Kv-scaling in thermal hydraulics: Background, applications and forthcoming uses

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ABSTRACT

Addressing the scaling issue refers to a rather complex process of demonstrating the applicability of activities devoted to predict the behaviour of actual nuclear power plants using the knowledge acquired in scaled-down test facilities. Such activities involve, among others, the evaluation of the capability of Best Estimate codes to scale-up processes from reduced scale test facilities to full scale Nuclear Power Plants (NPP) and the quantification of the effects of scale distortions. In this context, a K_v scaled calculation is a system-code simulation in which, defined test conditions of an Integral Test Facility (ITF) are scaled-up to a NPP nodalization to reproduce the same scenario. The practical use of such kind of calculation is to permit a comparison of the behaviour of the plant and the ITF nodalizations under the same conditions. The comparison between the NPP K_v-scaled results and those of the experiment post-test calculation will show unavoidable differences or distortions. Explaining such distortions is the key process in methods devoted to qualify plant nodalizations. The aim of this paper is to show the effectiveness of K_v-scaled calculations and to outline the forthcoming use of hybrid nodalizations and scale-up nodalizations. The paper includes a thorough literature review of these type of approaches as well as the perspectives of future use of the K_v scaling analysis. Such future uses include the feedback to experimentation. Despite the fact that the hybrid calculations presented here are related to existing ITFs and NPPs, feedback to experimentation intents to show the essentials of a future practice to be mainly implemented in modular ITFs.

1. Introduction

In 1988 the U.S.NRC approved a revision of the ECCS rule (USNRC, 1988)(10 CFR part 50) by which BEPU calculations could be used for licensing. Soon after, to address the complex application of BEPU methods, the USNRC presented the CSAU Methodology (USNRC, 1989) which established the requirements for quantifying code uncertainties in specific scenarios and NPPs. The CSAU guidelines provided a very valuable roadmap for developing specific uncertainty methodologies like the ones presented by Pérez-ferragut (2011), D'Auria and Giannotti (2008), Glaeser (2008) and IAEA (2008) but it also showed the relevance of scaling issues when using system codes for ECCS licensing.

Out of the many points that were tackled within CSAU, a few of them are crucial for the present paper as they are directly linked to scaling. First of all, the code needs to be validated with the use of both Separate Effect Tests (SET) and ITF experiments. Nowadays, we may also refer to Combined Effect Tests (CET) to refer to those facilities that represent several phenomena taking place in combination without being a complete (integral) mock-up of the reference reactor.

Steps 9 and 10 of CSAU deal directly on the estimation of the code accuracy and the determination of the effect of scale. Secondly, CSAU points out the necessity to define a procedure for the qualification of the nodalization of the full NPP. Step 8 deals with the construction of the NPP nodalization and CSAU already points out the possibility to compare NPP calculations with results at ITF facilities. This step directly refers to the transfer of knowledge from the small scale to the NPP scale and in a way tackles the problem of "user effect". The same nodalization and modelling strategies followed to simulate the experiments should be applied to the NPP nodalization. It may be worth to notice that another implication of Step 8 is that the accuracy at the low scale can be extrapolated to the NPP scale.

It is obvious that CSAU brought to its centre point both the computer codes and the use of data at integral test facilities. However, several questions were raised about the scalability of the experiments and the accuracy of the codes, and it is just at this point where the so-called "scaling issue" started.

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Nomenclature

Latin Letters

AM	Accident Management
APR	Advanced Pressurized Reactor
BE	Best Estimate
BEPU	Best Estimate Plus Uncertainty
BIC	Boundary and Initial Conditions
BWR	Boiling Water Reactor
CCFL	Counter Current Flow Limitation
CET	Combined Effect Test
CIAU	Code with capability of Internal Assessment of Uncertainty
CL	Cold Leg
CSNI	Committee on the Safety of Nuclear Installations
CT	Core exit Temperature
ECC	Emergency Core Cooling
ECCS	Emergency Core Cooling System
EPR	European Pressurized Reactor
FFTBM	Fast Fourier Transform Based Method
GRS	Global Research for Safety
HL	Hot Leg
HS	Heat Structure
IBLOCA	Intermediate Break LOCA
IET	Integral Effect Test
ITF	Integral Test Facility
JAEA	Japan Atomic Energy Agency
KNGR	Korean Next Generation Reactor
LBLOCA	Large Break LOss of Coolant Accident
LOBI	LWR Off-normal Behaviour Investigations
LOCA	LOss of Coolant Accident
LOFT	Loss-Of-Fluid Test
LOFW	Loss of Feed Water
LSTF	Large Scale Test Facility
LWR	Light Water Reactor
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
PCT	Peak Cladding Temperature
PIRT	Phenomena Identification and Ranking Table
PKL	Primarkreislauf (Primary Coolant Loop)
PUMA	Purdue University Multi-Dimensional Integral Test Assembly
PVST	Power to Volume Scaling Tool
PWR	Pressurized Water Reactor
PZR	Pressurizer
ROSA	Rig Of Safety Assessment
RPV	Reactor Pressure Vessel
SCUP	SCaling UP methodology
SET	Separate Effect Test
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SLOCA	Small Break LOss of Coolant Accident
SOAR	State Of the Art Report
TH	Thermal Hydraulic
UH	Upper Head
UMAE	Uncertainty Methodology based on Accuracy Extrapolation
UNIPI	UNIversita di PIsa
UP	Upper Plenum
UPC	Universitat Politècnica de Catalunya
USNRC	United States Nuclear Regulatory Commission
V&V	Verification and Validation
VVER	Water-Cooled Water-Moderated Power Reactor
WWER	Water-Cooled Water-Moderated Power Reactor

- The design of a test facility "cannot completely satisfy all the scaling requirements. Thus scaling distortions are unavoidable (…)".(Ishii et al., 1998).
- Also from D'Auria and Galassi (2010), "thermal-hydraulic phenomena are, in general, geometry scale dependent and thus no extrapolation of data from small scale experiments is acceptable".
- The state-of-the-art-report on scaling (OECD/NEA, 2017a) presents a full description of the problematic.

Despite the global consensus in this point, it is also true that the scientific community has demonstrated high advances in the understanding of scaling of complex phenomenology. As pointed out by D'Auria and Galassi (2010), one important milestone was achieved with the experimental reproduction of the Steam Generator Tube Rupture (SGTR) event at the Mihama NPP, a 2-loop PWR reactor located in Japan. "The event was closely reproduced at the LSTF facility in Japan. The volume scaling ratio or Kv factor is about 1 to 21. The experiment was configured with appropriate scaling criteria (Hirano and Watanabe, 1992) and successfully demonstrated qualitatively and quantitatively the similarity between the model and the prototype for a time duration of more than one hour after the transient started".

Further efforts have been done to address the question of scalability of results through the execution of counterpart exercises where the same scenario is configured in different ITFs. Counterpart exercises have been carried out between several facilities since the very beginning of the integral experimentation. Counterpart exercises can be classified in three categories:

1. Similar tests. Two or more independent facilities with different reference designs are used to replicate the same scenario that would take place in their respective reference plant. In this case, the experiments have been configured independently but nevertheless the data can be used to relate results and obtain common conclusions.
2. Counterpart experiment of a previous ITF experiment. In this case, starting from a previous experiment at the Facility A, the operating agent of the Facility B configures the boundary conditions to resemble as much as possible the Facility A experiment.
3. Counterpart exercise. Two or more operating agents of different facilities cooperate to configure the same scenario in their respective ITFs.

Such activities have been carried out since the early 80 s and in some occasions several facilities have been involved in one counterpart exercise like in the example provided before where a counterpart experiment (first category above) was performed on a SBLOCA event at the LOBI, SPES, BETHSY, LSTF and PSB facilities (Annunziato et al., 1992;

Let us first discuss on the scalability of the experimental results. In this subject, there is a common consensus amongst experts that the results obtained at a reduced scale cannot be directly extrapolated to the NPP level, mainly for two reasons:

D'Auria and Galassi, 2010). Another relevant counterpart exercise that falls in the third category above is the one performed between the LSTF and PKL facilities in 2010 (Freixa et al., 2015b), (Freixa et al., 2013) and (Schollenberger et al., 2017). For the second category, there has been a number of activities the most recent being a counterpart experiment at the ATLAS facility of a previous experiment at the LSTF facility (Al-Awad et al., 2021) and (Park et al., 2020).

Needless to say, that the counterpart testing requires significant efforts by the scientific community and tight cooperation between different organizations. The outcome of these efforts has represented a strong leap forward on the understanding of the scaling distortions.

All these activities have highlighted the similarity of the results at different scales pointing out that the events of a considered scenario evolve similarly. However, because of the points raised at the beginning of this section, we would like to endorse the statement from Professor D Auria (D'Auria and Galassi, 2010):

"The results discussed above should not authorize any extrapolation of data form any ITF to any NPP. However, they confirm the understanding by the scientific community that the scaling laws (and the design factors) are suitable for the transposition of phenomena between NPP and ITF".

If we now address the scalability of the code results and the accuracy of the codes, there is more controversy on whether the validation of computer codes at the lower scale may be sufficient to demonstrate the applicability of the codes at a higher scale. D'Auria and Galassi addressed this question in depth in their paper titled "scaling in nuclear reactor system thermal-hydraulics" (D'Auria and Galassi, 2010). Part of the scientific community considers the use of system codes inappropriate and proposes quantitative methodologies for NPP design and safety analysis, namely the FSA methodology (Catton et al., 2005), (Wulff et al., 2005) and (Zuber et al., 2005). They argue that the complexity of system codes veils the use of arbitrary parameters that are hidden in the codes to match the experimental data, thus system codes are inherently biased and cannot be applicable to other scales. Alternatively, D'Auria et al. (1995), developed the UMAE methodology for determining the uncertainty and similarity associated to the simulation of the ITF experiments in different nodalizations, and introduced a "roadmap to scaling" (D'Auria and Galassi, 2010) in order to follow up and progress on the guidelines that were set up in the CSAU methodology. Several studies, including the simulation of different counterpart exercises have shown the capabilities of system codes to reproduce the same phenomenology at very diverse scales (Martinez-Quiroga et al., 2014), (Freixa et al., 2015b), (Song et al., 2015) and (Choi et al., 2019). In addition, both the CSAU and the UMAE methodologies rely on the fact that the accuracy of the codes is scale independent. Citing directly from D'Auria and Galassi (2010):

"The demonstration that accuracy is not a scale dependent parameter constitutes a prerequisite for the applicability of the concerned methodologies. Further evidence of the same finding, e.g. accuracy independent upon scaling, is obtained by adopting the accuracy definition of the FFTBM (Fast Fourier Transform Based Method) (Ambrosini et al., 1990)".

This evidence can be found in the application of FFTBM to the counterpart experiment involving 5 different ITFs mentioned above (D'Auria et al., 1997).

Despite the controversy, the use of the best estimate system codes at NPP level for deterministic safety assessment and licensing are worldwide accepted as reported in IAEA and USNRC reports such as IAEA (2002, 2006), USNRC (1988)(10 CFR part 50), (USNRC, 1989).

2. K_v Scaling

2.1. The concept of K_v scaling

A K_v scaled calculation is a system code simulation in which defined ITF test conditions are applied to an NPP nodalization or to another ITF with a different scale in order to reproduce the same scenario. The approach is intended to transfer knowledge from one model to another by comparing the behaviour of the two scales under the same conditions. The final goal is to check the consistency of the two nodalizations and approaches and it can be eventually used to improve them. This concept is relevant in the framework of the NPP nodalization qualification and quality guarantee procedures and can be directly linked to the concepts introduced in Step 8 of the CSAU methodology.

In a K_v scaled calculation, the experimental conditions and safety actions of the ITF experiment are adjusted to match the boundary conditions of the scenario to be simulated in the other NPP or ITF. In this sense, only control systems and initial conditions are modified without changing the layout and the geometry of the nodalization. The most significant parameters are:

- Steady-state conditions
- Break size
- Break unit and containment
- Core power decay curve (if it is experimentally imposed)
- Pump coastdown curves (if they are experimentally imposed)
- Scram set point
- Isolation set points
- ECCS's set points
- ECCS injection curves (pressure versus mass flow curves)
- Blow down set points
- Specifications of the blow down valves (area, opening and closing ratios)
- Feed water controllers.
- PZR heater controllers (If this is the case)

The scaling-up adjustment is performed by following the scaling criterion and using scaling factors recalculated for the specific NPP nodalization. These are usually different from those used in the ITF design (related to the ITF reference plant). As explained in the previous subsection there are different scaling approaches that can be adopted for designing scaled-down systems, however, a greater number of ITF tests have been performed in facilities that have been designed using the Power to Volume scaling criterion, which encompasses time preserving scaling. Hence, the following scaling-up techniques will be related with the Power to Volume scaling. K_v scaled calculations start with the calculation of the scaling factor (K_v factor) which is commonly computed as the ratio between the primary liquid volume of the NPP and the ITF. This criterion should be revised given that several NPP components (PZR, SG plenums, pumps, ...) can differ significantly in volume with those of the ITF reference plant and is due to dissimilar design. Normally core power, core volume and total number of U-tubes (for PWR) are a good reference.

2.2. Goals and limitations K_v scaling

K_v scaling calculations have the potential to help in several steps in the simulation of accidental analysis and the licencing process. However, it is important to bear in mind the goals and limitations of such applications. The following is a list of goals and possible applications of K_v scaling approaches:

- Design effect analysis. K_v scaling calculations may be used to evaluate the effect of design configurations. This connects directly to the concept of the so-called "hybrid" nodalizations that will be addressed later.
- Scale effect analysis. K_v scaling calculations may be used to evaluate the effect of the scale. The best way to perform this evaluation is through the use of scaled-up nodalizations.
- Support in the design of ITFs. In connection with the previous points but in a more specific definition, K_v scaling calculations may provide valuable information in the design process of an

ITF which involves several decisions to cope with the economical constraints and the inevitable scaling distortions. K_v calculations between the prototype and the possible facility configurations can be used to justify the design. Some examples of such application are Song and Bae (1999), Ransom et al. (1998). Further details on these applications will be provided in the next section.

- Evaluation of ITF data. K_v scaled calculations may be used to perform parametric studies to broaden the understanding of phenomena observed in the ITF experiments.
- Qualification of NPP nodalizations. The nodalization of a system constitutes the connection between the code and the physical reality. The role of the nodalization can be synthetized with the following statement provided in (D'Auria et al. 2016): "If an excellent code is developed and properly qualified for an assigned application, and a poor nodalization is used, low-quality results are expected". K_v calculations can be used to check the applicability of the ITF test in the NPP nodalization for phenomena that has been validated in post-test analyses. K_v calculations become a reference for justifying as an expert judgment those discrepancies that appear in comparison with the results of the post-test analysis.
- Transfer of knowledge from IET to NPP nodalizations. System codes are very complex tools and require long term expertise, in fact, one may say that you will never fully master a system code. Every time an analyst performs a post-test calculation, he/she will learn some specific nodalization approach or use of special process that is needed in order to obtain a qualified nodalization for a particular phenomenon or system evolution. This knowledge can be transferred to the NPP nodalization and K_v calculations provide valuable support in this task.
- Support PIRT studies. K_v scaled calculations can check the adequacy of the ranking of processes by calculating the system response at different scales and in this way investigate whether the same ranking is consistent at the reactor scale.
- Eliminate or skip the issues of scaling distortions. As pointed out in the CSNI SOAR report (D'Auria et al. 2016), one of the important issues in scaling are the unavoidable distortions of some components. For instance, the hot leg inclined section connecting to the SG inlet plenum presents strong distortions that cannot be properly addressed by scaling techniques in the design process. Hybrid K_v calculations can be used to evaluate the impact of such a distortion. For doing so, the code must have been validated with different configurations at SET level.

Nonetheless, the applications of K_v scaling methods requires the understanding of the inherent limitations. The CSNI state of the art report (D'Auria et al. 2016), in its chapter 4, provides a detailed description of the limitations of applying scaling techniques, including those approaches that rely on K_v scaling. The most important aspects are outlined here:

- Scale dependent phenomena. Some phenomena strongly depend on the scale. In some occasions this is related to the small scale phenomena like the wall layer velocity, although for this case the scale of an ITF is already large enough so that the same behaviour is expected. In other occasions we are considering three dimensional effects where cross flows are strongly affected by the scale. For such situations in which the system code is not capable of accurately represent the dominant physics, K_v scaling approaches presented big limitations and should be applied with care. Some examples of this are:
  - Upper core plate
  - CCFL in hot legs
  - ECC bypass

- The inherent limitations of system codes apply to both low and large scale, however they may induce different impact depending on the scale. Hence, the analyst that apply K_v scaled calculations needs to bear in mind all the limitations of system codes. Some of the well-known system code limitations that are clearly described and introduced in OECD/NEA (2017a) are listed below:
  - Limits related to the use of flow-regime maps
  - Limitations may appear when an empirical or semi-empirical closure law is applied beyond the domain of the experimental boundaries.
  - Limits related to the dimensions of the model. Using a 0-D, 1-D or a porous 3-D approach involves the simplification of a complex 3-dimensional problem. There may be many situations for which the degree of approximation is reasonable, and does not affect the code's capability to solve safety issues. However, there are situations where the approach may not be sufficient to predict a specific phenomenon.
  - Limits related to space- and time-averaging. System codes were not developed to predict phenomena taking place at the small scale like the ones associated with turbulence and two-phase intermittency. The problem may appear where singular geometrical aspects induce increased alterations in the flow conditions. This inherently limits the scaling capabilities of the system codes, especially when addressing problems where these phenomena become dominant. The V&V process is crucial to tackle this problematic.
  - Non-modelled phenomena. From the inherent limitations of system codes, one can assume that they neglect many phenomena. If a non-modelled phenomenon plays a larger role at the reactor scale than in scaled ITFs, the scaling distortion will not be detected by K_v calculations. However, the important phenomena are detected in the PIRT step and the code developers should demonstrate the capabilities of the codes, therefore the importance of a correct and thorough PIRT.

Taking into account the goals and limitations it is recommended not to directly compare the K_v scaled calculations with the experimental data. The first step of any K_v calculation should start with the post-test calculation of the experiment in order to understand the ability and limitations of the code and nodalization to reproduce the phenomenology. By making the comparisons between code simulations we are limiting the analysis within the code capabilities. For instance, we cannot justify a distortion between the post-test and the K_v scaled calculation to the fact that the code is not able to simulate a particular phenomenon because this deficiency is expected in both cases.

3. Historical review of K_v scaling

The first attempt to use K_v scaled calculations was carried out at the Universita di Pisa (UNIPI) by Bovalini et al. (1992). The article dealt with NPP scaled calculations of a BWR SBLOCA scenario and it summarized the main results obtained by UNIPI with RELAP5mod2 simulations of the SBLOCA counterpart experiments carried out in BWR ITFs. The employed test facilities were PIPER-ONE, FIST and ROSA-III (LSTF). The transient was a small break in the recirculation line of a BWR-6 with the high-pressure injection systems unavailable. From the simulation of the ITFs, the test code accuracy is assessed and extrapolated to the NPP simulations.

The same year, UNIPI with the leadership of Prof. D'Auria performed several counterpart test calculations (of PIPER-I, FIST, ROSA-III, SPES, SEMISCALE, LOBI, PKL, BETHSY and LSTF facilities) and K_v scaled calculations (Caorso BWR NPP, Doel and Krsko PWR NPPs), D'Auria et al. (1992). Simulations were carried out for different test scenarios (BWR SBLOCA, PWR NC, SBLOCA and LOFW) and results at

different scales were compared. Two objectives were envisaged; (1) to attempt to scale-up the observed phenomena and (2) to evaluate the effect of the scale on the accuracy of the codes. Analyses of experimental data confirmed that direct scaling extrapolation from ITFs to NPPs is unrealistic and it was concluded that system codes are required to perform the scaling analyses.

In 1993 D'Auria et al. (1993) published a paper where K_v scaling calculations from ITFs to an NPP nodalization were performed. In particular the article dealt with the evaluation of the capabilities of RE-LAP5mod3 in simulating TH phenomena associated to LOFW scenario and related AM procedures. Two post-test analyses were performed for the LOBI BT-17 and SPES-1 SP-FW-02 tests and qualified. Related with the scaled calculations, a counterpart transient is also simulated in an NPP nodalization predicting the Nuclear Plant response under the same plant scenario.

It was at that time when Prof. Petelin started working intensely on K_v scaling, (Petelin et al., 1994; Petelin and Gunel, 1995; Petelin and Ravnikar, 1997; Petelin et al., 2007). The main objective of his work was again to analyse the scaling effects by the use of K_v techniques. A preliminary K_v scaled calculation of BETHSY 9.1B SBLOCA test (ISP-27) was performed over a Krsko NPP nodalization showing significant discrepancies in relevant TH phenomena as peak cladding temperature and system depressurization. Intermediate scaled-up nodalizations with the size of Krsko NPP were generated in order to analyse the effects of the scale: the first one preserving the Froude number, the second splitting the loops from two to three, and third one preserving the tensile stress of the structure's materials. This was probably the first attempt to up-scale the nodalization instead of the typical K_v scaling where the boundary conditions are scaled. This last nodalization showed a close agreement with the BETHSY 9.1B test results, justifying the impact of the walls and passive structures in the behaviour of an SBLOCA. This is probably the first time when hybrid nodalizations were born. As it will be shown in the following sections, hybrid models are the key in K_v scaling techniques.

In 1995, Prof. D'Auria at UNIPI presented a full application of the UMAE methodology over the SBLOCA Counterpart activity with 4 different facilities: BETHSY, LOBI, LSTF and SPES. The extrapolation of the post-test simulations accuracies (with RELAP5mod2) is applied to the PWR Krsko NPP nodalization. A K_v scaled calculation is completed as a step of the UMAE methodology for qualifying the Krsko nodalization in an "on transient level" of the Bonuccelli methodology, (Bonuccelli et al., 1993).

Another application of the Bonuccelli methodology was performed by Aprile et al. (1996) where a WWER-1000 Plant Nodalization (Kozlodoy-5 NPP) was qualified in different steps. The last step involved K_v scaling calculations. Specifically, the NPP nodalization was qualified by comparing an SBLOCA transient in a Western Type PWR (Krsko NPP) with a K_v scaled calculation.

K_v scaled calculations were applied in the design process of the Multidimensional Integral Tests Assembly (PUMA) at the Purdue University. Ransom et al. (1998) developed and applied the so-called Triad scaling-evaluation method devoted to investigate the scaling distortions between the designed facility and the prototype. The method is based on using three separate, but related nodalizations: (1) the prototype, (2) an ideal scaled facility and (3) the facility. The three models are used to evaluate qualitatively and quantitatively the degree of similarity for the relevant expected TH phenomena.

We can find also works related to K_v scaling in the Korean scientific community. The first one was the work by Song and Bae (1999) in which the results given by three different RELAP5mod3 nodalizations under counterpart SBLOCA conditions are compared. The input decks consisted of a whole model of the Korean next generation reactor (KNGR), and two scaled-down nodalizations representing two kinds of KNGR experimental test facilities, one following the power-to-volume scaling criterion, and another one that additionally reduced the heights and therefore, the timing (Ishii 3 level approach). Results show a close

agreement between the three inputs, validating the applied scaling-down criteria. This constituted an important step in the design of the ATLAS facility. Later in 2007, the similarity between APR-1400 and a scaled-down model with reduced heights was evaluated for a LBLOCA by Park et al. (2007). The APR-1400 NPP nodalization was scaled-down following the scaling criterion used in ATLAS ITF design with the MARS code and counterpart transients were compared. This constituted the second attempt to scale the nodalization, this time the NPP nodalization was downscaled. Results showed a very similar TH response (pressures, break mass flow rates, PCTs, void fractions distributions, ...) in both the NPP and the scaled-down nodalization. The authors concluded that similarity is expected in a hypothetical ATLAS LBLOCA test.

Prof. D'Auria continued his research on the "scaling strategy" with a publication on VVER simulators where the UNIPI team focused on the design of an SBLOCA PSB-VVER counterpart test and the evaluation of RELAP5 capabilities for simulating the involved phenomena at different scales (D'Auria et al., 2005). The comparison between experimental data of the different counterpart tests showed high similarity, reproducing the same TH phenomena with similar time trends. On the other hand, the results of the calculations obtained high accuracy following the FFTBM quantitative qualification criterion (Ambrosini et al., 1990). It demonstrated, together with the other qualified SBLOCA counterpart post-test simulations, the capabilities of RELAP5 for reproducing the same TH phenomena at different scales.

In 2006, Prof. Reventos from the Universitat Politecnica de Catalunya (UPC) presented his approach for the qualification of NPP nodalizations. The last step of the qualification is based on K_v-scaled calculations from relevant ITFs. The article presents a practical application of the methodology and K_v calculations from LOFT to Asco power plant model are shown (Reventos et al., 2007). In the following years, the research group led by Prof. Reventos presented a significant number of publications that placed K_v-calculations at the centre point. For instance, A K_v scaled calculation of LOBI BL-30 experiment was applied to Asco-2 NPP nodalization (Pla et al., 2007). Results showed a good agreement with experimental data with some discrepancies in the accumulator behaviour. Possible distortion sources were listed but not justified. In the same year, Jordi Freixa presented his PhD on SBLOCA with boron dilution events (Freixa, 2007) where K_v scaled simulations between the PKL Test F1.1 and Asco were performed. The K_v factor was calculated with the ratio of the total volume of the loops. BIC are scaled-up from PKL test, and pressures of Asco NPP are reduced to 45 bars in order to start the transients at identical pressures. The K_v scaled calculation yields similar results as the ones obtained in the PKL nodalization, however, for the plant nodalization, it was necessary to renodalize the loops with finer meshing in order to avoid numerical diffusion and to simulate properly the slug formation and evolution. This work is a very clear example that shows how the lessons learned in the simulation of an specific phenomenon in an ITF group of experiments were then transferred to the NPP nodalization in order to simulate the same scenario. The work was later published in Nuclear engineering and design (Freixa et al., 2009). UPC continued the research line on K_v scaling calculations (Martinez-Quiroga et al., 2008) and developed its own methodology in the framework of the PhD thesis of , Martinez-Quiroga (2014).

Continuing the literature review on K_v scaled calculations in chronological order, A. Petruzzi, in his PhD (Petruzzi, 2008) included a RELAP5 K_v scaled calculation of the LOFT L2-5 LBLOCA Test. Boundary and initial conditions of the test were scaled-up to ZION NPP nodalization with the ratio between the primary side coolant volumes. Results demonstrated the capabilities of Zion nodalization to reproduce the main phenomena in a LBLOCA event. No new phenomena were brought in the K_v scaled calculation and discrepancies were attributed to the differences in the hardware configuration. According to the author, with the K_v scaled calculation, the nodalization was "on transient" qualified following the Bonuccelli methodology. The discrepancy sources were listed in the document but not justified.

Another application of a K_v scaled calculation was presented by Kristof et al. (2009) where the CIAU methodology was applied including a K_v scaled calculation of the PH4-SLB test to the VVER-440/213 Mochovce plant. The selected scenario was a surge line break accident. All major phenomena of the experiment were successfully simulated with some differences in the timing of events as a result of discrepancies in the depressurization rate during ECCS injection. Authors attributed the discrepancies with the differences in the design of some components (safety injection pumps) and BIC. However, no sensitivity analyses or hybrid simulations were performed for justifying those discrepancies.

One of the first applications of hybrid nodalizations was applied by Freixa and Manera (2011) in their work to verify a plant nodalization of the Olkiluoto III EPR reactor. A K_v scaled calculation of the OECD/NEA ROSA Test 6.1 was applied to qualify the NPP model for SBLOCA scenarios. The test reproduced a SBLOCA at the UH of the RPV the post-test of which had been previously validated (Freixa and Manera, 2011). Two different K_v factors were applied to the BICs of the primary and secondary systems because of the differences in the geometries of the EPR and Westinghouse SGs. TRACE calculations showed very similar results in comparison with experimental data. The only significant discrepancy was observed in the faster depressurization associated to the core uncovery. Possible sources of distortion were listed and analysed with sensitivity analyses (hybrid models) of local scaling factors (break, passive HS, ...). Discrepancies were partially justified by the different hardware configuration of the RPVs. This work was revisited in 2019 with additional "hybrid" calculations (Reventos et al., 2019).

Hybrid calculations were also presented by Yu et al. (2013) in their work titled Systematic analysis of a station blackout scenario for APR1400 with test facility ATLAS and MARS code from scaling viewpoint. Yu et al. (2013) presented a post-test calculation of the ATLAS Test SBO-01 which was carefully validated prior to the execution of K_v scaling calculations to APR-1400. One hybrid calculation was used by removing heat losses in the ATLAS model. It was concluded that the effect of heat losses was very high and without heat losses the similarity between APR-1400 and ATLAS is observed. However, the authors did not perform further hybrid calculations to fully explain the scaling distortions.

The team at UPC carried out several research activities on K_v scaling and took the K_v scaling applications to a new level with the introduction, or better stated, consolidation of the two concepts: the use of hybrid models and the scaling of nodalizations. We have seen that only very few sensitivities had been used to justify/explain the scaling distortions, mainly (Yu et al., 2013; Yun et al., 2010; Freixa and Manera, 2011). In 2012, the term "hybrid nodalization" was introduced by Lucas (2014) in his master thesis. Two K_v scaled calculations of LOBI BL-30 and B-44 were performed over the Asco-2 NPP input deck. For both experiments, it was demonstrated that discrepancies between the ITF and K_v scaled calculations could be justified by the different environmental heat losses of both facilities. Hence revealing the potentials of "Scaled-up calculations" and intermediate simulations for qualifying and improving NPP nodalizations. The use of hybrid models was further consolidated within the PhD thesis of, Martinez-Quiroga (2014) and continuing works carried out at UPC, (Freixa et al., 2016; Martinez-Quiroga et al., 2014; Reventos et al., 2019). However, perhaps the most remarkable contribution is the implementation of a tool that allows the scaling of nodalizations. With that, the focus was shifted from the scaling of results to the scaling of models. This step was necessary to reduce the number of open questions or distortions. These two concepts constituted the core of the UPC scaling methodology (SCUP) (Martinez-Quiroga and Reventos, 2014) for qualifying NPP models which basically uses the PVST tool (Martinez-Quiroga et al., 2018) to scale up validated post-test simulations to the desired scale. The tool was validated (Martinez-Quiroga et al., 2014) and applied by Freixa et al. (2016) as described in the next section.

In recent years Polytechnical University of Valencia has also contributed with K_v calculations. Querol et al. (2015) followed the UPC methodology and the work presented (Martinez-Quiroga, 2014) and practised a scaling up of the ITF nodalization, in this case the TRACE code was used and the facility was LSTF. However, no sensitivities (hybrids) were performed and hence no justification of the observed distortions could be provided. Later, Munoz-Cobo et al. (2018) presented a top down scaling method that combined K_v scaled calculations with the H2TS theory. They concluded that there were no scaling distortions in the major variables that could lead to significant differences in the results obtained by both simulations. Finally, Lorduy-Alós et al. (2020) followed the same procedure to demonstrate the scalability of the counterpart exercise between the ATLAS and LSTF facilities. In this work, it was stated that there was high similarity in all the phases of the IBLOCA scenario, however there was no mention of the ECC bypass phenomenon taking place in and IBLOCA scenario. ECC bypass was very intense in ATLAS and not present in LSTF, again, no sensitivities or "hybrid" simulations were performed to address the scaling distortions.

Finally an interesting contribution was recently published by Petruzzi and Giannotti (2020) were K_v scaled calculations were used to support the adequacy of the Atucha-II power plant nodalization. The interesting process of selection of the facility is presented and within a list of facilities and tests, the LOBI A1.83 was chosen as the most appropriate. The results of Atucha-II are directly compared to the experimental data instead of comparing them with a qualified post-test calculation making it impossible to know whether the distortions are due to scaling or the inherent limitations of the code. A few sensitivities to explain the scaling distortions were performed with the Atucha-II model however the distortions could not be fully explained but were partially justified by the use of expert judgement.

4. State of the art on K_v scaling

4.1. NPP nodalization qualification

The use of the "hybrid nodalizations" and "scaled-up calculations" within the UPC-ANT SCUP methodology has allowed to establish a guideline for justifying the discrepancies that can appear between ITF and the NPP (K_v-scaled) calculations with equivalent boundary conditions. In this sense, Freixa et al. (2016) applied SCUP to qualify the full scale nodalization of Asco NPP devoted to reproduce safety phenomena related to the effectiveness of Core Exit Temperature (CT) as an Accident Management (AM) indicator (OECD/NEA, 2010). In order to apply the methodology, the OECD/NEA ROSA-2 Test 3 (OECD/NEA, 2017b), a SBLOCA in the hot leg, was selected as a starting point. This experiment was conducted at the LSTF and was focused on the assessment of the effectiveness of AM actions triggered by CT measurements.

In this summary, we focus on a single time trend, the primary pressure, to illustrate the whole process (Fig. 1). The illustration compares the simulation of the boundary conditions of the ROSA-2 Test 3 with 4 different RELAP5 nodalizations:

- RELAP5 post-test: simulation of Test 3 with UPC RELAP5 LSTF nodalization.
- RELAP5 ideal upscaling: simulation of the upscaled boundary conditions of Test 3 with an upscaled input deck of UPC RELAP5 LSTF nodalization. The whole LSTF nodalization is upscaled with PVST software to the scale of the Asco NPP. This means, the nodalization is maintained but areas and volumes are upscaled following the power to volume criteria.
- RELAP5 Asco K_v scaling: simulation of the boundary conditions of Test 3 with the UPC Asco nodalization. Firstly, the boundary conditions of Test 3 are adapted to the scale of the Asco NPP by following the rationale described in Section 2.1. Afterwards, these conditions are implemented in the nodalization of Asco NPP, the geometry and mesh distribution of the model remains intact.
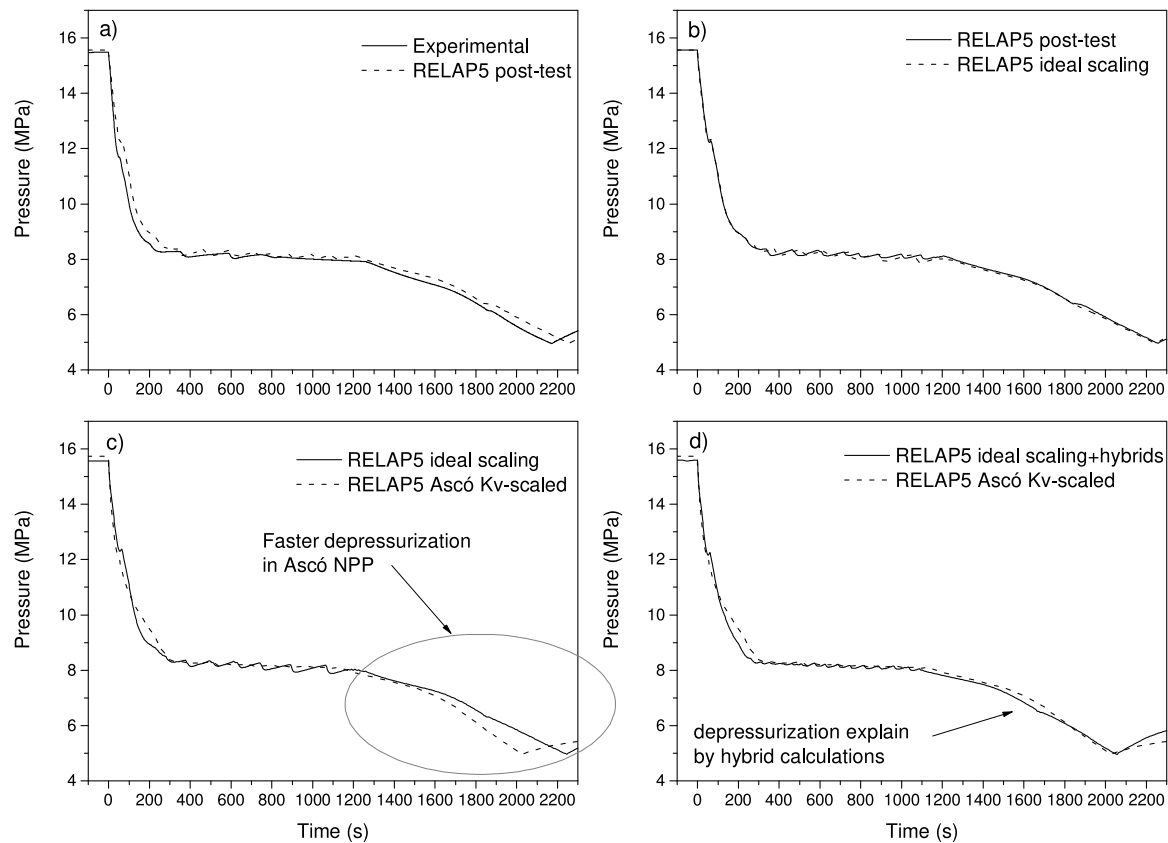
Fig. 1. The four subplots in this figure show the comparison of different hybrid models at the same scale. (a) Experimental data compared to the RELAP5 post test. (b) RELAP5 LSTF post-test compared with the ideal upscaled model (to the scale of Asco NPP). (c) RELAP5 LSTF ideal scaling compared to the RELAP5 Asco NPP model. (d) RELAP5 LSTF ideal scaling + hybrid configuration compared to the RELAP5 Asco NPP model.

• RELAP5 ideal scaling + hybrids: The RELAP5 ideal upscaling model which is the LSTF Test 3 nodalization upscaled to the Ascó NPP scale, is complemented with hybrid models. Hybrid models are implemented to identify the sources of distortion with the Ascó NPP nodalization. In particular hot legs, RPV bypasses and SG U-tubes and plenums are modified to have the same rationale and design than in Asco NPP nodalization.

Subplot (a) of Fig. 1 shows the comparison between the experiment and the RELAP5 post-test simulation. The results show the consistency between the experimental data and the simulation. The validation of the code capabilities for selected phenomenon is a very important first step in the SCUP methodology. In this sense, a comprehensive post-test analysis of the experiment was presented in an earlier work (Freixa et al., 2015b).

The second step is the application of the PVST tool to upscale the nodalization of the facility to the scale of the Asco NPP (idealized pure scaling). The pure scaling already considers both the preservation of heat losses and the Froude number in the hot legs due to the lessons learned in the work by Martinez-Quiroga and Reventos (2014). The main goal of this step is to evaluate the distortions induced purely by the scale. In that particular case, it was seen that the pure scaling implicated minimal distortions (see subplot b) in Fig. 1.

The paper explained also the improvements performed in RELAP5 Asco NPP input deck related to lessons learned in nodalizing tasks carried out in LSTF post-test. Such improvements had to do with: multichannel approach, detailed definition of the upper core plate heat structure, simulation of thermocouple heat structures and the definition of hydraulic diameter in core junctions. The aforementioned learned lessons are described in detail by Freixa et al. (2015a). Under these conditions a first approach of K_v scaled calculation was performed and

the results were compared with those of LSTF ideal upscaled calculation (see subplot c) in Fig. 1. Some distortions were identified, in particular, the Asco K_v scaled showed a faster decrease in primary pressure and as a consequence core heat up came also before and so did the injection from the accumulators.

According to SCUP methodology, the explanation of the identified distortions should be carried out using hybrid calculations. As established in the methodology hybrid nodalizations are prepared adapting the up-scaled ITF nodalization to the configuration of the real NPP in the affected part by each considered phenomenon. Hot leg Froude number, RPV bypasses and SG primary volume are most relevant candidates to explain distortions. The subplot (d) in Fig. 1 shows the adequacy of selecting them.

Once the distortions were explained, the paper concluded that the Asco nodalization was valid to analyse those equivalent scenarios that include some of (or all) the TH phenomena studied within the qualification process. The final step was then to use the Asco input deck with the actual boundary conditions expected in the power plant with the same break size and location but with the core power and Emergency Core Cooling (ECC) dimensioning of the Asco NPP. No new TH phenomena aroused during the sensitivity analysis, should this happen, then the qualification process should be repeated by selecting new integral test experiments that include such new phenomena. In this sense, in Freixa et al. (2016) the SCUP methodology was applied for RELAP5 code, Asco NPP nodalization and SBLOCA scenario. For different code, nodalization and/or scenario the whole process should be repeated.

4.2. The impact of scale on the uncertainties

Another application of the up-scaling approach was presented by Casamor et al. (2020) that focused on the evaluation of the scaling
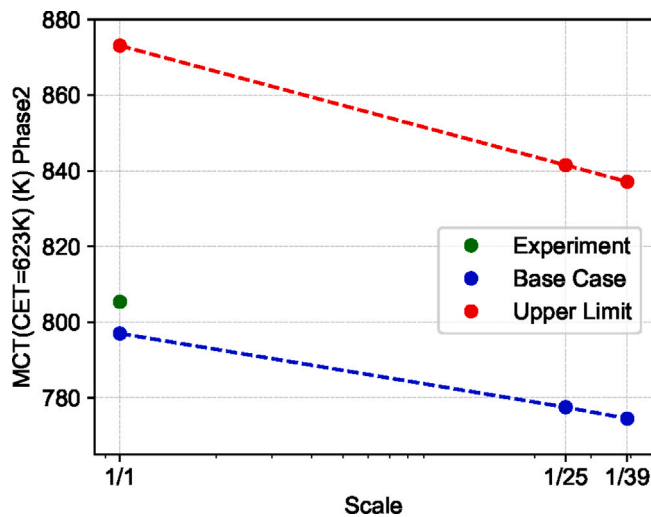
Fig. 2. Base case result and upper uncertainty limit for the maximum cladding temperature at the time the CT reached 623 K. The result is shown for 3 different scales (1, 25 and 39). The figure is courtesy of Casamor et al. (2020).

of uncertainties for BEPU methodologies. The work performed was based again on Test 3 of the OECD/NEA ROSA-2 project from the LSTF facility. The UPC team has extensively worked on this test which provides the necessary confidence on the scaling capacities of the SCUP methodology and on the post-test ability to simulate the important phenomenology. In this study, the RELAP5 nodalization was up-scaled to the Asco NPP reactor size (39/1), and to an intermediate scale (25/1) using the PVST tool. The comparison of the three calculations at different scales provided equivalent results when known scaling distortions like heat losses were omitted. The three calculations have been complemented by an uncertainty analysis. The comparison of the propagation of the uncertainties at different scales provides an insight on the scalability of the uncertainties and on the validation process of BEPU methodologies. Four figures of merit (FOM) related to the PCT and core exit temperatures were specified and the upper limits were calculated for each scale following the BEPU GRS methodology (Glaeser, 2008). It is important to firstly point out that the BEPU analysis confirmed that the upper limit of the 1/1 scale covered the experimental value with a margin. Secondly, the article focused on the influence of the scale on the upper limits of the important FOM. Three out of the four parameters displayed a correlation between the scale and both the base case and the upper limit. Fig. 2 shows the result for the maximum cladding temperature at the time the core exit temperature reached 623 K which triggered accident management procedures.

Finally, the Pearson correlation (see Fig. 3) between the input and output parameters allowed to compare the impact of each parameters depending on the scale. In this analysis, it was confirmed that the input parameters have equal or equivalent impact on the figures of merit.

Therefore, two conclusions are derived from this work. Firstly, the impact of each input parameters is scale independent. And secondly, the figures of merit might be subject to scaling distortions. This reinforces the general opinion that ITF data cannot be directly extrapolated to the NPP size and computer codes are essential to cover this bridge.

5. Forthcoming roles of K_v scaled calculations

5.1. Support to test design using hybrid calculation results

The current situation of integral test facilities (ITFs) in the world has to be considered in order to estimate this mentioned usefulness.

For this particular, one must distinguish between the existing ones and future built.

Regarding the existing ITFs, today a few of them are still operating, and important activities are carried out to share efforts and results obtained in the existing facilities. OECD-NEA is taking care of coordination tasks devoted to support experimental series to be launched in current ITFs like PKL in Germany, LSTF in Japan, ATLAS in Korea or ACME in China. Among such supporting tasks, analytical activities are especially significant. Experiments are nowadays designed after considering different calculations performed by working groups of different countries, discussing their results and reaching an agreement on the scenario and boundary conditions. Considered calculations are related to both ITFs and NPPs and they obviously involve scaling concerns. From now on, and in the context of existing ITFs the concept of reference plant almost belongs to the past. Today experimental results have to be extrapolated to different kinds of plant that could be similar, but not identical, to the original reference plant justifying long ago the first erection of the facility. The analytical support community is taking care of this particular and in many situations is highly motivated by the fact that new facilities are expensive.

The Framatome team at the PKL facility has already implemented such type of modifications to adapt the facility from a Siemens KWU design to a Westinghouse design. In particular, changes were performed in the upper core plate and the connection to the Upper Head.

In the past, the LSTF went under similar configuration modifications in the ROSA-III configuration to adapt the facility to a BWR design (Suzuki et al., 1986) and recently, LSTF has been adapted to represent the AP-600 design (Yonomoto et al., 2017).

Considering the construction of future test facilities, few proposals exist by now. The one presented by Hyvärinen et al. (2015) is particularly interesting since it shares many of the principles referred in this section. Such facility is, by now, being planned in Finland and it is intended to cope with experiments valid for different kinds of reactor, among them: VVER-440, ABWR, EPR and AES-2006 or even SMRs.

In a non-negligible number of situations, hybrid model results could suggest minor modifications for existing facilities or practical use of modularity for future ones. Implementing physically such modification in the ITF and re-launching again the same test in the reformed facility, could help understanding involved phenomena that could be crucial for the scenario. We are talking about versatile, easy to implement and easy to remove modifications. Obviously, the practicability of the whole thing depends on the feasibility of the modification in terms of cost and operation. Another important question to be considered is related to the expected results of the implementation. Expensive modifications will only be reasonably feasible in case they explain the analysed distortion.

To illustrate how the use of hybrid calculations could feedback experimentation, let us consider the scenarios introduced in the previous section related to Asco NPP hybrid calculations (Freixa et al., 2016). Such considerations, based on the knowledge acquired and the availability of data of the involved ITF and NPPs, could help determining the usefulness of such results in testing strategies.

In particular, the combined effect of three causes explained the distortions observed in the depressurization rate (subplot d) in Fig. 1. Such sources of distortion were:

- Froude number in hot legs
- RPV bypass paths configuration
- Reducing volume of primary loops

The corresponding facility modifications are important but look feasible. That related to Froude number would imply to connect a new hot leg with a new value of $\sqrt{L/D}$. That of RPV bypasses would need changes in RPV but there is some experience of similar changes in the past. Finally, that of reducing volume of primary loops is equivalent to plug some SG tubes. The implementation of such modifications would need further analysis and obviously a close cooperation with the Operating Agent of the facility.
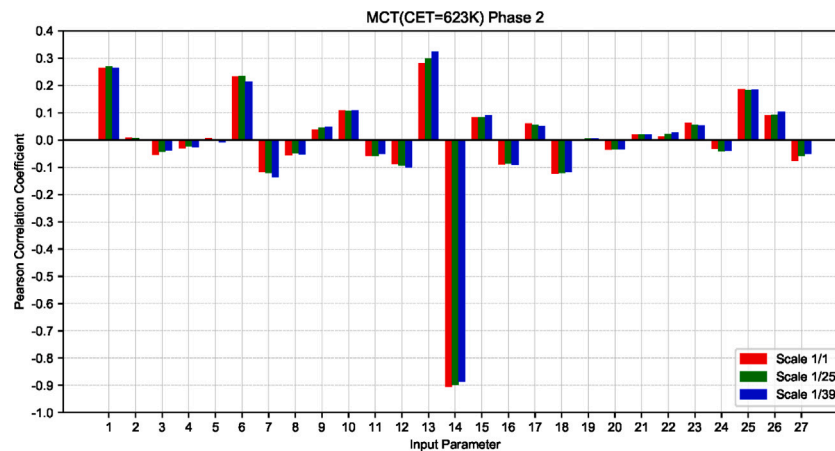
Fig. 3. Pearson correlation coefficient for the different input parameters. Each colour is the influence of the parameter for a scale to the figure of merit.

The fact of referring to the combined effect of three sources of distortion needs a comment. It is easy to show and demonstrate the source of a distortion when this is coming from a single parameter. However, these simple cases are not frequent and most of the times one has to deal with two or three (like now) causes at a time. SCUP methodology (Martinez-Quiroga and Reventos, 2014) establishes how calculations have to be combined in order to avoid compensating errors.

If modifications are feasible and a new test is launched, new experimental data help substantially extrapolation to NPP scale. All in all, K_v scaling calculations can provide valuable support in the qualification process of NPP nodalizations leading to the identification of inadequacies and errors made by the analyst in the model.

5.2. The impact of scale in the figures of merit

The current capacity of computer power along with the possibility to easily scale up models at different sizes opens the opportunity to explore the effects of scaling distortions with a broad scope.

We have seen in the previous section the study from Casamor et al. (2020) that focused on the evaluation of the scaling of uncertainties for BEPU methodologies. One of the conclusions of this work was that, despite there is no significant influence of scale to the correlation of uncertain input parameters with the figures of merit, some figures of merit display a scale dependency.

The results of this work are relevant, however, only three datapoints were used in the analysis which is not significant enough to extract any concluding remark. The logical future step, therefore, is to employ the PVST tool to generate more data points at different scales and evaluate the impact of scale to the safety relevant figures of merit. Additionally, the different scaling options available such as the preservation of heat losses or the Froude number in different sections of the model can be used in the analysis.

5.3. Perfecting nuclear power plant model qualification

The qualification of Nuclear Power Plant nodalizations by means of scale considerations is central goal of SCUP methodology. Among the concepts and techniques introduced K_v-scaled calculations and particularly the conceptions of "hybrid nodalizations" and "scaled-up nodalizations" have been shown as especially significant.

When a distortion between an idealized pure scaled ITF simulation and the corresponding NPP one is fully explained by one or several hybrid calculations, it is considered that NPP nodalization is qualified for its use in the scenarios including the phenomena identified in the previous steps of the method. Thus, SCUP considers hybrid calculations good enough to explain distortions and relies on modelling techniques

to complete the needed prediction at NPP scale. In summary, one empirical reference wrapped by several hybrid calculations contributes significantly to this qualification aspect.

Once hybrid calculations are used to feedback experimentation, in the way it is suggested in the previous section, new empirical evidence can be produced on equivalent scenarios and this will result on perfecting the level of qualification of the final NPP prediction.

6. Conclusions

The paper has shown important aspects of the usefulness of K_v-scaled calculations along with some ideas on the forthcoming uses of hybrid nodalizations. The article started describing the essentials of the K_v scaling also introducing a detailed compilation and description of the most relevant applications performed in the past.

The main part of this study is devoted to "hybrid" and "scaled-up" calculations, the way they are currently used to qualify NPP nodalizations, and the perspectives of future uses in the framework of the developed SCUP methodology.

The article manages to show how the correct choice of hybrid calculations allows advancing in the knowledge of both the behaviours observed empirically and those simulated using models. The use of these techniques combined with BEPU analyses also supports the statements that (a) input parameters are scale independent; and (b) output parameters can be scale dependent and distortions need to be justified.

The use of K_v scaling for justifying design modifications of experimental facilities are also presented. It is a different and innovative use of hybrid calculations that will for sure have future applications in feedback to experimentation. Examples on such use for existing facilities are introduced with interesting results.

CRediT authorship contribution statement

Victor Martinez-Quiroga: Literature compilation and review, System codes simulations, Writing – review & editing. **Jordi Freixa:** Literature compilation and review, System codes simulations, Writing – review & editing. **Francesc Reventos:** Writing – review & editing.

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

No data was used for the research described in the article.

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