Prioritization of nuclear thermal-hydraulics researches

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ABSTRACT

The difficulty in predicting locally and globally the transient evolution of two-phase or multiphase flows in complex systems is well recognized in nuclear thermal-hydraulics. Large efforts involving the expenditure of huge resources during the last three decades in previous century brought to the creation of giant databases (e.g. including experimental data and results of computer code calculations) and to the perception that the safety of nuclear reactors is guaranteed notwithstanding residual areas of unawareness. Nowadays, thousands of scientists continued to generate progress in the area having available much lower resources: more and more dead-ends for established research outcomes are experienced; the progress in knowledge resembles the slow expansion of a swamp rather than the fast moving of a river. In this paper a procedure is proposed to identify directions for research in nuclear thermal-hydraulics which are consistent with the needs in nuclear reactor safety. Two pillars for the procedure are constituted by the characterization of phenomena and by the application of qualified computational tools. Decision makers and scientists may prioritize research in areas where large impacts upon design and safety issues are identified in advance.

1. Introduction

Researches in nuclear thermal-hydraulics started with the design of water cooled reactors; these received a strong impulse from safety needs towards the end of 60's in previous century. Thus, about seven decades of continuous development brought to the current situation where gigantic amount of experimental data are gathered and (partly) stored in electronic format and myriads of models and theories are embedded into numerical codes which are run by more and more powerful computers.

The electricity production by the nuclear source nowadays achieved a level of exploitation far below what envisaged in the 70s, namely before the Three Mile Island event (1979). In a number of formerly so-called 'industrialized' Countries the interest towards nuclear energy is declining; however strong efforts are in progress in different Countries (i.e. 'new' or with renewed-continued interest for the nuclear fission technology), namely in Russia and Far-East and South of Asia, fostering the industrial application of the technology.

All of this can be further depicted by the following statements as far as nuclear thermal-hydraulics is concerned:

- Large research investments are now declining in formerly industrialized Countries with expertise loss in relation to several topics: this also implies lack of accepted declarations about what is achieved and what needs to be developed (despite the efforts by national and international institutions).
- The wide variety of research directions may reveal unmanageable or never ending by worldwide available funding: this includes

duplication of efforts, pursuing closed ends roads (i.e. no practical applicability), lack of comprehensiveness and quality in outcomes.

- Fundamental issues like turbulence and bubbles motions (many others can be mentioned) are not solved with the satisfaction of the international community.
- Research is needed and is in progress even for training of scientists and technologists in Countries where perspectives for nuclear technology exist.

The objective for the paper is to present a method for prioritizing research in nuclear thermal-hydraulics. The prioritization is based upon two key elements:

a) The list of phenomena relevant for the transient operation of water cooled reactors proposed by the Organization of Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and by the International Atomic Energy Agency (IAEA). The related documents have been merged and re-evaluated as discussed in recently published papers.

b) The virtual-ideal test facility, so called μλ-I^{3}TF (where μ = Modular; λ = Large, Advanced, Multi Basis & Discipline Apparatus; I^{3}TF = Ideal 3-time, Test Facility). Among the other things, reasons why the concerned facility is '3-time Ideal' are discussed in the paper.

System thermal-hydraulics (SYS TH) and Computation Fluid-Dynamics (CFD) codes [both of these may be seen as the repository for the knowledge in thermal-hydraulics], are developed and have been validated (as far as possible) based on the list of phenomena (this is mainly true in the case of YS TH code) and are applied to predict the transient performance of the μλ-I^{3}TF. The virtual facility design takes benefit for the recently issues OECD/NEA Scaling report, OECD/NEA/CSNI, 2017, and the related (calculated) scenarios are consistent with the existing experimental database and the Design Basis Accident (DBA) envelope for Nuclear Power Plants (NPP).

The ideas at the basis of the method are the cross link between phenomena and accident scenarios in Water Cooled Nuclear Reactors (WCNR) and the impact of variables characterizing the phenomena (or the key parameters) upon the integrity of safety barriers and the corresponding safety margins.

2. Drawbacks and motivation for prioritization

The rules of a global market and the related trends for development are part of the global market. There are attempts of individuals or even of Countries to control the directions: however, the impact of those actions never implies the full control. In the same way a few researchers may not have the ambition to impose directions for the development in nuclear thermal-hydraulics. This should prevent any attempt to prioritize research.

However the present paper was conceived after several years of engagement in research and,

a) having seen many research projects failed at least in displacing the boundaries of knowledge,

b) considering the situation in nuclear thermal-hydraulics when research is [nearly, relative to previous decades] stagnant in Countries where the technology was developed and new Countries appear interested in improving the understanding.

2.1. Insights into current state of art

Thermal-hydraulics, in the sense of study of steam-liquid flows constituted a discipline of interest well before the discovery of fission as energy source. Although nuclear thermal-hydraulics was established at the time of the design of water cooled reactors, D'Auria, 2012, and

Bestion, 2017, its development received a strong impulse following the issue of the Interim Acceptance Criteria (IAC) by United States Atomic Energy Commission (AEC), USAEC, 1971, and the contemporary availability of computers suitable to provide solution to numerical models. The IAC namely triggered the construction of (relatively) large experimental facilities expected to simulate the performance of typically much larger Water Cooled Nuclear Reactors (WCNR).

The impetus in research continued for two or three decades. Paradoxically, at a time when most of the issues raised for the design of Emergency Core Cooling Systems (ECCS) and for the safety demonstration of WCNR were solved, the industrial interest toward nuclear technology declined. Rather, according to Nam Dinh et al., 2013, "*nuclear thermal-hydraulics as a field has become sluggish, making < recently > only incremental, if not marginal, advancements in models and methods …, despite the critical challenges … facing the nuclear power industry in the 21st century*". Furthermore, solution of safety issues, or addressing in a satisfactory way the safety issues, does not imply full knowledge of transient thermal-hydraulics. Providing a comprehensive vision of the current status in nuclear thermal-hydraulics is beyond the boundaries for the present paper. Flash insights into selected troublesome topics are given below:

- Turbulence. Turbulence is the spirit of any moving fluid, however no principle based model is available for prediction.
- Bubble motion. Infinite number of bubbles having different shape and sizes characterize boiling and condensing two-phase flow system: theoretical approaches fail in predicting the time evolution of two-three bubbles in a boiling-condensing environment.
- Balance equations. The mass, momentum and energy equations were established in mechanics of continuum: otherwise, 'continuously' time changing discontinuities characterize two-phase flows.
- Averaging. Time and space averaging is needed for the solution of balance equations; approximations are part of the numerical process: unknown errors generated from the continuum mechanics hypotheses combine with unknown errors coming from numerics.
- Heat transfer and pressure drops. Convection heat transfer coefficient and two-phase flow multiplier are essential for the prediction of accident scenarios. In the latter case the condition 'at geometric discontinuity' applies, too. In all cases, computational approaches are based upon empirical formulations which necessarily do not account for all conditions of interest.
- Radiation heat transfer. The overall heat transfer in film boiling regime at high temperatures expected in accident analyses combines depends upon radiation mechanism: a foggy situation characterizes current predictions.

Two contradictory statements may be used to summarize the current status of nuclear thermal-hydraulics: a sound understanding of < global > phenomena coming from the huge database of experiments and code application guarantees the quality of design and the existence of appropriate safety margins for WCNR; a foggy knowledge characterizes fundamental mechanisms like turbulence and convection heat transfer which are at the basis of the prediction of transient performance in WCNR.

The importance of research in nuclear thermal-hydraulics is an outcome from the given outline. The connection between fundamental mechanisms and < global > phenomena, i.e. the impact of missing (or unsatisfactory) knowledge upon practical application, introduces to the need for prioritization of research.

2.2. Additional motivations

Further motivations for prioritization of research in nuclear thermal-hydraulics are connected with the following topics:

- The (proposed) prioritization process imposes a way through the competences and the expertise already available including a critical re-evaluation of selected findings.
- The prioritization process implies disconnecting legitimate wishes of researchers from (safety) technology needs.
- Many dead-ends (i.e. no progress) characterize nuclear thermal-hydraulics researches: the risk of unsuccessful outcome decreases when following a prioritization process.
- The prioritization process may imply engaging retired scientists, thus reducing the effect of irreversible loss of expertise in the area.

3. Methodology for prioritization

Characterization of phenomena and exploitation of capabilities of current computational tools are at the basis of the methodology as already mentioned and discussed below.

3.1. The phenomena

Phenomena expected in primary circuit of Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) have been classified in the 90's (previous century) with the purpose of demonstrating the qualification level of system thermal-hydraulic codes, OECD/NEA/CSNI, 1987, 1989, 1994, 1996. A wider range of phenomena has been recently collected, Glaeser et al., 2017; D'Auria & Galassi, 2017, and Aksan et al., 2018, to address the containment phenomena, see e.g. OECD/NEA/CSNI, 1986, 1987, 1989, 2014, and the entire class of WCNR, see e.g. IAEA, 2009, and IAEA, 2012 [a systematic identification of all documents at the basis of the recent collection can be found in Aksan et al., 2018]. Namely, an alphabetic list of 116 phenomena is proposed: a piece of related table is reported as Table 1 (phenomena are identified in the first column by an acronym X-Y-ZZ, where: X identifies the class of phenomena and can be 'B = Basic', 'S = Separate Effect', 'I = Integral Effect' or 'A = Expected in New Reactors'; Y identifies the phenomenon in the class; Z is the acronym for the phenomenon).

3.2. The (virtual experimental apparatus) μλ-I³TF

The investigation of Best Estimate Plus Uncertainty (BEPU) approach for the accident analysis of WCNR including application and a connected vision for the future of nuclear thermal-hydraulics, see e.g. D'Auria, 2012, Nam Dinh et al., 2013, and Bestion, 2017, brought to the proposal for the three times ideal test facility (μλ-I³TF), D'Auria, 2016. A simplified sketch is reported in Fig. 1. The facility has the features of a virtual reactor, i.e. software, rather than hardware product, better represents its essence, now. Key aspects for the facility design are outlined below, making reference to the words which form its acronym:

1) **Modular**: it should be possible to modify parts of the facility e.g. according to different scaling laws or scaling choices: noticeable examples are the configuration of the downcomer (annular, partly annular, or cylindrical) and the diameter (and length) of HL.
2) **Large** means the largest possible consistent with the targets for its construction and the technological constraints (including financial resources).
3) **Advanced** means consistent with the current state of the art, i.e. based on the knowledge acquired from the operation of a few dozen ITF and the execution of thousands of experiments.
4) **Multi-basis** implies the application of different scaling methods for its design. Furthermore, system codes and CFD codes are expected to be used for confirming the design of selected modules.
5) **(Multi)-discipline** implies a design accounting for structural mechanics (e.g. jet thrust, Condensation Induced Water Hammer, CIWH, loads on internals and Pressurized Thermal Shock, PTS), neutron physics (e.g. electrical power feedback to simulate Anticipated Transient Without Scram, ATWS, and BWR stability situation), chemistry (e.g. H2 production and measurement) issues in addition to system thermal-hydraulics.
6) **Apparatus**: the design (feasible) will end-up into a working system which will constitute a computational apparatus.
7) **Ideal-1**: technological challenges, with main reference to the target of having full power and 'large' scale, may prevent the construction of the facility: full electrical power by electrically heated fuel rod

Table 1
Excerpt from the list of phenomena for WCNR, Table II in D'Auria & Galassi, 2017, see also Glaeser et al., 2017, and Aksan et al., 2018.

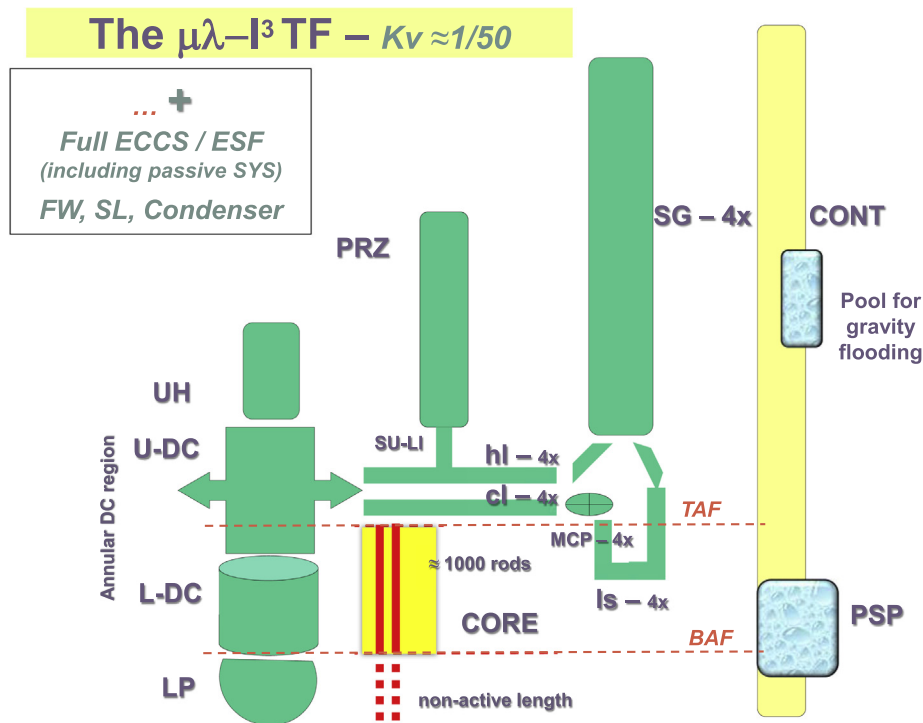| ID	PHENOMENA IDENTIFICATION	TYPE	REACTOR	DETAILS & NOTES
S-1-ACC	Accumulator behavior	SETF	PWR	Mainly
I-1-ASY-L	Asymmetric loop behavior	ITF		
I-2-ASY-D	Asymmetry due to the presence of a dam	ITF		Shutdown conditions
A-1-CHV	Behavior of check valves		New Reactors	Also containment
A-2-CC	Behavior of containment emergency systems (e.g. PCCS)			
A-3-CMT	Behavior of core make-up tanks			
A-4-DL	Behavior of density locks			
A-5-PC	Behavior of emergency heat exchangers including PRHR and IC			
A-6-POO	Behavior of large pools of liquid			
I-3-BD	Blowdown	ITF/SETF/Basic		PHW rather than PH
I-4-NCBC	Boiler condenser mode (of NC)	ITF	PWR-O	
	Boil-off	ITF/SETF/Basic		See B-4-EV2
S-2-BO	Boron mixing and transport (also A-12-BO)	SETF	PWR	Also ITF
S-3-CCF1	CCF/CCFL-Channel inlet orifice	.SETF	BWR	
S-4-CCF2	CCF/CCFL-Downcomer		PWR	
S-5-CCF3	CCF/CCFL-HL & CL			
S-6-CCF4	CCF/CCFL-SG tubes			
S-7-CCF5	CCF/CCFL-Surgeline			
S-8-CCF6	CCF/CCFL-UTP		N/A	
	Centrifugal pump			See Impeller pump
I-5-BC	Channel and bypass axial flow and void distribution	ITF	BWR	
I-6-CLDO	Collapsed level behavior in downcomer	ITF	BWR	See also phase separation
B-1-COH	Condensation due to heat removal	Basic	N/A	
B-2-COP	Condensation due to pressurization	Basic		

Fig. 1. The sketch of the μλ-I³TF.

simulators poses unsolved challenges to the seals between the rods and the pressure boundary.

8) Ideal-2: the concerned facility aims at improving the knowledge in nuclear thermal-hydraulics. Unavoidably its complexity requires the detailed knowledge of the reference WCNR, or the NPP unit, i.e. proprietary data shall become accessible (at least to selected scientists) outside the designer-owner company boundaries. This may cause unsolvable obstacles in the roadmap for the construction of the facility.

9) Ideal-3: although the facility cost may of the order of a few % of the cost of a single NPP unit, this may reveal unsurmountable in relation to current budgets for research.

10) Test Facility: it is expected to construct such a facility even though this is a utopia at the time being.

3.3. The methodology

The prioritization of research is as follows, Fig. 2: the originating-triggering (new) need may come either from thermal-hydraulics research (bottom-up way, also called 'idea') or from the design, operation or safety issues connected with thermal-hydraulics in NPP (top-down way), 'step 0'.

Then, 'step 1': a cross-link is established between the new need (or the idea) and the existing list of phenomena. The new need may affect one or more phenomena and being already qualitatively characterized. In this case the step 2 is performed (see below). If the new need is independent from each phenomenon a specific experimental campaign should start and new modeling capabilities are expected.

In 'step 2' the new need (or the idea) is associated with one or more parameters (and corresponding parameter range) which characterize the concerned phenomena. For instance, example (A): a new experimental outcome becomes available for the Counter Current Flow Limitation (CCFL), then a new correlation among system variables is proposed; example (B): a new CFD calculation shows that a modified κ-ε correlation provides a substantial improvement in predicting downcomer mixing; example (C): new NPP data show that pressure drops

across a Main Coolant Pump (MCP) with locked rotor after Loss of Coolant Accident are much larger than current estimates.

In 'step 3', the already established cross-link between phenomena and accident scenarios is considered. Then, the need or the idea [either (A), (B) or (C) in the examples] is associated with one (or more) accident scenarios.

In 'step 4', the μλ-I³TF comes into play. The concerned (calculated) accident scenario (or scenarios) derived from established knowledge is compared with the accident scenarios derived from the application of new need or idea.

In 'step 5', key Safety Margins (SM) values from two calculations of the same accident scenario at step 4 are compared: in the case SM values are not affected (or affected for a small amount, i.e. typically, lower than the uncertainty affecting the calculation results) then the new need or idea does not represent a priority for modeling changes or for planning new research; in the opposite case (SM value largely affected) a research priority is identified. The last situation, before expenditures of (large) research funding, may need confirmation from sensitivity studies, consideration of scaling, etc.

The entire process, properly supported by the proponent for the new need or idea may (easily) be repeated a number of times. In case where SM are not affected in any scenario, the new need or idea may remain a good idea for developments but should not get priority in nuclear thermal-hydraulics research.

4. The sample (virtual) application of the methodology

Three sample applications of the prioritization methodology for nuclear thermal-hydraulic issues are discussed hereafter, see Fig. 3; the objective is to clarify the related features and capabilities.

It may be noted that a dataset (input deck) suitable for the simulation of the μλ-I³TF performance by any system thermal-hydraulic code is beyond the scope for the present paper; a proper qualification for the input deck would imply the demonstration that predicted results for an assigned reference NPP unit are consistent with the expected transient scenarios and with the phenomena, Aksan et al., 2018, and
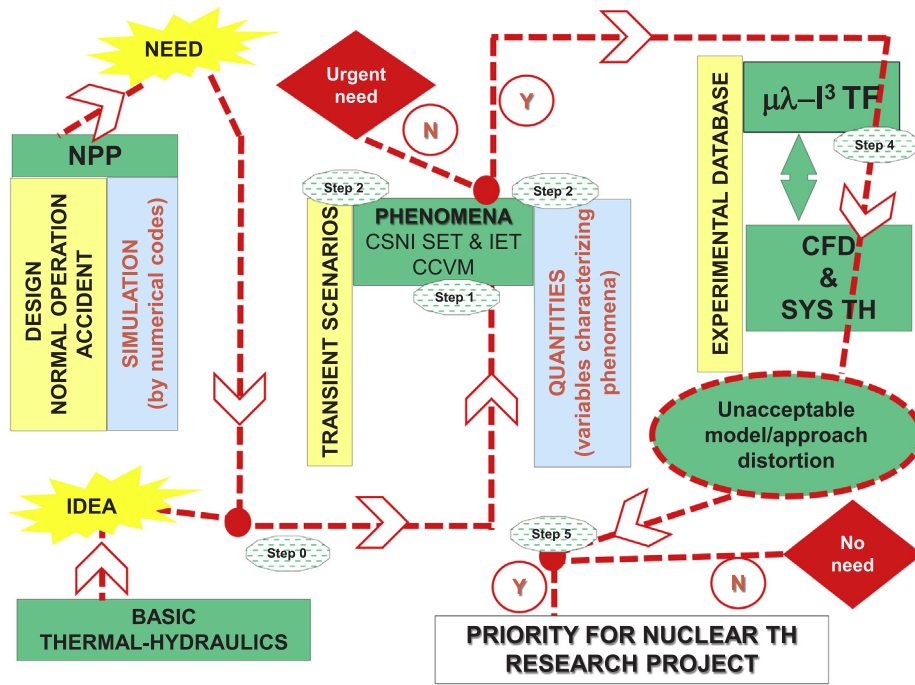
Fig. 2. Prioritization process in system thermal-hydraulics.

D'Auria & Galassi, 2017: suitable resources are needed and not available

Let's identify the sample applications as A-I, A-II and A-III and follow the steps from '# 0' to '# 5' as indicated on the left side of Fig. 3. The WCNR of interest, or the NPP unit, is assumed as assigned once entering into the process.

Triggering ideas (or issues), step 0, are connected with scaling, A-I,

and modeling of turbulence, A-II and A-III:

- Scaling constitutes a controversial issue in nuclear thermal-hydraulics and appears in various phases when evaluating transient performance of WCNR, case A-I. For instance, the impact of changes in scaling related parameters is studied by Martinez-Quiroga & Reventos, 2014; however, the characterization of those changes is
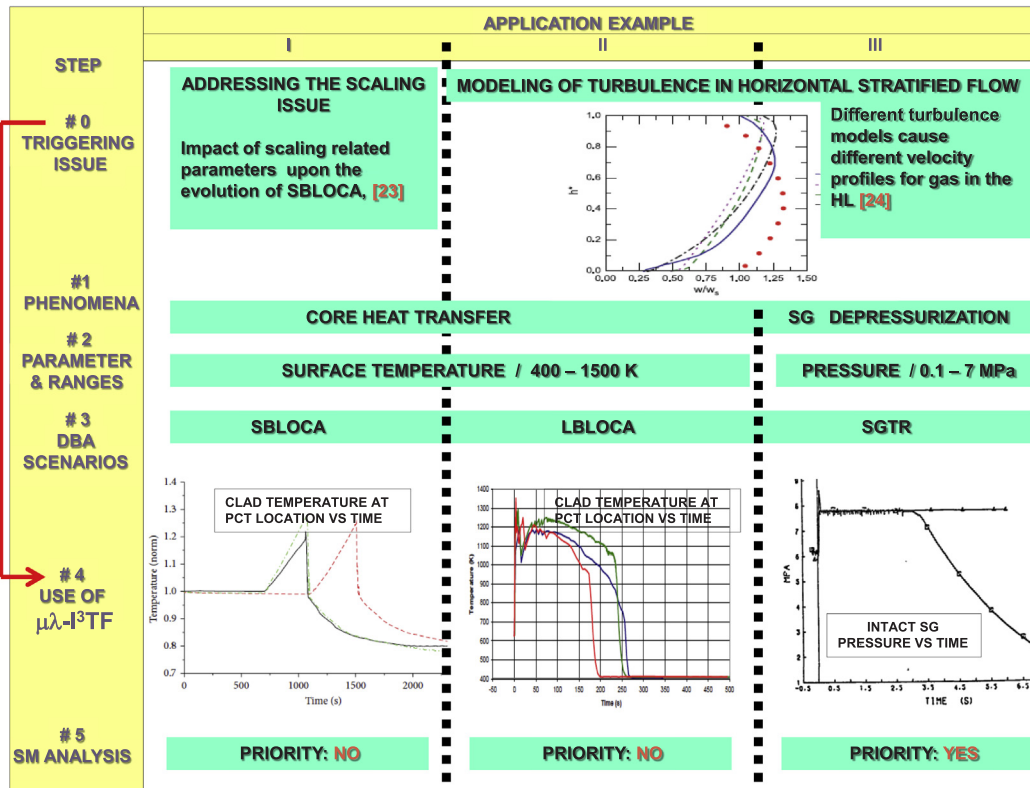

Fig. 3. Sample application of the prioritization process.

not of direct interest within the present context. Rather, the objective here is to find whether those (scaling-related) changes, which may imply arbitrary choices in the process of application of numerical codes to the nuclear reactor safety analyses, impact the result to a level which requires further research.

- Improved modeling of turbulence constitutes the target of many researches in thermal-hydraulics, cases A-II and A-III. The question to be answered within the research prioritization process is whether an assigned new model impacts the evaluation of accident scenarios. The triggering idea comes from Höhne & Mehlhoop, 2014, where different turbulence models are used to calculate the velocity profile of the gas phase in a horizontal pipe also showing large discrepancies with respect to experimental data (upper right diagram in Fig. 3, showing the non-dimensional gas velocity in the horizontal axis versus the height of the channel). Additional specific question in this case is to estimate the impact of those discrepancies upon the evaluation of accident scenarios.

Common motivation for steps 1, 2 and 3 is the commitment of drilling the expertise space in the concerned area.

The objective for the step 1 is to identify which phenomena derived from DBA analysis of WCNR are affected by the triggering issue. Several phenomena can be identified in this step which may require several calculations in forthcoming steps of the process. When performing step 1, it may happen that too many phenomena are concerned or that a phenomenon characterized from the triggering issue is not consistent with the available information (see e.g. Aksan, 2017, and D'Auria & Galassi, 2017). In the former situation a large number of calculations may be needed (not necessarily a problem with current computational capabilities); in the latter situation an urgent need is found, first way-out from the prioritization process (middle-top in Fig. 2). An over-simplified answer to the step 1 is provided here:

- 'Core Heat Transfer' (CHT) is the unique phenomenon selected for A-I and A-II, i.e. CHT is affected by scaling choices and by turbulence modeling (e.g. in Hot Leg).
- Turbulence modeling in Hot Leg (HL) is expected to affect the heat transfer and then the depressurization for Steam Generator.

Specific motivation for step 2 is the demonstration that the (triggering) idea in step 0 is actually a new idea. In step 2 parameters are identified which connect phenomena, models and equations and results of calculations. The ranges of variation for those parameters are also identified. In the applications A-I to A-III trivial solutions are proposed and innovation is not demonstrated or discussed: the innovation could be the combination of selected parameter ranges with other parameters which characterize the phenomenon at step 1. As a result, in order to progress with the application of the prioritization process, the surface temperature of fuel clad is selected as representative of CHT for A-I and A-II and the pressure is selected as representative of SG pressure for A-III.

A multiple solution is expected for the step 3, following the investigation into the DBA envelope for the concerned NPP unit. A cross-link between phenomena, parameters and scenarios shall be created: typically more than one scenario may result from one triggering idea. In the present case a simplified solution is proposed which involves the selection of SBLOCA, LBLOCA and SGTR for A-I, A-II and A-III, respectively.

The step 4 implies the availability of the qualified input deck for the μλ-I³TF as well as of the database of (qualified) results from its application for the evaluation of the selected transients (step 3). It shall be noted that:

- Before entering into the prioritization process, the full DBA scenario database for the concerned WCNR is assumed to have been calculated by the μλ-I³TF and called standard-reference scenarios (both

system codes and CFD codes are at the origin of the standard-reference scenarios);
- Any standard-reference scenario is consistent with current knowledge including experimental data in ITF having a similar size as the μλ-I³TF and the information in the Final Safety Analysis Report (FSAR) for the concerned NPP unit. Namely, accident scenarios results in FSAR are typically the outcome of conservative assumptions while μλ-I³TF results are Best Estimate (BE) type: differences between FSAR and BE results are expected and are explained.

The step 4 consists in performing a new calculation with changes in input deck driven by the idea at step 0 (see the arrow on the left side in Fig. 3). In A-I nodalization changes are needed to account for different scaling assumptions, Martinez-Quiroga & Reventos, 2014. In A-II and A-III, the CFD code model at the basis of the computational grid already adopted for the HL for the reference-standard scenario calculation is modified according to the new idea, Höhne & Mehlhoop, 2014.

The step 5 consists in comparing results from calculations of standard-reference scenarios and the modified one according to step 4, both derived from the application of μλ-I³TF. Either 'standard-reference scenarios' or 'scenarios from step 4' are not available for the scope of this paper; then, dummy diagrams are reported at the bottom of Fig. 3 suitable for describing the prioritization process. Each of those diagrams shall be considered as the tip of large database and includes two or more time trends: the unique curve of the reference scenario and the curves obtained at step 4. Differences are of interest, so distinction of curves is not considered (here). According to the discussion in Section 3.3 safety relevant variables and safety margins are considered; in addition, the uncertainty which characterize the calculation of the standard reference scenario can be considered, too. It may be noted that transient times are in the ranges 10^2 s, 10^3 s and 10^4 s for application A-II, A-I and A-III, respectively and consistent with the type of scenario. Outcomes are summarized as follows:

- A-I, diagram at left bottom in Fig. 3, clad temperature at PCT location versus time: let's assume that the dark line is the result from the standard-reference scenario calculation. Then, a) safety margin is (very) wide for any of the considered trend; b) discrepancies in time are smaller than the time-error expected in uncertainty evaluation, i.e. uncertainty bands (not reported) encompass all the other curves; c) no priority is identified for possible continuation of the research originated at step 0, i.e. concerned scaling issue.
- A-II, diagram in the middle bottom in Fig. 3, clad temperature at PCT location versus time: let's assume that the red line is the result from the standard-reference scenario calculation. Then, a) the small available safety margin in terms of PCT and the larger margin in terms of H2 production, i.e. connected with the quench time, are not affected by the modified calculation; b) uncertainty bands (not reported) encompass all other curves; c) no priority is identified for possible continuation of the research originated at step 0, i.e. concerned turbulence model.
- A-III, diagram in the right bottom in Fig. 3, intact SG pressure versus time: let's assume that the upper line is the result from the standard-reference scenario calculation. Then, a) SM are mostly connected with radiation releases and depend upon reaching the condition for depressurization of the intact SG; b) the modified calculation implies a depressurization time well before what calculated in the standard-reference scenario and outside the uncertainty bands (not reported); c) priority is identified for possible continuation of the research originated at step 0, i.e. concerned turbulence model.

It may be noted how the same starting idea, in the present case the modification of the turbulence model for the gas phase in a horizontal stratified flow, A-II and A-III, justifies or less deeper researches depending upon the transient scenario.

5. Conclusions

Improvements in fundamental thermal-hydraulics may largely benefit of new ideas or approaches which may reveal simple and cheap. Waiting for those ideas and approaches a methodological procedure for prioritization of researches in (applied) nuclear thermal-hydraulics is proposed which:

a) Allows distinguishing between strategies for improving nuclear reactor safety and legitimate needs by researchers (in thermal-hydraulics); this may reveal of outmost importance in Countries embarking in nuclear technology.

b) Brings to casting new activities into the established state of the art (in nuclear thermal-hydraulics) thus reducing the effect of the continuing loss of expertise we are experiencing; this also keeps alive the huge database of information gathered in the past.

c) Has a cost estimated as 100–1000 times lower than the cost of researches under investigation i.e. those researches (completed in the past) whose outcomes are used for currently proposed research prioritization: it is expected that expensive research programs ending into the swamp of existing competences can be avoided, thus reducing the overall cost of meaningful researches.

The proposed procedure for research prioritization shall be considered a working element of Knowledge Management in the area of nuclear thermal-hydraulics. Two pillar elements for the prioritization procedure are constituted by the phenomena in Water Cooled Nuclear Reactors and by a virtual facility. The virtual facility makes use of the capabilities of existing codes in the system thermal-hydraulics and computational fluid-dynamics domains.

The words 'virtual' or 'ideal' appear many times in this paper. This implies recognizing the difficulty to translate the ideas into application in the area of nuclear thermal-hydraulics.

Finally, prioritization of research shall be used to optimize the applied research budgets, to keep the expertise in the area, to minimize duplication of researches. Prioritization shall not penalize the fundamental research pursuing a different approach to the knowledge in nuclear thermal-hydraulics.

Acknowledgements

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