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Distortion Identification and Quantification: Advances Supporting Facilities Design

International Workshop on Thermal-Hydraulic Scaling for SMR Safety Demonstration – December 16-18, 2025 – Bologna

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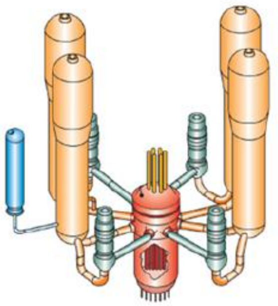
Agenda

- **Some works on distortions quantification:**
  - **Hybrid approach: “a generalized distortion correction strategy”**
  - **Sensitivity analysis in support of distortions quantification**
- **Development of a scaling tool in CATHARE code**
- **Scaling for passive systems**

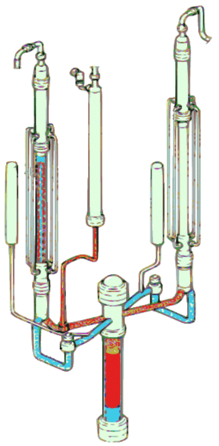
Context

<u>« Scaling » in support of the facility design</u>: Does the scaling analysis ensure that the studied installation/scenario/transient is representative of the full-scale reactor case?



Reactor Scale

Scaling analysis:
1. Thermal hydraulic analysis
2. Order of magnitude
3. PIRT
4. Design criteria



Reduced scale

Scaling analysis:
1. Thermal hydraulic analysis
2. Order of magnitude
3. PIRT
4. Design criteria
5. Distortion analysis (H2TS, FSA, DSS..)

Scaling analysis

- Identification of transient (safety issues)
- Identification of thermal hydraulic phenomena (THPs), FoM and PoI
- Identification of bifurcating events (BEs)
- Identification of scaling equations
- Choice of scaling methods
- Phenomena Identification and ranking table (PIRT)
  - Facilities Design
  - Distortions evaluation

How can we better quantify the distortions, and their impact on the reference transient?

S. Carnevali, (2025). **Scaling analysis and distortion quantification in nuclear reactor thermal-hydraulics: French advances and perspectives**. Nuclear Technology Journal. DOI: 10.1080/00295450.2025.2594341

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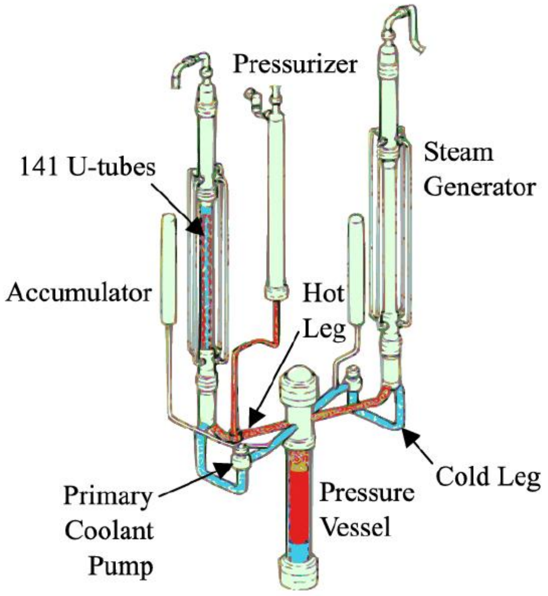
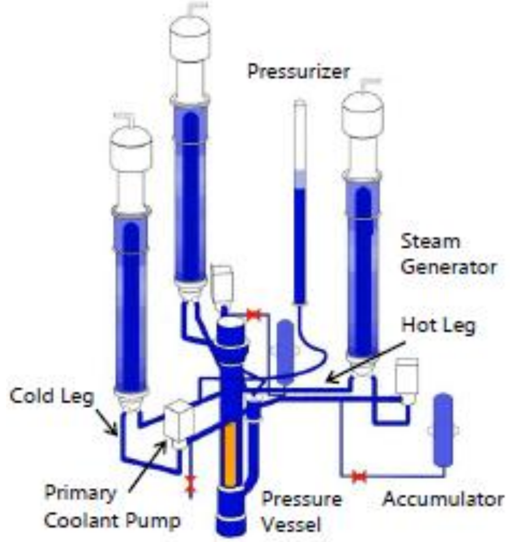
A generalized distortion correction strategy

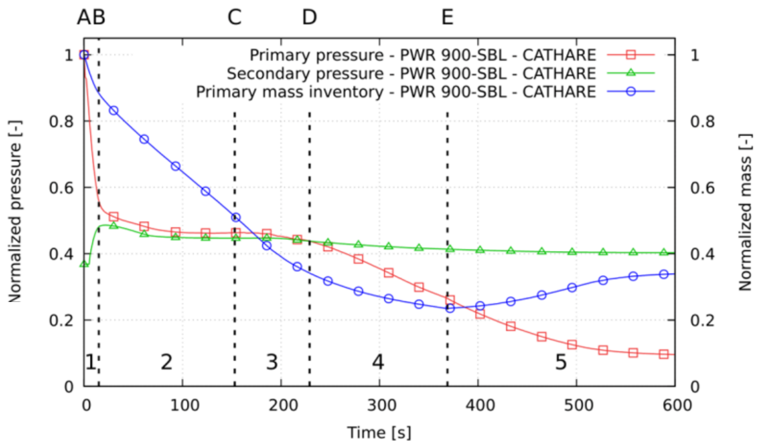
Example of a 6% CL break: LSTF, BETHSY and reactor scale



LSTF: Vol: 1/48, H: 1/1, PWR-4L



BETHSY: Vol: 1/100, H: 1/1, PWR-3L



1: Subcooled Blowdown

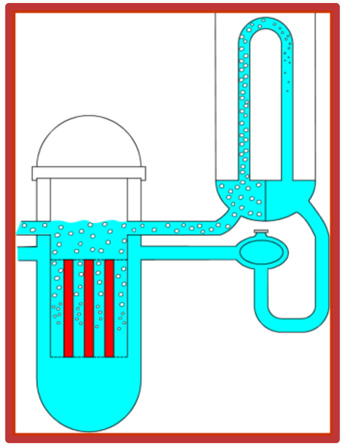
2: Natural Circulation (NC)

3: Reflux Condenser Mode (RCM)

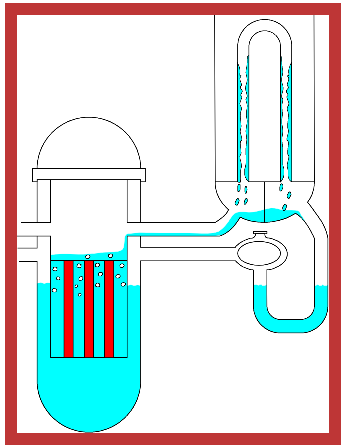
4: High Quality Break Discharge

5: Refill by accumulators

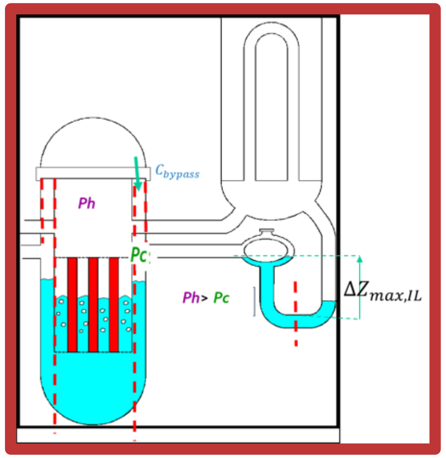
NC



RCM



LSP Loop seal plugging
LSC Loop seal clearing

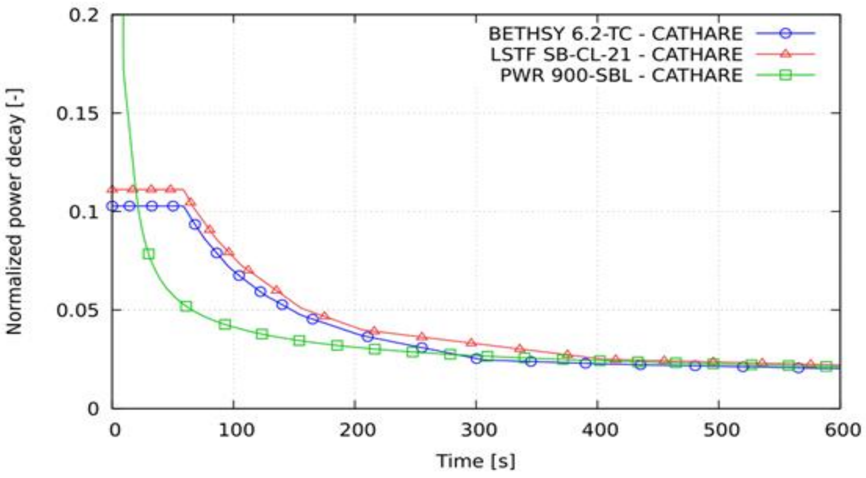


A.Ciechocki, S. Carnevali, D. Bestion and L. Rossi (2022). **Scaling analyses of a SB-LOCA counterpart test between BETHSY and LSTF facilities and a three loops PWR**. Nuclear Engineering and Design, Vol. 400, 112051. https://doi.org/10.1016/j.nucengdes.2022.112051

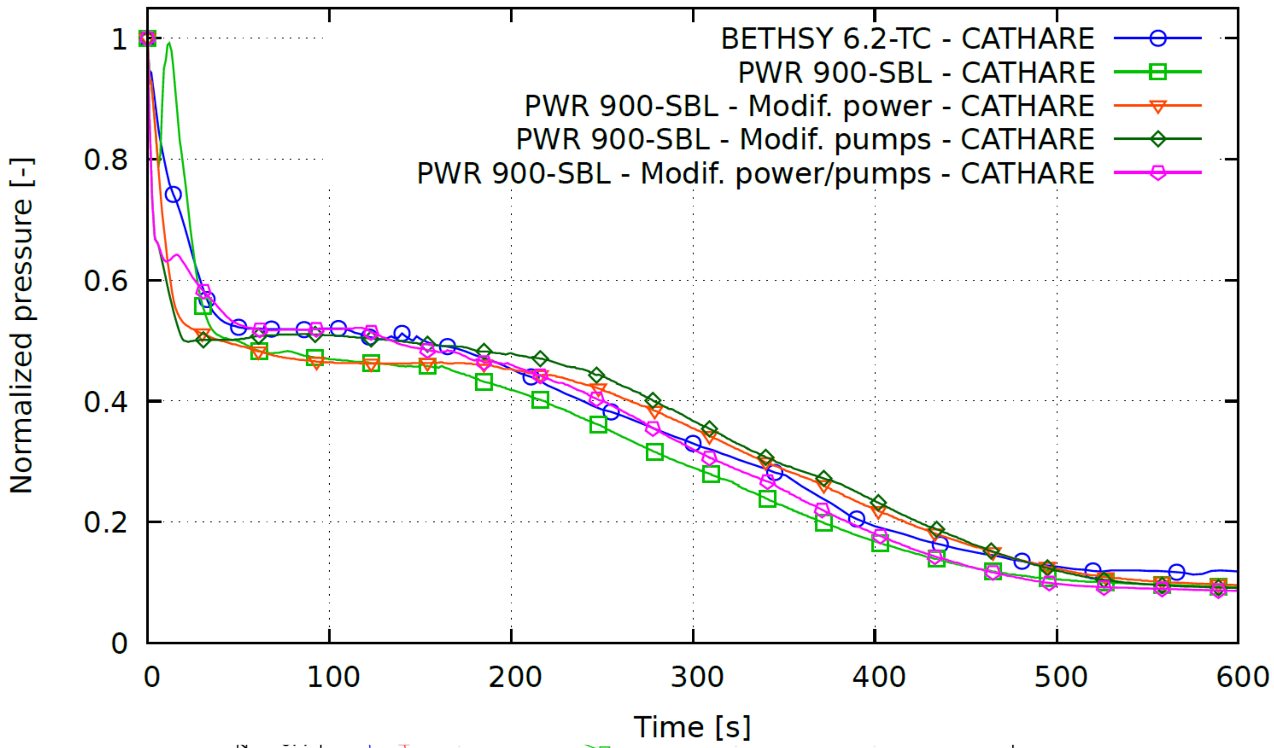
A generalized distortion correction strategy

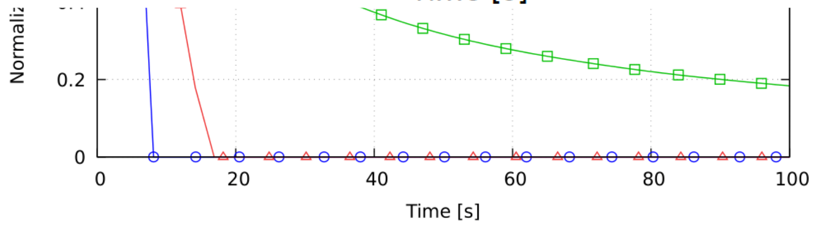
Some important conclusions:

1. Scaling analysis of three different scaled s
2. Identification of distortions and their origins
3. First application of "**a generalized distorti**
   by CEA in order to identify and correct dist



Distortion of BIC: decay power heat → correction of distortion by CATHARE → ***quantification of distortion and their origins***





Distortion of design: pump modelling → correction of distortion by CATHARE → ***quantification of distortion and their origins***

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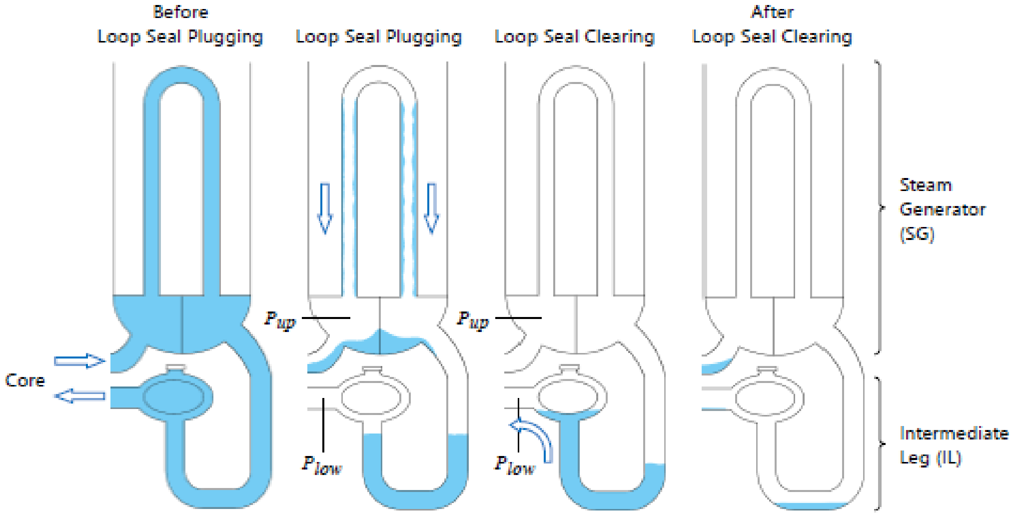
A generalized distortion correction strategy

Some exceptions : analysis of the LSP and LSC in a SBLOCA simulated by CATHARE

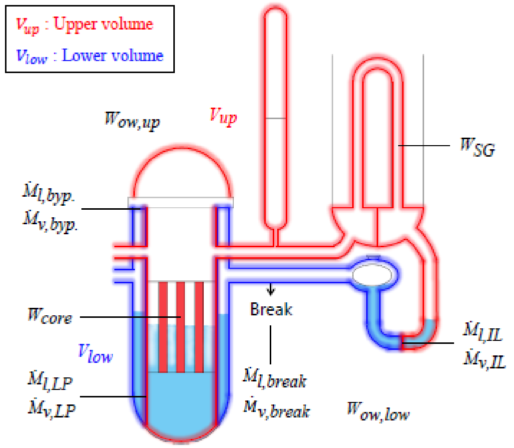


Prediction of the LSC/LSP is challenging for system codes

→ The analysis of BESTHY facility is performed starting from a **pressure balance equation** of the upper and bottom part of the loop. A scaling analysis is performed starting from the **experimental results**

Some important conclusions:

1. Contribution of the scaling analysis without the support of system codes.
2. Top-down approach
3. Characterization of the LPP/LSC and its impact on the PCT
4. Identification of important processes → sensitivity analyses



A.Ciechocki, S. Carnevali, D. Bestion and L. Rossi (2024). **Scaling Analysis of the Loop Seal Plugging and Clearing Phenomena in a Sb-Loca Transient on the Bethsy Facility**. Nuclear Engineering and Design, Vol. 422, 113145. https://doi.org/10.1016/j.nucengdes.2024.113145

The sensitivity analysis (GSA) in support of the scaling

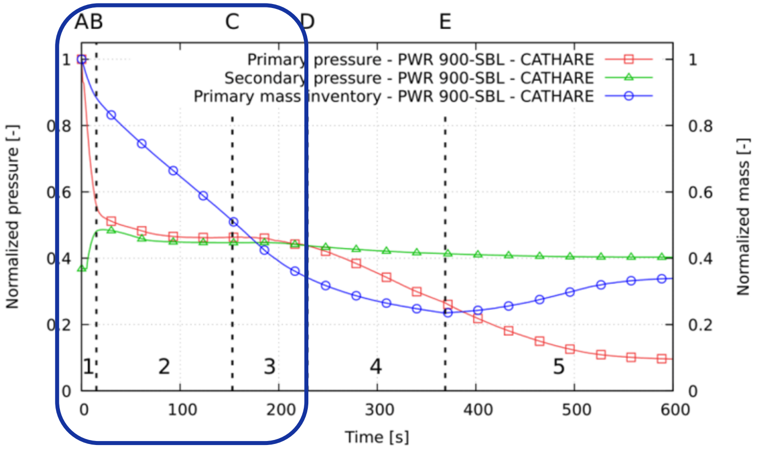
Objectif : the complementarity of the Scaling Analysis and the Generalized Sensitivity Analysis (GSA)

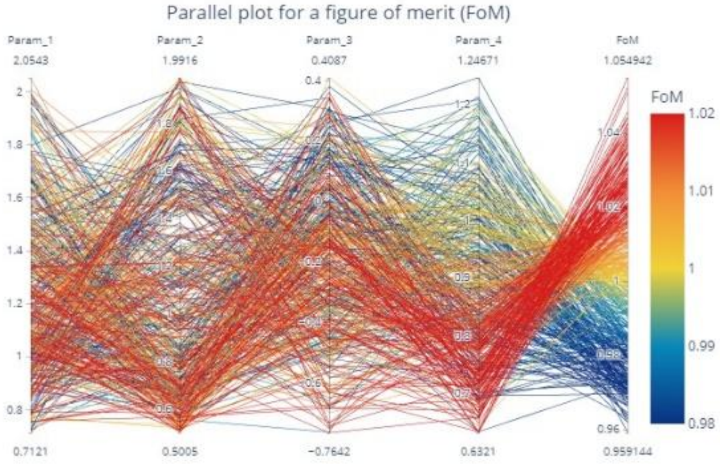
Application of the GSA to the SB-LOCA counterpart test performed in BETHSY, LSTF and reactor case. Focus on:

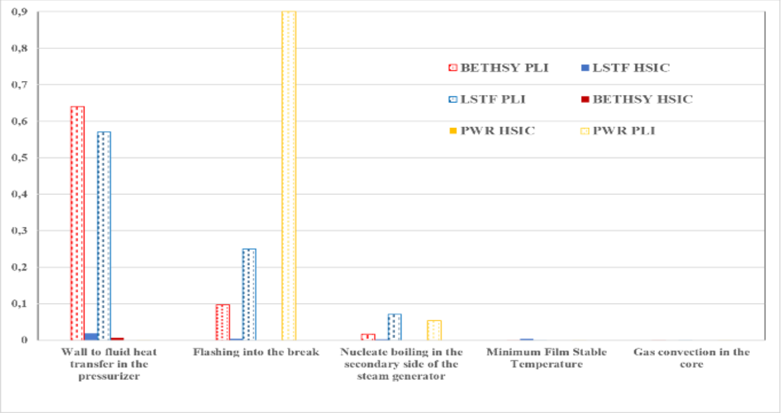
→ Blowdown
→ Natural circulation phase
→ Reflux mode

A possible synergy observed in:

❑ Transient analysis
❑ PIRT establishment
❑ Distortions quantification



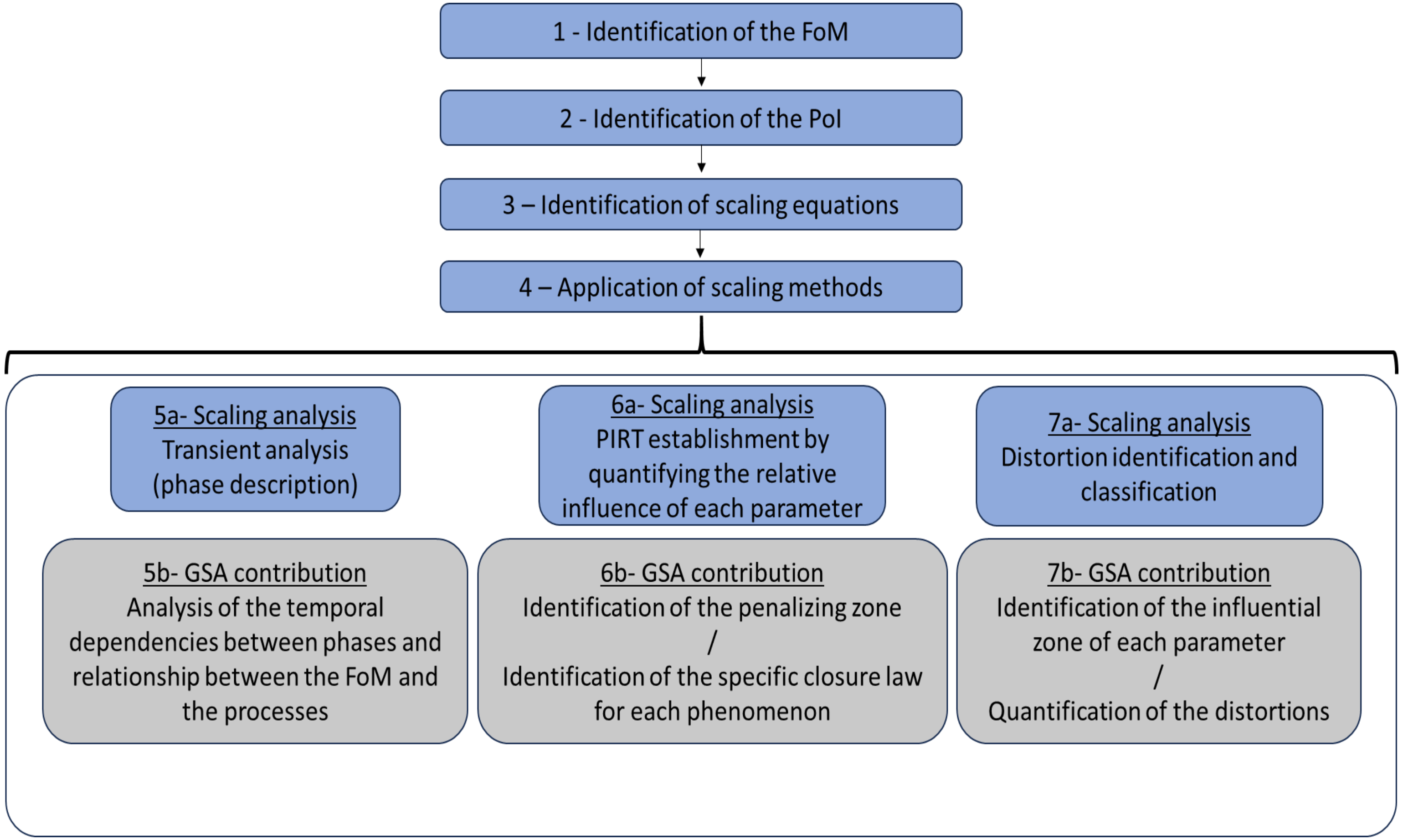




S. Carnevali, P. Gaillard, J.L. Vacher, T. Fercoq, D. Bestion, **Combining sensitivity analysis and scaling analysis for nuclear thermal-hydraulic studies**, Nuclear Engineering and Design, Volume 444, https://doi.org/10.1016/j.nucengdes.2025.114409

The sensitivity analysis (GSA) in support of the scaling

Some first conclusions GSA + scaling:



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Development of a scaling tool in CATHARE code

System code instrumentation with a « scaling » option

Scaling Mass, Momentum and Energy equations

Application of FSA as scaling method

CATHARE system code

Resolution of scaling equations by code

PIRT

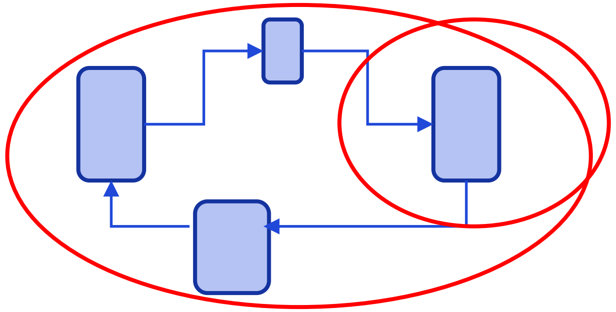
Evolution of processes on time

Work on progress

V. Cottarel, S.Carnevali, M. Montanini, D. Bestion **Using System Code for Scaling Analysis: A New Integrated Tool in the CATHARE Code Applied to a SB-LOCA Transient**. International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-21, 31 September-4 August 2025, Busan, Korea

Development of a scaling tool in CATHARE code

Resolution of balance equations for a control volume



Mass balance

$$\frac{dM_1}{dt} = \dot{M}_{IS} - \dot{M}_{l,br} - \dot{M}_{v,br}$$

Pressure equation (from mass & energy equations)

$$(\mu_l M_l + \mu_v M_v)\dot{P} =$$

$$\dot{M}_{l,in}[v_l + v'_{l,h}(h_{l,in} - h_l)]$$

$$+\dot{M}_{v,in}[v_v + v'_{v,h}(h_{v,in} - h_v)]$$

$$-\dot{M}_{l,out}v_l - \dot{M}_{v,out}v_v$$

$$+v'_{l,h}W_{wl} + v'_{v,h}W_{w,v}$$

$$+v'_{v,h}W_{iv} + v'_{l,h}W_{il}$$

$$-(W_{iv} + W_{il})/\varpi$$

$$+W_{w,i}/\ \varpi$$

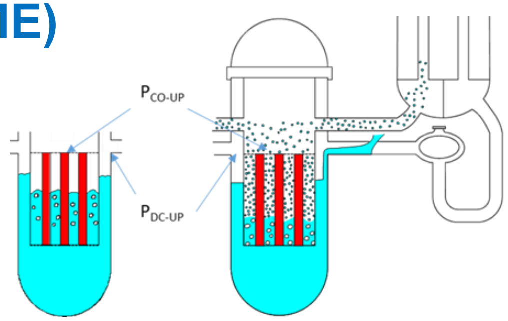
- *liquid & vapor isentropic expansion by P change*
- *Volume flowrate + thermal expansion of entering liquid*
- *Volume flowrate + thermal expansion of entering vapor*
- *Volume flowrate of exiting liquid and vapor*
- *thermal expansion of liquid & vapor by wall HX*
- ***thermal expansion of liquid & vapor by interfacial HX***
- *vaporization / condensation due to interfacial HX*
- *vaporization / condensation due to the walls*

System Pressure evolution governs the timing of many Bifurcating Events (BEs)

Development of a scaling tool in CATHARE code

Integrated Mixture Momentum Equation (MME)

…in a open loop:



$$\Delta P_{AB} \cong \Delta P_{gr} + \Delta P_{sing} + \Delta P_{w} + \Delta P_{pump} + \Delta P_{IS} + \Delta P_{br}$$

MME controls the relation $\dot{M} \longrightarrow (\Delta P_{pump}, \Delta P_{grav}, \Delta P_{fr}, \Delta P_{sing})$

Integrated Crossed Momentum Equation (CME)

$$\alpha_l MomEq_v + \alpha_v MomEq_l$$

$$\Delta P_{AB} \cong \Delta P_{buo} + \Delta P_{sing} + \Delta P_{w} + \Delta P_{pump} + \Delta P_{acc} + \Delta P_{IS} + \Delta P_{br} + \Delta P_{addM} + \Delta P_{inter}$$

CME controls the local slip ratio

Development of a scaling tool in CATHARE code

Rate of mass change due to the contribution of :	Results from Ciechocki [3]	Results from supervisor
SBD phase		
Liquid entering	-	0.355
Gas entering	-	0.020
Liquid exiting	-1.000*	-1.000
Gas exiting	-0.013*	-0.013
NC phase		
Liquid entering	-	0.001
Gas entering	-	0.012
Liquid exiting	-1.000*	-1.000
Gas exiting	-0.087*	-0.085
RR phase		
Liquid entering	1.000†	1.000
Gas entering	-	0.022
Liquid exiting	-0.022*	-0.041
Gas exiting	-0.464*	-0.972

Additional investigation

Effect metrics of the primary system during the transient

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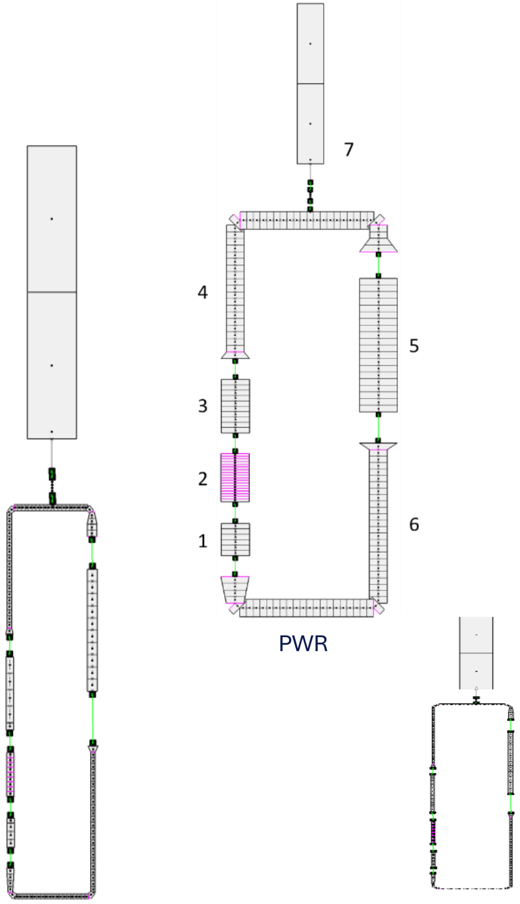
Distortions in passive systems

« Scaling analysis » in support of the passive systems (PhD of M. MONTANINI, Université Paris-Saclay)

- ❑ Development and application of the momentum equations:

  - <u>Mixing</u> : gas + liquid → global fluid behavior
  - <u>Crossed</u> : $\alpha_l MomEq_v + \alpha_v MomEq_l$ → interfacial friction

- ❑ **Impact of the design to the system behavior**



Scaling *Power to Volume*

Scaling *3 Level scaling*

M. Montanini, S. Carnevali, V. Cottarel, D. Bestion, L. Rossi (2025). **Some developements to perform a scaling analysis of a natural circulation loop in single-phase and two-phase flow using the CATHARE system code**. Nuclear Engineering and Design.

Perspectives

- Application of ***a generalized distortion correction strategy*** to additional transients
- Investigation of the **GSA in support of the scaling analysis**: additional application cases
- Finalization of **CATHARE scaling tool**
- Scaling analysis of **passive systems** in support of distortions assessment

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Thank you

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