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Scaling in nuclear reactor system thermal-hydraulics

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ABSTRACT

Scaling is a reference 'key-word' in engineering and in physics. The relevance of scaling in the water cooled nuclear reactor technology constitutes the motivation for the present paper. The origin of the scaling-issue, i.e. the impossibility to get access to measured data in case of accident in nuclear reactors, is discussed at first. The so-called 'scaling-controversy' constitutes an outcome. Then, a critical survey (or 'scaling state-of-art';) is given of the attempts and of the approaches to provide a solution to the scaling-issue in the area of Nuclear Reactor System Thermal-Hydraulics (NRSTH): dimensionless design factors for Integral Test Facilities (ITF) are distinguished from scaling factors. The last part of the paper has a two-fold nature: (a) classifying the information about achievements in the area of thermal-hydraulics which are relevant to scaling: the concepts of 'scaling-pyramid' and the related 'scaling bridges' are introduced; (b) establishing a logical path across the scaling achievements (represented as a 'scaling puzzle'). In this context, the 'roadmap for scaling' is proposed: the objective is addressing the scaling issue when demonstrating the applicability of system codes in the licensing process of nuclear power plants. The code itself is referred hereafter as the 'key-to-scaling'. The database from the operation of properly scaled ITF and the availability of qualified system codes are identified as main achievements in NRSTH connected with scaling. The 'roadmap to scaling' constitutes a unified approach to scaling which aims at solving the 'scaling puzzle' created by researches performed during a half-a-century period.

1. Introduction

Nuclear Reactor System Thermal-Hydraulics (NRSTH) constitutes one of the pillar disciplines for the safety and design technology of water cooled reactors. The discipline was established in the 1950s. Its development had a strong impulse since the 1960s as a response to the safety needs put by the US NRC (Nuclear Regulatory Commission), previously AEC (Atomic Energy Commission) (e.g. US AEC, 1971). The word 'system' became of common use following the OECD/NEA/CSNI (Organization for Economic Cooperation and Development, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations) Conference held in Aix-En-Provence in 1992 (see OECD/NEA, 1992).

The behavior of two-phase mixtures in NRSTH involves the simultaneous presence or the occurrence of phase change, transient conditions, non-developed flows, heated surfaces at different temperatures and complex geometries. Notwithstanding huge investments and thousands of engaged researchers, the prediction capabilities of current numerical (or computational) tools are continuously under scrutiny and improvements are requested and needed. Namely, question marks are put in relation to the 'scaling-capabilities' of the tools or the 'scaling-quality' of the results. This is discussed below.

Two topics (or issues) of the NRSTH testify of the complexity of the discipline and have been part of its half-a-century history:

- The stability of natural circulation in boiling systems, see e.g. SOAR on BWRS (State of the Art Report on Boiling Water Reactor Stability) (D'Auria et al., 1997a).
- The scaling, see e.g. J. NED (Journal Nuclear Engineering and Design) (Special Issue, 1998).

Both topics (related connection also mentioned in the paper) have been the challenge for the investigation by individual scientists who contributed to the development of the NRSTH discipline at least one time during their professional life. Moreover, the words 'closure-of-the-issue' are not part of conclusions of researches performed so far in relation to each of the two topics.

The present paper deals with the second of the above challenges with the generic objective of proposing a roadmap suitable for the closure of the issue. Namely, the target of scaling is the water cooled nuclear reactors whose nominal operating conditions are characterized by high pressure (of the order of 16 MPa), high thermal power (up to 4500 MW_{th}), high power density (either linear power up to 50 KW/m in one-cm diameter fuel rod, or flux up to

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1 Mw/m^2) and the volume bounding the two phase mixture is as large as a few hundred cubic meters. Those figures of merit refer to the typical primary circuit of a LWR (Light Water Reactor); if one includes the containment the volume to be considered comes to a value close to 10^5 m^3. Moreover, inside the bounding volume, flow paths having hydraulic diameters in the range 10^{-3}–10^1 m shall be distinguished.

Whatever is the target for the scaling analysis, the origin of the scaling issue can be characterized as follows: it is infeasible (or cost prohibitive) to perform meaningful experiments at full scale and the ability of numerical tools designed to simulate the performance of nuclear reactors can be proven only at reduced scale.

An agreeable solution for the scaling issue is mandatory within the framework of the so-called BEPU (Best Estimate Plus Uncertainty) approach where 'realistic' computational tools are applied to support the licensing of NPP (Nuclear Power Plants), see e.g. J. STNI (Journal Science and Technology of Nuclear Installations) (Special Issue, 2008). In this case, the qualification of system thermal-hydraulic codes against scaling remains an open question. The relevance of the issue can be recognized from the acronym used by the US NRC when planning the basis for the BEPU, i.e. when proposing the CSAU (Code Scaling and Applicability Uncertainty) methodology (see e.g. J. NED, 1990; USNRC, 1989).

A spot-type historical excursus may serve to focus on the concept of scaling:

(1) Archimedes (287–212 B.C.) was aware of the heating capability of a small mirror when exposed to the sun light. Then the scaling-up idea came (whether or not this is a legend or the history) to burn the Roman ships by large mirrors.
(2) Galileo (1564–1642) is reported to have dropped a ten-pound weight and a one-pound weight off the Leaning Tower of Pisa, and proved that both fall at the same speed. Whether or not this is a legend or the history, he used a large-scale facility (the Tower of Pisa) and real (full scale) cannon balls.
(3) The Buckingham Theorem (Buckingham, 1914) allows the dimensionless combination of variables which are part of a set of equations. The set of equations may be representative of the performance of a physical system. The choice of dimensionless parameters is not unique: the Buckingham Theorem only provides a way of generating sets of dimensionless parameters and will not choose the most physically meaningful. The systems for which these parameters coincide are called similar and the investigation performed in a down-sized (or scaled down) system is valid for a larger system.
(4) In Alamogordo (1945), the first atomic bomb test, the involved nuclear scientists decided to perform a full-scale experiment.
(5) Dimensionless or scale-independent quantities (however, 'dimensionless' is not a synonymous of 'scale-independence') like Re (Reynolds), Pr (Prandtl), Nu (Nusselt), Fr (Froude), Gr (Grashof), are of widespread use in thermo-fluid-dynamics, as reported in any text-book (e.g. Todreas and Kazimi, 1990). Guidelines for scaling complex nuclear systems are provided in the text-book by Levy (1999).

The 'scaling controversy' can be drawn from the items above. Namely, full scale tests (prototypical) have been preferred in a number of situations for addressing technological issues, rather than conducting scaled experiments, thus testifying of the lack of faith towards scaling (i.e. the scaling controversy). The controversy reflects to the area of NRSTH in which case the following can be added:

(a) Looking at the predictability of two-phase regimes in a vertical pipe in steady conditions: bubbly, slug, churn, annular and dispersed regime are (only) some of the regimes that can be distinguished. Empirical equations are (still) needed to characterize the flow-regimes and the flow regimes transitions: some are empirical but others are physically based, i.e. a Kelvin–Helmholtz instability limit for stratification. Related equations are a function of (at least) pressure and diameter of the pipe. Therefore, the possibility of scaling-up, i.e. of confirming the scaling validity, shall be excluded in the case of lack of experimental data.
(b) Looking at the predictability of the transient performance of a nuclear reactor where a numerical code is needed: several tens of closure equations (see e.g. Levy, 1999) are part of the code. Now, the paradox: closure equations in order to be qualified must be derived in the conditions of Steady State and Fully Developed (SS and FD) flow; however, they are unavoidably used in transient (as opposite of SS) and non-developed (as opposite of FD) flow conditions. Thus, even though the (closure) equations are qualified, no scaling-up outside the range of qualification is justified. The argument at the last sentence can be used within the present context, i.e. the difficulty to confirm the validity of scaling laws.

So, scaling is a-priori questionable in NRSTH, i.e. before attempting any analytical derivation, and it is a-posteriori questionable based on arguments at items a) and b). This is basically agreed within the scientific community as given in the conclusion of a relevant paper on the subject, Ishii et al., 1998: "... *the design < of a test facility> cannot completely satisfy all the scaling requirements. Thus, scaling distortions are inevitable ... Distortions are encountered for two major reasons: - difficulty to match the local scaling criteria; - lack of understanding of the local phenomenon itself...*".

Having this in mind, use is made hereafter of the established knowledge and of the recognized achievements in nuclear system thermal-hydraulics. The knowledge and the findings in NRSTH, other than in an dozen text-books (see e.g. Todreas and Kazimi, 1990; Levy, 1999, already mentioned), are embedded in the computer codes. The basis for the knowledge is constituted by the experimental data-base from the operation of a few hundreds Separate Effect Test Facilities (SETF, see OECD/NEA, 1993) and a few tens Integral Test Facilities (ITF, see OECD/NEA, 1987, 1996). Furthermore, scaling refers to space, pressure, power and nature of the fluid.

The answer to the licensing relevant question '*how the scaling capabilities of currently available system codes can be evaluated?*' can be taken as the specific objective for the paper. The field of investigation is restricted to the predictability of transient scenarios in water cooled reactors.

A very wide literature exists in relation to scaling. Thus, bringing innovation in terms of new data or new elaborations of equations constitutes an awkward goal at a time when investments in system thermal-hydraulics are largely reduced (i.e. compared with what was done in the 1970s to 1990s). Thus, an attempt is made to reconcile major approaches and achievements in NRSTH connected with scaling, keeping in mind the scope and the specific objective identified above. Namely, it is not the purpose of the paper to present a comprehensive and consistent review of the scaling in nuclear reactor system thermal-hydraulics, although an attempt to consider main approaches has been made.

2. The background information

Scaling, see the definition given for the scaling issue, can also be characterized as the capability to transpose the values of parameters detected or calculated under an assigned set of Boundary and Initial Conditions (BIC) to a different set of BIC. In the present case

BIC should be intended as having a wide meaning including the geometric data. Thus, in Nuclear Reactor System Thermal-Hydraulics typical parameters which may need to be scaled-up are either fluid and solid material temperatures, fluid velocities, void fractions and mass flow-rates; the relevant BIC that vary due to scaling are the set of geometric dimensions, the power of the core, the power produced per unit length, the pressure of the system.

Although a large amount of important research work has been carried out in relation to fluid-to-fluid scaling (e.g. Ahmad, 1973) the use of fluid different from water appears to be not justified in NRSTH, i.e. water should not be considered as a BIC in the sense mentioned in the previous paragraph. For instance, the advantage of using Freon instead of H20 in experiments simulating water cooled reactor conditions derives from the possibility of lowering the pressure and thus the cost of the research. However, complex accidents exist where temperature differences may drive the thermal-hydraulic scenario evolution in conjunction with local pressure drops (also affected by local voids). In this case, the use of Freon as working fluid may drive the transient to situations far from those predictable when water is circulating in the system. The use of the fluid-to-fluid scaling technique is more justified when 'local' phenomena are of interest. However, caution remarks apply in relation to the 'extrapolation possibility' to water related scenarios of parameters measured in experiment with fluid different from water (see e.g. Tain et al., 1995). In the following, 'scaling-credit' (or credibility for scaling) is given only to experiments or analyses where water constitutes the working fluid.

A comprehensive and suitable synthesis or a State-Of-the-Art (SOA) in the area of scaling in NRSTH would imply the engagement of several scientists and an effort outside the present framework. Nevertheless, an attempt is made in this chapter to give an idea of the current understanding about scaling. This shall be considered as a non-comprehensive 'scaling SOA'.

Different meaningful scales for a scaling study and different approaches to scaling are discussed in Sections 2.1 and 2.2, respectively. Moreover, the connection between scaling and the ITF design and the development of numerical codes is outlined in Sections 2.3 and 2.4. Otherwise, the already mentioned inherent difficulty in performing a comprehensive system scaling analysis can be derived from the discussion in Section 3.

2.1. Different scales for a scaling study in NRSTH

It is well established that thermal-hydraulic phenomena in nuclear reactors are characterized by different scales; connected representative diagrams can be found in the literature (e.g. McClure et al., 2010). Three sectors for scaling analyses are recognized with geometric dimensions playing a major role in the classification:

- The macro-scale, or system-scale. The whole primary circuit, or the containment, constitutes the object of scaling. In steady state conditions, fluid and solid surface temperatures, fluid velocities, void fraction and pressure drops are example of variables that shall be correlated in the model and in the prototype (see definitions below). In transient conditions, system pressure, total mass inventories and level distribution are examples of variables that shall be correlated.
- The component-scale, or zone-scale, or phenomenon-scale. At first, one of the following should be identified: (a) a component, e.g. the pump, or the separator, or the core region, (b) a zone, e.g. the upper plenum, or the connection between cold leg and downcomer, (c) a phenomenon, e.g. the Two-Phase Critical Flow (TPCF) at the break, or the Countercurrent Flow Limiting (CCFL) at the Upper Tie Plate (UTP), or the Critical Heat Flux (CHF) in the core region. Then, the variables affecting the component performance, the phenomena occurring in the assigned zone or the time window for the evolution of the phenomenon, shall be identified. Finally, suitable links shall be established between evolutions of the variables in the model and in the prototype.
- The micro-scale, or local-scale. The attention is focused to one geometric point or better to a 'small zone' (volume as small as of the order of 1 mm^3) of the reactor system. The basic question addressed is: '*does a qualified experiment or qualified calculations exist from which data can be derived that have the same values (or eventually scaled-down values with available scaling factors) that are expected in the assigned small zone of the reactor at a given time?*'. In other terms, '*do there is the possibility to affirm that, either experimental data or code calculation results, are able to characterize the value of a thermal-hydraulic parameter valid 'locally' (e.g. the location of PCT <Peak Cladding Temperature> or the steam velocity at the PCT location) with no or 'small' uncertainty?*'. The answer to the above questions is no.

A comprehensive scaling analysis in nuclear reactor technology shall address and actually addresses each of the three sectors (bullet items above). However, reasonable demonstration of fulfilling the objectives is provided, from the available literature, in relation to the first two sectors, as discussed below (see e.g. the use of Fractional Scaling Analysis including data from Integral and Separate Effect facilities).

Now, let us consider the question at the 3rd bullet item which also applies to the two previous bullet items with proper changes in wording. Two sides of the question are distinguished: (1) the 'values expected at full scale' are unknown; (2) there is no theorem or principle which allows the attribute 'qualified' either for scaled-down test data or for calculation results which, eventually, need extrapolation. Therefore, the strict answer to the question is "no", as already reported. This definitely applies to the 'micro-scale' and can be propagated to other two scales, also reflecting the 'scaling controversy' mentioned in Section 1.

2.2. The classic approaches to scaling

How to simulate the transient performance of an up-to-4500 MW_{th} LWR (also called prototype hereafter) by a less than approximately 10 MW_{th} ITF (also called model hereafter), with the noticeable exception of LOFT (Loss of Fluid Test, OECD/NEA, 1991), constitutes the 'classic' scaling problem. Key aspects connected with the problem (see also the operating conditions values given in Section 1) can be summarized as follows:

- Thin cylindrical bars with external diameter of the order of 0.01 m constitute the nuclear fuel rods in any LWR (up to about 50,000 rods having 'active' length of about 4 m are part of the core).
- The rod surface (or clad) temperature, T_w, constitutes a target variable for the scaled design; linear power, q', produced inside the fuel rods is among the key parameters affecting the clad temperature.
- During steady-state (nominal operation) as well as in case of a transient (accident), T_w is affected, when the core geometry is the same for the model and the prototype, by q' (already mentioned), by fluid pressure, temperatures and velocities and by void fraction. Namely, the influence of fluid velocities upon the heat transfer coefficient may impose the need for pumps if T_w constitutes an important variable for the simulation.
- In case of accident conditions the performance of Emergency Core Cooling Systems, e.g. affecting the coolant mass inventory in the system, shall be simulated in the scaled system.
- In a great number of transient conditions core cooling is ensured by gravity: thus consideration of gravitational heads is essential.
- Water is the accepted working fluid in the model and in the prototype: thus, large changes in the steam and liquid properties

with pressure may impose the condition of 'full pressure' in the simulation.

The power-to-volume scaling, typically associated with the full-pressure, full-height and time-preserving requirements can be seen as the first (in historical terms) proposed solution to the scaling problem in NRSTH. This is discussed in Section 2.2.1. In that section, design factors derived from basic principles (i.e. not even the balance equations) and suitable for building NPP simulators are listed all together.

It is easily seen that the power-to-volume scaling together with associated requirements has two main drawbacks, specifically in the case when transients governed by gravity heads are concerned: (a) cost of the facility; (b) strong impact upon the transient evolution of thermal power release from passive structures. In order to overcome these drawbacks, fundamental research has been performed by Ishii and is outlined in Section 2.2.2.

Starting from the 1960s, Zuber, primarily with the support from US NRC, provided a continuous contribution to key issues in thermal-hydraulics including the scaling. His ideas are discussed in Section 2.2.3.

At some point in the history of system thermal-hydraulics, i.e. beginning of 1980s, the issues of validation of computational tools and of evaluation of uncertainty associated with any calculated results became relevant. The connection between scaling and uncertainty is discussed in Section 2.2.4 dealing with the CSAU (Code Scaling, Applicability and Uncertainty) procedure. Otherwise, the connection between scaling and validation is mentioned primarily in Section 4.2.

During the last two decades, i.e. 1990s and 2000s, reactor specialists from Russia and Far East Countries (primarily South Korea and Taiwan) made available their contributions to the solution of the scaling issue and the same issue became important for the design of advanced reactors. Thus, a short survey of related scaling achievements is provided in Section 2.2.5.

As already mentioned (e.g., see J. NED Special Issue, 1998), a large number of top level scientists were engaged to address the scaling issue and excellent scaling reviews can be found (e.g. Yun et al., 2004). Selected findings are summarized in Section 2.2.6, where emphasis is given to selected-representative scaling factors that are cross-correlated with design factors from Section 2.2.1.

The connection between scaling and licensing is emphasized in Section 2.2.7.

Within the present framework and consistently with Zuber recommendations the need of hierarchy among scaling factors (however, this idea is shared or accepted by the majority, or even by all researchers in the area), is recognized. Hereafter, inconsistently with Zuber recommendations (discussed below) the computer code is put at the center of the attention for performing the scaling process. This is characterized as the 'key-to-scaling'.

2.2.1. The power-to-volume scaling and the design factors

The needs to design and to construct experimental facilities capable of 'simulating' the NPP performance, noticeably the PWR, constituted a challenge for the involved scientists due to the contradictory requirements coming from 'safety relevance' and 'cost constraints'. This happened the first time in the 1960s when the US NRC (Nuclear Regulatory Commission, AEC at that time) requested a suitable evidence of the capabilities of the ECCS (Emergency Core Cooling Systems) to keep cooled the core following LOCA (Loss of Coolant Accident).

Primordial set of scaling parameters were introduced for justifying the design and the operation of Semiscale and Loft facilities in the US, see e.g. the pioneering works by Carbiener and Chudnik (1969) and Ybarrondo et al. (1974), that later on were put in an archival form by Navahandi et al. (1982), Larson et al. (1982), Karwat (1983), and Kiang (1985). Till the TMI-2 accident, i.e. 1979, the attention for the simulation was focused toward the LB-LOCA (Large Break LOCA), however in the 'post-TMI' the above referenced papers also considered SB-LOCA (Small Break LOCA) phenomena (additional details related to the role of Loft in relation to scaling, are given in Section 3.4 with focus to LB-LOCA).

Facilities like Lobi, Spes, Bethsy and the Rosa series (noticeably the Lstf) were designed and built (or modified) in Europe and in Japan for the simulation of SBLOCA in PWR, after the occurrence of the TMI-2 accident; see e.g. the data base collected by D'Auria et al. (1994) and Ingegneri et al. (1997).

At this point in the history of NRSTH, i.e. decades 1980s and 1990s, the power-to-volume scaling approach, time-preserving, full-height, full-pressure was the preferred practical way to address the scaling issue within the area of ITF design, as already mentioned. However, three kinds of principles were distinguished (e.g. Navahandi et al., 1982)

(1) Time reducing or linear scaling.
(2) Time preserving or volume scaling.
(3) Idealized time preserving.

The first set implies the reduction of the linear dimensions of the prototype by a given factor and, in transient conditions, the reduction of time by the same factor. In this case, the amount of power transferred to the fluid is reduced as the square of the linear dimension factor. The second set of criteria is at the origin of the dimensionless design factors discussed below and the third set of criteria actually resembles the second set, with more flexibility left to the designer, being the 'time preserving' the main objective for the application.

The dimensionless design factors are applicable for the design of facilities and experiments. They can be derived directly from the principles of conservation of mass, momentum and energy. As a difference, the scaling factors are derived from the more or less complex balance equations for single and two phase flow. Scaling factors obtained from simplified balance equations can be used to derive design factors.

A synthesis list of design factors that characterize the power-to-volume scaling can be found in Table 1 (e.g. D'Auria and Vigni, 1985; D'Auria et al., 1988, in these papers, where a hypothetical PWR simulator and an experiment are designed, respectively). Two groups of design factors '*K*' can be distinguished dealing with the ITF hardware and the test BIC, respectively. Here, '*K*' is the ratio 'quantity value in the model/quantity value in the prototype'.

The hardware of the hypothetical ITF is subdivided into the following zones: (a) LP (Lower Plenum) of RPV (Reactor Pressure Vessel); (b) CO (Core); (c) CO-BY Core Bypass; (d) UP (Upper Plenum); (e) UH (Upper Head); (f) HL-h (Hot Leg, horizontal part); (f) HL-v (HL, vertical part); (g) PRZ (Pressurizer); (h) SU-LI (Surge Line of PRZ); (i) LS (Loop Seal); (j) MCP (Main Coolant Pump); (k) CL-h (Cold Leg, horizontal part); (l) DC (Down-Comer) of RPV; (m) SGI (Steam Generator Inlet Plenum, Primary Side); (n) SGO (Steam Generator Outlet Plenum, Primary Side); (o) SG UT PS (Steam Generator, U-Tubes, Primary Side): (p) SG UT SS (Steam Generator, U-Tubes, Secondary Side); (q) SG DC (Down-Comer, Secondary Side); (r) SG UP-SEP (Upper Plenum and Separator, Secondary Side); (s) SG UH-DRY (Upper Head and Dryer, Secondary Side).

The information in the table is self-explanatory. However it can be noted that the *Kv* value is the key for the design and its value is strictly connected with the available financial resources. Adopted criteria imply that mass and energy in the model are properly scaled (according to *Kv*) in relation to the prototype.

In case of LOCA, the break area should be scaled according to the parameter at row 6 in the table, i.e. the ratio A_R/V shall be preserved. Furthermore, the break location should also be preserved consid-

Table 1
Synthesis of dimensionless design factors characterizing the power-to-volume scaling (top level hierarchy factors).

No	Design factor	Scaling of:	Zone of the ITF	Notes
1	$K_v = K_{v\text{-max}}$	Volume	Each Zone	The largest is the best.
2	$K_h = 1$	Elevation change	CO, CO-BY, UP, HL-v, PRZ, SU-LI, LS, MCP, DC, SGI, SGO, SG UT PS, SG UT SS, SG DC	In the case of LS, the pipe axis or the bottom edge of the pipe in the prototype should be considered.
3	$K_{N.L.} = 1$	Number of loops	System	To study asymmetries.
4	$K_h \leq 1$	Elevation change	LP, UH, SG UP-SEP, SG UH-DRY	
5	$K_L = 1^*$	Length of horizontal components	HL-h, CL-h	* Not possible in general. Friction pressure drop must be preserved (see also row 7).
6	$K_A = K_{Abr} = K_v$	Cross and break area	Each vertical zone	Related to fluid flow.
7	$K_{D.eq.} = 1$	Hydraulic diameter	CO and SG UT, primarily. Each zone as far as possible.	Froude number scaling is preferred for horizontal pipes.
8	$K_W = K_v$	Power	CO, SG UT	Energy to fluid shall be scaled.
9	$K_t = 1$	Time	System	Key target for transient simulation.
10	$K_{q'} = 1$	Linear power	CO, SG UT	Number of heated rods and of U-Tubes scaled as K_v. Volumetric power is a target.
	$K_{q'''} = 1$	Volumetric power		
11	$K_{f.r.g.m.} = 1$	Fuel rod geometry and material	CO	Target for the design together with previous condition.
12	$K_T = 1$	Fluid temperature	Each zone	Initial condition. Target for transient simulation.
13	$K_P = 1$	Pressure		
14	$K_{r.s.T.} = 1$	Rod surface temperature	CO (primarily) and SG UT	Target for transient simulation.
15	$K_{r.s.h.f.} = 1$	Rod heat flux		
16	$K_{p.h.t.a.} = K_v$	Passive heat transfer area	Each zone	Impossible to achieve. Resulting distortions to be characterized.
17	$K_{th.p.s.} = 1$	Thickness of passive structures		
18	$K_{h.l.e.} = 1$	Environment heat losses		Impact to be minimized.
19	$K_G = K_v$	Mass flow rate		–
	$K_\upsilon = 1$	Fluid velocity		
20	$K_{\Delta p} = 1$	Pressure drops (friction and local)		Flexibility (e.g. orifice optimization) needed.
21	$K_{G.ECC} = K_v$	ECC flow	ECCS	ECCS injection ports shall be preserved.
22	$K_{T.ECC} = 1$	ECC temperature		
23	$K_{G.SL} = K_v$	Steam line flow-rate	SG UH-DRY	Quality at steam line inlet shall be the same.
24	$K_{G.FW} = K_v$	Feed-water flow	SG DC	Boundary condition.
25	$K_{T.FW} = 1$	Feed-water temp		
26	$K_{RR} = 1$	Recirculation ratio		Target for the design.
27	$K_{MCP.ch} = 1$	Non-dimensional characteristics for pumps and valves	MCP	Boundary condition.
28	$K_{VLV.ch} = 1$		Valves of PS and SS	

ering the proper geometric location and the curve 'pressure-drop vs loop length', i.e. criterion at row 20.

The scaling factors which give origin or are consistent with the design factors in Table 1 shall be classified as the 'primary scaling parameters', as discussed in Section 2.2.6. The following remarks apply (i.e. in addition to the notes provided in the last column of the table):

- Even though an attempt is made to list scaling criteria independent among each other, priority is given to get a comprehensive list of parameters suitable for the design of the PWR-ITF.
- The design factors at rows 6, 7 and 20 may appear inconsistent. The key requirement is represented by item 20 ($K_{\Delta p} = 1$). The remaining two parameters should be adjusted accordingly, i.e. minimizing other (unavoidable) scaling distortions.
- The requirement (target) at row 14 is ensured by the condition set at row 10, primarily. However, proper consideration shall be given to the materials and to the control of the electric power supply when fuel rod simulators are (in the majority of cases) electrically heated. The material configuration of electrically heated rods (in the typical ITF, i.e. fuel rod simulators) should be considered in order to ensure that energy to the fluid is properly scaled down (e.g. Carbone et al., 1980). The thermal energy to the fluid shall be evaluated during the entire transient (namely, a LB-LOCA) evolution time, also considering the stored energy at nominal operating conditions.
- The parameter at row 20 includes the MCP head in nominal conditions, also reported at row 27. The parameter at row 20 should be checked all around the primary loop and, in the secondary loop as far as possible.
- The parameter at row 26 should be a consistent with the pressure drop distribution in the secondary side of the steam generator.
- The parameter at row 28 can also be taken as a consequence of parameters at rows 6 and 20.

2.2.2. *The Ishii scaling*

Remarkable four decades contributions related to the scaling issue came from Prof. Mamoru Ishii (e.g. Ishii and Jones, 1976; Schlegel et al., 2009), with key document constituted by the paper Ishii et al. (1998). Two topics/subjects (underlined below) are taken from this last paper and discussed hereafter; the second one characterizes the so-called Ishii approach:

(1) Recognizing the scaling hierarchy (i.e. when designing an ITF): an 'integral system scaling' is performed whose components comprise the first two levels, and the phenomenological scaling constitutes the third level. More specifically, the scaling is considered as follows: (a) the integral response function scaling, (b) the control volume and boundary flow scaling, and (c) the local phenomena scaling. A top-down approach is pursued in the first two levels and the bottom-up approach in the third level.
(2) Identifying the 'reduced length (and height)' as a scaling advantage, also in connection with cost reduction when building up a facility.

Related to item (1), sub-item (a), eight established numbers are proposed to be preserved from non-dimensionalising the balance equations: the "Zuber" (or "Phase-change"), the "Sub-cooling", the "Froude", the "Drift Flux", the "Friction", the "Orifice", the "Time" and the "Thermal Inertia". The first six (over 8) 'numbers' are consistent with the design parameters listed in Table 1. The last two 'numbers' include the parameter 'conduction depth' which depends upon the thickness and the material of solid structures: these constitute a target for scaling and not a parameter depending upon the thermal-hydraulic designer. Therefore, these parameters are not part of Table 1: this implies that an attempt is made at the design level to fulfill the targets put by the "Time" and the "Thermal Inertia" numbers, but distortions are unavoidable.

When performing the scaling analysis under the sub-item (b), the basis for reduced height scaling is introduced as discussed under the item (2). Other parameters introduced under the sub-item (b) are basically consistent with the design parameters listed in Table 1.

A variety of local phenomena are considered when performing the sub-item (c): when the variables characterizing the local phenomena are the same as the independent unknowns of the balance equations, consistency with design criteria in Table 1 is achieved; otherwise, Ishii requirements are not consistent with the design criteria in Table 1. An example of this is the design factor for the break flow area which is connected with the height (or length, see also below) scaling criteria: in case the length scaling criterion is 1/4, the break flow area results 2 times smaller than the (ordinary) fluid flow area. This implies the consideration of homogeneous flow upstream the break, which cannot be among the design criteria in Table 1.

Related to item (2) the authors emphasize the need to satisfy the equation $[fL/D+\kappa]_R = 1$ (symbols are given in Table 2). They realize that, in any model, the flow area is necessarily smaller than in the prototype and, apart for the core region (as the authors note), the equivalent diameter '*D*' is also smaller. Thus, reducing 'L' contributes to make easier the fulfillment of the above equation. This is the consideration at the basis of the 'Ishii-scaling' and is mentioned hereafter as Ishii scaling attribute.

The authors found, consistently with the balance equations at the basis of the design criteria in Table 1, that ". . .if the axial length is reduced in the model, then the time scale is shifted <e.g.> in the two-phase flow natural circulation loops. In such a case, the events are accelerated in the scaled-down model by a factor given by $(K_L)^{1/2}$ (symbol in Table 1) over the prototype. . . . This leads to the very important conclusion that for systems involving both single and two-phase flow in a reduced length model, real-time scaling is not appropriate".

The result from the overall scaling analysis, namely connected to sub-items (a) and (b) of step (1) is constituted by the following design parameters for the Puma ITF, simulator of the Simplified Boiling Water Reactor (the same symbols as in Table 1 are adopted) (Ishii et al., 1998), already mentioned:

- $K_p = 1$
- $K_h = 1/4$
- $K_t = (K_h)^{1/2}$
- $K_\upsilon = (K_h)^{1/2}$
- $K_{q'''} = (K_h)^{-1/2}$
- $K_A = K_v K_h$
- $K_{Abr} = K_A (K_h)^{1/2}$

It shall be noted that all design parameters would coincide with the parameters in Table 1 in the situation (not suggested by Ishii) when $K_h = 1$ (2nd bullet item in the list above and row 2 in Table 1).

The 'direct' impact of the Ishii scaling upon the present framework is connected with the application of the scaling factors and the consequent demonstration of quality for the value of those factors. The demonstration can be achieved from the comparison between corresponding experimental data measured in ITF designed following the Ishii-scaling and ITF designed based on $K_h = 1$ and time preserving laws, as mentioned in Section 3.5.

2.2.3. The progress due to Novak Zuber

A special mention is deserved to Novak Zuber owing to his long-term engagement in the area of system thermal-hydraulics (e.g. from Kroeger and Zuber, 1968; Zuber et al., 2007, see also contribution to CSAU in Section 2.2.4). In addition, the reputation of the co-authors of his papers about scaling (see below), and the impact of his personality upon the scientific community justify the consideration hereafter. An excursus through the Zuber contribution to the scaling issue is given in two parts hereafter, the former including original writings from his paper, the latter summarizing relevant analytical achievements.

The original writings taken from the paper (Zuber, 2001), can be used to synthesize the author opinion toward the results of the complex computational tools. Thus, simple and straightforward scaling analysis was proposed. Four paragraphs from the paper by Zuber (2001), are relevant within the present context (where, as already mentioned, the thermal-hydraulic code is proposed as the 'pivot', or 'key-to-scaling', for performing scaling analysis):

(1) The (compulsive) vision of code complexity and of 'compensating errors'. "The difficulties in modifying codes to accommodate new requirements stem, in large part, from their complexity, i.e. the vast number of closure relations (the 'constitutive package'), together with transition criteria and splines, each introducing a set of coefficients (dials). The latter may be adjusted or 'tuned' to produce an acceptable agreement between code calculations and a specific set of experimental data (say, the Peak Clad Temperature). However, this 'tuning' procedure also generates compensating errors, which limit the applicability of the code to a different set of requirements or design. Thus, through complexity, these codes have already become more inflexible and maladaptive to changes."

(2) The achievement and the evaluation of results from code calculations. ". . .one of the greatest concerns of any professional in this field should be the indiscriminate use of two- or three-fluid models, which invariably claim a 'good agreement' with experimental data. Yet, some of these formulations and codes are known to be inadequate, flawed and/or incorrect. The 'good agreement' may be explained only in terms of the carefully tuned dials hidden in the code . . . Although 'good agreement' with experimental data may ensure the continuation of project funding, such formulations cannot contribute to the fund of knowledge. Laws of 'variable coefficients' and 'tuning dials' are not yet laws of physics. Yet these continuous claims to success have institutionalized the 'art of tuning' as an acceptable methodology for addressing and resolving technical issues and/or scientific problems.".

(3) The user is (guilty and) code-jockey. "Although cultures are not easily changed, I see no reason to promulgate the inane wastefulness of the 'code jockey' attitude. . . . Organizations that allow the 'code jockey' culture to prevail, will be inevitably relegated to the 'evolutionary junk heap'.".

(4) (Finally . . .) scaling may help. ". . .An ever-increasing complexity in formulating and analyzing problems leads to inefficiency, obsolescence and evolutionary failure. By contrast, simplicity, which allows for parsimony, synthesis and clarity of information, ensures efficiency, survival and replication. This comparison (complexity versus simplicity) also provides the requirements and guidance for a success path in T-H development. . . . Then . . . scaling provides the means to process

Table 2
Sample list of dimensionless scaling factors characterizing various approaches (High [H] and Low [L] level hierarchy scaling factors).

No.	Scale factor	Meaning	Ref.	*	** Criteria in Table 1, rows:
1	$(G\Delta p/W)(c_v k/\beta)$	Mechanical compliance	Wulff (1996)	H	1, 8, 12, 19, 20
2	$\Delta u G/W$	Thermal compliance			1, 12, 19
3	$W_{HL,max}/W$	Effect of heat losses		L	18
4	$\Delta p_{PP} G/W$	Effect of pumping power		H	27, 20, 8, 19
5	$\Delta h_0\ G_{ECC}/W$	Thermal effect of (ECC) injection			21, 22
6	$(\rho_f/\rho_g)\ G_{CR}/G$	Effect of break flow		L	TPCF
7	$G^2\ (L/A)/g\ L_{2\Phi} V \Delta\rho_0$	Flow inertia in 2-Φ flow		H	19, 5, 1, 13
8	$G^2(N_{Zu} - N_{Subc})/\Delta p_{PP}\ \rho_f A^2{}_{HT}$	Momentum flux changes in 2-Φ			19, 13, 27,10
9	$\gamma_{1,1,0}\ W\ \Delta t_{ph.w}/P$	Ratio of pressure change due to int. energy change to ref. pressure	Banerjee et al. (1998)	L	TPCF
10	$G_{ADS}\ \Delta t_{ph.w}/M$	Ratio of integrated flow-rate to reference mass			
11	$(\Delta t_{ph.w}/V)(g\ L/\Delta p)^{1/2}$	Ratio of core make-up flow to vessel volume		H	1, 9, 20
12	$[fL/D + \kappa]_R$	Friction and local pressure drop	Ishii et al. (1998)	H	20
13	$[(L/\upsilon)/(\delta^2/\alpha_s)]_R$	Transport time/conduction time		L	Struct. thickness
14	$[A_{ch} = A\ \upsilon]_R$	Break flow area scaling			If $K_h = 1/4$
15	$(\beta g W L)/(\rho_f\ c_p\ \upsilon_f{}^3 A)$#	1-Φ nat. circ. (operational mode)	Reyes and Hochreiter (1998)	H	2,6,8,13,19
16	$h_{fg}(1-\alpha)\alpha\Delta\rho\upsilon_f A/W$#	2-Φ nat. circ. and sump circ.			6,8,13,19
17	$W_{DC}/(Gh)_{DVI}$	Down-comer fluid heat-up		L	Struct. heat release
18	$(G_{ADS} + G)/G_{IRWST}$	IRWST injection			TPCF
19	$\Delta t_{ph.w} j_{k,x}/\alpha L$	Momentum conservation along 'x'	Yun et al. (2004)	L	Three-dimensional effects
20	$\Delta t_{ph.w} j_{k,y}/\alpha L$	Momentum conservation along 'y'			
21	$1/S_x$	Slip ratio along 'x'			

Nomenclature

A = cross sectional area
A_{HT} = heated section heat transfer area
$c_{p,v}$ = fluid specific heat at constant pressure/volume
D = equivalent diameters
f = friction pressure drop coefficient
G = mass flow-rate
G_{ADS} = ADS (Automatic Depressuriz. Syst) flow-rate
G_{CR} = critical flow-rate (core if no subscript)
G_{ECC} = ECC (emergency core cooling) flow-rate
G_{IRWST} = IRWST (in-reactor water storage tank) flow
h, h_{fg} = Enthalpy, Latent heat of vaporization
$j_{k,x;y}$ = Superficial velocity for phase 'k' along 'x' or 'y'
k = thermal conductivity
L = length (of one component)
$L_{2\Phi}$ = two phase (or boiling) length
M = (system) mass
N_{Subc} = sub-cooling number
N_{Zu} = Zuber number
P = pressure
S_x = slip ratio along 'x'
V = (system) volume
W = power (core, if no subscript)
W_{DC} = power from down-comer walls
$W_{HL,max}$ = heat losses, maximum value

Greek

α = Void fraction
α_s = Thermal diffusivity
β = Thermal expansion coefficient
$\gamma_{1,1,0}$ = Coefficient depending upon break flow
δ = 'Conduction depth', see Ishii et al., 1998
Δh_0 = Excess injection enthalpy above initial enthalpy
Δp = Pressure drop due to friction
Δp_{PP} = Pressure gain due to pumping power
$\Delta t_{ph.w}$ = Duration of phenomenological window
Δu = Internal energy change
$\Delta\rho = \rho_f - \rho_g$
$\Delta\rho_0$ = Function of N_{Zu} and N_{Subc}
κ = local pressure drop coefficient
ρ_f, ρ_g = liquid and steam density
υ = velocity (un-chocked flow)
1-Φ, 2-Φ = single-phase, two-phases

Subscripts

ch = critical flow conditions
DVI = direct vessel injection (line)
f = liquid
R = ratio model/prototype

* Hierarchy scaling factors, [H] or [L].
** Or reason for non-compliance.
# More precisely defined in the original paper.

information in an efficient manner, as required by competitive (and, thereby, replicating) systems. . . . The Fractional Change, Scaling and Analysis approach . . . offers a general paradigm for quantifying the effects that an agent of change has on a given information system.".

Significant scaling achievements can be found in the document by Zuber (1991), and in the papers by Zuber et al. (1998, 2005, 2007), Zuber (2001), Wulff et al. (2005), and Catton et al. (2005). Two acronyms can be used to characterize those achievements, i.e. H2TS (Hierarchical Two-Tiered Scaling) and FSA (Fractional Scaling Analysis). Related key ideas are synthesized below.

2.2.3.1. H2TS (primarily, Zuber, 1991; Zuber et al., 1998). At the basis of the H2TS there are two main objectives (or needs):

- To be comprehensive, systematic, yet practical, auditable, traceable and technically justifiable.
- To create a hierarchy among scaling factors and scaling design or requirements, thus eliminating the arbitrariness in scaling and providing a quantitative estimate of the importance of the scaling factors.

The '1st tier', or top-down scaling analysis, examines the synergistic effects on the system caused by complex interactions between the constituents. Therefore a complex system or a complex process is subdivided into pieces. The PIRT (Phenomena Identification and Ranking Table, e.g. see J. NED, Special Issue, 1990) procedure is applied, thus requiring expert judgment. This also brings to the identification of the important processes to be addressed in the bottom-up scaling analysis. Fluid conservation equations at a given scaling level are considered to obtain similarity criteria.

The '2nd tier', or bottom-up scaling analysis, provides similarity criteria for specific processes such as flow pattern transitions and flow dependent heat transfer. The focus of the bottom-up scaling analysis is to develop similarity criteria to scale individual processes of importance to system behavior as identified in the step above. Closure equations, typically addressing local phenomena, are considered to obtain similarity criteria.

The result from performing the top-down and the bottom-up analyses is a large number of scaling ratios. In order to create the hierarchy among those parameters, e.g. the objectives at the second bullet above, time ratios are introduced (according to Zuber et al., 1998, time ratios were proposed in previous years, e.g. by Moody, 1990, as one outcome of the methods for establishing dimensionless groups). The numerical values of time ratios for an assigned system and an assigned process are used for establishing the hierarchy, thus for identifying the most influential scaling parameters. This is done by considering each time ratio as the product of 'specific frequency' by the 'residence time'. The former quantity defines the mass, momentum or energy transfer rate for a particular process. The latter quantity defines the total time available for the transfer process to occur within the control volume.

2.2.3.2. FSA (primarily, Zuber, 2001; Zuber et al., 2005, 2007; Wulff et al., 2005; Catton et al., 2005). The H2TS procedure discussed in the previous paragraph connects the scaling method and the (complex) system thermal-hydraulic phenomena. This may be used to create a virtual link with the (complex) structure of related computer codes. Namely, the bottom-up approach of the '2nd tier', may need the use of mechanistic models whose implementation in the codes is at the origin of a number of 'degrees of freedom' for the code-users that are heavily criticized e.g. by Zuber (2001) and reported above.

The FSA for system thermal-hydraulics was established in a set of three papers by Zuber et al. (2005), Wulff et al. (2005), and Catton et al. (2005), presented in the same conference (Avignon, 2005, see list of references). However the origin of FSA is attributed to the work documented in Zuber (1991) by Zuber (2001); furthermore, in the paper by Zuber et al. (2005), the authors make reference to other authors who introduced the words 'fractional analysis'. In order to apply the FSA method, balance equations are needed: simplified (lumped parameter model) balance equations are used in the reported application. Key parameters named Fractional Rates of Change (FRC) and Fractional Change Metric (FCM) are considered: the former quantifies the intensity of each transfer process (or "agent of change"), which changes a state variable by a fraction of its total change during an assigned transient and allows the ranking of the agents of change; the latter is representative for scaling the fractional change of a state variable. The FCM is used for scaling the fractional change of a system state variable such as pressure: noticeably, state variable trajectories representative of different transients reported versus FCM show similarities that do not appear when the same variables are reported versus time. The FRC and the FCM have the role that 'specific frequency' and 'time ratio' have inside the H2TS, respectively.

The FSA procedure appears as an attempt to get rid of complex computational tools and to create a different framework for the analysis of complex scenarios, even though, according to Wulff et al. (2005) "*... FSA is a scaling analysis, not a prediction tool. However, the combination of FSA and scaled experiments can sharply reduce the need for computer code calculations.*". Rather, again according to Wulff et al. (2005), FSA can be seen as "*...the quantitative hierarchy that supersedes the widely used, but subjectively generated Phenomena Identification and Ranking Table.*". Definitely, the concerned attempt is highly desirable from a scientific point of view, specifically in case of succeeding in duplicating the same capabilities (e.g. by system codes) by an independent analytical infrastructure, as demonstrated by recent applications (e.g. Wan, 2007; Aydemir, 2009).

The 'direct' impact of the Zuber scientific activity upon the present framework, other than the deep understanding of phenomena scaling processes, is constituted by the importance given to scaling. More specific connections are:

- the use of balance equations in the '1st tier' of the H2TS and in the FSA, is consistent with the design criteria in Table 1;
- the vision by Zuber about code applicability and user impact upon the results contributes to provide additional reasons for the 'scaling controversy' mentioned in Chapter 1, thus supporting the objective for the present effort.

The straightforward scaling analysis based on open and user-independent code application, e.g. the procedure proposed in the present paper, may help in tackling the aversion toward sophisticate computational tools, as well as, toward the results obtained by end-users of the codes including independent assessors and auditors of calculations.

2.2.4. The scaling requirements in CSAU

The CSAU (Code Scaling Applicability and Uncertainty) constitutes a pioneering effort made by US NRC aimed at making available to the scientific and technology society a suitable uncertainty method. Six papers (each paper is hereafter recalled as paper-*n* with '*n*' varying from 1 to 6, connected with the page numbering in the volume) were published in J. NED, Special Issue, 1990 (pp. 1–117, devoted to CSAU) which provide the full description of the method. Before discussing the scaling requirements, two notes apply:

- The word 'Scaling' is part of the CSAU acronym: this testifies of the importance of the issue, according to US NRC.
- The CSAU shall be considered as a basket of (very) valuable requirements for performing an uncertainty study or for setting up an uncertainty method, rather than an 'uncertainty method'. This is because of the large number of steps of the method that require expert judgment and are left to the user of the method (this item is not discussed any further in the present paper).

Key sentences or paragraphs dealing with scaling are listed below, including paper identification (e.g. 1–6: note that only papers −1, −2, −3 and −4 are considered hereafter), original writing reported in italics and comments from the present authors.

(a) Paper-1, related to the step 6 of the CSAU aimed at determining the code applicability: "*...whether the code ... accuracy and scale-up capabilities ... are adequate to model processes important to the scenario...*". It is requested to evaluate whether "adequate code scale-up capabilities" exist, but no way is suggested about how to do, neither acceptability threshold for a possible process are envisaged, see item 7) in Section 4.1 for a possible answer provided by UMAE.
(b) Paper-1, related to the step 10 of the CSAU titled "Determine Effect of Scale": "Differences for similar physical processes, but at different scales, should also be quantified for bias and deviations to establish a statement of potential scale-up effects ... It is necessary to evaluate the capability of the BE code to scale-up processes from reduced scale test facilities to the full scale NPP. It is also necessary to quantify the effects of limitations on the data base used to develop models and correlations that are present in the code.". Same comment as in the previous item applies, except for the last sentence that is not dealt with by item 7) in section 4.1.
(c) Paper-2, related to step 5 of the CSAU: The scale-up capability of each correlation ("*...ideally the result of a line by line coding check...*") should be part of the code documentation. Thus the last statement in italics of the previous item is reiterated.

(d) Paper-3: The (incomplete) table-list of experiments which must be at the basis of the qualification of a code includes a column devoted to counterpart test.
(e) Paper-3, related to steps 8 to 10 of the CSAU: "Parameters ... such as HTC [Heat Transfer Coefficient], pump performance ... must have their uncertainties from ... SET [Separate Effect Test] data ... The comparison must encompass data from a range of TF [Test Facility] scales, to facilitate extrapolation ... Otherwise conservative estimates ...". Following this statement implies the extensive use of conservatism in input data, owing to impossibility to fulfill the (scaling) requirement.
(f) Paper-5 devoted to scaling, or to step 10 of the CSAU: The following requirements that also constitute sub-steps (i.e. 10-*n* below, where '*n*' identifies the sub-step) in the method are: *[10-5] Evaluate whether the database* [for code assessment] *covers the NPP range; [10-7] Evaluate the scale-up capability of closure relationships; [10-9] Evaluate whether the closure relations cover the NPP range. If any of the above evaluations is negative, then add bias to the results*. Firstly, it appears that sub-step [10-9] is part of sub-step [10-7] and sub-step [10-7] is part of sub-step [10-5]. Secondly, it seems clear that the outcome of any evaluation is negative in the sense that NPP ranges are not covered, in general. Finally, there is no systematic procedure or suggestion about how to determine the bias (even though some examples are given).

The importance given to the scaling issue, for the application of CSAU, constitutes the final remark from the short overview. Noticeably, key problems associated with scaling are envisaged, but suitable solution is not provided. Therefore, the final results from the present effort, i.e. the Road-map to Scaling, can be taken as an attempt to address the scaling issue in the CSAU.

2.2.5. Scaling studies in selected countries and for advanced reactors

The purpose here is not to present a State-of-the-Art on the subject, as already mentioned, rather to connect key findings from various studies with the topics discussed in the present paper and to show the background for building-up the Roadmap to Scaling. To this aim, a review of scaling contributions is given below, in the first two cases focusing on ITF: (a) related to Russian reactors; (b) provided from Far-East Countries, noticeably from South Korea and Taiwan; (c) connected with the design of new reactors (including also generation III plus, AP-600 [Advanced PWR] and, later on, AP-1000 and SBWR [Simplified Boiling Water Reactor]).

(a) *Russian Reactors scaling*. Three main ITF have been built and operated (all of these are still in operation at the time of issue of this paper) to simulate the VVER reactors: the Pmk in Hungary, the Pactel in Finland and the Psb in Russia (the Isb facility was also constructed by the same Institution that designed and constructed Psb). The power-to-volume, full-height, time-preserving scaling is adopted in all cases, as reported by Szabados et al. (2007), Tuunanen et al. (1998), and Melikhov et al. (2003), respectively. Proper attention has been given to counterpart testing (discussed in Section 3.5), see e.g. Szabados et al. (2009) and Blinkov et al. (2005).
(b) *Far East Countries scaling activities*. Two main ITF have been built and operated in Far East Countries (excluding Japan): the Iist in Taiwan and the Atlas in South Korea. The reduced-height, reduced-pressure scaling and reduced-height, full-pressure, basically pursuing Ishii scaling criteria, see above, is adopted in the case of the two ITF, as reported by Hsu et al. (1990), and Baek et al. (2005), respectively.
(c) *Scaling activities connected with the design of new reactors*. At least three ITF simulators of PWR or BWR, listed in Section 2.3, have been modified to perform a few or a number of experiments relevant to the new generation reactors. These include Spes, Lstf, and Piper-one. Moreover, among ITF mentioned at items (a) and (b), Pactel and Iist have been modified for simulating passive phenomena relevant to new generation reactors (e.g. Tuunanen et al., 2000; Chang et al., 2006). Thus, ITF simulating AP-600 or AP-1000 include Spes and Lstf (also known as Rosa-AP600), already mentioned, and Osu-Apex. ITF simulating SBWR include Panda, Puma and Giraffe. Significant contributions to scaling dealing with AP-600 and SBWR, are provided by Yadigaroglu (1993), Ishii et al. (1998), Reyes and Hochreiter (1998), Banerjee et al. (1998), and Cho et al. (2005), the last one related to a specific phenomenon.

2.2.6. Derivations of scaling factors

This section has been built-up having in mind the purpose of completeness for the present survey and aiming at counter posing top and bottom level scaling factors. To this aim, a parallel is established between the design factors in Table 1 and the scaling factors reported in Table 2.

The scaling factors which are at the origin of the design factors should be considered as primary scaling requirements (or top hierarchy level scaling factors). The remaining ones should be considered as secondary scaling requirements (or low hierarchy level scaling factors).

Scaling studies considered in Table 2 are by due the following authors (the adopted scaling methodology and attribute are reported in parentheses, if applicable):

- Wulff (1996),
- Banerjee et al. (1998),
- Ishii et al. (1998) (Ishii scaling attribute),
- Reyes and Hochreiter (1998), (H2TS Methodology by Zuber, and Ishii scaling attribute),
- Yun et al. (2004).

A few hundred scaling factors are obtained in those papers and a sample-indicative fraction of these is reported in the table.

In the papers by Ishii et al. (1998) and Reyes and Hochreiter (1998), both scaling and design factors are presented: namely, design factors are basically those presented in Section 2.2.2. Furthermore, an evaluation is made in the paper by Reyes and Hochreiter (1998), of so-called '<non-dimensional> *characteristic-time-ratios for the dominant-processes*': it is worth noting that all dominant characteristic time ratios (e.g. Table 3 of paper by Reyes and Hochreiter, 1998) are satisfied by the design factors listed in Table 1, including the noticeable exceptions of those time ratios where critical flow-rate (discussion in Section 3.1) or thermal power release from structure appear.

Summing-up, scaling distortions associated with the design criteria in Table 1 and expected due to the scaling factors in Table 2, are originated by TPCF, thermal power release from structures and three-dimensional effects. Designers of ITF may act to minimize those distortions, without impacting other design parameters and keeping in mind a key objective of the ITF construction that is code validation.

As a further investigation of scaling data, let's consider the data below taken from the paper by Banerjee et al. (1998). These are the values of dimensionless factors (relevant to scaling) related to three ITF and to the reference prototype. This is AP-600 for each of the three ITF (nomenclature for the following is: CMT = Core Make-up Tank; ADS = Automatic Depressurization System).

	Prototype value	Range of value in models
(1) Ratio of CMT flow to vessel volume	0.82	0.77–1.21
(2) Ratio of ADS flow to vessel volume	0.96	0.98–2.00
(3) Ratio of ADS flow to CMT flow	1.18	0.81–2.58

The following remarks apply to the data above and to the information in Table 2.

(A) The usual/typical interpretation of differences among data is, (e.g. taken by Banerjee et al., 1998, above reported in bold characters) "*. . .the magnitude of the non-dimensional coefficients were similar for the ITF and the AP-600 . . . the same 'important' processes occurred in the ITF as might be expected in the AP-600.*". Other, more rigorous interpretations of the same information are: differences are large; there is no threshold of acceptability to justify or to accept distortions; the dimensionless factors are irrelevant during the concerned transient if the second part of the sentence in italics is true.
(B) The design factors in Table 1 (high hierarchy value) should be applied and have been applied for the design of ITF. The scaling factors in Table 2 (low hierarchy value) can be applied for the design of zones or components in the ITF without generating conflict with previous factors and considering constraints like those at rows 7 and 20 in Table 1.
(C) The answer to the question 'what is the practical use of the amount of scaling distortions like those outlined above?', is 'no practical use within the framework of the present scaling activity', mostly because criteria for acceptability of scaling distortions are not available.
(D) The 'agreeable' statement that constitutes the second part of the sentence in italics at item A), can apparently be achieved only with the help of a system code that is capable of simulating the scenario in the prototype.
(E) Then the conclusions: similarity can be evaluated based upon the application of the system code. It is necessary to ensure, among the other things, that the code is qualified against scaling. This can be achieved in two steps: (1) by testing that the code satisfactorily reproduces (e.g. adopting suitable thresholds of acceptability for accuracy) the scenarios in differently scaled models, designed according to criteria in Table 1; (2) by testing that criteria like those in Table 2 are part of the 'genetic' structure of the code or may be obtained from the equations embedded into the codes. In other words, the applicability with suitable quality demonstration of system codes to situations in different geometry or pressure scale conditions constitutes the key requirement for scaling in the context here considered; otherwise, the use of the 'low hierarchy value' scaling factors is restricted to the demonstration of scaling capabilities of code models. Any application of those scaling factors also allows a deep understanding of phenomena by the analyst.

The following two paragraphs (reported in italics) are taken from the paper by Wulff, 1996. Related comments may be illustrative for the roadmap pursued in the present paper. "*Complete similitude, however, is physically impossible because the sheer number of scaling requirements cannot be met at the same time for a system in which areas and volumes and, therefore, area dependent transfer rates and volume-dependent capacities scale with different power of length* <are present> *and produce conflicting scaling requirements.*". In other terms, what are called here 'detailed scaling parameters' imply (or introduce the potential to imply) conflicting scaling requirements related to the parameters in Table 1. "*Therefore scaling should be carried out during the early conceptual design of experiments, lest its usefulness be limited later to post-factum quantification of avoidable scale distortions.*". Thus, at a time (even 1996) when facilities have been built and operated and codes have been qualified as far as possible, the use of detailed scaling parameters is restricted to the characterization of "previously avoidable" scaling distortions.

2.2.7. Scaling and licensing

The licensing process for NPP can also be reported as the 'legal-safety' environment for NPP. In the area of NRSTH, the application of Best-Estimate codes for Deterministic Safety Assessment, i.e. within the already mentioned BEPU approach, brings to the direct link between Scaling and Licensing.

In generic terms the 'Licensing' can be seen as formed by two parts which must reach suitable consistency: (a) the requirements set by the proper Authority, and, (b) the answer from the applicant, including the support from the research side.

Without entering the details of the licensing process that is beyond the scope here, in simplified terms, it can be remarked that the present paper deals with a proposal for item (b). Furthermore, the current situation for item (a) is summarized by the documents US NRC (2005) and IAEA (2010). In both documents the requirements set by the CSAU in relation to scaling, discussed in Section 2.2.4, are basically translated into the 'legal-safety' language of the licensing.

2.3. The experimental facilities

Several tens experimental facilities characterized as ITF have been designed built and operated in the area of NRSTH (see e.g. D'Auria, 2001). Cooperative efforts have been completed to identify and characterize the research programs associated with those ITF (e.g. see OECD/NEA, 1996; Addabbo et al., 2001). Valuable summary of expertise from the operation of individual ITF have been published in a number of cases, see also summary information given in Section 2.2.5.

Relevant information related to scaling can be derived from the design and the operation of SETF (e.g. see OECD/NEA, 1993). An example of this is given in Section 3.2 related to the CCFL phenomenon. Here it may be sufficient to notice that in the mentioned document more than 200 SETF suitable for demonstrating code capabilities have been classified that are at the origin of about 2000 experimental datasets. All over the world it can be easily estimated that more than 1000 SETF have been or are in operation in the area of NRSTH.

It is outside the scope to summarize here even the key scale relevant findings and the interested reader can easily access the two OECD/NEA documents. However, making reference to the ITF document, a few facts can be mentioned to make clearer the perspective for the present paper:

- The ITF considered in the mentioned OECD/NEA documents include PWR simulators like Semiscale, Loft, Lobi, Spes, Bethsy, Lstf, Pkl, Mist, Umcp and Uptf and BWR simulators like Fist, Fix-II, Piper-one, Rosa-III and Tlta.
- The overall cost associated with all experimental programs conducted primarily during the decades 1970–1990 is of the order of Billion-Dollars (value of the year 2000). This testifies of the importance given to the experimental scaled-evidence, namely by nuclear safety regulators.
- Around 2000 ITF tests have been performed with data recorded and electronically stored, typically 100–1000 signal per experiment, with recording frequency of the order of 1 Hz.
- Among those experiments, 'counterpart' tests and 'similar' tests (definitions provided in the reference document) performed in differently scaled facilities till the year 1996, i.e. directly addressing the scaling issue, are classified in the OECD/NEA (1996), report, see also Section 3.5 below.
- Less than 10% of the above tests have been analyzed, with documented post-test studies, by system thermal-hydraulic codes, even though the key goal for the execution of those experiments is the qualification of code-nodalizations. The cost of the analyses (roughly one man-year per experiment) constitutes a justifica-

tion for not analyzing the experimental data, thus preventing the possibility to improve the understanding in relation to the scaling issue.
- It will be difficult to find individual analysts (or code-users) who have performed analyses of more than 10 experiments in ITF and it will be very difficult to find analysts who have modeled (i.e. developed input decks suitable for code analyses) more than 5 ITF and performed test analyses accordingly.

A conclusive remark from the above bullet items is that the experimental data base from ITF is not fully exploited, namely from the viewpoint of scaling, or that common views about scaling are biased by the lack of detailed knowledge of existing databases.

2.4. The computational tools

Noticeably, two computational tools, i.e. the code and the nodalization (or input deck or interface between the code and the reality), and the user (or code user, or nodalization developer, or analyst) are relevant in NRSTH and affect the quality of any calculated database and, consequently, the scaling process. These can be identified here as the 'three components' of a calculation.

Related to each of the components of a calculation, wide bibliography exists and it is not within the scope of the present paper to synthesize the state of the art on the subject. Rather, in four bullet items below, key literature reports are recalled that may give an idea of the features and of the importance upon the calculation results of each of the four components and do constitute a starting point for interested reader to enter into more details:

- System codes are obviously at the center of the development of NRSTH, as already mentioned in this paper. Six balance equations model, i.e. mass, momentum and energy for liquid and steam phases, with proper set of around one-hundred, constitutive models (and/or closure equations) are at the basis of those codes. Relap5, Athet, Trac, Cathare are familiar names. Development and description of the main features of those codes can be found in the related manuals and even in textbook (e.g. Forge et al., 1988), or international reports (e.g. OECD/NEA, 2004a–c). The qualification of the system thermal-hydraulic codes constitutes a discipline by itself and the scaling issue is part of this. Overview papers dealing with procedures for qualification (one may also find V and V, Verification and Validation) are those by D'Auria and Galassi (1998), D'Auria et al. (2006a), and Petruzzi and D'Auria (2008). As a key remark here is the note that the resources needed for code V and V can be even larger than the resources needed for code development.
- The numerical solution method affect the result of any calculation. The lack of convergence of some system codes comes from the use of ill-posed non-hyperbolic systems of equations which result in unstable problems. The equations require large enough meshes to prevent instability through numerical diffusion. When decreasing the mesh size, numerical diffusion is decreased and the unstable nature of equation is revealed (Ferreri et al., 1996).
- The nodalization is the results of a brainstorming process that connects the reality, i.e. the NPP, with the code, i.e. the system thermal-hydraulics code. Suitable understandings of the NPP and of the code nature and structure are needed to develop a nodalization. The nodalization in the concerned NRSTH code suffers of the so called [CV + J], i.e. Control Volume plus Junction approach, based on a modular approach that on the one hand makes it possible the construction of mountain by simple stones, on the other hand requires a suitable definition by the users of the interface conditions among the stones. The [CV + J] approach requires a high level of expertise by the code user. The empirical observation that results of a code calculation are affected by changes of control volume dimensions is mainly a consequence of the same [CV + J] approach; the empirical equations implemented into the code may also have a connection with the choice of control volume dimensions. Thus, an optimal nodalization exists valid in principle for each code application, such that an increase in the detail (e.g. in the number of nodes) does not bring to improvement in the results (i.e. better simulation of the reality). The effort to develop a nodalization for a water cooled nuclear reactor may be of the order of a few man-years thus giving an idea of the complexity of such an endeavor. Thus, qualification is needed for the nodalization to a similar extent of what needed for a code (e.g. Bonuccelli et al., 1993; Aprile et al., 1996); suitable information can also be found in the J. STNI Special Issue, 2007.
- The code-user (or the analyst) is typically the nodalization developer (see the definition given above) and is responsible to set-up the best nodalization taking into account of the code capabilities and deficiencies. The analyst should be seen, not only as the formal responsible for the result of a calculation, but also as the responsible of the quality of the same results. A wide literature exists in relation to the User-Effect (UE), i.e. documenting the impact of users upon the results (UE), the Requirements for User Qualification (RUQ) aiming at reducing the UE, and the User Training (UT), dealing with the recommended list of competencies suitable for an analyst. The issues of UE, RUQ and UT are dealt with by Aksan et al. (1993), Ashley et al. (1998) and D'Auria (1998), respectively, see also Aksan et al. (2000) and Petruzzi et al. (2005), for supporting information. Obviously, the analyst must be fully aware of the scaling issue.

3. Topics relevant to scaling

The scope for the present chapter is to put together objective (as far as possible) facts and findings that are relevant to scaling and may provide a support or may justify, together with the 'standard' knowledge synthesized in the previous chapters, the proposed scaling approach (Chapter 4). Mentioning or giving emphasis to the work of some authors in the previous chapters, does not imply for the present authors, neither endorsing the concerned scaling strategies, e.g. H2TS or FSA in the case of Zuber, neither the related applicative results, e.g. $K_h < 1$, in the case of Ishii. Namely, those derivations shall not be taken as the bases for the present work.

3.1. Non-scalability of phenomena

A comprehensive discussion about scaling of phenomena should be based upon the list of thermal-hydraulic phenomena prepared by OECD/NEA/CSNI (see OECD/NEA, 1993, 1996), respectively related to SETF and ITF phenomena. This goes beyond the purpose of the present framework, although scaling information can be found in the mentioned reports.

As an example here, the impossibility to scale-up one phenomenon, i.e. the Two-Phase Critical Flow (TPCF), is discussed hereafter, based on the work by D'Auria et al. (2003b). Let us consider the sketch in Fig. 1 where the simplified lower plenum of the Bethsy ITF is shown together with the break device. A time period, or snap-shot into the transient, lasting a few tens of seconds during a SB-LOCA scenario is considered.

The reason for the study of the concerned time-period derived from a not-explained discrepancy between measured and calculated time trends of break mass flow starting at time when the situation depicted in Fig. 1 occurred. In particular, the experimental data showed a 'sudden' decrease of break flow-rate that could not be calculated by the code.

During the concerned time period, the TPCF phenomenon is affected (at least) by thermal non-equilibrium phenomena like

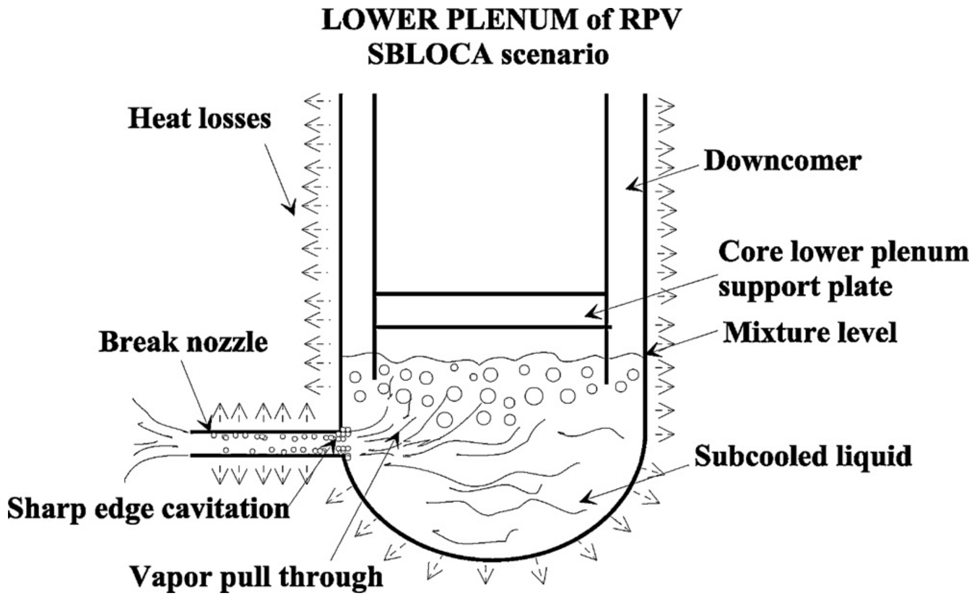


Fig. 1. Scaling of TPCF.

'vapor pull through' and sub-cooled vapor formation by 'sharp edge cavitation'. The last phenomena, at their time, are affected by (local) system parameters that do not appear into balance equations or into 'scalable' mechanistic models, like: (a) ratio between break nozzle diameter and vessel diameter, (b) geometrical parameters representative of the configuration of internals in lower plenum that are releasing thermal power to the fluid, (c) rounding edge at the connection between break nozzle and vessel. Those parameters and connected phenomena are not reproducible in different ITF and at different scales (i.e. simply because the rounding edge at the connection between break nozzle and vessel is not measurable).

The situation during the concerned snap-shot is even more complex if one considers heat losses primarily in the exit nozzle, mixture level formation and fluid temperature stratification in the lower plenum of the facility. All those phenomena also affect the target TPCF phenomenon and cannot be controlled by the designer of the ITF or by the designer of the experiment. Again, those phenomena are not reproducible in different ITF and at different scales.

At this point it is straightforward to conclude that 'non-reproducible' parameters and 'non-reproducible' phenomena affect the TPCF phenomenon which affects the overall SB-LOCA scenario. Thus neither TPCF nor the overall scenario (SB-LOCA in this case) can be scaled-up or extrapolated. Rather, the concerned issue should be considered when performing uncertainty analysis.

The 'only' use of experimental information like what discussed is the validation of computational tools where "all" relevant boundary conditions are modeled. An important role is taken in this connection by the user of the code and by the flexibility of the code-user interface, where 'tuning' (i.e. unjustified change of input parameters with the goal of matching the experimental data) shall be avoided.

3.2. Phenomena and accuracy scaling

As a complement to the introductory remarks in Section 3.1, one may add that, in principle, all thermal-hydraulic phenomena (e.g., see the CSNI [Committee on the Safety of Nuclear Installations] matrices (OECD/NEA, 1993, 1996)) are geometry scaling dependent. For instance, two-phase pressure drop depend on diameter because flow regimes depend on diameter. Then, a number of phenomena depending on pressure drops are geometry scaling dependent.

The geometry scale dependence has been the subject of direct investigation in relation to selected phenomena. Noticeable examples are constituted by:

- The demonstration that liquid penetration (i.e. down-flow) in down-comer, or across the upper core plate namely in the case of hot leg injection, strongly depends upon the system dimensions (e.g. Wolfert, 2008 and CCFL occurs, see also Glaeser and Karwat, 1993). In case of small scale experiments liquid penetration is made difficult by the fluid interaction with wall in narrow passages and by the high steam speed. In this situations level formation may occur in the upper region with voided bottom region. At a large scale (e.g. UPTF, see below) this phenomenon is basically prevented by three-dimensional effects: downward liquid flow occurs preferably in selected zones (e.g. low power fuel channels in the case of core), level formation does not occurs and the liquid directly contributes to the core cooling.
- The safety issue raised because of inadequate effectiveness of ECCS measured in small scale facilities during the blow-down phase of LOCA, caused by the ECC bypass phenomenon (Beckner et al., 1979, see also Sudo, 1984). In this case, Semiscale small scale experiments performed at beginning of 1970s were at the origin of the issue. Later on, the availability of large scale experiments allowed the demonstration of the suitability for the current design of ECCS.
- The finding that natural circulation performance, namely the natural circulation mass flow-rate in the core region reported as a function of the mass inventory of the primary system, is a function of the number of U-tubes (then of the volume scaling ratio) of steam generators (D'Auria et al., 1991).

As a conclusion from the above, thermal-hydraulic phenomena are, in general, geometry scale dependent. Thus no extrapolation of data from small scale experiments is acceptable.

Let us consider now the possibility to scale-up the capability to calculate phenomena. In this case we can consider as a measure of the modeling capability (or capability to calculate phenomena), one of the possible definitions of accuracy or error in the prediction, e.g. the ratio $Y_{\text{exp}}/Y_{\text{calc}}$. Here, '$Y$' is the generic parameter representative of the thermal-hydraulic phenomenon under investigation. The possibility to scale-up the capability to calculate phenomena is considered in the works by D'Auria and Karwat (D'Auria et al., 1988, see also below). The evaluation of such possibility is considered by Belsito et al. (1994), Bovalini et al. (1993), and by a number of papers dealing with the bases or the development of the UMAE and CIAU uncertainty methodologies (D'Auria and Pellicoro, 1995; D'Auria and Giannotti, 2000), respectively (see below, for the acronyms and for more details). The demonstration that the accuracy is not a scale dependent parameter constitutes a prerequisite for the applicability of the concerned uncertainty methodologies. Further evidence of the same finding, e.g. accuracy independent upon scaling, is obtained by adopting the accuracy definition of the FFTBM (Fast Fourier Transform Based Method) (e.g. Ambrosini et al., 1990). This evidence can be found, for the specific case of the SB-LOCA Counterpart Test (see below) in the paper by D'Auria et al. (1997b). Additional information connected with accuracy scaling can be found hereafter in relation to Fig. 3 and related discussion. The accuracy is the measure of the discrepancy between code calculation results and (relevant) experimental data.

Definitely, accuracy does not depend upon scaling and, thus proper analytical definitions of accuracy shall be considered as a non-dimensional, scale-independent statistical parameters. In different words, one may conclude that there is no demonstration that calculation accuracy is connected with scaling. In case a different evidence would appear, this should be considered as a modeling deficiency requiring code improvement. This conclusion does not constitute a principle neither a theorem; rather it is an observation to be continuously validated against the experience.

3.3. The experimental simulation of the Mihama NPP SGTR accident

A milestone in scaling is constituted by the demonstrated capability to reproduce with an experiment the complex transient scenario resulting from a SGTR (Steam Generator Tube Rupture) in a NPP. The involved NPP and ITF are the Mihama-2 unit and Lstf, respectively. The Mihama-2 unit is a 1475 MWt, 2-loop PWR. The Lstf is the scaled model of a PWR according to power-to-volume, time-preserving, full-pressure, full-height (see also Section 3.6) scaling. The volume scaling ratio between Lstf and the Mihama-2 NPP is close to 1/21.

The use of fundamental scaling criteria in the design of the test SB-SG-06 and the analysis of experimental data, Hirano and Watanabe (1992), demonstrated qualitative and quantitative 'measured' similarity between the model and the prototype for a time duration of more than one hour after the transient start. Namely, the time of pressurizer emptying and start of refill were measured in the Lstf within a difference of a few seconds, although the second event takes place nearly 3000 s after the transient start. Depressurization of the intact steam generator and of the primary system and opening cycles of the relief valve in the affected steam generators are also measured in the experiment and strictly match the corresponding time trends of the NPP. No dry-out condition was either detected or expected in any of the two measured scenarios, thus decreasing the complexity level of the simulation.

The results discussed above should not authorize any extrapolation of data from any ITF to any NPP. However, they confirm the understanding by the scientific community that the scaling laws (and the design factors) discussed in Section 2.2.1 are suitable for the transposition of phenomena between NPP and ITF. The experimental simulation of the Mihama-2 transient constitutes one of the 'scaling bridges' introduced in Section 3.6.

3.4. The 'scaling' role of Loft and Uptf

Any discussion about scaling cannot 'forget' the facts that facilities like Loft and Uptf have been designed, constructed and operated to gather experimental data that have been used to demonstrate the quality level of computational tools.

3.4.1. Loft

Loft ITF (OECD/NEA, 1991), is actually a Nuclear Plant producing around 50 Mwth power. Six fuel bundles having the same cross-section of actual nuclear fuel and reduced height constitute the core. One steam generator and one coolant pump are part of the 'intact loop' while (roughly) pressure drop simulators of the steam generator and of the pump are part of the 'broken loop', where breaks of the primary circuit are located. A few tens of experiments have been performed during the around 20 years of the life of the reactor, where the word 'experiments' can be substituted by 'nuclear accidents'. Noticeably, in this list there are the Double Ended Guillotine Break LOCA (further discussion below) and the ATWS (Anticipated Transient Without Scram) (e.g. Bayless and Divine, 1982). Both these two experiments are unique in terms of boundary and initial conditions that cannot be achieved inside ITF equipped with electrically heated rod simulators.

Related to scale, Loft can be considered either a 1:1 (small) nuclear reactor or an ITF, having volume and power scaling ratio in the range 1/15 to 1/50 (roughly) depending from the size of the reference reactor, i.e. either a 2-loop or a 4-loop NPP. This last one is the 'official' reference prototype plant, thus the 'official' volume and power scale is 1/50. Design-scaling parameters related to pressure, temperature, time, rod-surface- temperature and linear power are equal to one (e.g. fulfilling conditions at rows 13, 12, 9, 14 and 10, respectively, in Table 1). However, length is reduced for a factor around 2.

Several hundreds or even thousands of papers and reports in the public literature deal with Loft experiments and the application of system codes. It is outside the scope of the present effort to summarize related findings. Moreover, all (or the large majority) of the above papers and reports conclude about 'satisfactory agreement' between measured and calculated trends and unavoidably suffer, mainly because of size, of non-adequate or non-traceable documentation. The related results and findings are prone to the criticism raised in Section 2.2.3.

Analyses of Loft experiments are documented in the paper by Cerullo et al. (1985), including the LB-LOCA test L2-5. 'Revisiting' of the same experiment was performed by Bedrossian et al. (1998). More recently the L2-5 test was selected at the basis of the OECD/NEA BEMUSE Project (e.g. Petruzzi et al., 2004). The several hundred pages report by Petruzzi and D'Auria (2005), and the paper by De Crecy et al. (2006), describe calculation results by a dozen qualified groups of code users. A wide variety of findings and conclusions from the mentioned researches have an impact upon the present work. However, the following key-remark directly addresses the strategy pursued here:

System codes are able to predict Loft LB-LOCA with 'adequate precision' without any adjustment or tuning. 'Adequate precision' implies (all together):

- prediction of all relevant phenomena and event measured during the test (critical heat flux, reflood, time of pressurizer emptying, time of occurrence of peak clad temperature, accumulator intervention, etc.) with suitable qualitative and quantitative accuracy, fulfilling acceptability criteria;
- that the errors or differences between measured and calculated values, do not impact the safety limits: for instance the error in predicting rod surface temperature does not cause over-passing the safety threshold when added to the predicted value;
- that the experimental data are bounded by the calculation of uncertainty, without adjustments or tuning when applying the uncertainty methods.

The remark from the analysis of Loft experiments can be the same as from the analysis of any ITF experiments, however, the 'intrinsic value' can be higher due to the dimensions of the facility: errors in predictions exist and shall be bounded by uncertainty. As corollary statements: (1) any best estimate computer calculation is meaningless if not supported by uncertainty evaluation; (2) the code in relation to which the above conclusion applies is eligible for being considered within a suitable scaling process to demonstrate applicability in licensing.

3.4.2. Uptf, Sctf and Cctf

The Uptf (Damerell and Simons, 1992; Damerell and Simons, 1993) was constructed with the internals of the vessel of a (roughly) 4500 Mwt NPP. Other than the vessel, four hot legs and four cold legs, pressurizer and proper simulators of steam generator and pumps are part of the facility. It is definitely a full scale facility, however,

- power is produced by a nearby steam plant that feeds suitable amount of steam in the core region,
- the steam generator simulator remove energy by removing mass from the primary system,
- the main coolant pumps suitably reproduce pressure drops of the prototype pumps,
- the vessel design pressure allows operation at 2 MPa.

As in the case of Loft, a large number of papers deals with the experiments performed in the Uptf. Those works address either code qualification (e.g. D'Auria et al., 1999b; Glantz and Freitas, 2008, or, remarkably, the scaling, e.g. Takeuchi et al., 1998). The same conclusive remarks reported in the case of Loft are applicable here. However, no deep international activity has been performed so far making use of Uptf data.

Experiments performed in Sctf and Cctf (e.g. Murao et al., 1993) are complementary to Uptf considering the scale of the facilities and the simulated region of the vessel, i.e. the core region in the case of Cctf and Sctf. The same conclusion/finding reported for Uptf is relevant as far as the present framework is concerned.

No claim shall be made that experimental data from Loft, Uptf, Sctf and Cctf researches can be used to determine the behavior of any NPP. Rather those data, like data measured in any 'relevant' facility, shall be analyzed by codes and the capability of those codes in reproducing the experiments with suited-quantified accuracy shall be evaluated.

3.5. The counterpart testing and the similar tests

The idea to perform experiments at different scales came together with the decision to build the first ITF: it is enough to note that the first ITF even built was named "Semiscale", under the plan that a larger ITF (actually this was Loft) should have been put in operation at a later date. So, following the example of Semiscale and Loft, experiments with properly scaled boundary and initial conditions have been performed. These are identified as counterpart or similar tests. Several counterpart and similar tests have been performed during the last four decades (a partial list of counterpart and similar tests can be found in the OECD/NEA (1996), document, as already mentioned, where also the distinction between similar and counterpart tests can be found).

Because of the number of the involved ITF and of the performed experiments, because of the homogeneity and rigor in scaling the initial and the boundary conditions and because of the complexity of the considered scenario, the most relevant counterpart test activity was performed during a time frame of about 20 years involving 5 ITF and 7 experiments.

The involved ITF are Lobi (simulator of German four loop PWR by two un-equal loops), Spes (simulator of US three loops PWR by three equal loops), Bethsy (simulator of French three loop PWR by three equal loops), Lstf (simulator of US four loops PWR by two equal loops) and Psb (simulator of Russian four loops VVER-1000 by four equal loops). Four of the involved ITF are equipped with U-tubes steam generators and the fifth one, Psb, is equipped with horizontal tubes steam generators.

The concerned experiment is a SB-LOCA originated by a break in cold leg, without the intervention of the high pressure injection system. Selected interesting aspects of this counterpart test are:

- Occurrence of three dry-out conditions: (a) loop seal controlled; (b) accumulator controlled; and (c) LPIS (Low Pressure Injection System) controlled.
- In relation to all the ITF experiments, the reduced initial power condition was adopted in the design. However in Lobi and Spes both reduced and full initial power condition were possible and were adopted (owing to this, 7 experiments in 5 ITF are part of the counterpart test program).
- Measured data from the 7 experiments resulted fully consistent with the objectives of the tests and discrepancies among the corresponding time trends could be explained.
- Accuracy in the predictions, by adopting more than one code, was found independent upon scaling (see discussion in Section 3.2).

Needless to remark that a large number of papers and documents are available in the literature dealing with the analysis of one or more among those PWR SB-LOCA counterpart test (e.g. D'Auria and Galassi, 1992; D'Auria et al., 1999a; Blinkov et al., 2005; Cherubini, 2004, or with the entire (or large part of the) database, e.g. Annunziato et al., 1993; Ingegneri and Chojnacki, 1997; D'Auria et al., 1997b, 2005). Thus, the full description of the counterpart test activity is also outside the scope of the paper. However, a few remarkable values taken from the SB-LOCA counterpart test database (e.g. see D'Auria et al., 1994; Blinkov et al., 2005), are reported in Fig. 2 (the following nomenclature is adopted: MI = mass inventory; ND = non-dimensional; P = pressure; RST = rod surface temperature; W = power).

Three levels for the data are distinguished, from the top to the bottom of the figure: ITF design data (related to 5 facilities), test design data (related to 7 experiments) and test result data (related to 7 experiments and 7 code-calculations). The ranges covered by the data can be deduced from the given tables. The aim of Fig. 2 is to give an idea of the Counterpart Test database. The diagrams in the bottom left deal with experimental data and show: (a) upper, experimental variables from 7 tests in the selected phase-space plane where similarity among the scenarios can be observed; (b) lower, three-dimensional representation of one experiment that may be used to demonstrate (demonstration not provided here) that all experiments produce a similar image. Otherwise, each of the three diagrams in the bottom right shows the comparison between (seven) measured and (seven) calculated trends. This gives an idea of the capabilities of computational tools to calculate phenomena at different scale with a comparable level of accuracy.

Analyses of counterpart tests in PWR for scenarios different from SBLOCA and performed in ITF scaled according the time-preserving laws, can also be found in the literature (e.g. Bazin et al., 1992), dealing with natural circulation.

The attempt to scale result measured in ITF to full scale NPP, by adopting the code can also be classified as part of counterpart or similar tests related activities. Examples can be found in relation to the SB-LOCA (i.e. the counterpart test discussed above) by Ingegneri et al. (1997), and in relation to the Loss of Feed-water scenario, by D'Auria et al. (1993). Similar test data extrapolated to NPP are also those discussed under Natural Circulation, see item (6) in Section 4.1.

Parameter	BETHSY	LOBI	LSTF	PSB-VVER	SPES
Kv	1.00E-3	1.40E-3	2.08E-2	3.33E-3	2.34E-3
Pressurizer pressure	1	1	1	1	1
Core exit temperature	1	1	1	1	1
Number of fuel rod	Kv	Kv	Kv	Kv	Kv
Core active height	1	1	1	1	1
Fluid volume	Kv	Kv	Kv	Kv	Kv
Core power	0.1 Kv	Kv	0.14 Kv	Kv	Kv
Core inlet flow	0.1 Kv	Kv	0.14 Kv	Kv	Kv
Hot leg diameter (m)	0.118	0.074/0.046	0.207	0.076	0.066
Hot leg L/D (-)	38	73/119	18	54	58
Number of loops (-)	3	2	2	4	3
Number of tubes in SG (-)	34	8/24	141	34	13

ITF design data (5 sets) – selected quantities

H = 'High Power (full initial power) experiments (LOBI & SPES)

Parameter	BETHSY	LOBI	LOBI_H	LSTF	PSB-VVER	SPES	SPES_H
Core power (kW)	2863	630	5280	7930	1129	768	5600
PRZ pressure (MPa)	15.38	15.47	15.46	15.4	15.6	15.06	15.16
SG pressure (MPa)	6.86/6.84/6.84	6.94/6.91	5.12/5.11	7	408/4.14	6.94/6.87/6.88	6.7
Core inlet flow rate (kg/s)	17.5	3.6	28	48.4	5.94	4.21	31.8
PRZ level (m)	7.45	5	5.1	1.7	4.94	3.23	3.77

Test design data (7 sets) – selected quantities

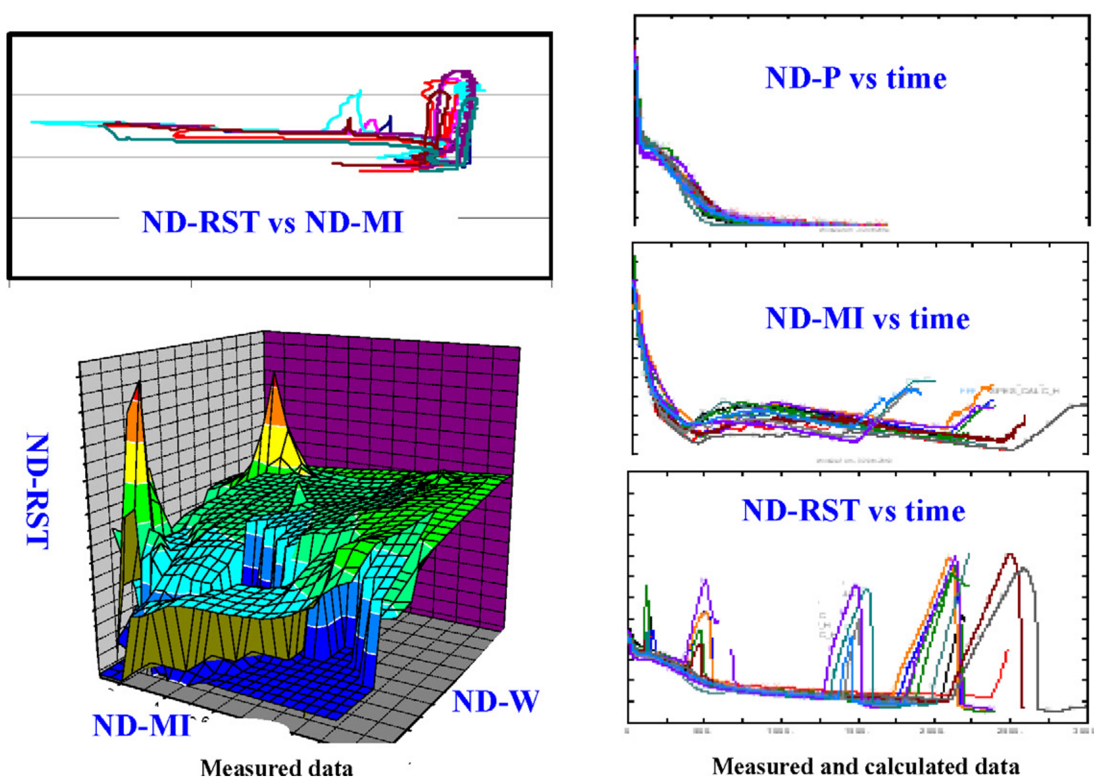


Fig. 2. Spot information from the PWR SB-LOCA counterpart test database. .

The analyses of counterpart tests in BWR are discussed by Kumamaru et al. (1987), and Bovalini et al. (1992). Moreover, the analyses of counterpart tests in VVER-440 and in VVER-1000 are discussed, by Szabados et al. (2009) and D'Auria et al. (2006b), respectively.

Scaling activities and test data related to VVER-1000 can be found, other than in the paper by Blinkov et al. (2005) already mentioned, in the papers by Araneo et al. (2005), Groudev et al. (2005), and Del Nevo et al. (2008).

Counterpart scaling includes facilities designed according to the Ishii-scaling (Section 2.2.2) which adopt the 1:4 length ratio, and according to the time-preserving laws (1:1 length ratio). Related findings constitute the subject of the papers by Liu et al. (1997) and Reyes and Hochreiter (1998). Comparison between relevant measured time trends, i.e. involving ITF experiments scaled according to Ishii-scaling and to time-preserving laws, is discussed, confirming again the proper understanding of the scaling laws.

3.6. *The Scaling Pyramid and the scaling bridges*

The water cooled nuclear reactor system, in relation to scaling, can be assumed at the top of a virtual multi-D pyramid whose bases are constituted by the research achievements and by the technology findings in the area of system thermal-hydraulics. Several edges, i.e. the scaling bridges, connect, more or less tightly, the research achievements and the technology findings with the top of the pyramid.

Hereafter, we wish to show in a pragmatic way that the NPP and the related phenomena do not constitute an unbeaten fortress on the top of a hill, but vice-versa, that researchers and scaling research results, (namely those discussed in previous sections) have contributed to make clear the phenomena and the scenarios envisaged at the top of the pyramid.

A not-exhaustive set of scaling bridges connecting the NPP with what we may call the established-understanding is depicted in Fig. 3. Some explanation is provided by the following bullet items, where the NPP is the 'central-top-triangle'.

- *NPP operational transients*, left top box. For a reduced range of parameter values, codes-nodalizations results are compared with transients data measured in NPP (e.g. Borges et al., 2002). No code deficiency is drawn from the papers dealing with the simulation of operational transients: however, small regions of the phase-space domain at full scale are within assessed code capabilities.
- *TMI-2*, right top box. In the case of the TMI-2 accident, recently revisited (e.g. OECD/NEA, 2009), thermal-hydraulic phenomena occurred before core melt and involving phase non equilibrium, could be predicted at full scale during a couple of hours of transient evolution without showing any model deficiency.
- *Loft and Uptf*, right and left middle boxes. The existence of those two facilities (including Cctf and Sctf) and the completion of the related research programs (Section 3.4) need proper consideration when dealing with the scaling issue: phenomena and parameters have been measured at full scale and must be considered. Those two boxes are connected with the NPP through the line 'Straightforward Scaling Connection'.
- *NPP Mihama-2 SGTR* (Steam Generator Tube Rupture) right middle box. The capability was demonstrated to reproduce by an experiment the NPP performance (see Section 3.3): in this case, no computational tool was needed to show the capabilities of the concerned scaling procedure and the adopted test design factors. A "straightforward" scaling test was performed according to the nomenclature of Fig. 3. Related results allowed gaining of unique confidence in the understanding of NPP transient performance (Yokobori and Nakamura, 2008).
- *The Counterpart Tests*, left lined boxes. An outline of the world-wide Counterpart Tests activities is mentioned in Section 3.5. The related main roles within the Scaling Pyramid are: (1) possibility to confirm the understanding of scaling factors by using experimental data; (2) opportunity to demonstrate that accuracy of code prediction does not depend upon scale (namely volume scale). Owing to those reasons, the completion of the counterpart test activities allows the connection of the Counterpart Test boxes with the NPP through the line 'Straightforward Scaling Connection'.
- *The Similar Tests*, left-middle lined box. The same statement and the conclusions given for the Counterpart Tests can be applied to the Similar Tests. It can be recalled that Similar Tests, related to Counterpart Tests, require lower amount of work for test design and facility hardware preparation and larger amount of work for interpretation of measured scenarios.
- *Conduction Heat Transfer*, middle-bottom left box. The prediction of any NPP transient scenario needs a variety of models, e.g. embedded into a computer code as outlined in Section 2.4. Some of those models may not be at the origin of scaling issues which need investigation. One example is the conduction heat transfer that is modeled by the Fourier balance equations and by the Fourier law (e.g. Todreas and Kazimi, 1990; Zudin, 2007). Thus whatever is connected with the conduction heat transfer in the NPP constitutes an 'island of knowledge' and 'No further Scaling (theory) Need', as indicated by the discontinuous dotted line in Fig. 3.
- *HTC rod-fluid*, middle-bottom central box. The parameter 'HTC rod-fluid' together with the conduction heat transfer in the fuel rod (not affected by scaling) constitutes the key for determining the CHF (Critical Heat Flux) occurrence and the rod surface temperature. This, at least in case of LOCA, constitutes the most relevant safety parameter and justifies the presence in the diagram. The core of a nuclear power, typically 4 m diameter, 4 m height, can be seen as an ensemble of replicating elements that are the fuel rods, the spacer grids or the fuel bundles that interact with the fluid-coolant under different thermal-hydraulic conditions (basically characterized by pressure, velocities, void fraction, temperatures). The replicating elements are characterized by 'small scale geometric dimensions'. Several tens of experimental programs to measure the various relevant parameters including the HTC rod-fluid have been completed and related findings are available in the literature (e.g. Tong and Weisman, 1996; US NRC, 1976, 1988). There is no reason to expect a thermal-hydraulic performance of the replicating elements, when these are installed in the NPP, different from what is measured in the experiments, i.e. not only the single rod, but ensembles of rods, or even a number of fuel bundles. The same considerations apply to all thermal-hydraulic parameters which characterize the interaction between fuel bundles and coolant, including pressure drops in single and two phase flows. Thus, 'No further Scaling (theory) Need' is identified for those situations and the direct connection with the NPP scenario, namely core behavior, is stressed in Fig. 3. At this point a caution-statement appears relevant: in case fluid conditions are well-evaluated at the boundary of the core, reliability in the prediction or in the measurement of the mentioned (top of this bullet item) safety parameters can be high. However, fluid conditions at the core boundaries constitute typical targets of the system analysis in relation to which the scaling issue must be addressed.
- *Sub-channel mixing*, middle-bottom right box. Whatever written in relation to HTC rod-fluid is relevant in this case. Relevant scientific and technological information can be found by Ninokata and Aritomi (1992), although a large progress in recent years is due to the CFD (Computational Fluid Dynamics) and similar tools (e.g. Hassan and Barsamian, 2001). Furthermore, computational capabilities in this case are more adequate in the case of single phase flows compared with two-phase flows.
- *Established similitude*, bottom central-right box. Established dimensionless groups (or numbers) in fluid mechanics and heat transfer are widely used by the scientific community (a couple of dozen of those numbers can be found in the Appendix G of the book by Todreas and Kazimi (1990)). The observation here is that those numbers create specific islands of established knowledge (i.e. the same comment given in the case of conduction heat transfer) when predicting the transient performance of NPP. For instance, making reference to single phase flow (for the sake of simplicity), nobody doubts that the Re-dependency of friction pressure drop that is measured and calculated in a 0.01 m diameter pipe is also valid in the case of 1 m diameter pipe. This creates a further connection between established science and (full scale) NPP performance.
- *Code-Nodalization Qualification and Uncertainty Evaluation*, pyramid bottom boundary. This paragraph focuses on the computational tools and intends to emphasize cross-connections among different parts of the paper. Two sub-paragraphs are distinguished: (I) general comments, (a)–(d) below, and (II) <specific> comment, (e) below, relevant to the 'Scaling Pyramid'.
  (a) General comment #1. The code alone including all of its implemented models and the numerical solution methods is not the only responsible for results. The nodalization and the

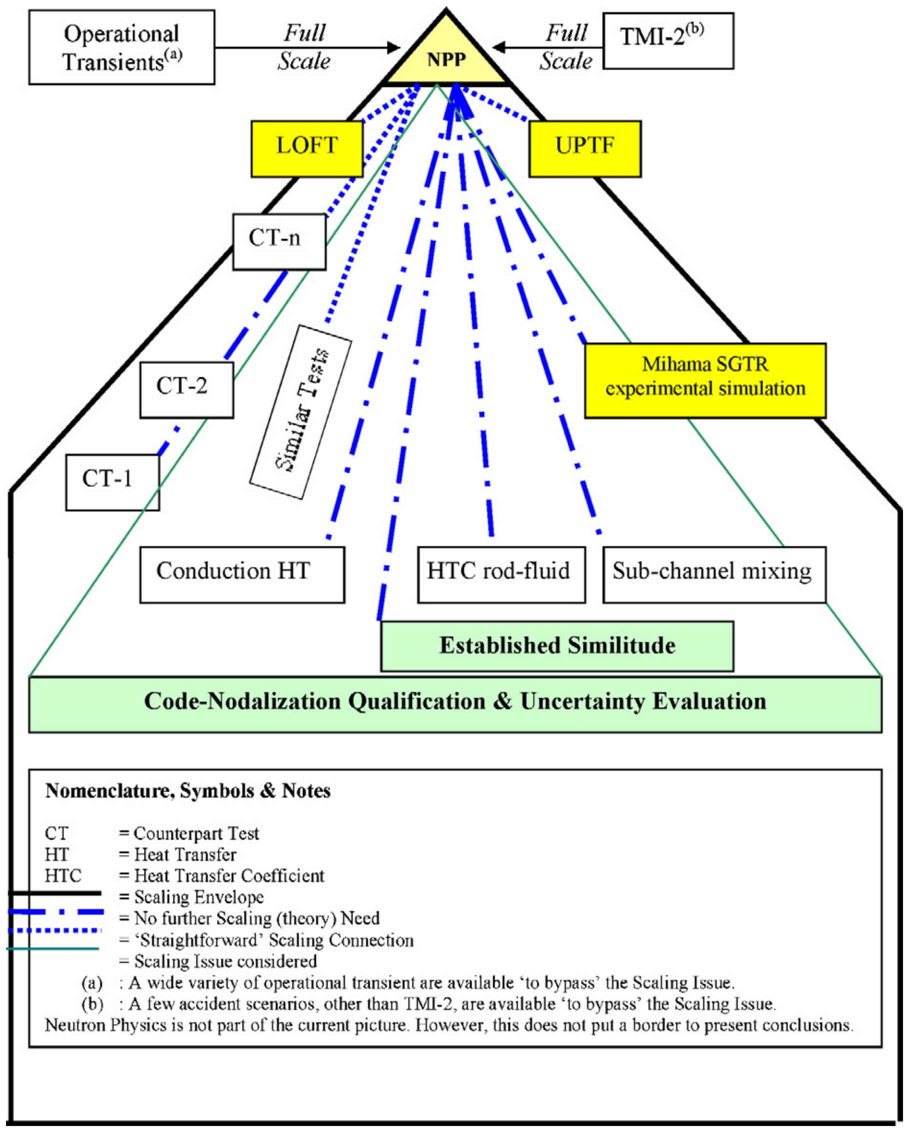


Fig. 3. The Scaling Pyramid and the Scaling Bridges.

code-user (Section 2.4) also have a significant share in relation to the quality of the set of results related to a NPP calculation.

(b) General comment #2. Code, nodalization and code-user, need qualification independent of scaling (e.g. Section 2.4), (D'Auria and Galassi, 1998; Petruzzi and D'Auria, 2008). Lack of qualification for any of those three elements contributes to the 'Scaling Controversy' (Chapter 1).

(c) General comment #3. Uncertainty is needed for any best-estimate code calculation and the scaling issue must be addressed together and consistently with uncertainty, as also requested by CSAU, Section 2.2.4.

(d) General comment #4. Code, nodalization and code-user qualification against scaling is outlined in Section 4.2.1, where the procedure at the basis of the UMAE is mentioned (Section 4.1).

(e) <Specific> comment relevant to the Scaling Pyramid: The relationship between scaling, qualification of computational tools and uncertainty (i.e. comments #1 to #4) is clear to the scientific and technological community (e.g. Frepoli, 2008; Glaeser, 2008; Martin and O'Dell, 2008), and constitutes a relevant matter within the licensing processes of NPP. This is not the proof that the problem is solved, but it provides the reason for the role of computational tools in the Scaling Pyramid.

The Scaling Pyramid shows that connections exist between, on the one side, established knowledge in the area of Fluid-Dynamics and Heat and Mass Transfer, the subjects of basic and applied research including the development and the qualification of computational tools, the licensing activities and, on the other side, the (full scale) NPP.

According to this, scaling bridges have been identified in Fig. 3: the nuclear reactors and the related transient performance in case of accident shall not be considered as an un-accessible fortress related to thermal-hydraulic phenomena which are studied and characterized at the research level.

4. The proposed approach to scaling

Distortions are characterized and the impossibility to fulfill all together the scaling requirements is one conclusion from the previous sections. Different 'familiar' purposes for scaling analysis are reported by Wulff (1996) (hereafter given in a synthetic format):

- To design a reduced-size test facility.
- To design an experiment in a reduced size test facility.

- To identify non-dimensional parameters which apply to many systems, including both the model and the prototype.
- To identify the dominant processes part of an assigned transient scenario (i.e. in order to substantiate quantitatively, or to revise, the expert-opinion based [still subjective] ranking of phenomena).
- To provide the basis for quantifying scale distortions.
- To derive the scaling criteria for simulating component interactions within a system from the global component and system models, with the focus on system, rather than component scaling.

Keeping this in mind, the purpose for the proposed approach to scaling is:

- To demonstrate that a transient scenario calculated by a system thermal-hydraulic code with reference to an assigned NPP (i.e. the model) is validated related to scaling.

The proposed approach to scaling, or roadmap for scaling, aims at showing that all the ideas or scaling spot studies, partly discussed in the previous chapters, can be unified or integrated within the roadmap. This is particularly true in relation to the final remarks in Section 2.2.6. Key role in this connection is assumed by concepts as computational-tool-validation and scaling-of-accuracy. The roadmap, Section 4.2, can be seen as the end-result of several supporting studies performed at University of Pisa within a few decades time frame. Those studies are outlined in Section 4.1.

4.1. An overview of scaling activities at UNIPI

The following 'historical' steps are milestones for the scaling research in NRSTH performed at UNIPI. Achievements from four decades of attention to the problem (the scaling issue) are shortly described that constitute a support (or justification and substantiation) to the proposed Roadmap to Scaling. Referenced documents, in the wide majority published papers, are available and provide suitable details in addition to documents (and papers) already part of the list of references. Scaling activity and achievements at UNIPI deal with:

1) Design and operation of the Piper SETF, Vigni et al., 1973, to simulate the blow-down transient in a BWR (Boiling Water Reactor) in case of LB-LOCA (Large Break - Loss of Coolant Accident) scenario. The transient mass and energy balance equations for a single control volume were adopted for the design of a cylindrical pressure vessel, height and diameter equal to ≈3 m and ≈0.3 m, respectively. Relevant achievements are:
   - A_R/V (Break Area over [fluid] Volume inside the vessel) ratio is the key scaling parameter for blow-down when initial system pressure and average fluid temperature are the same in the model and in the prototype (see also Eq. 2.4.5 and subsequent discussion by Levy, 1999).
   - The break area associated to a cylindrical nozzle having diameter $\phi = 0.0136$ m and horizontal axis located at a 'mass-scaled' axial distance from the initial collapsed liquid level was used to simulate the time-pressure history of the BWR following LBLOCA, Vigni et al., 1978.
   - The break flow in a transient, or TPCF (Two Phase Critical Flow), is a function of both 'scalable' intensive and extensive properties like pressure, temperature and mass inventory and of 'non-scalable' variables like pipe roughness, nozzle fitter radius, void fraction at the entrance of the exit nozzle and even density of nuclei for nucleation in the fluid (D'Auria and Vigni, 1980). Therefore, TPCF cannot be controlled in a scaled experiment as confirmed by the example in Section 3.1.
   - Based on the result from the 2nd dashed item above, measurements of pressure wave propagation and friction pressure drops in the presence of choked flow (D'Auria and Vigni, 1984b), jet impingement and thrust (D'Auria and Vigni, 1984a), load on internals (D'Auria and Vigni, 1989), TPCF (D'Auria and Vigni, 1983) and related code assessment activities were performed inside parameter range boundary, i.e. properly scaled, values which are relevant to BWR (e.g. D'Auria et al., 1983a).
2) Design of Piper-one (the added-word 'one' means 'big' in Italian) ITF. The Piper-One was designed to simulate the SB-LOCA (Small Break LOCA) performance of BWR (D'Auria et al., 1985a) according to the power-to-volume, time-preserving scaling laws. As an achievement relevant within the present context, scaling factors were derived considering the Natural Circulation occurrence between core and down-comer, (D'Auria et al., 1985b). Namely, the liquid head acting at the level of the core BAF (Bottom of Active Fuel) was the key parameter to be preserved in the design. In addition, inside an about 15 m high, full pressure facility, local pressure drops in the lower and the upper plena regions were designed to produce a facility transient behavior consistent with the expected (calculated) BWR behavior. A typical inconsistency that one encounters when designing ITF is embedded in the statement above and requires the following explanation:
   - Computer codes are used in different steps of the design of ITF. However, the same codes, that are assumed to need qualification, constitute the ultimate objective for the design and operation of the same ITF. Thus, if computer codes produce wrong results, the ITF design is wrong. How to go out from the circle constituted by 'wrong' experimental (w-e) data generated by a 'wrong' ITF (w-I) design whose origin is a 'wrong' code (w-c)? In the sentence above the words w-e imply data measured in w-I where w-I is a facility designed and built without considering scaling; the words w-c imply a (not necessarily existing) code where wrong equations are implemented. The answer to the question is given in the following dashed items.
   - At first, the word 'wrong' should be supplemented by 'from point of view of scaling or of phenomena expected in the model'. Actually, three question-items apply and should be considered all together to avoid the inconsistency: (a) All design choices that are taken based on the use of the code should be identified and recorded and no-one should be irreversible as far as the ITF configuration is concerned: for instance the diameter of a orifice could be the result from a code calculation, but the active length of the core region should not be based upon the result of the code. (b) Experiments should be planned by varying the parameter values that have been fixed with the help of code calculations. In case measurements from those experiments strongly differ among each other, caution should be taken in interpreting the 'scaling quality' of the concerned phenomena. (c) Measurements from one ITF should be compared with available NPP (or prototype) data and with data values from other facilities (that may not 'suffer' from the application of the same code in their design), i.e. performing Counterpart Test or Similar Test.
   - Finally, 'wrong' experimental data can be helpful for code assessment purposes and should not be extrapolated to forecast accident scenarios in NPP.
3) Operation of Piper-one. From the operation of Piper-One, relevant achievements connected with scaling (see also Bovalini et al., 1991), can be summarized as follows:
   - The question-item (c) mentioned in the previous paragraph is positively answered in the papers by Bovalini et al. (1992) and Ambrosini et al. (1993): in the former, SBLOCA scenario in Piper-One was compared with scenarios measured in Fist and

Rosa-III facilities; in the latter, natural circulation power-to-flow curve was compared with NPP data.

- When the scaling approach identified as power-to-volume scaling, time-preserving, full-height, full-pressure is adopted two distortions unavoidably appear: (I) the thermal energy transferred to the unit coolant mass by the passive structures is much larger in the model than in the prototype (for a factor greater than 10, however depending upon the scale). The corresponding thermal power transfer can be even larger depending also upon the depressurization rate during an assigned accident scenario. (II) The ratio between power loss to the environment, or heat losses and power generated in the core or core simulator can be one or two orders of magnitude (again depending on scale) higher in the model with respect to the prototype.
- Documents where subjects (I) and (II) under the previous item are discussed, are D'Auria et al. (1983b), Ambrosini et al. (1985), and D'Auria et al. (1987), the last one dealing with the conduction heat transfer in PWR typical conditions. In the first of the above documents, the design of cooling coils wrapped and welded around the piping of the primary system is presented: cooling fluid flow inside the coils was controlled by the process of heat release from passive structures to the primary fluid. The operation of cooling coils brought to minimize the scaling distortion originated by the cause I) (see also Bovalini et al., 1991). In the second paper above, the propagation of the temperature front inside the thickness of the structural material is characterized as a function of the relevant boundary conditions. Definitely it is found that a full-pressure, (volume) scaled-down facility may not be suitable for the simulation of long lasting transients where heat losses and heat release from thick structures significantly distort the expected transient in the reference NPP. Otherwise, a reduced pressure, (volume) scaled-down facility, which may not 'simulate' the initial high pressure phases of a transient, more easily reproduces the long term performance expected for the reference NPP.
- An additional finding from the paper by Bovalini et al. (1992), is derived from the analysis of counterpart tests although limited to selected SBLOCA scenarios. This is the use in the ITF design of a limited number (i.e. a dozen) of scaling ratios that brings to a suitable experimental reproduction of complex phenomena. Thus, a large number (i.e. several tens) of scaling ratios (e.g. Reyes and Hochreiter, 1998), is not strictly needed for the ITF design and not justifiable scaling distortions for those parameters might be detected during the experiments.
- An exciting scaling relevant finding is documented by D'Auria and Pellicoro (1996), also reported by D'Auria et al. (1997a). Foreword statements are to recall that: (a) the concept of instability in boiling channels is notoriously linked to the concept of propagating pressure wave across the core; (b) the Piper-one is equipped with differential pressure transducers covering each 0.5 m of core active region (full core height about 4 m) that is characterized by an axially cosine-shaped electrical power production. During one natural circulation experiment, oscillations of decreasing amplitudes were measured from the center of the core toward the top and the bottom. In other words, pressure (and presumably void fraction) was oscillating in the region of high power, but a transducer put from bottom to top of core did not show any oscillation. So, a 'standing-wave' oscillation was detected from measured signals. Interesting enough, the same phenomenon was observed from a system code calculation result in BWR fuel channel conditions.
- The capability to predict relevant stability related parameters with suitable uncertainty (or error) is discussed by D'Auria and Pellicoro (1995), also based on measured data in the Ringhals NPP.

4) The derivation of scaling factors (e.g. D'Auria et al., 1982, 1988) involving the cooperation of the present authors with Prof. Karwat. The factors listed in Table 1 can be considered as the key outcome from the research documented in those papers and are suitable for the design of ITF (e.g. Piper-one facility, Bovalini et al., 1991, see above) and of counterpart tests (e.g. D'Auria et al., 1988) as already mentioned. In the last paper, the curve for extrapolation of accuracy was introduced and it was recognized that direct scaling of ITF-measured thermal-hydraulic phenomena is not feasible. The meaning of accuracy scaling was also clarified and constituted the seed for the development of the UMAE and the CIAU methodologies (see below).
5) The study of the counterpart test. The UNIPI had a role in the design and/or in the analysis of the PWR SB-LOCA Counterpart Test discussed in Section 3.5 (e.g. D'Auria et al., 1999a, 2005). Moreover, UNIPI was the leading institution for the BWR SB-LOCA Counterpart Test (e.g. Bovalini et al., 1992).
6) The analysis of Natural Circulation. Natural Circulation (NC) experiments were foreseen as characterization tests in the experimental matrix of each PWR simulator (or ITF): thus, similar tests have been performed in a number of ITF and, at least in relation to two facilities, one NC counterpart test has been performed (e.g. Bazin et al., 1992) already mentioned. The resulting database of similar and counterpart tests for NC constitutes a mine of information for related phenomena. This has been exploited to derive the scaling oriented NC regime map and the NC flow map for PWR (e.g. D'Auria et al., 1991; D'Auria and Frogheri, 2002) respectively. Those papers are also part of the reports (IAEA, 2002, 2005). The use of NC experimental data to evaluate the NC performance of NPP is discussed by Mousavian et al. (2004) and D'Auria et al. (2008). Elements of the NC database for BWR including NPP and ITF, can be found in Ambrosini et al. (1993). Connected with NC and NC scaling, the reliability of the NC phenomenon is discussed by Jafari et al. (2003), and the stability of experimental loops working in NC is discussed by Misale et al. (1998) and by Jafari et al. (2002).
7) The development of the UMAE (Uncertainty Method based on Accuracy Extrapolation) uncertainty procedure (e.g. D'Auria et al., 1995). The UMAE allows the calculation of uncertainty for system code calculations based on the analysis of a suitable number of transients in differently scaled ITF. The un-availability of suitable experimental data prevents the possibility to calculate the uncertainty. The connection between UMAE and scaling can be recognized from the acronym itself: the 'extrapolation of accuracy' is proposed primarily along the scaling coordinate 'Kv' (see Table 1). Without entering the description of the procedure, the following is recalled:
   - The seed for the development of the procedure is the 'accuracy extrapolation diagram' discussed (above) under the item 'Derivation of Scaling Factors' (e.g. D'Auria et al., 1988).
   - The computational tools including the code, the nodalization and the code-user must be sufficiently qualified (all together) in order to apply the procedure (some details are given in Section 4.2.1).
   - The CSAU requirements related to scaling, various items in Section 2.2.4, are considered by UMAE.
8) The development of CIAU (Code with capability of Internal Assessment of Uncertainty), automatic uncertainty procedure (e.g. D'Auria and Giannotti, 2000). The CIAU can be seen as an automatic version of the UMAE. Furthermore, UMAE constitutes the 'engine' for CIAU. A key peculiarity of CIAU is the association of uncertainty with the concerned computational tools and the consequent 'automatic' derivation of uncertainty bands each time a transient is calculated. This is made possible by the avail-

ability of a database of errors (or of accuracies). The database is calculated following the rules set in the UMAE including the related scaling requirements. The outline of CIAU is beyond the scope for the present paper. However, it seems worthwhile to emphasize one connection with the FSA proposed by Zuber (Section 2.2.3) as given below in two steps:

- The so-called phase-space (e.g. one system variable versus another variable typically connected with energy and mass balance) is adopted in the case of CIAU to exploit the similarity among different transients. Trajectories are created for each scenario.
- In the case of CIAU, fractions of the phase space constitute hypercubes where accuracies coming from the (previous code) calculations of different transients are combined (e.g., Piagentini et al., 2001).
- In order to establish (qualitative) similarity among different transients the FSA uses trajectories in the phase-space created by one system variable and the FCM (i.e. Fractional Change Metrics in Section 2.2.3) i.e. a quantity derived from energy and mass balance (e.g. Catton et al., 2005).
- The CIAU, other than defining the similarity of transients by an FSA similar way, exploits the similarity by characterizing the accuracy that is used in further processing as at the basis of the uncertainty in the predictions by codes.

4.1.1. The 'Scaling Puzzle'

Many activities can be classified and are actually classified in the literature as scaling related research, as can be seen from Sections 2 and 3. The 'Scaling Puzzle' has been created in order to provide a rough visualization of the scaling activities performed at UNIPI (discussed in the section above) and to demonstrate the need to identify a road-map through those activities. This is given in Fig. 4 in relation to which the following additional information applies. Reference is made to the sketches 1–11 (in Fig. 4) each taken from a paper part of the list of references, as also indicated in the figure.

(1) This can be taken as the seed figure for accuracy extrapolation.
(2) The data base of NC experiments performed in PWR-ITF is reported in a suitable 'dimensional' phase space.
(3) The 'in-principle' or the 'UMAE-precursor' flow diagram for obtaining NPP transient scenario either by ITF experiments or by ITF qualified calculations (not any of these ways is pursued hereafter or in the framework of UMAE and of CIAU application).
(4) Data accuracy is reported as a function of *Kv* (logarithmic scale is adopted in the horizontal axis).
(5) The scale independent formula for single phase natural circulation in PWR was proposed.
(6) The flow diagram of UMAE: stop of the (scaling-up) process should be noted when assigned acceptability conditions are not met.
(7) Table showing the result of the application of the FFTBM to quantify the accuracy in the case of Counterpart Test: calculated values of the errors do not depend upon scaling. It may be noted that an analytical formulation of the accuracy different from FFTBM is used for extrapolation.
(8) Demonstration that thermal-hydraulic phenomena, in this case connected with natural circulation, depend upon scaling.
(9) Use of the natural circulation flow map to evaluate the (natural circulation) performance of a NPP.
(10) 'Enlarging' the geometric parameters of a code input deck (or nodalization) is not a recommended way to perform a scaling analysis.
(11) The simplified flow diagram of CIAU emphasizing the 'error-filling' and the 'error-extraction' processes.

4.2. The roadmap to scaling

Following the 'Scaling Controversy', a non systematic 'SOA on Scaling' is given, complemented by 'Topics relevant to Scaling'. This brought to the 'Scaling Pyramid' with emphasis given to the 'Scaling Bridges'. Moreover, the 'Scaling Puzzle' has been built based on the scaling work done at UNIPI. The present Roadmap to Scaling aims at finding the way throughout the Scaling Puzzle considering the background information provided in the paper and adopting the system thermal-hydraulic code as the 'key-to-scaling'.

The objective for the Roadmap is as stated in the Section 1 and under the heading of Section 4. The detailed description of the objective itself implies the fulfillment of the step (I) of the Roadmap (see below). This constitutes a requisite for the planning of the remaining steps. The objective is thus reformulated with more detail in the paragraph hereafter.

Within the licensing process of water cooled reactors where best estimate codes are used (BEPU approach) a typical request from Regulatory Authority deals with the demonstration of the scaling at different levels. This implies the demonstration of the scaling capabilities of the adopted computational tools including the code, the nodalization and the analyst or code user (the qualification of the input data constitutes a complementary issue not necessarily connected with scaling). Thus, objective of the Roadmap is to streamline an answer to the regulatory request making use of the information discussed in the paper.

Steps of the Roadmap to Scaling are as follows and the flow diagram given in Fig. 5.

The framework and the objective for the scaling analysis

I) Establishing the objective and the scope for the scaling analysis including the significant boundary conditions (the objective and scope are defined in the paragraph above). This implies the identification of the reference NPP and the consideration of accident scenarios.

Phenomena investigation and obtaining scaling parameters

II) Select the power-to-volume, full-height, full-pressure, time-preserving approach as the reference scaling approach. This at the system level or at the macro-scale level.
III) Select the (hot) rod surface temperature as reference parameter at local level or at the micro-scale level, as the most important safety related parameter. This parameter may be different in different frameworks (e.g. in new reactor design or in case of selected SB-LOCA, main focus at micro-scale might be the core liquid level).
IV) Consider the component-zone-phenomena scaling.

Use of scaling parameters (e.g. based on the design criteria in Table 1)

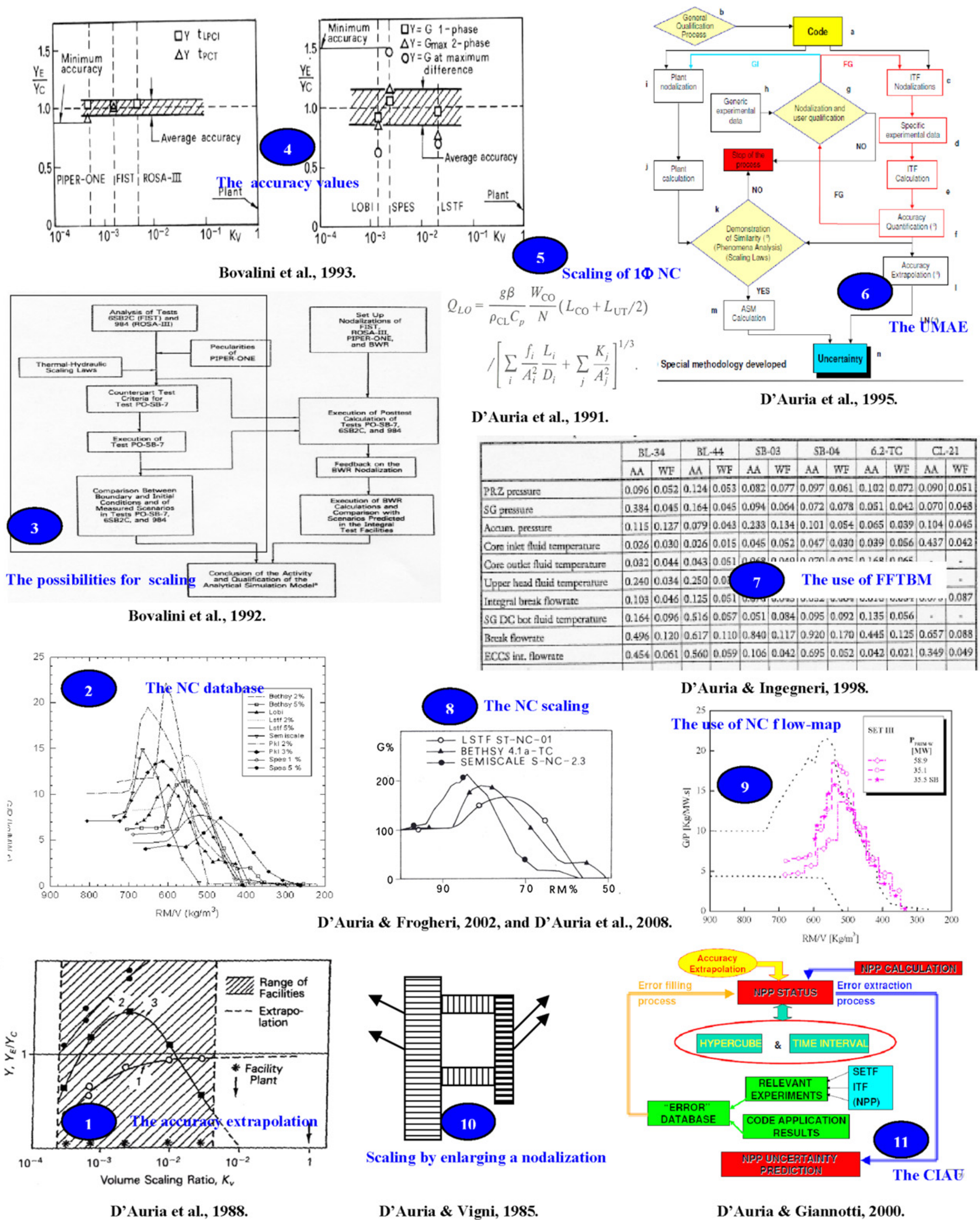
V) Confirm the suitability of the scaling design of selected ITF.
VI) Confirm the suitability of the design of selected tests including counterpart tests.
VII) Confirm the suitability of the code design against scaling.

Exploitation of experimental data and demonstration that

VIII) Experimental results are similar.
IX) Accuracy of code prediction is independent of scale.

Development of NPP nodalization and

X) Performing Kv-scaled analysis.



	BL-34		BL-44		SB-03		SB-04		6.2-TC		CL-21	
	AA	WF	AA	WF	AA	WF	AA	WF	AA	WF	AA	WF
PRZ pressure	0.096	0.052	0.124	0.053	0.082	0.077	0.097	0.061	0.102	0.072	0.090	0.051
SG pressure	0.384	0.045	0.164	0.045	0.094	0.064	0.072	0.078	0.051	0.042	0.070	0.048
Accum. pressure	0.115	0.127	0.079	0.043	0.233	0.134	0.101	0.054	0.065	0.039	0.104	0.045
Core inlet fluid temperature	0.026	0.030	0.026	0.015	0.045	0.052	0.047	0.030	0.039	0.056	0.437	0.042
Core outlet fluid temperature	0.032	0.044	0.043	0.051	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-
Upper head fluid temperature	0.240	0.034	0.250	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-
Integral break flowrate	0.103	0.046	0.125	0.051	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.087
SG DC bot fluid temperature	0.164	0.096	0.516	0.057	0.051	0.084	0.095	0.092	0.135	0.056	-	-
Break flowrate	0.496	0.120	0.617	0.110	0.840	0.117	0.920	0.170	0.445	0.125	0.657	0.088
ECCS int. flowrate	0.454	0.061	0.560	0.059	0.106	0.042	0.695	0.052	0.042	0.021	0.349	0.049

Fig. 4. Scaling Puzzle based on the work done at UNIPI.

XI) Performing reference NPP accident analysis and evaluation of results

Looking at steps II, III and IV, hierarchy shall be established in relation to the scaling parameters in the order of importance from II to IV. Furthermore, the "CSNI list and Use of RTA (Relevant Thermal-hydraulic Aspects)" refers to phenomena list and procedures indicated in the documents (OECD/NEA, 1993; OECD/NEA, 1996), for the CSNI list and to D'Auria et al. (1999a), for the RTA list, respectively. The expected outcome from the steps is a list of a few hundred scaling parameters (i.e. per each NPP scenario) that are distinguished into two groups: (A) related to the Macro-Scale in relation to which a set of parameters like those in Section 2.2.1 should be formed; B) related to the Micro-Scale, and Component (or Zone, or Phenomena) Scale in relation to which a set of parameters consistent with those discussed in Section 2.2.5 (and Section 2.2.2) should be formed.

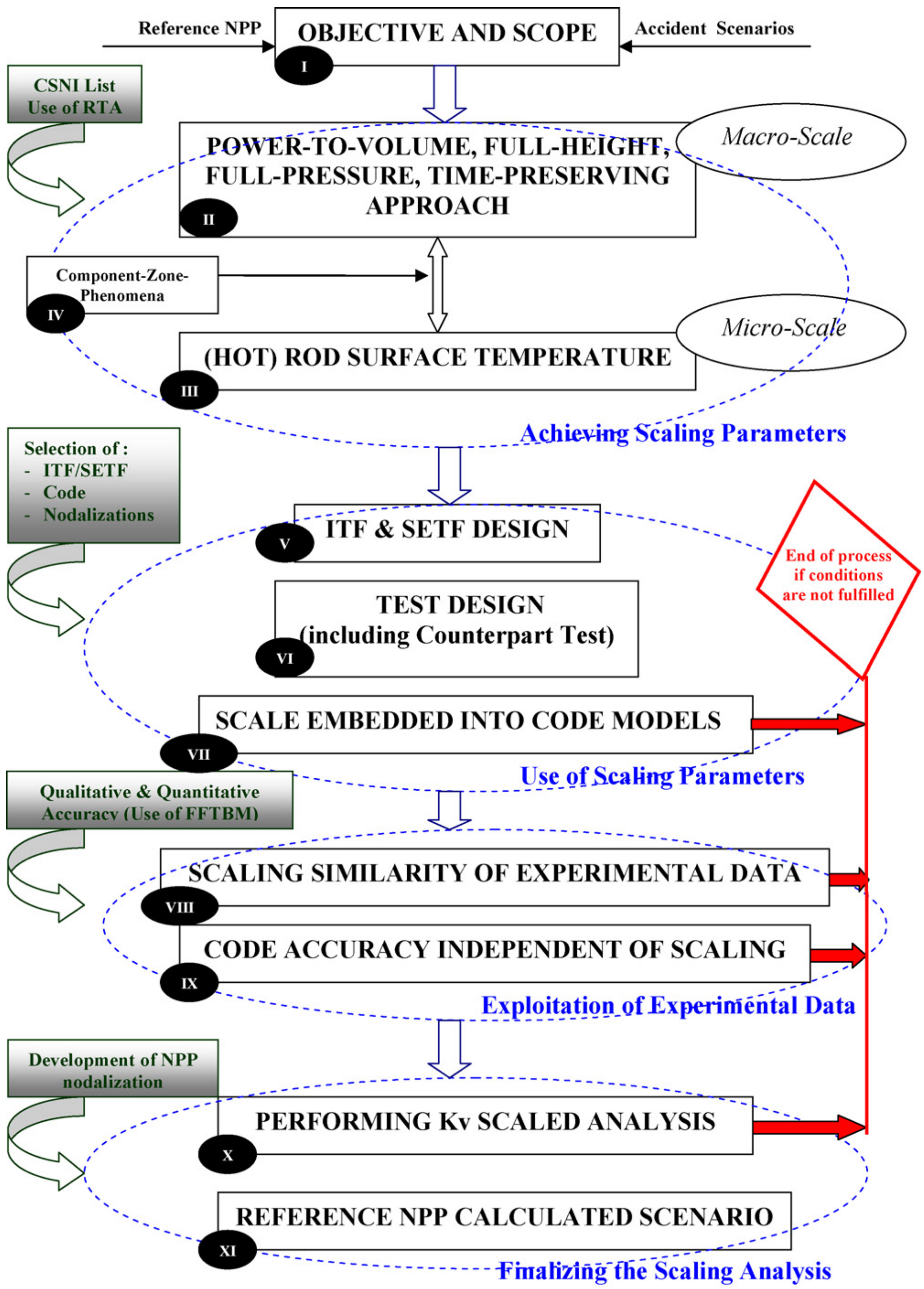


Fig. 5. 'Roadmap for scaling' analysis with assigned objective.

In relation to steps V, VI and VII, relevant experimental database (ITF, SETF and measured data) should be selected. Again, documents (OECD/NEA, 1993, 1996), are relevant to this aim. If possible, new experiments should be designed and performed, according to the scaling rationale identified by steps II to IV. Furthermore, one code should be selected and suitable nodalizations should be developed and qualified according to assigned criteria (e.g. Bonuccelli et al., 1993). Parameters of the group A) above are relevant here and possible distortions (i.e. differences between 'calculated' or 'ideal' values and actual values) should be minimized or fully understood. Parameters of the group (B) should not affect the application of parameters of the (A) group. In this case, distortions are expected and acceptable and full understanding of individual distortions is recommended. A procedure should be fixed in relation to the step VII: the works by D'Auria and Vigni (1985), and Ransom et al. (1998), are relevant in this connection. Namely, in the case of geometric scaling, nodalizations should be built having different dimensions. Furthermore, phenomena recognized to be scale independent or with assigned scale dependency (e.g. friction pressure drop versus Re number) should be calculated accordingly. The procedure for accomplishing step VII should account and benefit of the derivation of design criteria and scaling factors in Tables 1 and 2, respectively (see section 4.2.1). Thus, the 'low hierarchy value' dimensionless factors (e.g. Table 2) could have a relevant role for assessing the scaling capabilities of the computer codes.

Related to steps VIII and IX, it should be demonstrated that no qualitative discrepancies exist between measured and calculated trends. The possible discrepancies in quantitative terms should be found as affected only upon Boundary and Initial Condition values, within the known variation ranges (more details given in Section 4.2.1). Procedures for judging the involved facilities and the comparison between measured and calculated data should be adopted as by Billa et al. (1991). This activity is identified as "similarity analysis" in the paper by D'Auria et al. (1995). As a key recommendation, same nodalization choices should be adopted (i.e. no 'tuning') when setting up input decks for different ITF or SETF. Definitely, the roadmap for scaling here reflects the UMAE procedure (D'Auria et al., 1995). However, in the case of UMAE, the database of errors acquired from the steps VIII and IX of Fig. 5 is adopted for obtaining the uncertainty. The quantitative accuracy evaluation, at the step IX could be performed by the FFTBM method (i.e. see Ambrosini et al., 1990; Prosek et al., 2002), for the development and the application of the method, respectively. Suitable thresholds of acceptability of a calculation are considered in the application of the method to the comparison between measured and calculated time trends (around forty per each individual transient scenario).

Steps X and XI involve the development of the NPP nodalization. This should be done according to strict requirements (e.g. see the already mentioned paper by Bonuccelli et al., 1993) and reflect the noding scheme and the user choices adopted for the ITF nodalizations. Three-dimensional (3D) zones of the NPP shall be identified and 'fictitious' 3-D noding schemes can be set-up (e.g. D'Auria et al., 2003a). The procedure identified as *Kv*-scaled calculation is adopted, as planned and requested by D'Auria et al. (1995) and D'Auria and Giannotti (2000), and applied by Borges et al. (2003) and D'Auria et al. (2004). The procedure consists in simulating by the NPP nodalization the experimental scenario in one ITF, by adopting scaling factors (power-to-volume scaling) for assigning virtual boundary and initial conditions to the NPP. Calculation results compared with experimental data should show-up 'proper similarity' and distortions should be understood. Scaling activities which can be classified as *Kv*-scaled are also discussed by Groudev et al. (2005) and Park et al. (2007). In case the step X is satisfactorily completed, the final NPP calculation consistent with the objective of the scaling analysis will be performed, step XI. In this case, the results of the NPP calculation can be different from those obtained under step X, but again key phenomena should be the same and reasons for possible differences should be understood.

In order to shed more light over the proposed approach to scaling, let's see how to address the following (scaling) questions, e.g. put by Zuber et al. (2005):

- What are the effects of scale distortions (if present) in geometry and/or time, on the change of a state variable?
- Given a component, what are the effects of various processes on the change of a state variable?
- What is the ranking of scaling distortions?
- What are the effects of the component distortions, if present?
- What changes can be made and what is the trade-off?

At first it is noted that scale distortions are unavoidable when building an Integral Test Facility and performing the simulation of an NPP accident scenario (first and fourth question). One can identify (e.g. by the methods proposed by Zuber (1991), or Zuber et al. (2005)), the relative importance (or the ranking, third question) of scaling factors and of scaling distortions. However, no absolute measure of the effect of a scaling distortion can be derived by making use of (conservation) equations. The effect of scaling distortions might be evaluated by changing the design of the facility or, in some cases, of the experiment. This is impractical in the wide majority of situations.

Having available a scaling-qualified code, according to the proposed methodology, constitutes the only possibility to answer all the above questions. At least this is true considering the current NPP technology and the availability of already built ITF and of already performed experiments. Within the framework of a new 'nuclear technology', possibly, more precise answer to the questions could be planned.

4.2.1. The code qualification against scaling

The NRSTH code plays a central role in the Roadmap: namely, it constitutes the 'key-to-scaling'. The code, in order to be used for licensing applications needs a consistent and robust Verification and Validation (V and V) process, as discussed in Section 2.4. Furthermore, calculation results are dependent upon the code, the nodalization and the code user in relation to which the V and V process must be extended.

Considering the roadmap in Fig. 5, the following is noted in relation to the use and the applicability of the computational tools:

- The code, nodalization and the code-user are needed for steps V and VI, where 'confirmatory' results are expected and feedbacks upon the process should be avoided (unless to detect possible errors or drawbacks), considering in accordance with Wulff (1996), that "*...the validation of that system code is still the subject of the same experimental program for which the scaling analysis is being performed.*".
- The verification process for the code should imply the right framework for ensuring the objective of step VII, i.e. proving the validity of the code models against selected non-dimensional (scaling) parameters.
- The validation process for the code, the nodalization and the user should imply the right framework for ensuring the objective of step IX, i.e. demonstration that the code accuracy is not affected by the geometric scale of the problem.
- The *Kv*-scaled calculation still needs the application of the code and the nodalization and the engagement of the code user. Also in this case 'confirmatory' results are expected and feedbacks (including tuning of results) upon the process should be avoided.

Thus, the applicability of the code for the scaling roadmap is the result of executing the steps VII and IX. Typically, the former can be assigned to the verification and the latter to the validation process of the code. In both cases, the development and the qualification of the nodalization constitute pre-requirements.

Basic sub-steps for proving the validity of code models against scaling, i.e. accomplishing the step VII of the roadmap, are:

(1) Identification of relevant non-dimensional parameters like Re, Fr, Gr, Bi, etc..., by an established method (i.e. Buckingham 1914). Pressure, length (or diameter or equivalent diameter) and heat transfer rate should be considered as the independent variables to be scaled-up. Scale ranges should vary between maximum and minimum values expected for NPP, e.g. 0.001–20 MPa, 0.005–1.0 m, and 0–3 $\times$ 10^6 W/m^2, for pressure, length and heat transfer rate, respectively.
(2) Setting up a procedure where each code model or constitutive equation which includes one variable part of the non-dimensional parameters is identified. The result here is a list of models as they are coded.
(3) Setting up of a procedure for proving the scaling invariance from the application of code models in relation to each selected non-dimensional parameter when it varies within the assigned range. The results are vector of values per each model per each independent variable. The check of scaling invariance should be made.
(4) Setting up of basic input decks and calculation by the entire code of scaling invariance where applicable. For instance, check that

friction pressure drops are not affected by diameter when Re is invariant in single phase flow.

(5) Introduce range of acceptability for the scaling errors derived from the two previous steps, consistent with the overall requested precision for the code. Based on the comparison between acceptable errors and calculated errors take decision whether introduce change in the concerned code models.

Basic sub-steps for demonstrating that the code accuracy is not affected by the geometric scale of the problem, i.e. accomplishing the step IX of the roadmap, are those proposed for the exploitation of the UMAE methodology (D'Auria et al., 1995). These are synthesized as follows:

(1) Set-up input decks of three (up to five, preferably) differently scaled ITF according to proper criteria for nodalization development.
(2) Prove the quality level of the input decks (or nodalizations) by analyzing experiments in each ITF different from those utilized for the scaling analysis.
(3) Use the 'frozen' code and the 'frozen' ITF nodalizations (including assigned user choices) for the analysis of counterpart or similar tests according to definition given by OECD/NEA (1996).
(4) Check the quality of results by performing quantitative accuracy evaluation with suitable acceptability thresholds (e.g. application of FFTBM, Prosek et al., 2002).

It seems worthwhile noticing (again) at this point that the quality of a calculation depends upon the code models, the nodalization and the expertise of the user. Furthermore, the step VII does not necessarily involve complex nodalizations and the step IX involves specific ITF nodalizations.

Because of the influence of nodalization and of code-user on the results, the step VII and the step IX do not ensure that results of any scaling analysis are necessarily correct, but only ensure that the code has the potential to be successfully applied within the defined roadmap for scaling.

5. Conclusions

The objective and the framework for the performed activity are to address and to solve the scaling issue within a licensing process where best estimate computational tools are adopted. The conclusions here achieved are functional to such objective.

Relevant information about scaling in nuclear reactor system thermal-hydraulics has been collected. This showed the existence of phenomena which cannot be scaled-up (e.g. Two Phase Critical Flow) and of phenomena which strongly depend upon the geometrical scales (e.g. Counter Current Flow Limitation). Thus, the 'Scaling Controversy' could be characterized from a spot historical review of activities and might be taken as a synthesis picture of the current understanding in nuclear reactor system thermal-hydraulics.

The huge dimension of the scaling database (e.g. scaling factors formulations and related derivation theories, facility design, test execution and test analysis) and the connected non-comprehensive 'State of the Art on Scaling' may be seen as the first valuable outcome from the present investigation. The presumed lack of knowledge of the database, or of relevant parts of it, contributes to the 'Scaling Controversy'. The parallel established between the dimensionless design factors, e.g. derived from basic principles of mass momentum and energy conservation and used for the design of facilities and experiments, and the scaling factors, e.g. derived from balance equations, might help understanding the 'Scaling Controversy'.

The tight connection between the scaling issue and the issues of code qualification, nodalization development and qualification, as well as of the user or the analyst training and expertise, was observed: this constitutes the second outcome (perhaps well established before) from the paper. Then, the system thermal-hydraulic code has been taken as the 'key-to-scaling' in the present framework. The importance of the counterpart testing was confirmed: the results from, typically expensive, counterpart experiments definitely validate the understanding of scaling laws.

The 'Scaling State of the Art' and various topics relevant to scaling, including the Counterpart Tests brought to the definition of the 'Scaling Pyramid' and of the connected 'Scaling Bridges'. This allowed the observation that an established scaling knowledge is available to the scientific community and applicable to understand and to evaluate any (predictable) NPP scenario and may be seen as the third outcome from the paper.

The variety of scaling researches performed worldwide, making reference to the activity performed at UNIPI brought to the drawing of the 'Scaling Puzzle'. This shows the need to find a way though the available scaling findings or achievements.

The power-to-volume scaling, aiming at the condition of time-preserving when simulating complex accident scenarios in Nuclear Power Plants, is the best suited approach for the objective and the context established for the present paper. The contributions of Zuber in that context are remarkable and the concept of scaling hierarchy is essential and well recognized. The alternative 'Ishii scaling' allows the solution of issues like high cost of a facility and large impact of heat stored in passive structure upon the transient evolution. However, the 'Ishii scaling' needs the time-preserving scaling for validation and, adopted alone, would have not created the current level of confidence in the simulation of complex phenomena.

In relation to the main scaling approaches for Integral Test design, identified as 'time-preserving' and 'Ishii-scaling', the availability of a myriad scaling parameters may reveal useless. This is because of the difficulty in defining the quantitative acceptability for a scaling distortion or in quantifying the impact of a distortion upon a scenario. This is also noted by Wulff (1996), i.e. scaling distortion use is "*. . .limited. . .to post-factum quantification of <avoidable> scale distortions.*". Otherwise, those scaling parameters may be useful for code verification purposes.

Definitely, one 'spot' statement taken from the paper-2 of CSAU, J. NED, Special Issue, 1990 (see Section 2.2.4 for the definition of paper-2), does constitute a (twenty-year in advance) precursor of a statement-finding from the present activity and shall receive the proper attention: "*Because many different-scaled experiments* [as well as full scale experiments] *have been successfully simulated, no evidence exists that would preclude applying the code to a full scale NPP simulation.*".

The 'Roadmap for Scaling' does constitute the fourth and the main achievement from the present work. Here, the computational tools are selected as the pivot elements for applying the procedure. The code is one element responsible for proper scaling (i.e. the 'key-to-scaling'); however, nodalization and code-user are as important as the code in the scaling process. The quality of code can be estimated only once in the life-time of the code, but the quality of code-user and of nodalization must be estimated before each (scaling) application of the procedure. Noticeably, arbitrary tuning must be avoided and any tuning introduced for the prediction of one transient must be shown as applicable to all transients that are at the basis of the scaling procedure, including those transients considered within the code qualification process.

There is no claim of originality for the individual steps of the present methodology. The main characteristic of those steps is to have the system code and the 'many different-scaled experiments' as the basis to transpose the understanding of phenomena acquired at a small scale to the scale of the NPP; this is discussed in previous papers by the same authors and by others (e.g. Wilson and Boyack, 1998, Ransom et al., 1998). Rather, the proposal for the overall Roadmap for Scaling might be considered as an original outcome from the present effort.

The application of the 'Roadmap for Scaling' is strictly connected with the availability of experimental data. The experimental data base gathered so far within the system thermal-hydraulics area, including Counterpart Tests and Similar Tests, makes possible the full application of the roadmap.

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