
	Intermediate heat exchanger (IHX) thermal exchange	0 – 40 blocked tubes
	Global fuel-clad thermal exchange coefficient	+ or – 20%
Head losses	Singular head loss at IHX inlet	+ or – 20%
	Singular head loss in assembly	+ or – 10%

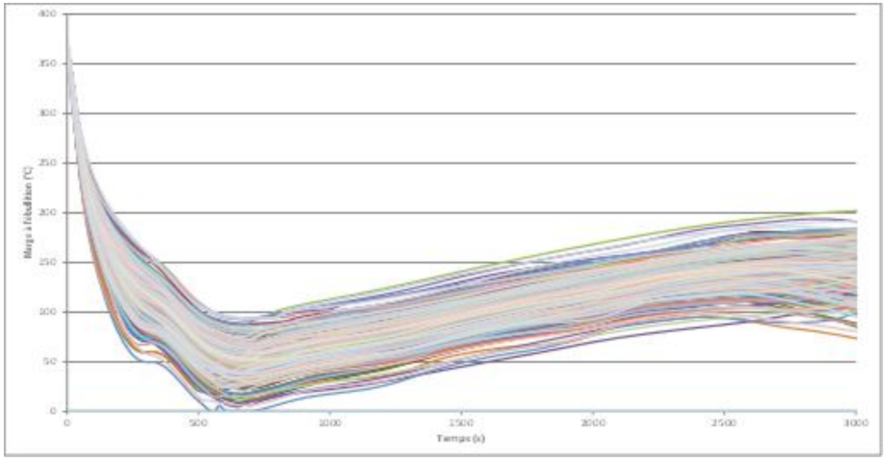
Identification and quantification of the uncertainties based on bibliographic analysis, on experience feedback on the existing SFRs and expert elicitation

UNCERTAINTY PROPAGATION

- Monte Carlo simulation
- Each transient calculation with CATHARE2 : 4 hours
- Simulation in parallel on a computer cluster (38 nodes)
- Workable number of simulations: several hundreds

Example: evolutions of the gap to sodium boiling obtained during a ULOF/SBO transient

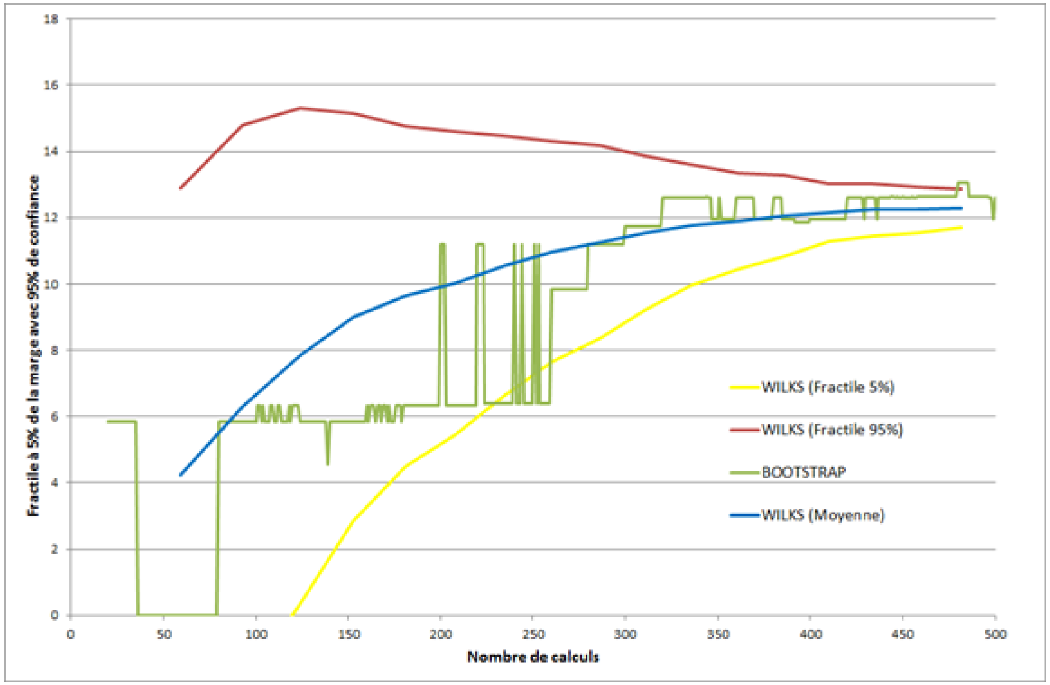
Result of the uncertainty propagation



Statistical results

Moyenne	Ecart-type	Mini	Maxi	$M_{5,95}$	5%	10%
46	18.6	0	99.	**12**	18	25

COMPARISON WILKS / BOOTSTRAP



- For an **accurate estimation of the percentile $M_{5,95}$, at least 300 simulations** with the CATHARE2 code **are necessary**: both methods would give equivalent results
- **With only 100 simulations** performed with the CATHARE code (number of simulations workable at the conceptual phase of the ASTRID project, where the models and the hypothesis are often modified), **bootstrap method will provide a slightly conservative result**

GLOBAL SENSITIVITY ANALYSIS

- **Using of Standard Regression Coefficient**: relation between the output (margin to sodium boiling) and the input parameters is quite linear (determination coefficient R^2 close to 1)

Example:

Rank	Input parameter	SRC	SRC^2
1	Primary pumps inertia	0.43	0.19
2	Doppler coefficient	-0.41	0.17
3	Fuel-clad thermal exchange	0.39	0.15
4	Control rods anti-reactivity	0.33	0.11
5	Emptying time of steam generator	-0.25	0.06
6	Pump friction	-0.25	0.06
7	Initial reactor power	0.16	0.02

- Importance of inertia of the primary pumps, of Doppler coefficient and of fuel-clad thermal exchange, in this type of scenario

SOME ISSUES OF THE BEPU ANALYSIS

PERCENTILE EVALUATION WITH A HIGH CONFIDENCE LEVEL

- One safety criterion to fulfill: Wilks method or Bootstrap
- Several safety criteria to fulfill simultaneously:
  - **Wald method** : extension of the Wilks method

    → increases significantly the number of simulations

    → validity when the responses (associated to the criteria) are dependent ?

    → result depends on the order of elimination of the extreme values
  - **GRS method:** evaluation of the probability to fulfill all the criteria

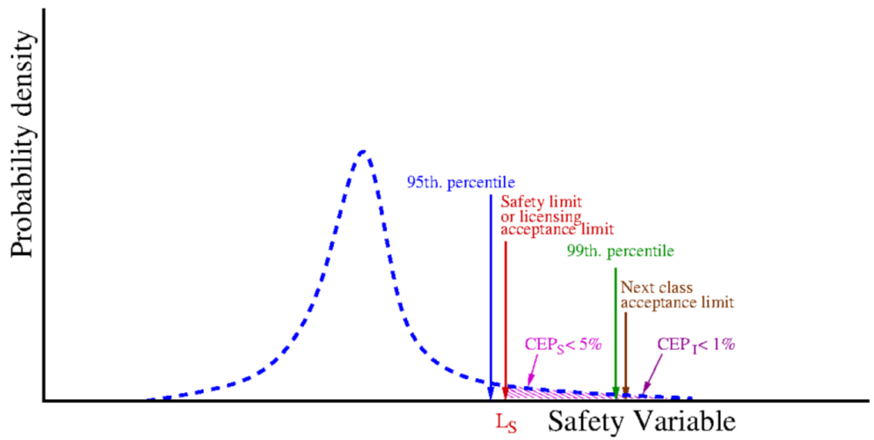
  → Wilks method applied to the probability

EXPENSIVE CALCULATION TIME

- **Problematic**
  - Each simulation lasts from several hours (for system code) to several months (CFD codes)
  - The number of simulations to obtain a stability of the percentile may be high
  - If the relation between the response of interest and the input uncertain parameters is not linear nor monotonous → Sensitivity analysis based on variance decomposition (SOBOL indices) : several thousands of simulation required
- **Metamodels**
  - Metamodels with good prediction quality in the zone of interest (percentile) : i.e. Polynomials, splines, neural networks, Gaussian Process (GP)
  - Adaptive sampling: improvement of the GP predictivity, controled importance sampling…
  - Problem: persistent suspicion of regulators towards use of metamodels
- **HPC**: parallel Monte Carlo simulations easy to implement

OPTION 4 (RISK INFORMED REGULATION)

- Option 3: BEPU + conservative assumptions on the availability of safety systems (SS) → envelop scenario
- **Option 4 (BEPU + PSA):** methodology which includes the availability of systems in the uncertainty analysis
  - Event tree from an Initiating Event: If all the sequences i=1,…,m fulfill the acceptance criteria, the IE also fulfills the same criteria with the same tolerance level
  - For the non-failed sequence: verification that there is no *cliff edge effect* (small deviations in plant parameters that could give rise to large variations in plant conditions)



  - Static event tree → Dynamic event tree: ex. Monte Carlo Dynamic Event Tree (MCDET) from GRS: dynamic-stochastic interactions