Severe Accident Phenomenology short course

ETSII – Universidad Politécnica de Madrid
19-23 June 2023

Lecture 12b: Uncertainty Quantification in Severe Accident Analysis

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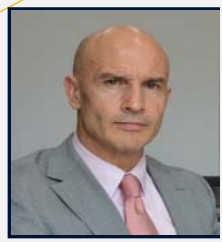
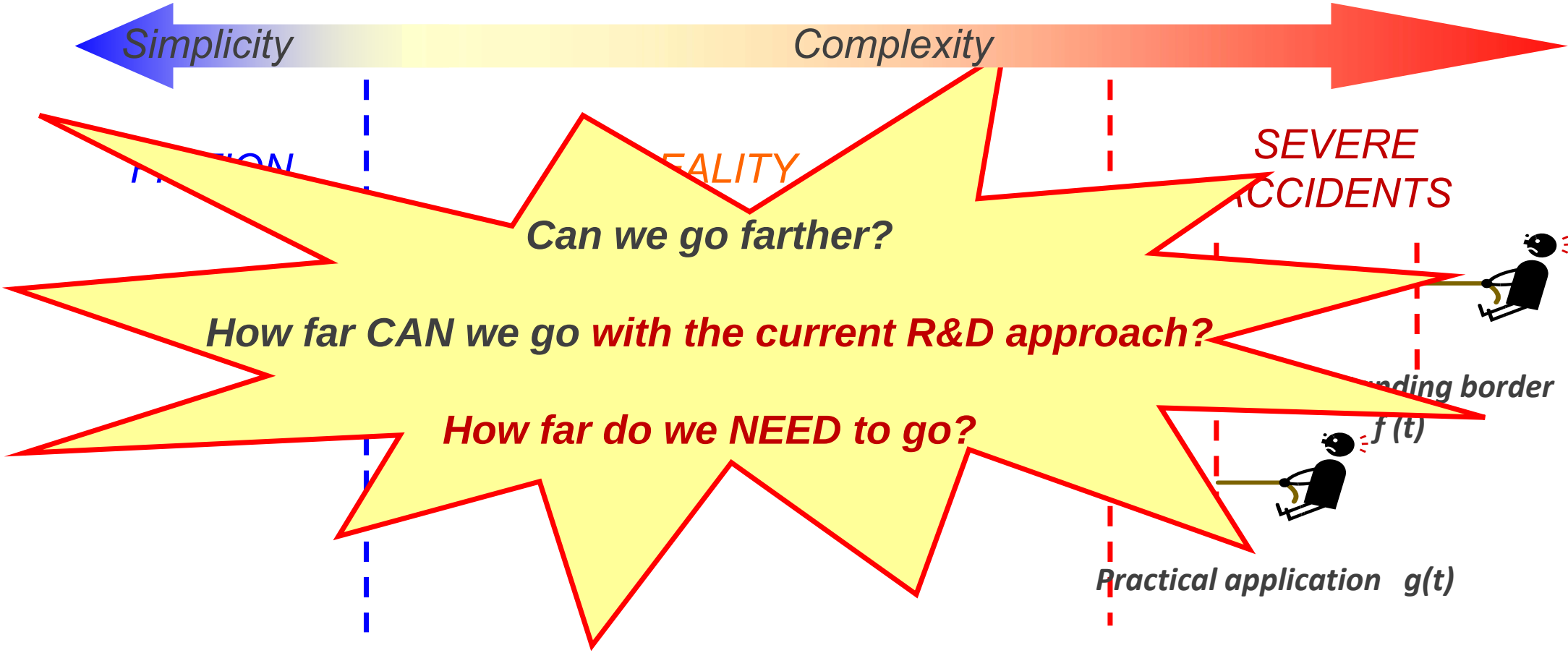


Funded By European Union

The Complexity Domain



Contents

Terms & Acronyms

- **BEPU** *Best Estimate Plus Uncertainties*
- **UaSA** *Uncertainties and Sensitivity Analysis*
- **FoM** *Figure of Merit*
- **PDF** *Probability Density Function*

The Source

- ***BEPU*** *was born within the domain of* ***Thermal-hydraulics!***

  Application of BE to ***ECCS licencing*** *(USNRC: 1974-1986)*

- *In early 90's,* ***OECD/CSNI*** *WGs took over.*

  (NEA/CSNI/R(1994)20; NEA/CSNI/R(97)35; NEA/CSNI R(97)4; …)

  WGAMA:
  - *BEMUSE (2004-2010);*
  - *PREMIUM (2012-2015);*
  - *SAPIUM (2017-2019);*
  - *ATRIUM (2021-2024)*

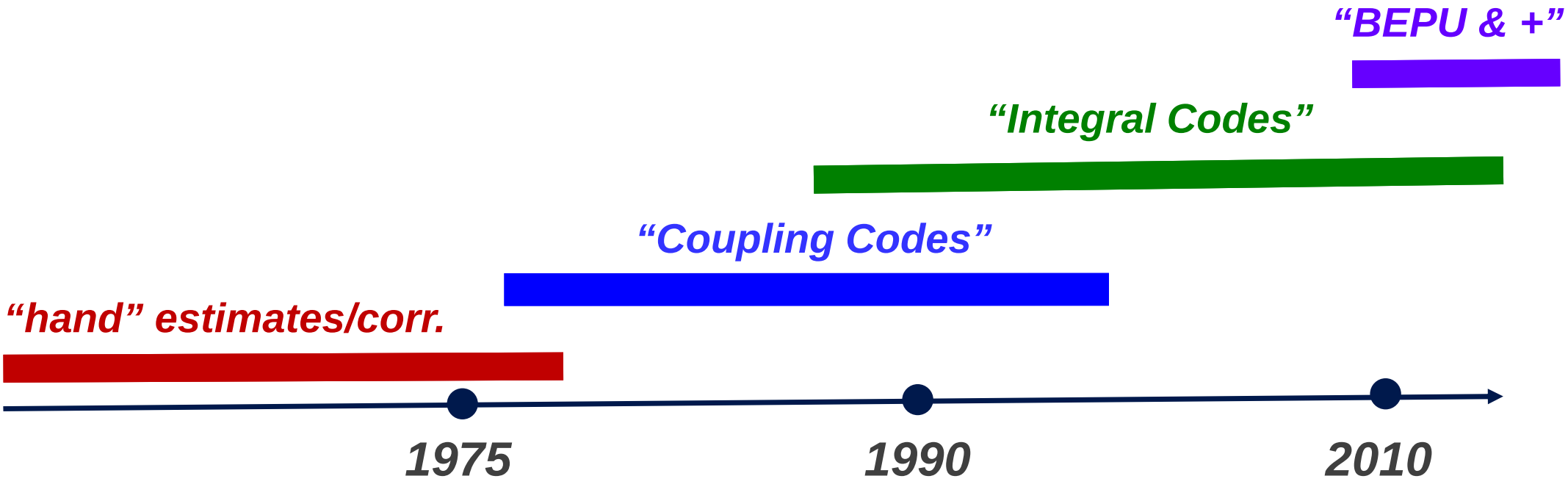
The Severe Accident Radiography

- ***Phenomenological domain***
  - *A huge number of phenomena.*
  - *Multidisciplinary (thrm-fluid, mechanical, phys., chem, …).*
  - *Strong feedback.*

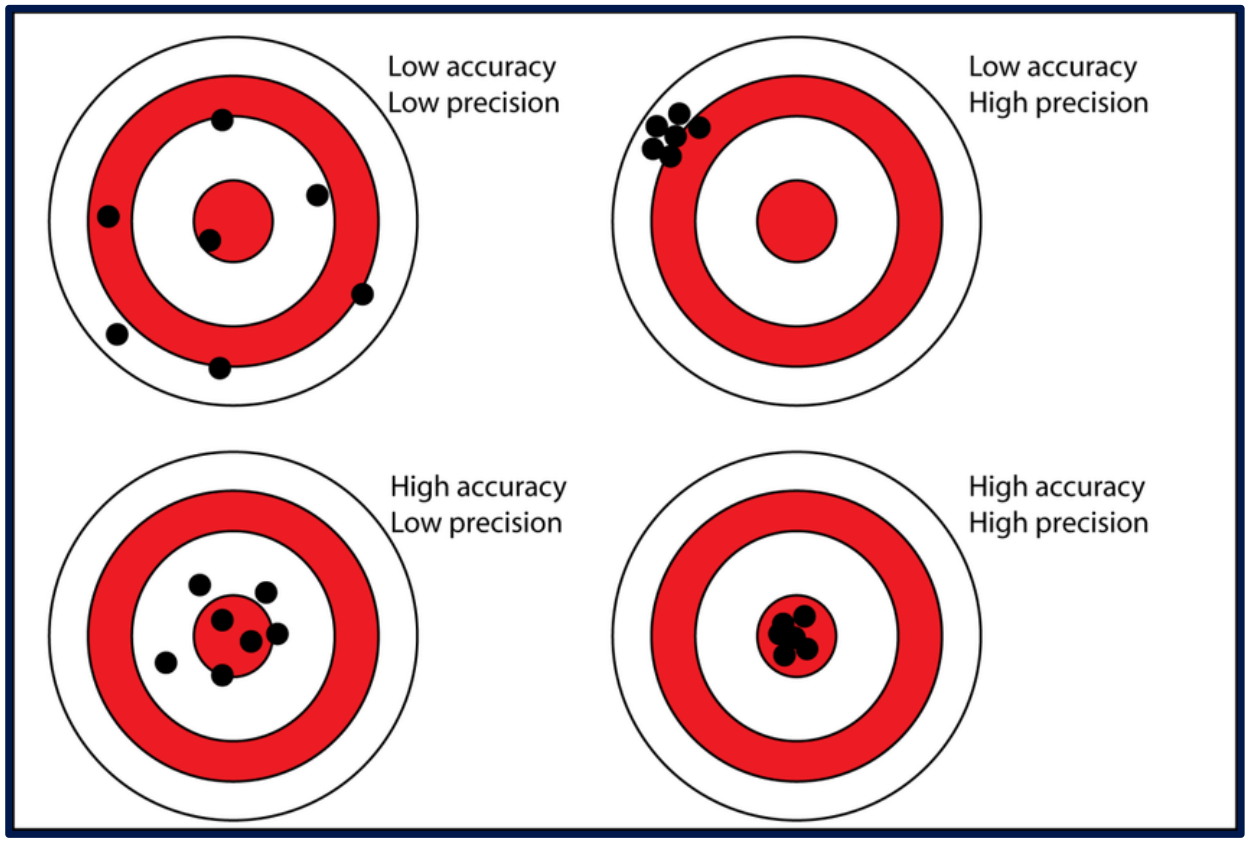
- ***Boundary conditions***
  - *Broad ranges (T, P, D, …).*
  - *Extreme values.*

- ***Timing & Extension***
  - *Integration over long periods (fast & slow phenomena).*
  - *Full NPP scope (micro & macro scale; safeguards; human action).*

The Time Perspective



The Challenge



The Opportunity

- ***"Maturity" of severe accident codes*** *(integration;phenomena;"validation";numerics)*
- ***Computational resources presently available.***

Major advantages:

- *Avoidance of conservative assumptions.*
- *Better identification of safety margins.*
- *Quantification of likelihood of reaching specific values.*
- ***Insights into dominating uncertainties***

How accurate SA simulations are?

Severe Accident Codes

Capitalization of knowledge on severe accidents

- ***Input build:*** *Major hypo's & approximations*
- ***Nature of models:*** *"from empirical to pseudo-mechanistic".*
- ***Models integration*** → x_i, x_j, x_k, … (+ Δ_i, Δ_j, Δ_k, …) *transfer*
- ***Variability of BC*** → *nodalization*
- ***Accident mgmt*** → *timing?; efficiency?; equip. perform.*

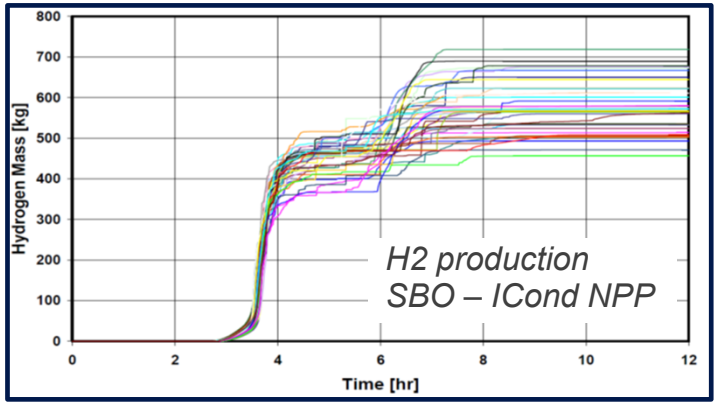
Uncertainty Quantification (UQ)

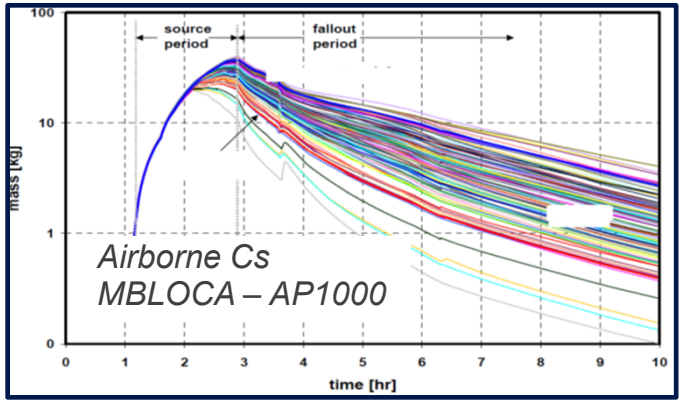
BEPU in SA Analysis (I)

- ***A pioneer work based on STCP*** *(Khatib-Rahbar et al., 1989)*
  - *Identification of input param.*
  - *Determination of pdf's*
  - *Random combination samp.*
  - *Calculation running*

  → ***Source Term uncertainties***
  - *Meltdown parameters*
  - *FP release coefficients*
  - *Chemical activities (MCCI)*
  - *Containment performance*

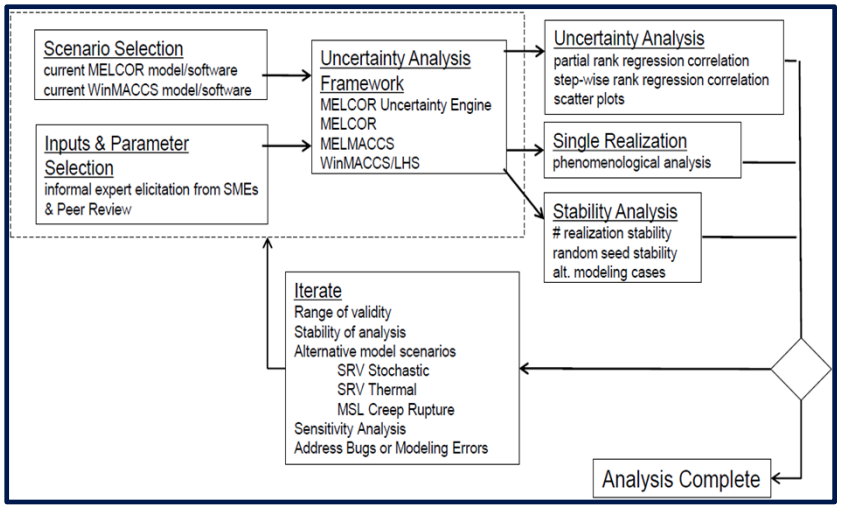
- ***Similar methodology based on MELCOR 1.8.5*** *(Gauntt R.O., 2005)*

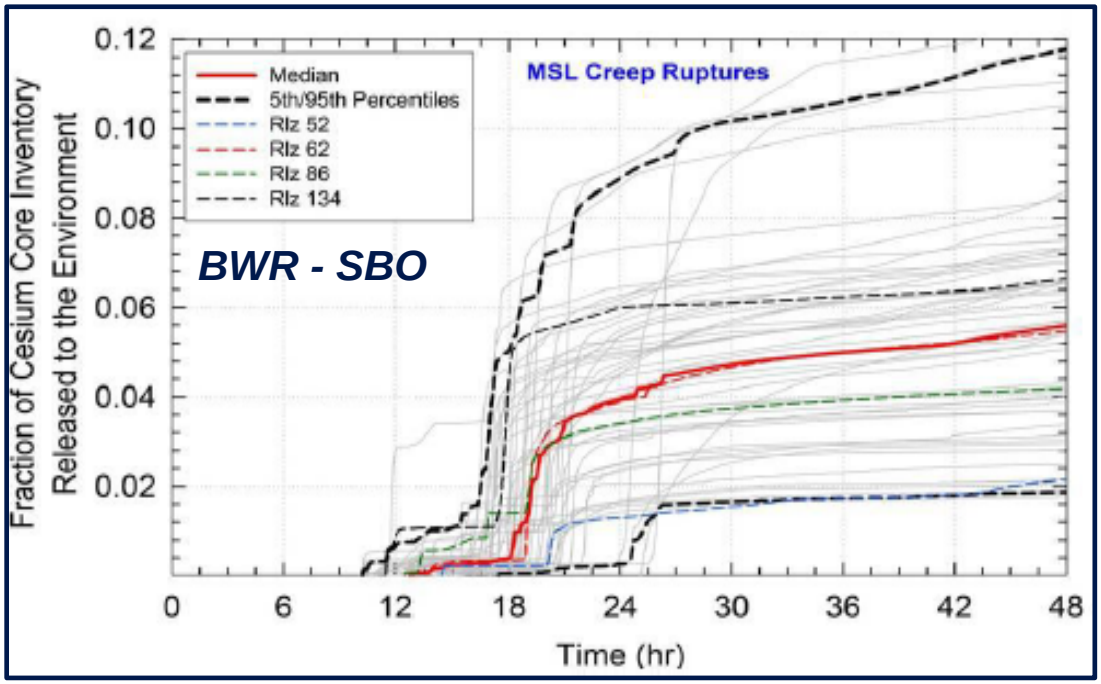




BEPU in SA Analysis (II)

State of the Art Reactor Consequence Analyses (2017)





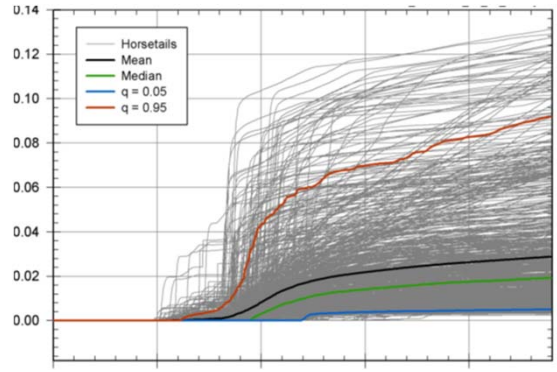
- *Battery duration; SRV failure rate; MSL creep rupture area; …*
- *Zry breakout T; molten clad drainage drain; debris radial relocation; …*

A comprehensive list of uncertain parameters is practically unapproachable!

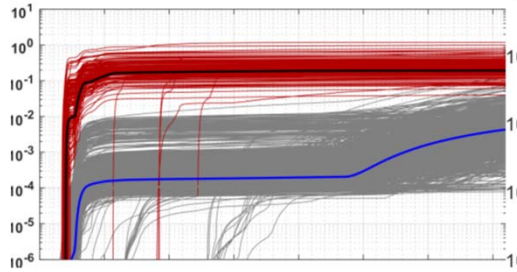
BEPU in SA Analysis (III)

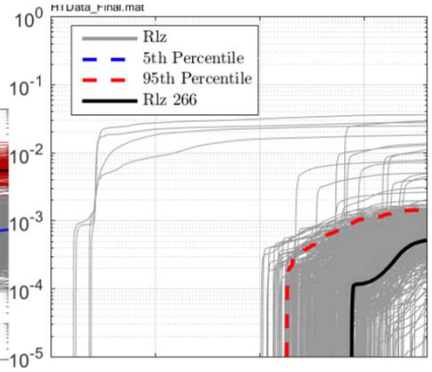
"Summary of the Uncertainty Analyses for the State-of-the-Art Reactor Consequence Analyses Project"

(NUREG-2254; 2022)



- *2010-2019.*
- *3 "full-scope" UaSAs: PBottom; Surry; Sequoyah.*
- *Unmitigated LTSBO (PB), STSBOs (S&S).*
- *MELCOR-MAACS; MC (865, 567, 1147); LHS.*
- *Assumptions on SVs, breach (SGTR), time (48 h; 72 h), ...*
- ***Expert judgement!!!** (input parameters, 15-20).*





BEPU in SA Analysis (IV)

The EU-MUSA Project

(2019-2023)

MUSA

https://sh1.sendinblue.com/3izxfv2tldxpfe.html?t=1685539873

NUGENIA TA2 Nuclear Generation II&III Alliance

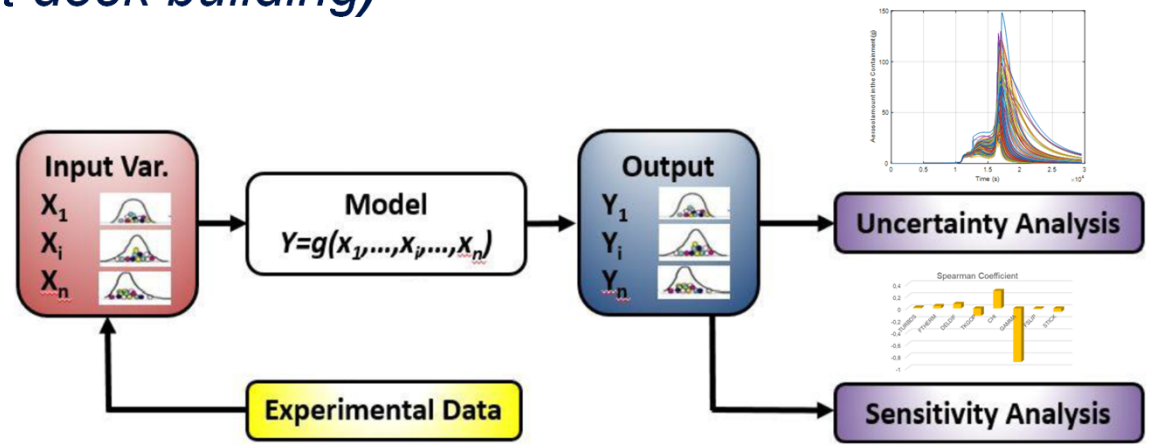
SNETP Sustainable Nuclear Energy Technology Platform

SEAKNOT

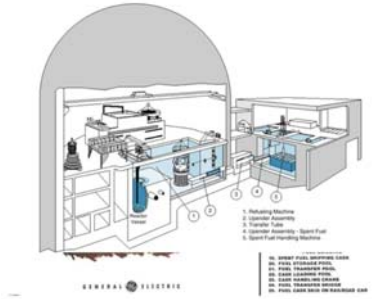
Funded By European Union

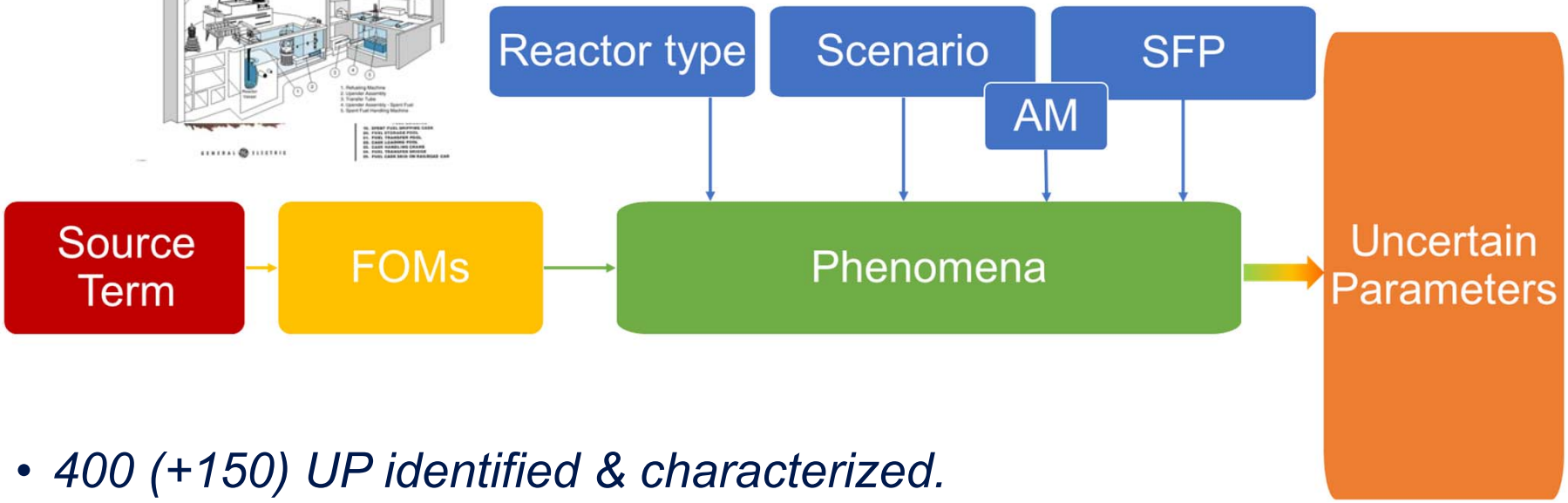
Fundamental Steps

- *Characterization of* ***Input parameters***
- ***Generation of samples (****input deck building****)***
- ***Propagation of samples****.*
- ***Evaluation of uncertainties***
- ***Sensitivity Analysis***



Characterization of Uncertain Parameters
(The MUSA Project)





- *400 (+150) UP identified & characterized.*
- *Substantiated "expert judgement".*

Characterization of Uncertain Parameters
(The MUSA Project)

Phenomena	Uncertain Parameter	Reference value	Lower bound	Upper bound	pdf	References
Sedimentation	Gas viscosity [kg/ms]	1.0 / N/A	-5% / N/A	+5% / N/A	Uniform	Expert Judgment
	Gas temperature [K]	N/A	N/A	N/A	N/A	N/A
	Gas pressure [Pa]	1.55E+07 / N/A	-1.5% / N/A	+1.5% / N/A	Normal	Expert Judgment
	Gas mean free path	N/A	N/A	N/A	N/A	N/A
	Particle diameter Lower Bound [m]	0,000000011	0,00000001	0,0000002	Triangular	1986 Helton et al. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics"; 2009 NEA/CSNI. "State-of-the-Art Report on Nuclear Aerosols"
	Particle diameter Upper Bound [m]	0,000199	0,000005	0,00002	Triangular	1986 Helton et al. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics"; 2009 NEA/CSNI. "State-of-the-Art Report on Nuclear Aerosols"
	Slip factor (default = 1.257)	1,257	1,14	1,28	Triangular	1990 D. J. Rader. "Momentum slip correction factor for small particles in nine common gases"; MELCOR Default; Expert judgment (pdf)

Characterization of Uncertain Parameters
(The MUSA Project)

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	Gas pressure [Pa]	1.55E+07 / N/A	-1.5% / N/A	+1.5% / N/A	Normal	Expert Judgment
	Gas mean free path	N/A	N/A	N/A	N/A	N/A
	Particle diameter Lower Bound [m]	0,000000011	0,00000001	0,0000002	Triangular	1986 Helton et al. "Uncertainty and Sensitivity Analysis of a Model for Multicomponent Aerosol Dynamics"; 2009 NEA/CSNI. "State-of-the-Art Report on Nuclear Aerosols"
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	Slip factor (default = 1.257)			1,28	Triangular	1990 D. J. Rader. "Momentum slip correction factor for small particles in nine common gases"; MELCOR Default; Expert judgment (pdf)

- ***Reasonable***
- ***Justifiable***
- ***Defensible***

Generation of Samples
(The MUSA Project)

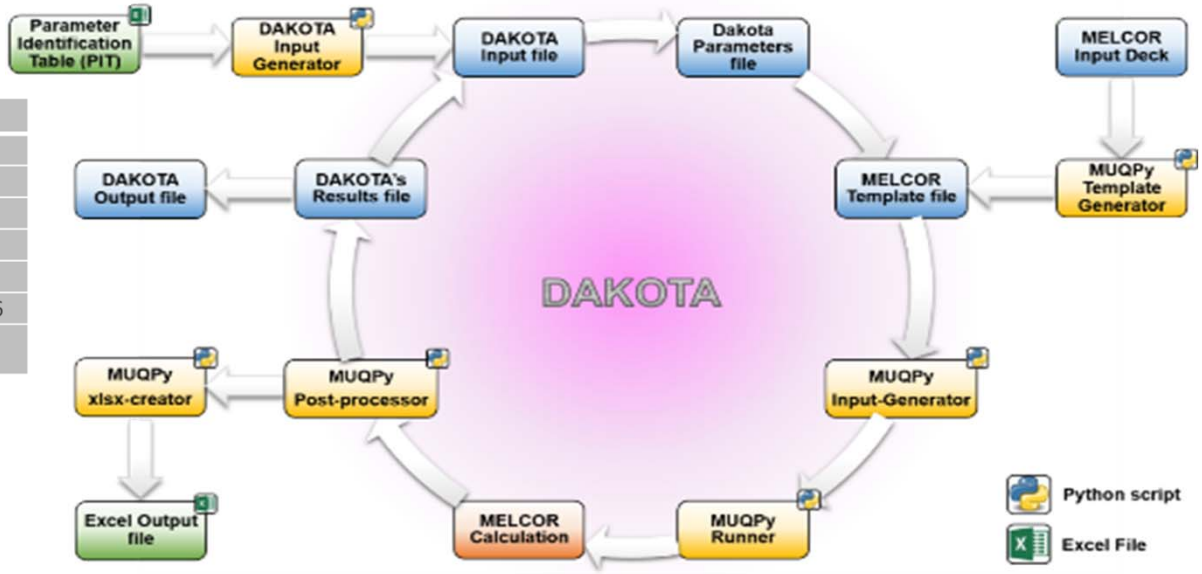
- ***Monte Carlo*** *($n \sim 10^3$)*
- ***Wilks*** *($n \sim 10^2$)* *Order statistics*

- ***Sampling*** *SRS (random)*
  LH (Latin Hypercube)

Propagation of Samples
(The MUSA Project)

UQ Tool	SA Code
DAKOTA/Python scripts	MELCOR2.2
DAKOTA	MELCOR2.2
DAKOTA /SNAP	MELCOR2.2
DAKOTA/SNAP, MATLAB script	MELCOR2.2
DAKOTA/SNAP	MELCOR2.2
DAKOTA	MELCOR1.8.6
DAKOTA, Python, ass. packages	MAAP5.05

UQ Tool	SA Code
Python Tools	MELCOR 2.2
Python in-house Tool	MELCOR 2.2
Scripts	MELCOR2.2



UQ Tool	SA Code
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b
SUNSET	ASTEC2.2b

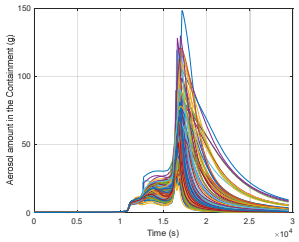
UQ Tool	SA Code
SUSA4.2	AC^2
SUSA4.0	MELCOR2.2
SUSA4.2	RELAP/SCDAP

UQ Tool	SA Code
RAVEN	MELCOR2.2
URANIE	ASTEC2.1

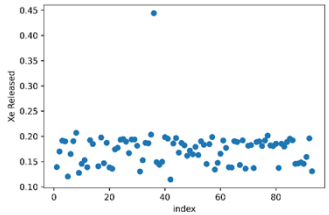
Automatization!

Evaluation of Uncertainties
(The MUSA Project)

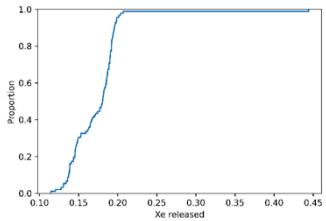
- ***Dispersion plots***



- ***Scatter plots***



- ***CDF; PDF***



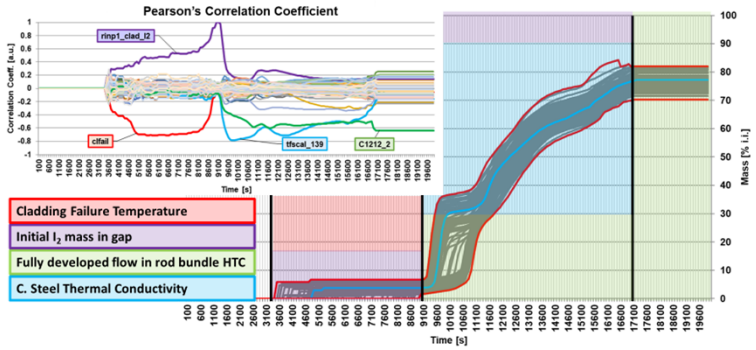
- ***Descriptive statistics***

Statistical parameter	Xe
MELCOR reference case (%i.i.)	24.21
Mean (% i.i.)	17.33
Median (% i.i.)	18.07
Lower bound (% i.i.)	11.44
Upper bound (% i.i.)	44.42
Standard deviation (% i.i.)	3.71

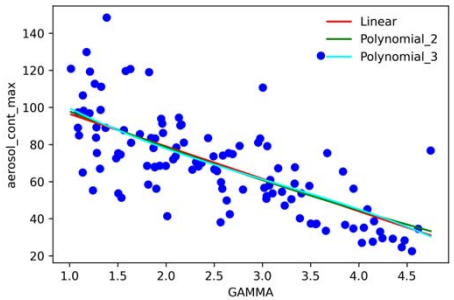
…

Sensitivity Analysis
(The MUSA Project)

- ***Correlation coefficients*** *(Pearson; Spearman)*



- ***Simple regressions***



- ***More advanced techniques*** *(stepwise reg.; Lasso reg.)*

Present Challenges

- ***The UP database optimization*** *(filling; extension; restrc.).*
- ***A consolidation of UaSA application in SA*** *(#UP; nodding; FOMs; …)*
  – ***Innovation.***
- ***A "balanced" use of expert judgement.***
- ***Further attention to accident management*** *(forward/reverse effect).*
- ***Show-cases for innovative technologies*** *(ST-ATFs; LW-SMR)*

Main Takeaways

- ***Uncertainties quantification of SA analysis is timely and necessary.***
- ***A systematic application of UASA in SA is far from straightforward.***
- ***Innovation needed to make UQ in SA a reality.***
- ***Cooperation of UQ application is the way*** *(MUSA; IAEA/CRP).*
- ***New knowledge*** *(statistics)* ***brought and mastering needed.***
- ***Input deck characterization*** *is fundamental.*
- ***Post-processing: Engineering judgement*** *more necessary than ever.*

References

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- *Nagase F., Gauntt R.O., Naito M., 2016. Overview and outcomes of benchmark study of the accident at the Fukushima Daiichi NPS (OECD/NEA BSAF Project). Nuclear Technology 196, 3, 499-510.*
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Thank You!
Any questions?

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NUGENIA TA2 Nuclear Generation II&III Alliance

SNETP Sustainable Nuclear Energy Technology Platform

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Wilks One-Sided	$\beta = 1 - \alpha^N$
Wilks Two-Side (Interval)	$\beta = 1 - \alpha^N - (N-1)(1-\alpha)\alpha^{N-1}$

Table 1: Minimum sample size required for $(100 \times P)/(100(1-\alpha))$ Wilks tolerance limits and bounds. Results are shown for four common predication/confidence combinations for ranks from 1 to 10.

r	95%/95%		95%/99%		99%/95%		99%/99%	
	Bound	Interval	Bound	Interval	Bound	Interval	Bound	Interval
1	59	93	90	130	299	473	459	662
2	93	153	130	198	473	773	662	1001
3	124	208	165	259	628	1049	838	1307
4	153	260	198	316	773	1312	1001	1596
5	181	311	229	371	913	1568	1157	1874
6	208	361	259	425	1049	1818	1307	2144
7	234	410	288	478	1182	2064	1453	2409
8	260	458	316	529	1312	2306	1596	2669
9	286	506	344	580	1441	2546	1736	2925
10	311	554	371	631	1568	2784	1874	3179

Porter, 2019. Wilks' formula applied to computational tools: A practical discussion and verification. Annals of Nuclear Energy.