PROBABILISTIC SAFETY MARGIN EVALUATION OF MSFRs DESIGN BASIS ACCIDENTAL SCENARIOS

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Safety assessment of MSFRs design basis accidents

The objective of this work was to perform a **control-oriented safety evaluation** of different **design basis accidental scenarios** in a Molten Salt Reactor. The design of choice is the Homogeneous Fluoride MSFR:

1. **Primary** loop → $\mathrm{LiF} - \mathbf{Th}\mathrm{F_4} -^{\mathbf{235}} \mathbf{U}\mathrm{F_4} - (\mathbf{TRU})\mathrm{F_3}$
2. **Intermediate** loop → Fluoroborate salt
3. **Power conversion** loop → Joule-Brayton gas-turbine cycle

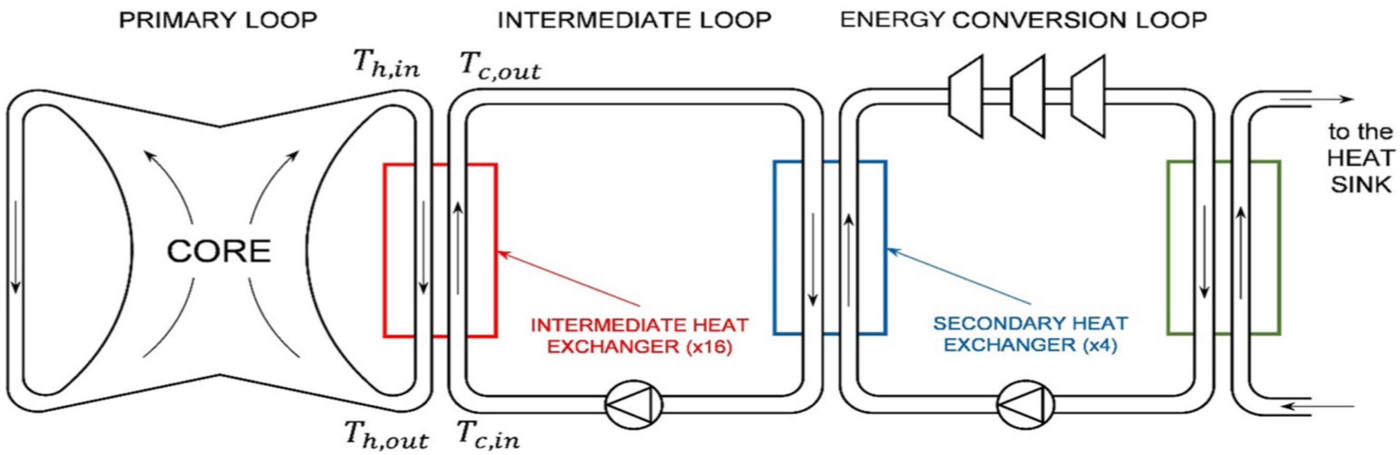
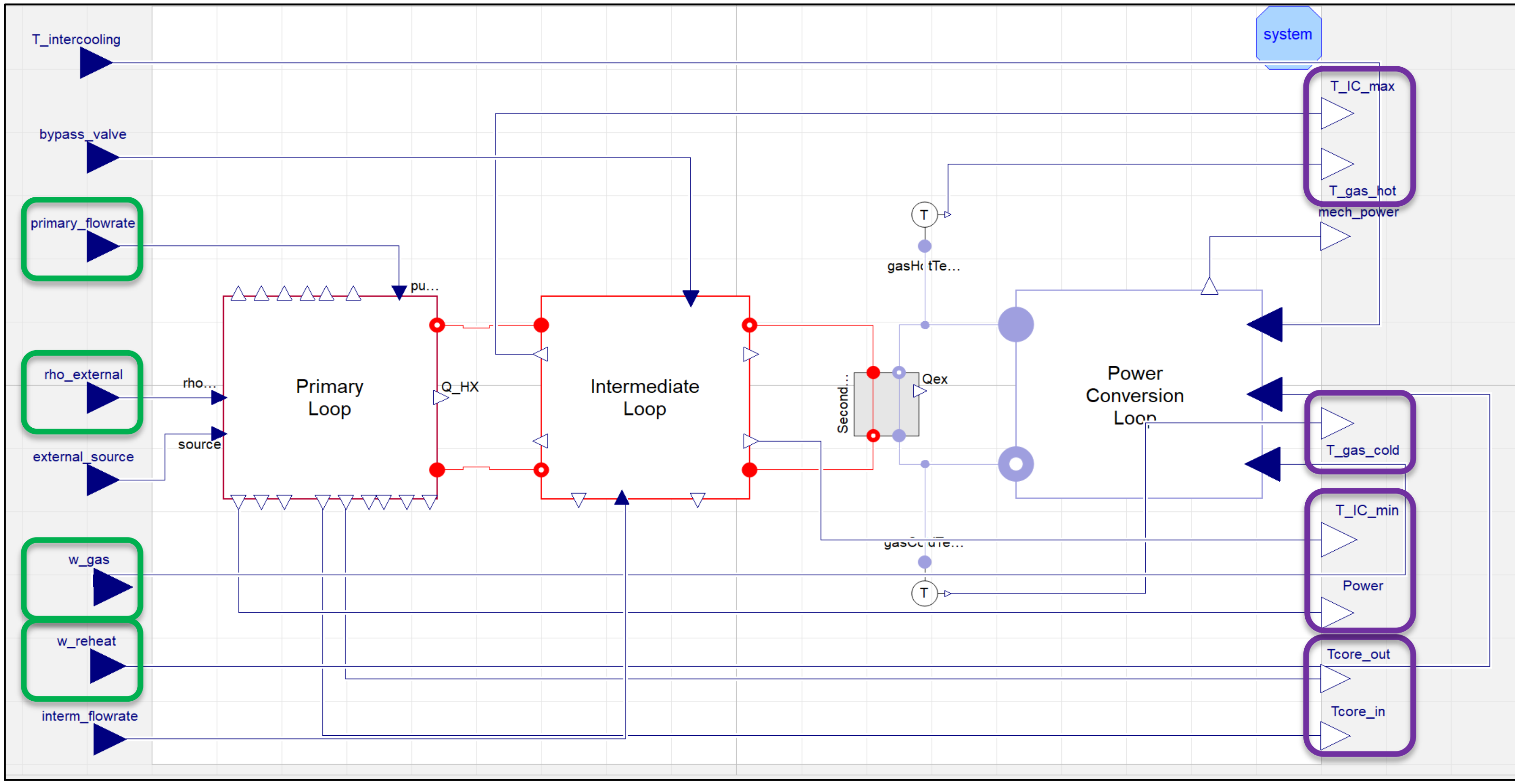


Figure 1: General plant scheme [1].

Plant simulator

The chosen model is a **plant-dynamics tool** developed in Modelica language at the Dept. of Energy, Nuclear Eng. Division, PoliMi [1].



INPUTS **Figure 2**: Overview of the deterministic model. OUTPUTS

Methods - Specification of failure modes

The **failure modes** are selected by investigating different temperature nodes inside the simulated plant. The result of this process is the identification of seven indicative parameters and the setting of the respective thresholds (mimicking a safety & control framework).

Failure modes	Safety parameters	Nominal at criticality	Safety limits
Thermomechanical failure	Core outlet temperature	1014 K	1250 K (Upper)
U-Th salt freeze inside the core	Core inlet temperature	914 K	760 K (Lower)
Thermomechanical failure	Intermediate maximum temperature	934 K	1200 K (Upper)
Fluoroborate salt freeze inside the IC	Intermediate minimum temperature	864 K	706 K (Lower)
Freeze valve drain	Specific energy received during transient	Freeze valve is in incipient melting	$1.29 \cdot 10^5$ J/kg
Local freeze close to intermediate IHX	Gas temperature	Steady state	±25%

Table 1: Failure modes statement.

Methods – Scenarios simulation using ANNs

A single run of the deterministic code takes more than a minute.

Four **Artificial Neural Networks** were trained and tested assuming independent failures.

Scenario – Input parameter [1]	Nominal @ criticality	Lower bound	Upper bound	Ramp
A – External reactivity	0 pcm	-1000 pcm	+1000 pcm	5 s
B – Primary mass flow rate	29703 kg/s	-87.5%	+ 20%	2 s
C – Intermediate mass flow rate	28992 kg/s	-63.5%	+20%	2 s
D – Helium mass flow rate	1330 kg/s	-87.5%	No overspeed	5 s

Now running a simulation for one parameter variation is in the order of milliseconds.

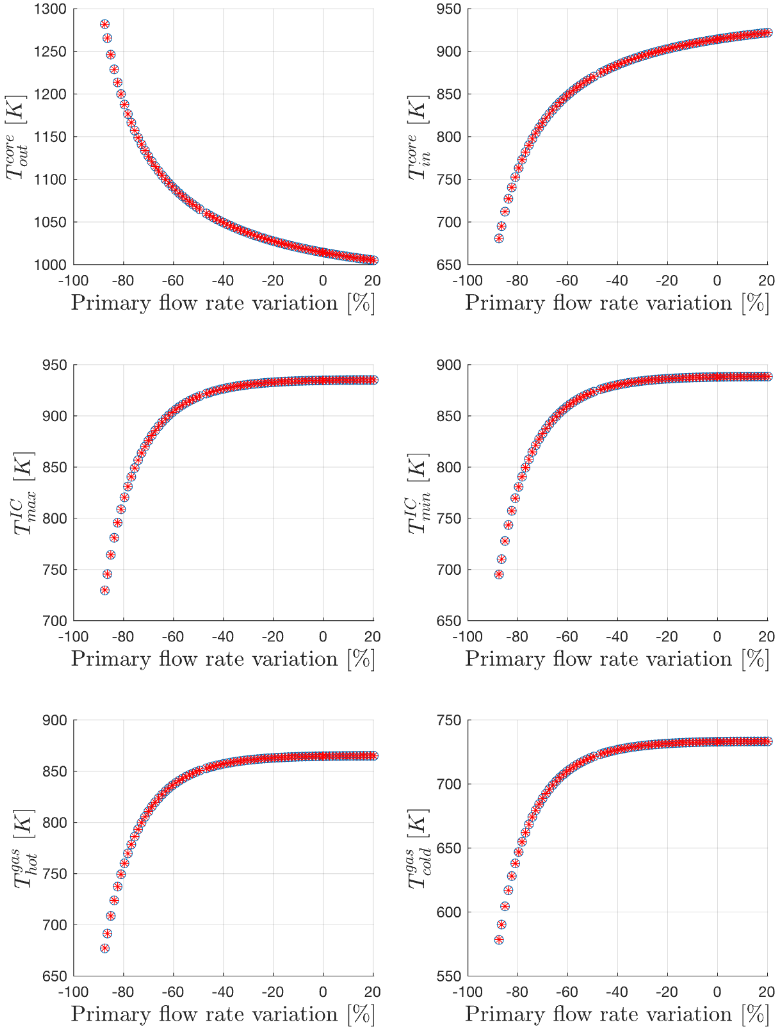


Figure 3: ANN outputs for scenario B.

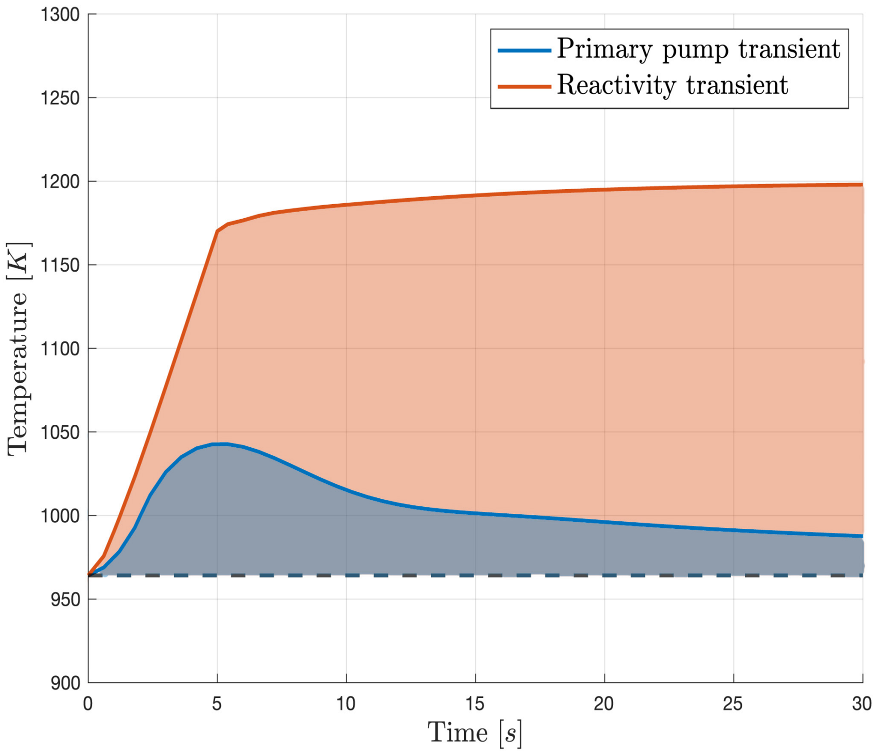
Modelling the freeze valve behavior

The activation of the freeze valve was connected to the energy transferred during transients from the primary fluid to the device, proportional to the average core temperature.

HPs:

- ▶ Freeze valve is in incipient melting → latent heat
- ▶ Thermal power linked to one of the available temperature nodes → curve integration
- ▶ Transient ends at 300 s

Figure 4: Average core temperature transients.



Methods - Order Statistics theoretical framework

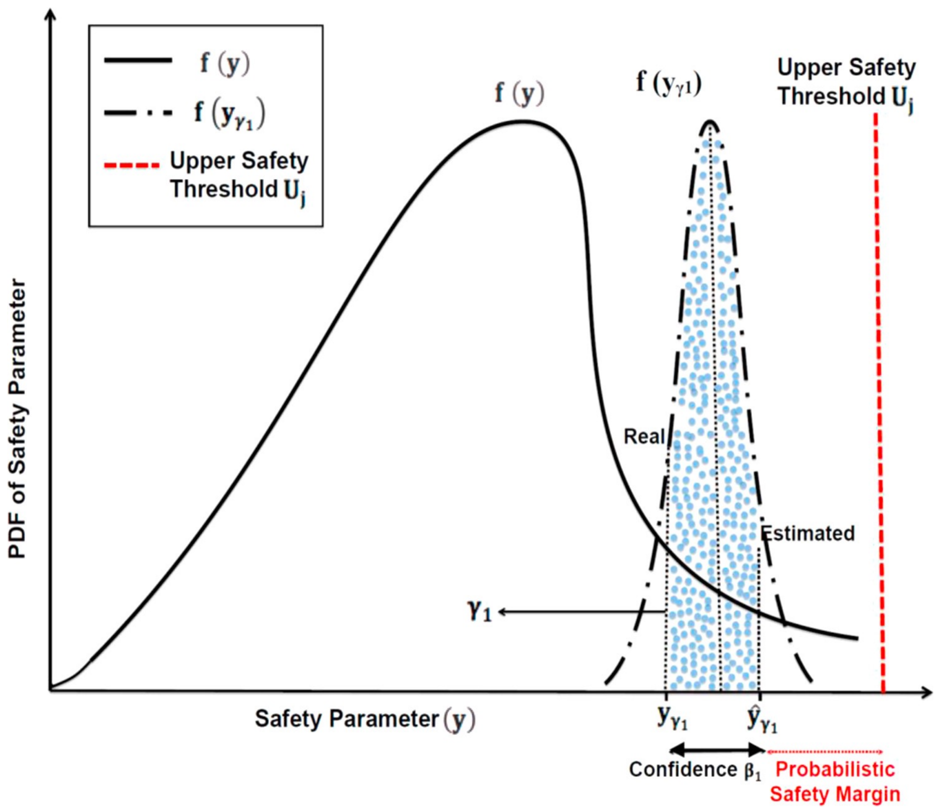


Figure 5: Safety margin evaluation with OS [2], [4].

This allowed us to perform one full statistical analysis in just 20 seconds, instead of more than a week in some scenarios!

Coverage and Bracketing

The selected scenarios are characterized by **different degrees of correlation between the outputs**, hence the need of a tailored approach for each case. The value of **number of samples (N)** was extracted by means of an iteration with all the other known parameters fixed.

- For the case of **single output one sided** it was used the **coverage** approach [2]:

$$\beta = \sum_{k=0}^{N-m} \binom{N}{k} \gamma^k (1-\gamma)^{N-k} \quad (1)$$

- For the case of **single output two sided** the **bracketing** approach [3] was used:

$$\beta = 1 - \gamma^N - \mathrm{N}\,(1-\gamma)\,\gamma^{N-1} \quad (2)$$

- In case of **two fully anti-correlated outputs** for **one-sided** safety margin [3]:

$$\beta = 1 - 2\gamma^N + (2\gamma - 1)^N \quad (3)$$

- Finally, for **three fully anti-correlated outputs** for **one sided** safety margin:

$$\beta = 1 - 3\gamma^N + 3(2\gamma - 1)^N - (3\gamma - 2)^N \quad (4)$$

Monte Carlo Simulation

The probabilistic analysis was performed using **direct Monte Carlo** samples of input values, each drawn from one out of three types of **pdfs**:

- **Uniform** distribution
- **Normal** distribution
- **Mixture of normals**

The support and parameters of the distributions were chosen according to expert judgement and with the assumption of independent input variables.

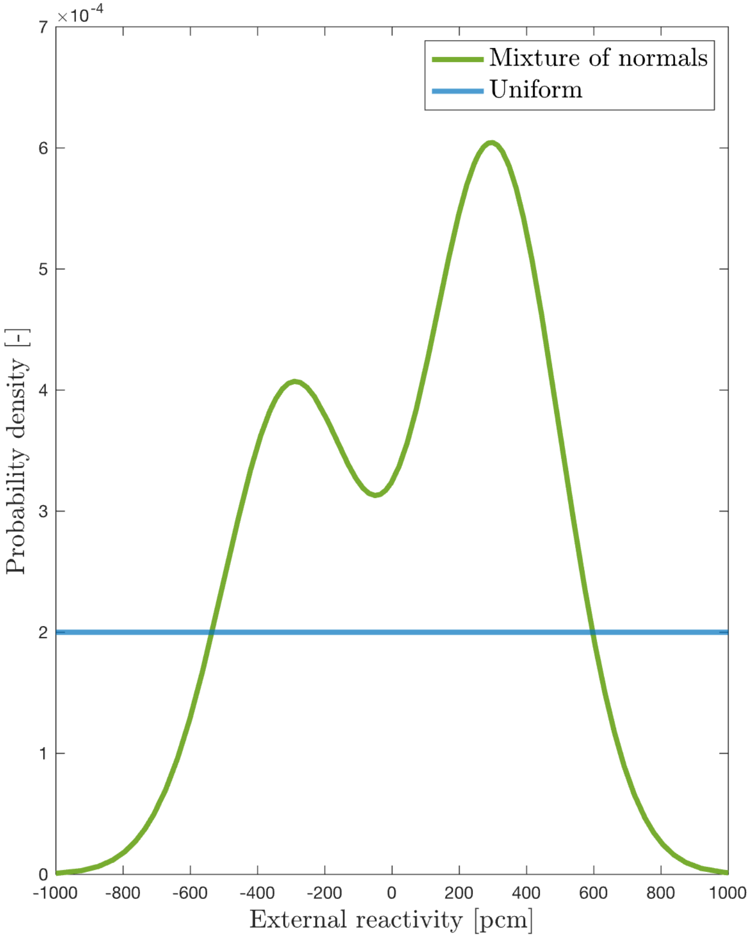
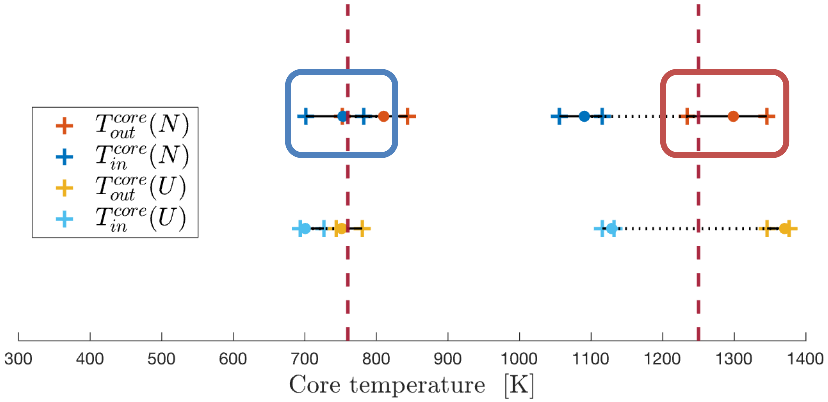
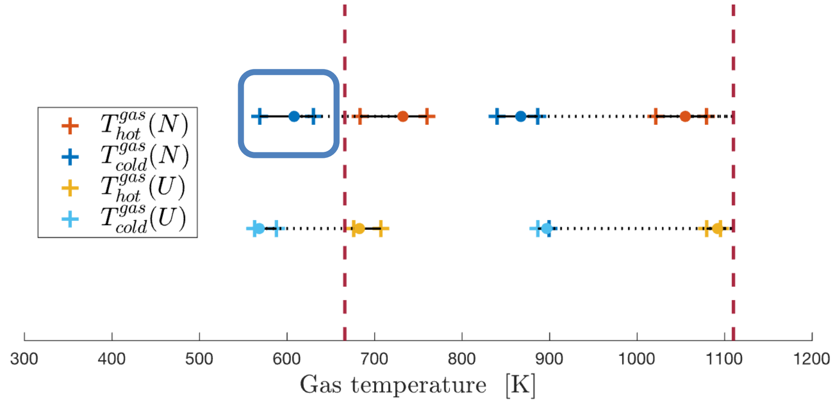
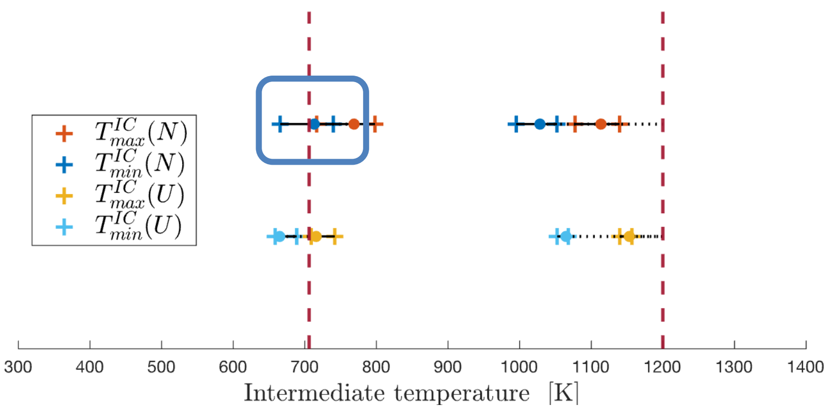


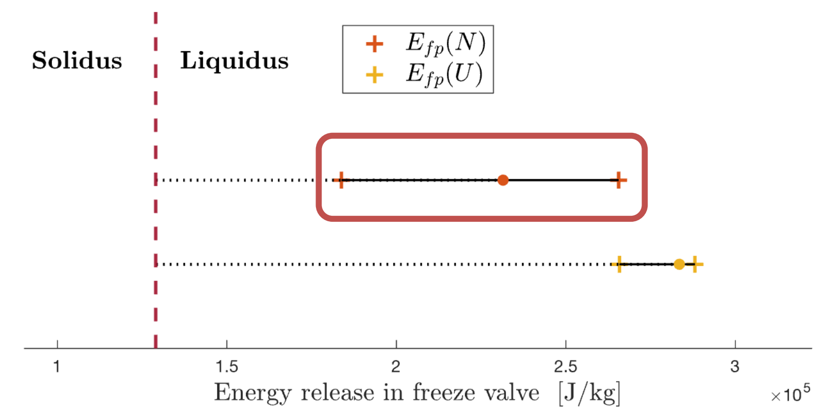
Figure 6: Distributions used for scenario A

Scenario A – External reactivity insertion

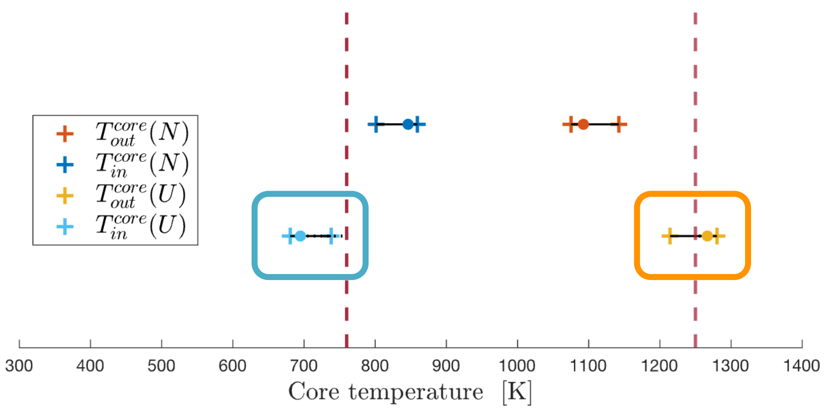


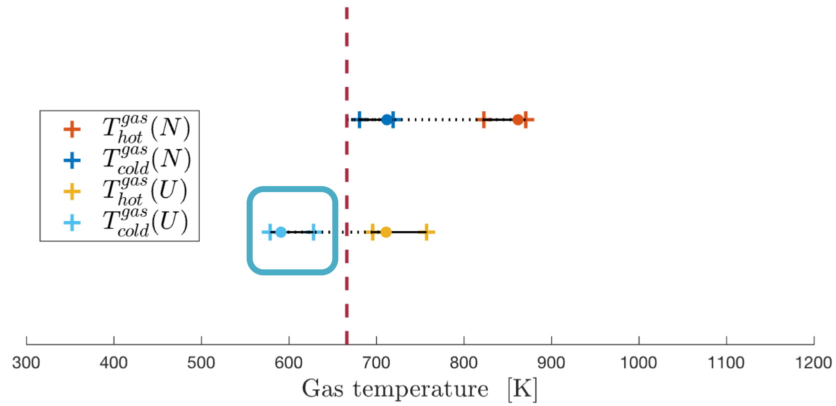


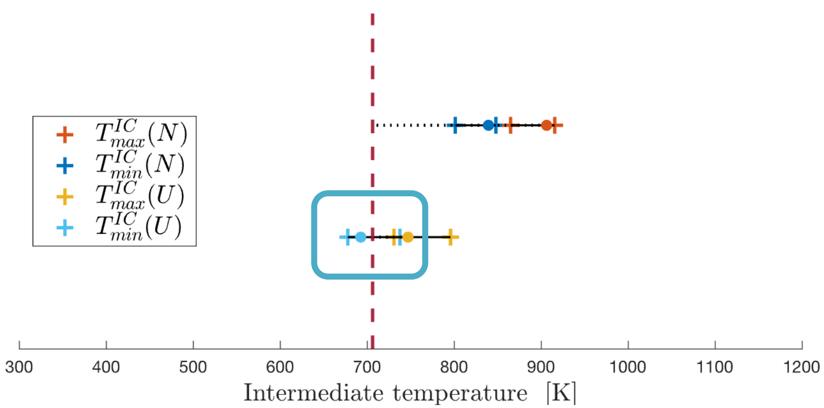


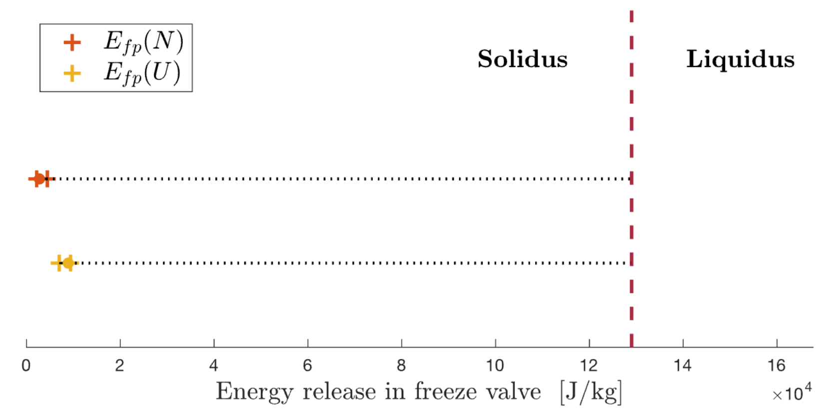


Scenario B – Primary circuit pump failure

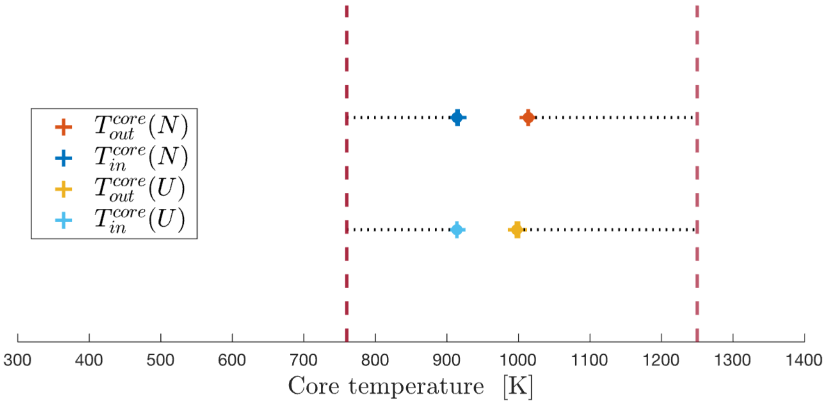


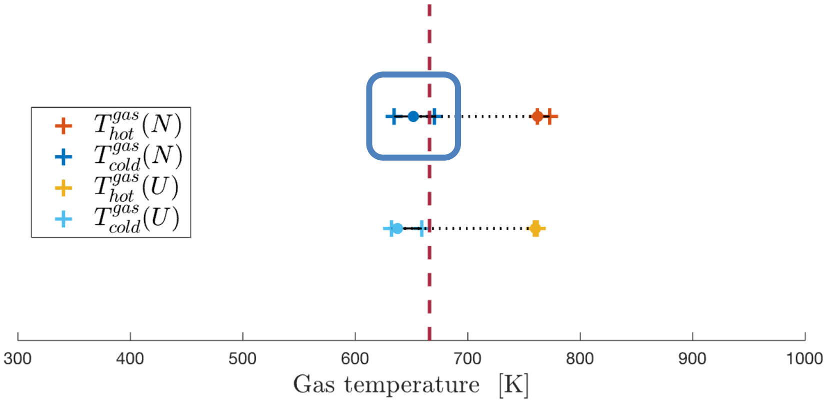


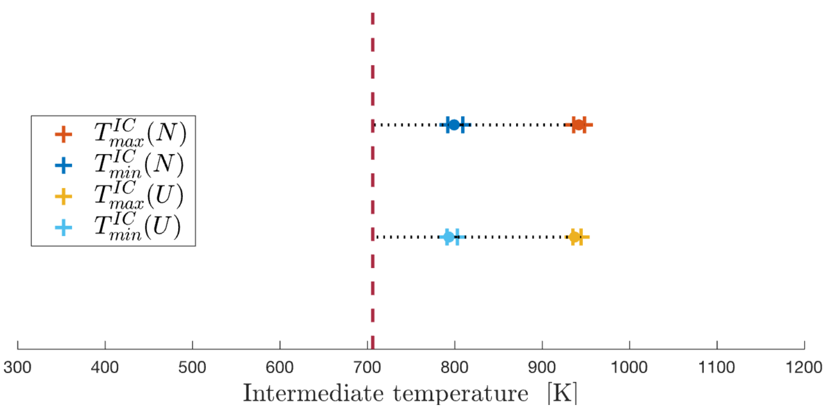


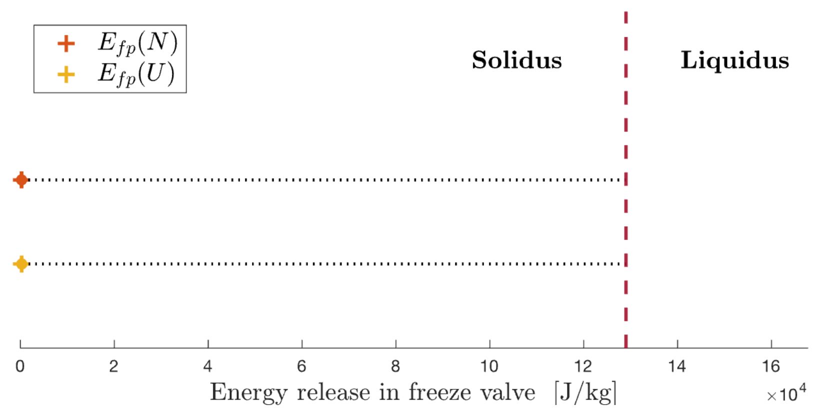


Scenario C – Secondary circuit pump failure

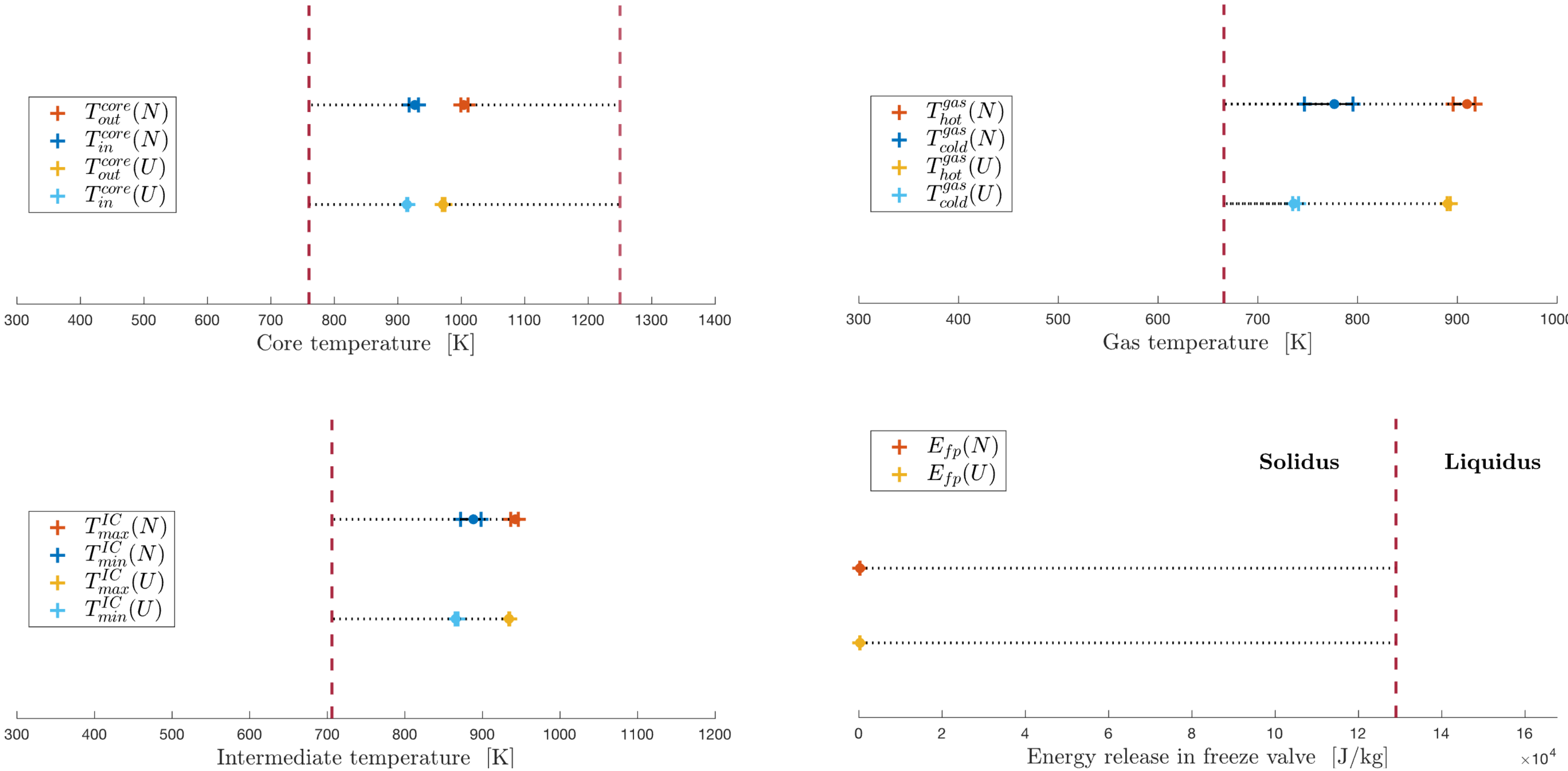








Scenario D – Turbine compressor failure



Conclusions & further improvements

- The **combination of ANNs and order statistics,** we were able to perform a complete evaluation of the selected set of safety margins in a probabilistic framework with a **minimal computational effort**.

- The peculiar behavior of the **freeze valve** seems to be effectively **modelled as a failure mode** in the context of probabilistic safety margin evaluation.

- To further develop this work, the implementation of a **modified meta-model** could be used to define a **safety domain** for the **three principal mass flow rates**.

- Moreover, the development of a **single ANN** simulating **combined failures** and a **proper model** for the behavior of the **freeze valve**, could improve the validity (and significance) of the results, especially in a control-oriented framework.

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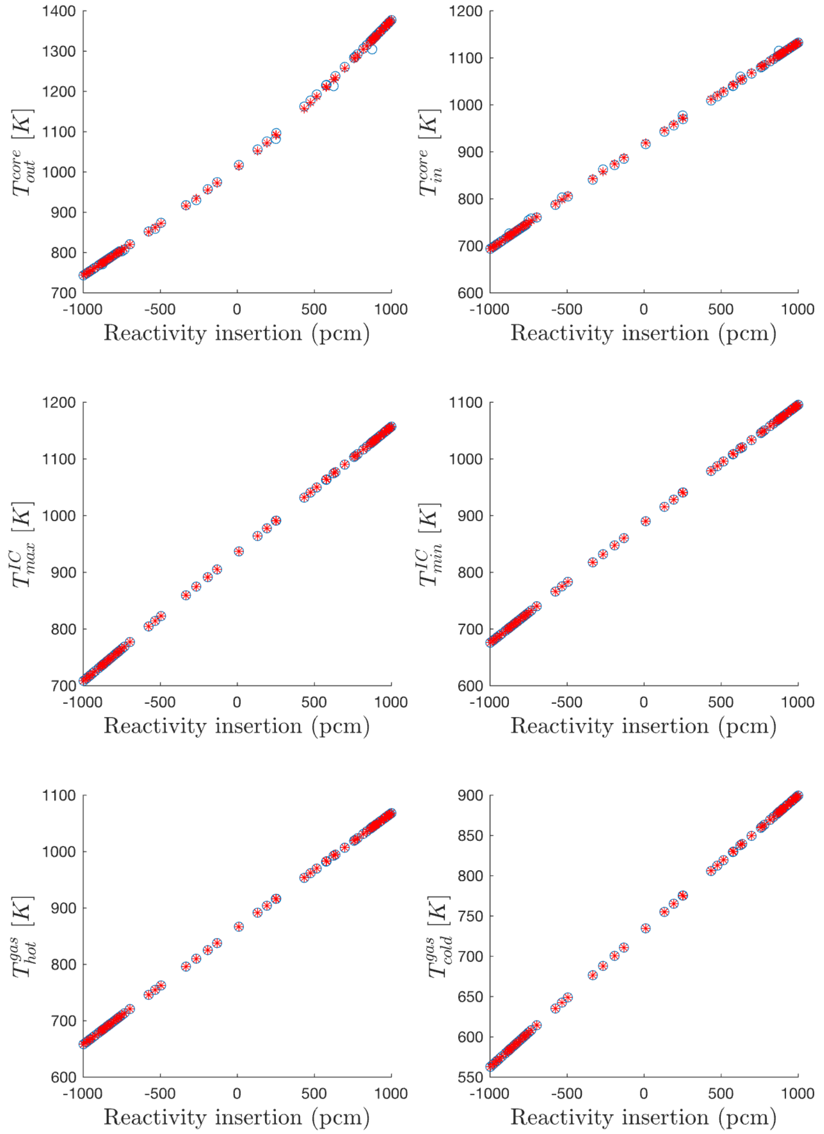
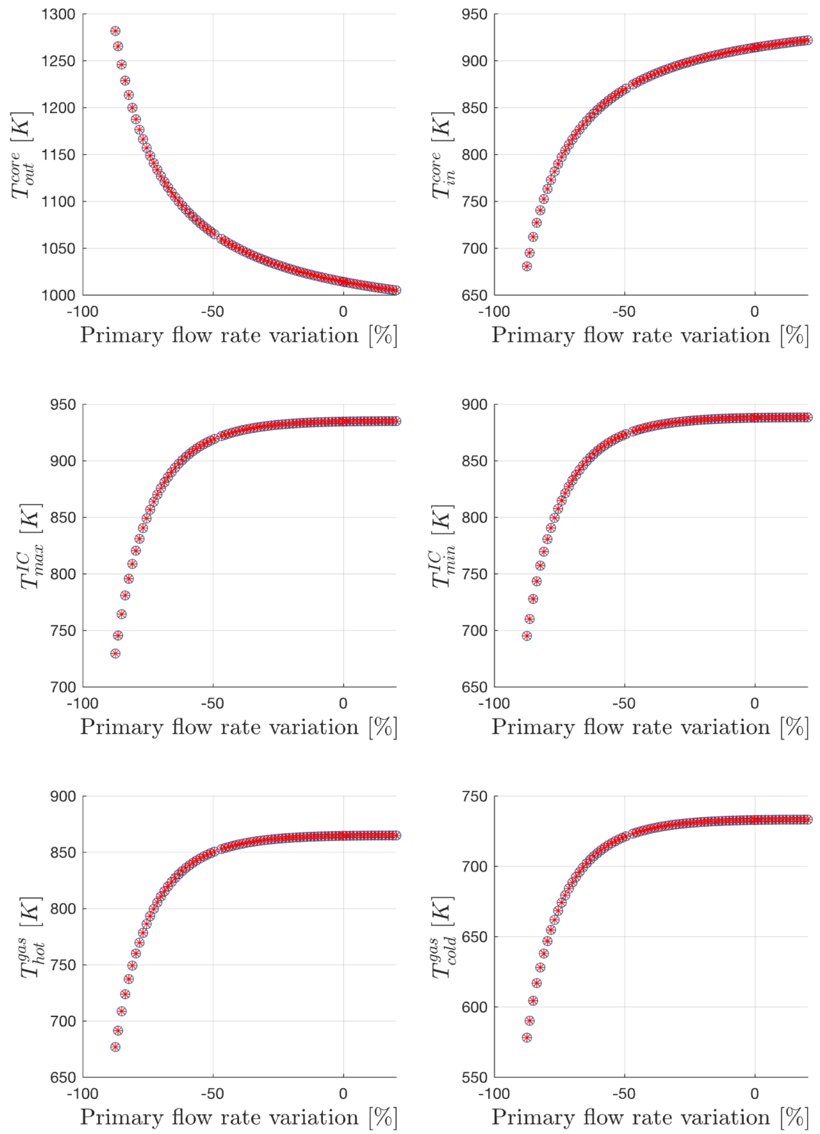
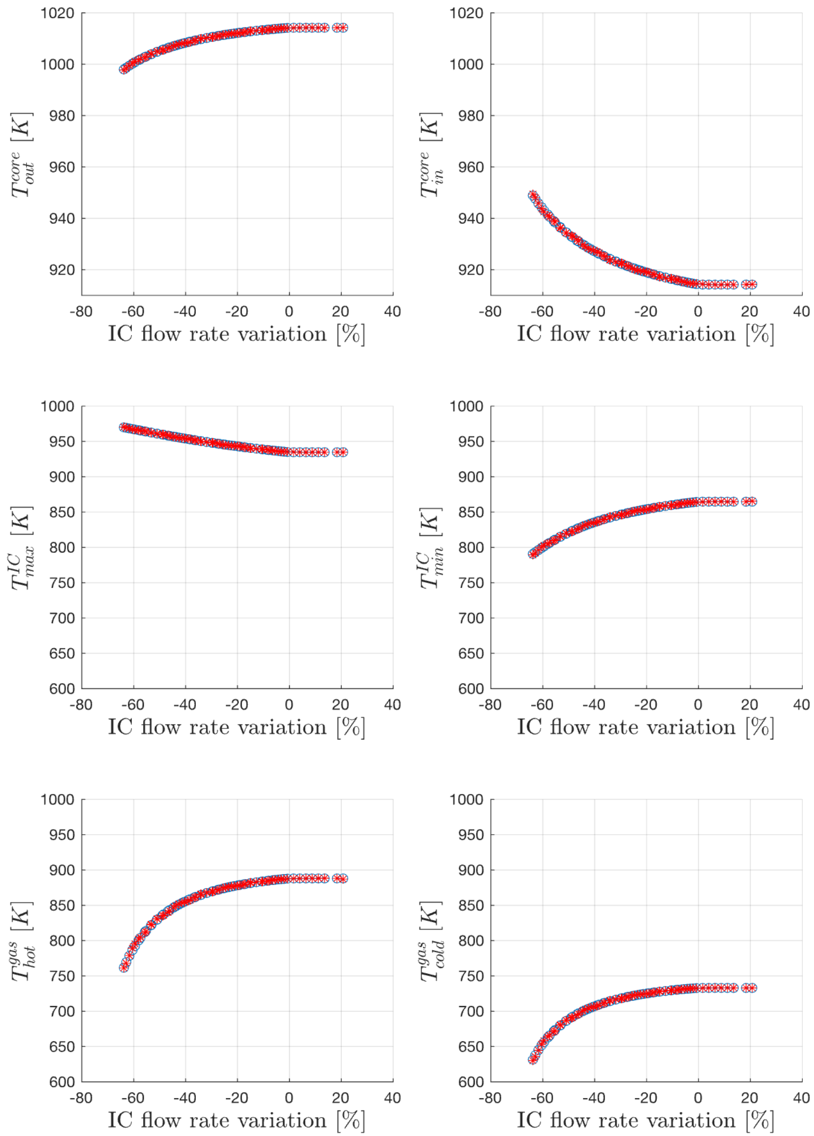
ANN output – Reactivity



ANN output – Primary mass flow rate



ANN output – Intermediate mass flow rate



ANN output – Helium mass flow rate