Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

EMUG

APPLICATION OF THE REPAS METHODOLOGY TO ANALYZE THE RELIABILITY OF THE EHRS IN THE DECAY HEAT REMOVAL STRATEGY FOR AN SMR

16th Meeting of the European MELCOR and MACCS User Group

07 – 11 April, Brno

Speaker: Gianmarco Grippo

Contributors: Lorenzo Tempesta, Erik Cilia, Marcello Savini, Fulvio Mascari

Introduction

Integral Severe Accident (SA) codes, such as ASTEC and MELCOR are widely used to simulate the **behavior of NPPs in transient conditions** allowing to characterize **the thermal-hydraulic and the possible degradation phenomena**.

Investigate the **applicability of these codes to LWSMRs** designs due to their **envisaged deployment** and the **consequent licensing** needs

iPWRs are ready to be licensed as new builds

LWR technology
- Operational plant experience
- Feedback

\+ *Design modifications* to increase the inherent *safety of the plant*

Introduction

The "**safety by design**" concept must **not** be used to **justify the absence of SA management** features.

All the five levels of DiD are applied to SMR design

Reinforcement of the level 1 and 2

Implementation of specific design features

Reinforcement of the level 3 and 4

Demonstration of the safety systems effectiveness implemented to mitigate PIE and SA sequences

Reinforcement of the level 5

The mitigation of radiological consequences must be considered even if the previous levels are strengthened

Natural Circulation

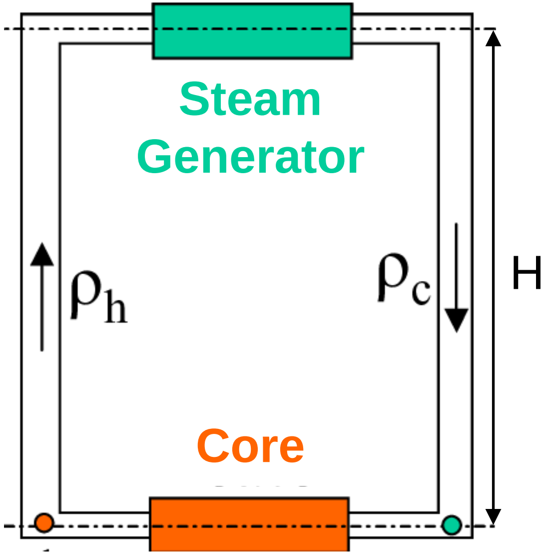
*Reference: **IAEA-TECDOC-1677***

The **complex set of physical phenomena** that occur in a **gravity environment when geometrically distinct heat sink** and **heat source are connected by a fluid flow path** can be identified as **Natural Circulation**. **No external sources** of mechanical energy for the fluid motion are **involved.**

Heat source located at lower elevation with respect to the **heat sink**

$$\dot{m}^2 = \frac{2g\rho(\rho_h - \rho_c)H}{R_h}$$

- **Difference in densities** between the vertical legs ($\rho_h < \rho_c$) in the presence of a body force
- **Pressure difference** created between stations which is the cause of the flow.
- At steady state the driving buoyancy force is balanced by the retarding frictional force



It is the basis of all the Passive Safety Systems design

Passive Safety Systems

*Reference: **IAEA-TECDOC-1624***

Either a system which is composed entirely of **passive components** and **structures** or a **system which uses active components in a very limited way** to initiate subsequent passive operation.

4 categories were established to distinguish the different degrees of passivity

A B C D

ADVANTAGES

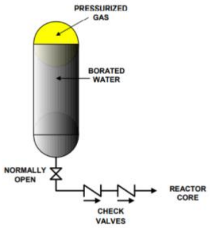
- Simpler design;
- In principle higher reliability;
- Operation without external power supply;
- Operation without operator intervention;
- Reduced cost and the easier maintenance.

CHALLENGES

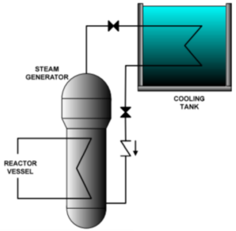
- Lower driving force;
- More complex safety evaluation;
- Reduction of operator intervention;
- Possible presence of instabilities;
- Functional failure without mechanical failure;

For core decay heat removal

Accumulator

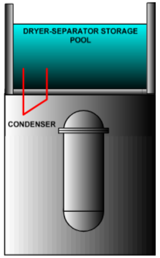


DHR using a passively cooled SG

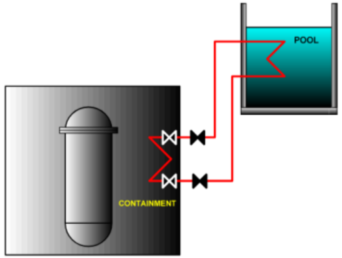


For containment cooling and suppression

Condensation on condenser tubes



External natural circulation loop



Passive Safety Systems

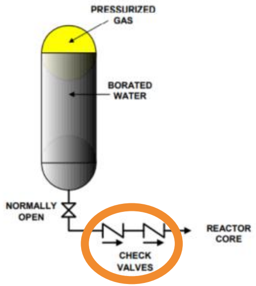
Several passive systems necessitate active initiation or involve the movement of mechanical components (e.g **check and relief valves**)

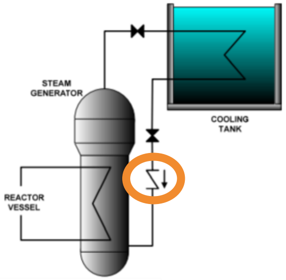
Not complete reliability:

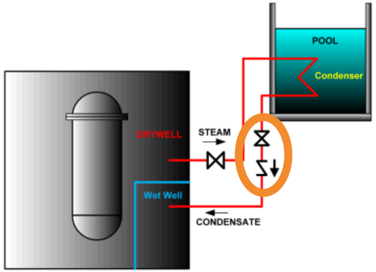
- In the system actuation itself;
- For natural circulation phenomena driving the safety functions.

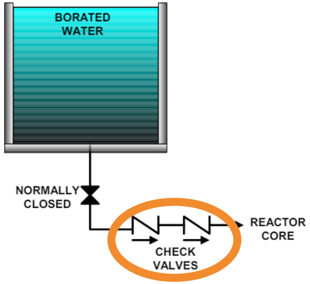
Possible failures, or deviations from the working conditions during transient and design specifications may occur;

Analysis of the T/H phenomena that may occur in the PSS by using BE T/H system codes is **necessary** to assess the performance;



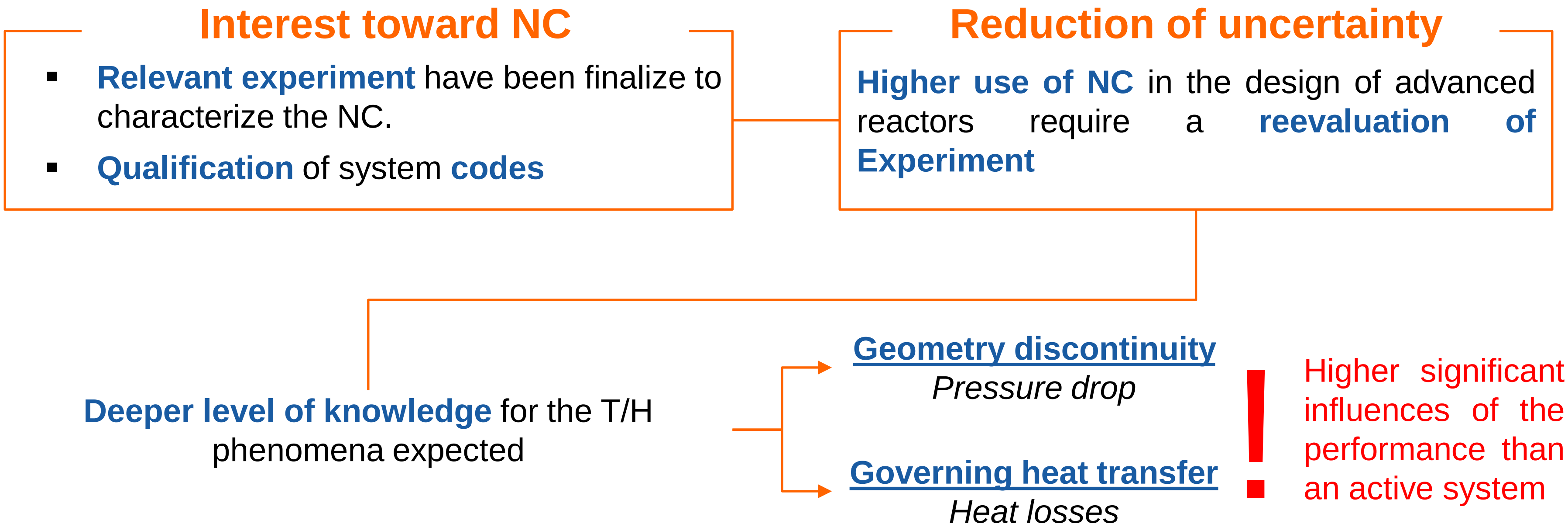






Problems?

The usage of **NC mechanisms to increase the safety level** and **reducing the cost** of the plants **requires** a **deep knowledge** of these **types of mechanism**.



Interest toward NC

- **Relevant experiment** have been finalize to characterize the NC.
- **Qualification** of system **codes**

Reduction of uncertainty

Higher use of NC in the design of advanced reactors require a **reevaluation of Experiment**

Deeper level of knowledge for the T/H phenomena expected

Geometry discontinuity
Pressure drop

Governing heat transfer
Heat losses

!

Higher significant influences of the performance than an active system

PSA and reliability assessment of PSS

Including failure modes and **reliability** estimates of passive components for all systems is recommended **in PSA study**

This methodology is valuable to **provide insight on the plant safety.**

⚠ **Limitation**

The analysis generally considers **only failed** or **fully functioning states**, ignoring intermediate state.

A **passive system's status** is **divided** into **multiple states**

The **reliability assessment of PSS**, defined as the probability of performing the required mission to achieve the intended safety function, became an **essential step**.

PSA and reliability assessment of PSS

The number of uncertainty impacting the operation of T-H passive system significantly influences the process of reliability evaluation within a PSA framework.

- Deviation in Natural circulation forces
- Changes in initial and boundary conditions
- T-H factors

Potentially causing the functional failure of PSS

Aleatory Uncertainty

Random and stochastic phenomena

Geometrical properties: Discrepancies between actual layout and the used design in the analysis;
Material Properties: estimation of failure mode, undetected leaks and heat loss;
Design parameters: initial and boundary conditions

Epistemic Uncertainty

Confidence on PSA prediction and model accuracy

Phenomenological analysis:

- Definition of system failure
- Simplified models employed
- Choosen analysis methods
- Focus on specific fail location
- Selection of parameters that influence the performance.

REPAS history

Mid – 90s Activity aimed at the evaluation of the reliability of passive systems

Bilateral contract between CEA and ENEA

Begin – 00s Propose of a methodology called Reliability Evaluation of Passive Safety Systems (REPAS)

Cooperation between ENEA, University of PISA and Polytechnic of Milan

2001 - 2004 Reliability methods for passive safety functions project

- *Identification and quantification of the sources of uncertainties;*
- *Propagation of the uncertainties through a T-H model and reliability assessment;*
- *Introduction of passive system unreliability in the accident sequence analysis;*

2004 - 2024 Several application of repas

- Application of REPAS to analyze the sump clogging issue following a LOCA and its impact on the reliability of the ECCS long-term core cooling function

2024 - 2028 EASI – SMR Project

- *Work on adapting reliability assessment methodologies for passive systems will enable us to characterize the reliability of passive systems for safety studies*

REPAS method

The general objective of REPAS is **to characterize in an analytical way the performance of a passive system.**

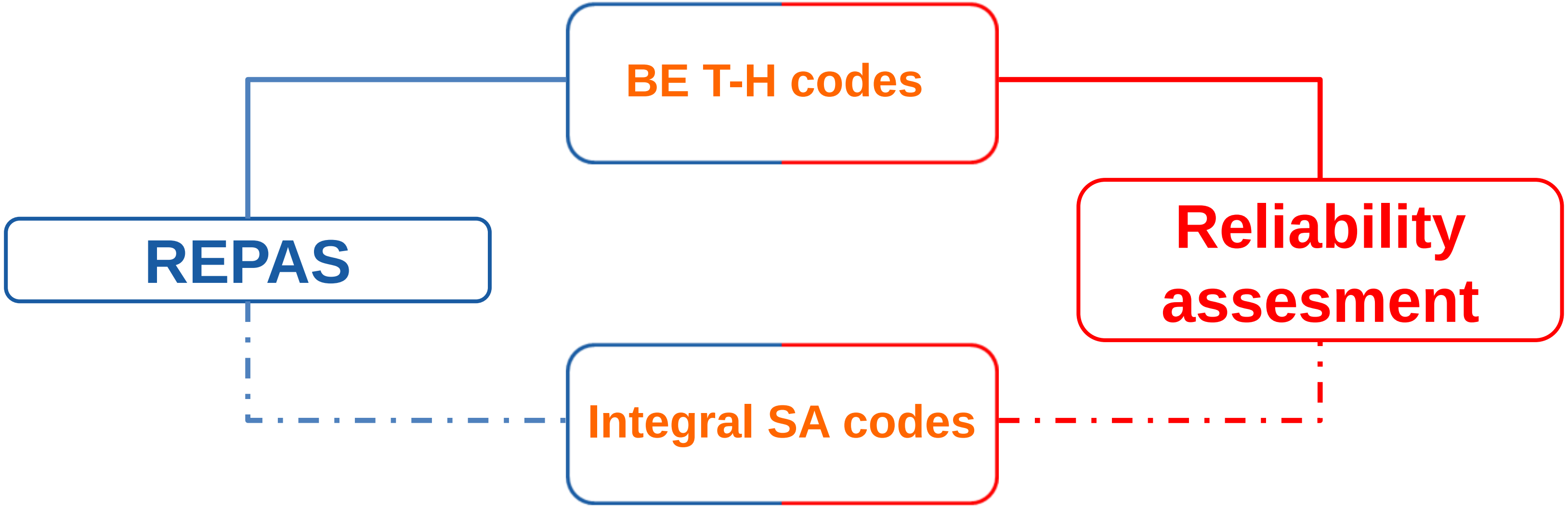
- To increase the **confidence** toward its operation
- To compare **performances** of active and passive systems and performances of different passive systems, moreover the methodology is in setting up process for **absolute reliability evaluation**

The methodology provides **numerical values** that can be used in more complex safety assessment study and can be seen as the equivalent of the ‘Fault-Tree’ analysis (as a support for a PSA study)

Introduction to the activity

AIM OF THE ACTIVITY

Application of the Reliability Evaluation of Passive Safety Systems (**REPAS**) **methodology to assess the reliability of** the passive Emergency Heat Removal System (**EHRS**) in a **LW-SMR design type reactor**.



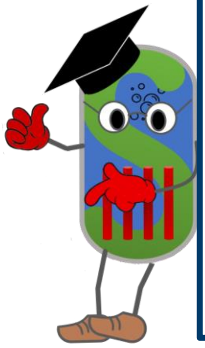
BE T-H codes

REPAS

Reliability assesment

Integral SA codes

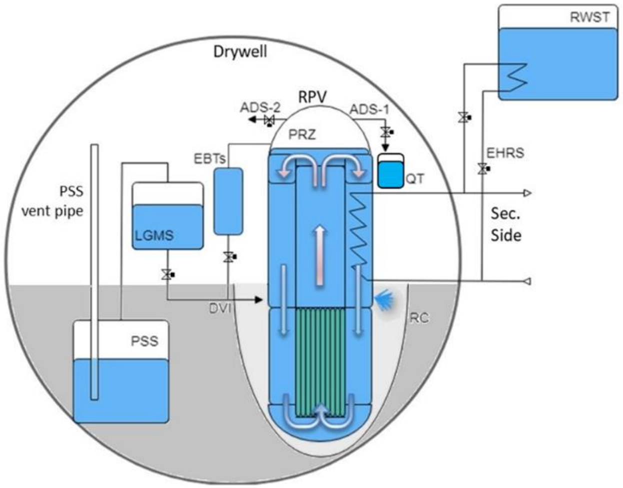
Introduction to the activity



The input deck used for the present work has been developed in the framework of **SASPAM-SA project**. It is coordinated by ENEA and 23 organization from 14 countries are involved.

Funded by the
European Union

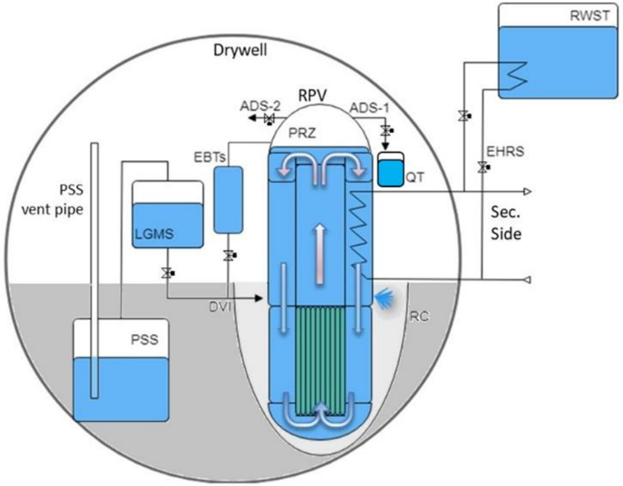
Design 2 – General view



The iPWR Design-2 is characterized by the use of several passive systems and by a dry containment.

- The reactor operates in **forced circulation during normal operation** and employs a **passive mitigation strategy in accidental transients**.
- It consists of an **integral RPV**, which contains the core, a compact SG, the Control Rod Drive Mechanism (CRDM), the primary pumps and the **pressurizer included in the upper head**.
- The hot water at the core outlet **flows upward in a circular riser up** to the primary pumps suction.
- Above the riser, a perforated plate separates the riser from the PRZ, which is enclosed in the RPV upper head.

Design 2 – Nodalization information



- In order to develop the **MELCOR input-deck**, a **reference database** was needed.

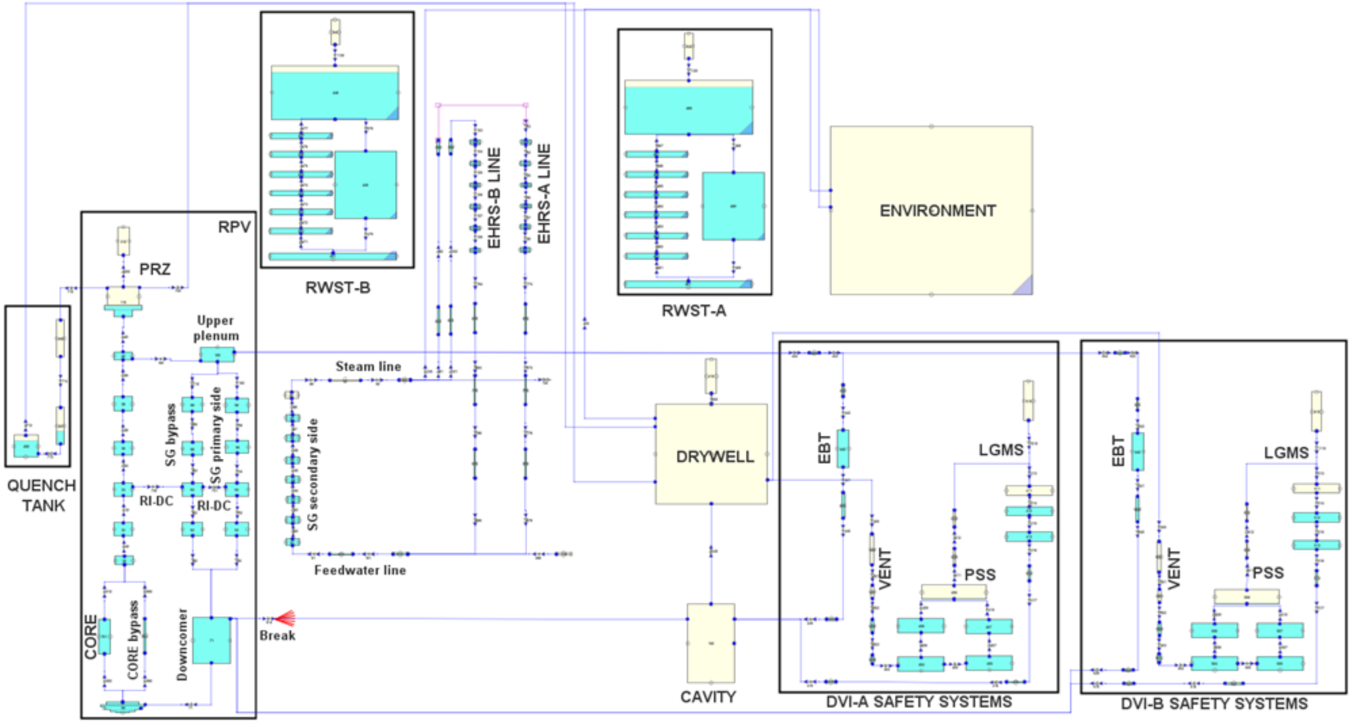
- Considering the **characteristics of Design 2 reactor type** and the selected passive systems, a **generic IRIS SMR type has been considered as reference** for this analysis.

- During the **development of the MELCOR nodalization of the generic IRIS design, no proprietary data have been used.**

- The **main geometric information** has been determined by **scaling the data available from the SPES-3 facility**, by **engineering evaluation** or **public general data available** for the IRIS reactor.

MELCOR input deck

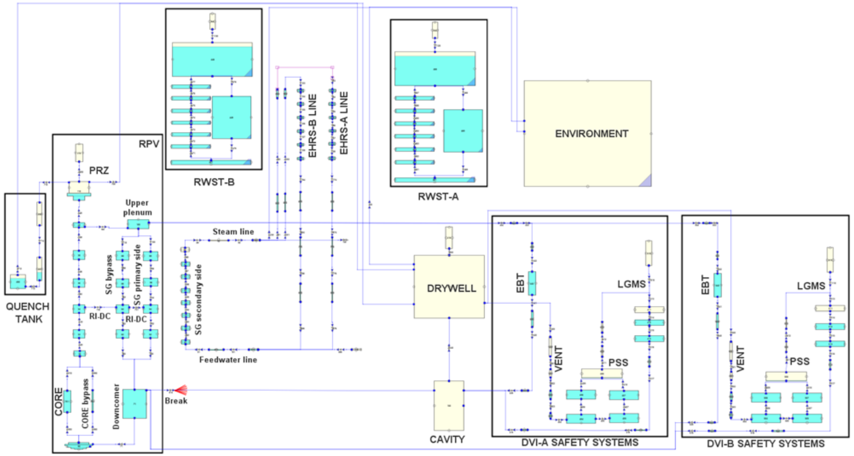
Symbolic Nuclear Analysis Package (SNAP) to develop the **nodalization** and for the **post processing** of data by using its animation model capabilities



MELCOR input deck

CVH and FL packages have been used for modeling all the RPV hydraulic regions:

- LP,
- Core,
- Core bypass,
- Riser,
- UP,
- SGs
- Downcomer



The **two passive systems lines** have been **modelled separately**

The **SGs** (8 line) have been **modelled** as an **equivalent one**.

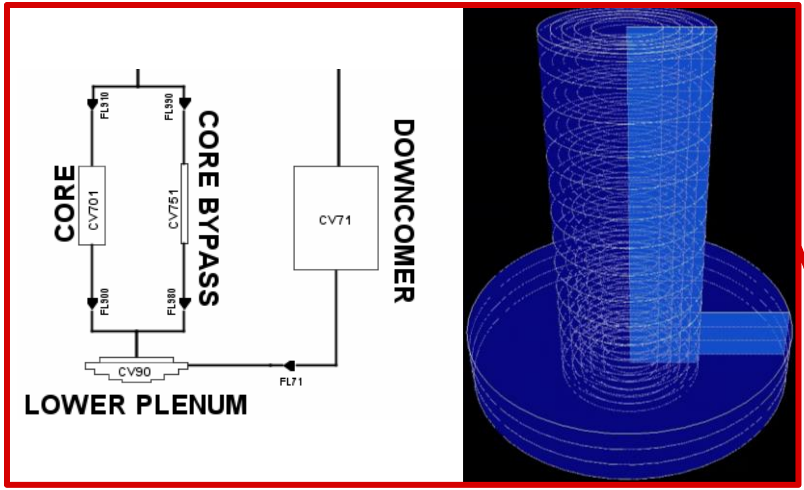
The **EHRS** (4 line) and the **RWST** (2 pool) have been **modelled** as an **equivalent two**.

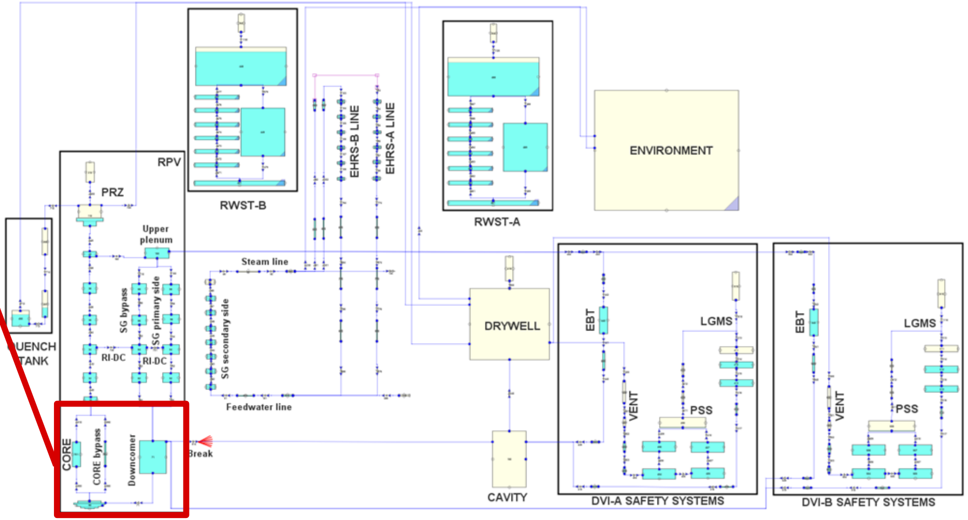
The **reactor core**, the **core bypass** and the **downcomer** has been modelled by a **single hydraulic CVH CV**

The **containment region** has been modelled with one **CVH volume of the RC**, coupled with the correspondent **CAV package**, and with **one CVH volume for the DW region**, **thermally coupled** with the **environment** CVH volume

HS package have been used, **coupled with the CVH** package, to **model the heat transfer** between the CVH Control Volumes

MELCOR input deck





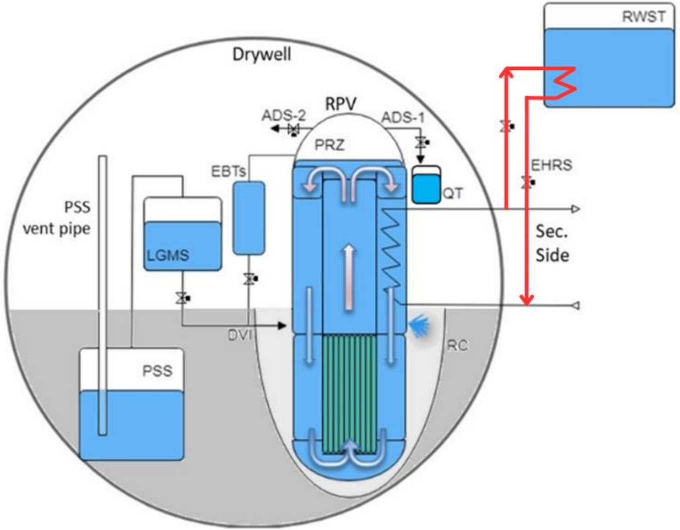
- **2D cylindrical** axial-symmetric **geometry** of the **COR package**;
- A **detailed nodalization** has been chosen for the COR package with respect to the CVH one;
- **16 axial** levels and **6** concentric **rings**;
- The **LP** is made of **one single CVH CV**, which extends to the core supporting plate;

REPAS – 1° Step

Characterization of operating modes

Point out the mission

Removing decay heat through condensation in HXs → RWST

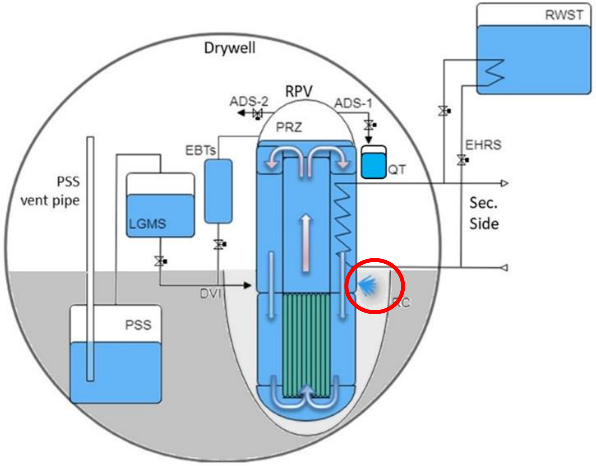


REPAS – 2° Step

Selected scenario for reference calculation

DBA

Guillotine break of one Direct Vessel Injection (DVI) line, considering the availability of all safety systems.



BREAK OF DVI LINE

High Containment Pressure signal
- SCRAM
- Secondary system isolation
- EHRS actuation

Low PRZ level signal
- RCP coastdown
- RI-DC valves opening

Low PRZ pressure signal
- EBTs actuation
- ADS stage-1 actuation

Low DP RPV-Containment signal
- LGMSs actuation

Low LGMS mass signal
- ADS stage-2 actuation

REPAS – 2° Step

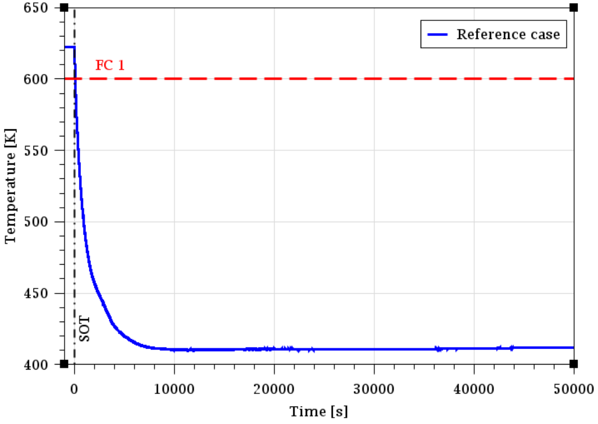
Failure Criteria definition

The **reference calculation** is conducted to establish the FC.

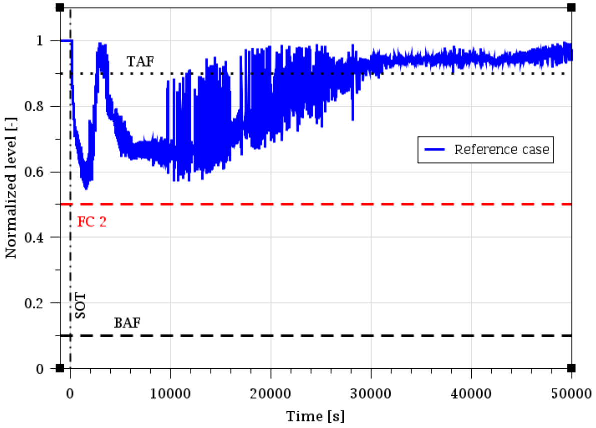
- Each parameter is set to his nominal value;
- 50,000 seconds of transient analysis have been carried out.

FC 1	*Cladding temperature > 600K*
FC 2	*Collapsed level < ½ of the active core*
FC 3	*Power removed < 70MW*

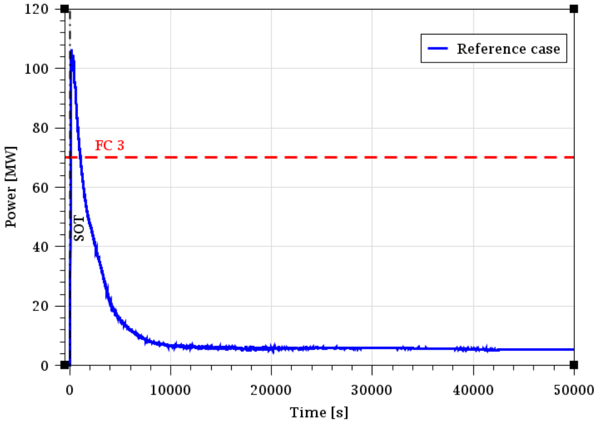
Cladding temperature



Core level



EHRS power



REPAS – 2° Step

Failure Criteria definition

The mission of the passive system or component under consideration must be duly considered in the process of defining failure criteria.

🟦 Reference Calculation

🟥 Failure Criteria

Maximum Cladding temperature	
$T_{Clad} \approx 400K$	*Cladding temperature > 600K*

Core collapsed level	
Core level above the TAF	*Collapsed level < ½ of the active core*

Power removed	
Initial power removed ≈ 100MW	*Power removed < 70MW*

REPAS – 3° Step

Impact parameter definition

The Key parameter that could impact the passive system's operation have been identified and selected.

Loss coefficient

Surface roughness

Valve opening ratio

Increasing of pressure loss

- Impact the NC efficiency;
- Enancing the friction and turbolence disrupting flow;
- Influencing flow resistance;

Pool initial level

Non-condensable fraction

Influence of heat losses

- Influence of EHRS's HTC;
- Thermal capacity of the heat sink;

! **Important**

Parameters and Ranges were determined throught expert judgement.

The considered **probability value** given to the parameter are based on **engineering judgement** and the **distribution is discrete**.

REPAS – 3° Step

Impact parameter definition

Parameter	Nominal Value	Parameter range	Comments
Loss coefficient	0.6	0.6 – 1.2	▪ 1.2 = extreme case with a low probability of occurrence. ▪ Maximum probability assigned to the nominal value.
Surface roughness	5.0E-05	4.75E-5 – 5.25E-5	Due to the Gaussian distribution, the nominal value is assigned the highest probability, while values further from the nominal receive progressively lower probabilities.
Valve opening ratio	100%	0 – 100 %	▪ Nominal value and thus the maximum probability. ▪ Lower limit has been given the lowest probability.
Non-condensable fraction	0.1667	0 – 0.1667 m	▪ 0.1667 m = absence of non-condensable. ▪ 0 m = presence of 100 % of non-condensable at the inlet volume of the EHRS HX.
Pool initial level	2.0	1.25 – 2 m	▪ 2.0 m = maximum pool level, resulting in nominal value. ▪ 1.25 m = minimum pool level, resulting in HX uncover.

REPAS – 4° Step

Reference: **NUREG/IA-0532**

MELCOR – DAKOTA coupling

DAKOTA is an open-source software developed by SNL in C++.

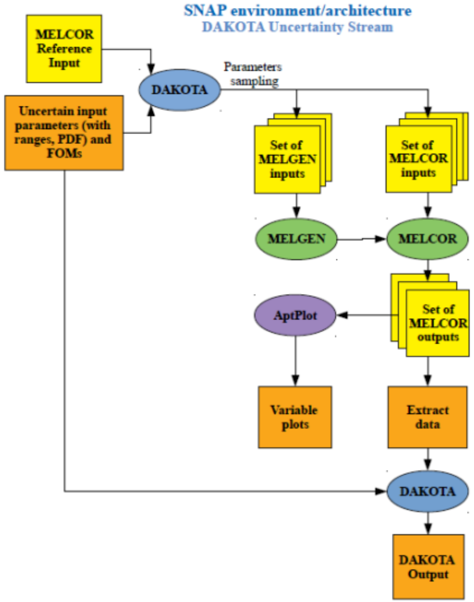
- It facilitates sensitivity analysis, optimization, parameter estimation, parametric studies, and UA;
- Available as a plug-in for SNAP, the graphical user interface designed for USNRC computer codes.

Input the uncertain parameters along with their ranges and PDFs;

Choose the sampling method, either direct Monte Carlo sampling or Latin Hypercube stratified sampling;

Specify the FOMs to be analyzed;

Generate the final report, which automatically compiles the results of the uncertainty quantification analysis upon completion.



REPAS – 4° Step

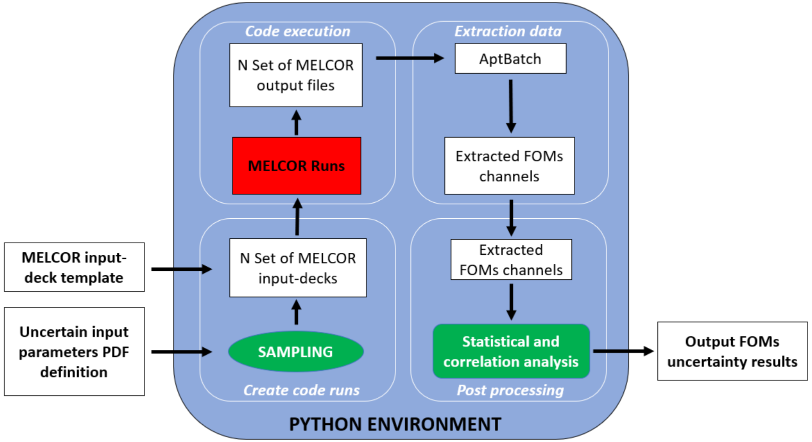
Python tool for UA

Developed and applied along the H2020 **MUSA project**, coordinated by CIEMAT.

Funded by the European Union

Full independent in-house tool developed

Development of the MELCOR/DAKOTA coupling in a Python environment/architecture



- ❑ More **flexibility than** using **external software** that **requires** to manage **several scripts to interface the UT** to the code;
- ❑ Continuous **update** and **customization** of the tool according to the **user's needs**;

REPAS – 4° Step

Probability propagation analysis

It is necessary to find the **minimum number of code runs** (transient scenarios of the system) that provide sufficient information about the overall system performance.

Wilks' formula provide the minimum number of calculations needed to characterize system performance.

1 FoM

$$1 - \alpha^N = \beta$$

More FoMs

$$\sum_{j=0}^{N-p} \frac{N!}{(N-f)!\ j!} \alpha^j (1-\alpha)^{N-j} = \beta$$

Where

- *N number of Run*
- *α desired probability*
- *β confidence level*
- *P number of FoMs*

150 Monte Carlo simulations were performed instead number of **124 required**.

24 runs not considered due to numerical failures

126 runs were conducted in the analysis

REPAS – 4° Step

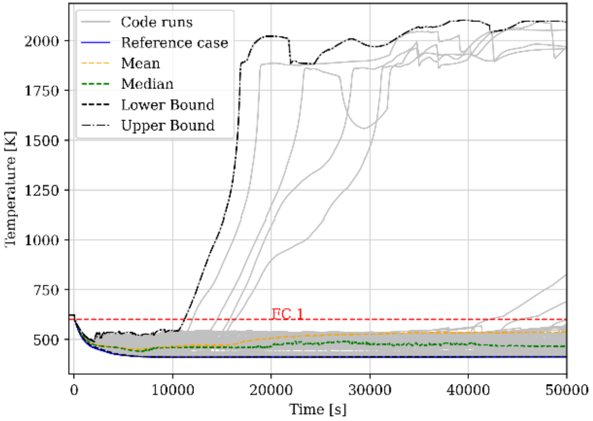
Probability propagation analysis

The reference case is not centered within the uncertainty band of probabilistic cases due to the definition of input parameters and their value ranges;

Probability distribution

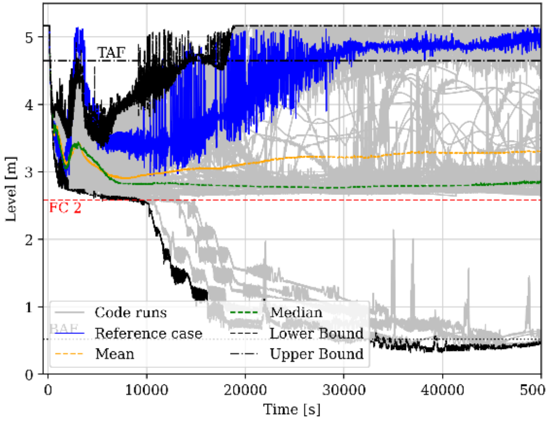
Nominal value not centered, leading to consistently worse scenarios respect the reference one.

Cladding temperature



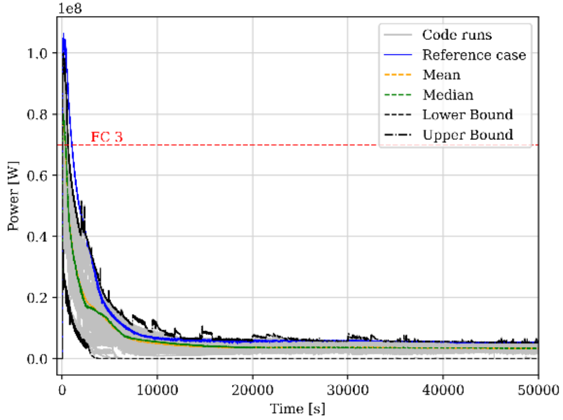
7 cases passed FC 1

Core level



5 cases passed FC 2

EHRS power

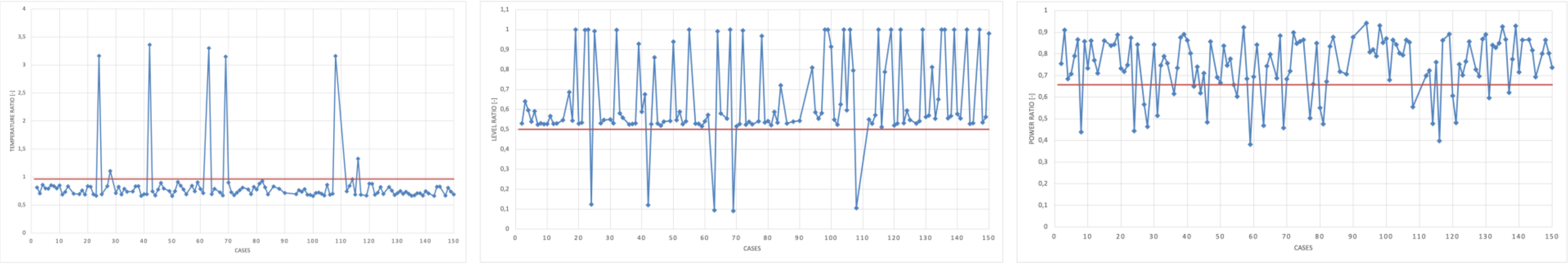


23 cases passed FC 3

Performance indicators

Facilitate the evaluation of system’s performance showing **how close** the system is to **fulfilling** its intended **mission**.

Ratio of the FoMs from each run to their corresponding nominal value



Cladding temperature

Core level

EHRS power

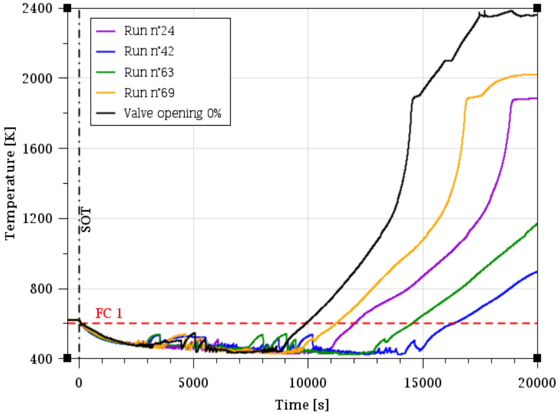
REPAS – 5° Step

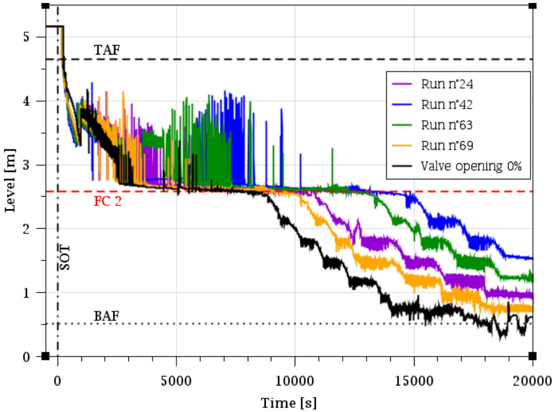
Deterministic analysis

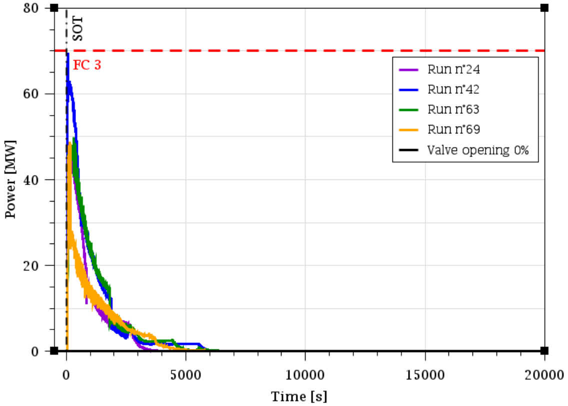
Deterministic calculation was included to address low-probability scenarios that may not be captured through probabilistic sampling.

Extreme case within the parameter's variation range

Specifically, a deterministic calculation was added to consider the case of a valve opening ratio of zero.

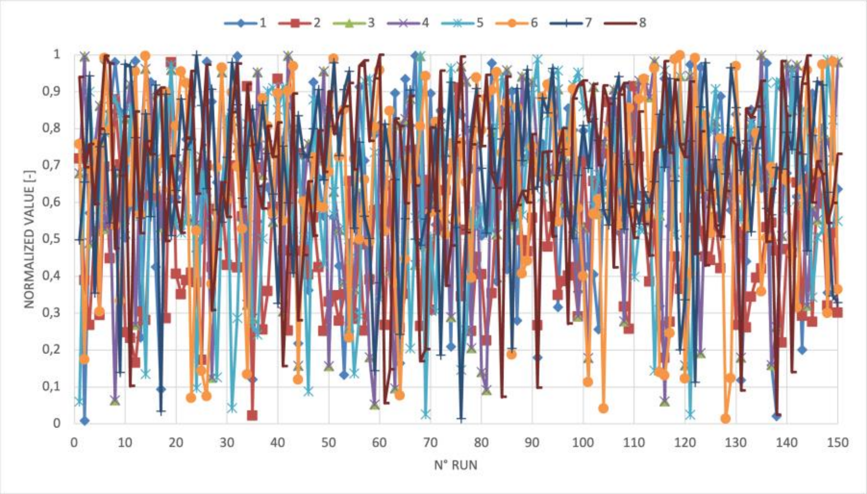






Sampling of the paramenter

- Parameter samples are depicted as points along vertical lines.
- Each set of inputs is treated as a vector, with each element representing a sample value for a specific parameter.



!

Not fully sampled across their entire range

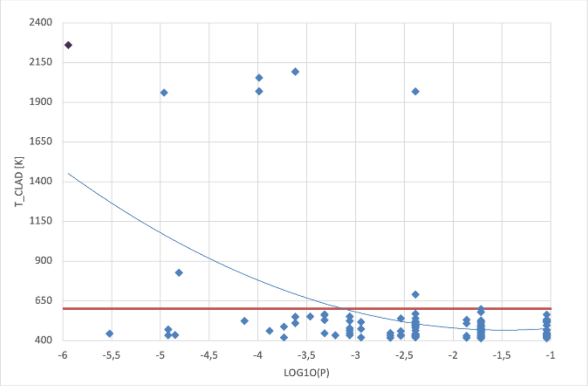
Need to generate additional deterministic cases to ensure a more comprehensive study to consider also the lowest probability regions.

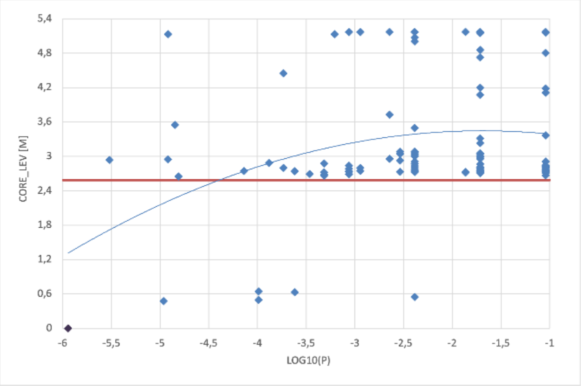
REPAS – 6° Step

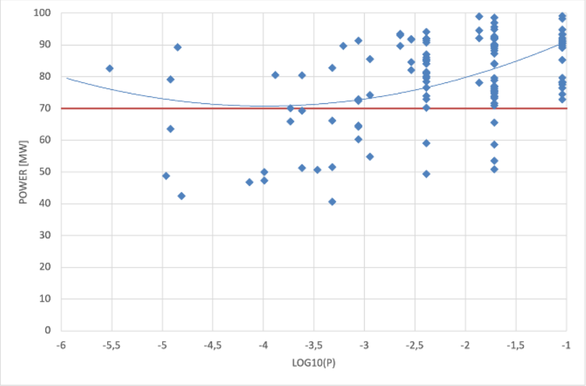
FOM as a function of the occurrence probability

Representing the FOMs following the initiation of NC inside the EHRS, respectively, as a function of their probability P of occurrence.

● Deterministic calculation ● Probabilistic calculations







Observation

Fully achieved the target mission despite having a very low probability of occurrence. The explanation comes from the parameters of loss coefficient and surface roughness.

Spearman correlation coefficient

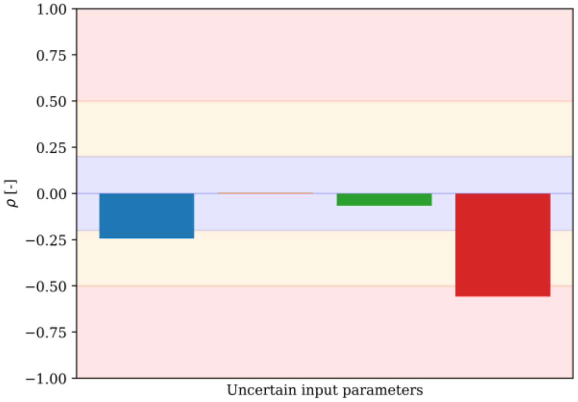
- 🟥 Significant Statistical Correlation
- 🟨 Moderate Statistical Correlation
- 🟪 Low Statistical Correlation
- 🟦 Valve_opening_ratio
- 🟧 EHRS_loss_coefficient
- 🟩 EHRS_roughness
- 🟥 NCG

EHRS roughness

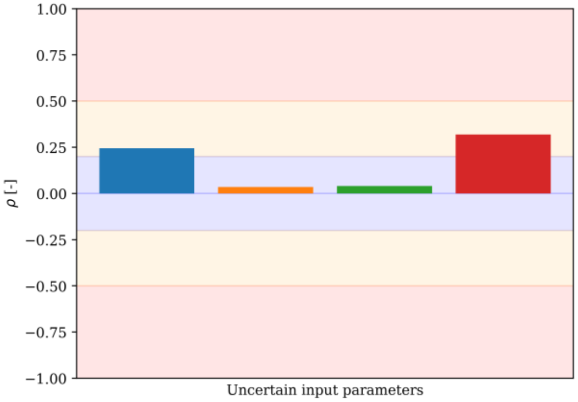
EHRS loss coefficient

→ **Low statistical correlation**

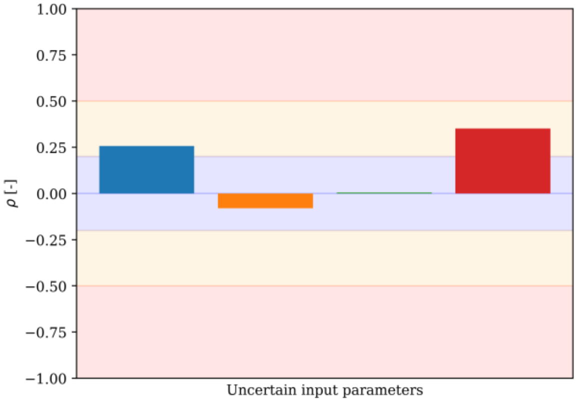
Cladding temperature



Core level



EHRS power



Effect evaluationt of parameter

Cladding temperature

High temperatures
> 520 K

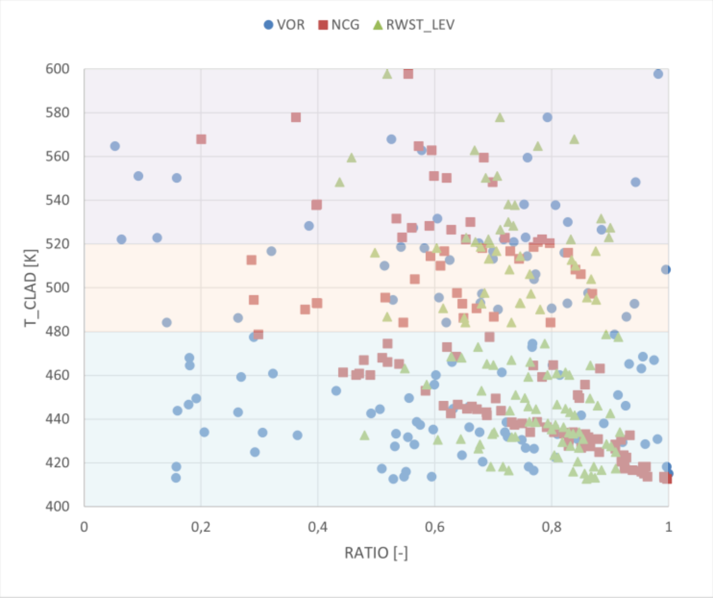
- Low valve opening ratio values
- High Presence of NCG

Moderate temperatures
480 K < T < 520 K

- 0.4 < VOR < 1.0
- NCG partially hinder heat removal
- Pool level maintain temperatures

Low temperatures
< 480 K

- 0.4 < VOR < 1.0
- Minimal NCG
- High pool levels



🟥 NGC

It is not the quantity but the pool elevation of the upper EHRS CVH volume

Effect evaluationt of parameter

Core level

High core level

> 4.0 m

- VOR > 0.6
- Near-nominal pool levels
- Minimal NCG

Moderate core level

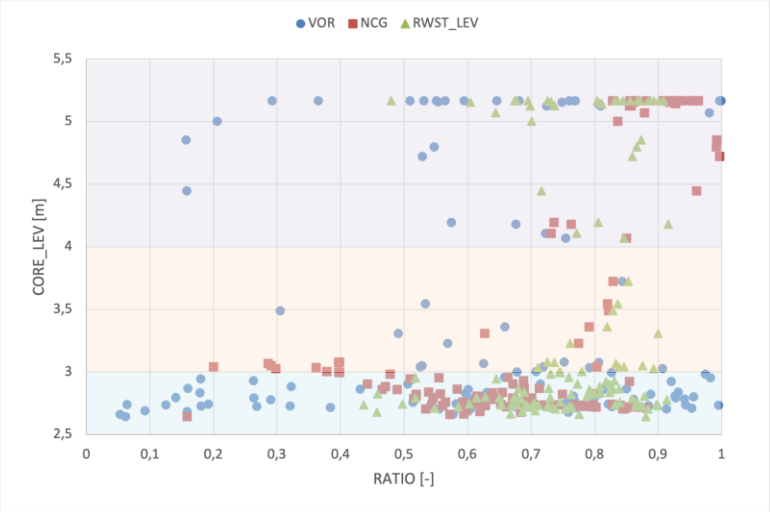
3.0 m < L < 4.0 m

- 0.4 < VOR < 0.6
- Relatively high pool level

Low core level

< 3.0 m

- VOR < 0.3
- Considerable presence of NCG
- Moderate pool levels



🟥 NGC

It is not the quantity but the pool elevation of the upper EHRS CVH volume

Effect evaluationt of parameter

EHRS power

High Power removal
> 90 MW

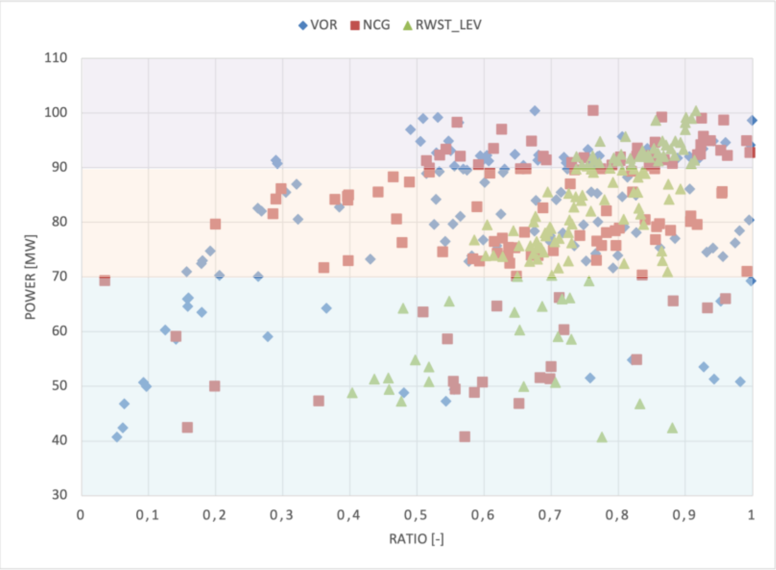
- VOR > 0.7
- NCG appear less concentrated

Moderate power removal
70 MW < P < 90 MW

- 0.4 < VOR < 0.7
- Moderate NCG
- Adequate pool level

Low power removal
< 70 MW

- Low VOR
- Hight NCG presence
- Moderate pool levels



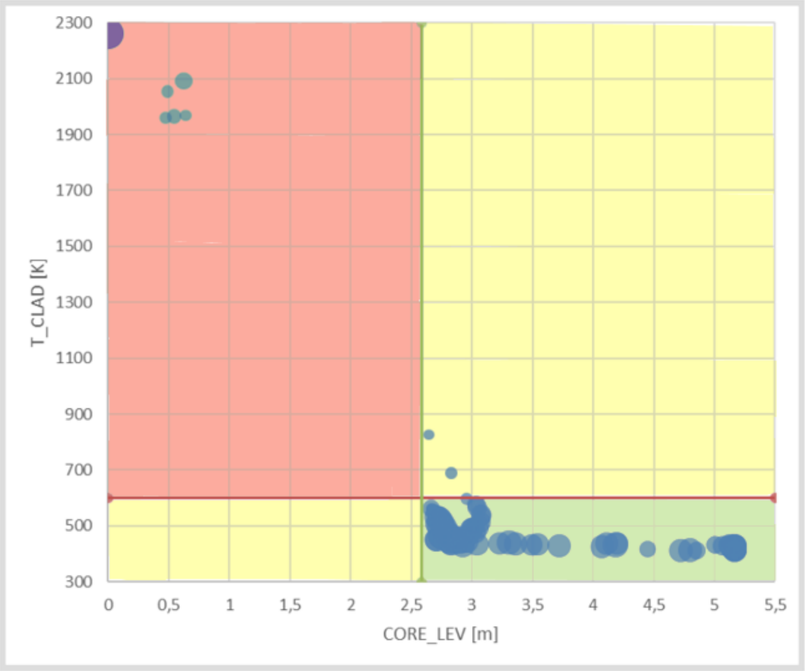
🟥 NGC

It is not the quantity but the pool elevation of the upper EHRS CVH volume

Instability map

The relationship between core water level and cladding temperature for various probabilistic simulations.

- Each point represents a single run, plotted according to its core water level and cladding temperature.
- The size of the marker is proportional to the power removed by the EHRS



| Failure criteria 2 (Core level)
— Failure criteria 1 (Cladding)
● High EHRS power removed
● Low EHRS power removed

Instability map

Stable conditions

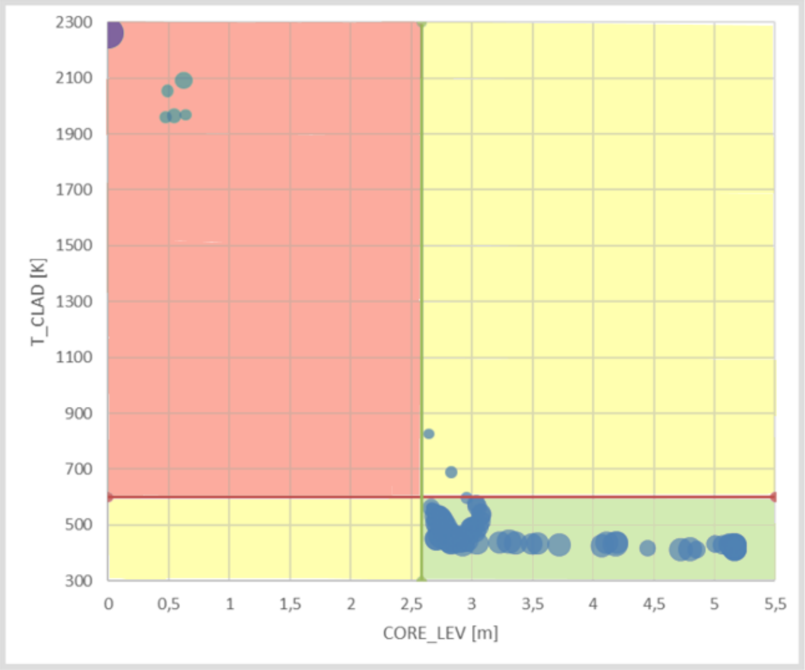
Simulations do not meet either FC

Possible instability

Simulations meet one of the FC

Instability

Simulations do meet all the FC



The system's performance in probabilistic simulations and assessing whether it meets the required safety standards.

Conclusion

REPAS methodology was applied to a full generic iPWR having as a focus the EHRS performance, with the aim of evaluating its reliability under appropriate assumptions through a probabilistic-deterministic approach.

Needs

- Increase the specific deterministic calculations in analysing low-probability or boundary system states that may not be captured in probabilistic analysis;

- Functional failure of the EHRS and related probability occurs under specific conditions: very low valve opening ratios, high concentrations of non-condensable gases, and low RWST levels, which compromise FC1 and FC2.

- Characterization of input uncertainty parameters significantly influences the reliability analysis outcomes.
  - ❑ Attention must be paid to the selection of PDFs and parameter ranges (reliable references or sound engineering judgment)
  - ❑ Combination of experimental data, analytical findings, and expert input is essential
  - ❑ The PDFs should be categorized into more specific values

Acknowledgment/Disclaimer

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission-Euratom.
Neither the European Union nor the granting authority can be held responsible for them.

ENEA carried out the research activity with MELCOR code and SNAP, obtained in the framework of the ENEA-ISIN agreement signed on March 23rd 2020 as part of the General Arrangement between the United States Nuclear Regulatory Commission (US-NRC) and the Italian National Inspectorate for Nuclear Safety and Radiation Protection (ISIN).

Thank you for your attention!

Gianmarco Grippo,
PhD student,
ENEA R.C,
Via dei Mille 21, Bologna, Italy
Email: gianmarco.grippo2@unibo.it

Additional slides

Probabilistic method to propagate input uncertainty

Input uncertainty

Uncertainty input parameters

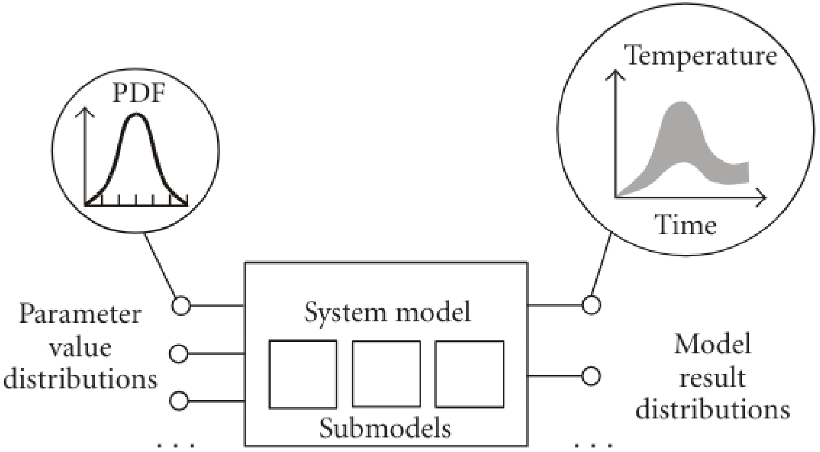
Statistical approaches

Output uncertainty

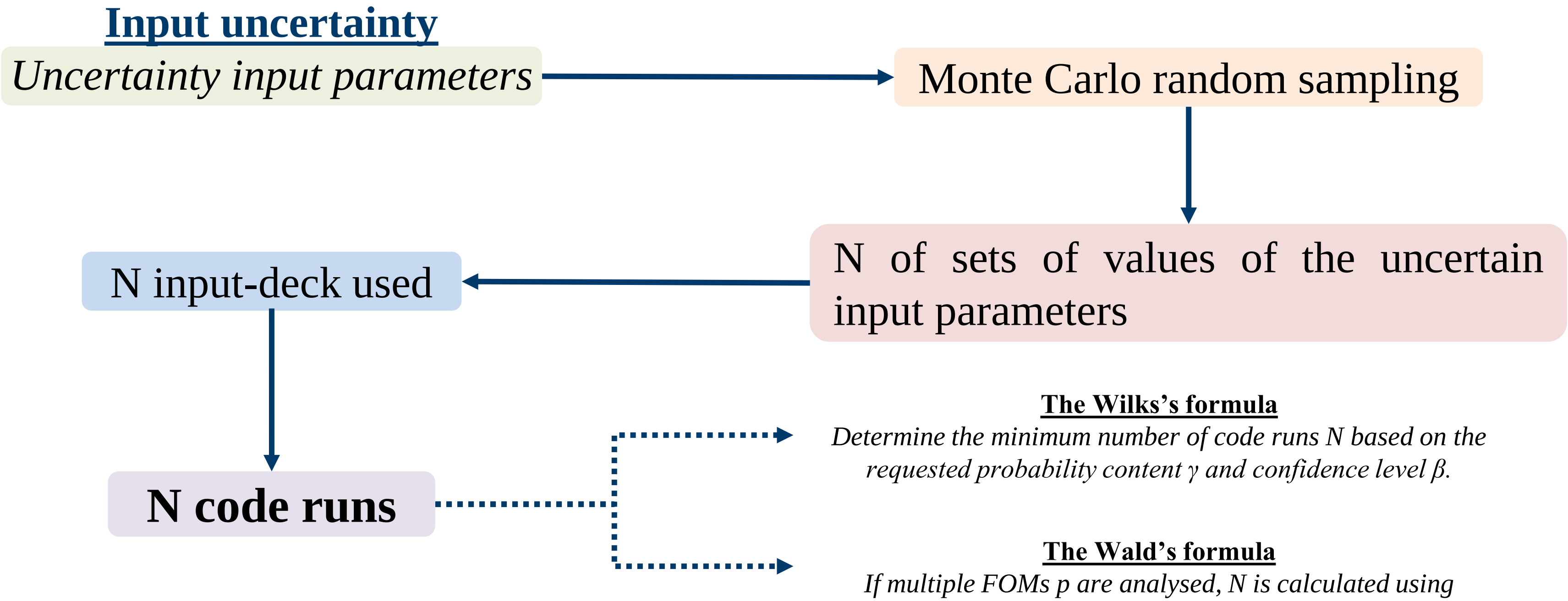
Uncertainty of selected FOMs

Probability Density Function (PDF), usually selected based on:

- Previous analyses,
- Available experimental data,
- Engineering judgment



Probabilistic method to propagate input uncertainty



Input uncertainty

Uncertainty input parameters

Monte Carlo random sampling

N of sets of values of the uncertain input parameters

N input-deck used

N code runs

The Wilks's formula

Determine the minimum number of code runs N based on the requested probability content γ and confidence level β.

The Wald's formula

If multiple FOMs p are analysed, N is calculated using

To have **insights** about the **statistical correlation** between the FOMs and the **selected uncertain input parameters** the *simple* and *simple rank* ***correlation coefficients*** are considered

Uncertainty tool

Developed and applied along the H2020 **MUSA project**, coordinated by CIEMAT.

Funded by the
European Union

Full independent in-house tool written in Python has been developed

Development of the MELCOR/DAKOTA coupling in a Python environment/architecture

❑ More **flexibility than** using **external software** that **requires** to manage **several scripts to interface the UT** to the code;

❑ Continuous **update** and **customization** of the tool according to the **user's needs**;

4 independent scripts performing all the steps needed for the development of an uncertainty analysis.

Uncertainty tool

1 *create code runs*

a.

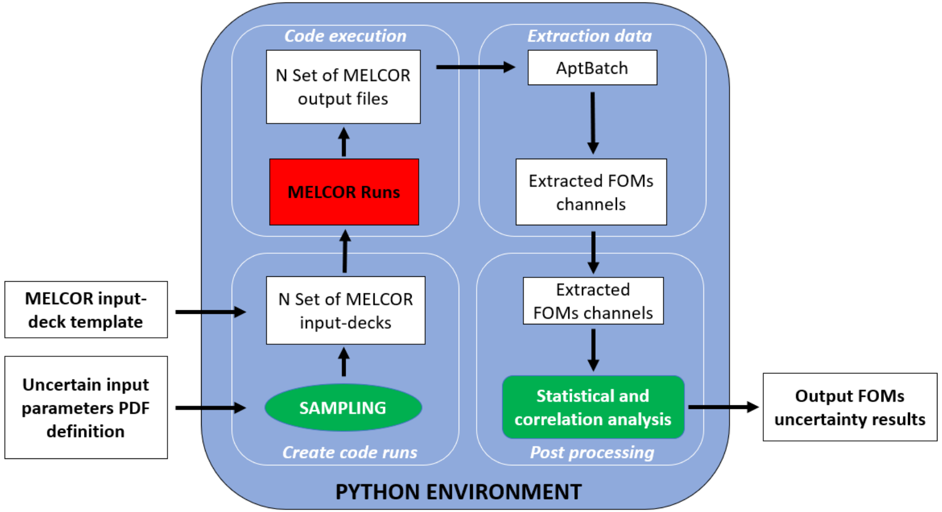
User specification of **n° of** code **runs** N and **uncertain input parameters.**

b.

Sampling of the **uncertain input parameters** from specified **PDFs**.

c.

Creation of the N **sets** of **uncertain input parameters** to be replaced in the input-deck template.



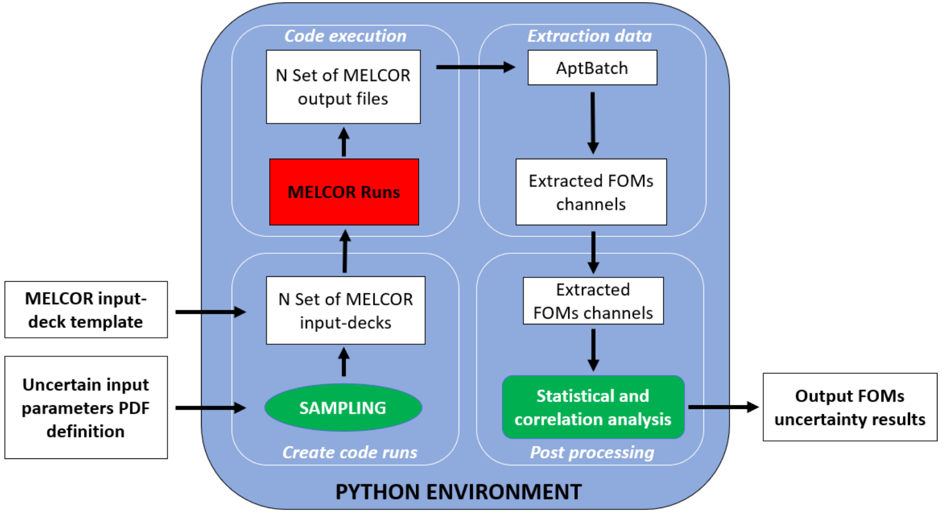
Uncertainty tool

2 *Code execution*

Through the *ProcessPoolExecutor* Python function, user select the **number P of parallel runs.**

3 *Extraction data*

Manages the **FOMs channels extraction by AptBatch** executable from the N code runs output files. The **User can set the number of parallel processes** to be divided into.



Uncertainty tool

4 *Post-processing*

Allow to **develop the statistical analysis** of the results and **the post-processing of the data**

- ☐ Mean,
- ☐ Median,
- ☐ Upper and lower bounds,
- ☐ Empirical PDF and CDF,
- ☐ Standard deviation
- ☐ Coefficients of variation of the FOMs
- ☐ Correlation coefficient