NUCLEAR SAFETY AND THERMAL HYDRAULICS: PERSONAL THOUGHTS AND SOME RECENT PROGRESS

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ABSTRACT

An attempt is made to review the history of reactor safety and draw conclusions about trends that could be avoided and directions that could lead to robust reactor designs which would not be susceptible to severe accidents. In the second part of the paper, progress in reactor thermal-hydraulics is observed by considering the list of conference sessions and finally a report is made on some recent work on two computational problems: the prediction of DNB and the potential spatial coupling of CMFD methods to achieve multi-scale, high-resolution simulations.

KEYWORDS
Reactor safety, thermal-hydraulics, severe accidents, DNB, computational coupling

1. INTRODUCTION

I am very grateful to the organizers for their kind invitation to present a keynote at NURETH-16. Rather than talking only about recent thermal-hydraulics achievements that other, younger and more active colleagues will cover with well-deserved enthusiasm, I will attempt a retrospective and try to convey a few personal thoughts. I will cover an area broader then thermal-hydraulics; I would like to talk more generally about reactor safety. Indeed, although the very first nuclear safety concerns where more on the neutronic side – mainly reactivity-excursion concerns – the nuclear safety history has been dominated to a large extent by thermal-hydraulics.

I take this opportunity to present some personal (sometimes radical or maybe controversial) thoughts and ideas; some of these may not be fully justified or meticulously documented but I feel that they could provide good starting points for discussions… After a long time in the nuclear arena, I tend to look at things a little more critically, with maybe less than full enthusiasm…

The great promise that nuclear energy has shown in their 50s and 60s, and then later again during the so-called Nuclear Renaissance period has been challenged, as we all very well know, by the three major severe accidents, TMI, Chernobyl and Fukushima, Fig. 1. Only the second was essentially a reactivity accident, although the damage was done mainly by thermal-hydraulic forces; thermal hydraulics is needed to create a non-chemical explosion. The first and the last major accidents were clearly thermal-hydraulics dominated.

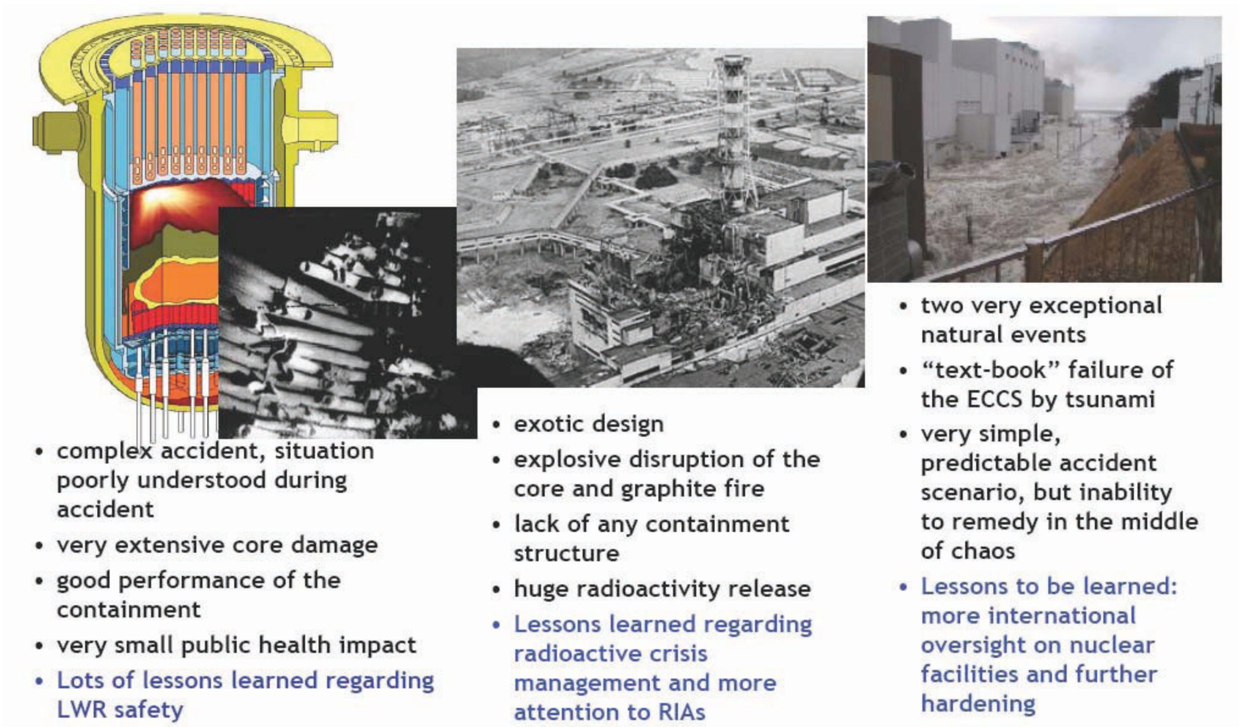

Figure 1. The three severe accidents: TMI, Chernobyl, Fukushima: 1979, 1986, 2011

The Nuclear Renaissance announced in the 90's has not materialized and the world today is rather divided regarding nuclear energy: Although countries in Asia are developing nuclear power rapidly, Europe, US, and Japan are hesitating or moving with very cautious steps. Europe at least is divided in two blocks, the pro-nuclear one and the anti-nuclear set of countries where the opposition takes various degrees, ranging from cautious to missionary. Germany is moving out, France is having some second thoughts while at the same time making very large post-Fukushima safety investments, while the UK is cautiously going ahead… The very strong and rather unexpected development of other primary or renewable energy sources in the US and is a few other countries had certainly a strong impact on nuclear new build.

This talk is in two rather disjointed parts; I (GY) wished in the first part to express some personal thoughts (the reason for the first-person, singular). In the second part, where the second author (DL) is a major contributor, we will be much closer to the immediate concerns of the NURETH conferences and not resist the temptation of looking a little bit into present and future thermal-hydraulic developments and presenting some samples of exciting work from in-home activities or work close to home.

2. PART I. RETROSPECTIVE AND PERSONAL THOUGHTS ON REACTOR SAFETY AND THERMAL HYDRAULICS

The development of nuclear energy and of nuclear safety in particular have been marked by the three severe-accident milestones that have been mentioned in the Introduction. The philosophy of nuclear safety has changed after each accident, Fig. 2, and this had a very important impact, of course, also on thermal-hydraulics; I will certainly not repeat hear the "lessons learned." I would like to try, however, to remind you of some developments that followed each major accident and see where these have led today.

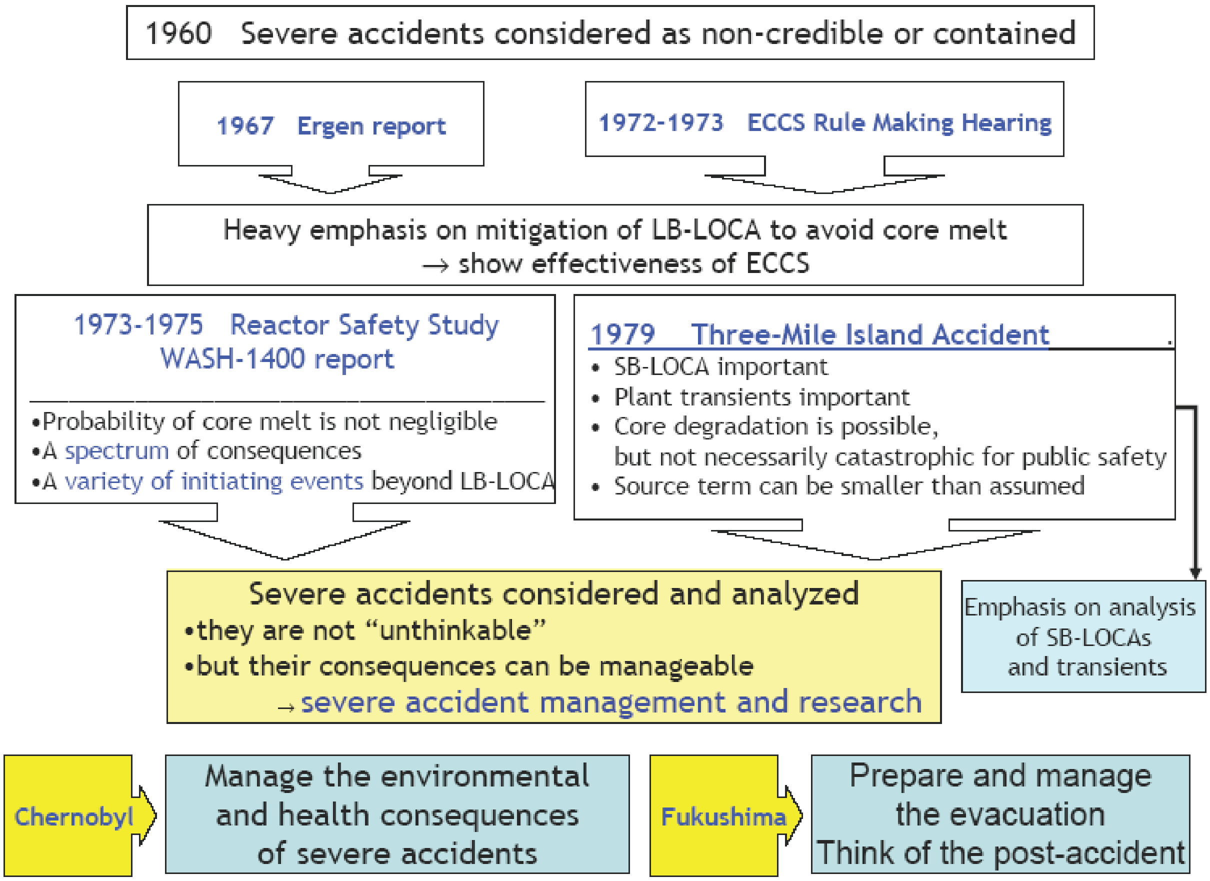

Figure 2. Evolution of safety philosophy in relation to the severe accidents.

2.1 Severe accidents, Fukushima and the follow-up Stress Tests

All three nuclear severe accidents have shown the importance of severe accident thermal hydraulics; a most challenging area where we do not only have to deal with the classical (steam-water) situations but also with the most difficult to understand and describe situations involving fluid dynamics, thermodynamics, chemistry, physico-chemistry, materials, etc. etc. A thermal-hydraulics dream and nightmare.

Figure 2 shows how the safety philosophy has evolved regarding severe accidents after each major accident. The "unthinkable" severe accident before TMI, was no longer unthinkable after TMI and we had to find ways of understanding and managing it. Chernobyl has shown that we had to better understand and learn how to manage large radioactive releases and their health and environmental impacts. With Fukushima, we went one step further and we are trying now to better understand how to manage the human evacuation crisis and even looking at ways of decontaminating large areas following a severe accident. Although, I may say, the public health consequences linked directly to radioactivity have not been truly catastrophic in all three major severe accidents, it is clear that the nuclear industry and society cannot accept severe accidents. The social and economic aspects have been very large and the impact on the nuclear industry huge.

2.2 New designs

During the "nuclear winter" that followed TMI and Chernobyl, when new reactor orders went down to zero, several national and international organizations attempted to revive the nuclear option by proposing actions and initiatives such as:

- The developments led by EPRI in the US to define the Utility User Requirements in the Utility Requirements Document, URD, and new power plant design criteria stemming from the users rather than the regulators
- Similar efforts by a consortium of European utilities that resulted in the European User Requirements or EUR.
- The Generation IV International Forum organized to design the reactors of the future.
- Following the Fukushima Stress Tests, there have been serious efforts in Europe from the regulators to harmonize reactor safety criteria.

Two sets of Generation III designs followed the EPRI efforts, the evolutionary plants and the passive ones; they both met, I would say, with modest commercial success. Plants based on older designs and or plants designed by other vendors (Russian, Korean, Chinese,…) are also being built and have commercial success (most likely for political and financing reasons) and are competing with these. Generation IV plants are still in the design or early testing phase, and some of them, at least, remind older designs.

The passive plants in particular promised a new level of reactor safety as their non-dependence from active power sources was certainly a safety plus and at the same time simplified the design and the safety requirements (safety class classifications, fewer components, etc.). Looking back, however, only one of the original passive plants was capable of capturing a sizable part of the market so far. It is rather obvious that if Fukushima were a passive plant, it would have had a better chance of surviving the tsunami.

Several innovative or exotic designs and small or medium reactors (SMR) have also been proposed and supported by national and international organizations, but they never went much beyond the paper-study stage. Prominent nuclear actors such as Edward Teller promoted the "obviously safe" reactor and Carlo Rubbia the subcritical, accelerator-driven reactor that was given attention in European projects. Designers in several nations have in the past and continue proposing additional novel designs. Some of these may be making exaggerated claims, some others may present relatively modest improvements and their small sizes and sometimes exotic, non-practical features do not necessarily convince the utilities.

The market is still dominated by large light water reactors, most of them now in Generations II-plus and III. The typical thermal-hydraulics problems associated with the light water reactors are still there.

Probabilistic considerations that show that serious accidents have very low probabilities do not convince the public and do not convince me personally. The "acceptable" 10 to the -7 probability (of core melt per year) is hard to comprehend, while the 10 to the -4 is unacceptable. Although Probabilistic Safety Assessment (PSA) is a great tool for improving design and setting standards, the 10 to the -7 is not universally convincing; it only brings forward the very old dilemma of very low probabilities versus high risks. The reactor safety's and the thermal- hydraulics' main concern is how to make sure that the huge radioactive core inventory is not released during an accident. Now I am going to defend another radical thought: the only way to definitely eliminate the unacceptable severe accident with the large radioactive release is to eliminate the in-core radioactive inventory.

The fission reactions and the innumerable possibilities they offer to a tremendous variety of rector designs are amazing; think about conversion, breeding, the variety of possible fuel cycles. There is only one drawback: each fission inevitably results in the production of fission products that remain in the core of all operating reactors. Circulating fluid-fuel systems offer the possibility of continuously extracting the fission products and eliminating the potential release of the very large volatile core inventory during a severe accident. Higher actinides may remain in the fluid core, but the early threats from the most volatile fission products can be eliminated. Molten salt reactors are an example in this category. I am not an expert in severe accidents, I am not a molten-salt reactor promoter or designer, but I strongly believe that this option is worth some additional development. I realize that the continuous extraction of the fission products may pose some non-negligible or even serious safety concerns; we may have lots of nasty small releases, but these may be an acceptable alternative if they eliminate the large severe-accident release that in the eyes of the society threatens nuclear power.

One of the major tasks of reactor thermal-hydraulics has been to produce the predictive tools for design-basis and beyond-design-basis accidents; given the complexity of the severe-accident situations, the second set of severe-accident codes is even more challenging to produce and validate. We have made tremendous advances in the severe-accident area, we have learned a lot about phenomenology, on how to manage severe accidents, but I do not think that anybody should make a serious decision during a severe accident based only on code predictions. Obviously, the best severe accident management strategy is to avoid the severe accident in the first place by design.

And a last thought: The European Stress Tests following the Fukushima accident have resulted mainly in actions to prevent and or at least to mitigate the severe accident; avoid core melt by making sure we have sufficient water and power supplies. The initiators of the potential severe accident have also been investigated, but the emphasis has been on external meteorological and geological events; I believe that there is a risk in putting the main emphasis on these as it may lead to a lesser weight on other potential initiators. Fukushima could have been a trigger to a comprehensive re-evaluation of reactor safety.

2.3 Economics, anti-nuclear forces, and nuclear safety

Core power density (one of the most important thermal hydraulic variables) and plant lifetime are two factors strongly influencing nuclear power economics. Although increasing core power density and extending plant lifetime can be achieved and licensed in a safe manner, I do not think anybody could challenge the fact that these two trends are inherently not increasing plant safety. The economics of the plants are pushing, however, toward higher core power densities and, strangely enough, antinuclear forces are unknowingly promoting plant life extension: in many countries, it may be easier to increase core power density and get a license for longer plant lifetime then get a license for a new power plant that will inevitably have safety improvements over the older, ageing plant.

There was a trend towards lower core power densities during the period of the design of the Generation III plants, in particular the passive ones. Unfortunately this trend did not persist; both boiling and pressurized passive LWRs have today much larger core power densities. Plant economics was one of the design criteria for the Generation IV plants. Although I cannot deny that economics is commercially very important, on the other hand, I am tempted to make the radical remark that nobody will build a nuclear power plant only for economic reasons; in fact the economics of nuclear power plants have been seriously challenged recently from other emerging primary energy sources. In today's world, nuclear is the option when there is no other option, mainly for environmental, resource, or political reasons. If the anti-nuclear forces where ready to sit down and discuss the pros and cons without *a priori* positions, I do not see why we could not subsidize with a couple of cents the nuclear kilowatt-hour and lower core power density when some countries at least are very heavily subsidizing the renewable one.

2.4 Thermal-hydraulics and reactor safety

2.4.1 Continuing efforts

Light water reactors have so far dominated the market. Water is a wonderful coolant, has excellent heat capacity and very high latent heat; in a necessarily pressurized system, however, it exhibits a major draw-back: when depressurized, it flashes and … disappears from the system that it is intended to cool. This behavior was the driving force behind most developments in thermal-hydraulics that took place the last 50 years: it was necessary to understand, model, compute or simulate the behavior of the LWR systems un-der very complex thermal-hydraulic conditions. We have made tremendous progress, but some issues, situations, phenomena or accident scenarios are *still* keeping us busy; this was one of the themes that one of us (GY) tried to address at NURETH-15 [1]: A quick look into the contents of the present conference shows LWR sessions that certainly existed in previous venues of NURETH, on:

- Multifield two-phase flow modeling (several sessions)
- Two-phase flow and heat transfer fundamentals (several sessions)
- Boiling and condensation fundamentals (several sessions)

- CHF and post-CHF heat transfer, flooding and CCFL
- Advances in enhancement, understanding and prediction of CHF and quenching (several sessions)
- Investigation of reflood phenomena (now in partially blocked core with fuel relocation)

- Operation and safety of existing reactors (several sessions)
- Safety systems and related phenomena
- NPP transient and accident analysis (several sessions)
- Plant system code development and validation (several sessions)
- Realistic BWR LOCA evaluation: methodology development and application
- Containment analysis (with V&V)
- Natural Convection and Mixing Phenomena, Modeling and Experiments

- Critical heat flux in a fuel bundle: modeling, prediction, and experimental measurements (several ses-sions)
- Core thermal hydraulics and subchannel analysis; fluid dynamics and heat transfer
- Interfacial area transport

- Severe accident phenomenology (several sessions)
- Modeling and experiments of severe accidents (several sessions)
- Debris bed cooling

2.4.2 New methods and tools

The reader notes, however, that the methods and tools have progressed significantly; there are now ses-sions on:

- Computational Fluid Dynamics and Computational Multi-Fluid Dynamics (several sessions)
- Session on CFD applications such as the "Benchmark of NESTOR High Fidelity PWR Rod Bundle Data at In-Core Conditions"

and

- sessions on the results of the two projects that promised to provide modern computational platforms, the US CASL and NURESAFE, the latest in the European series.

And, it would be fair to say that some of the work reported in the classical sessions listed on top is conducted now with much more modern tools. There is also a very timid presence of a couple of posters on the molten salt reactor; nobody seems to like this project.

2.4.3 Slow progress and some new methods

The ratio of "old to new" topics visible in the program outlined in the previous sections is not indicating favorable innovation trends. We have been continuously making progress, but the issues that have kept us busy from the 50s on have not disappeared. It is obvious that there must be continuous progress in the fundamentals, such as boiling heat transfer. We are applying now, not always though, more modern computational fluid dynamics methods to very old problems such as subchannel analysis. The CHF problem is still present as the eternal problem that does not go away, but we are trying now to address it with computational multi-fluid dynamics; we will mention later some recent achievements in this area. Compared to other industries or fields, are we innovating?

The analysis of severe accidents and their phenomenology is still very much in the picture. My (GY) personal belief is that the severe accident phenomenology is so complex that is always to some extent unpredictable; let us rather design systems not likely at all to lead to severe accidents and put the effort on eliminating the severe accident rather than understanding it, computing it, analyzing it, managing it, mitigating it; a rather radical position. However, if we see a large-scale future for nuclear energy, it should be unavoidable to think in this direction. Otherwise, the next accident will surprise us, create lots of interesting new work but also make a few more countries have second thoughts about nuclear power.

Dinh and his collaborators [2] made some thoughtful remarks in NURETH-15 and noted the "Expanding Needs vs. Sluggish Developments" and the limits of present-day thermal-hydraulics modeling and simulations. Bestion in this conference [3] presents a Keynote lecture on "System Thermalhydraulics for DBA Analysis and Simulation Status of Tools and Methods and Direction for Future R&D" that shows the achievements and the limits of code work. We should maybe think more in these directions.

More generally, regarding reactor safety, in a recent paper Dinh et al. [4] make remarks similar to the ones made above regarding the "complexity of nuclear power technology that is a source of uncertainty and perceived risk to … a public that exhibits low confidence in science and high risk aversion…". They claim, however, that "by 2050, the research and development [would have] enabled […] a robust risk and knowledge management process. The heart of the process [would be] risk-informed decision-making based on available, including sparse and marginally applicable, data." The authors have lots of faith in "advances in computer hardware and software to support development of the technology of risk management for such complex systems as nuclear power plants." I do not fully share the belief in risk-informed decision making based on information technology, but the paper by Dinh et al. makes very interesting reading. Otherwise we implicitly agree with Dinh et al. that environmental concerns may make nuclear power more acceptable, as noted above in the discussion on economics and safety. We also agree on the importance of [obvious] "safety margins" although I would like to see these margin based on inherent properties (e.g., low core power density) rather than super-sophisticated calculations of very complex situations, their "multi-physics simulation engine."

3. PART II RECENT ADVANCES IN REACTOR THERMAL-HYDRAULICS

3.1 Critical Heat Flux Predictions

In the NURETH-15 paper [1] and in [5] one of the authors (GY) had noted the "not going away" nature of the CHF problem. He had remarked that all the difficulties of the classical CHF methods – correlations and/or subchannel analysis – would have been eliminated by Computational Multi-Fluid Dynamics (CMFD) simulations of the flow in a rod bundle and simultaneous prediction of the CHF condition from first principles. He also made the pessimistic remark: "This was indeed one of the aims of the European NURESIM project launched in 2003 and followed by NURISP and NURESAFE. Prediction of CHF by CMFD methods could have been considered ten years ago as "a trip to the moon"… The Apollo program has landed a man on the moon in nine years, 11 years from the creation of the NASA in 1958." Although a lot of progress has been made since the launching of NURESIM in 2003, not only in Europe but world-wide with similar projects, e.g., the CASL project in the US, we have not reached the CHF goal yet in 2015. However, we can certainly say that during this exciting CMFD "trip to the moon" there have been already very important spin-offs in spite of the fact that we have not landed yet. In the following paragraphs, we report on some recent progress in this direction.

3.1.1 Direct Numerical Simulations (DNS) of pool boiling for DNB prediction

Until now, in simulating DNB in bubbly flows, we were able to predict fairly well the distribution of the voids in the flow cross-section, but we have still to fully simulate the phenomena that produce heatup of the wall and lead to CHF. For the time being, we are relying on criteria like "CHF when the void fraction near the wall is 80%" or slightly more sophisticated ones.

To arrive at a first-principles prediction of a DNB situation, bubble crowding on the surface and the response of the surface temperature should be computed. In most papers dealing with this problem, the full coupling of the growth of the bubble with the transient temperature field in the wall (the conjugate heat transfer problem) has not been considered, so that there is no spontaneous appearance of the DNB by an automatically and naturally predicted, local overheating of the wall. One of the reasons for this shortcoming is probably that the temperature field in the wall near a nucleation site can present very sharp, time-dependent gradients and this requires a very fine mesh to resolve it. We also need reliable modeling of the dynamic contact angle of the bubble with the wall and a good sublayer model.

At a more fundamental "boiling" level, there will always be great difficulties in linking the characteristics of the cavities on the wall to the boiling process, something that we are not going probably to achieve in the near future, at least. Indeed, this issue has made all nucleate boiling predictions approximate, unless the effect of the combination of wall material and fluid is somehow imported into the problem, e.g., via experimental test data: attempts of linking the surface roughness of the material analytically or by simulations to boiling behavior have not met with much success.

A paper dealing with this conjugate heat transfer problem is presented at this conference [6]. The computed results for a single nucleation site show agreement with various measurements in terms of bubble growth rate and bubble lift-off time. PSI has developed new micro-layer models, and implemented them into the PSI-BOIL code together with the immersed boundary method for conjugate heat transfer (fluid and bubble – wall). Cases of simulations for nucleate pool boiling flows were performed including boiling from a single nucleation site and from multiple nucleation sites. This is getting us closer to the DNB prediction.

Progress was made also on DNS/LES of pool boiling at ASCOMP within the NURESAFE project: pool boiling was simulated from a single nucleation site, as well as from multiple nucleation sites, including the important conjugate heat transfer with the wall. The transient temperature distribution of the wall surface underneath the growing bubble is reproduced in the simulations. Simulations have been performed by initiating boiling both at single and multiple nucleation sites.

Figure 3 shows the computational domain for such a simulation (8 mm in the horizontal and 15 mm in the vertical direction) and Fig. 4 the results of a fully three-dimensional high-resolution Level Set (LS) simulation of a single steam bubble, including conjugate heat transfer and a sub-grid microlayer model [7]. The setup was chosen according to Gerardi et al's experiments [8]. The simulation was run with the multi-block code TransAT [9] using the diffuse-interface model for macro phase change and the dynamic contact angle model.

Two different grid resolutions (medium and fine) were studied. The grid is refined towards the nucleation site giving smallest grid sizes of 50 µm and 30 µm respectively. The corresponding grid contains 2.4 million and 7.2 million grid cells, respectively. A bubble nucleus of the radius 0.4 mm is placed in the center of the substrate, which is heated homogeneously from below as illustrated in Fig. 3. At the side walls periodic boundary conditions are applied.

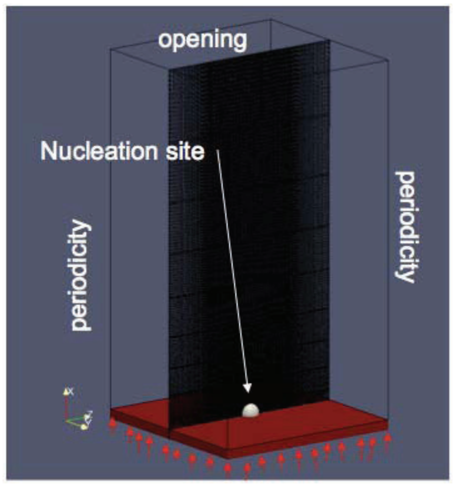

Figure 3. Computational domain including the substrate.

The bubble shapes show qualitative agreement despite differences in the time scale. However, the temperature distributions on the heater surface show differences that can be related to the applied sub-grid microlayer model that affects, of course, the conjugate heat transfer. The next step, bubble growth at multiple sites is underway.

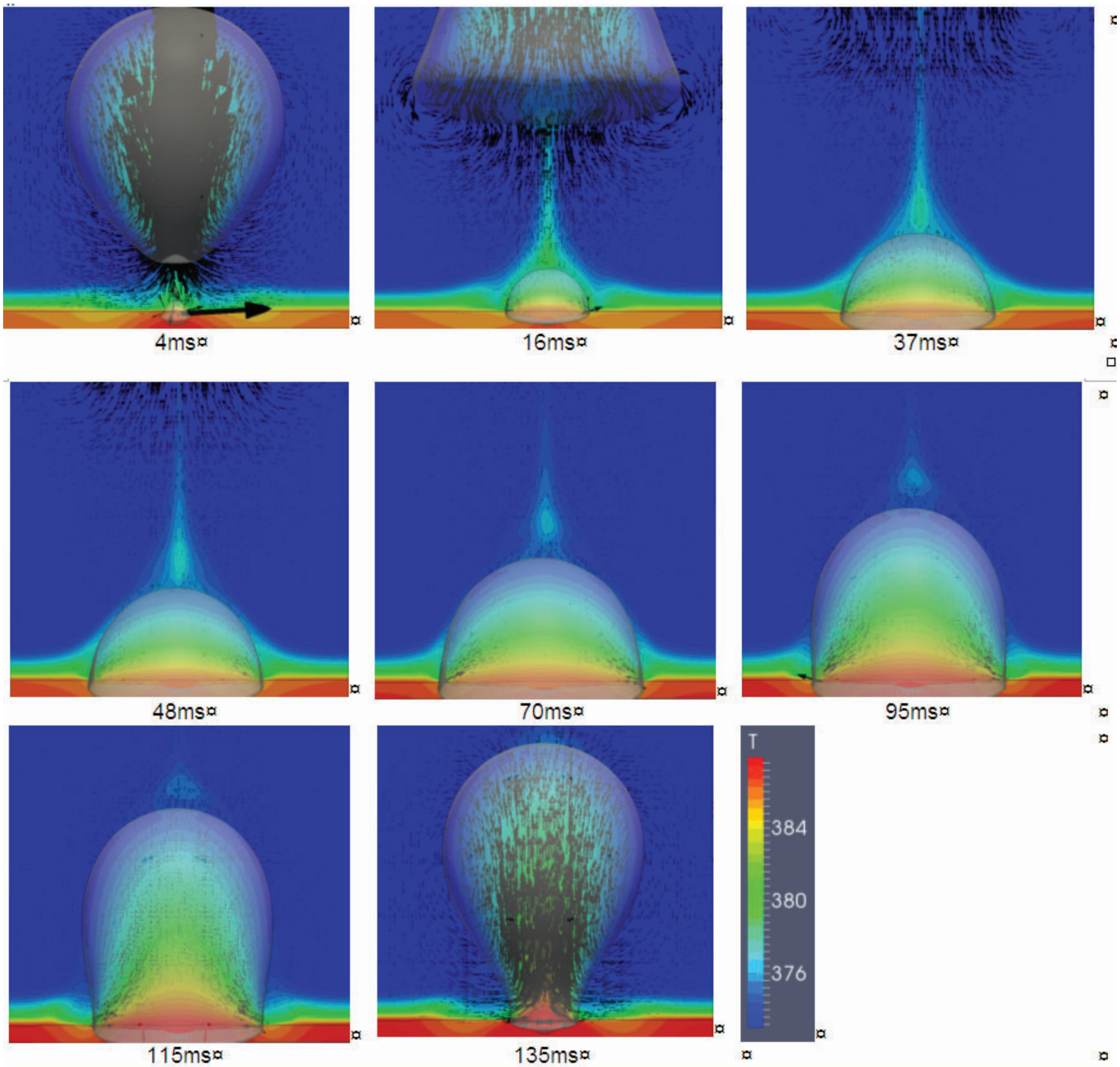

Figure 4. Temperature field and velocity vectors on the center plane for the 2nd ebullition cycle (coarse grid).

3.2 Attempts to couple different two-phase flow approaches

At drawback all of the interface tracking models such as Volume of Fluid (VOF) and Level Sets (LS) is that, when using a reasonable grid resolution, are unable to resolve fragments of each phase "on the other side of the interface": the bubbles created on the liquid site and the droplets created on the vapor side. Slug flow is an example. Such flows involve a hierarchy of length scales intricately combined into turbulence scales and interfacial scales. Large-scale interfacial structures such as waves, jet cores, or slug evolution should be simulated using Interface Tracking Methods (ITM's); as the bubbles or droplets are typically smaller than the grid size. Dispersed or mixed flows on either side of the interface should be treated with mixture models or two-fluid models — in case of mixtures. If the discrete particles are very small, Lagrangian particle tracking methods could be used. The idea is illustrated in Fig. 5 for mixtures on both sides.

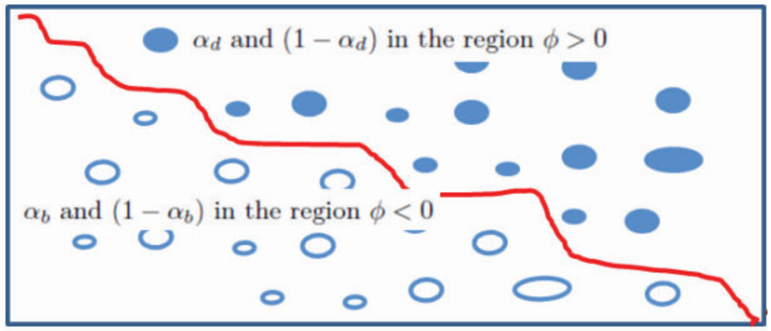

Figure 5. Interface (in red) separates bubbly flow from dispersed-droplet flow

All the methods mentioned are mature but they have not been coupled. To test these ideas, an attempt was recently made to link ITMs with mixture models within the NURESAFE project. The tests were conducted using numerical and physical cases, showing that the approach is sound but requires more tuning, in particular regarding the "drift" between the subscales populating each field evolving from the other side of the resolved interface. Another difficulty stems from the fact that realistic simulations require inclusion of particle breakup and coalescence, something that at the present still requires modeling.

Figure 6 shows the first results obtained with an LES simulation (with a WALE subgrid model) coupled to the interface tracked by means of a LS approach. In general very similar multiphase flow structure is obtained as in the experimental data, as shown in Fig. 6.

After the first bubble is formed, there is an intermediate bubbly flow regime observed, and then a large plume zone with small and large bubbles, Fig. 7. The local Weber number varies widely in the distinct zones, from 100 to 20’000. The same behavior is observed in the velocity field: very large bubbles have obviously much higher rising velocity, which is additionally increasing their Weber number quadratically.

This exercise has shown that the implementation of the coupling turned out to be harder than was expected; still, the approach holds great potential and a powerful way to describe the configuration of phases. One advantage over other approaches to coupling is that locations where break-up and coalescence might be occurring are well-defined. Further, we believe it would not be so difficult to expand this coupling to include the mass transfer rates for boiling and condensation. However, the phase change could be occurring either on the large structures or in the sub-grid mixture. This would require a new approach to description of such phenomena. The proposed approach also has difficulty with the coalescence of subgrid bubbles to form a grid-scale bubble (to be then treated with LS), when there is no grid-scale LS mesh present initially. Much more research would have to be invested to properly identify and define all these cases with this approach to coupling.

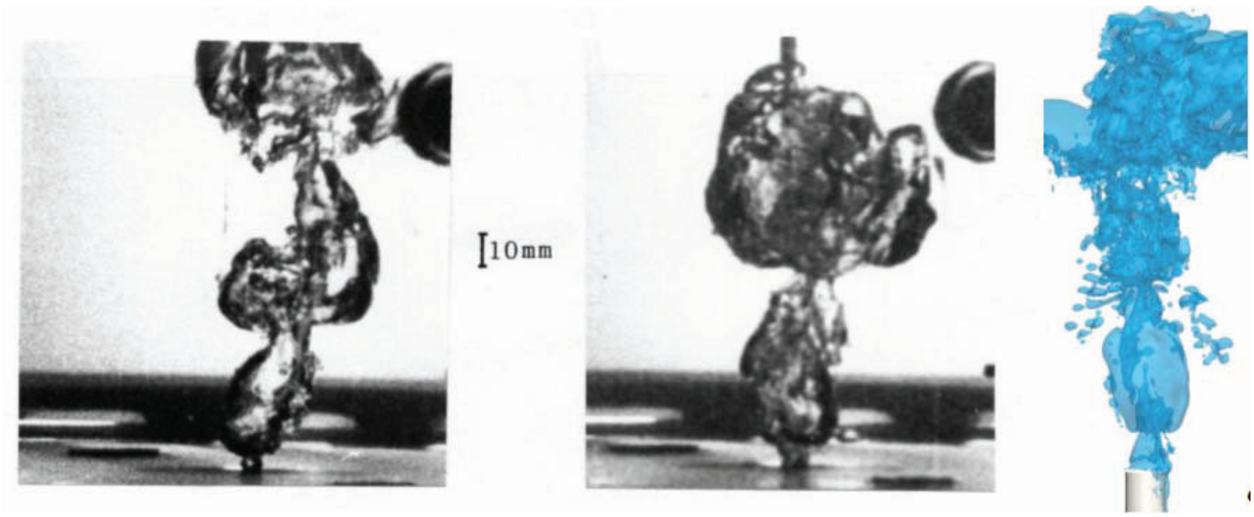

Figure 6. Experimental snapshots of a bubble plume showing large bubbles occurring at different positions (left). Instantaneous interface iso-surface extracted from the simulation (right).

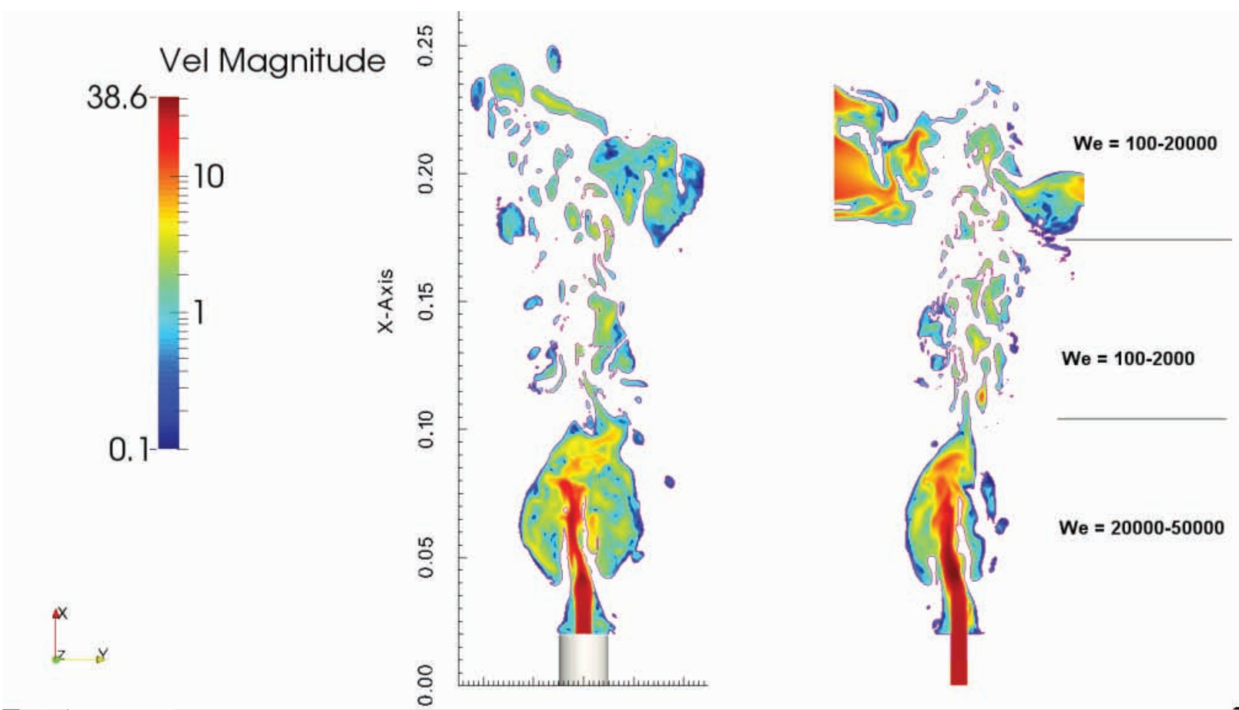

Figure 7. Velocity map and Weber number regions marked. Three regions with different flow structure are observed: jetting, bubbly flow, and plume with small and large bubbles present.

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