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OECD/NEA/CSNI state-of-the-art report on scaling in system thermal-hydraulics applications to nuclear reactor safety and design (The S-SOAR)

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ABSTRACT

The present paper deals with scaling in nuclear-system thermal-hydraulics (SYS TH), including the connection with Nuclear Reactor Safety Technology (NST). The paper is entirely derived from the S-SOAR document issued by CSNI of NEA, NEA/CSNI/R(2016)14, 2016 (Bestion et al., 2016). Scaling has constituted 'an issue' since the beginning of the exploitation of nuclear energy for civil purposes, with main reference to the generation of electricity. A Nuclear Power Plant (NPP) constitutes a technologically complex industrial system and it is characterized by the impossibility of, or the large difficulty in, characterizing the system's performance under the conditions of the design. So, models were designed, constructed, and operated under downscaled ranges of values for one or more of selected parameters (e.g. power, volume, height, pressure, etc). These features lay at the origin of the scaling issue, i.e. the difficulty in demonstrating that a model behaves like the prototype. Integrated definitions of the widely adopted terms, 'scaling', 'scaling issue', and 'addressing the scaling issue' are part of the present document. The related application domain includes the NST, and the licensing for water-cooled nuclear reactors under operation, under construction, or under an advanced

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Abbreviations: BEMUSE, Best Estimate Methods plus Uncertainty and Sensitivity Evaluation; BEPU, Best Estimate Plus Uncertainty; BC, Boundary condition; BIC, Boundary and Initial Conditions; BWR, Boiling Water Reactor; CCFL, Counter Current Flow Limitation; CCVM, CSNI Code Validation Matrix; CFD, Computational Fluid Dynamics; CHF, Critical Heat Flux; CIAU, Code with capability of Internal Assessment of Uncertainty; CITF, Coupled Integral test facility; CSAU, Code, Scaling, Accuracy and Uncertainty; CSNI, Committee on the Safety of Nuclear Installations; CT, Counterpart Test; DBA, Design Basis Accident; DNS, Direct Numerical Simulation; DSS, Dynamic System Scaling; ECC, Emergency Core Cooling; ECCS, Emergency Core Cooling System; ECLN, Equal CL number; ELN, Equal Loop Number; ENRL, Equal Number Recirculation Loop; EM, Evaluation Model; EMDAP, Evaluation Models Development and Assessment Procedure; FH, Full height; FOM, Figure of Merit; FPr, Full pressure; FPw, Full power; FRC, Fractional Rate of Change; FSA, Fractional Scaling Analysis; H2TS, Hierarchical two Tiered Scaling; I, Integral design; IAEA, International Atomic Energy Agency; IC, Initial Condition; ICSP, International Collaborative Standard Problems (from IAEA); IET, Integral Effect Test; IIETF, Integrated Integral Test Facility; ISP, International Standard Problem (from NEA/CSNI); IETF, Integral Effect Test Facility; LOCA, Loss-of-Coolant Accident; LBLOCA, Large Break LOCA; LES, Large Eddy Simulation; LWR, Light Water Reactor; MASLWR, Multi-Application Small Light Water Reactor; MSLB, Main Steam Line Break; NC, Natural Circulation; NC, Nuclear Core (Table 3); NEA, Nuclear Energy Agency; NNC, Non-Nuclear Core; NPP, Nuclear Power Plants; NST, Nuclear Reactor Safety Technology; OECD, Organization for Economic Cooperation and Development; OSU, Oregon State University; OTSG, Once-Through Steam Generator; PIRT, Phenomena Identification and Ranking Table; PCT, Peak Cladding Temperature; PCV, Primary Containment Vessel; PTS, Pressurized Thermal Shock; PWR, Pressurized Water Reactor; RANS, Reynolds Averaged Navier Stokes; RH, Reduced Height; RL, Recirculation Loop; RLN, Reduced Loop Number; RNJP, Reduced Number of Jet Pump; RPr, Reduced Pressure; RPV, Reactor Pressure Vessel; RPw, Reduced Power; SBWR, Simplified Boiling Water Reactor; SETF, Separate Effect Test Facility; SG, Steam Generator; SGTR, Steam Generator Tube Rupture; SMR, Small Modular Reactor; S-W, Steam Water; S-W-A, Steam Water Air; ST, Similar Test; S-SOAR, Scaling State of Art Report; SYS TH, Nuclear-system thermal-hydraulics; UMAE, Uncertainty Method based on Accuracy Extrapolation; TNP, Time Not Preserved; TP, Time Preserved; VVER, Water cooled Water moderated Energy Reactor; V & V, Verification and Validation.

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design stage at the time of publication of the (Bestion et al., 2016). Scaling-related analyses are done in different areas of SYS TH and NST. These include the design of test facilities (both integral and separate-effect test facilities, IETF and SETF), the design of experiments (including Counterpart Test, CT), the demonstration of the capability of any computational tool, and the evaluation of uncertainty affecting the prediction of the same computational tools. A variety of approaches have been used to address the scaling issue, including non-dimensional analysis of mass, energy- and momentum-balance equations, derivation and application of scaling factors, including the hierarchy of relative importance, performing experiments at different scales, and running the SYS TH computer codes. This paper discusses the key areas and the key approach for scaling. It was found that the SYS TH computer codes, following their application to differently scaled experiments, demonstrate that the accuracy of their predictions may not depend upon the scale of the considered experiments. The TH codes also may constitute an additional valuable tool for addressing the issue of scaling.

1. Introduction to scaling

Industry uses plants of large geometric size, coupled with high pressure and high power to produce electricity at reasonable cost. A Nuclear Power Plant (NPP) constitutes a technologically complex industrial system and its complexity is related to the need to reduce the cost of producing electricity and to manage the radioactive fission products. This resulted, among the other things in the large pressure vessel, high power and, mainly, high power density (power per unit-core volume), high pressure, and the need for engineered safety-features, including an Emergency Core-Cooling System (ECCS). Nuclear reactors, therefore, are a combination of various components with different geometry and orientation, and include many safety systems (e.g. coolant injection, safety valves, control rods, etc) that need to be assessed for their performance under accident conditions.

Through the history of design, safety assessment, utilization, and maintenance of the Light Water Reactors (LWRs), thermal-hydraulics has played a central role and experiments were utilized, even before the advent of computers, to estimate, understand, and prepare models of thermal-hydraulic phenomena that may appear in the prototype LWRs of various sizes and the initial & boundary conditions. Therefore, experiments have formed the basis of nuclear-thermal-hydraulics to meet requirements of the safety evaluation of LWRs, being connected to the development of computational tools that include SYS TH codes.

However, the size and the complexity of the nuclear reactors, including the operating conditions is at the origin of scaling-related problems. In fact it is not possible to run tests at the NPPs and it is impractical to perform experiments with the same size, pressure, and power. Therefore, experiments are undertaken when either one or more of the parameters that characterize the geometry, the pressure and the power, are smaller than those in the original prototype system.[1] Therefore, scaled-down facilities are used to characterize the thermal-hydraulic behavior of a NPP by investigating the local/component (Separate Effect test facility – SETF-) and overall/system phenomena (Integral Test Facility -IETF -). To assure the relevance of these tests, they should represent the NPP under the correct thermal-hydraulic conditions expected during postulated accident conditions. These tests should scale the phenomenon expected in the plant and the applicability of the data measured in the models to the conditions expected in the prototype is the origin of the terms 'scaling', 'scaling issue' and 'addressing the scaling issue'. In particular:

- "Scaling" is the process of converting any plant parameters at reactor conditions to those either in experiments or in numerical code results in order to reproduce the dominant prototype phenomena in the model.
- "Scaling issue" arises from the impossibility of obtaining transient data from the prototype system, under off-nominal conditions, and indicates the difficulty and complexity of the scaling process and the variety of connected aspects.
- "Addressing the scaling issue" refers to a process of demonstrating the applicability of those actions performed in scaling.
- "Solving the scaling issue" implies developing approaches, procedures, and data suitable for predicting the prototype's performance utilizing small-scale models.
- "Scaling-controversy" sometimes is used to depict the status of our current understanding about scaling.

With the advances in NPP technology, the plant's design and operation rely more on the computer code safety analyses. Nowadays, the assessment of reactor safety under design-base accidents or plant transients is accomplished through the use of computer codes that have been created for this purpose. These codes predict the Figure of Merit (FOM) such as Peak Clad Temperature (PCT), and containment pressure, and the safety margins are ascertained by comparing them with the acceptance criteria established by the regulators. Before computer codes can be used for safety evaluation, they must be assessed for their applicability for the intended plant and the transient. This is done through a code-validation process established by comparing the results of the code's prediction for SETs and IETs data. Confidence in the safety margin of the FOM (e.g. PCT) requires a statement of uncertainty in the prediction.

Due to the reality that a full-size reactor experiment is not achievable, and the codes only can be validated from the data obtained in scaled experiments, scale distortions affect the estimate of uncertainty in FOM, and the safety margins. Therefore:

- The requirement for and the evaluation of scaling in regulatory process is necessary to ensure the safety decision.
- To overcome the scaling distortions and limitations, new scaling techniques were developed and applied in scaled experiments.
- Due to the lack of actual data from full-sized plants data, it is difficult to verify the scaling laws; therefore scaling has remained a significant source of uncertainty.

Considering this, the appraisal of scaling through history, revealed its existence and importance since the beginning of the nuclear era. From the impressive amount of research addressing the "scaling issue", three categories of activity having as a goal address the scaling issue, can be identified, Fig. 1:

- **Technological bases for scaling:** It includes experimental data, results of analyses, journal papers, and OECD reports;
- **Requirements for scaling and for the system codes Verification & Validation (V&V):** It includes those derived in Codes Scaling, Applicability And Uncertainty (CSAU), Code with Capability Of Internal Assessment Of Uncertainty (CIAU), Best-Estimate Methods Plus Uncertainty And Sensitivity Evaluation (BEMUSE).
- **Scaling techniques and approaches used in scaling analyses:** It includes methods such as power-to-volume, Hierarchical Two-Tiered Scaling (H2TS), Fractional Scaling Analysis (FSA), Dynamical System Scaling (DSS), and the application of system codes.

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[1] PROTOTYPE can be defined as the concerned nuclear system, water cooled nuclear fission reactor, whose transient performance constitutes is the target for the scaling studies. MODEL can be defined as a scaled-down (experimental) system designed and operated in order to simulate the performance of the prototype.

The objective of the paper is to outline the CSNI State Of Art Report on Scaling including the selection of topics of interest for planning future activities.

2. Scaling issues

As previously underlined, the scaling issues refer to the complexity of the scaling process, and its associated aspects. Two categories of scaling issues have been identified in (Bestion et al., 2016): the scaling distortions, and the scaling of complex thermal-hydraulic phenomena.

2.1. Scaling distortions

Any deviation between a reference system (NPP) parameter value and the same value calculated by a model or measured in an experiment constitutes a scaling distortion. It is well recognized that distortion is inevitable in scaling a complex system like the nuclear-reactor system and they could arise due to:

- Assumptions and simplifications in scaling methods.
- Limitations in constructing and operating test facilities.
- Scalability issues embedded in the computer codes.

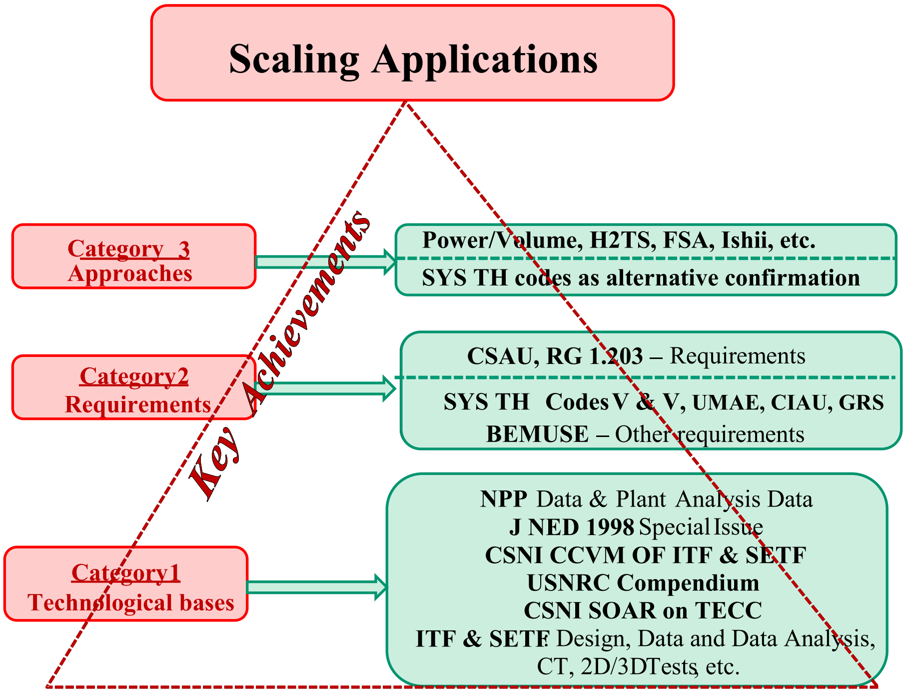

Fig. 1. Knowledge management for scaling ((Bestion et al., 2016).

It is very unlikely to attain perfect similitude between the prototype and the model for all phenomena and processes in a transient. As a consequence, the common practice is to optimize the similitude of phenomena of the greatest interest -dominant phenomena-, which usually accompanies distortion in the less important processes. Therefore, scaling laws usually are derived from the dominant physics in each phase of the transient and/or scaling methods. The dominant phenomena will change from one phase to another of the transient, and, with this, the scaling groups will also change. The impact on the transient by these distortions (of the model design) needs to be evaluated and justified before the construction of the model. In the scaling analysis, the scaling ratios usually are derived from non-dimensional parameters. These parameters are set to be equal between the prototype and the model. It is natural to judge the distortions by evaluating the difference of the non-dimensional parameters of the prototype and the model. Acceptability is based on a tolerable criterion for the difference. A well-accepted criterion for scaling distortion remains controversial in the international nuclear community. The level of distortion that is acceptable is based on the application of the tests (e.g. the requirements are less rigorous for validation, but lot more so when the findings are used for quantitatively estimating uncertainty). However:

- It is difficult to compare the relative importance of the phenomena/processes, and to determine the acceptability of the scaling design.
- It is desirable to know the direct relationship between the parameter of interest (i.e. FOM) in the transient and the distortion. The available quantification methods for distortions do not provide this linkage.
- Propagation of the effects caused by distortions raises another need to call for a method that can evaluate the accumulated distortion of a particular phenomena/processes as a function of time, not just its distortion evaluated at a particular time.[2]

2.2. Scaling of complex thermal-hydraulic phenomena

Another element in scaling issues is scaling the complex thermal-hydraulic phenomena in an experiment. Most of these phenomena are subject to or affected by fluctuations and local, therefore, are difficult to describe with standard field-equations. They usually affect the operation, among other things, of the ECCS, and cannot be neglected in the scaling process. Examples of these phenomena are: Two-phase critical flow; Counter-current flow limitation; Entrainment and de-entrainment; Reflood; Fuel-rod ballooning; Special plant components; pumps, separators, and similar ones; Core local phenomena at sub-channel level. Due to their complexity and subject to or affected by fluctuations nature, empirical correlations are normally used to derive the scaling laws. This may pose a great challenge to the scaling capability of the scaling laws so

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[2] or dividing tests in several tests with adjusted initial and boundary conditions.

far obtained since the correlations were mostly developed in scaled SETFs.

2.3. *Achievement from scaling studies*

After having discussed the scaling distortions and the scaling of complex thermal hydraulic phenomena, the achievements from scaling studies are presented. A wide variety of scaling research activities have been completed during the past half-century. In some cases, scaling was not the main concern of the investigation, but the information obtained can be beneficial in addressing scaling issues. The focus of attention should be in evaluating existing findings and the connection of these findings to resolve the scaling issues or to prove them non-existent. As example, a lesson learned, from reviewing ECC bypass phenomenon in different small facilities, is that there can be changes in flow regimes at higher sizes that cannot be predicted by extrapolation or scaling. Scaling analysis only is effective when the underlying physics remains the same. In the Chapter 2 of S-SOAR, significant achievements accomplished in scaling studies are discussed. Examples are:

- Flashing, flooding and Counter-Current Flow Limitation (CCFL) in the downcomer of the PWR Reactor Pressure Vessel (RPV) during a Large-Break Loss-of-Coolant Accident (LBLOCA).
- Wall evaporation, flooding, and CCFL in the downcomer of the Steam Generator's (SG's) secondary side, during accident-recovery conditions;
- Influence of reversed-flow U-Tubes on the natural circulation performance of the SG primary-side flow.
- Simulation of nuclear-fuel rods in IETFs using electrically heated rods with and without a gap.
- Concept of scaling distortion in the uncertainty method, based on extrapolating uncertainty.
- Concept of a Scaling Pyramid (D'Auria and Galassi, 2010) that summarizes current scaling approaches.

2.4. *Addressing the scaling issue*

Resolving scaling issues is an important step toward nuclear safety. Regulatory agencies acknowledge this fact by including the scaling evaluations in standard regulatory procedures. Their objective is to ensure the validity of the tools used in safety analyses, and to address the scaling distortions in the reactor's design and operation. Two regulatory procedures that involve scaling are introduced in (Bestion et al., 2016). In the first procedure, Evaluation Models Development and Assessment Procedure (EMDAP), (USNRC, 2005), scaling evaluation is used in guiding the model development and assessment.[3] In the second procedure, CSAU, (USNRC, 1989), scaling distortion is one of the uncertainties that must be quantified.

3. Scaling analyses for safety review process

As said before, experiments were utilized, even before the advent of computers, to estimate, understand, and prepare models of thermal-hydraulic phenomena that may appear in the prototype LWRs of various sizes and the initial & boundary conditions. Later, with the advances in NPP technology, the plant's design and operation rely more on the computer code safety analyses. Considering this the strategy to do a safety determination of reactor design and operation is to evaluate the prototype thermal-hydraulic response through data from experiments, and/or computer code calculations. Due to inherent difficulties in conducting full-scale tests, most of SETs, and IETs have been performed in scaled-down test facilities with the assumption that the experimental results obtained are applicable and relevant to the full-scale reference reactors. The test facilities, as well as the operating conditions, should be properly scaled. Since it is difficult to apply all the scaling factors obtained by the application of scaling methods, the scaling compromise arises, during the design process of the scaled test facilities, and the designer's has to focus on the highest ranking scaling factors affecting the target thermal-hydraulic phenomena; this should be considered when we are going to analyse the experimental results produced in the facility.. The scaling distortion then inevitably occurs in any of scaled tests and they should be minimized so that they do not affect important phenomena and system global behaviour. Computer codes have the capability to extrapolate knowledge from scaled experiments to the prototype. However, uncertainty in the predicted results should be estimated by using the existing experiment data afterwards. In this sense, the role of the experiments used to develop and validate computer codes is very important. For these reasons, the scaling plays key roles in the design and operation of experiments, and the validation of the computer codes. The scaling technique[4] is used to design the test facility and it is a key element for understanding the validity of experimental data.[5] In the case of facility design, scaling analyses are performed taking into account available resources, therefore two main elements should be considered: the scaling approach and the scaling methods.

3.1. *Scaling approaches*

For the design and construction of a test facility, the test objectives and transient scenarios to be simulated should be specified as a first step. All the relevant- and necessary-processes and phenomena thus should be identified during and even before such design work, based on engineering judgement, code evaluation, and/or experiences. A Phenomena Identification and Ranking Table (PIRT) is generated appropriate to the particular transient scenarios. One of key factors involved in the efforts of facility design, construction, and operation is the cost (and space) of the facility constructed in a certain size of facility building. Significant time and money may be needed to develop, install, and operate special yet appropriate instrumentation suitable for prototype test conditions, while this factor does not constitute a technical aspect; it is pointed out here as one of major aspects in the effort on facility scaling. Geometrical scales, such as height and volumetric ratio, operating conditions such as pressure, mass flux, linear heat rate, and working fluid are determined roughly according to the available resources and cost. Also, the influences of time scale and fluid physical properties are considered. The

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[3] To demonstrate the safety of a nuclear-reactor design, the licensees are required to present plant- specific safety analyses for evaluation. Before the safety analyses are presented, the tools used in the safety analyses must be reviewed and accepted. In regulatory world, the tools commonly are referred to as "evaluation models (EM)", [USNRC, 2005]. According to NRC's definition, EM is a calculation framework for evaluating the behaviour of the reactor system during postulated Chapter 15 events, [USNRC, 2000], which include one or more computer programs, and all other information needed for use in the target application. Most regulatory agencies worldwide have their own regulatory procedures regarding EM development and assessment. For example, in December 2005, the USNRC published Regulatory Guide 1.203 – Evaluation Models Development and Assessment Procedure (EMDAP), [2]. This regulatory guide is intended to provide guidance for developing and assessing EMs for accident- and transient-analyses. EMs developed under this guidance will sufficiently provide a reliable framework for risk-informed regulation, and a basis for estimating the uncertainty in understanding transient- and accident-behaviours.

[4] SCALING TECHNIQUE: A technique to pursue and achieve a planned scaling approach by using some of scaling methods.

[5] In [NEA/CSNI 2001] it is detailed the qualification criteria of the facility for the validation matrix for assessing thermal–hydraulic codes for VVER LOCA and its transients. The facility's qualification criteria are useful for designing and operating the integral- and separate-effect test facilities. The qualification criteria of the quality of a facility were based on five items related to the facility's design, construction, operation, use in an international framework, and personnel qualification.

scaling approach is therefore a technical (and economical) strategy to provide a design of scaled test facility (scaled model) that may give the best simulation of reference reactor under certain initial and boundary conditions (within given budget). For example, depending on the objectives of an experiment, as well as the constraints due to such conditions of budget, and facility building size, "scaling approach" is applied for the scaling of height (volume), time and/or pressure. It is usually applied during the preliminary stage of test facility design. Table 1 briefly compares the advantages and disadvantages of phenomena scaling. A scaling approach is an essential step to provide the "best" scaled facility design to generate experimental data for developing models, correlations, and closure laws as components of computer codes, and to validate the computer codes, taking into account the available resources. A scaling approach is also needed to identify and characterize the hierarchy of scaling factors affecting thermal-hydraulic phenomena at each level of local, component and reactor system. The following scaling approaches has been identified and in detail discussed in (Bestion et al., 2016): time scaling, linear scaling, volumetric scaling, fluid scaling, pressure scaling, nuclear core simulator scaling, SG simulator scaling, number of loop scaling and main coolant lines scaling. In (Bestion et al., 2016) they have been discussed in detail analyzing examples of experimental test facilities used for thermal hydraulically characterizing PWR, BWR, VVER, and advanced designs.

3.1.1. *Time scaling*

In relation to time scaling, an "Expected time of event 1" (time-preserving approach) is obtained when the distribution of mass and energy along the loop is preserved. This is accomplished via a proportional reduction of power and facility volume, (NEA/CSNI, 1989). When the body forces due to gravity are small compared to local pressure differentials an "Expected time of event $\neq$ 1" (time not preserved approach) could be used. Linear-scaling reduction of any dimension of the facility determines time scaling of the facility. However, when the "expected time of event is $\neq$ 1", severe distortion in the heat-transfer process should be expected, (NEA/CSNI, 1989).

3.1.2. *Linear scaling*

In relation to linear scaling, since each reduction of the linear dimension of the facility determines a time reduction for the facility, it is important to consider the length reduction (for example, the loop length) and the height reduction of the facility compared with the prototype.

The height reduction of the facility influences the capability of the facility to simulate the gravitational effect that determines natural circulation characteristics through primary loop. In general, the reduction of the facility height (linear scaling) determines the extent of reduction in time of the simulated phenomena; time preservation should be obtained by installing orifices in the loop to control the local and/or system-wide velocity of flow, as also in detail discussed with examples in (Bestion et al., 2016). The relative height distribution of the facility components (height distribution ratio), coupled with the relative volume distribution influences the energy and mass distribution along the loop. Of particular interest is the volume versus height plot that is used for qualifying a code nodalization.

3.1.3. *Volumetric scaling*

In relation to volumetric scaling, considering the influence of the height of the experimental test facilities for correctly simulating natural circulation phenomena, a decrease in the cross-sections of the vertical flow section in general is used for fulfilling the volumetric scaling target, (Karwat, 1985). The volumetric scaling of the facility determines the ratio of wall surface/hydraulic volume. In particular, a decrease of the facility volume, compared with the prototype reactor, causes an increase in the ratio of the wall surface/hydraulic volume. The ratio of the wall surface/hydraulic volume affects the structural stored heat and the heat losses. The key role of structural heat in a short term accident, as a LBLOCA, and the key role of the heat losses in a long term accident as SBLOCA have to be emphasized, (NEA/CSNI, 1996). Various test facilities are designed to compensate, at least partially, for these effects by using the thermal insulation of the circuit, by using the electrically heated coils surrounding the circuits, and also using the modified decay heat curve, (NEA/CSNI, 1996).

It is emphasized that in an IETF the distribution of the volume (volumetric distribution ratio), in comparison with the prototype distribution, should be preserved, in order to assure that the facility component volume is proportional to the respective volumes of the prototype. This arrangement, coupled with the preservation of the relative height and the location of the single reactor components (i.e. the core relative height, the height of cold leg and hot leg, and the like), maintains the distribution of energy and mass along the loop.

3.1.4. *Fluid scaling*

In relation to fluid scaling, e.g. fluid considered for the simulation of the PWR RCS-facility is, in general prototypical, i.e. water for both the liquid- and steam-phases. For example, all the main RCS-IETFs, used to simulate current- and advanced-PWR, use water as a working fluid. An example of a non-prototypical fluid facility is the DESIRE facility, simulating the Dodewaard NC BWR, which uses Freon 12 as working fluid (reported in Appendix 3 of (Bestion et al., 2016).

As for experiments that employ a simulant fluid such as Freon, it is important to confirm the applicability of scaling laws that should include influences of the fluid properties in some scaling factors. A simulant fluid is employed for experiments at low pressures for representing the thermal-hydraulic responses expected for water under high pressures. This approach offers such advantages as the saving of resources and simplification in managing experiments, which may include easy visualization of flow structure (such as flow patterns) in complex geometries.

Justification should be needed when simulant fluid is used to reproduce phenomena during a full transient of LWR accidents because the interactions between gas- and liquid-phases, including phase changes, depend on the fluid properties. The utilization of a simulant fluid is favorable as long as it is confirmed that it is suitable even for in-depth investigation of details of an assigned phenomenon.

3.1.5. *Pressure scaling*

In relation to pressure scaling, the operating pressure of the facility influences the physical properties of the fluid.

3.1.6. *Nuclear core simulator scaling*

In relation to core simulator scaling, the heat-transfer characteristics due to geometry, material and electrical-heating methods and operational mode are important scaling factors to simulate thermal response of nuclear core of reference reactor during reactor accidents and abnormal transients. In fact, the inner structure and materials of simulated fuel rods and their cross-sectional size, such as diameters and pitch (sub-channel size) as well as the heated length and the radial- and axial-distribution of the linear heat rate should determine the characteristics of heat transfer of the core, and thus, the simulation capability of the IETF. The heating methods, such as direct skin (clad) heating and indirect rod-inside heating, also influence the heat-flux transient. Since the electrically heated simulator usually has a much smaller thermal capacity, (NEA/CSNI, 1989), than that for nuclear fuels, electrical core power for IETFs should be controlled to compensate for the difference from the reactor in the simulated heat- flux, even during the accident transient. It is emphasized that full core-power scaling is not inevitable selected in the scaling approach.

3.1.7. *SG simulator scaling*

In relation to the SG simulator scaling, the SG simulator heat-transfer characteristics (secondary-side heat-deposition rate) for the SBLOCA transient are important scaling factors. The SG geometrical data, viz.,

Table 1
Sample comparison of different scaling approaches.*

Approaches/ Design factors	Height scaling (Full height versus Reduced height)	Time scaling (Preserved vs. Reduced)	Pressure scaling (Operation) (Full vs. Reduced)	Loop scaling (Full prototype number vs. Lumped)
Space/cost	**Full**: Higher. **Reduced**: Lower.	**Preserved**: Higher. **Reduced**: Lower.	**Full**: Higher. **Reduced**: General savings in construction and experiments. May represent low-pressure transients	**Full**: Higher. **Lumped**: Considerable savings in constructing the facility.
Time scale	**Full**: Preserved. **Reduced**: Reduced but still possible to preserve time by increasing flow resistance.	**Preserved**: Possibility of attaining the same timing of the event and the local thermal–hydraulic response. **Reduced**: Speed up of slow transient.	**Full:** Preserved. **Reduced:** Distortion may appear during the phenomena transition with phase change.	Not related.
Heat transfer phenomena	**Full**: Possibility to reproduce local phenomena, such as CHF, PCT, and re-flood, as well as phase separation. **Reduced**: Short length of heating may cause distortions.	**Preserved**: Possibility of reproducing mass & energy distribution and heat-transfer responses. **Reduced**: Distorted due to time-dependent effects.	**Full**: Possibility to reproduce phenomena up to prototype pressures. **Reduced**: Some phenomena are distorted if using different fluid.	**Full**: Possibility to reproduce mass and energy distributions in loops and core. **Lumped:** Possible distortion in mass & energy distribution at core's entrance (3-D).
Gravity/ fluid acceleration	**Full**: Driving force by gravity preserved, good for natural circulation. **Reduced**: Some gravity-driven phenomena distorted.	Same as left comparison.	Not related.	**Full**: Better replication of BICs for asymmetric NC, e.g. Counter drive for NC during SGTR in 3- or 4-loop PWRs.
Flow regime/ 3-D phenomena	**Full:** With very small volume scaling, limitations in multi-channel scaling, distortions in multi-D phenomena. **Reduced:** Improved.	Not related.	Not related.	**Full**: Good to represent BICs for NC, e.g., PTS at MSLB, re-criticality for boron dilution. **Lumped**: Good for 3-D phenomena in horizontal legs.
Experiment design & control	**Full**: Real time operation and control. **Reduced**: Easier operation and control for slow transient in prototype.	Same as left comparison.	**Full**: Not particular. **Reduced**: Needs interpretation via scaling method. More flexible for measurements of instrumentations.	**Full**: Precise realization of BICs to represent multi-loop response. **Lumped:** Limited spectrum of possible asymmetries.
Stored heat/ heat losses	**Full**: Distorted in a very small-volume test facility due to high wall-surface to volume ratio (S/V). **Reduced**: S/V could be reduced.	Not related.	**Full**: Higher than prototype. **Reduced**: Closer to prototype due to thinner RCS walls.	**Full**: Higher compared to lumped loops with identical scaling factors. **Lumped**: Improved.
Coolant property	Not related.	Not related.	**Full**: Prototype property possible. **Reduced**: For fluid-to-fluid simulation, nonlinearity may appear. Difficult to fully match similarity parameters. Some phenomena not possible.	Not related.

*Note 1: This table is a high- level sample comparison. Refer to the main text of the (Bestion et al., 2016) for complete details. Scaling approach of an experiment depends heavily on its objectives.
Note 2: BIC: boundary and initial conditions, NC: natural circulation, RCS: reactor coolant system.

the diameter and pitch of the inner and outer tubes determine the characteristics of the SG heat transfer and are, in general, close to the prototype values. The energy released into the SG secondary side (the heat-deposition rate) during an SBLOCA transient comes just from the simulated core wherein the rate of power generation is pre-programmed or manually controlled, (NEA/CSNI, 1989). Since the SG heat removal rate is the primary factor in controlling the primary pressure, the correct simulation of the chronological change in the rate of SG removal is the key factor for the IETFs to simulate the SBLOCA scenario in a chronologically correct manner. The position of SG relative to core is a very important factor for simulating the natural circulation.

3.1.8. Number of loop scaling and main coolant lines scaling

In relation to scaling the loop and main coolant lines, it is important to underline the configuration of the reactor loop. For example, in a simplified noding for safety analysis, typically, a three- and four-loop PWR is characterized such that each loop has a single HL, a single CL, a single U-tube SG, and a single Reactor Coolant Pump (RCP). A typical B&W-PWR may have in each loop a single HL, a single once-through SG, two CLs, and two RCPs in each loop. Typical CE-PWR has a single HL, a single U-tube SG, two CLs, and two RCPs. This type of layout should be realized in the IETF facility to obtain adequately simulated data to validate the computer code predictive capability.

In case of multiple loops, the lumped loop representation may influence the core uncovery phenomena/process during SBLOCA, (NEA/CSNI, 1989), and may suppress the effect of asymmetric boundary conditions between the individual loops on the evolution of the accident scenario.

When multiple loops in the IETF represent different number of reference reactor loops, the diameter of loop piping would be different. Since the level of liquid in the horizontal pipe, hot legs, and cold legs influences the condition of the break flow upstream, one should decide how to arrange the elevations of each pipe; center, top, or bottom of the pipes. In any case, a different response between two loops is more or less inevitable when different size loops are employed.

In general, the cross- section of the primary loop piping is reduced due to the volumetric scaling approach, resulting in a great pressure drop when the fluid velocity is preserved. Therefore, an artificial increase in the scaled cross-section (no preservation of the fluid velocity) is made, coupled with the reduction in the pipe length so to best conserve the volumetric-scaling ratio, (Karwat et al., 1985).

The reduction of the cross section of pipe may have some influence on the phase separation phenomena/process in an SBLOCA transient. As example, the transport characteristics in the horizontal pipe are achieved in SPES, BETHSTY, and the LSTF facility by conserving the Froude number, see e.g. (NEA/CSNI, 1989) and (Zuber, 1980).

The pump scaled behaviour in the two-phase condition is important for simulating the SBLOCA facility transient. It serves to underline that scaled-down pump head and torque characteristics usually are different from those of the prototype. Therefore, the analysis of influences on the different response is required. Separate-effect studies are important with regard to this issue (NEA/CSNI, 1989) (NEA/CSNI, 2000) (Karwat et al., 1985).

Another important parameter is the depth of the pump loop seal that influences the core water level transient during a loop-seal clearing that typically happens in cold-leg break LOCA, (Karwat, 1985).

3.2. *Scaling methods*

Scaling method(s) are selected in conjunction with the scaling approach to design[67]a "best" scaled test-facility and to understand the data from the test facility SET and IET. To assure the proper simulation and preservation of important phenomena and processes at local level, or at system level, appropriate scaling methods should be established to scale-down those phenomena and processes from the prototype to the test facility. Scaling methods may affect the interpolation or extrapolation of the obtained experimental data within a certain range of applicability that may differ among the phenomena. Appropriate scaling factors are defined corresponding to the thermal-hydraulic phenomena at each level, local, component, and reactor system, which may appear during experiments to simulate prototype in the scaled facility. Following a given scaling approach, a scaling method is used to:

- Design a test facility (concept, strategy, principle) to best simulate aimed thermal-hydraulic response of local phenomena and/or system response of reference reactor;
- Specify test initial and boundary conditions;
- Understand the observed test results;
- Make the test results applicable to the reference reactor with evaluations of uncertainty in the applied (extrapolated or interpolated) results.

A major aim of the SETs is to investigate fundamental phenomena and processes at a local level and to prepare physical models and correlations for computer codes. A major aim of the IETFs is to investigate the integrated system responses during reactor operation and accidents, therefore it is necessary to preserve important local thermal-hydraulic phenomena/processes and the system behaviour. The geometric-, kinematic-, and dynamic- (chronological) similarity of thermal-hydraulic phenomena/processes should be preserved. First, global system behaviours, such as the natural circulation of single- and two-phase flows are preserved by using global scaling criteria that are obtained from non-dimensional governing equations. Second, local Sscaling criteria are obtained to preserve the important thermal-hydraulic phenomena that may happen in a component. Scaling distortions may occur in the simulated local phenomena because of the difficulty in matching the local scaling criteria with the global scaling ones, and the dearth of knowledge on the local phenomenon itself. The important local phenomena and processes can be identified from the PIRT. Having so identified them, scaling analysis can be performed for the major local phenomena.

3.3. *Scaling methods for local phenomena*

The scaling parameters for many local phenomena can be derived by using:

- Empirical approach: examples are.
- Dimensional analysis, such as Buckingham Pi theorem, can be adopted for scaling local phenomena by considering conventional non-dimensional parameters. The Buckingham Pi theorem provides functional relationships among the variables that govern the phenomena of interest. However, this theorem has inherent difficulties, such as the identification of important phenomena.
- Use of existing correlation and models available in literature to derive scaling parameters or to estimate scaling distortions (e.g. Froude number to govern the stratified-to-non-stratified flow regime transitions). The problem of this approach lies with the fact that correlations and models often do not represent the local phenomena expected in the full-scale prototype. Correlations and models are mostly developed in steady-state and/or well-developed conditions while transient and/or developing conditions may be expected during an anticipated accident scenario of the nuclear power plants. Also, the correlations and models often are developed based on experimental data that are collected using other working fluids, non-prototypical conditions, and/or using small geometries.[8]
- Mechanistic approach: obtain the dimensionless parameters by non-dimesionalizing the governing equations. However, the governing equations need a process of approximation and assumption(s) for thermal-hydraulic behaviour, especially in the prototype, because of the complexity in the representation of three-dimensional single- and two-phase flows. Related to this process, the following paradox may arise; balance equations, including constitutive terms that are, in principle, difficult to be solved/qualified because they do not undergo V & V processes, e.g. SYS TH codes, are used for deriving non-dimensional parameters and even performing scoping calculations within the framework of scaling analyses

3.4. *Scaling methods for system phenomena*

The most important discussed scaling methods to investigate the integral-effect tests in prototypes are described together with their major characteristics, merits, limitations, and their areas of application. More details are reported in (Bestion et al., 2016).

3.4.1. *Linear scaling*

The key characteristic of this method is to have the same aspect ratio and the same velocity in the model as in the prototype. Similarity requirement of the main parameters in the linear scaling method under the same fluid and same operation conditions, are summarized in Table 2. This approach can excessively increase the influences of gravitational acceleration.

3.4.2. *Power to volume scaling*

This scaling method conserves time and heat flux in the prototype. Unlike the linear-scaling method, this method preserves the scale of the gravity term. Therefore, it offers an advantage in reproducing the phenomenon in which the gravitational effect is significant. Furthermore, it is suitable to simulate an accident in which flashing occurs during

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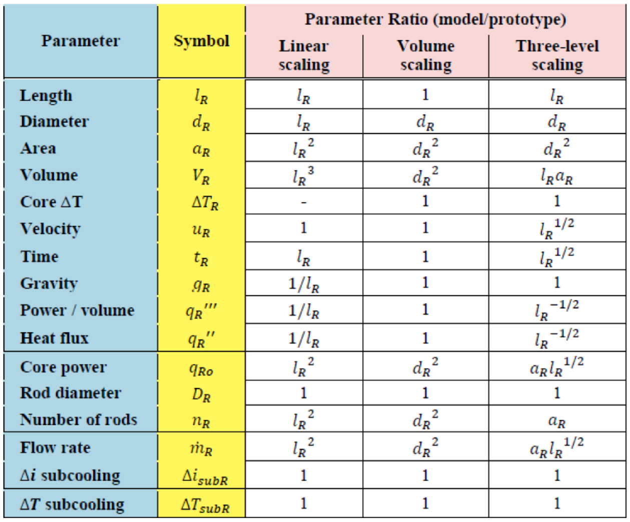
[6] One criterion that should be considered in designing the scaled-down facility is to maintain the minimum dimensions to preclude some size effects that would not occur in the prototype, for example, the surface tension effect: Boucher et al., 1990] established the concept of a minimum dimension from flooding considerations, and a dimensionless diameter was established. As long as the dimensionless diameter is greater than approximately 32–40, the geometry is sufficient to preclude the influences of surface tension. Other criteria related to hydraulic resistance (friction numbers), stored heat, and heat loss need also to be considered.

[7] [Levy, 1999] observed that if the facilities are at least one third in the size of the prototype, there will be minimum impact of the scale or size.

[8] As example, two-phase flow regime maps have been established mostly based on experimental data using air–water in low-pressure conditions for pipes of small diameter lastly, the correlations and models are mostly developed based on well isolated and well controlled experimental conditions. On the contrary, thermal–hydraulic phenomena in the full scale prototype during transient accidents may have significant interactions and influences from other local phenomena.

Table 2
Comparison of main scaling ratios of each scaling method.



Parameter	Symbol	Parameter Ratio (model/prototype)		
		Linear scaling	Volume scaling	Three-level scaling
Length	l_R	l_R	1	l_R
Diameter	d_R	l_R	d_R	d_R
Area	a_R	${l_R}^2$	${d_R}^2$	${d_R}^2$
Volume	V_R	${l_R}^3$	${d_R}^2$	$l_R a_R$
Core ΔT	ΔT_R	-	1	1
Velocity	u_R	1	1	${l_R}^{1/2}$
Time	t_R	l_R	1	${l_R}^{1/2}$
Gravity	g_R	$1/l_R$	1	1
Power / volume	q_R'''	$1/l_R$	1	${l_R}^{-1/2}$
Heat flux	q_R''	$1/l_R$	1	${l_R}^{-1/2}$
Core power	q_{Ro}	${l_R}^2$	${d_R}^2$	$a_R {l_R}^{1/2}$
Rod diameter	D_R	1	1	1
Number of rods	n_R	${l_R}^2$	${d_R}^2$	a_R
Flow rate	$\dot{m}_R$	${l_R}^2$	${d_R}^2$	$a_R {l_R}^{1/2}$
Δ*i* subcooling	Δi_{subR}	1	1	1
Δ*T* subcooling	ΔT_{subR}	1	1	1

depressurization. It was successfully used to design most of the integral-effect test facilities, such as LOFT, SEMISCALE, LOBI, ROSA-II, ROSA-III, PKL, LSTF, and BETHSY. Also, this method is suitable for the heat-transfer test with electric fuel bundles. However, when it is applied to a smaller facility with the full height, due to the smaller area ratio, some important phenomena can be distorted, for example, the excessive stored heat in structures, and a higher-surface-to volume ratio leading to higher heat losses from structures, and loss of multidimensional-flow phenomena.

3.4.3. *Three-level scaling*

The first step is an integral- or a global-scaling analysis to conserve a single- and/or a two-phase natural circulation flow. The similarity requirement is obtained from a 1-D non-dimensional, governing the equations of natural circulation. The second step is a boundary flow, and inventory scaling. The geometry is determined to scale the flow rate at the junction of a broken part, the safety-injection system, and various filling- or discharge-systems in the IETF to ensure the inventory of the mass and energy similarly is preserved in the IETF as a model of the prototype. In the last step, a local phenomenon scaling is performed to conserve the important thermal-hydraulic phenomena occurring in each system. The result from scaling the local phenomenon takes priority if the similarity requirement differs from that derived in the integral scaling. The three-level scaling method is characterized by relaxing restriction on the length-scale. By adopting a proper length-scale, some distortion of the flow regime and multi-dimensional scaling in the scaled IETF can be reduced. On the other hand, the scales for time and velocity are lowered due to the reduced length. Consequently, some local phenomenon could be distorted.

3.4.4. *The hierarchical 2-tiered scaling (H2TS)*

The procedure consists of four stages, i.e. system decomposition, scale identification, top-down analysis, and bottom-up analysis. At the first stage, the system conceptually is decomposed into subsystems, modules, constituents, phases, geometric configurations, fields, and processes. The scale identification as the 2nd stage provides the hierarchy for the characteristic volume fraction, spatial scale, and temporal scale. To establish the hierarchy of the temporal scale, the characteristic frequency of a specific process is defined, and then the characteristic time ratio can be found by dividing the system's response time based on a volumetric flow-rate. The top-down scaling as in the 3rd stage offers a scaling hierarchy, using the conservation equations of the mass, momentum, and energy in a control volume. In the non-dimensionalized balance equations, the characteristic time ratio represents a specific transfer-process between constituents. All the processes can be compared, and ranked for importance on the system to establish priority in the scaled models. The bottom-up scaling, as the 4th stage, offers a detailed scaling analysis for key local phenomena, such as the CCFL and choking. Along with this top-down analysis, similarity groups (called Pi groups) are identified, and the scaling criteria and time constants can be obtained to evaluate the relative importance of the processes.

3.4.5. *Power to mass scaling*

To determine the test conditions for a reduced-height and reduced-pressure (RHRP) facility, the power-to-mass scaling method, was developed. This method determines scaled core-power according to the initial coolants' mass inventory in the reactor's coolant system. The temperature of the hot leg in the test facility is determined from the subcooling of the primary system, which is made the same between the model and the prototype. From the hot-leg temperature, the cold-leg temperature is determined by the equivalence of the core temperature's difference for the model and prototype. The mass flow rate of the core is scaled down according to the power and heat capacity relationship. Finally, secondary system pressure is determined from the difference in temperature between the primary- and the secondary-side. Since pressure is not preserved, the differences in fluid's thermal properties could induce distortions.

3.4.6. *Modified linear scaling*

The multi-dimensional behaviors of the ECC water in the downcomer (e.g. the ECC bypass) are observed during the LBLOCA refill-phase. The modified linear scaling method was developed to overcome this distortion in a small-scale test facility. Twelve dimensionless parameters were obtained from the two-fluid momentum equations in the downcomer. By preserving those parameters in the model, the method resulted in the same geometric similarity criteria as in the linear scaling method. However, this method conserves the gravity scale. It also was found that the three-level scaling method provides the same requirements when the area aspect ratio is preserved as square of linear ratio in a test facility.

3.4.7. *Fractional scaling analyses (FSA)*

FSA is a hierarchic approach similar to H2TS. In the first step, the regions of interest and the durations of the transients are specified. The rate of change of the state variables over the region are connected to the transfer functions defined at the boundary, and inside the volume. The relative effect of components is based on their relative impact on state variables in the transfer function connected to that component. These relative values determine the importance of these transfer terms. The fractional change-of-state variable (effect metrics) over the characteristic time (fractional change metric) should be made the same between the prototype and its model in top-level scaling. The characteristic time is obtained either from the experiments, or from an aggregate fractional rate of change (FRC, also called the aggregate frequency). The individual FRC can be positive or negative. The reference value of the agent-of-change should be the maximum value over the period of the phase. FSA offers a systematic method of ranking components and their phenomena in terms of their effect on the FOM, or the safety parameter. It also can estimate scale distortions, and synthesize data from different facilities for the same class of transients. This multistage scaling can guide the design, and simplify the scaled facility by identifying important components and corresponding processes. This approach does not require the preservation of time.

3.4.8. *Dynamical system scaling*

To address the time dependency of scaling distortion, an innovative approach was developed recently. The strategy is to convert the transport equations into a process space through a co-ordinate transformation, and exploit the principle of covariance to derive similarity relationships between the prototype and model. After the transformation, the target process can be expressed in the process-time space as a three-dimensional phase curve, called geodesics. If a similarity is established between model and prototype, these two phase-curves will overlap at any moment of the transient. Any deviation of the process curves represents the deviation of scaling as a function of time. By specifying the ratios of the conserved quantity and the process (called 2-parameter transform), the generalized framework can be converted to a specific scaling method, such as the power-to-volume scaling. Furthermore, this generalized approach offers the benefit of identifying the distortion objectively and quantitatively at any moment of the transient.

From Table 3-6 are summarized the scaling approaches and methodologies used for the design of the IETF revised in (Bestion et al., 2016). The information's have been extracted from the Appendix A3 (LIST OF SELECTED SETF AND IETF) of the (Bestion et al., 2016). The following abbreviations are used in the tables: ECLN: Equal CL number; ELN: Equal Loop Number; ENRL:- Equal Number Recirculation Loop; FH: Full height; FPr: Full pressure; FPw: Full power; I: Integral design; IIETF: Integrated Integral Test Facility; L: Number of Loop; NC: Nuclear Core; NNC: Non-Nuclear Core; RH: Reduced Height; RL: Recirculation Loop; RLN: Reduced Loop Number; RNJP: Reduced Number of Jet Pump; RPr: Reduced Pressure; S-W: Steam Water; S-W-A: Steam Water Air; TNP: Time Not Preserved; TP: Time Preserved.

The key objective of the scaling methods is to design test facilities as well as the related test conditions. Scaling methods are essential tools in the area of nuclear thermal-hydraulics facilities. However, the following four drawbacks or limitations may still remain in the application to nuclear reactor safety:

- Choice of starting equations.
- Approximations in selecting non-dimensional numbers for scaling some local phenomena.
- Details of geometry and the initial conditions of the NPP.
- Local validity.

4. Role of experiments in scaling

As said before, experiments have formed the basis of nuclear-thermal-hydraulics to meet requirements of the safety evaluation of LWRs, being connected to the development of computational tools that include the SYS TH codes. Experiments can be classified into three categories, basic tests, SETs, and IETs. Table 7 shows a comparison of merits and issues of SET and IET.

4.1. Basics test

Basic tests aim at understanding the phenomena mostly under simple and steady boundary conditions, sometimes with less reference to actual LWR conditions, including those expected in accidents. In particular, basics test may address:

- Fundamental phenomena (e.g. pressure drops, heat transfer, including boiling and condensation, etc).
- Complex phenomena due to combination of fundamental processes like countercurrent-flow limitation.

These problems usually involve very simple geometries and may have an analytical solution. Example of basic test are the Bernoulli test, the drain-fill problem, the single tube flooding. Basic tests may reveal information essential for developing models and correlations also embedded into balance equations that are part of the SYS TH codes. Considering the previous considerations, basic tests have a weak connection with scaling.

Table 3
IETF simulating PWR main characteristics related to scaling approach and methodology (Bestion et al., 2016).

Facility	Reference reactor	Scaling approach	Scaling Method	Counter Part Test	ISP-ICSP
LOFT	W-PWR-4L	TP, RH, FPw, FPr, NC, RLN, S-W	P-to-V (Kv)	YES	05, 09, 11, 13
SEMISCALE	LOFT (MOD1); W-PWR-4L	TP, FH (Mod 2–3), FPw, FPr, NNC, RLN, S-W	P-to-V (Kv)	YES	02, 04, 08
LOBI	KWU-PWR-4L	TP, FH, FPw, FPr, NNC, RLN, S-W		YES	18
PKL-III	KWU-PWR-4L	TP, FH, DPw, RPr, NNC, RLN (for PKL I and PKL II), S-W		YES	10 (PKL I)
LSTF/ (ROSA IV)	W-PWR-4L	TP, FH, DPw, FPr, NNC, RLN, S-W		YES	26
CCTF	W-PWR-4L	TP, FH, DPw, RPr, NNC, ELN, S-W			
BETHSY	F-PWR-3L	TP, FH, DPw, FPr, NNC, ELN, S-W		YES	27, 38
SPES	W-PWR-3L	TP, FH, FPw, FPr, NNC, ELN, S-W		YES	22
OTIS	B&W PWR Raised L – 2 × 4L	TP, FH, DPw, FPr, NNC, RLN, S-W	P-to-V (Kv) modification of GERDA		
MIST	B&W PWR Lowe. L-2 × 4L	TP, FH, DPw, FPr, NNC, ELN, ECLN, S-W	P-to-V (Kv)		
UMCP	B&W PWR Lowe. L −2 × 4L	TP, RH Core, FH SG, DPw, RPr, NNC, ELN, ECLN, S-W	See note		
GERDA	B&W PWR Raised L – 2 × 4L	TP, FH, DPw, FPr, NNC, RLN, S-W	Scaling similar to OTIS		
SRI-2	B&W PWR −2 × 4L	T, RH, RPw, RPr, NNC, ELN, S-W	See note		
APEX-CE	CE-PWR −2L- 1HL 2CL	TP, RH, RPw, RPr, NNC, ELN, ECLN, S-W	H2TS, Modification of APEX		

SEMISCALE Mod 1 vs. LOFT volume scale is 1/1570.
Cylindrical Core Test Facility (CCTF), Slab Core Test Facility (SCTF) and Upper Plenum Test Facility (UPTF) are part of the 2D/3 D program.
OTIS: A modification of GERDA facility.
UMCP: Scaling method adopted is similar to method by (Ishi and Kataoka, 1984). Time preserved. Elevations of the various components not preserved.
SRI 2: Scaling method adopted is the method by (Ishi and Kataoka, 1984). However, pressure scaling was modified.

Table 4
IETF simulating BWR main characteristics related to scaling approach and methodology (Bestion et al., 2016).

Facility	Reference Reactor	Scaling Approach	Scaling Method	Counterpart test	ICSP-ISP
TLTA	GE-BWR-4 and 6	TP, FH core only, FPw, FPr, NNC, RNJP, ENRL, S-W	P-to-V (Kv)	YES	
FIST	GE-BWR/6	TP, FH, FPw, FPr, NNC, RNJP, ENRL, S-W		YES	
ROSA-III	GE-BWR/6	TP, RH, RPw, FPr, NNC, RNJP, ENRL, S-W		YES	ISP 12
TBL	GE-BWR/5	TP, FH, FPw, FPr, NNC, RNJP, ENRL, S-W			
FIX-II	AA-BWR	TP, FH, FPw, FPr, NNC, S-W			ISP 15
Piper-1	GE-BWR-4 and 6	TP, FH, DPw, FPr, NNC, RNJP, NO RL, S-W		YES	ISP 21
DESIRE	Dodewaard NC BWR	RH, NNC, Freon-12	*		
CIRCUS	Dodewaard NC BWR	FH, RPr, NNC, S-W			

TLTA: Predecessor of FIST. The jet pumps are linearly scaled to the height and diameter. In FIST these are modified to full height.
DESIRE: pressure range: 8 13 bar.
CIRCUS: pressure range: 1 5 bar.
CIRCUS: riser diameter is 47 mm.
* see also (Van De Graaf, 1994).

Table 5
IETF simulating VVER main characteristics related to scaling approach and methodology (Bestion et al., 2016).

Facility	Reference Reactor	Scaling Approach	Scaling Method	ISCP-ISP
PACTEL	VVER 440-6L	TP, FH, RPw, RPr, NNC, RLN, S-W	P-to-V (Kv)	ISP 33
PMK-2	VVER 440-6L	TP, FH, FPw, FPr, NNC, RLN, S-W		Test IAEA-SPE4
REWET-III	VVER 440-6L	FH, RPw, RPr, NNC, RLN, S-W	Note	
KMS		FH reactor scale, R scale cont., FPr, S-W		
PSB	VVER 1000-4L	TP, FH, FPw, FPr, NNC, ELN, S-W	P-to-V (Kv)	
PM-5	VVER 1000-4L	RA, RH, RPr, RLN, S-W		
SB	VVER 440 −6L	FH, RPw, FPr, RLN, S-W		
ISB	VVER 1000-4L	TP, FH, FPw, FPr, NNC, RLN, S-W	P-to-V (Kv)	Test UPB-2.4 is first Russian Standard Problem
BD	VVER 1000-4L	RPr, RLN, S-W		

REWET: for natural circulation (NC) test:pressure is 1 bar; For compensated leak test (single-phase NC) pressure is 0.1–0.35 MPa.
REWET-III: Modified from REWET II for two-phase natural circulation studies.
KMS: Containment linear scale is 1:3 (D: 6.0 m; H: 20 m; V: ~2000 m3; P up to 0.6 MPa).
PM 5: Pressure: 1 3 bar (1 1.5 bar for 'transparent' model).
BD: One circulation loop with scale 1:5 loop seal and circulator & three working loops without circulator (see also Table A3 4A of the (Bestion at al., 2017)).
ISB: Test UPB 2.4 provided data for the first Russian Standard Problem.
SB: It models also a VVER 1000 4Loops with a volumetric scale of 1/3000 and full height.

4.2. SETF

SETFs are designed to observe phenomena in selected zones in a NPP's system or in specific plant components and some specific process in a particular period of a given transient. The major role of SET is to provide experimental data to develop and validate the physical models, and/or empirical correlations under prototypical- or simulated-conditions.

SETF may address:

- A specific basic flow process (e.g. critical flow, etc).
- A specific closure term for a given flow or for a given range of flow parameters.
- The specific behaviour of a specific reactor component (e.g. loop seal, etc).
- A specific flow process occurring in a specific reactor component during a selected time period of an accidental transient identified as phenomenological window (reflooding, refill).
- A specific closure term in a specific reactor component (or reactor zone).

SETF main characteristics are:

- Desirable to have minimum scaling distortions (full/almost full-scale; prototype/almost prototype fluid conditions).
- Instrumentation dedicated to characterize selected phenomena.
- Well imposed boundary conditions necessary to simulate interactions with the other reactor components, and, not simulated in the experimental test-facility.

SETF scaling distortions (facility scaling limits) (Karwat and Austregesilo, 1985) are mainly due to:

- Scaling of external boundary conditions causing a distortion on the interacting phenomena at the facility boundary.
- Possible initial condition deviations.
- Local geometric distortions.
- Discrepancies in fluid properties.

In many cases, the data obtained from a SETF can be applied to the full-scale prototype, although the direct extrapolation at the full-scale prototype requires caution, considering the facility's scaling limits. It is foreseeable that the influence of the facility's scale is observed in many SETF tests, and the LOCA phenomena easily are influenced by 2-D/3-D effects.[9] Therefore, a full-scale SETF such as UPTF is valuable to characterize multi-D phenomena. In addition, CTs for the same phenomenon also will provide confidence in extrapolating uncertainties to a full-scale plant. Recently, heavily instrumented SETFs were built to produce spatially and temporally fine-resolution data (called the CFD-grade experiment) for validating the CFD codes.

4.3. IETF

An IETF is designed and scaled-down having as a reference a specific reactor and can be used to investigate:

- The overall system behaviours and the related phenomena and processes.
- The interaction of two or more components.
- The local phenomena that are typical of the overall system design target function.

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[9] The 2-D/3D effects take place in several accident conditions. LOCA conditions are among the most difficult to predict.

Table 6
IETF simulating advanced PWR main characteristics related to scaling approach and methodology (Bestion et al., 2016).

Facility	Reference Reactor	Scaling Approach	Scaling Method	Counterpart /similar Test	ICSP-ISP
PWR PACTEL	EPR Like-4L	RPw, RPr, NNC, RNL, S-W			
ATLAS	APR1400 – 2L (1HL-2CL)	TNP, RH, RPw, FPr, NNC, ELN, ECLN, S-W	Three-level scaling	YES	
SNUF	APR1400 – 2L (1HL-2CL)	RH, RPw, RPr, NNC, ELN, ECLN, S-W	Three-level scaling		
APEX	AP600-2L (1HL-2CL)	TNP, RH, RPw, RPr, NNC, ELN, ECLN, S-W	H2TS	YES	
SPES-2	AP600-2L (1HL-2CL)	TP, FH, FPw, FPr, NNC, ELN, ECLN, S-W	P-to-V (Kv) Modification of SPES	CT, ST	
ROSA-AP600	AP600-2L (1HL-2CL)	TP, FH, RPw, FPr, NNC, ELN, NCLN, S-W	P-to-V (Kv) Mmodification of LSTF	YES	
OSU-MASLWR	MASLWR -IWCR	TP, RH, FPw, FPr, NNC, I, S-W-A	H2TS		IAEA ICSP
VISTA-ITL	SMART-IWCR	TNP, RH, FPw, FPr, NNC, S-W	Three-level scaling		
FESTA	SMART-IWCR	TP, RPw, FPr, NNC, S-W	Three level scaling		
IST	mPOWER IWCR	TP, FH, FPr, NNC, S-W			

OSU MASLWR: Upper region of the hot leg riser has an OD equal to 114.3 mm.
NIST: A modification of the OSU MASLWR facility and used for the simulation of NUSCALE IWCR and TP, RH, FPw, FPr, NNC, I, S W A are the main characteristics.

IETF scaling distortions (facility scaling limits) (Karwat and Austregesilo, 1985) are mainly due to the scaling approaches used to design an IETF; several distortions will be present causing the partial or the total failure of properly simulating phenomena. In general, the data obtained from an IETF cannot be applied directly to full-scale prototype, if the validation of computational tools (code) is not ensured. The direct extrapolation at the full-scale prototype requires caution in considering the facility scaling limits and the appropriate methodology; using codes are necessary to do the extrapolation. CTs are important to assess the effectiveness of scaling criteria, to evaluate the influences of scale distortions, and to assess the scale-up- and scale-down[10]-capabilities of codes within a certain range of validation data.

4.4. NPP data

NPP data are scarce but they are the only data which actually allow a validation on real geometry, and actual physical condition. In this respect they play a role in the scaling assessment and in the validation of reactor nodalization.

Transient data are measured with very limited instrumentation in NPPs during operational tests, e.g. commissioning, start-up, and various unplanned situations, including accidents. Although they are typically not suited for code assessment to the same extent as are basic experiments, SETF and IETF. However, NPP data do not suffer of any scaling limitations. It is to underline however that most of the data are proprietary (especially in relation to geometrical parameters) and the data provided usually is quite limited in relation to the accident of interest.

4.5. S-SOAR facility scaling considerations

A comprehensive Appendix has been prepared in (Bestion et al., 2016) to summarize the key parameters of the major test facilities in the world, mainly the IETF and selected SETF. The facility types considered are IETFs for each of PWR, BWR, VVER, advanced reactor and containment, with selected SETFs. Major design parameters and scaling information are given for reference. The focus of this database is on how scaling has been considered in the design and the experiment results and has been used for a better understanding of chapter 3.2 (Scaling and experiments) of the (Bestion et al., 2016). Table 8 shows the list of Table collected in the Appendix A3 of ((Bestion et al., 2016). Here some information related to scaling have been in briefly discussed for reactor types.

A generic PWR design is characterized by the primary system, with an open-channel fuel bundle in the reactor core, where the power is generated and transferred to the secondary system through the SG (vertical U-tube SG, horizontal SG, and the OTSG: viz., the Once-Through SG). Both active and passive systems are connected to the loop piping. An experimental test facility has to reproduce the main components of its layout and the peculiarities of its main design. For example, the B&W design is characterized by OTSG and by a 2×4 Loop configuration. Most of these main features should be reproduced in the test facilities. Scaling approach and methods used to design the IETF simulating PWR are reported in Table 3. The time, height, linear, volumetric, fluid, pressure, nuclear core simulator, SG simulator, the number of loop scaling and main coolant lines scaling have been discussed. Once the scaling approach is defined, a scaling method is used to design the IETFs. For example, the power-to-volume scaling method was used to design such facilities as LOFT, SEMISCALE Mod-1 to 3, LOBI, PKL, LSTF (ROSA–IV), CCTF, BETHSY, SPES, OTIS (a modification of GERDA), MIST. Another example is the UMCP (University of Maryland at College Park) 2×4 loop that simulates a B & W reactor. In this facility, the time scaling is preserved but not the height scaling (core height 1: 3). In the SRI-2 facility at Stanford Research Institute, the Ishii and Kataoka (1984) scaling rationale was applied whilst considering the non-prototypical pressure. The APEX-CE facility, a modification of the APEX facility, was designed using the H2TS methods. Table A3-2 in Appendix A3 of the (Bestion et al., 2016) summarizes the scaling information for the main facility for current PWR IETF-related facilities.

BWR design is characterized by a core composed of fuel bundles, each enclosed in a zircaloy channel box, along with a system for circulation of the coolant, jet pumps driven by two external loops (BWR/3 to 6), or internal pumps (ABWR). Steam is generated in the core and an active ECCS, or a passive system, such as an isolation condenser is installed. Throughout the history of the evolution of the BWR design the layout of components inside the RPV has not been changed much, concerning their elevation. Since the core structure is unique the test facility design mainly should consider how to simulate the thermal-hydraulic conditions in the core and thus a fuel bundle in channel box. The main design choice would then be to have a full-sized fuel bundle. Then, the volumetric distribution and height scaling are determined. Scaling approach and methods used to design the IETF simulating BWR are reported in Table 4. The time, height, volumetric, the fluid, pressure, nuclear core simulator, recirculation and jet-pump scaling have been discussed. In many cases, the power-to-volume scaling method was used for the design of IETFs such as TLTA, FIST, ROSA-III, TBL, FIX-II, PIPER-ONE. Table A3-3 in Appendix 3 of the (Bestion et al., 2016) reports the main information on facility scaling for BWR IETF.

In relation to the VVER reactors, the main considerations valid for the PWR can be applied. The Power/Volume ratio and Power/Mass ratios are considered in attempting to preserve time in the measured

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[10] SCALE-UP: This is to extrapolate phenomena, local and/or system-wide, observed in a scaled-down test facility to prototype phenomena that may appear in the reference facility. SCALE-DOWN: This is to design a test facility with smaller size and/or lower pressure/temperature conditions compared with those conditions of reference reactor by using an appropriate scaling method.

Table 7
Comparison of merits and issues of SETF and IETF (Bestion et al., 2016).

Items	SETF		IETF	
	Merits	Issues	Merits	Issues
Geometry and Fluid Conditions	• Possibility to minimize scaling distortion by employing (almost) full- scale conditions	• Distortions may exist depending on facility design; local geometry and/or non-prototypical fluid	• Main reactor configuration / key system components relevant for safety and design studies can be represented • Representation of multi-D phenomena and their mutual interactions during a system transient, depending on IETF BC design	• Reduced-scale in volume for all IETFs, with further reductions in height, pressure (temperature), power, and/or the number of loops, depending on IETF-scaling approach • Compensating actions may necessary to minimize scaling distortions; ex. orifice in main circulation loop of PWR IETF to control pressure drop, heat losses, etc.
Initial & Boundary Conditions (I&BC)	• Well defined I&BC to characterize local phenomena by simulating interactions at facility boundary with other components• Hardware control of discharge (critical) flow under steady conditions	• Distortion in interacting phenomena at facility boundary due to BC scale effect(s) • Distortion / difference in evolution of phenomena at location of measurement depending on facility geometry and/or I&BC • Condition range may not fully cover expected response of prototype due to limitation in I&BC, depending on facility design constraints	• Well- defined IC & BC at system level: pressure and temperature distribution, FW and steam flow rate.• Control of break discharge (critical) flow under accident simulation conditions	• Precise definition difficult for local parameters, such as flow rate in each of PWR SG U-tubes and core sub-channels.
Phenomena Representation	• Reproduction or detailed simulation of local (single) phenomenon and specific parameter(s) by avoiding or reflecting influences from the periphery• Characterization of TH behavior of target component for specific parameter(s) by decreasing or reflecting influences from the periphery • Suitable for observing strongly scale-dependent phenomena. including 3-D effect • While most of the SETF is aimed for steady experiments, transient phenomena could be observed: ex. UPTF, CCTF, SCTF for 2D-3-D program designed to reproduce local prototypical phenomena under both steady- and transient- conditions	• Most of SETF is designed for steady experiments that may not include transient phenomena, while depending on SETF design • Sometimes, SETF design does not fully consider scaling to reference reactor	• Simulation of accident phenomena, in multi-dimensional in general, with mutual interactions through the system transient within the limitations of the IETF design limitations • Component simulation under either of steady operation and transient conditions	• Distortion in flow rate, energy, and mass- distribution and/or phase separation / stagnation due to constraints in facility design• Time-scale and/or phenomena evolution (ex. mixture level in core) may change in some reduced height IETFs, basically following scaling approach and the method used for facility design
Counterpart Test	• Advantages in investigating single phenomenon with various views from complementary facility size and test conditions	• Difficulty in developing counterpart tests • Distortions in I & BC and facility size can affect test results	• Advantages in clarifying influences of scaling and local geometry • Possibility of addressing scaling issues via similar tests even when the reference reactor is different	
Data Measurement	• Data for local phenomena understanding, model / correlation development and code validation • Instrumentation dedicated to characterize target phenomena and easier improvements than for IETF • Spatially precise measurement both for steady- and transient-phenomena•Possibility of CFD-grade (very precise and high spatial- & temporal-resolution) measurements with specific facility design	• Limited parameters within test planning	• Measurement of both of steady- and transient- phenomena at specified (fixed rather small number of) points• Data for local and system-wide phenomena understanding and code validation (incl. CFD codes)	• Spatially coarse measurements for limited parameters and difficulties in changing/adding instrumentation • Difficulties in simultaneous measuring multiple parameters to understand multi-D two-phase flows • Development of instrumentations that withstand high-pressure and temperature

sequence of main events. The power-to-volume scaling method, coupled with a full-height approach, was used for designing PACTEL, PMK, and PSB, and the ISB test facilities. An important feature of the VVER reactor is the horizontal SG. Scaling approach and methods used to design the IETF simulating VVER are reported in Table 5. Table A3-4 in Appendix A3 of the (Bestion et al., 2016) shows the scaling information for the main facilities of VVER related IETFs.

Some passive- and advanced-designs for water-cooled reactors are characterized by new phenomena, and accident scenarios such as containment phenomena and interactions between the containment and RCS, low-pressure phenomena, and the phenomena of new components or reactor configurations. In relation to the common features with current reactor designs, it is observed that they may have different rankings in the phenomena. Therefore, review of the experimental database available for the current-reactor designs, indicated that further experimental investigations are necessary to characterize the thermal-hydraulic behaviours that are specific to advanced reactors. Several IETFs have been used to investigate natural-circulation phenomena and the thermal-hydraulic response of passive safety systems in advanced reactor designs. For designing experimental test facilities for simulating advanced reactors, such scaling methods as H2TS, and three-level scaling are used. For example, for the design of the APEX, and the for the OSU-MASLWR, the H2TS method was used, while for the design of ATLAS, SNUF, PUMA, VISTA-ITL, FESTA, the three-level scaling method

Table 8
List of Table in the Appendix A3 of (Bestion et al., 2016).

Table No	Key Content
A3-1	IETF constructed and operated for the simulation of RCS including advanced designs
A3-2	IETF simulating PWR, main characteristics
A3-2A	IETF simulating PWR, pump data
A3-2B	IETF simulating PWR, core data
A3-2C	IETF simulating PWR, SG data
A3-3	IETF simulating BWR, main characteristics
A3-3A	IETF simulating BWR, core data
A3-4	IETF and SETF simulating VVER, main characteristics
A3-4A	IETF and SETF simulating VVER, pump data
A3-4B	IETF and SETF simulating VVER, core data
A3-4C	IETF and SETF simulating VVER, SG data
A3-5	IETF simulating advanced PWR, main characteristics
A3-5A	IETF simulating advanced PWR, pump data
A3-5B	IETF simulating advanced PWR, core data
A3-5C	IETF simulating advanced PWR, SG data
A3-6	Facilities constructed and operated for the simulation of CONTAINMENT including advanced designs
A3-7	Containment facilities, main characteristics
A3-8	Pressure Suppression CONTAINMENT systems, comparison of selected data
A3-9	Pressure Suppression CONTAINMENT facilities, comparison of selected geometrical data
A3-10	Pressure Suppression CONTAINMENT facilities, key scaling factors

was used. Existing facilities were also used with some modifications for simulating the advanced design. Examples are SPES-2 and ROSA-LSTF for the AP600 simulation. A list of IETFs used for the analyses of the advanced reactor designs are given in Table A3-5 in Appendix A3 of the (Bestion et al., 2016). Scaling approaches and methods used to design the IETF simulating advanced design are reported in Table 6.

For the SETF of the primary containment vessel (PCV), the scope of the present SOAR does not include a scaling review of severe accidents. In addition, each SETF corresponds to specific situations, depending on the design's objectives. Therefore, the review focused on some highlights on the scaling techniques related to the DBA phenomena. Different containment designs for each reactor type are compared, which include PWRs, BWRs, VVERs, and new NPP designs, such as Small Modular Reactors (SMRs).

For the PWR PCV-IETF, due to the fact that earlier existing facilities were a part of small yet real power plant able to provide experiments and data, the scaling analyses received limited attention. The interest on scaling for the PCV-IETF arose when discrepancies were observed in the results between HDR (Heissdampfreaktor) and BFC (Battelle-Frankfurt Containment). In the PCV-IETFs, the 'expected time of event' is preserved when the addition of energy and mass from the reactor's primary system and the subsequent distribution along the several compartments of the containment is preserved. The facility's material and the relative spatial distribution and proportion are important in designing facilities. Other scaling characteristics of the PCV-IETF are the compartmental subdivisions and energy-release scaling into PCV.

BWR containment designs are characterized by a "pressure suppression containment" being constituted with "wet well" that has a large suppression (water) pool covered by gas-space above it, a "dry well" that is a pressure-retaining structure surrounding the RCS, and a "vent system" that connects the dry well gas space to the wet well below the surface of the suppression pool water surface. In relation to the LOCA-related tests, and the BWR containment scaling of particular interest is the "single cell" hypothesis.[11]

In the new advanced passive-reactor designs, it is not possible to consider the RCS as a boundary condition for the PCV, but it is necessary to consider the physical behaviour of the PCV coupled with the RCS physical behaviour and it is necessary to characterize the RCS/PCV coupled behaviour during the evolution of the transient. This requirement is due to the strong coupling effects and feedbacks between the RCS and PCV. The passive mitigation strategy depends on the characteristics of natural circulation loop that are in response to both components (PCV and RCS) to remove decay heat. Two PWR examples can be the AP600 and MASLWR concerning their SBLOCA passive-mitigation strategy. An example of the behaviour of an advanced BWR containment coupled with the primary side is present in the SBWR design. The major integral test programs related to the SBWR have been conducted at the GIST, GIRAFFE, PANDA, and PUMA IETF. Another advanced BWR is the KERENA reactor. The INKA facility is a full-height, volumetric-scaled test facility (1: 24 in volume) of the KERENA containment aiming at characterizing the performance of the passive safety-systems of KERENA.

The scaling compromise is one of the major reasons to cause scaling distortions due to the difficulty of complete similitude in all local phenomena and even the lack of knowledge of the local phenomena themselves. In this review (Bestion et al., 2016), the following main scaling distortions observed in the experiment are identified as follows:

- **Circular sections**: due to hydraulic diameters not being preserved.
- **Structural heat loss and stored heat**: due to a larger structural mass and structure surface area per unit coolant volume relative to the prototype.
- **Inventories and inter-component flows**: due to choked flow.
- **Pressure drop**: due to the ratio of length divided by diameter is very large.
- **Multi-dimensional phenomena**: due to tall and skinny nature to preserve power volume and height.

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[11] The dynamic similarity is obtained if the volumes of the dry well, the wet well, and water in the suppression pool are in proportional to the corresponding prototypical volume divided by the prototypical number of vent pipes. This should be coupled with a full-vent pipe dimension, representative pool surface area, and geometric volumes. Other important points are the specific energy additions, fluid–structure interactions, and the simultaneous interactions of a large number of vent pipes. The rate of specific-energy additions rate per vent pipe has to be preserved to assure dynamic similarity. The confinement of the wet well pool was, in general designed with an eigen-frequency behaviour similar or identical to that of the prototype plant of interest so to assure the warranted proper fluid–structure interaction. Simultaneous interaction of a large number of vent-pipes is of interest for the loads on the prototype structures caused by oscillations in condensation and steam chugging. In relation to this subject, seven full-size vent pipes were used to simulate the vent-system response in the JAERI full scale MARK-II containment response test program. In relation to the fluid structure interaction and the overall system response, great care was taken to assure for the correct distribution of structural masses of the entire system. A similar approach has been used for the design of the FSTF facility for the MARK-I containment.

- **Scaled-down reactor coolant pump**: reliable two-phase pump model is not available until now, specific speeds and single-phase characteristics are recommended to be preserved.
- **Fuel simulators**: electrically heated fuel simulators may behave differently from nuclear fuel rods.
- **Scaling distortions of local phenomena**: due to inherent scaling distortions by design and simulation constraints, and non-typicality of local phenomena.

4.6. ISP AND IAEA ICSP

The International Standard Problem (ISP) of the NEA/CSNI is a long-term international cooperation activity wherein scaling is one of the key topics of study. Typically, within each of these ISP reports, a summary of the scaling-related discussions and findings is given; a full introduction of them is beyond the scope of the (Bestion et al., 2016) although an attempt is made to take into account those scaling findings. Therefore the DBA related SETF and IETF ISP and scaling information are summarized; the PCV ISPs within the DBA envelope are identified and the relevant scaling. In relation to the IAEA activity, the International Collaborative Standard Problem (ICSP) on Integral PWR Design, Natural Circulation Flow Stability, and Thermo-hydraulic coupling of the Primary System and Containment during Accidents, is mentioned in the text.

4.7. Counterpart test, similar Test, complementary Test, daughter facility

4.7.1. Counterpart test and similar tests

As data acquired in experiments at a single (scaled) test facility may be questionable due to inherent scaling distortions, the concept of CTs involving several IETFs or SETFs at different scales and design concepts have been considered important. It is desirable that the following minimum set of BC/IC values and related parameters are preserved between the CTs:

- Thermal-hydraulic state and parameters (pressure, temperature, and flow condition) in each component of the facility;
- Scaled values to power-to-volume scaling ratio (kv);
- Characteristics of primary- and secondary-side safety and operational systems (e.g. accumulator injection and safety-injection systems (SIS) characteristics);
- Heat- and mass-sinks or sources (e.g. location and size of break);
- Timing of operator's actions based on pre-defined operational criteria.

IETF tests whose boundary and/or initial conditions (BC/IC) were not aligned according to the requirements of CT are referred to as Similar Tests (ST).

CTs and STs have to be used to clarify scaling distortions, affecting the facilities, and the possibility of extrapolation/interpolation of the obtained data. They provided a great amount of information to promote the understanding of accident phenomena observed mainly in IETFs at different scales. This understanding enhances confidence that these phenomena may also occur in the reference NPP,[12] and is suitable for the computer code assessment. However, further extrapolation of the results beyond the scale of the test facility with the maximum scaling ratio (nearest to the prototype) is not guaranteed, so providing an upper limit of applicability of the knowledge from the counterpart testing, as long as the maximum sized facility also has scaling distortions.

4.7.2. Complementary test, daughter facility

For some scenarios, certain relevant phenomena dominated by highly-heterogeneous, three-dimensional flow patterns cannot be reproduced by sub-scaled IETFs due to scaling distortions imposed by constructive compromises. For such applications, complementary tests in test facilities dedicated to investigating separate effects, that is, SETFs become invaluable. In the frame of complementary testing, whereas the IETF concentrates on studying the overall system response, the SETs investigate the responses of the plant subsystems, and, in particular, study individual phenomena that are highly dependent on the geometry, in scales up to 1:1 full-scale (in the case of the UPTF). Another category of tests or combination of tests referred to as daughter (facility) tests employ results available in 1:1 full-scale as reference for comparison with results from scaled-down experiments on the same phenomena, and aims at evaluating the scalability of relevant phenomena and their understanding in general. In this way, the representativeness or the limits of scaled down facilities with respect to certain important phenomena can be analysed, and the impact of scaling distortions on the overall system behaviour during accident transients evaluated.

5. Scaling and system codes

SYS TH codes model the thermal-hydraulic physical system, and other related coupled systems. The thermal-hydraulic system can be either the cooling circuits of a nuclear reactor, or the circuits of a test facility, which are simulated by solving systems of equations. SYS TH codes integrate the knowledge gathered from the huge data base produced so far for LWRs, and which can help at every step of the analysis of complex transients. A best estimate code (approach) uses more realistic information about plant behaviors and phenomena for calculation and analysis and it is usually combined with uncertainty analysis to provide realistic margin between the results and acceptable criteria. A best-estimate system code is designed for:

- Being able to model correctly all the important phenomena with sufficient accuracy for safety analyses, the code must be able to:
- Predict global parameters in any IET (e. g. system pressure, mass inventory, etc);
- Predict with the same reliability the same transient at different scales using counterpart tests.
- Predict important local parameters, (e.g. clad temperature in SETs and IETs).
- Predict correctly at the reactor scale those phenomena which are distorted in IETs.

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[12] Good examples of CT include the SBLOCA tests by LOBI, SPES, PSB, BETHSY, and LSTF. All five test facilities simulate the primary circuit of a PWR (VVER in the case of PSB and Western PWR for the other facilities) with original heights covering a broad range of volume-scaling factors: LOBI: 1:712; SPES: 1:427; PSB: 1:300, BETHSY: 1:100; LSTF: 1:48. The similarity of the overall results confirms the choice of the adopted scaling laws and the suitability of the individual test facilities to reproduce a plant's typical behavior under the given BCs. The CT tests conducted between PKL and LSTF (between the NEA PKL-2 and ROSA-2 projects) demonstrated the effectiveness of a secondary-side depressurization in removing the heat from the primary side, which achieved almost identical primary-depressurization behaviors, which enabled a systematic comparison of the thermal–hydraulic response between the two IETFs.

- Applying the necessary simplifications to make the code applicable for solving nuclear reactor safety and design problems.

In the process of developing code, several averaging simplifications are made on the space- and time-scale of the processes. Some distortions are introduced due to simplifications of the physics, non-modeled phenomena, and limited accuracy of the closure laws. The limits are related to:

- **Space and time averaging:** System codes do not predict small-scale thermal-hydraulic phenomena due to space averaging and cannot predict all the small time-scales associated with turbulence and two-phase intermittency.
- **Dimensions of the model:** Using the O-D (or lumped) model, 1-D models, or a porous 3-D approach consists of simplifying a complex 3-D flow; using a 1-D heat conduction in heating structures and in passive solid structures is an approximation for more complex 3-D conduction.
- **Flow regime maps:** The highly empirical flow-regime maps are valid only in some states, such as the steady state, the quasi-steady state, the fully developed and the quasi-developed states; while the rapid transient- and non-established-flows could exist in accident conditions. The flow regime also depends on geometry, conduit size, and the fluid's physical properties. These differences from established flow regime maps should be introduced in the numerical model.
- **Scaling of each closure law:** Closure laws in system codes may be purely empirical, mechanistic, or semi-empirical. Therefore, the scalability of the closure law is questionable.
- **Non-modeled phenomena:** System codes neglect many complex phenomena.

These limits determine scalability issues, therefore the code scaling capability needs to be confirmed along the verification and validation process.

5.1. *Scaling aspects in the verification and validation process*

The verification process should take care of following main aspects related to scaling:

- **Space and time scales:** Checking that the numerics solve properly the required time- and space-scales.
- **Measuring accuracy versus scale:** The numerical scheme solves the equations with an accuracy that depends on its mathematical properties. When solving a similar problem in a reduced-scale test or in a reactor, there may be a unique solution if the two problems are actually "similar". Then, the equations to be solved are identical in a non-dimensional form, and the accuracy of the solution should be the same at both scales. However, since equations are not written in a non-dimensional form, the accuracy may differ at different scales.
- **Tracking scale-dependent coding errors:** Coding errors may induce any type of error, and may include errors that affect the code's scalability (e.g. numerical errors that may have a larger effect at the reactor scale than at a reduced scale).

The validation process against SETF and IETF should take care of following main aspects related to scaling:

- **Scalability of each closure law:** The validation on SETs should be able to demonstrate the scalability of each closure law.
- **Scalability of each module of the code used for the situation of interest:** The validation on both SETs and IETs may demonstrate the correctness of the choice of a specific module (O-D, 1-D, 2-D, 3-D) for a specific component, and/or situation.
- **Scalability of the code for a reactor transient:** it should be demonstrated, at least, through validation on IETs that the code properly predicts the main parameters of the transient in different IETs having different scale factors.
- **Scalability of the code for some scale distortions:** The impact of a distortion in an IET is studied by using an appropriate SET. Then, the resulting validation of the code may demonstrate that it predicts the distorted- and non-distorted-phenomenon with the same quality.

5.2. *Scaling aspects in the input-deck development and qualification process*

The nodalization,[13] constitutes the connection between the code and the physical reality and is an indispensable component for code applications. Therefore, since there is a need to prove the validity of SYS TH code against scaling, there is the need to develop input decks for differently scaled experimental facilities. The origin of the relationship between scaling and nodalization is related to:

- **The length-over-diameter ratio (L/D) is associated with meshes or "control volumes":** it is impossible or impractical to preserve the L/D when setting up nodalizations for differently scaled facilities. Unavoidably, the results of calculation are affected by the L/D: it must be proved that the impact of different L/Ds is tolerable, i.e. within acceptable error.
- **Averaging region:** The averaging region, including the cross-sectional flow area or volume of the single node (or control volume) cannot be the same for NPPs and a typical scaled down facility. It must be proven that the impact of the sizes of the averaging regions upon the numerical solution is tolerable.
- **Steady State, and flow region not fully developed:** Qualified models and correlations embedded in a thermal-hydraulic system code are developed based on experimental data gathered under the condition of steady-state fully developed flow; these conditions do not occur in applying the codes to the accident analysis of a NPP. Therefore the structure of the thermal hydraulic system codes not allow considerations about not fully developed flow.
- **The coefficient for local pressure drops at a geometric discontinuity including branching, i.e. the so called K-factor**: since this may have large impact upon any transient scenario, a specific

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[13] NODALIZATION: The set of input data developed and needed for a SYS TH code calculation. The nodalization is the results of a brainstorming process performed by the code users where the facility to be modeled and the features of the specific-concerned code play a role.

scaling-qualification for the K-factors part of a nodalization is needed.

The nodalization features as well as the processes for developing and qualifying a nodalization have been, and still are the subject of numerous papers in the open literature, e.g. (Bonuccelli et al., 1993). Four main steps should be considered:

- **Development processes and criteria used to develop the nodalization:** Scaling is relevant to address along the nodalization development.[14]
- **Qualification at steady-state level:** it is not directly connected with scaling.
- **Qualification on the-transient level:** it is not directly connected with scaling, with the noticeable exception of the Kv-scaled analysis;
- **KV-scaled calculation:** it is directly connected with scaling.

A Kv-scaled calculation is a procedure for system code simulation procedure in which well-defined (measured) scaled IETF- are converted to an NPP-nodalization, and the test is simulated with this nodalization. The purpose is to reproduce, by sensitivity studies, same phenomena as seen in IETF by the NPP nodalization; namely, number of nodes and node sizes are changed in the framework of the process. Performance of both NPP and IETF nodalization can be compared to check the validity of the NPP nodalization for any needed corrections and improvements. The procedure is systemized to qualify NPP nodalization.

5.3. SYS TH code for assisting scaling analyses

Scaling methods are used to design facilities that minimize distortions in important phenomena over the range of the transient of interest. Scaling methods, such as H2TS and FSA, have proven to be very useful tools in:

- Analysing a complex problem;
- Identifying dominant processes;
- Supporting the PIRT analysis;
- Scaling adequate SETs and IETs, and
- Synthesizing the data obtained in a useful manner for applications to reactors.

System code is a tool for assisting scaling analysis and solving problems, in fact they can reduce the cost of manpower by quickly doing evaluations that are done “by hand” in H2TS and FSA. In this regard, system codes can:

- Identify the dominant processes.
- Predict, more easily, how the relative importance of each process may change all along the transient.
- Give a more precise evaluation of the relative importance of each process, provided that they are qualified with V&V.
- Open the possibility of investigating phenomena that may be of second order importance, but might require some attention.
- Analyse the transient performance of a complex system and help to clarify phenomena due to interacting components and that are difficult to include in a PIRT.
- Check the adequacy of the ranking of processes by calculating a transient performed in several IETs having different scaling ratios, and by investigating whether extrapolating the scale to the reactor proves or disproves the ranking.

Study the effects of distortions in IETs, and may provide more reliable extrapolations to the case of a reactor, They may prove their capability in predicting the distortion using appropriate SETs that investigate the process of interest with and without the distortion. In this way, system codes can quantify the scale distortion due to some processes that could not be properly scaled in the IET design.

5.4. Triad methods

The system code can be used in the preliminary verification of the scaling laws, although it is inevitable to have scaling distortions due to compromises in design or construction. To study these distortions, (Ransom et al., 1998), devised a triad method, somewhat reflecting the Kv-scaled method, to relate the scaled experiment to the prototype system. The method is based on three separate, but related system-code models: (1) The prototype; (2) an ideally scaled model; and, (3) the actual scaled experiment. These three models are created to investigate the degree to which qualitative- and quantitative-similarities are maintained among the three systems in a particular process. The benefits of this triad of models are to ensure homology and to ensure:

- The response of the prototype and the ideally scaled model are comparable to assure their qualitative- and quantitative-similarity.
- The effect of any experimental non-typicality, such as physical configuration, heat loss, real valves’ opening times are evaluated via the scaled model and the prototype.

5.5. SYS TH code to accomplish up-scaling from IET

Codes that are validated on some scaled SETs and IETs may be able to predict the phenomena of interest at the reactor scale, provided that some conditions are satisfied. For most reactor issues, applying the SYS TH code often is the best way and the only way to accomplish up-scaling from IET to the reactor by compensating for the scale distortions of the IETs. However, there are requirements to demonstrate the up-scaling capabilities that ideally should include the following:

- The code has been validated on the transients of interest performed in scaled IETs that represent the main phenomena of the transient as identified in a PIRT, and also predict well, both qualitatively and quantitatively, the main phenomena.
- The code has been validated on the transients of interest performed in several scaled IETs at different scales (CTs), and the code predicts the effect of scaling or its absence.
- Within the process of developing the code, it has been proved that closure laws have a good up-scaling capability by the validation of all important phenomena at both local- or component-scale against several SETs at different scales, thus covering as much as possible of the prototypical thermal hydraulic range of interest.

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[14] Following the analysis of experimental data, the analysis optimizes the nodalization choices for the reduced-scale test facility, and finds unavoidable errors or differences between the measured and calculated variables. Other than accepting the ‘unavoidable’ errors (otherwise he has to refer to code developers for improving the codes), the analyst must address unavoidable scaling-related questions:

- o What procedure and/or what key criteria have to be followed to pass from the scaled facility’s nodalization to that of the PWR NPP?
- o Recall in advance that accuracy is the ‘known’ error that characterizes the results of simulations of IETF experiments which were found acceptable, and uncertainty is the ‘unknown’ error which characterizes the NPP’s (reference) calculation. Then the question is “Under what conditions the uncertainty can be derived from accuracy? or, Under what conditions the process of extrapolation of accuracy is feasible?”The answer to the former scaling-question already requires a variety of considerations and recommendations. A key recommendation is to keep unchanged, as far as possible, the length of the nodes. In this case, referring to the comparison between the test facility and PWR-NPP nodalization, the L/D ratio also is distorted: the L/D ratio appears in any scaling study, and plays an important role in its numerical solution.

- Since scaled IETs are necessarily characterized by some scale distortions, the code should be able to predict correctly the distorted phenomena. This may require validating the distorted (in IETs) phenomena in non-distorted SETs.
- The code is used in reactor simulation with the same numerical schemes and numerical options as were used for its validation on SETs and IETs.
- The code is used in reactor simulation with the same set of equations and closure relations and the same empirical constants as were used for validation analyses based on SETs and IETs.
- The code is used in reactor simulations with a nodalization and a time step as close as possible to those used for validations on SETs and IETs relative to the physical situations of interest, and following all recommendations on the best nodalization and time steps that were derived from validation studies, and that may be given in User's Guidelines.

5.6. SYS TH code, scaling and uncertainty quantification

The relationship of scaling and the uncertainty method is another important subject in the review presented in (Bestion et al., 2016). The purpose is to show how scaling is quantified as a source of uncertainty in the prediction of NPP transient. It is emphasized that the purpose of this description is not to recommend any specific approaches to meet the safety requirements set by any regulatory agencies, but to illustrate the role of scaling in them. To achieve this objective, three established procedures have been discussed in the report:

- **CSAU**: it is the pioneering procedure, including the uncertainty roadmap widely adopted by industry.
- **UMAE-CIAU**: it is a methodology as the prototype uncertainty-method based upon the propagation of output errors in the calculation.
- **GRS methodology**: methodology as the prototype uncertainty-method based upon the propagation of input errors in the parameters.

In the CSAU procedure, three uncertainty sources are quantified as follows: (a) The code and experiment accuracy, (b) the effect of scaling, and, (c) the reactor's input parameters and state. The first two are normally combined. A scaling study is performed based on such information as the PIRT results and on the code assessment manual. With this information, uncertainties and biases are determined based on the following two sources as:

1. Evaluation of scaling distortion from test facilities of different scales in the same important phenomenon.
2. Evaluation of scale-up capabilities of closure correlations used in the code.

All available scaled data used to develop the correlation or model in the code are compiled to determine the uncertainty or bias so to reach the 95 % confidence level. Additional biases are needed if the range of NPP conditions is not covered in the tests. After evaluation, all the uncertainties and biases are added together as the total uncertainty in the FOM.

The GRS method is a widely used uncertainty method based on probability calculus and statistics. The main advantage to using these tools is that the number of calculations is independent of the number of uncertain parameters to be considered. The necessary number of code calculations is given by the Wilks' formula, which depends only on the chosen tolerance limits, or the intervals of the uncertainty statements of the results. The method requires first identifying the important phenomena (PIRT), and then the potentially important contributors to the uncertainty of the code results. Uncertainty due to scale effects is one of them. The probability distributions of each uncertain parameter must be characterized. After qualification process is done for code, and the nodalization is established, the combination and propagation of uncertainties is executed. Finally, the scale-up effects in the method are evaluated by quantifying model uncertainties in facilities of different scales and uncertainties due to input.

In UMAE, experimental data is related to the corresponding calculated results, and an 'error-scaling' procedure is performed. Therein a database is constituted by time trends of the relevant thermal-hydraulic parameters measured in IETFs with different scales and their 'qualified' code calculations. As some conditions are met, e.g. a sufficient number of experiments in different scales and the error of prediction is not scale-dependent, then the error which shows a random character can be extrapolated to the NPP' conditions. A key scaling step of UMAE is the similarity between the NPP prediction and one set of IETF experimental data. This state is achieved through the Kv-scaled calculation.

5.7. Scaling roadmaps

Scaling roadmaps are discussed which focus on the design of experimental facilities, and on the nuclear reactor's safety assessment.

Address scaling issues in a safety-review process uses the available data, tools, methods, and approaches. A scaling roadmap is proposed to group these actions and information. Due to the different BEPU approaches, there are different ways to meet the safety requirements. Two scaling roadmaps are provided for the reader's reference.

A generic scaling roadmap is proposed, first based on CSAU with a scaling method chosen to design test facilities. These test facilities provide essential information for designing the plant, and for assessing the efficacy of safety systems. With the data, the expected thermal-hydraulic processes and phenomena of power plant can be simulated through calculations with the system code. The results obtained are evaluated by regulators. The fidelity of predictions is estimated by aggregating the contributions of uncertainties from the code models, nodalization, numerics, user options, and approximations in the power plant's representation.

Another scaling roadmap, proposed by (D'Auria and Galassi, 2010), is also described. In this approach, most elements in the Scaling Database and Knowledge Management constitute the major steps. Differences from the previous roadmap are that some qualitative- and quantitative-acceptability thresholds are embedded in the major steps. These safety requirements either are established by the regulator or first proposed by the licensee and accepted later by the regulator. Non-compliance of safety requirements leads to halting of the procedure and requesting for additional calculations, experiments, and/or R & D.

5.8. Role of CFD tools for multi-dimensional and multi-scale phenomena

3D CFD tools become valuable when multi-dimensional effects play an important role in issues such as single-phase turbulent mixing problems, including temperature mixing, mixing of chemical components in a multi-component mixture (boron in water, hydrogen in gas) and temperature (density) stratification. Two-phase CFD is much less mature than single-phase CFD, but significant progress has been made in the past decade. Two different 3-D simulation approaches can be used in reactor thermal hydraulics for design, safety and operation studies:

1. CFD in porous medium: This approach is dedicated to design, safety, and operation studies for reactor cores, heat-exchangers, and to the pressure vessel. Each mesh or control volume may contain both fluid and solid structures. The minimum spatial resolution is fixed by the hydraulic diameter, i.e. the sub-channel's size (scale in centimeters) in a sub-channel analysis.
2. CFD in open medium: The space and/or time resolution is smaller than in the previous approach. It includes turbulence modelling, using either the Reynolds-averaged Navier–Stokes (RANS) approach or large-eddy simulation (LES). It also is the only scale that, in

principle, can predict the fluid temperature-field, thermal shocks, or thermal fatigue.

6. Conclusions

The purpose of this state-of-the-art review is to survey the status of scaling technology from different perspectives. However, the technology continues to evolve, and new methods and approaches are being developed. Therefore, it is not appropriate to draw specific conclusions. A few broad conclusions are summarized as follows:

1. The information in scaling studies, namely the experimental database, is available for most reactor types but has not been fully exploited.
2. Scaling methods and models are available for specific targets or objectives. The application to a generic objective may suffer from the limitations of these methods.
3. Many non-dimensional scaling groups are derived in scaling methods and models: Knowing the hierarchy of these groups is important when applying scaling methods.
4. Distortions cannot be avoided in any reduced-scale experiment where transient two phase flow is involved. Even in the case of single-phase conditions phenomena, like stratification and entrance effect, may induce distortions in scaling, particularly in passive systems.
5. The impact of scaling distortions upon the performance predicted for any reference system, prototype, or reactor, remains difficult to quantify.
6. Data from scaled experiments cannot be directly extrapolated to the reactor in most cases dealing with two-phase flow.
7. Use of a suitable existing scaling method or development of a new method for a specific experiment is essential in minimizing scaling distortions.
8. The use of a well validated and verified SYS TH code can support any scaling analysis, including checking the scaling hierarchy, evaluating the impact of scale distortions, and correcting the distortions in reactor applications. For a safety determination of an NPP, the application of SYS TH codes can support, but not replace the formal scaling analysis, and is the best tool for up-scaling to the reactor transient of interest after the two following requirements are met. Conclusions 9 and 10 below are requirements that need to be met for a suitable code application.
9. Uncertainty from scaling should be accounted for in the overall uncertainty when the SYS TH code is used in predicting the thermal-hydraulic phenomena in NPP accident scenarios.
10. Accurate evaluations of scaling uncertainty in the validation results, model correlations, numerical schemes, and nodalizations are needed to meet the requirements of nuclear reactor safety.
11. Based on the key findings in each chapter of the (Bestion et al., 2016), the recommendations are summarized here without prioritization, for planning future activities:
12. To resolve a safety issue related to a postulated reactor accident, the most reliable approach should combine the use of PIRT analysis, scaling analysis, analysis of a wide SET and IET experimental database (including CTs), and the use of a system code in a BEPU approach. In some cases a multiscale simulation using CFD tools may provide better insights into local 3-D phenomena.

1. The capability of SYS TH codes to predict facilities of different scales is needed to evaluate the safety of LWR. The recommendation is to include the scalability requirements in SYS TH code validation. The CTs will also be important asset for validating scalability of the codes.
2. The database of existing SETF and IETF CCVM, should be extended to include possibly data related to advanced reactors (including those using passive safety systems), radial transfers due to diffusion, dispersion of momentum and energy, and cross flows in the core.
3. There is a need for well instrumented tests for validating CFD codes for the water cooled reactors in relation to mixing problems, such as boron dilution, MSLB, PTS, thermal fatigue, or mixing with buoyancy effects in some passive systems, to be considered in the general TH validation matrices. CFD codes must first be validated on single phase tests at different scales.
4. There is a need to identify a qualitative and quantitative framework (precision targets) to judge the quality of a scaling approach. This step is connected with the acceptance criterion for scaling distortions, and with the quantification of uncertainty due to scaling.
5. Full height scaling with suitable flow areas (and volume) are recommended for experimental simulation of passive system, wherein the important phenomena are the boiling and condensation processes, and buoyancy effect due to density change. Full height will provide an accurate characterization of phenomena such as natural circulation and related stability.
6. Specific scaling related training is worthwhile in a number of contexts. On both the industry and regulatory sides, good training and education of safety analysts should include, in addition to basic single phase and two-phase thermal-hydraulics, advanced topics of scaling techniques, identification of the dominant phenomena of major transients, code V & V and UQ requirements and code scalability requirements.
7. Revisiting systematically the scalability of system codes at the basic level of each closure law may be a good exercise for training new code users, so to improve the understanding of code scaling, uncertainty and to improve code documentation.

Multiscale analysis using several numerical tools at different scales will help in future to provide more accurate and reliable solutions to reactor issues. This approach requires first that the capabilities and limitations of 3-D two-phase flow calculation (CFD) methods for flows relevant to an NPP are well identified. The simulation capability of details of local phenomena aiming for a replica of the phenomena must be improved. Up-scaling methods for modelling should be developed to use small-scale simulations for improving the closure laws used in SYS TH codes. The CFD tools also should follow an appropriate process of code validation to prove their capability for extrapolation to the NPP-prototype phenomena.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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