# UaSA Application in Severe Accidents: Challenges & Path Forward

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# OUTLINE

- Background
- The MUSA Outcomes
- What’s next
- INNOMUSA

# The Drivers

**Severe Accidents are the major contributors to NPP risk!**

**The “safety case” heavily relies on simulations!**

**How accurate are SA simulations?**

**Priorities for further research?**

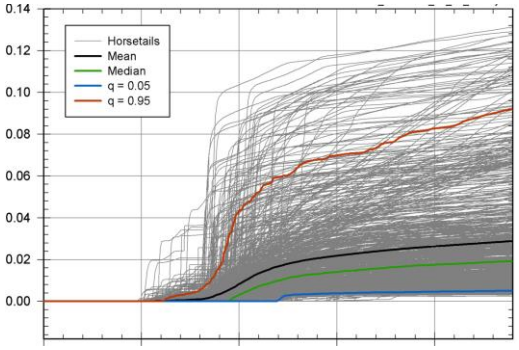
# Not the first, BUT ...

- **BEPU** was born in **Thermal-hydraulics** (USNRC: 1974-1986).
- **BEPU** was "passed to & taken forward" by OECD/CSNI.

  (NEA/CSNI/R(1994)20; NEA/CSNI/R(97)35; NEA/CSNI R(97)4; …)
- **BEPU** has since been under development.

  BEMUSE(2004-2010); PREMIUM(2012-2015); SAPIUM (2017-2019); ATRIUM ( 2021-)

- Pioneering work brought **BEPU into SA** (Khatib-Rahbar et al., 1989).
- And … updated 15 years later (Gauntt et al., 2005).
- Ending up in the SOARCA Study (NUREG-2254; 2022)



# The Right Timing

**SA codes "maturity"**
(phenomena; integration; numerics)

**Computational resources!**

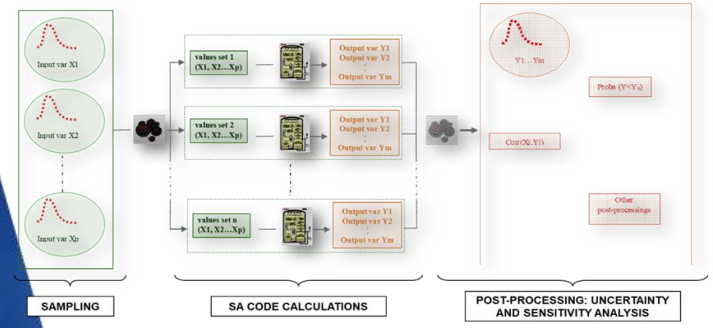
**Predictive ability?**

**SA research optimization**
(C/B)

**The UaSA Age in SA Analysis**

## The EC **MUSA** Project

Background

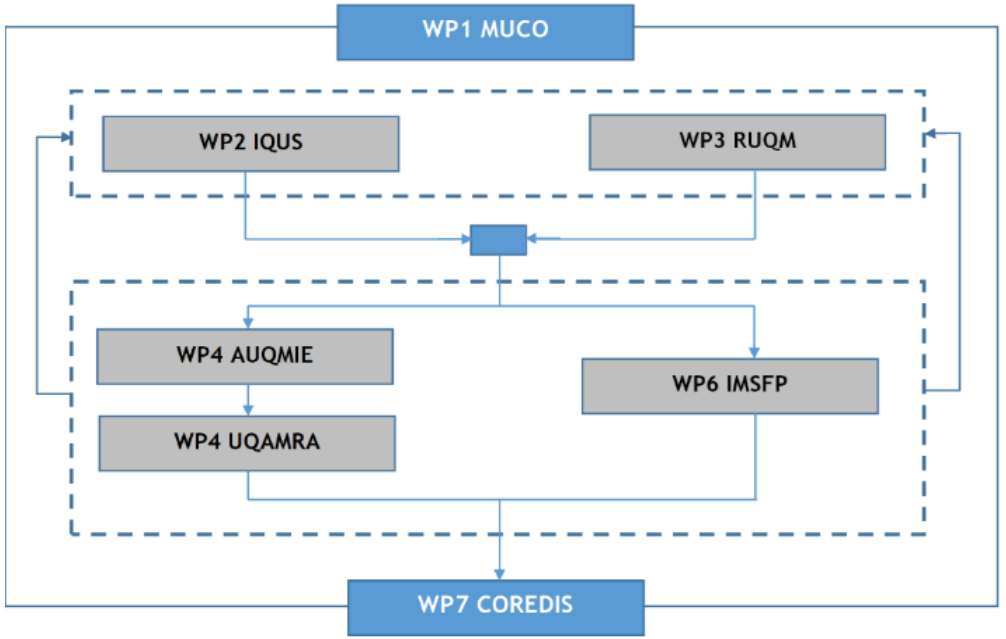



# MUSA Objectives & Structure

- Management and Uncertainties of Severe Accidents).

  H2020 GA nº 847441 (625 p-m); 2019-2023.

- **Aim:** To quantify uncertainties in SA codes' predictions (AM!) (FOM: Source Term).



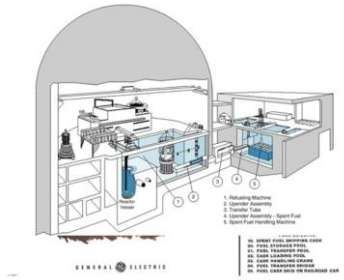

(Gen. II & III; SFPs)

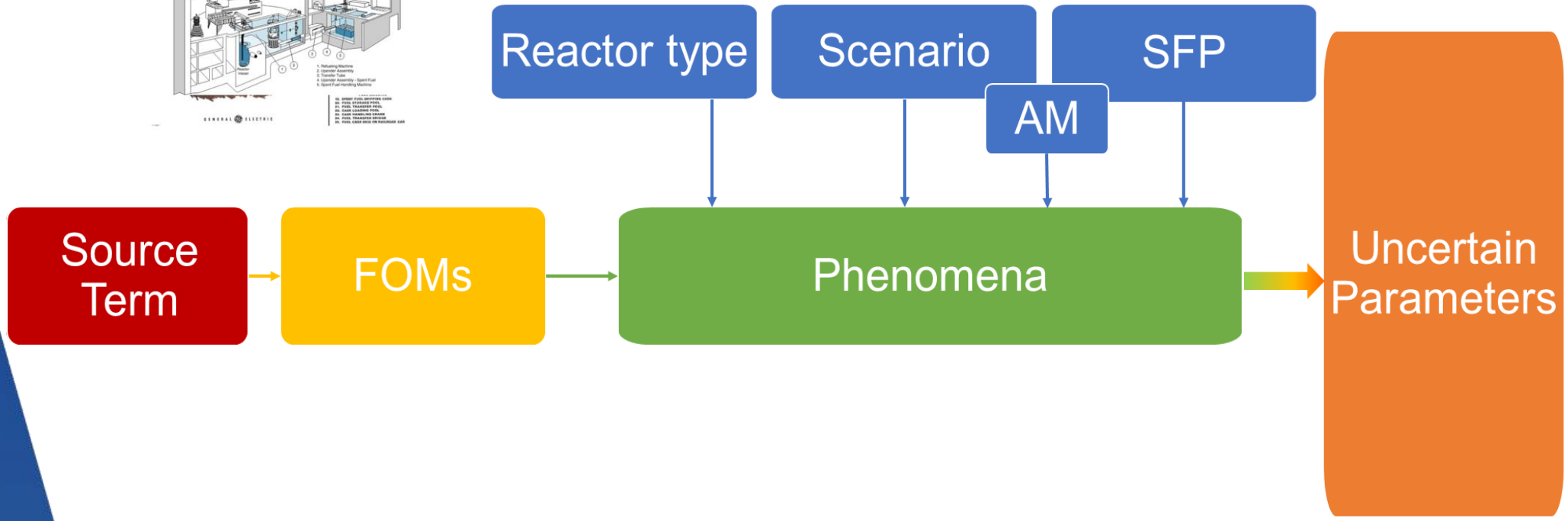
# Major «tangible» achievements

- An extensive **UP* database!**
- A vastly diverse & tested range of **methods & tools!**
- A large variety of reactor & scenarios **UQ database!**
- A “first-of-a-kind” **UQ SFP application!**
- A “still growing” dossier of **open references & more!**

* Uncertain Parameter

# The UP Database





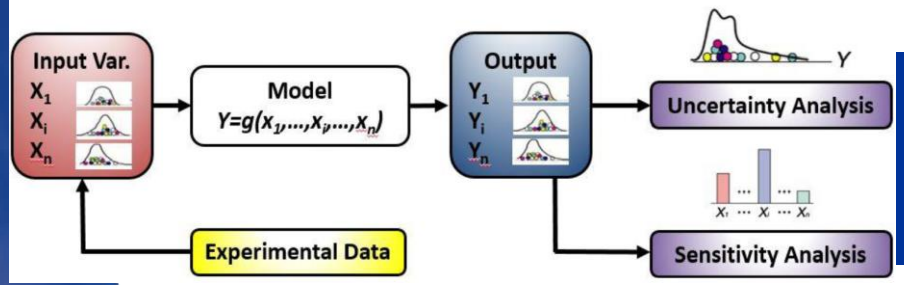

- **400 (+150) UP identified & characterized** (UB; LB; pdf).
- "Substantiated expert judgement".

# The UP Database: Characterization

| 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] | | | 0,00002 | 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) | | | 1,28 | Triangular | 1990 D. J. Rader. "Momentum slip correction factor for small particles in nine common gases"; MELCOR Default; Expert judgment (pdf) |

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

# Methods & Tools




| 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 |
|---|---|
| SUNSET | ASTEC2.2b |
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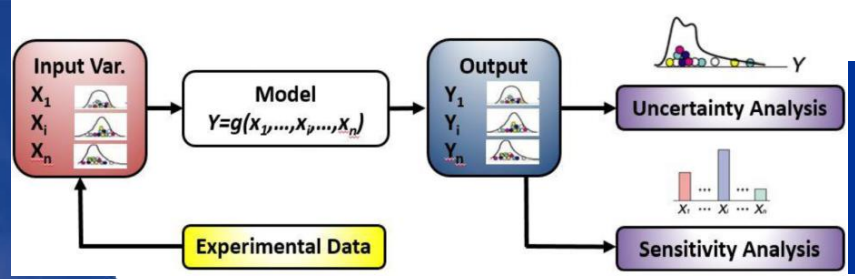
| UQ Tool | SA Code |
|---|---|
| SUSA4.2 | $AC^2$ |
| SUSA4.0 | MELCOR2.2 |
| SUSA4.2 | RELAP/SCDAP |

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

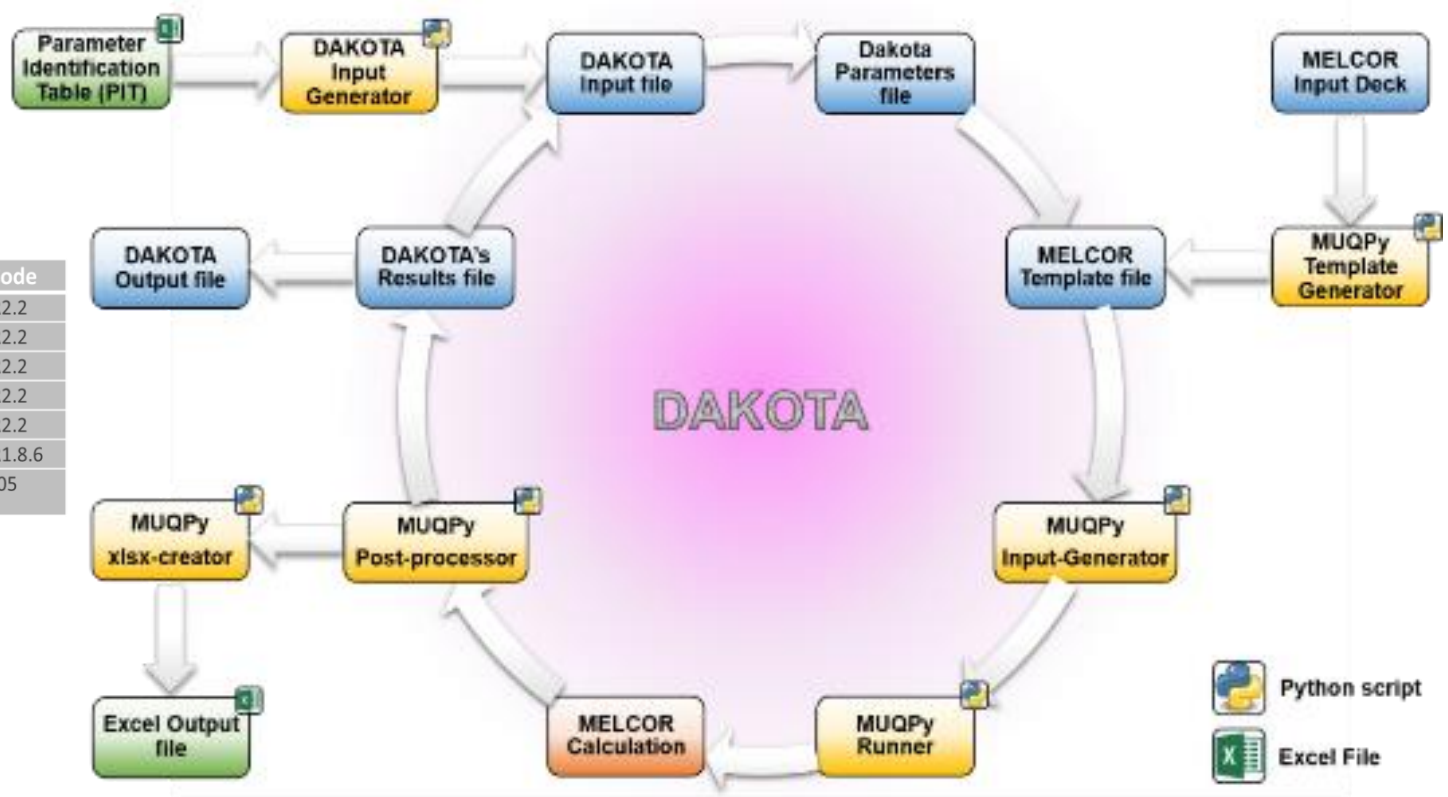
| UQ Tool | SA Code |
|---|---|
| RAVEN | MELCOR2.2 |
| URANIE | ASTEC2.1 |

- **Diversity in codes and tools** (strength/weakness).
- **Convergence in key choices … to come!**




# Methods & Tools

# Propagation of Uncertainties

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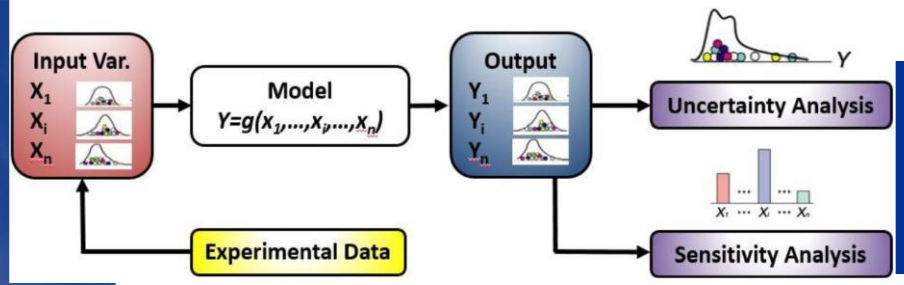
## Automatization!



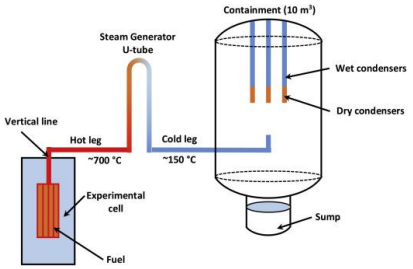



# Generation of Samples

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

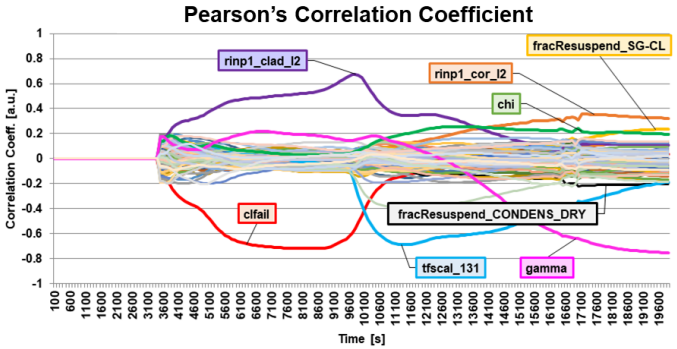
- **Sampling** SRS (random)
  LH (Latin Hypercube)

The MUSA Outcomes



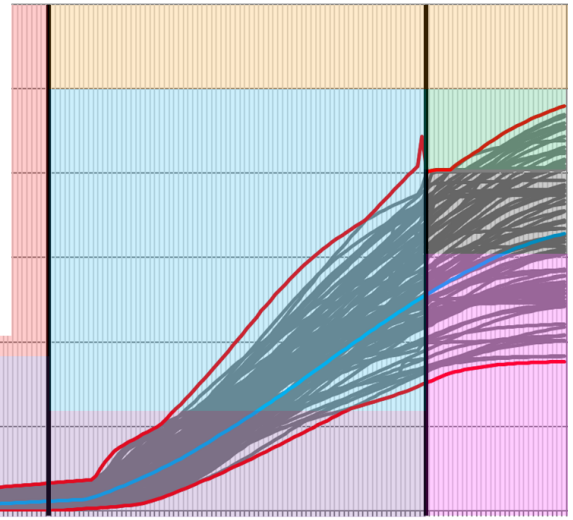

# The Coupling & Training

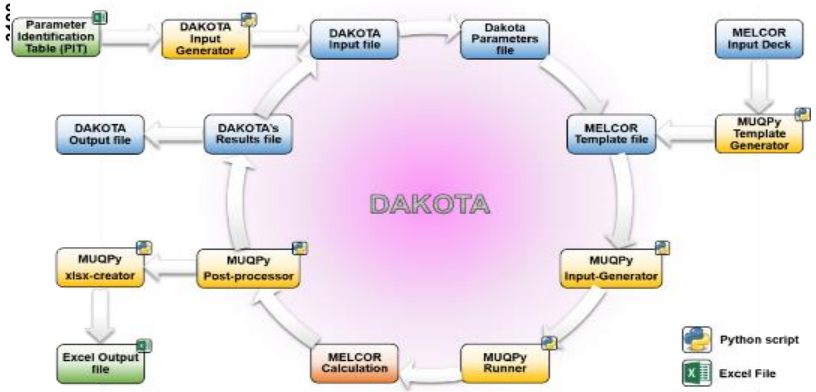
## PHEBUS-FPT1 modeling




- Initial $I_2$ mass in gap
- Initial $I_2$ mass in fuel
- Cladding Failure Temperature
- $ZrO_2$ Thermal Conductivity
- Aerosol Dynamic Shape Factor
- Aerosol Agglomeration Factor
- Aerosol Resuspension Fraction

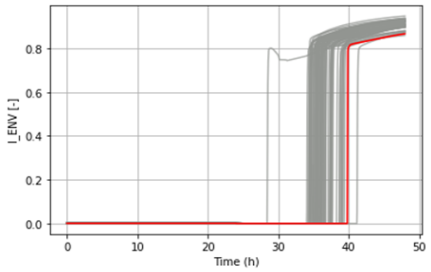
Iodine Aerosol in Containment

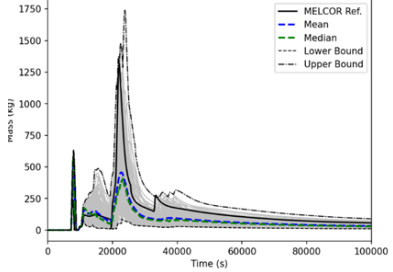





(Bocanegra & Herranz, 2022)

The MUSA Outcomes

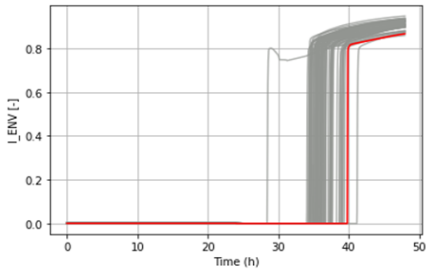


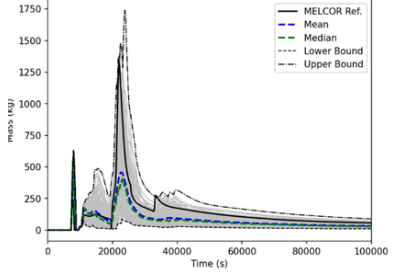




# In-Reactor Applications

| # | Partner | NPP | Scenario(s) | SAM |
|---|---|---|---|---|
| 1 | BelV | **PWR-1000** | **LBLOCA** | |
| 2 | CIEMAT/UNIPI | **PWR (Surry)** | **SBO** | |
| 3 | CNPRI | **HPR-1000** | **LBLOCA** | |
| 4 | ENEA | **PWR-900** | **SBO** | |
| 5 | ENSO | **PWR 4-Loops** | **LT-SBO** at Low P | |
| 6 | EPRI | **PWR (Surry)** | **ELAP** w/o SAM<br>**ELAP**+SAM | **AC restored at RPV failure** |
| 7 | GRS | **KONVOI** | **MBLOCA+SBO** | |
| 8 | IRSN | **PWR-900** | **SBO**+Loss of aux. FW | **Sump flooding, CFVS** |
| 9 | KAERI | **APR-1400** | C-SGTR by **SBO** | |
| 10 | KIT/Framatome | **KONVOI** | **MBLOCA** w/o SAM<br>**MBLOCA+SBO**<br>**MBLOCA**+SAM | **CFVS** |
| 11 | PSI | **PWR-1100** | **SBO**+SGTR | **SG re-flooding** |
| 12 | SNERDI | **CAP-1400** | **LOCA+SBO** | |
| 13 | TRACTEBEL | **PWR-1000** | **SBO** | **Cavity flooding+CFVS** |

The MUSA Outcomes



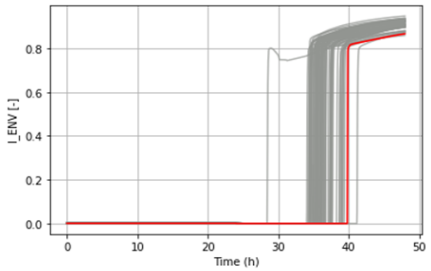

# In-Reactor Applications

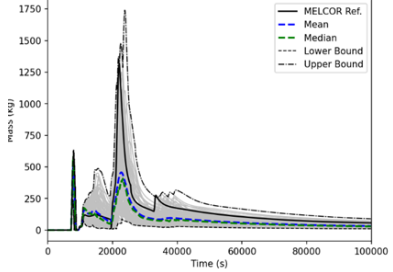
| # | Partner | NP |
|---|---|---|
| 1 | BelV | PWR- |
| 2 | CIEMAT/UNIPI | PWR ( |
| 3 | CNPRI | HPR- |
| 4 | ENEA | PWR |
| 5 | ENSO | PWR 4- |
| 6 | EPRI | PWR ( |
| 7 | GRS | KON |
| 8 | IRSN | PWR |
| 9 | KAERI | APR- |
| 10 | KIT/Framatome | KON |
| 11 | PSI | PWR- |
| 12 | SNERDI | CAP-1400 |
| 13 | TRACTEBEL | PWR-1000 |

| # | SA Code | U&S Tool | #UPs | #FoM | #Calcs. for UQ |
|---|---|---|---|---|---|
| 1 | MELCOR | URANIE | | | |
| 2 | MELCOR | DAKOTA | 24 | 3 | 93 |
| 3 | ASTEC | SUNSET | 5 | 8 | 100 |
| 4 | MELCOR | DAKOTA | 8 | 1 | 130 |
| 5 | RELAP/SCDAP | IUA2.0 | 19 | 26 | 124 |
| 6 | MAAP | Python | 232 | 12 | 500 |
| 7 | AC2 | SUSA | 81 | 10 | 100 |
| 8 | ASTEC | SUNSET, Python | 43 | 12 | 100 |
| 9 | MELCOR | DAKOTA | 6 | 4 | 300 |
| 10 | ASTEC | KATUSA | 18 | 6 | 900 (300*3) |
| 11 | MELCOR | DAKOTA, Python | 17 | 2 | 100 |
| 12 | MAAP | DAKOTA | | | |
| 13 | MELCOR | Python | 15 | 6 | 111 |

| | | |
|---|---|---|
| LOCA+SBO | | |
| SBO | | Cavity flooding+CFVS |

Outcomes




# In-Reactor Applications

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| 3 | CNPRI | HPR- |
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| 5 | ENSO | PWR 4- |
| 10 | KIT/Framatome | KON |
| 11 | PSI | PWR- |
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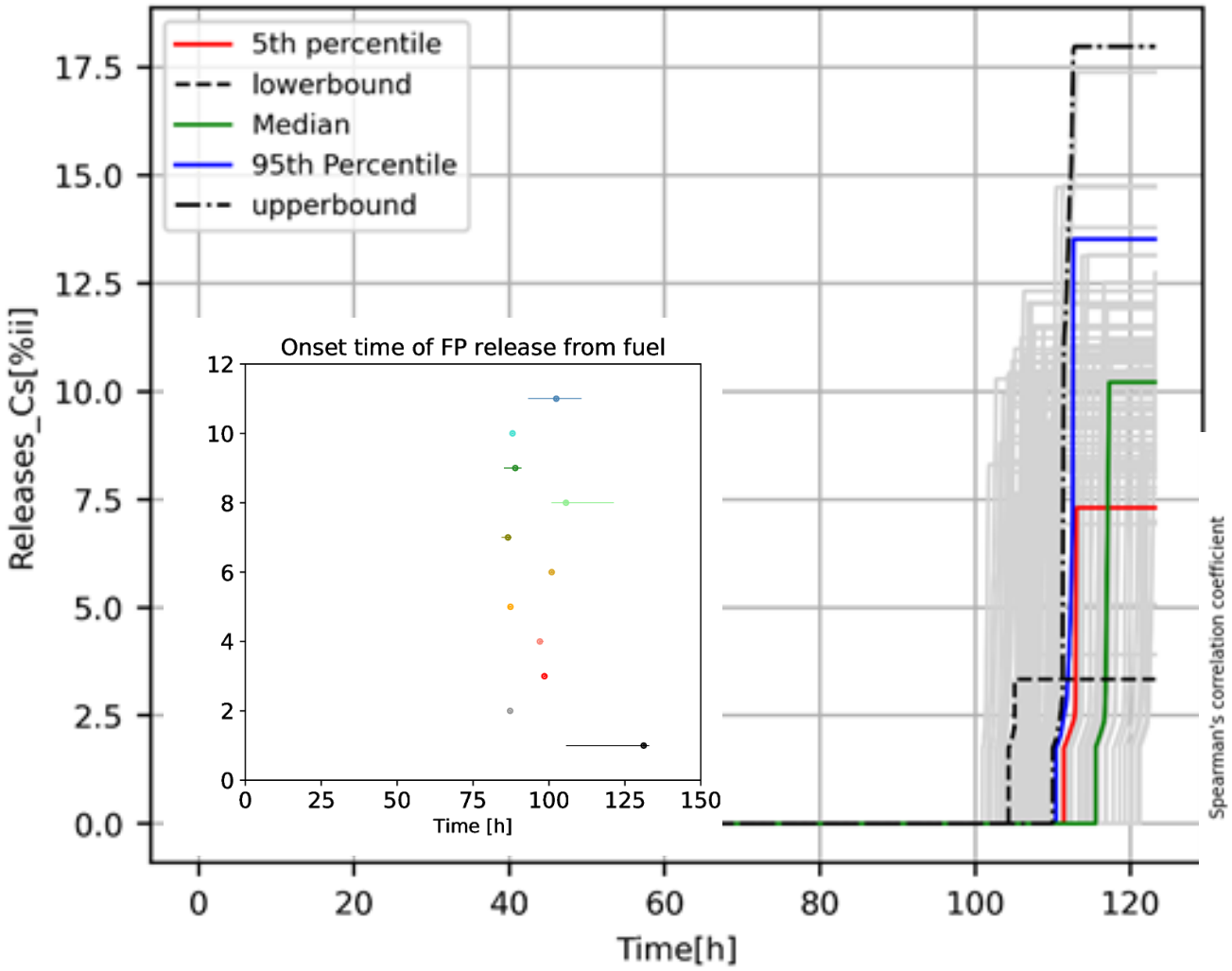
| 13 | MELCOR | Python | 15 | 6 | 111 |

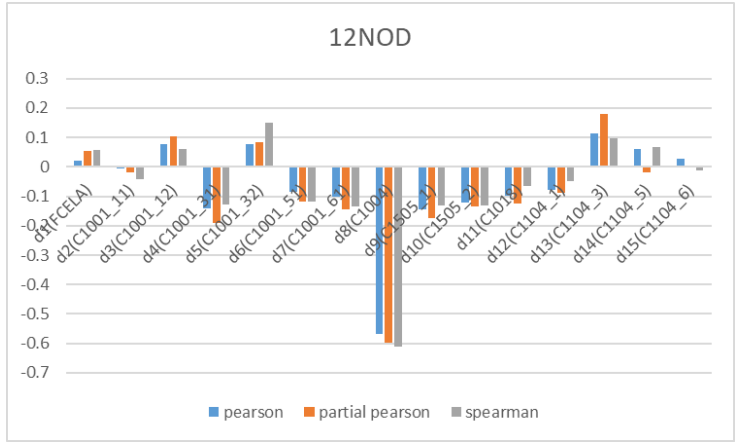
- **DB in technology/scenarios/UQ approaches/ …** (strength/weakness)**.**
- **Preliminary insights into AMgmt.**
- **Cross-comparison might “substantiate” some options!**

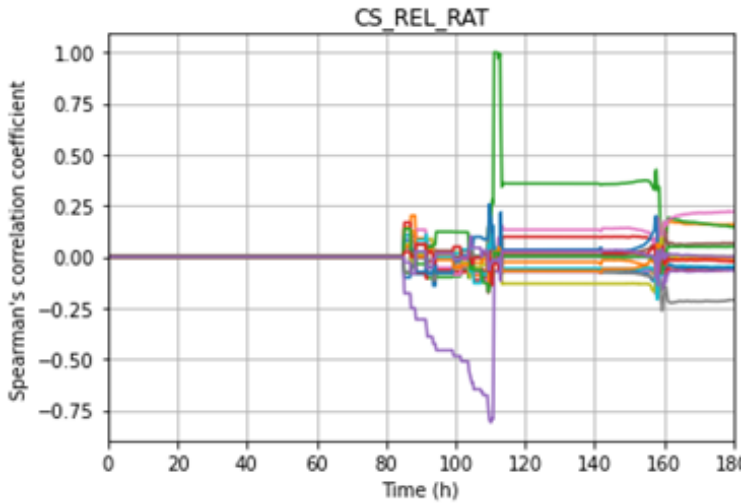
| | | | | |
|---|---|---|---|---|
| 12 | SNERDI | CAP-1400 | LOCA+SBO | |
| 13 | TRACTEBEL | PWR-1000 | SBO | Cavity flooding+CFVS |

The MUSA Outcomes

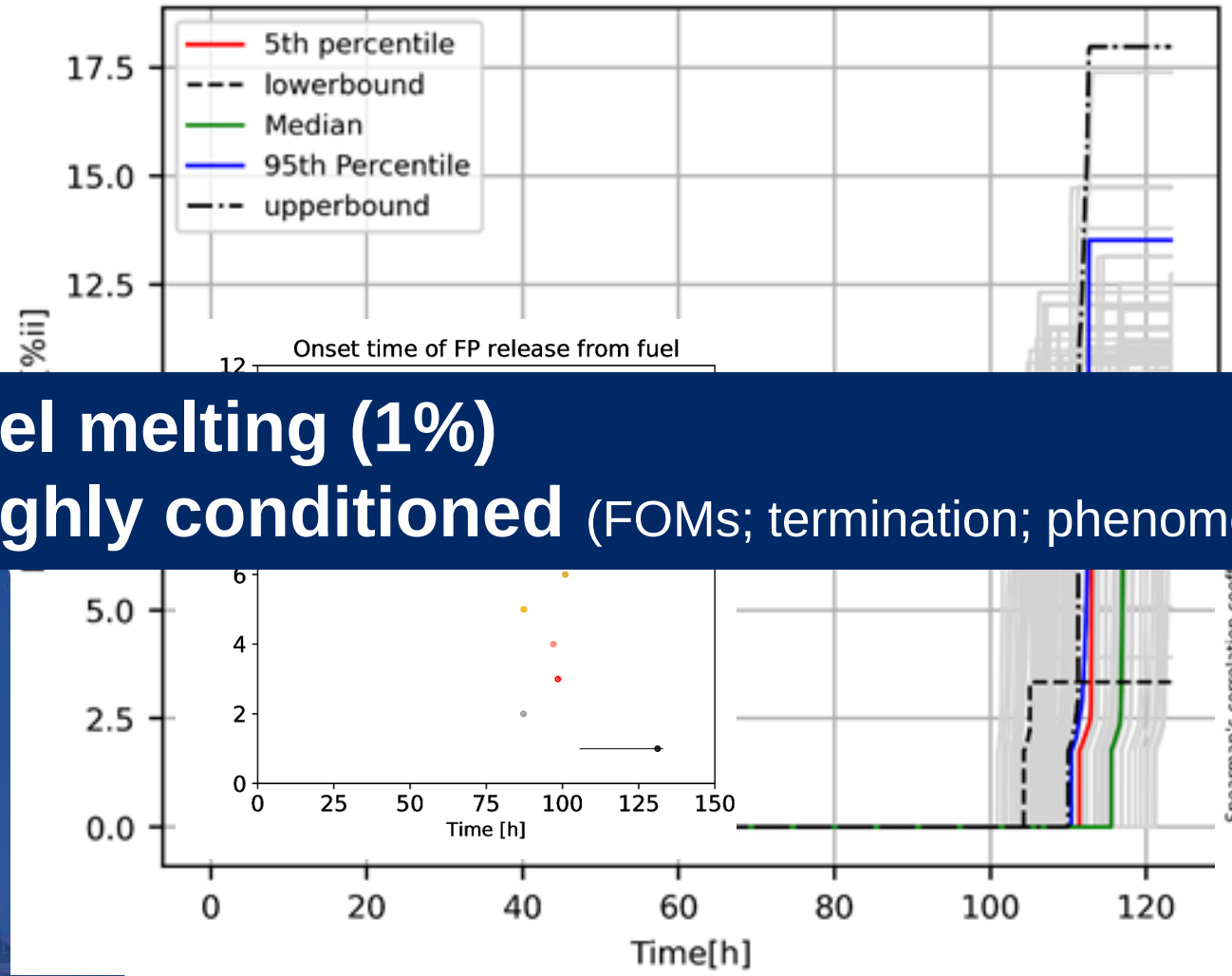
# In-SFP Applications

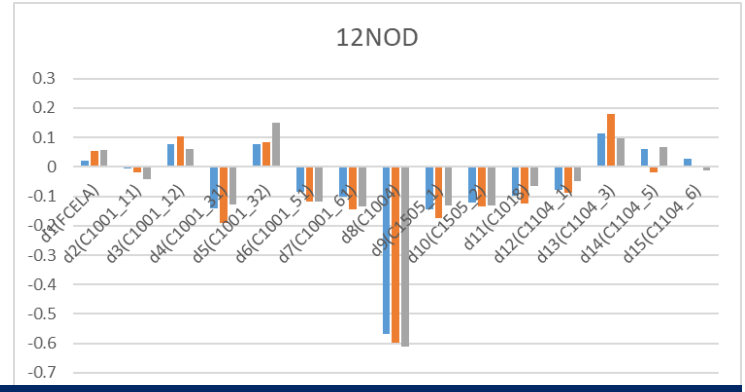


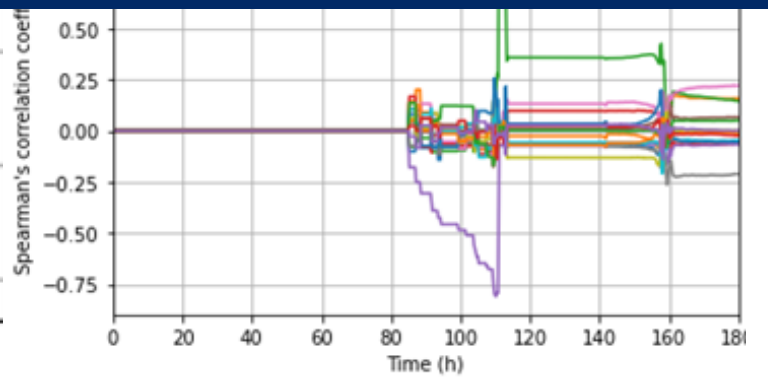



# In-SFP Applications



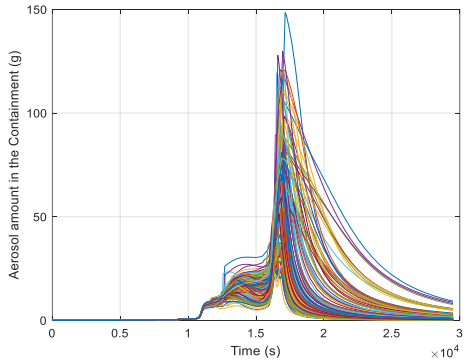



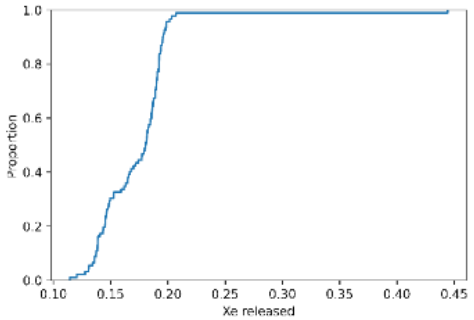

- **Onset of fuel melting (1%)**
- **Specific, highly conditioned** (FOMs; termination; phenomena; BCs; codes; …) scenario.

# Evaluation of Uncertainties

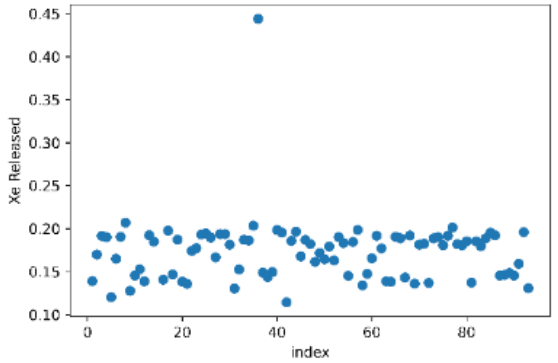
- **Dispersion plots**




- **CDF; PDF**




- **Scatter plots**



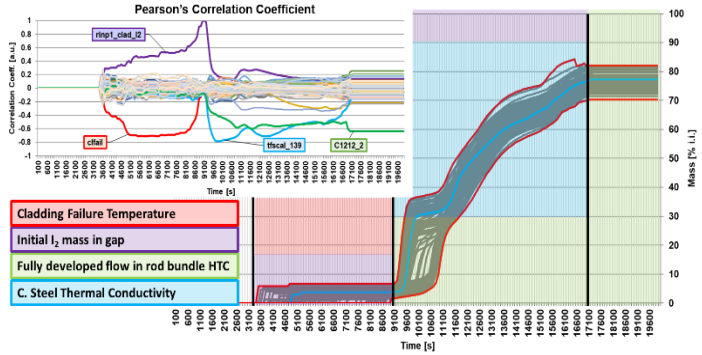

- **Descriptive statistics**

| 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 |

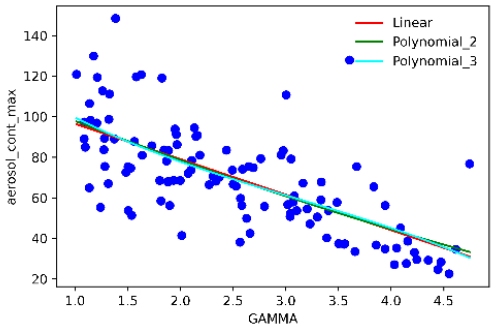
- ...

# Analysis of Sensitivity

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




- **Simple regressions**




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

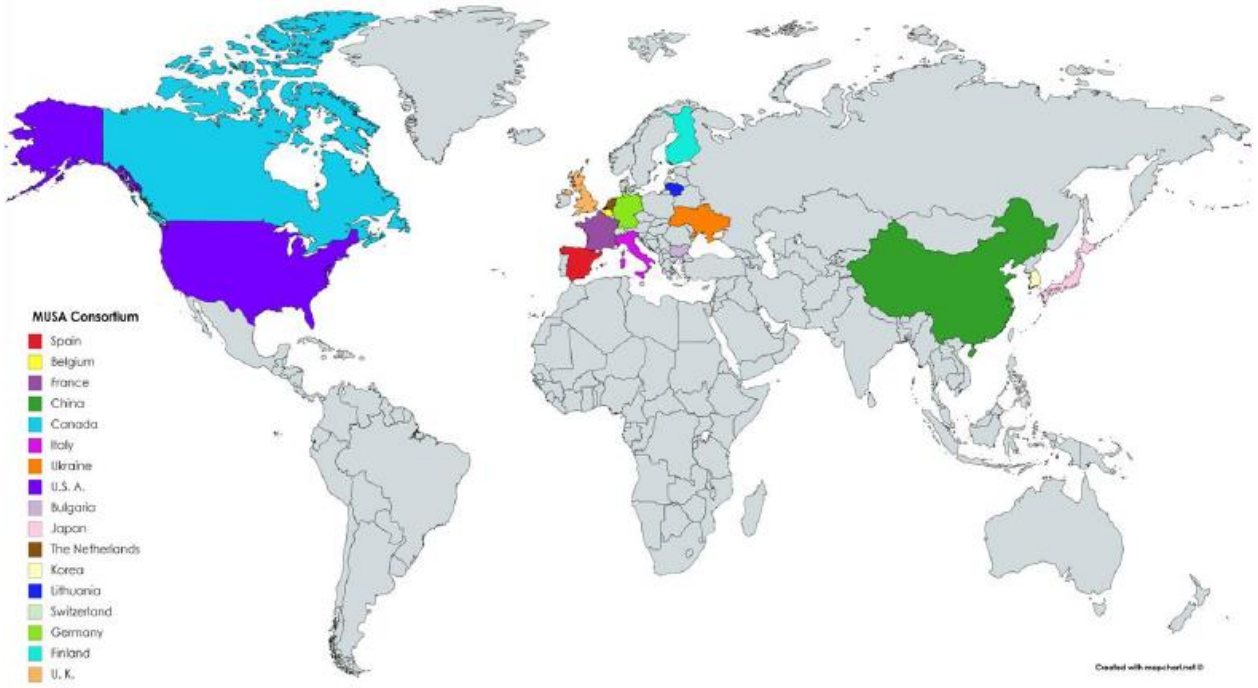
# Major «intangible» achievements

- A journey from an uneven to **an "even" community:**

  "Diffusion driven by expertise & knowledge forward/backward gradients".

- **A "large grown" community** in an "unexplored world"

  "Team work" proved to be resourceful when working out of the comfort zone.



What's Next

# Challenges Ahead

- **The UP database optimization** (filling; extension; restrc.).
- **A systematic 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-SMRs)

# Remaining Issues

## UP Database

- Id. & charac.
- AM-related
- Equip.-related
- Restrct.

## Systematic UaSA

- FoM
- Parameters
- Code crashes
- Bifurcations
- Outliers
- Data analysis
- Noise
- Phasing
- Nodalization

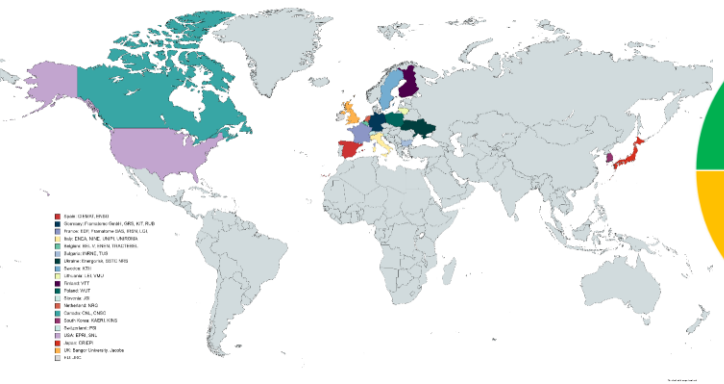
## Extensive Application

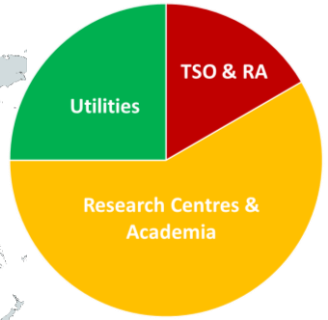
- G. II & III
- WC-SMRs

# INNOMUSA: General Goals

- To **exploit the achievements made in MUSA.**
- To **consolidate a systematic methodology.**
- To **focus on AM*:** Effect of U on AM & Effect of AM on U.
- To **address innovation Ntech.:** NT-ATFs; WC-SMR

*** Decision making efficiency and effectiveness**






# INNOMUSA: Working Structure

& (UNIPI)

Dissemination

## METHOD
(KIT; GRS)

- Uncertainty DB
  (approach?; qualification; extensión; …)
- UA Approach
  (MC, Wilks, others, …;
  FOMs; parameters;
  bifurcations; outliers; bias; crashes; …)
- Data analysis (SA)
  (“Best suite”; physical consistency; …)
- Noding/ Phasing / Noise / Nmrcs

EDUCATION & TRAINING
(ENEN)

## APPLON
(ENEA; INRNE)

- Water-cooled reactors
  (Gen-II & Gen-III; AMgmt)
- WC-SMRs
  (Av. Designs; SASPAM)
- Near-term ATFs (shc)

Communication

# Thank you for your attention!