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# The use of System Codes for Scaling Analysis and the use of Scaling tools for the Analysis of Code Predictions

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## ABSTRACT

Both system codes and experiments are used for simulating nuclear reactor thermal-hydraulic transients in safety analysis. System codes model the whole reactor and must demonstrate their quality by extensive validation against experimental data, which cover the important phenomena. Integral effect test facilities intend to simulate reactor thermal-hydraulic behaviour in reduced scale conditions. Advanced scaling methods exist to define how to respect the dominant phenomena in a scaled experiment and to evaluate distortions. They perform a similarity analysis applied to equations governing the evolution of important parameters at system, component and local levels. They require an evaluation of the order of magnitude of every term of these equations.

Today, system codes have reached a good maturity and reliability, and one defines in this work the conditions for a proper use of codes for evaluating terms of the equations used in scaling analyses. It appears that scaling tools at system level can help in the analysis of code predictions, in the establishment of a structured PIRT and for identifying the sources of code predictions differences with experimental data.

This paper presents the lessons learnt from a combined use of scaling methods, scaling tools, system codes and integral effect tests data. Some conclusions and recommendations are drawn on the merits of the various scaling methods, on the selection of the equations to be used in the scaling analyses, on the various methods for estimating terms of the selected equations, and on the acceptability limits for the distortions. The applications refer to some PWR LOCA analyses.

## KEYWORDS

Scaling analysis, System thermal-hydraulic codes, ITF design, LOCA transients

## 1. INTRODUCTION

Reactor transient thermal-hydraulic simulations uses both experiments and numerical simulation tools such as system codes. Reduced scale Integral Test Facilities (ITF) are used to simulate the whole reactor and scaling methods are necessary to identify and minimize the scale distortions. A state of the art on scaling was published by OECD-NEA-CSNI in 2016 [1]. Among the conclusions of this report, one may find:

- The use of a well-validated and verified system code can support any scaling analysis, including checking the scaling hierarchy, evaluating the impact of scale distortions and correcting the distortions in reactor applications.

- Counterpart Tests are highly valuable to verify the scaling effects.
- There is a need to identify a qualitative and quantitative framework (precision targets) to judge the quality of a scaling approach. This step is connected with the acceptance criterion for scaling distortions, and with the quantification of uncertainty due to scaling.
- Specific scaling-related training is worthwhile. Good training and education of safety analysts should include, in addition to basic single-phase and two-phase thermal-hydraulics, advanced topics of scaling techniques, identification of the dominant phenomena of major transients, code V&V and UQ requirements, and code-scalability requirements.

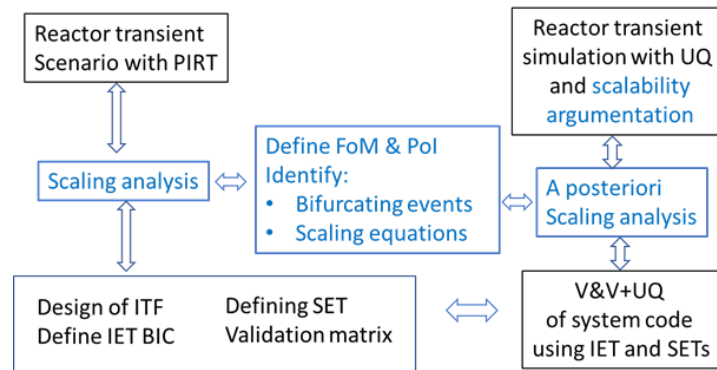
Based on these conclusions, the present work aims to summarize some lessons learnt from applying system codes for scaling analysis with evaluation of scaling distortions, and from using counterpart tests.

Only the Hierarchical Two-Tiered Scaling (H2TS) [2] and the Fractional Scaling Analysis (FSA) [3,4] methods applied with the support of system codes are commented here. The applications are here related to PWR Loss Of Coolant Accident (LOCA) transients. Several authors have reported such analyses (Munoz-Cobo et al., [5], Reventos et al. [6] Martinez-Quiroga & Reventos [7]). Examples commented here are based on recent work performed at CEA by Ciechocki et al. [8,9].

Some guidelines and recommendations are drawn on the selection of the “scaling equations” to be used in the scaling analyses, on the various methods for estimating terms of the selected equations, and on the acceptability limits for the distortions.

## 2. THE SCALING METHODS AND THE BENEFIT OF USING SYSTEM CODES

Scaling methods were initially conceived to define design criteria for ITF without using system codes. The reason was that the experiments resulting from the scaling are used to validate the codes and can only be used after their validation. However, the current system codes are now extensively validated and can be used for scaling analysis as stated in the state of the art report on scaling [1]. The general process of safety demonstration for a reactor transient is summarized in the Figure 1.



**Figure 1. Process of safety demonstration for a reactor transient**

A scaling analysis is here performed first for defining design criteria of ITF and IET boundary and initial condition (BIC). An “a posteriori scaling analysis” is added after the code validation to give arguments to the code scalability demonstration. After the validation, one can better identify the origin of differences observed between the IET and reactor calculations, which can be attributed to either code deficiency, IET scaling distortions, code nodalization effects, or bad scalability of some code closure laws.

This work intends to bring some guidelines for the steps colored in blue in Figure 1.

## 2.1. The common features of H2TS and FSA

The scaling of an ITF with a top-down approach followed by a bottom-up approach was proposed in the H2TS method [2] and is also used in the FSA method [3,4]. The analysis starts at the system scale and is based on equations written for Parameters of Interest (PoI) characterizing the status of the system, e.g. the primary circuit. It gives some first scaling criteria for the selection of scaling ratios for the circuit volume, the core power, the flow rates and the time scale. Equations are written first for the reactor for such PoI in the following form:

$$\frac{dPoI_j}{dt} = \sum_k R_j^k \quad (1)$$

Each  $R_j^k$  represents a physical process which is an Agent of Change of  $PoI_j$ .

The same equation is written for the IET to identify the scaling factor  $\lambda_j$  applied to  $PoI_j$  and the scaling factors  $\lambda_{k,i}$  applied to  $R_j^k$ .

$$\frac{dPoI_j}{dt} \lambda_j \cong \sum_k \lambda_{j,k} \cdot R_j^k \quad (2)$$

One may classify the Agents of Change  $R_j^k$  into the dominant or influent ones  $RDI_j^k$  and the negligible ones  $RNI_j^k$ , which may be eliminated from the analysis:

$$\frac{dPoI_j}{dt} = \sum_k R_j^k = \sum_k RDI_j^k + \sum_k RNI_j^k \cong \sum_k RDI_j^k \quad (3)$$

If all scaling factors are equal ( $\forall i, \lambda_j = \lambda_{j,i}$ ), Eq. (3) is almost similar to Eq. (1) and the experiment preserves a good prediction of  $PoI_j$  evolution and preserves the time scale. If  $\lambda_j \neq \lambda_{j,i}$  and all  $\lambda_{j,i}$  are equal, Eq. (3) is almost similar to Eq. (1) and the experiment preserves a good prediction of  $PoI_j$  evolution with a change of time scale. When a scaling factor of a  $RDI_j^k$  is different from the others, the Agent of Change is distorted and one must give some acceptability limit to this distortion.

This analysis may be repeated for several successive phases of a transient since the dominant, influent and negligible terms may change during the transient.

It may happen that the term  $dPoI_j/dt$  is negligible in the equation when there is a quasi-steady state during a given phase of a transient. Some of these  $R_j^k$  are representing a physical process, which occurs only in a reactor component. A specific analysis may be necessary at another scale, in order to evaluate this term using other scaling equations or existing physical models. This is the top-down approach.

## 2.2. The Hierarchical Two-Tiered Scaling (H2TS) method

In the H2TS method [2], the scaling equation for a PoI is written for a specific quantity  $\psi$  (e.g.  $\psi = \rho, \rho v, \rho h$ ) within a control volume  $V$  considering the convective terms  $Q\psi$ , the diffusive terms  $J_i$  and the volumetric source terms  $S_k$ .

$$\frac{dV \cdot \psi}{dt} = [Q\psi]^{in} - [Q\psi]^{out} + \sum J_i \cdot A_i + \sum S_k \quad (4)$$

A reference time scale is defined: for example a residence time:  $\tau_R = V_0/Q_0$  where  $Q_0$  is a reference (e.g. initial) volume flow rate of  $\psi$ . Then for each process, a non-dimensional process time scale ratio is defined:  $\Pi_{proc} = \tau_R/\tau_{proc}$ , for example the diffusion time scale:

$$\frac{1}{\tau_{diff}} = \omega_{diff} = \frac{J_{io} \cdot A_{io}}{\psi_0 \cdot V_0} \quad (5)$$

The behaviour of  $\psi$  is controlled by largest  $\Pi_{proc}$  corresponding to the smallest process time scales. Experiment scaling should respect  $\Pi_{proc}^{exp}/\Pi_{proc}^{reac}$  of largest  $\Pi_{proc}$ . Scaling distortion is quantified by:

$$D = 1 - \frac{\Pi_{proc}^{exp}}{\Pi_{proc}^{reac}} \quad (6)$$

Some authors (Wulff & Rohatgi, 1999 [10]) have defined limits such as  $0.5 < D < 2$  for a well-scaled phenomenon. The basic idea is simple: “when several agents of change contribute in parallel to a change of a quantity  $\psi$ , the dominant agents are those who contribute faster than the others” and one must respect the process time scales of the dominant ones.

This is an easy way to identify quickly the impact of some design differences between a reactor and an ITF but also between several reactors and several ITF in a counterpart test. For example for PWR LOCA, one may easily compare the emptying time of the whole circuit by applying a reference critical break flow rate. One may compare the emptying time of the pressurizer to estimate the duration of this phase. One may compare the emptying time of the part of the circuit above the break elevation to estimate the initiation time of the high quality discharge at the break, which makes the primary pressure falling below the secondary pressure in many SBLOCA transients. One may compare characteristic heating or cooling time scales of the core power and of heat losses or heat release from metallic structures during a phase of a transient. One may compare the pressurizing or depressurizing time scales due to core heating or volume flow rate at a break.

### 2.3. The Fractional Scaling Analysis (FSA) method

FSA is an analytical approach for complex problems (economy, ecology, ...) based on “fractional analysis” (Zuber et al. [3,4]). The FSA method considers state variables  $\psi$  that are influenced by processes (convection, diffusion, wave propagation, ...). A single state variable in a control volume denoted by  $\psi$  varies by the action of non-dimensional Agents of Change  $\phi_j^+$  multiplied by Fractional Rate of Change (FRC)  $\omega_j$ . They are the measures of the relative magnitude of a process on the variable  $\psi$ .

$$\frac{d\psi^+}{dt} = \sum_j \omega_j \cdot \phi_j^+ \quad (7)$$

The FRC  $\omega_j$  are shown being the cause  $\phi_j$  over the effect:

$$\omega_j = \frac{1}{\psi} \cdot \frac{d\psi}{dt} = \frac{\phi_j}{\psi} \quad (8)$$

The dominant phenomena in the different phases of the transient are identified by ranking them according to the relative magnitude of the FRC. The Effect Metrics  $\Omega_j$  are obtained, representing the rate of change of the variable  $\psi$  over a reference period  $\tau_{ref}$ , consequence of the contribution of the Agents of Change:

$$\Omega_j = \omega_j \cdot \tau_{ref} \quad (9)$$

## 3. IDENTIFICATION OF PARAMETERS OF INTEREST AND BIFURCATING EVENTS

The Figure of Merit(s) (FoM) is (are) the main thermal-hydraulic parameters, which are used for the safety demonstration. For LOCA simulations, the Peak Clad Temperature (PCT) is the first FoM. This PCT depends on the occurrence of Critical Heat Flux (CHF) either by Departure from Nucleate Boiling (DNB) or by Dry-Out. DNB depends on the mass flux  $G$ , the pressure  $P$  and the thermodynamic quality  $\alpha$ . Then in LBLOCA and IBLOCA where DNB may be reached in the early phase of the transient one should pay a special attention to these three PoI. In SBLOCA the fuel rod temperature excursions may occur by core uncovering in case of lack of water in the core. Therefore, the total primary mass  $M_1$  and the core mass are

important PoI. They depend a lot on the SI injections and the break flow rate, which depend a lot on  $P_1$  history.

Then the fluid mass repartition in the various components is controlled by some force balance equations, which may be specific to the component and to the physical situations. Table I gives an example for a 6% cold leg break SBLOCA as investigated in [9]. For each PoI, the effects are given, as well as the impact on the PCT and the scaling equation that may be used in a scaling analysis.

**Table I. Example of identification of Parameters of Interest for a PWR Cold leg SBLOCA (see [9])**

Parameter of interest	Effects	Impact on PCT	Scaling equation
Primary mass $M_1$	Impacts $M_{core}$	Big impact on PCT	Eq. (10)
Primary pressure $P_1$	Impacts SI and $Q_{break}$	Big Impact on PCT	Eq. (14) or (15)
Break flow rate	Impacts $M_1$ and $P_1$	Big Impact on PCT	Break model
Mass flow rate in loops	Impacts end of NC and $P_{core} - P_{DC}$	Some Impact on PCT	Eq. (17)
$P_{core} - P_{DC}$	Impacts core uncover	Some Impact on PCT	Eq. (18)
Accumulator flow rate	Impacts $M_1$ and $P_1$	Big Impact on PCT	Eq. $P_{acc.} - P_1$
Mass in core $M_{core}$	Controls core uncover	Big impact on PCT	Eq. $P_{core} - P_{DC}$
Mass in Intermediate Legs $M_{IL}$	Impacts $M_{core}$ by Loop Seal Plugging (LSP) and Clearing (LSC)	Low Impact on PCT	Eq. (18)

There exist some particular events, which change the phenomenology and the FoM may be very sensitive to the timing of these “bifurcating events”. The Table II below illustrates the main bifurcating events and their potential effects for the same SBLOCA transient.

**Table II. Example of identification of bifurcating events for a PWR Cold leg SBLOCA (see [9])**

Bifurcating events	Type of impact	Effect on $M_1$ and PCT
SCRAM signal	May impact DNB occurrence in early blowdown	No effect in SBLOCA
SI signal	Impact on HPSI injection	Some effect on $M_1$ No effect on PCT
Emptying of pressurizer	Impact on $P$ and on $Q_{break}$	Some effect on $M_1$ No effect on PCT
End of natural circulation	Change of fluid mass repartition Loop seal plugging	Effect on a possible core uncover and PCT
Loop Seal Clearing	Increases swell level in core	End of core uncover: effect on PCT
$P_1$ falls below $P_2$	Necessary to reach accumulator injection and to minimize $Q_{break}$	Significant effect on $M_1$ , on timing of core uncover and on PCT
Accumulator discharge	Increases $M_1$	Significant effect on $M_1$ , on timing of core uncover and on PCT
End of accumulator discharge	$M_1$ will decrease again	Significant effect on $M_1$ , on duration of core uncover and on PCT
LPSI actuation	Increases $M_1$	Significant effect on $M_1$ , on timing and duration of core uncover and on PCT

## 4. THE SCALING EQUATIONS AT SYSTEM AND COMPONENT SCALES

### 4.1. The mass equation at system scale

The equation for total primary mass is:

$$\dot{M} = \dot{M}_{l,in} + \dot{M}_{v,in} - \dot{M}_{l,out} - \dot{M}_{v,out} \quad (10)$$

In a PWR LOCA there is usually a source of water by SI and a sink of liquid and vapour at the break:

$$\dot{M}_1 = \dot{M}_{SI} - \dot{M}_{l,break} - \dot{M}_{v,break} \quad (11)$$

If the SI flow rate and the break flow rate are reduced by the volume ratio, the equations for PWR and IET are similar with the same timing.

### 4.2. The pressure equation at system or component equation

Based on the phase energy equation, the phase mass equation and the constant fluid volume one may derive the following pressure equation (see Bestion, 2019, [11]).

$$\begin{aligned} (\mu_l \cdot M_l + \mu_v \cdot M_v) \cdot \dot{P} = & \dot{M}_{l,in} \cdot [v_l + v'_{l,h} \cdot (h_{l,in} - H_l)] + \dot{M}_{v,in} \cdot [v_v + v'_{v,h} \cdot (h_{v,in} - H_v)] \\ & - \dot{M}_{l,out} \cdot v_l - \dot{M}_{v,out} \cdot v_v + v'_{l,h} \cdot W_{w,l} + v'_{v,h} \cdot W_{w,v} + \frac{W_{w,i}}{\varpi} + v'_{l,h} \cdot W_{i,l} + v'_{v,h} \cdot W_{i,v} \\ & - \frac{W_{i,v} + W_{i,l}}{\varpi} \end{aligned} \quad (12)$$

With:  $v'_{k,p} \triangleq \frac{\partial v_k}{\partial p} \Big|_{h_k}$  ;  $v'_{k,h} \triangleq \frac{\partial v_k}{\partial h_k} \Big|_p$  ;  $\mu_k = -v'_{k,p} - v_k \cdot v'_{k,h}$  ;  $\varpi \triangleq \frac{h_v - h_l}{v_v - v_l}$

$M_i = \frac{W_{i,v} + W_{i,l}}{\varpi}$  being the mass flow rate at interface by vaporization or condensation (kg/s).

$M_{i,w} = \frac{W_{w,i}}{\varpi}$  being the mass flow rate by vaporization or condensation at the wall (kg/s).

All the terms are equivalent to a volume flow rate or Volume Rate of Change (VRC). Since the volume is constant, the sources of fluid volume are compensated by the sinks. The l.h.s term is the change of volume by contraction/expansion in pressure increase/decrease. The two first r.h.s terms are the fluid volume sources entering and the corresponding thermal contraction/expansion due to mixing. The 4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> r.h.s terms are due to thermal contraction/expansion and boiling/condensation due to wall heat exchanges. The 7<sup>th</sup>, 8<sup>th</sup> and 9<sup>th</sup> r.h.s terms are terms due to thermal contraction/expansion and boiling/condensation due to interfacial heat exchanges.

There are situations where both phases are close to saturation in a circuit (e.g. during SBLOCA). One may have a simpler pressure equation assuming perfect thermal equilibrium.

$$\begin{aligned} (\lambda_l \cdot M_l + \lambda_v \cdot M_v) \cdot \dot{P} = & \dot{M}_{l,in} \cdot \left( v_{ls} + \frac{h_{l,in} - h_{ls}}{\varpi_s} \right) + \dot{M}_{v,in} \cdot \left( v_{vs} + \frac{h_{v,in} - h_{vs}}{\varpi_s} \right) \\ & - \dot{M}_{l,out} \cdot v_{ls} - \dot{M}_{v,out} \cdot v_{vs} + \frac{W_w}{\varpi_s} \end{aligned} \quad (13)$$

With:  $\lambda_k = \frac{h'_{ks,p}}{\varpi_s} - \frac{v_{ks}}{\varpi_s} - v'_{ks,p}$  ;  $\varpi_s \triangleq \frac{h_{vs} - h_{ls}}{v_{vs} - v_{ls}}$  ;  $h'_{ks,p} \triangleq \frac{dh_{ks}}{dp}$  ;  $v'_{ks,p} \triangleq \frac{dv_{ks}}{dp}$

This assumes that all wall HT are creating vaporization or condensation. In a PWR SBLOCA, one can use Eq. (12) or Eq. (13) and write:

$$(\mu_l \cdot M_l + \mu_v \cdot M_v) \cdot \dot{P} = Q_{SI} - Q_{break} + Q_{core} - Q_{SG} + Q_{ow} + Q_i \quad (14)$$

$$(\lambda_l \cdot M_l + \lambda_v \cdot M_v) \cdot \frac{dP}{dt} = Q_{SI} - Q_{break} + Q_{core} - Q_{SG} + Q_{ow} \quad (15)$$

With:  $Q_{SI} = \dot{M}_{LSI} \cdot [\nu_l + \nu'_{l,h} \cdot (h_{l,in} - H_l)]$  ;  $W_i = \varpi \cdot Q_i$

### 4.3. The mixture momentum equation and $\Delta P$ equations

A mixture momentum equation or a  $\Delta P$  equation may express the relation between the mass flow rate and the pressure differences due to pumps, gravity, and wall friction:

$$\frac{\partial G}{dt} + \frac{1}{A} \cdot \frac{\partial A \cdot [G_v \cdot u_v + G_l \cdot u_l]}{dz} + \frac{\partial P}{\partial z} = \rho_m \cdot g_z - \frac{C}{A} \cdot \tau_w - \frac{K_s}{\delta z} \cdot \frac{G^2}{2 \cdot A \cdot \rho_m} + \frac{\Delta P_{pump}}{\delta z} \quad (16)$$

$$\rho_m = \alpha \cdot \rho_v + (1 - \alpha) \cdot \rho_l$$

The two last terms are related to singular pressure losses and to pump head. Integrating this equation along a closed cooling loop from  $z_0$  to  $z_0$  writes:

$$\frac{\partial \dot{M}}{dt} \sum_i \frac{L_i}{A_i} = \int_{z_0}^{z_0} \rho_m \cdot g_z dz - \sum_i \frac{C f_i \cdot G_i^2 \cdot L_i}{2 \cdot D_i \cdot \rho_{m,i}} - \sum_j \frac{K_{s,j} \cdot G_j^2}{2 \cdot A \cdot \rho_{m,j}} + \Delta P_{pump} \quad (17)$$

The circuit has been split into successive sections of length  $L_i$ , diameter  $D_i$  and cross section  $A_i$ . It is often useful to integrate it from top of core to top of the downcomer (DC) in a quasi-steady approximation for a natural circulation situation:

$$-P_{DC} = \int_{core}^{DC} \rho_m \cdot g_z dz - \sum_i \frac{C f_i \cdot G_i^2 \cdot L_i}{2 \cdot D_i \cdot \rho_{m,i}} - \sum_j \frac{K_{s,j} \cdot G_j^2}{2 \cdot A \cdot \rho_{m,j}} \quad (18)$$

This pressure difference is often approximately equal to the difference of liquid head in core and DC:

$$P_{core} - P_{DC} \approx (\rho_{ls} \cdot H_{C,core} - \rho_l \cdot H_{C,DC}) \cdot g \quad (19)$$

However all these equations are coupled to energy equations to predict the evolution of liquid and vapour flow rate and to force balance to predict the void fraction distribution or the slip velocity between phases.

### 4.4. Equations for the void fraction

Elimination of the pressure gradient between liquid and vapour momentum equations results in this force balance:

$$A \cdot \frac{\partial \alpha \cdot (1 - \alpha) \cdot [\rho_v \cdot u_v - \rho_l \cdot u_l]}{\partial t} + \frac{\partial A \cdot \alpha \cdot (1 - \alpha) \cdot [\rho_v \cdot u_v^2 - \rho_l \cdot u_l^2]}{\partial z} + A \cdot p_i \cdot \frac{\partial \alpha}{\partial z} = \quad (20)$$

$$A \cdot \alpha \cdot (1 - \alpha) \cdot \Delta \rho \cdot g_z - A \cdot \tau_i - (1 - \alpha) \cdot C_v \cdot \tau_{wv} + \alpha \cdot C_l \cdot \tau_{wl} + F^{AM} + A \cdot \Gamma_{iv} \cdot W_i$$

In quasi-steady-state vertical flow at medium velocity, it simplifies to:

$$\tau_i = A^i \cdot C f_i \cdot \rho_v \cdot (u_v - u_l)^2 \approx \alpha \cdot (1 - \alpha) \cdot (\rho_l - \rho_v) \cdot g_z - (1 - \alpha) \cdot C_v \cdot \tau_{wv} + \alpha \cdot C_l \cdot \tau_{wl} \quad (21)$$

In quasi-steady-state vertical flow at low velocity, it simplifies to:

$$\tau_i = A^i \cdot C f_i \cdot \rho_v \cdot (u_v - u_l)^2 \approx \alpha \cdot (1 - \alpha) \cdot (\rho_l - \rho_v) \cdot g_z \quad (22)$$



In a core with low velocity, one can use this equation to determine the swell level  $H_{sw}$  as a function of the collapsed level  $H_c$ , which corresponds to the core liquid mass (see Figure 2).

#### 4.5. The fuel rods energy equations

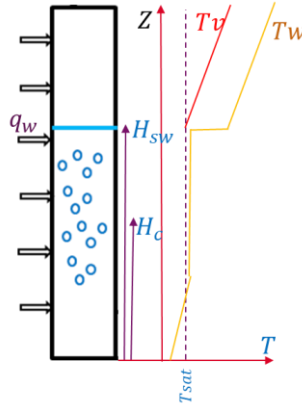
Before reaching a quasi-steady state with the stabilized  $T_v$  and  $T_w$  axial profile, the main inertia is on the rods side controlled by the equation:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \lambda \cdot \left[ \frac{1}{r} \cdot \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right] + W_{vol} \quad (23)$$

One may estimate the conduction time scale in the rods and the heating time scale of the rods by:

$$\tau_{cond} = \frac{\rho \cdot C_p \cdot \Delta r^2}{\lambda} ; \quad \tau_{inertia} = \frac{\rho \cdot C_p \cdot \Delta T}{W_{vol}} \quad (24)$$

$\tau_{cond}$  may be respected by respecting bundle geometry and  $\rho \cdot C_p / \lambda$ .  $\tau_{inertia}$  may be respected by respecting  $\lambda_v = \lambda_w = \lambda_Q$ . This imposes  $\lambda_z = 1$ .



**Figure 2. Illustration of a core uncover situation in a PWR SBLOCA with temperature excursion above the swell level**

By integrating the vapour energy equation along  $Z$  and using the HT law, one may determine  $T_v(Z)$  and  $T_w(Z)$  in a steady state:

$$T_v(Z) - T_{sat} = + \int_z \frac{4 \cdot (Z - H_{sw})}{G_v \cdot D \cdot C p_v} \cdot q_{w,v}(Z) \quad (25)$$

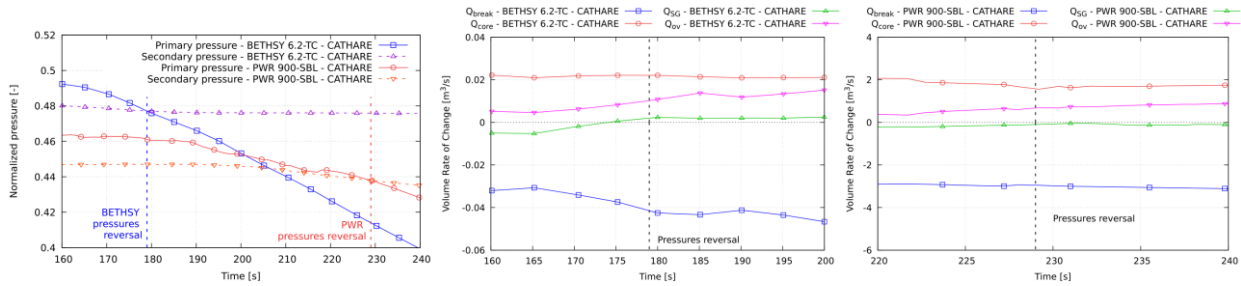
$$T_w(Z) = T_v(Z) + \frac{q_{w,v}(Z) \cdot D_h}{\lambda_v \cdot Nu_v} \quad (26)$$

One can also estimate the PCT for a stabilized swell level and the time period  $\Delta t$  to reach this stabilized clad temperature profile. This is an example of using scaling equations to quantify the impact of distortions on the PCT.

#### 4.6. The benefit of using system codes for scaling and for code model improvements

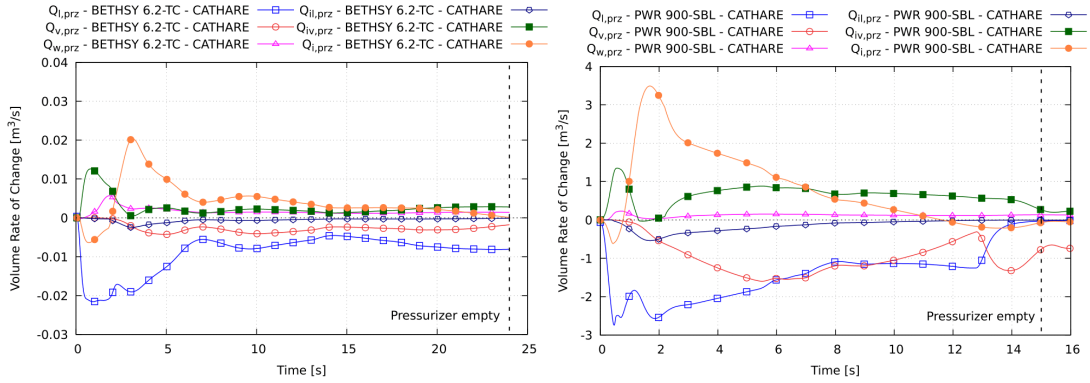
One main benefit of using system codes for scaling analyses is that the terms of the scaling equations can be estimated as function of time and may provide more information than a coarse estimation of terms for a transient phase. Figure 3 shows the CATHARE code simulations (from Ciechocki et al, [9]) of a 6% cold

leg SBLOCA transient of a PWR and the corresponding 6.2-TC transient in the BETHSY ITF, which was scaled using the power-to-volume scaling method and the height conservation [12]. A very important bifurcating event is the crossing of primary and secondary pressures since it initiates a second depressurization and has an impact on the timing of the accumulator discharge. The various terms of a primary pressure equation are grouped into four contribution: the volume flow rate at the break  $Q_{break}$ , the Volume Rate of Change (VRC) in the core due to heating and vaporization  $Q_{core}$ , the VRC due to heat transfer in SG  $Q_{SG}$  and the interfacial and wall heat and mass exchanges in other components  $Q_{ov}$ . The time of pressure crossing is earlier in BETHSY than in the PWR and this was attributed to different pressure in the SG. However, one may observe (see Figure 3) that the primary pressure evolution is governed by two counteracting dominant processes  $Q_{core}$  which decreases due to decay power and  $Q_{break}$  which decreases due to increasing of steam quality at the break that increases the volume flow rate. Then the heat release by walls  $Q_{ov}$  is not negligible but has approximately the same relative influence at the time of crossing (called pressure reversal) although one would expect a significant distortion in the IET. This heat release depends on the history of the transient and no coarse evaluation for a transient phase can predict its relative weight better than a code transient simulation.



**Figure 3. Analysis of the pressure crossing in a SBLOCA simulated by CATHARE code. Primary and secondary pressure evolution in a PWR and in the BETHSY IET (left). Contributions to primary pressure decrease for BETHSY (center), and for the PWR (right)**

During the first blowdown phase of the 6% cold leg SBLOCA (Ciechocki et al, [9]), the pressurizers empty and their pressures are mainly governed by the exiting liquid volume flow rate  $Q_{l,prz}$  and the flashing  $Q_{i,prz}$  (Figure 4). During the first one or two seconds  $Q_{l,prz}$  is partly compensated by vapour heating at the interface  $Q_{iv,prz}$ . Then vaporization starts after a “flashing delay” and  $Q_{l,prz}$  is partly compensated by vaporization  $Q_{i,prz}$ . One can see that although the full height scaling of the BETHSY pressurizer maximizes a lot the wall thermal capacity and HT area. The wall HT do not induce a significant distortion of the pressure history. Then one may be surprised by the significant impact of the exiting vapour flow rate  $Q_{v,prz}$ , which is equivalent to the liquid flow rate in the PWR transient. After analysis, one may attribute this to a too coarse nodalization of the pressurizer with a 2-nodes volume module, which does not predict the void gradient in the liquid with a minimum at the bottom where the surge line is connected and a maximum at the free surface due to rising bubbles created by flashing. Therefore, one may suggest a more detailed 1-D modelling of the pressurizer for transients where the pressure history during the pressurizer emptying may affect the CHF occurrence in the core. This does not apply to SBLOCA but may occur in LBLOCA and in some IBLOCA. This simple use of a “scaling equation” evaluated by a system code illustrates how it can help capturing the physics of the transient phase, identifying quickly the dominant processes and quantifying the impact of distorted phenomena, but also suggesting some weaknesses of the code nodalization.



**Figure 4. Analysis of pressure evolution during the emptying of the pressurizer in a SBLOCA. Contributions to the depressurization for the BETHSY simulation (left) and for the PWR simulation (right).**

Another distortion was observed in the BETHSY calculation [9] due to an accumulator discharge, which is much faster than in the reactor. This is due to the full height design of the BETHSY accumulator. It has the advantage to represent the gravity head in the accumulator even during the discharge but it overestimates the heating of the nitrogen ( $N_2$ ) by walls when pressure decreases. A linear scaling of the accumulator would be more realistic with a distortion of the gravity head but a much lower distortion of the  $N_2$  heating. One may use two pressure equations for the primary circuit and for the accumulator to predict the discharge flow rate. One may also expect another distortion of this flow rate due to Direct Contact Condensation (DCC) in the cold leg due to safety injections (SI). When there is a stratified flow in CL, the interfacial heat transfer laws overestimate the condensation for a reduced CL diameter. The two distortions overestimate the discharge flow rate, which may significantly underestimate the PCT. One may then recommend to paying a specific attention on the uncertainty and the scalability of the condensation model to guaranty the code scalability for the reactor calculation.

## 5. COMMENTS ON THE ACCEPTABILITY THRESHOLD OF DISTORTIONS

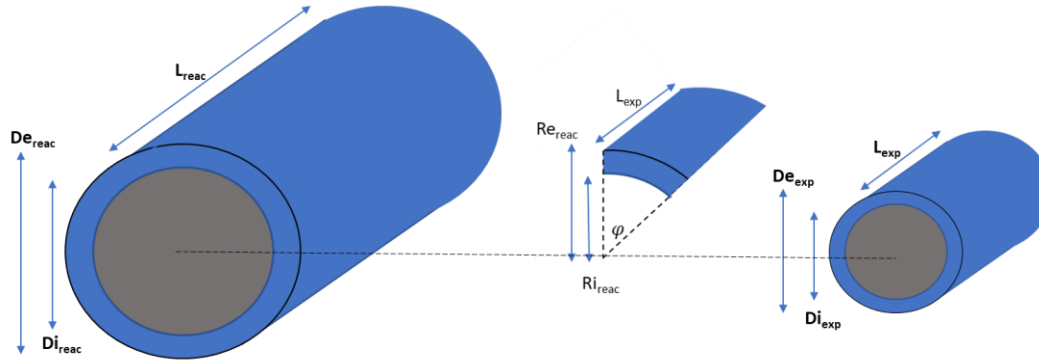
The existing acceptability thresholds for the distortions just give arbitrary limits to ratios  $R_j = \Pi_j^{exp} / \Pi_j^{reac}$  of non-dimensional numbers for each distorted process  $j$  such as  $0.5 < R_j < 2$ . These criteria are very coarse and do not provide reliable guaranty of sufficient fidelity of the phenomenology. One should check first that the distortions do not miss any important bifurcating event. Then one may estimate the quantitative impact of each distortion on the PoI and on the FoM. This may be achieved by adding calculations with changes in the IET or reactor model to remove one by one the distortions. They were called “hybrid calculations” by Reventos et al. [6]. An example is given below.

### 5.1. Removing distortions of thermal inertia and heat losses of ITF metallic structures

External wall of circuits have an overestimated thermal capacity in reduced scale ITF. They may also have an overestimated heat transfer area with fluid and external atmosphere. There is a possibility to correct this distortion by modelling fully scaled heat structures in the ITF model as shown in Figure 5. If a power-to-volume scaling is used ( $\lambda_V = \lambda_W$ ) for the reduced scale experiment, one should apply a thermal structure to the experiment wall of a pipe that is a fraction of the corresponding reactor pipe wall such as:

$$Ri = Ri_{reac}, Re = Re_{reac} \text{ and } \varphi \cdot L_{exp} \cdot Ri_{reac} = \lambda_W \cdot L_{reac} \cdot Ri_{reac}. \quad (27)$$

This guaranties that the heat transfer areas between fluid and wall and between wall and atmosphere are well scaled and that the conduction time scale is respected.



**Figure 5. Extraction of a part of a reactor wall to be affected to an experiment to obtain scaled heat transfers - Reactor pipe on the left - ITF pipe on the right- portion of reactor pipe wall affected to ITF pipe**

## 6. THE USE OF SYSTEM CODE FOR AN A POSTERIORI SCALING ANALYSIS

An a posteriori scaling analysis is performed after the ITF is built and the transient simulated. A comparison of code predictions with IET results may reveal code weaknesses. Some of them may be corrected by improvements of some models or some changes of the nodalization. Then the scaling analysis may be revisited and one may better identify what difference between IET and PWR results are due to code weaknesses or to IET distortions and what code model requires a specific attention in UQ and scalability demonstration. In this a posteriori scaling analysis, the use of hybrid calculations is very useful to estimate the impact of scaling distortions.

## 7. CONCLUSIONS AND RECOMMENDATIONS

The application of scaling methods like H2TS or FSA is of great interest to design ITF with controlled distortions but also to analyze system code predictions of reactor transients and of corresponding IET. The use of process time scales in H2TS is an efficient way to identify the impact of some different designs between several ITF, e.g in case of counterpart tests. For each transient, after a PIRT, it is necessary to identify the Figure of Merit (FoM) and a list of Parameters of Interest (PoI) for which “scaling equations” are written to identify the possible scale distortions of a reduced scale ITF.

The circuit fluid mass  $M$ , the system pressure  $P$  and the circulation loop flow rate  $\dot{M}$  are the main PoI to perform the scaling analysis at the system scale since they may challenge the coolability of the core during transients. It has been shown that the estimation of the order of magnitude of each term of such equations can be better obtained using predictions by mature and extensively validated system codes. It provides a time evolution of each PoI although H2TS and FSA just estimate them for a time period called either “transient phase” or “phenomenological window”. This reveals greater accuracy in identifying some distortion or the timing of some bifurcating event.

The cooling loop flow rate is controlled by a mixture momentum equation integrated along the loop. However, the natural circulation flow rate also depends a lot on the void distribution, which requires other specific interfacial force balance equations, which may be specific to the component and to the physical situations. Examples are given.

One may recommend to use system codes for an a priori scaling devoted to the design of ITF and then to revisit the scaling analysis with code calculations including comparison to IET data. This helps in identifying not only distortions of IET but also possible weaknesses of code model. As a guidance for safety analysts, for each transient of interest, one should establish a list of most important PoI, a list of most important bifurcating events, and define a “set of scaling equations” to perform the scaling analysis.

Additional calculations (hybrid calculations) removing one by one the differences between IET and reactor models may help quantifying the impact of distortions. There is no general acceptability threshold for distortions and one should give first a targeted accuracy for the FoM and then try to determine the impact of the distortions on the FoM.

Finally, the combined use of “scaling equations” and of system codes for IET and reactor calculations has several benefits:

- It helps in understanding the phenomenology of a transient.
- It helps identifying weaknesses of the code models.
- It provides more accurate scaling analyses and quantification of distortions.
- Using hybrid calculations can provide an estimation of the effects of distortions on the FoM.
- It helps identifying the code models that require a specific attention in uncertainty quantification and scalability demonstration.
- It is a useful tool in the demonstration of the scalability of a system code.

This work is in progress and requires further efforts for identifying FoM, PoI, bifurcating events and scaling equations for LOCA and other transients.

## NOMENCLATURE

$A$	Cross section of the duct	$m^2$
$C_p$	Specific heat capacity	$J/kg/K$
$C$	Friction perimeter	$m$
$D$	Diameter	$m$
$g$	Acceleration of gravity	$m/s^2$
$G$	Mass flux	$kg/m^2/s$
$H_C$	Collapsed level	$m$
$h_k$	Local specific enthalpy of phase k	$J/kg$
$H_k$	Volume averaged specific enthalpy of phase k	$J/kg$
$H_{sw}$	Swell level	$m$
$K_S$	Singular pressure loss coefficient	-
$M$	Mass	$kg$
$\dot{M}$	Mass flow rate	$kg/s$
$Nu$	Nusselt number	-
$P$	Pressure	$Pa$
$Q$	Volume flow rate or Volume Rate of Change	$m^3/s$
$q$	Heat transfer	$W/m^3/K$
$Re$	External radius	$m$
$Ri$	Internal radius	$m$
$t$	Time	$s$
$T$	Temperature	$K$
$u$	Velocity	$m/s$
$V$	Control volume	$m^3$
$W$	Power	$W$
$z$	Curvilinear abscissa	$m$
$\alpha$	Void fraction	-
$\Gamma$	Interfacial mass transfer per unit volume	$kg/s/m^3$
$\lambda$	Heat conductivity	$W/m/K$
$\lambda_X$	Scaling factor for quantity X	-
$\rho$	Density	$kg/m^3$
$\nu$	Specific volume	$m^3/kg$
$\tau_i$	Interfacial friction force per unit volume	$N/m^3$

$\tau_w$	Wall friction force per unit area	N/m <sup>2</sup>
$v_k$	Specific volume of phase k	m <sup>3</sup> /kg

### Subscripts and superscripts

<i>exp</i>	Experimental	<i>s, sat</i>	Saturation conditions
<i>i</i>	Related to interface	<i>v</i>	Related to vapor
<i>in</i>	Related to entering quantity	<i>w</i>	Related to walls
<i>k</i>	Related to phase k	0	Initial/reference value
<i>l</i>	Related to liquid	1	Related to primary system
<i>m</i>	Related to liquid-vapour mixture	2	Related to secondary system
<i>out</i>	Related to exiting quantity	'	Partial derivative
<i>ov</i>	Related to other volumes than core/SG	.	Variation over time
<i>ow</i>	Related to other walls than core/SG	+	Dimensionless variable

### ACRONYMS AND ABBREVIATIONS

BETHSY	Boucle d'Etudes ThermoHydraulique SYstème
CCFL	Counter-Current Flow Limitation
CEA	Commissariat à l'Énergie Atomique et aux énergies alternatives
CHF	Critical Heat Flux
CL	Cold Leg
CSNI	Committee on the Safety of Nuclear Installations
DC	Downcomer
DNB	Departure from Nucleate Boiling
ECCS	Emergency Core Cooling System
FoM	Figure of Merit
FSA	Fractional Scaling Analysis
HL	Hot Leg
HPSI	High Pressure Safety Injection (see also HPIS)
H2TS	Hierarchical Two-Tiered Scaling
HT	Heat transfer
IET	Integral Effect Test
ITF	Integral Test Facility
IBLOCA	Intermediate Break Loss Of Coolant Accident
LBLOCA	Large Break Loss Of Coolant Accident
NC	Natural Circulation
PCT	Peak Cladding Temperature
PIRT	Phenomena Identification and Ranking Table
PoI	Parameter of Interest
PRZ	Pressurizer
PWR	Pressurized Water Reactor
SBLOCA	Small Break Loss Of Coolant Accident
SG	Steam Generator
SI	Safety Injection
UQ	Uncertainty Quantification
VRC	Volume Rate of Change
V&V	Verification and Validation

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