Statistical Analysis of NPP transients: LBLOCA in a PWR; Parametric, non-parametric methods and EBEPU

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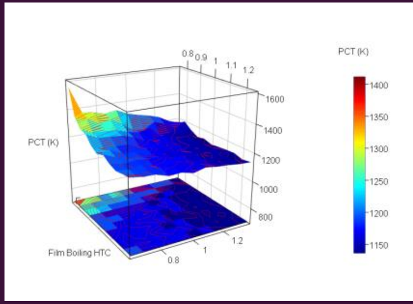

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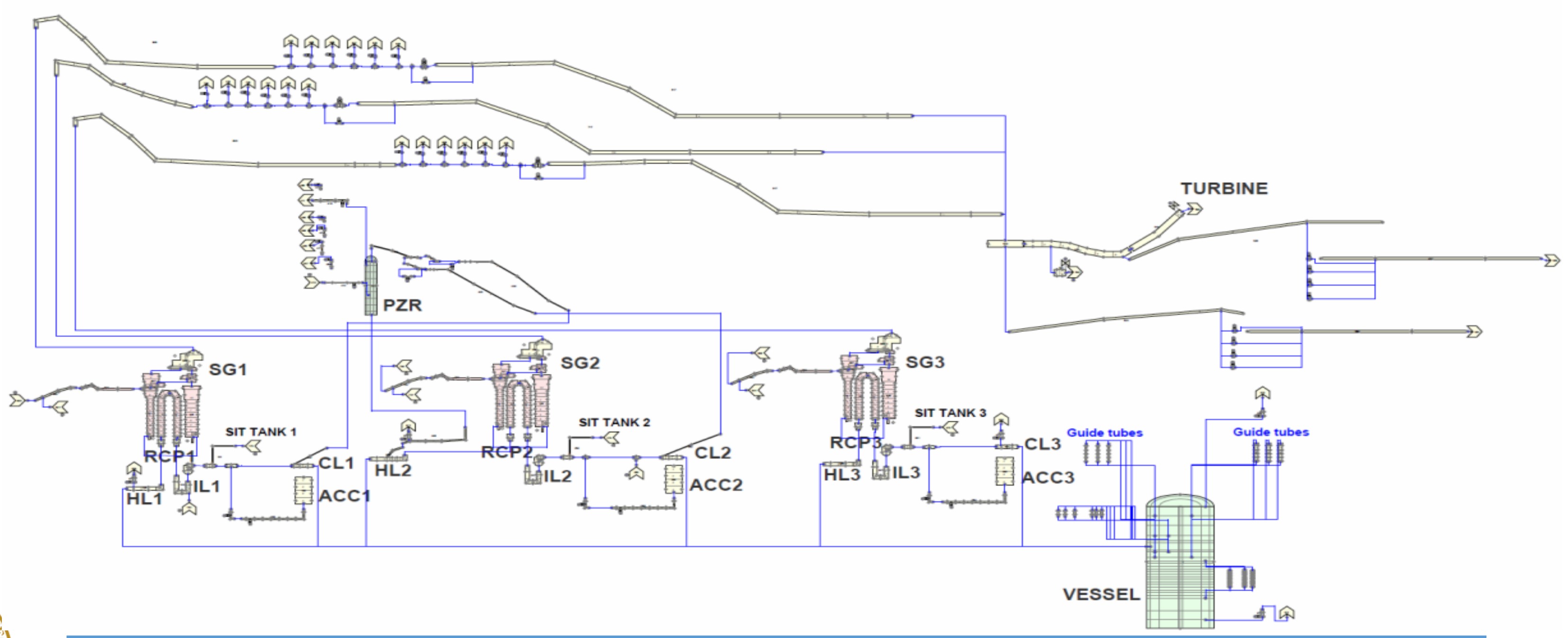
1. Plant Model

Reference NPP TRACE model:

3-LOOP PWR WESTINGHOUSE, 3000 MWt

- 279 Thermal Hydraulic components:
  - 2 VESSELSs
  - 73 PIPEs
  - 43 TEEs
  - 54 VALVEs
  - 3 PUMPs
  - 12 FILL
  - 33 BREAK
  - 56 HS
  - 3 POWER
- Control Systems:
  - 740 SIGNAL VARIABLES
  - 1671 CONTROL BLOCK
  - 58 TRIP



1. BE core model

Sector 2

Sector 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							0.360	0.360	0.360						
2					0.360	0.730	1.150	1.150	1.150	0.730	0.360				
3				0.360	1.150	1.150	1.235	1.160	1.235	1.150	1.150	0.360			
4			0.360	0.730	1.235	1.130	1.130	1.260	1.130	1.130	1.235	0.730	0.360		
5		0.360	1.150	1.235	1.230	1.260	1.130	1.165	1.130	1.260	1.230	1.235	1.150	0.360	
6		0.730	1.150	1.130	1.260	1.130	1.193	1.260	1.193	1.130	1.260	1.130	1.150	0.730	
7	0.360	1.150	1.235	1.130	1.130	1.193	1.260	1.130	1.260	1.193	1.130	1.130	1.235	1.150	0.360
8	0.360	1.150	1.160	1.260	1.165	1.260	1.130	1.087	1.130	1.260	1.165	1.260	1.160	1.150	0.360
9	0.360	1.150	1.235	1.130	1.130	1.193	1.260	1.130	1.260	1.193	1.130	1.130	1.235	1.150	0.360
10		0.730	1.150	1.130	1.260	1.130	1.193	1.260	1.193	1.130	1.260	1.130	1.150	0.730	
11		0.360	1.150	1.235	1.230	1.260	1.130	1.165	1.130	1.260	1.230	1.235	1.150	0.360	
12			0.360	0.730	1.235	1.130	1.130	1.260	1.130	1.130	1.235	0.730	0.360		
13				0.360	1.150	1.150	1.235	1.160	1.235	1.150	1.150	0.360			
14					0.360	0.730	1.150	1.150	1.150	0.730	0.360				
15							0.360	0.360	0.360						

Sector 3

2. Base Case: CL-LBLOCA

2/2 effective ACC - 2/2 LPSI

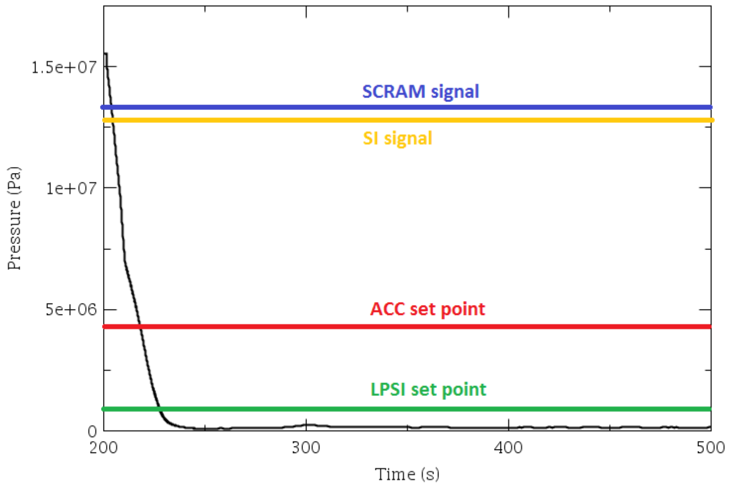


Figure: RCS pressure.

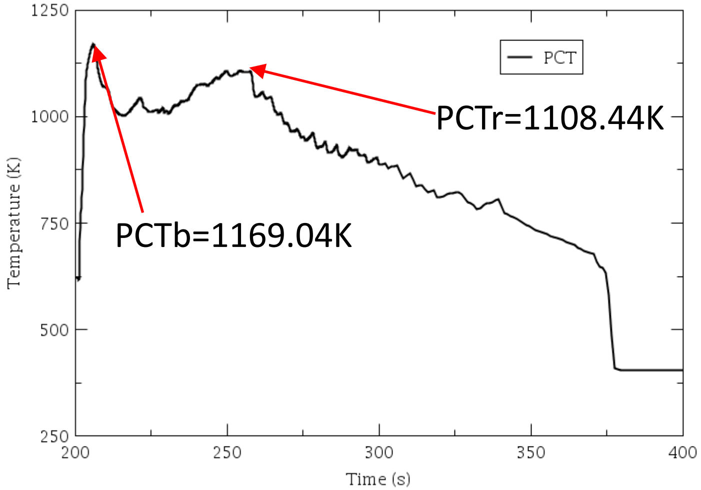


Figure: Peak Cladding Temperature.

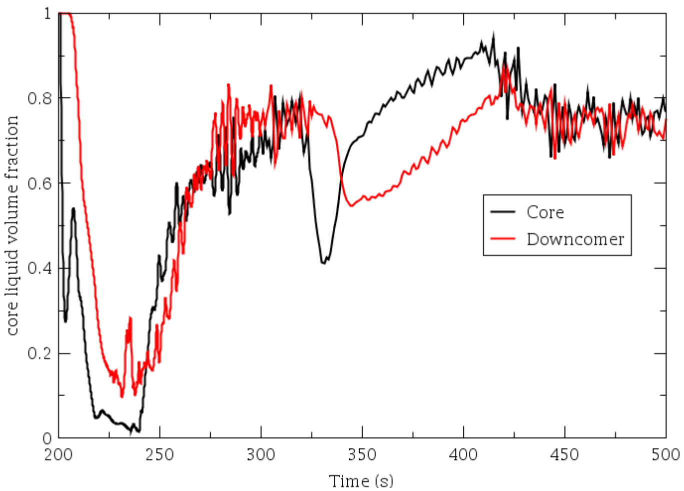


Figure: Core and downcomer coolant level.

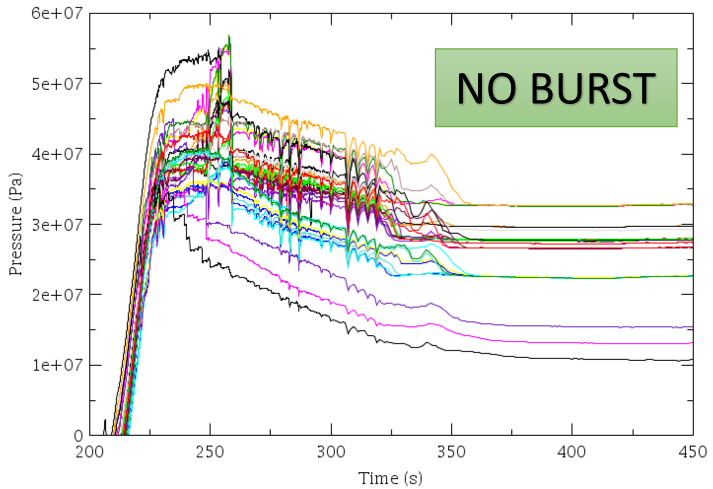


Figure: Cladding Hoop Stress.

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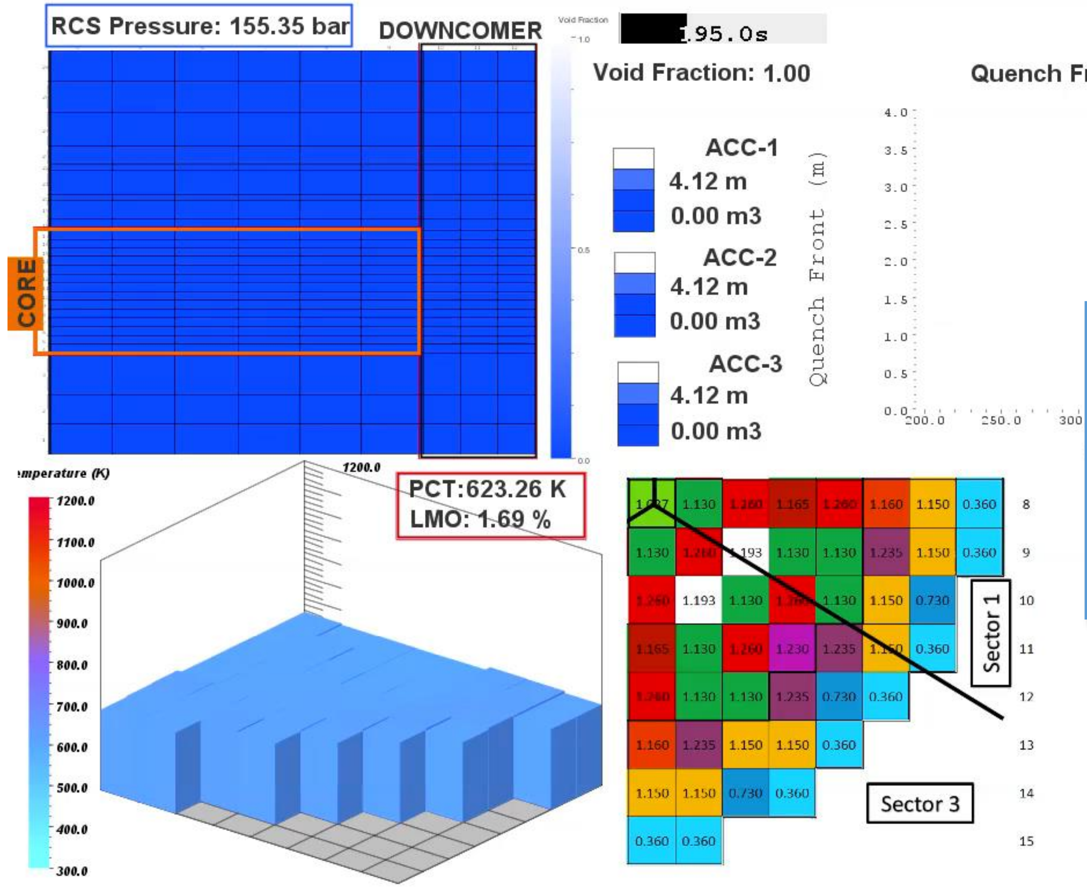
2. Base Case: CL-LBLOCA

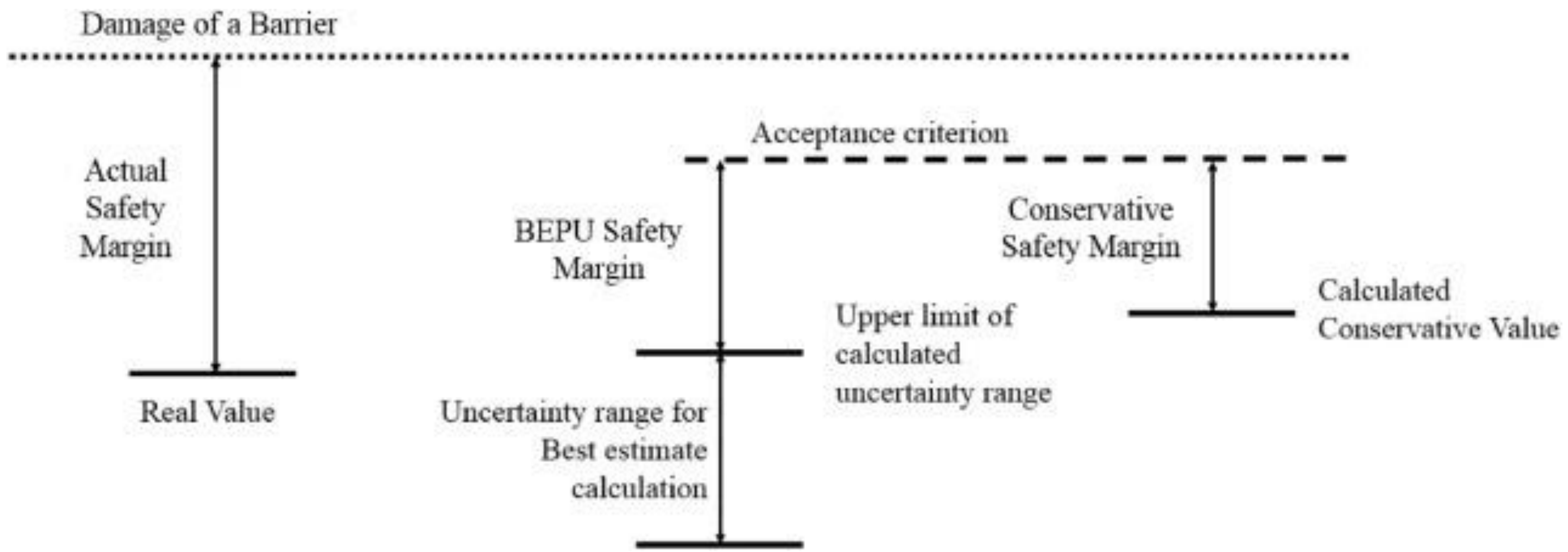
2/2 effective ACC - 2/2 LPSI



Analysis objectives

- PCT = 1169.03K < 1477K
- LMO = 1.69% < 17%

3. Best Estimate Plus Uncertainties : CL-LBLOCA



- RG-1.157, Best-Estimate Calculation of Emergency Core Cooling System Performance (1989)
- RG-1.203 Transient and Accident Analysis Methods (2005).

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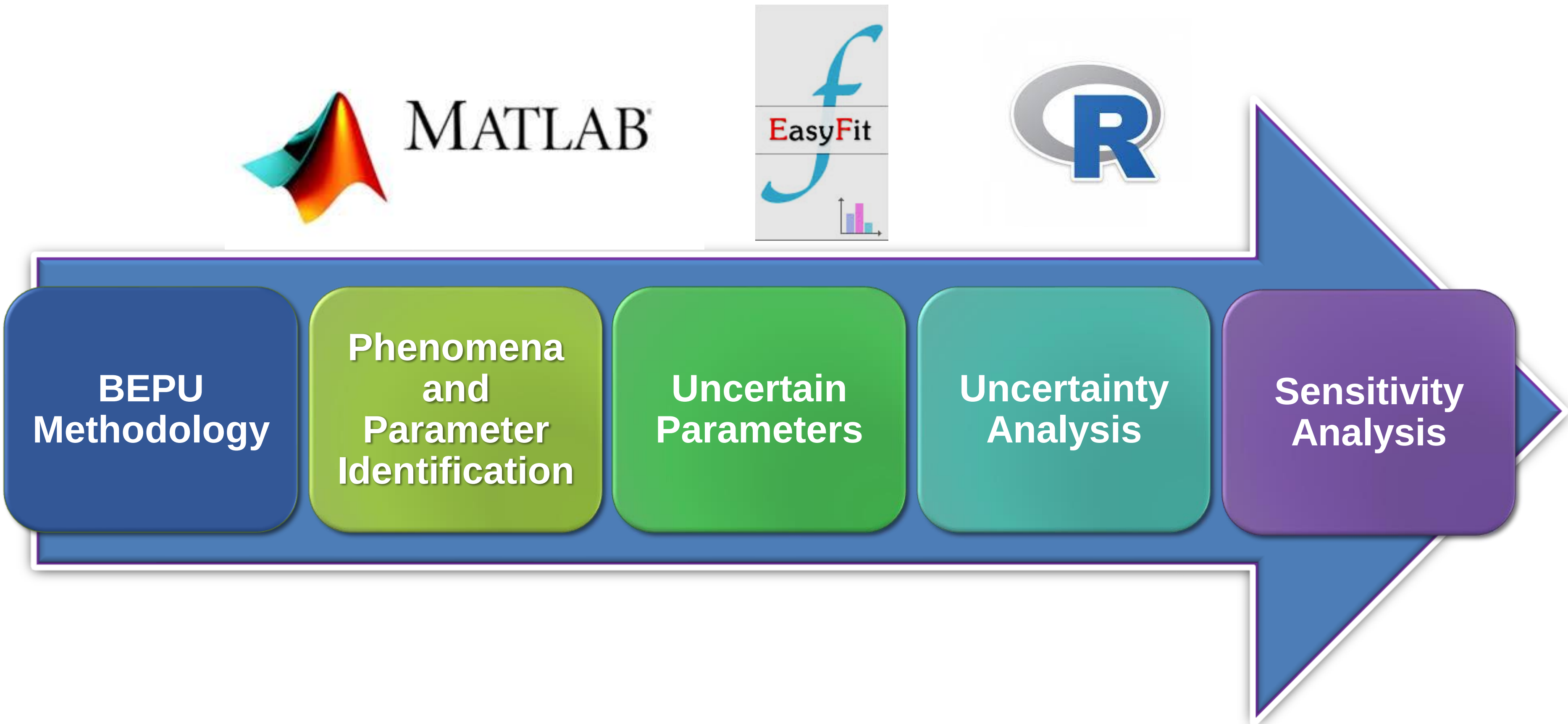
3. Best Estimate Plus Uncertainties : CL-LBLOCA



3. Best Estimate Plus Uncertainties : CL-LBLOCA

MATLAB

EasyFit

R

- BEPU Methodology
- Phenomena and Parameter Identification
- Uncertain Parameters
- Uncertainty Analysis
- EBEPU Remarks

3. BEPU: Methodology

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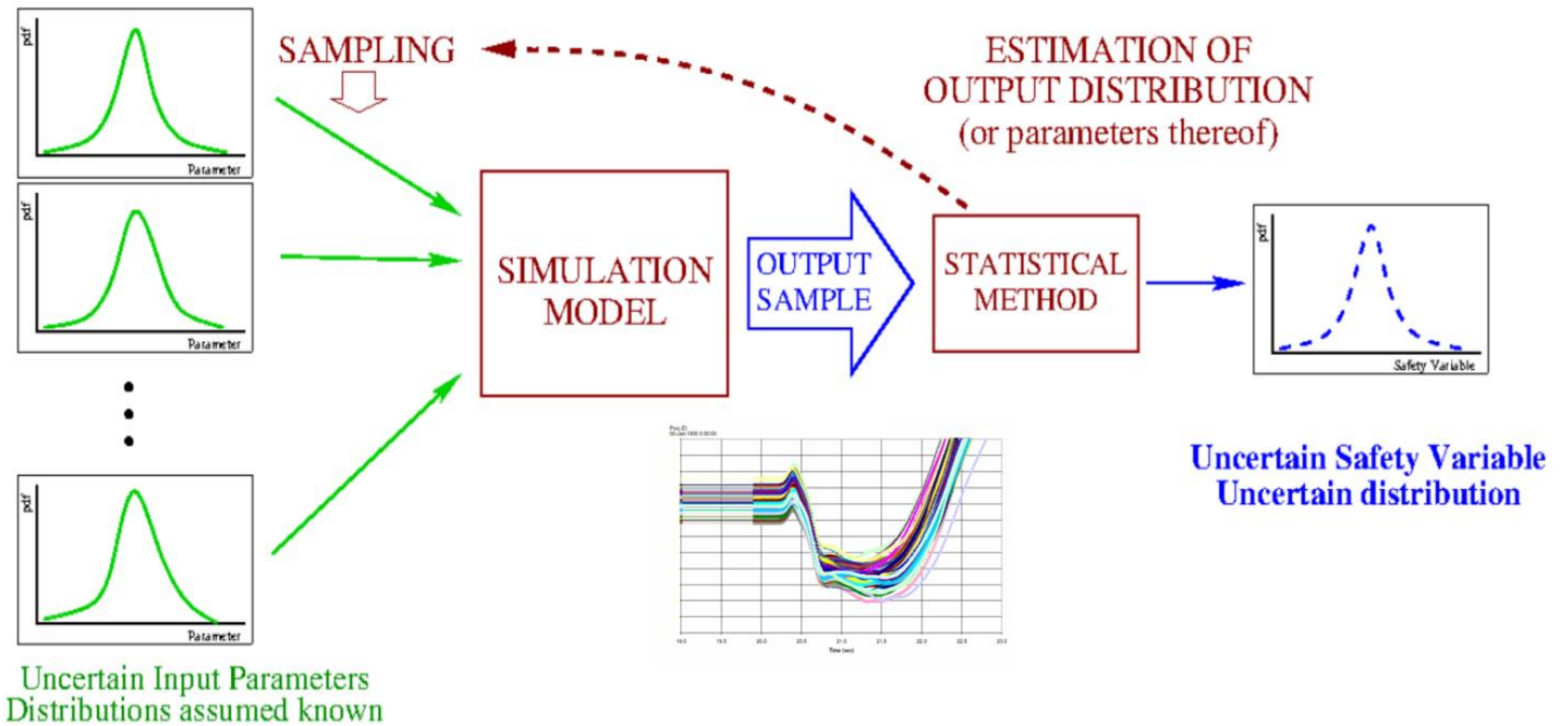

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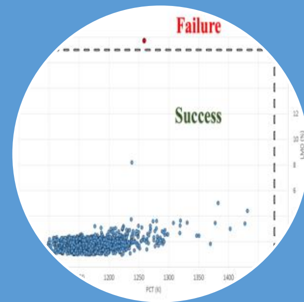
3. Best Estimate Plus Uncertainties : CL-LBLOCA

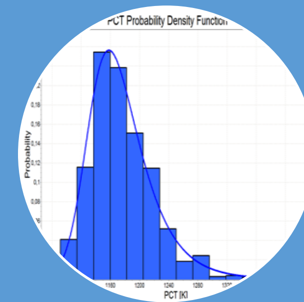
$$\beta = \sum_{j=0}^{N-R^*} \binom{N}{j} \gamma^j \cdot (1-\gamma)^{N-j}$$

$$R^* = p \cdot \left(\sum d_i \right)$$

Wilks/Wald non-parameteric method



Non-parametric Binomial Distribution w Clopper-Pearson Interval



Parametric Adjustments

- ASTRUM (WEC: LBLOCA)
- WILAP verification (IB: ΔCPR, GIRALDA)
- TRACG (GE: AOO, LOCA, ATWS)

- TRACG (GE: AOO, LOCA, ATWS)

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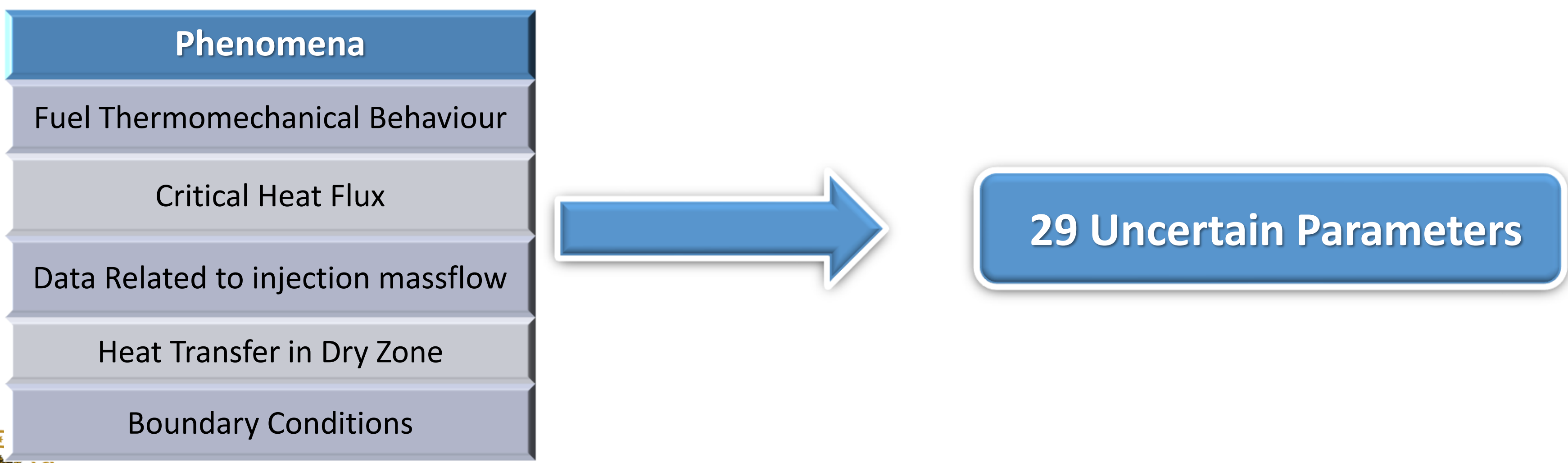
3. BEPU: Phenomena and Parameter Identification

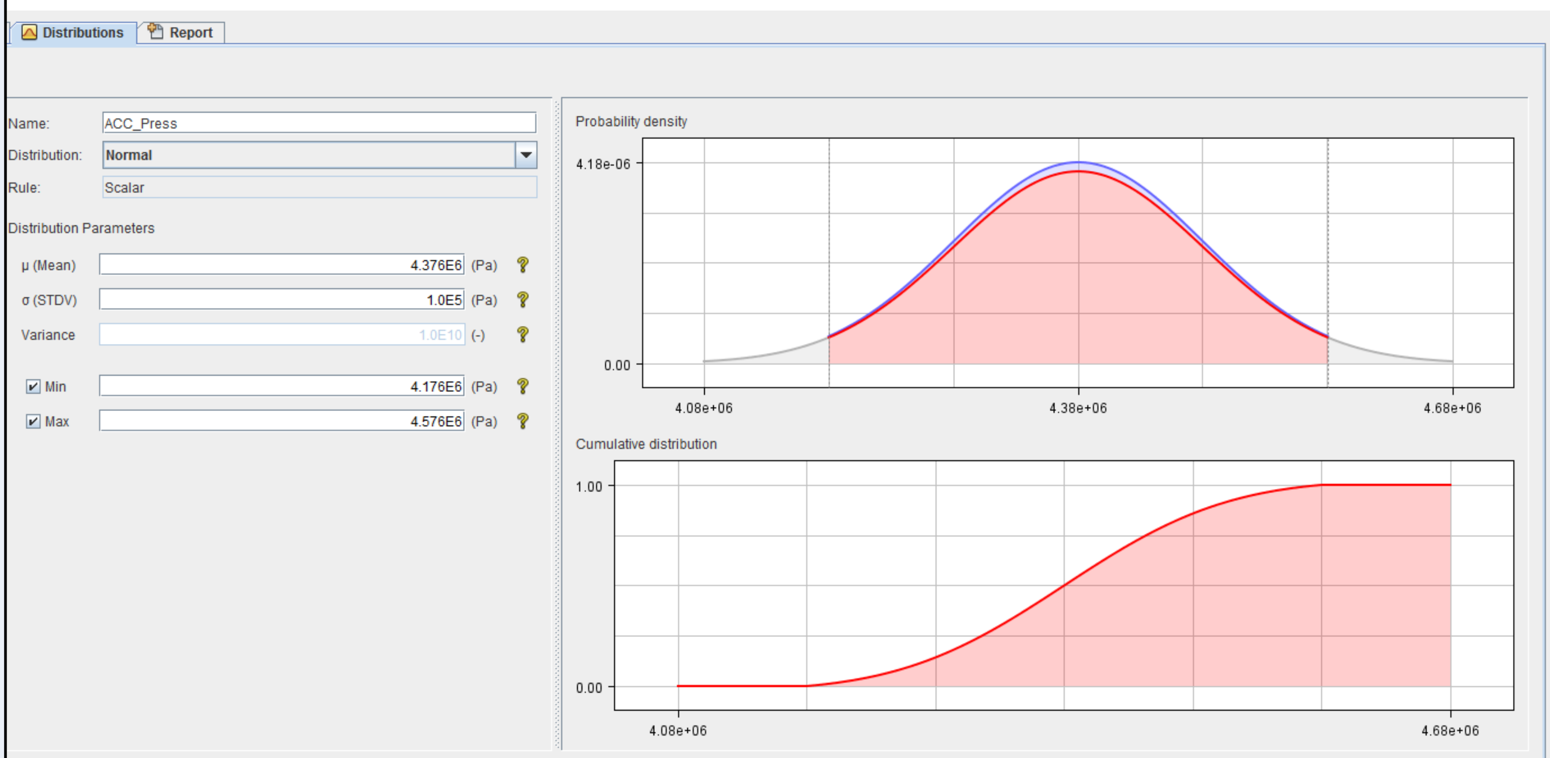
- Identification of up to **40 parameters** in previous LBLOCA studies, including:
    - Ranges of uncertainty.
    - Probability Density Functions (PDF).
- Identification of LBLOCA phenomena: LBLOCA-PIRT (**NUREG/CR-6744**).
- Selection of parameters and phenomena by means of previous importance analyses.
- New fuel rod parameters due to the new **TRACE** thermomechanical models.
- 29 uncertain parameters selection.



3. BEPU: Uncertain Parameters

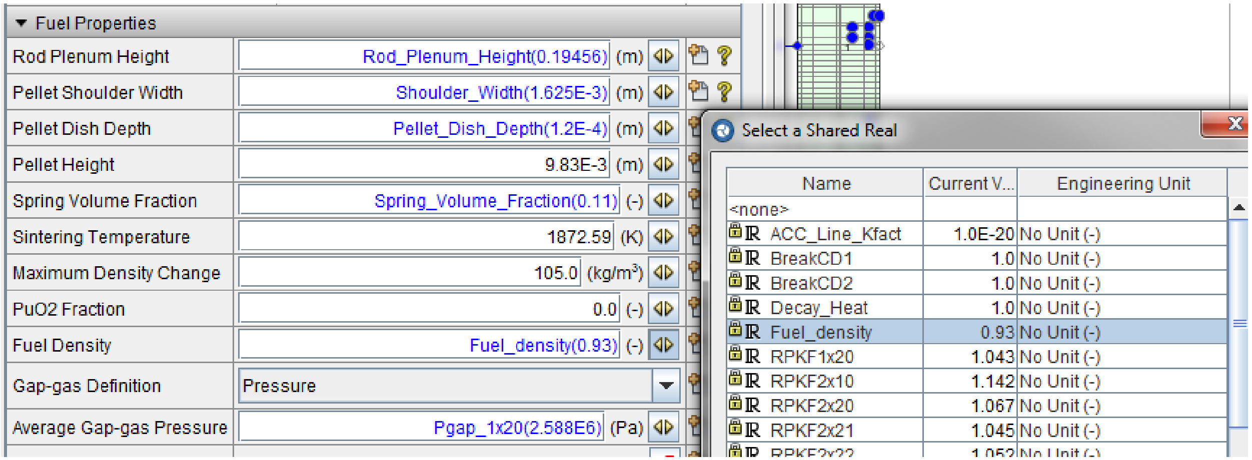
- Break DC
- Power
- DHeat
- PPF
- Forced Convection HTC
- Film Boiling HTC
- Transition Boiling
- CHF
- ACC Pressure
- LPSI injection Factor
- RCP Broken
- RCP Intact
- Gap HTC
- Cladding Inner Radius
- Cladding Thickness
- Pellet Radius
- Pellet Dish Depth
- Pellet shoulder
- Spring Volume
- Plenum Height
- Fuel Density
- KUO2
- Burst Temperature
- M-W Reaction
- Containment Press.
- ACC Temperature
- Gap Pressure
- Burst Strain
- Oxide Layer

Characterization of uncertain parameters and Monte-Carlo sampling by means of **DAKOTA** code coupled to **TRACE** code in **SNAP** platform.

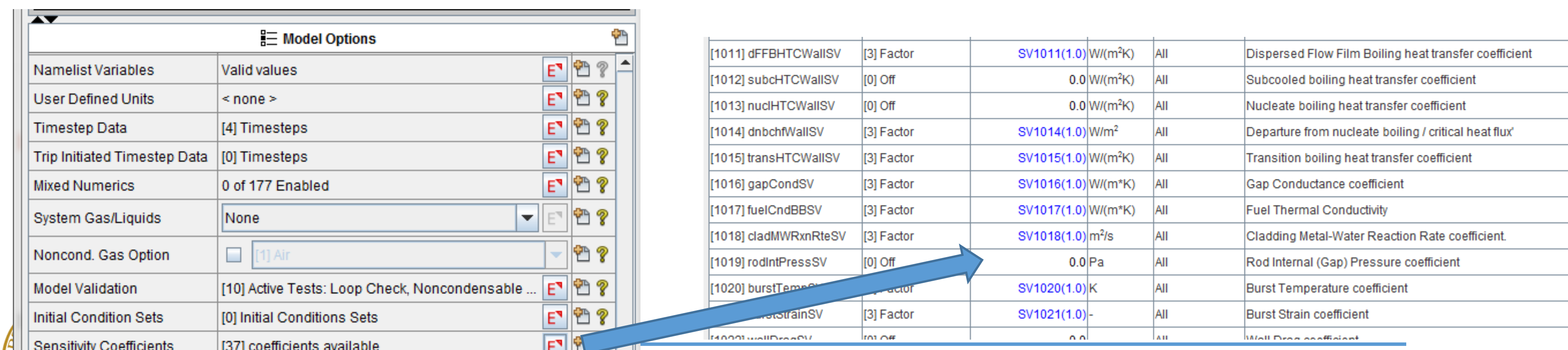


3. BEPU: Uncertain Parameters

- Characterization of uncertain parameters in **SNAP** platform:
  - Definition of the variable in **Numerics** option.
  - Model input parameters via “**Select a Shared Value**”.

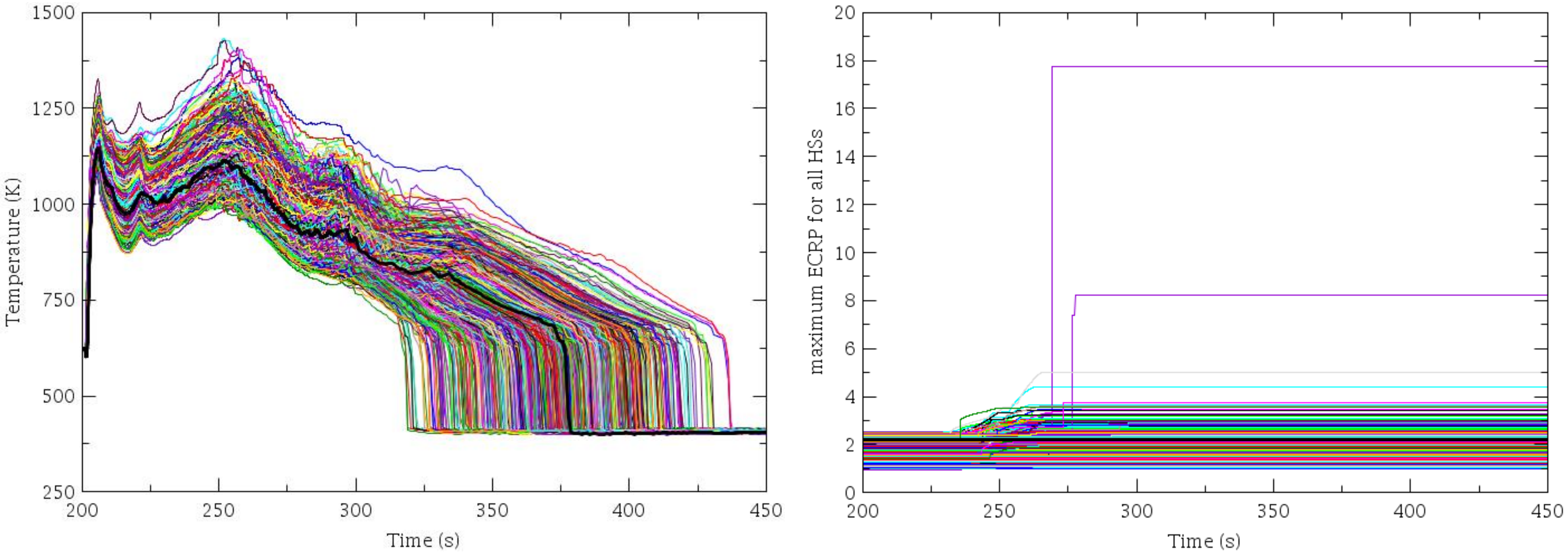


  - Internal models: 37 Sensitivity coefficients available in **Model Options**.



3.1 BEPU: Uncertainty Analysis.

- **Monte Carlo sampling: n=1020**



Non-parametric statistics results:

1. **Wald criterium**
2. **Binomial distribution with confidence interval.**

3. BEPU: Methodology

Wilks/Wald statistics: Easy Example

Bag full of infinite marbles

Take 1 marble and measure diameter, and annotate it.

Repeat this process 59 times

Arrange all 59 measurements from lowest to highest.

Maximum Value obtained = X

Repeat the 59 diameter collection an infinite number of times

On 95 % of the times (confidence), the initial highest value obtained X, will be larger than the measurement corresponding of percentile 95.

3. BEPU: Methodology

Wilks/Wald statistics:

- Monte-Carlo random sampling of input and internal models parameters (defined by their PDFs) with **DAKOTA** code.
- Number of code calculations **N**:
  - Depends on the probability content **γ**, confidence level **β** of the acceptance criteria (PCT, LMO) and order **p**. Number of bounds (upper and/or lower) = d. R = nº of FOM
  - Independent of the number of uncertain parameters
- BEPU LBLOCA analysis: **γ/β = 95/95**, PCT and LMO as output parameters, one sided-tolerance. 93 (p=1) cases are enough to verify the 95/95 acceptance criteria.

$$\beta = \sum_{j=0}^{N-R^*} \binom{N}{j} \gamma^j \cdot (1-\gamma)^{N-j}$$

$$R^* = p \cdot \left(\sum_{i=1}^{R} d_i \right)$$

β	γ values		p
	0.95	0.99	
0.95	93	473	1
	153	773	2
	208	1049	3
0.99	130	662	1
	198	1001	2
	259	1307	3

Wald with two FOM one-sided

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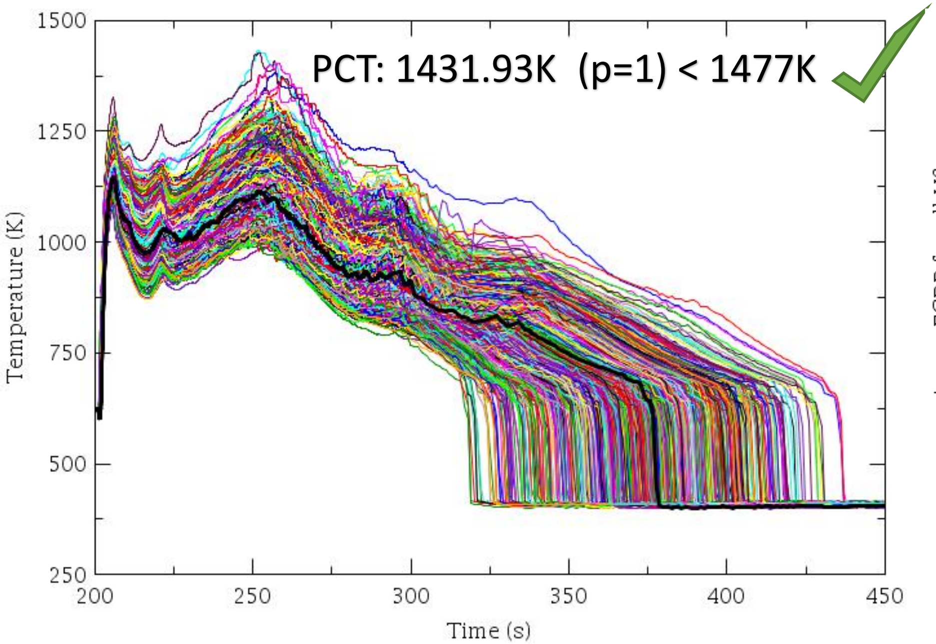
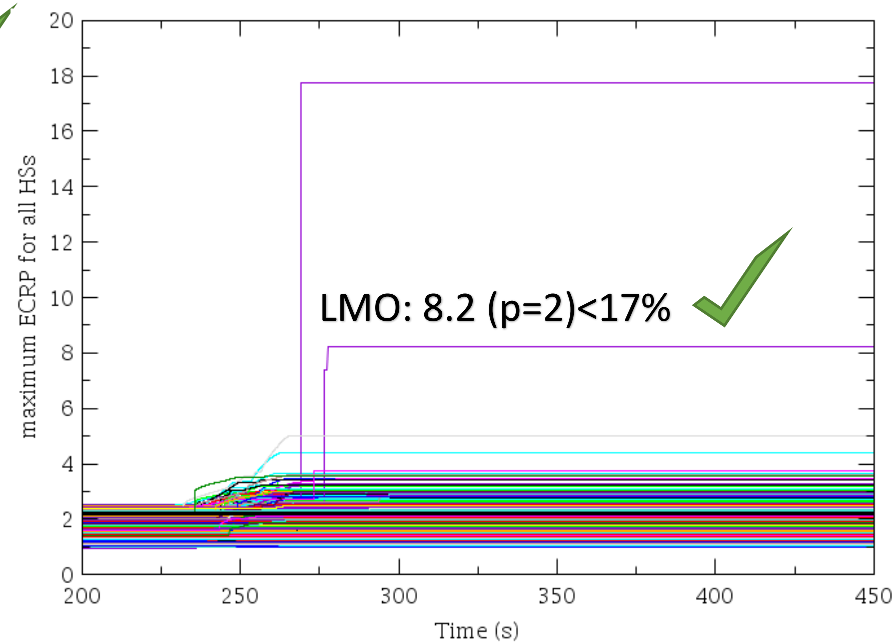
3.1 BEPU: Uncertainty Analysis

- **Non-parametric statistics** results. **Wald criterium**.





confidence level β	γ values (probability) 0.95	γ values (probability) 0.99	p
	93	473	1
	153	773	2
	208	1049	3
	…	…	…
0.95	1013	5088	20
	130	662	1
0.99	198	1001	2
	259	1307	3

95/95 and n=1020 → p=20
PCT= 1291 K LMO= 3.1 %

For p=2 and n=1020 **β = 95 %, γ = 99,22%**

Joint Core Damage Probability < 1E-2 with 99% CL

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3.1 BEPU: Uncertainty Analysis.

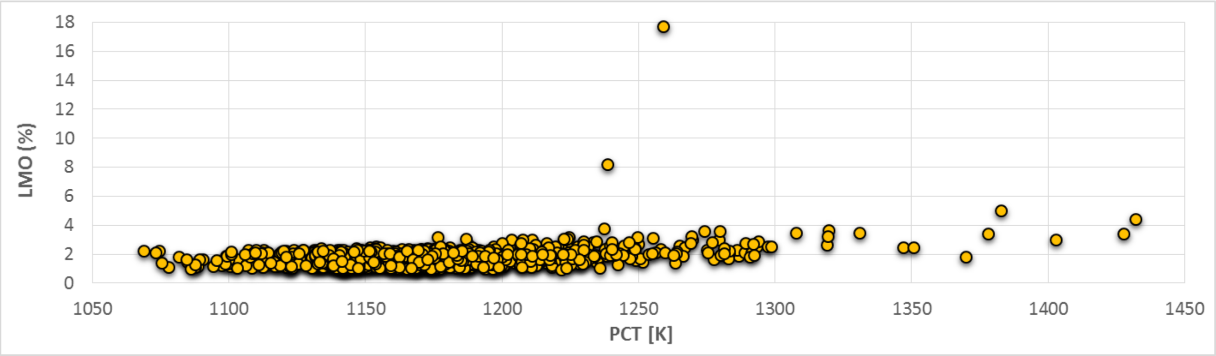
- **Non-parametric statistics** results. **Binomial distribution with confidence interval**
- Binomial distribution. **PCT** or **LMO** > acceptance criterion: Failure/no-failure.
- The 95% confidence interval has been obtained by means of the **Clopper-Pearson**.
- Equivalent to Wilks one-sided.
- Joint Core Damage Probability with 95% confidence interval:

  Mean = 0.98E-1%

  Upper 95% = 5.5E-1%

3.1 BEPU: Uncertainty Analysis.

- **Parametric statistics** results. It is quite difficult to obtain a single JPDF for PCT and LMO



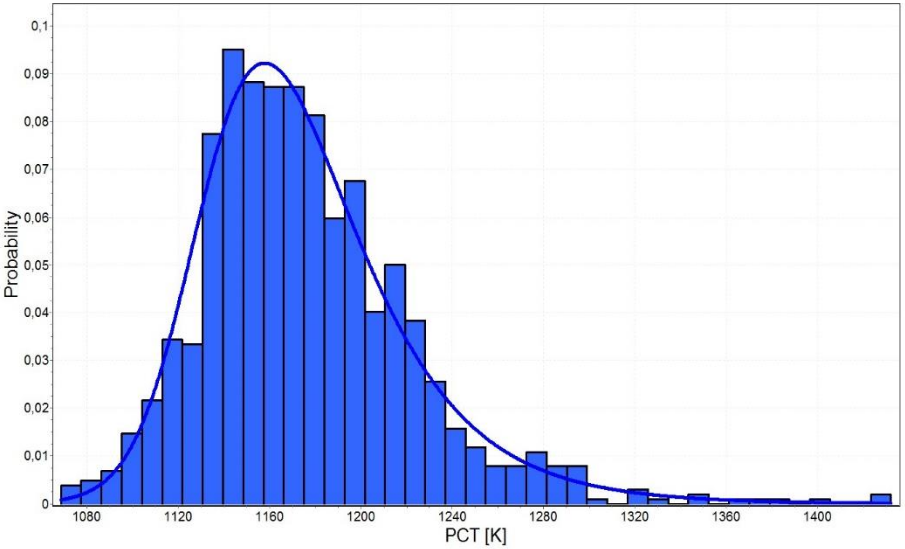
- The goodness of fit (**GOF**) tests measure the compatibility of a random sample with a theoretical probability distribution function.

- MC results have been measured against **3 GOF tests** and up to **60 different distributions**:
    - Kolmogorov-Smirnov
    - Anderson-Darling
    - Chi-Squared

- **Anderson-Darling** criterion is used as benchmark due to the test giving more weight to the tails than the Kolmogorov-Smirnov and Chi-Squared tests.
    - More adequate to determine exceedance probabilities.

3.1 BEPU: Parametric Statistics - PCT

- **Parametric statistics** results: Probability Density Functions



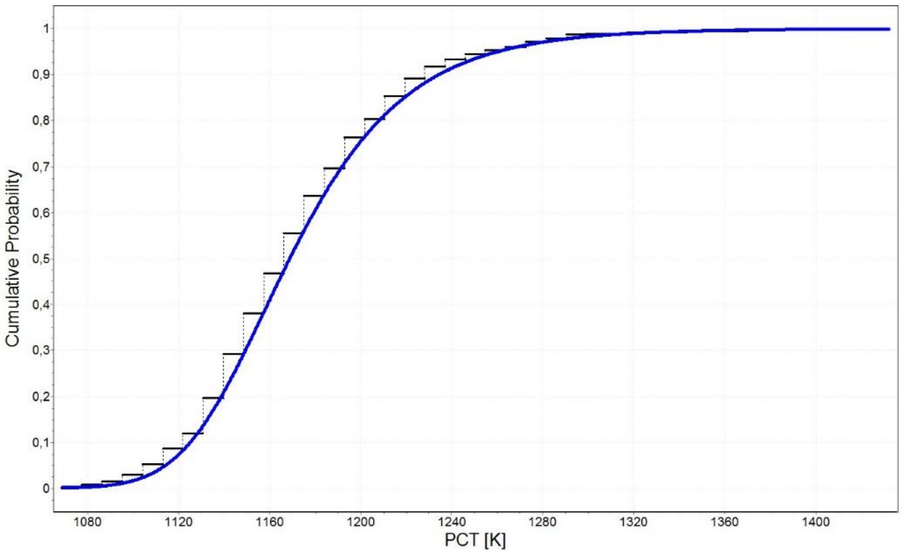


Figure: (Left) PCT histogram and associated PDF. (Right) PCT CDF

- PCT Monte Carlo results fit to the following PDF:
  - PCT (**Johnson SU**): P(PCT>1477K)= **2.7E-2**% (<5%).

But this value needs a Confidence interval.

3.1 BEPU: Parametric Statistics - LMO

- **Parametric statistics** results: Probability Density Functions

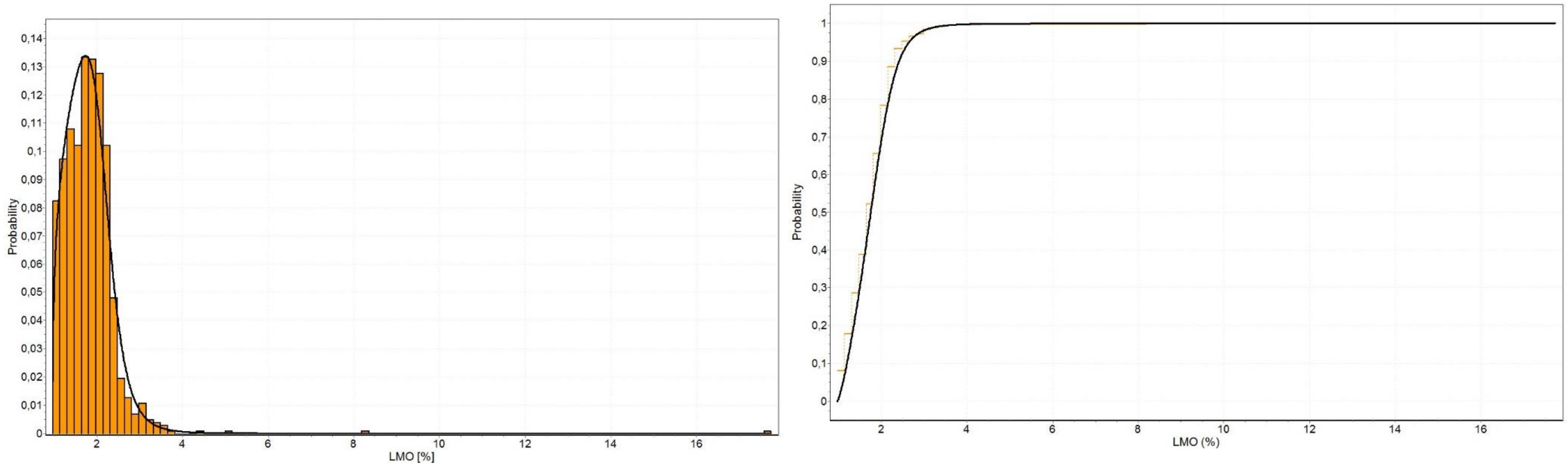


Figure: (Left) LMO histogram and associated PDF. (Right) LMO CDF

- LMO Montecarlo results fit to the following PDF:
  - LMO (**Dagum**): P(LMO>17%)=**1.5E-5**% (<5%).

But this value needs a Confidence interval.

3.1 BEPU: Parametric Statistics

- **Parametric statistics** : Different Methods to obtain a confidence Interval.

  - Creating a p-box using confidence interval of the distribution parameters by:

    1. Using Wald confidence interval for distribution parameters
    2. Using the Likelihood Function to obtain distribution parameters confidence interval

    Both methods are easily applicable **only for a limited set of distributions** (e.g. normal).

  - Using the computationally demanding Bootstrap Method. (fully used in the present study)

3.1 BEPU: Parametric Statistics

- **Parametric statistics** results: 500 **Bootstrap** Samples to obtain the confidence interval

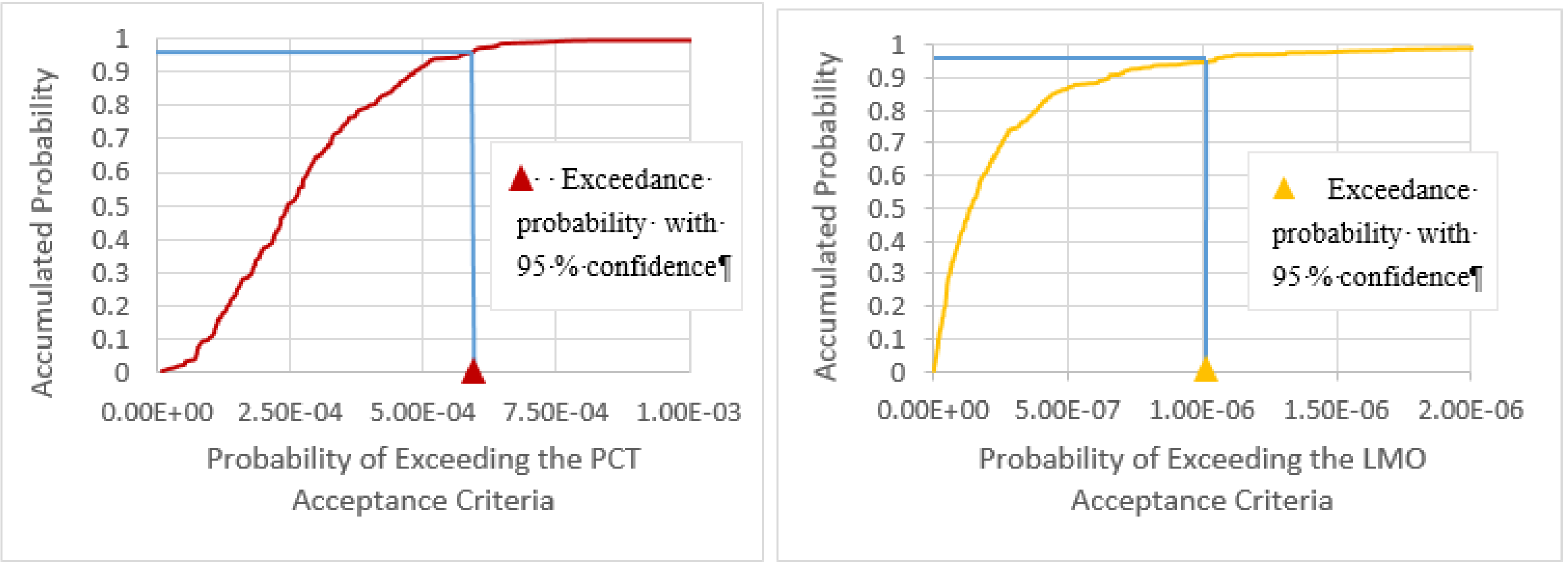


Figure: CDF of the 500 Bootstrap Samples for PCT (left) and LMO (right)

- Upper confidence interval for PCT : **6.00E-02%** for 95 % confidence
- Upper confidence interval for LMO: **1.02E-04%** for 95 % confidence

3.3 BEPU:Comparison Non- parametric .vs. Parametric Statistics

- **Non-Parametric statistics** results: Wald criterium

Joint Core Damage Probability < 7.8E-01% with 95% CL

- **Binomial distribution with 95% confidence interval (Clopper-Pearson)**

Joint Core Damage Probability < 5.5E-01% with 95 % CL

- **Parametric statistics** results: Probability Density Functions with Boostrap

Joint Core Damage Probability < 6.01E-02% with 95% CL

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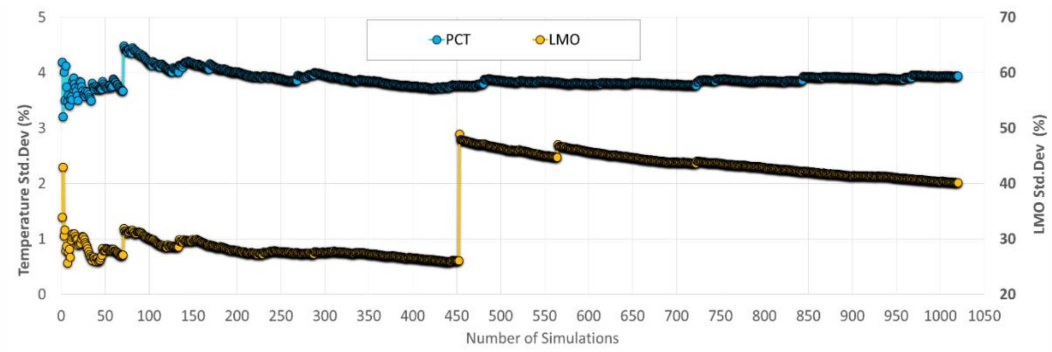
Wald is conservative compared with parametric results

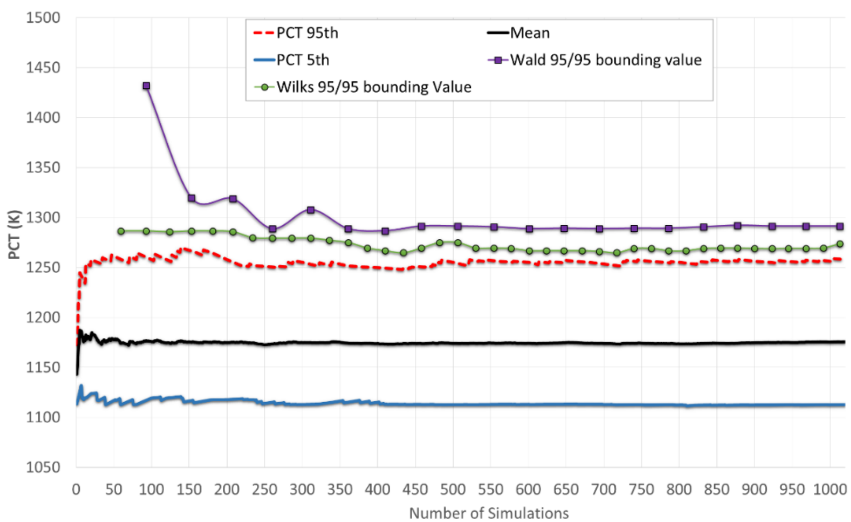
3.1 BEPU: Uncertainty Analysis

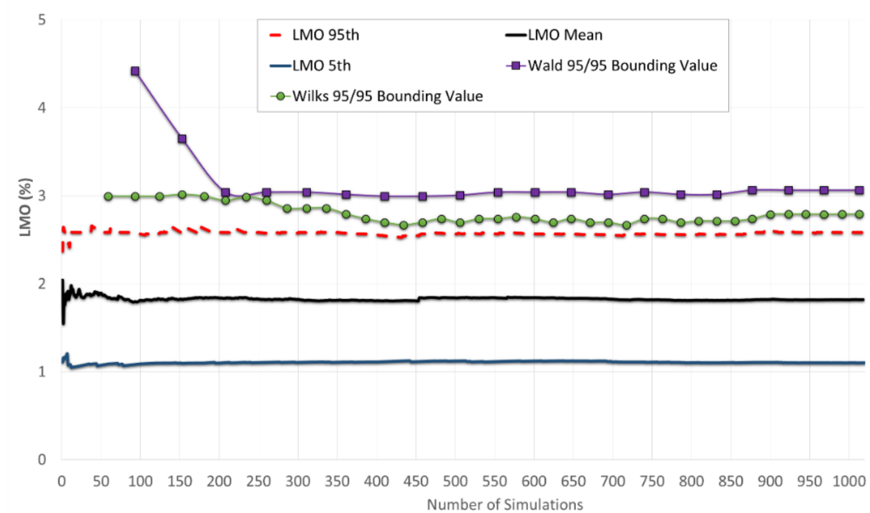
- **Sample discussion**: Parameters Convergence.

Convergence of Values across the simulation



Low order shows higher variance in all parameters

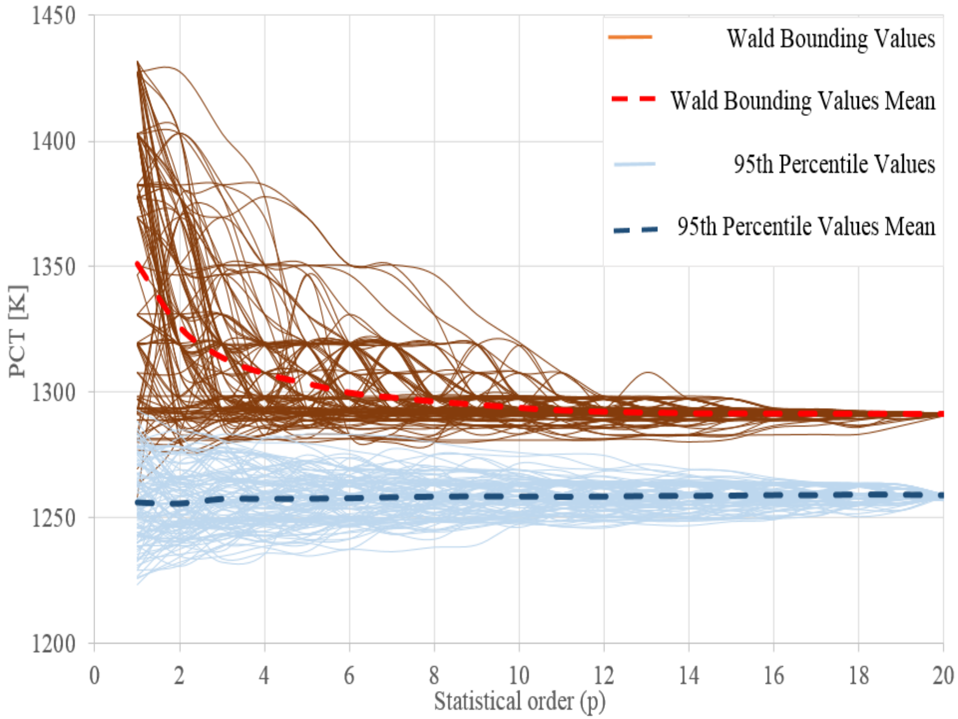


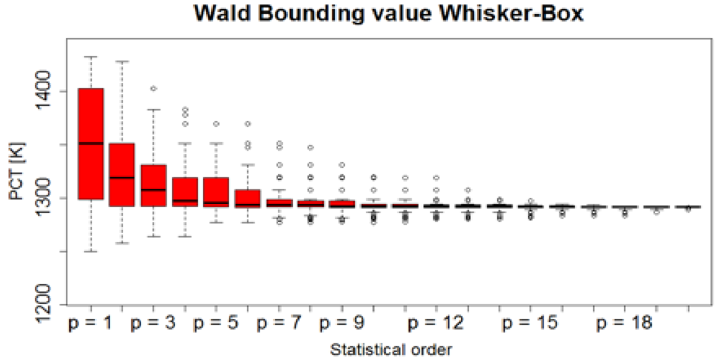


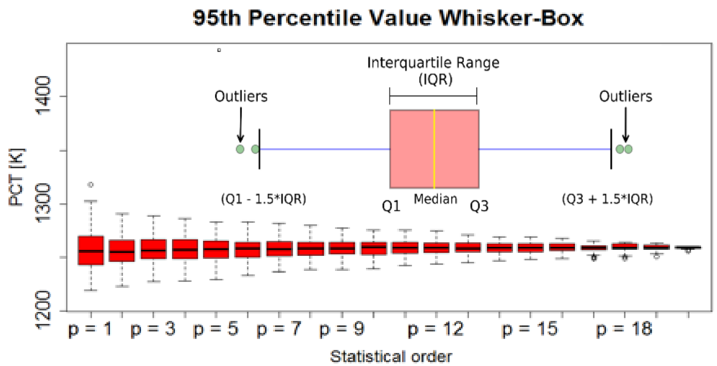
3.1 BEPU: Uncertainty Analysis

- **Sample discussion**: Parameters Convergence.

500 samples taken in random order (without substitution)





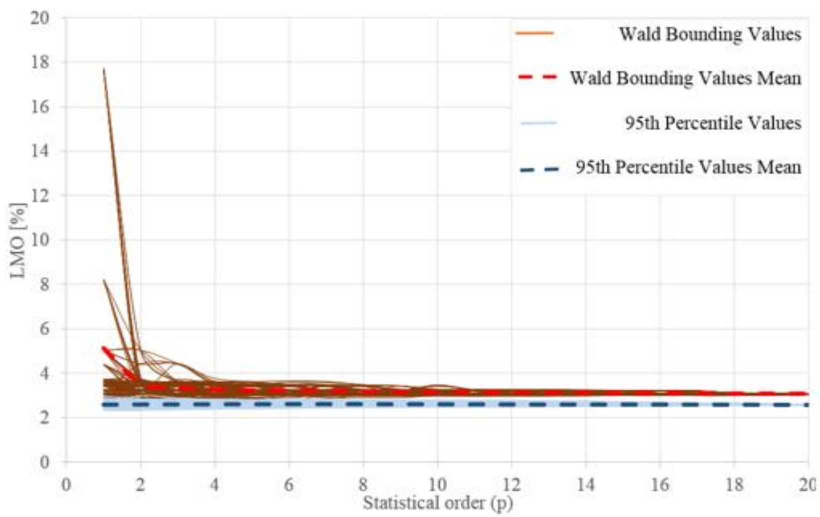


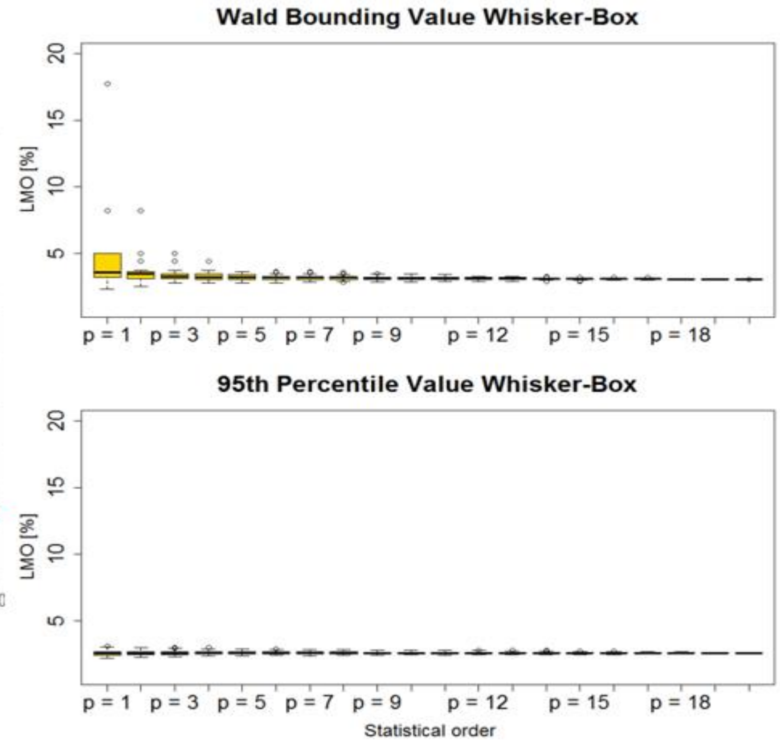
With a low order, the Wald bounding value tends to be more conservative

3.1 BEPU: Uncertainty Analysis

- **Sample discussion**: Parameters Convergence.

500 samples taken in random order (without substitution)



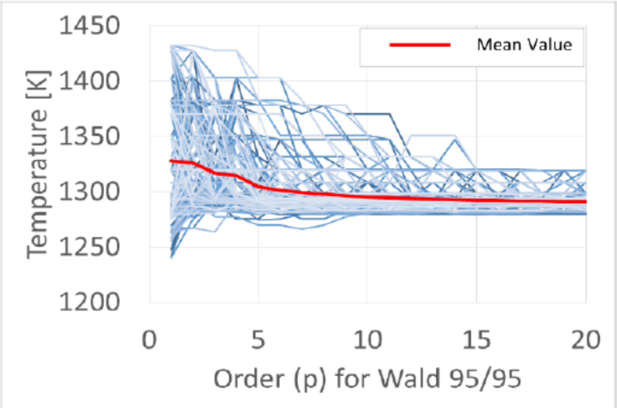


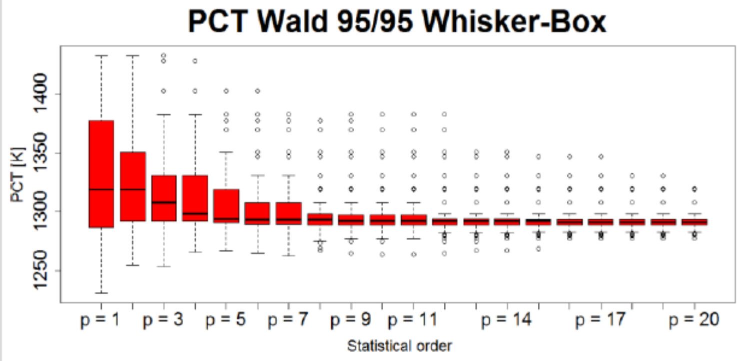
With a low order, the Wald bounding value tends to be more conservative

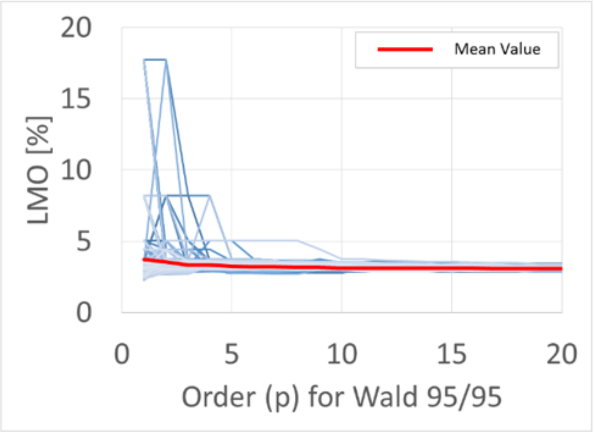
3.1 BEPU: Uncertainty Analysis

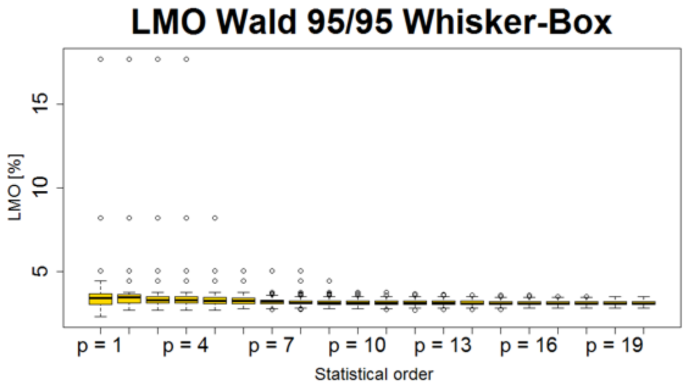
- **Sample discussion**: Parameters Convergence

500 Bootstrap (with substitution) samples for LMO and PCT









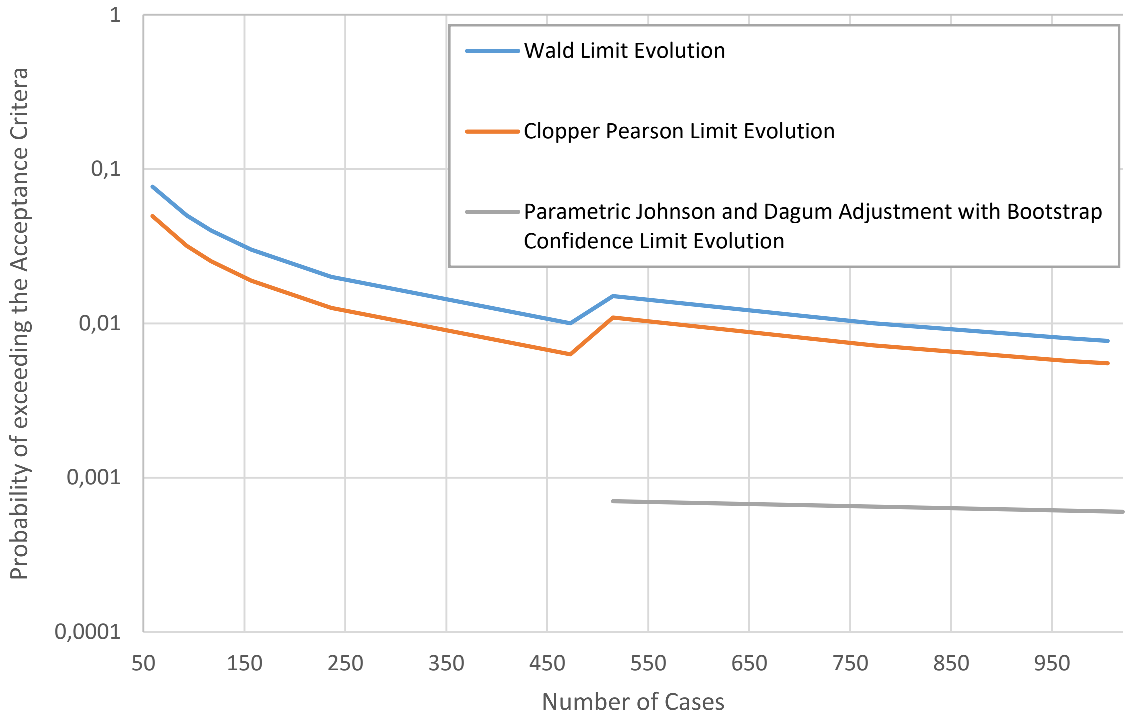
Confidence interval for Wald bounding values can be obtained with Bootstrap approach.

With a low order, the Wald bounding value tends to be more conservative

3.1 BEPU: Uncertainty Analysis

- **Sample Discussion:**

Evolution of the exceedance probability 95% confidence level with increasing number of simulations



With a low order, the Wald bounding value tends to be more conservative

4. EBEPU - Introduction

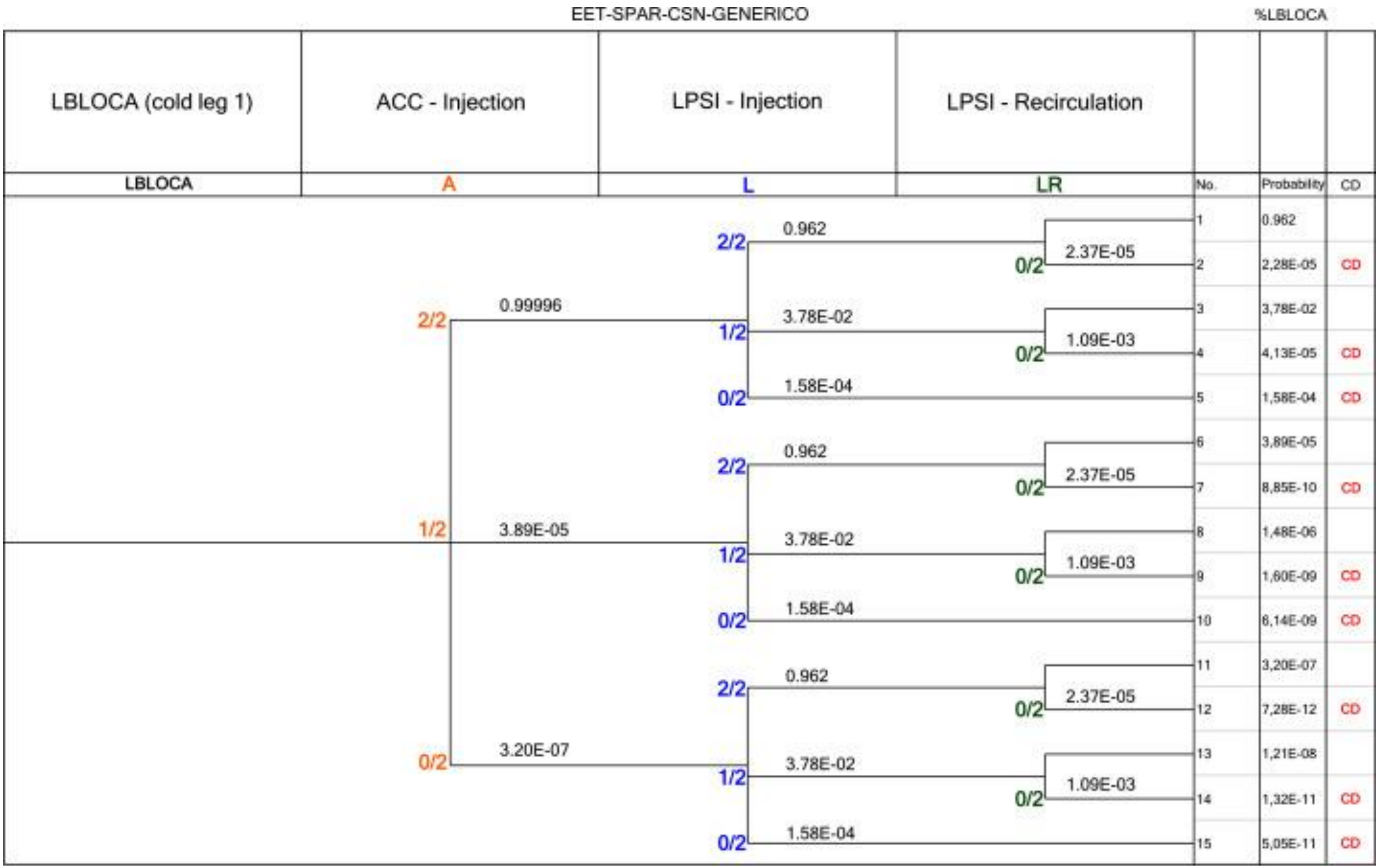
Can methods from PSA be integrated in DSA to obtain deeper insights of a NPP sequence?

TABLE 1. OPTIONS FOR PERFORMING DETERMINISTIC SAFETY ANALYSIS

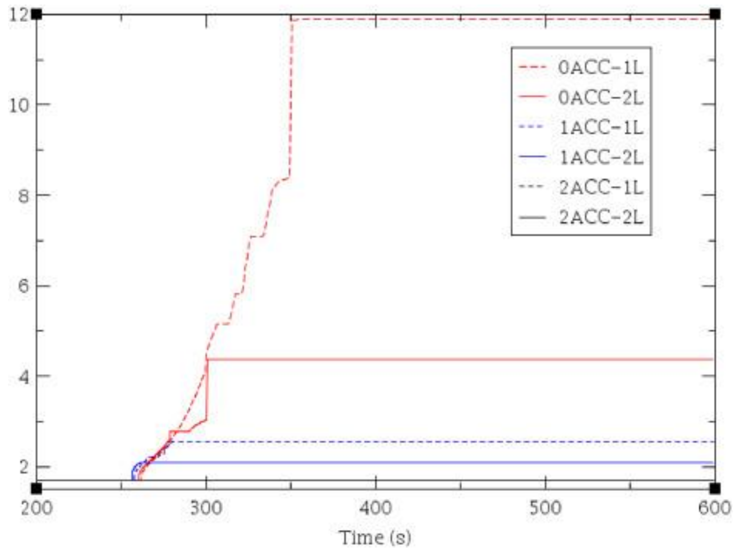
Option	Computer code type	Assumptions about systems availability	Type of initial and boundary conditions
1. Conservative	Conservative	Conservative	Conservative
2. Combined	Best estimate	Conservative	Conservative
3. Best estimate plus uncertainty	Best estimate	Conservative	Best estimate Partly most unfavourable conditions
4. Realistic*	Best estimate	Best estimate	Best estimate

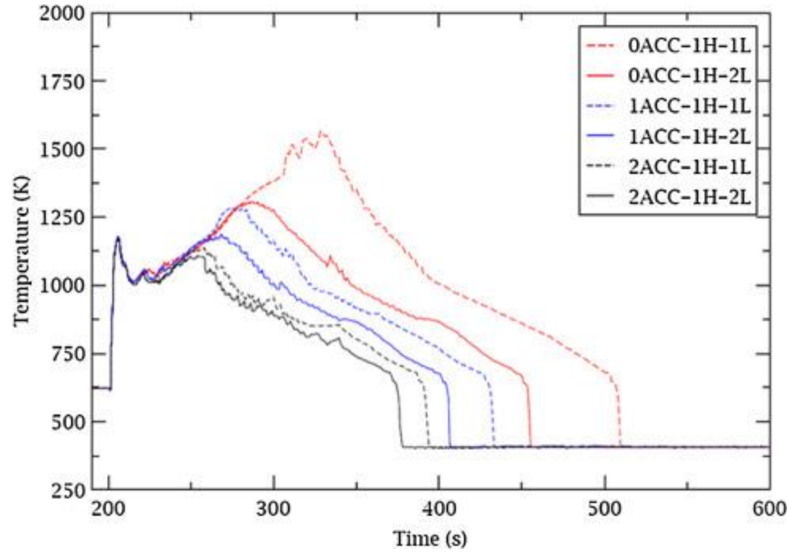
Deterministic safety analysis for nuclear power plants. Specific Safety Guide No. SSG-2. IAEA 2019

4. EBEPU - Example

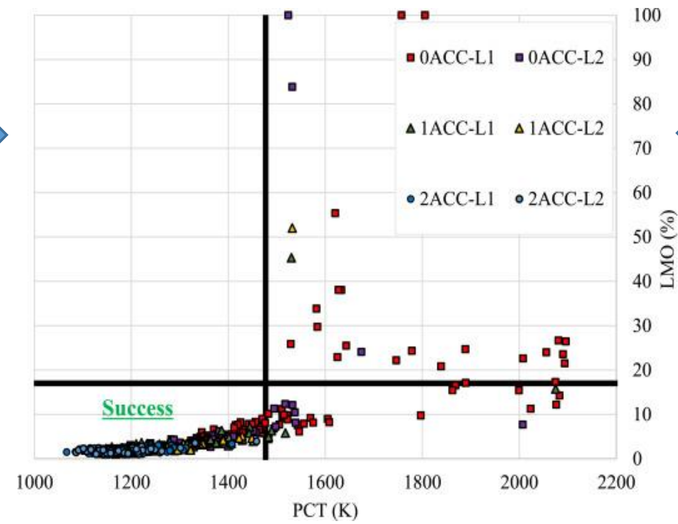


4. EBEPU



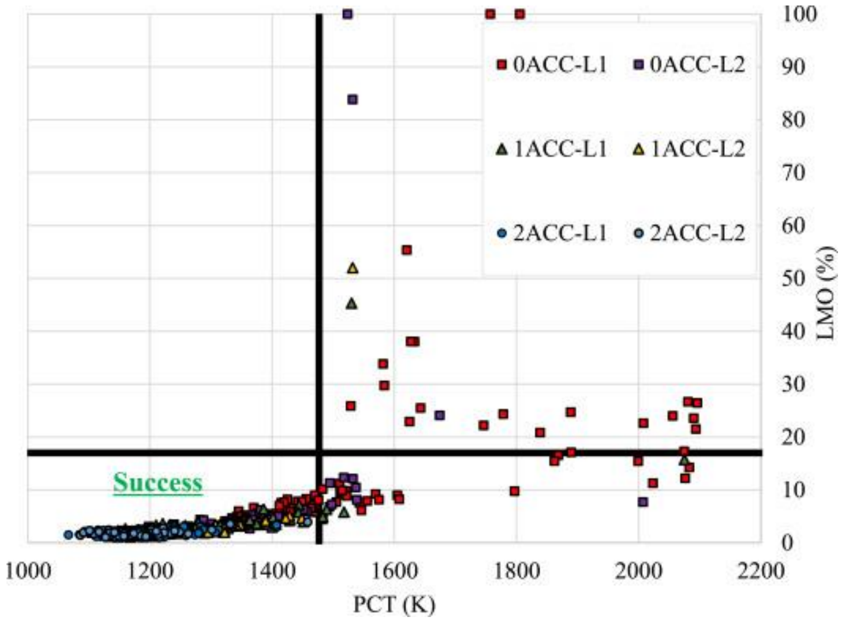


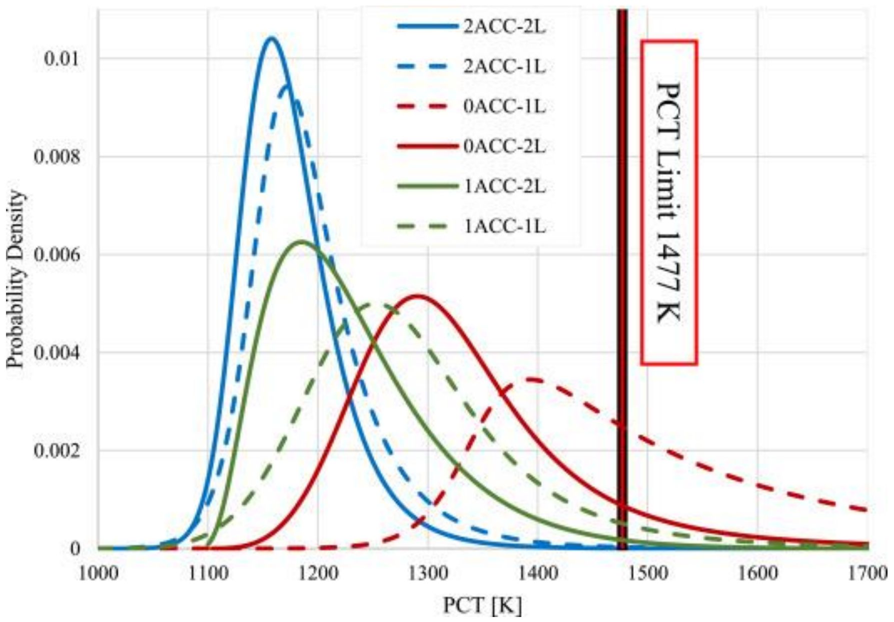
100 Cases with Monte-carlo Sampling for assessing uncertainties



100 Cases with Monte-carlo Sampling for assessing uncertainties

4. EBEPU





Non-Parametric Statistics

Parametric Statistics

4. EBEPU

FROM PSA

FROM DSA BEPU

Sequence	Pseq	IE ·Pseq [year $^{-1}$]	100% Power Damage probability	CDF [year $^{-1}$]
2ACC-2L	9.69E-01	1.11E-03	2.95E-02	**3.27E-05**
2ACC-1L	3.00E-02	3.45E-05	2.95E-02	1.02E-06
2ACC-0L	9.00E-04	1.03E-06	1.0	**1.03E-06**
1ACC-2L	2.58E-04	2.97E-07	4.66E-02	1.38E-08
1ACC-1L	8.00E-06	9.20E-09	1.02E-01	9.38E-10
1ACC-0L	2.40E-07	2.76E-10	1.0	2.76E-10
0ACC-2L	2.91E-05	3.34E-08	1.80E-01	6.01E-09
0ACC-1L	9.00E-07	1.04E-09	5.40E-01	5.62E-10
0ACC-0L	2.70E-08	3.11E-11	1.0	3.11E-11
No-recirc	6.41E-05	7.31E-08	1.0	7.31E-08
Total	1.00E+00	1.15E-03	3.04E-02	**3.49E-05**

5. Conclusions – LBLOCA BEPU

- The analyses performed have allowed to evaluate the new thermomechanical models included in **TRACE**.
- Results show the compliance with the **10 CFR 50.46** requirements for the PCT and LMO:
  - Non-parametric analysis proves the compliance with a 95/95 probability and confidence.
  - PCT and LMO PDFs obtained by means of parametric analyses show marginal probabilities of acceptance criteria exceedance.
- Employing Extended-BEPU technique to assess a transient can provide interesting outcomes not seen with just PSA or DSA.
- All these discussions **can be seen in**:

ELSEVIER — Reliability Engineering & System Safety, Volume 205, January 2021, 107246
Application of Expanded Event Trees combined with uncertainty analysis methodologies

ELSEVIER — Annals of Nuclear Energy, Volume 144, 1 September 2020, 107505
Statistical characterization of NPP transients: Application to PWR LBLOCA

ELSEVIER — Reliability Engineering & System Safety, Volume 193, January 2020, 106607
Uncertainty and sensitivity analysis of a PWR LOCA sequence using parametric and non-parametric methods

Statistical Analysis of NPP transients: LBLOCA in a PWR; Parametric, non-parametric methods and EBEPU

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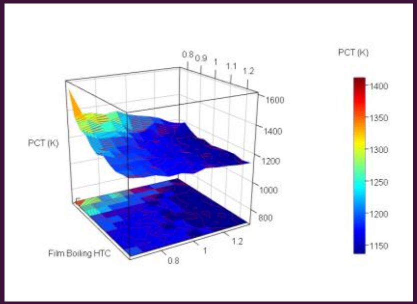
Texas A&M University

Seminarium Zakładu Energetyki Jądrowej i Analiz Środowiska, Jan 2022



Extra Slides