



Optimization of prevention and mitigation of severe accidents through Research: Major outcomes and outlook of the Spanish programme

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ABSTRACT

Severe accidents research activities in Spain have grown substantially since the Fukushima-Daiichi accident. Most of these research activities have been conducting by a few organizations (national research center and academia) with the support of the Regulatory Authority, utilities and engineering companies. A great number of these activities were conducted in the analytical field and their main outcomes are contributing to a better understanding of severe accident phenomena (i.e., pool scrubbing; combustible gas distribution and combustion; fission products transport; etc.) and the efficiency of severe accident management actions (i.e., FLEX; PARs; activation of safety systems, long-term measures; etc.). The national framework set between researchers and end-users (regulators and utilities) is improving the safety of the Spanish nuclear power plants and allows for the assimilation of the research results by the nuclear industry.

1. Introduction

Severe Accident research started in Spain the early 80's of last century. From the very beginning, the Spanish severe accident research community strongly felt the need of joining the most forefront international activities. It did not take long till a Spanish consortium signed up in projects like OECD/LOFT (Fell and Modro, 1990), LACE (Rahn et al., 1988), PHEBUS (Von der Hardt et al., 1994) or ACE (Sehgal et al., 1992). The Cooperative Severe Accident Research Program (CSARP) signed by CSN (Consejo de Seguridad Nuclear) with USNRC (US Nuclear Regulatory Commission), was instrumental for the Spanish performance in these frameworks.

Nowadays, the Spanish community of severe accident research continues strongly embedded in international research frames (i.e., EURATOM, OECD/NEA and IAEA), with direct access to severe accident system codes and experimental results. In this regard, it is worth mentioning that through the CSARP agreement, Spanish institutions access to MELCOR and other USNRC codes (i.e., STCP, CONTAIN, VICTORIA, etc.) has been granted since its signature. Besides, other agreements, either national or bilateral, allow using other codes, like GOTHIC or ASTEC. Coupled with analytical capabilities, Spain adds a distinctive facility that has been used in a large number of international projects, the Laboratory for Analysis of Safety Systems (LASS), located at CIEMAT headquarters.

Nuclear research, particularly, severe accident investigation is not among the priority areas in the national research plan of the Ministry of Science and Innovation. Fortunately, the research program of CSN and the support of nuclear utilities allows building a consistent program that nicely matches the international ongoing activities. In the case of CSN, the research on severe accident phenomenology and analysis has been considered a strategic area of the Research and Development Plans (2016–2020 and 2021–2025). Through them, CSN joined some of the most impacting projects in the area, particularly under the frame of the OECD/NEA (i.e., BSAF, ARC-F, HYMERES, etc.); and presently, CSN is a partner in the FACE and THEMIS projects. This participation allows Spanish severe accident community access to the data produced and the technical partnership associated.

There are three main groups currently conducting research on severe accidents: the Unit of Nuclear Safety Research in CIEMAT (National research Centre for Energy, Technology and Environment), the group from the School of Mining and Energy Engineering (hereafter, ETSIME-UPM), and the group from the School of Industrial Engineering (hereafter ETSII-UPM). The coming sections describe the recent and ongoing research conducted by the three aforementioned groups and the main outcomes obtained and/or expected from them.

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2. Research synthesis

The Fukushima accident has strongly oriented Spanish research, either by focusing on relevant phenomena that determined the accident footprint, both in-reactor and spent fuel pools, or by exploring new modeling approaches. Spanish organizations have played a visible role at an international scale by: participating in the main ventures, leading work tasks in projects under different frames, being coordinators of EC EURATOM projects (i.e., MUSA, AMHYCO and SEAKNOT), and heading expert groups under OECD/NEA and NUGENIA/TA2 references concerning all of them are given in the reference section.

In addition to the research areas described in the following sections, there are a number of activities that for different reasons are not developed further in this article. Several Spanish teams have spent substantial resources to update their Nuclear Power Plant (NPP) models to the most recent versions of the system codes they use. As a consequence of their research on severe accident, the ETSIME-UPM group has reviewed and verified Level 2 PSA analyses of BWR with Mark-II and Mark-III containments, and also VVER plants; this piece is fully described in the article concerning PSA-2 applications of the present VSI, but not in the present article. The application of the BEPU approach into the severe accident analysis has been heavily dealt with by some of the Spanish severe accident teams, mostly based on the MELCOR code (Humphries et al., 2015); this is, however, left out of the scope of this paper as there is a specific article on BEPU analysis in the Spanish VSI. The same also applies to the impact assessment of ATF claddings on severe accident development or the application of Artificial Intelligence (AI) to severe accident modeling. Finally, all the teams are partners of the recently launched SEAKNOT project, which major outcome will be a roadmap for severe accident research in the coming decade; but the project status is too premature to include any of it in the present paper.

As commented above, severe accident research in Spain is, to a good extent, conducted in international frameworks. Nonetheless, other institutions not directly responsible for the research activities themselves, like the Spanish Nuclear Regulatory Commission (CSN) and some Spanish utilities (Iberdrola Engineering; CNAT), do support it and they keep a strong involvement in their development.

2.1. Centro de Investigación Energéticas Medio Ambientales y Tecnológicas (CIEMAT)

Soon after the Fukushima accident, OECD/NEA, under the request of Japanese organizations, launched collaborative projects aimed first at achieving a deep understanding of the accident unfolding (BSAF, phases I and II) and, later, including also activities to support the post-accident site management and units dismantling (ARC-F and FACE). Additionally, these projects have resulted in significant severe accident codes improvement over the years. Through bilateral agreements with CSN, CIEMAT has been able to join the mentioned projects to perform forensic analysis that might lead to gain insights into the three units undergoing a severe accident (Pellegrini et al., 2020; Pellegrini et al., 2021; Sonnenkalb et al., 2021; Lind and Suckow, 2010), particularly Unit 1 (Herranz et al., 2018).

Through a study of the Fukushima Daiichi Unit 1 data recorded, CIEMAT postulated an accident scenario based on MELCOR 2.1 analyses (Herranz and López, 2020) that reproduced the thermal footprints in terms of RPV and PCV pressures during 500 h. A number of assumptions were made mainly, but not only, concerning: the reactor pressure vessel (RPV) leaking pathways and failure mode; the water flow rate entering the reactor; the potential leaking pathways and failure mode and location from the primary containment vessel (PCV) to the reactor building; the corium relocation from RPV to the cavity and its distribution in the PCV; and, the potential stratification of the suppression pool and the hypotheses made a priori concerning fission product release and transport (Herranz et al., 1997). In particular, CIEMAT has made meaningful contributions to assess the trapping of fission products in the Unit 1

suppression pool (Herranz et al., 2020b; Herranz, 2023) and it is involved in a comparative study of models addressing the interaction between hot corium and concrete in the pedestal of Unit 1 (Pellegrini et al., 2022). For these containment studies, CIEMAT has used the containment model sketched in Fig. 1.

Based on the boundary conditions estimated by MELCOR 2.1 in the Unit 1, most of fission products entered the suppression pool under jet injection regime, which had been hardly explored in the past. Under the frame of the EC PASSAM project (Albiol et al., 2018), CIEMAT conducted an experimental campaign in the PECA-PS facility (Fig. 2) of the Laboratory for Analysis of Safety Systems at CIEMAT (Herranz et al., 2018) to address fission products retention in the jet injection regime. The experimental conditions were set in terms of non-dimensional variables supposed to play a major role on fission products scrubbing: saturation ratio and Weber number. The former characterizes the potential for diffusiophoresis retention, particularly at the pool injection point; the latter balances the inertial and surface tension forces and is frequently used to discriminate between globule and jet injection regimes. Table 1 synthesizes the experimental conditions set in the experiments. The submergence was set to 0.3 m in all the tests and the same particles were used all across the test matrix: 1 μm SiO₂. The reduced submergence is set to preclude the region of bubble swarm as much as possible.

After PASSAM, CIEMAT has continued the investigation of pool scrubbing in the frame of the IPRESCA project (SNETP/NUGENIA/TA2). By reviewing all the available information in the open literature from the early days to 2017, more than 500 experiments have been scrutinized and classified as: “qualified for validation”, “useful for understanding”, or “not useful”, depending on a set of criteria described in Herranz et al., (2022a). As a major outcome, only 15 % of the tests reviewed were considered in the proposed pool scrubbing validation matrix.

Other aspect CIEMAT has paid attention to is in-containment combustible gases (H₂ and CO) behavior, particularly their generation, distribution and recombination in PARs (Passive Autocatalytic Recombiners). This area of work started as a CIEMAT-CSN joint project to explore the effects of PARs and FCVS (Filter Containment Venting System) in a Spanish PWR (Pressurized Water Reactor). It was found that an evaluation of the in-containment deflagration risk would need an accurate containment model, as H₂ distribution was shown to be highly sensitive to it. As for the FCVS performance, the studies indicated that fission product release to the environment might be substantially attenuated by the system, which efficiency was found to be dependent on the opening/closure criteria (Fontanet et al., 2016; 2018). In the international arena, the activities were started under SNETP/NUGENIA/TA2 in the SAMHYCO-Net project (Herranz et al., 2020c) and it has continued in the frame of EC AMHYCO project (Jiménez et al., 2022) and the OECD/NEA THEMIS project). The investigation emphasis was initially put on the better characterization of PAR performance (Fontanet et al., 2022). After launching AMHYCO, the focus has shifted towards the distinctive ex-vessel phase conditions, including the effect of oxygen starvation and the presence of CO. As one of the first steps of the project, a search for challenging conditions in terms of combustible gases management within containment was conducted by simulating more than 40 accident sequences in three types of reactors (PWR-W; PWR-Konvoi; VVER). In addition to model LB- and SB-LOCAs and SBO sequences in a PWR-W 1000 MWe, CIEMAT was responsible for coordinating the entire calculation campaign. This has meant to provide input for experimentalists and containment modelers. CIEMAT modeling work continues by modeling scenarios proposed with MELCOR 2.2.

2.2. Universidad Politécnica de Madrid (UPM)

The main lines of research on severe accident within the UPM are: accident management strategies (including FLEX); severe accident

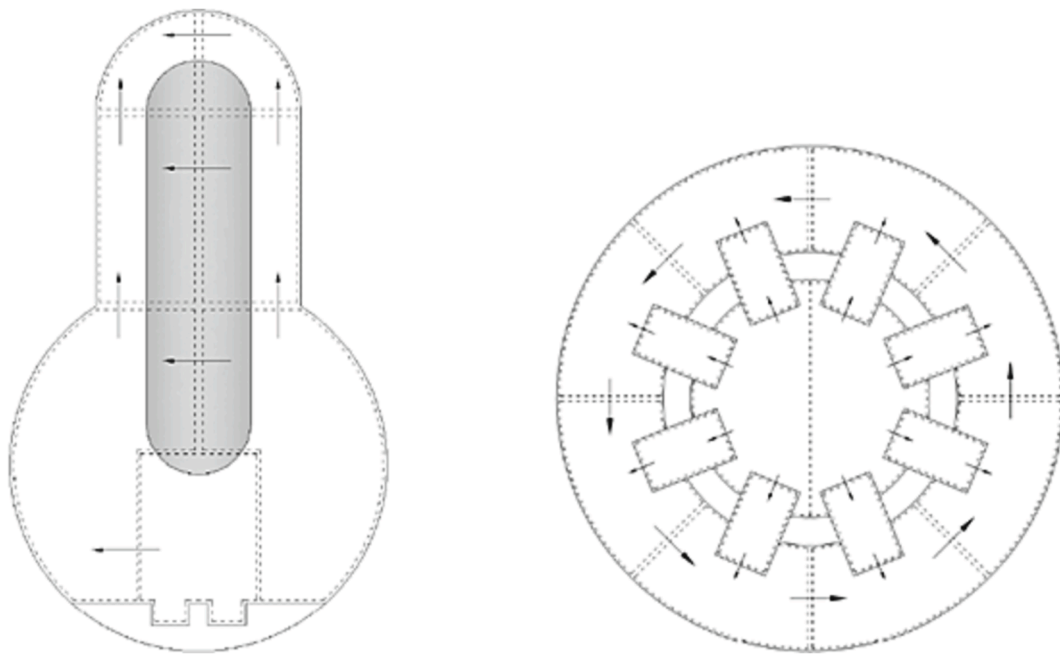


Fig. 1. Primary containment nodalization: Dry-well (left) and Wet-well (right).

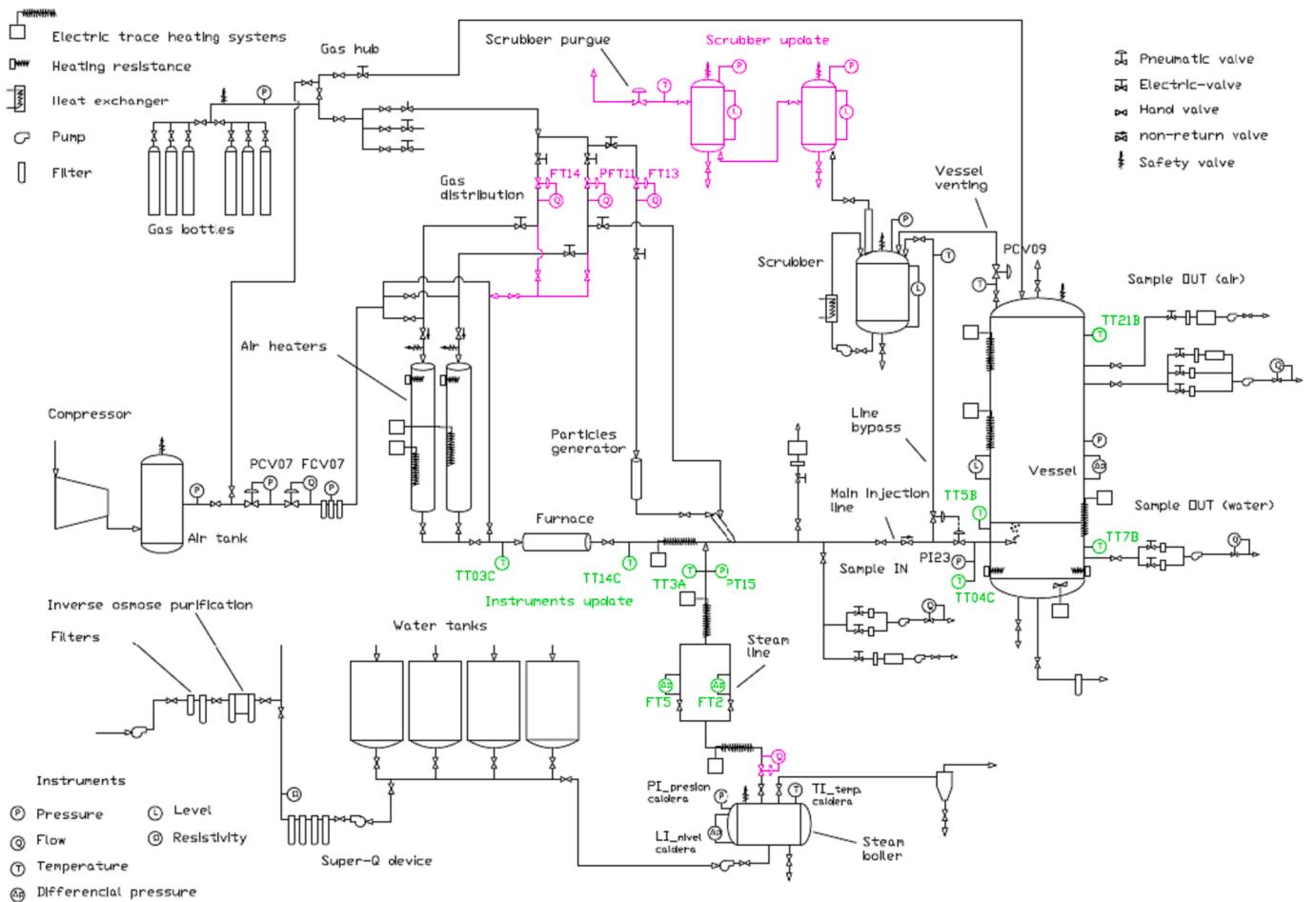


Fig. 2. Configuration of the PECA-PS facility for PASSAM pool scrubbing tests.

Table 1
PASSAM pool scrubbing experimental matrix.

	T_g °C	T_{pool} °C	Q_{steam} l/min	Q_{total} l/min	X_{steam} %vol	We_g	S
PSP0	100	35	5	160	3.13	698	0.60
PSP1	100	35	6	210	2.86	482	0.54
PSP2	100	35	9	310	2.9	1050	0.56
PSP3	100	35	15	460	3.26	2312	0.66
PSP4	100	35	30	460	6.52	2312	1.32
PSP5	100	35	45	460	9.78	2312	1.98
PSP6	Tenv	Tenv	0	460	0	2312	0.00

instrumentation; and 3D containment modeling with emphasis on combustion risk management.

After the Fukushima Daiichi accident, ETSIME-UPM group, in collaboration with other Spanish and international institutions reviewed various SAM strategies in SBO sequences of PWR Westinghouse design. Both seal and non-seal LOCA were analyzed with MAAP4 code (Queral, et al., 2016; Mena-Rosell et al., 2018). The analyses of the results of the simulations resulted in the elaboration of new diagrams called “multiple damage domains”, where the best suited strategy depending on the degree of core degradation could be identified. This approach was extended also to external events (Fernandez-Cosials et al., 2015) and even to Konvoi-type plants (Gómez-García-Toraño et al., 2017; Gómez-García-Toraño, et al., 2018).

Given the extensive implementation of FLEX strategies over the world based on the access to power from protected portable equipment, ETSIME-UPM investigated the prevention and management of severe accident sequences by adopting several FLEX strategies with MELCOR 2.1 (Fernandez-Cosials, et al., 2020). The work, done in collaboration with CSN based on previous MELCOR model (Bocanegra et al., 2016) showed that FLEX strategies effectively complement the SAMGs, with standard installation timings (approximately 1 h) and typical portable equipment mass flow rates (20–60 kg/s) proving adequate to manage the sequence of a LBLOCA with recirculation failure. Fig. 3 shows some of the options explored for RCS injection.

Fukushima also highlighted how crucial instrumentation survivability and reliability might be in case of a severe accident. Online measurements might be used both as indicators of accident progression and as signals for implementing mitigation actions. In this line, the ETSIME-UPM group, in collaboration with CSN, proposed a methodology to assess instrumentation survivability and to identify the suitable mitigation actions and their initiator parameters based on MELCOR 2.1 simulations (Fernández-Cosials, et al., 2022). The instruments damage is continuously assessed throughout the accident progression, ranging from a slight loss in accuracy, to its complete destruction. The method is devised to support the Main Control Room (MCR) and Technical Support

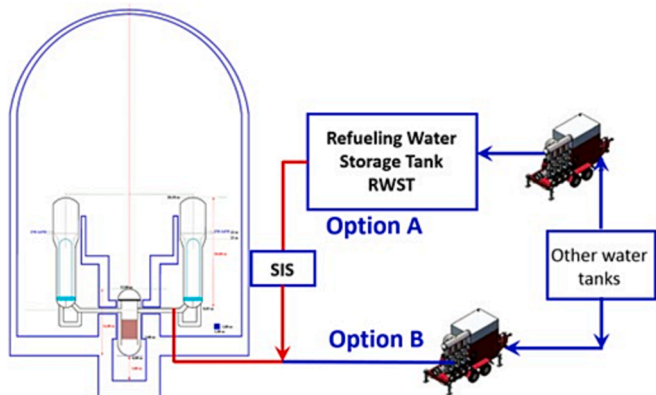


Fig. 3. Example of different options for FLEX portable equipment for RCS injection.

Center (TSC) staff and walk through the accident comparing the requirements of the SAMGs relative to equipment and instrumentation and its degradation level. The methodology has been applied to accident scenarios in PWR and BWR reactors. Fig. 4 shows the MELCOR reactor coolant system (RCS) model used for PWRs and location of instrumentation.

The main activities conducted in the last five years by the ETSII-UPM are framed under the GO-MERES project, sponsored by CSN, and the EC AMHYCO project. The bases for them are rooted on activities initiated from the stress tests conducted in Spanish NPPs and the subsequent implementation of severe accident systems in some of them (Jimenez et al., 2015; Serrano et al., 2016; Díez Álvarez-Buylla et al., 2021; Fernández-Cosials et al., 2018; Jimenez et al., 2017; Fernández-Cosials et al., 2017).

The main goals of the GO-MERES project are the validation of GOTHIC code for containment phenomenology and afterwards some demonstrative applications of the code at full-scale plant in similar conditions than in the selected experiments. In this project, experiments from ERCOSAM-SAMARA, SETH-2, HYMERES, HYMERES-2 and PANDA OECD/NEA project have been simulated to validate GOTHIC 3D capabilities (Vázquez-Rodríguez et al., 2023). Additionally, analytical support for some test definition (HYMERES-2 and PANDA) was also provided. These activities allowed strengthening the GOTHIC capabilities to model suppression pool steam injection, spray actuation or hydrogen mixing in full containment models. Some full-scale plant containment analysis for prototypical BWR and PWR Spanish plants have been conducted with GOTHIC in this project, which will continue in a second phase for the next four years. The behavior of a Mark I BWR suppression pool was studied and the conditions for thermal stratification or fully mixing were explored. Finally, the activation of the containment spray system and its impact on hydrogen risk were studied for a 3 loop W.PWR equipped with a large dry containment. Also within this activity different strategies for the containment spray system activation have been analyzed for a severe accident sequence with maximized hydrogen generation in the in-vessel phase.

The main objective of the AMHYCO project (Jiménez et al., 2021, 2022; Herranz et al., 2022b) is to propose innovative enhancements in the way combustible gases are managed in case of a SA in currently operating reactors. AMHYCO intends to do so by improving the understanding of H₂/CO combustion risk and incorporating this knowledge into SAMGs. ETSII-UPM plays a crucial role in several of the projects activities, as described below.

In collaboration with other project partners, ETSII-UPM contributed to build a critical review of the status of knowledge concerning risk management of gas combustion in the late phase of an accident at the first stages of the project. In particular, contributions were related to: PAR performance modeling based on physical-chemical processes and the 3D model capabilities (GOTHIC); criteria and principles of Environmental Qualification and Survivability Assessment, alongside with a technical data repository of interesting values of the main stressors assessed in PWR NPP qualification programmes for Design Basis Accidents (DBA) and beyond DBA conditions (Fernández-Cosials, 2017); and the publicly available information of Spanish NPP SAMGs.

Based on the experience gained in SAMHYCO-Net project (Kelm et al., 2014), generic containment models for PWR-W, PWR-Konvoi and VVER reactor containments have been built by ETSII-UPM with the support of other organizations (Fig. 5). By building a common database for lumped parameter (LP), 3D, and CFD codes, different nodalizations are recommended depending on the code approach. The Generic Containment (GC) models were developed with the aid of Computer Aided Design (CAD) tools, using publicly available layouts up to the highest level of achievable detail (Serra et al., 2021). Afterwards, a common nodalization for the LP codes and a common database for the 3D models were proposed. This approach is expected to assist the cross-comparison of code predictions and, more importantly, might allow LP model enhancement by being informed through 3D and CFD insights.

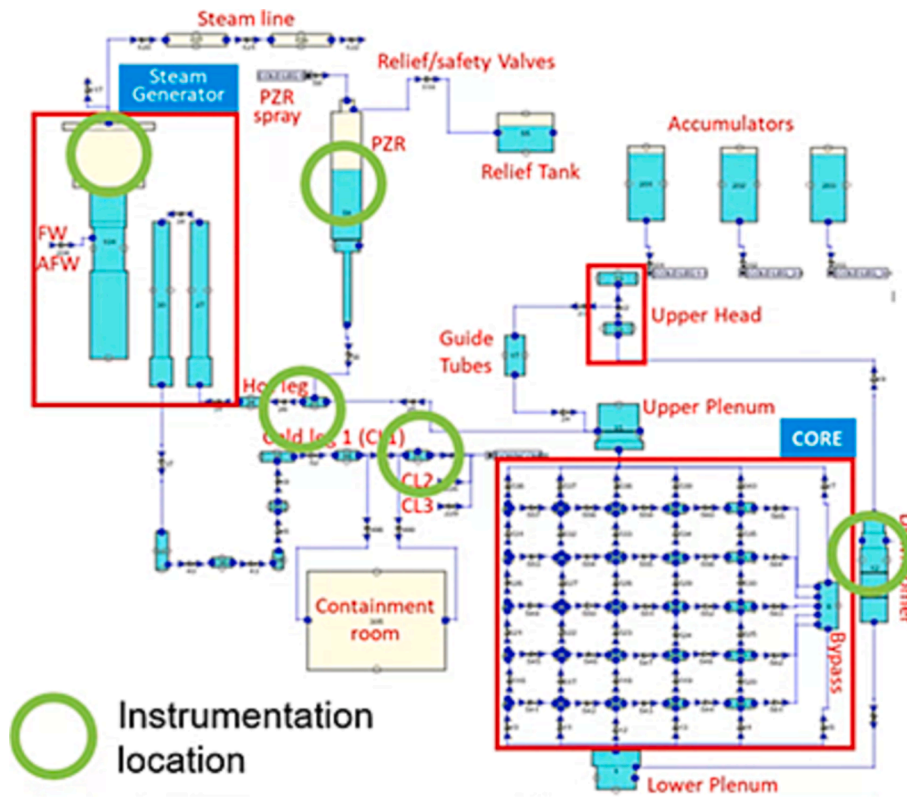


Fig. 4. RCS PWR model (MELCOR code).

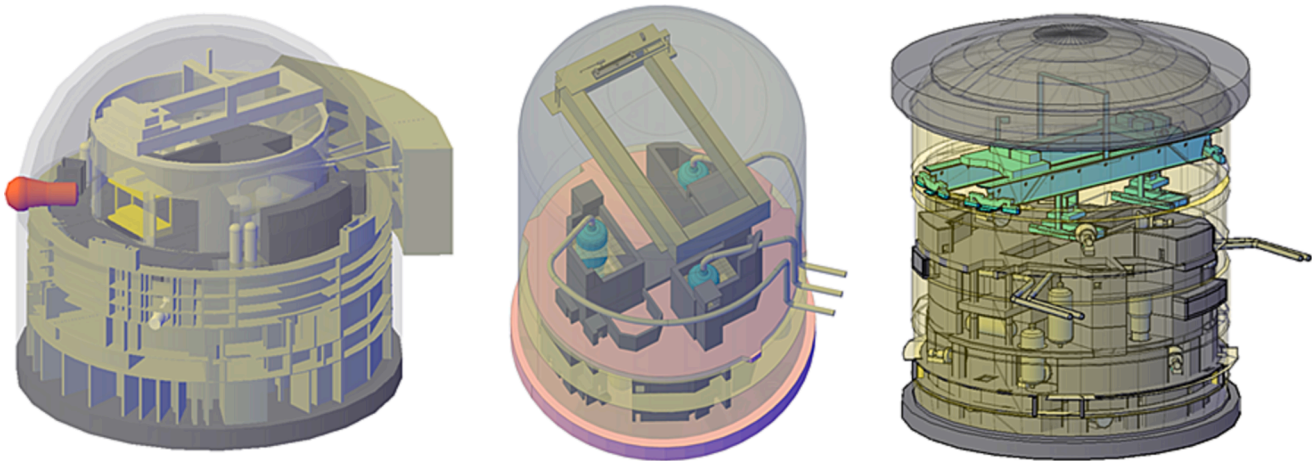


Fig. 5. AMHYCÓs PWR-KWU, PWR-W, PWR-VVER CAD models.

Anyway, this approach will open the discussion on the differences induced by the distinct space discretizations and physical models.

ETSII-UPM is validating the PARUPM code (Domínguez-Bugarín et al., 2022), which was developed based on surface reactions taking place at the PAR plates (Jimenez et al., 2007). The validation of this code was run with both experimental data from the facilities of REKO-3 (FZJ) and the THAI facility (Becker Technologies). The capabilities of the code for simulating different PAR performance conditions (O₂ starvation, CO poisoning, etc.) was tested for both steady state and transient conditions and favorably compared with the experimental database. This model will be used for the 3D full containment model that is planned to be done with GOTHIC as part of the three-level modeling planned to be carried out in AMHYCO: LP, 3D and CFD.

3. Research key outcomes

Next, the key outcomes of the activities and projects described above are given. As highlighted in section 2, some related activities to severe accident research will be reported somewhere else in the Spanish VSI-NFT issue (i.e., uncertainty quantification; ATF effect; AI application; etc.).

3.1. Ciemat

Throughout the analysis of the challenges posed by the Fukushima Daiichi Unit 1 data recorded, CIEMAT proposed a postulated accident based on major assumptions in several regards, particularly on: systems and component responses; effectiveness of accident management

actions; and, the MELCOR model applied. The main features of the scenario are: three leaking pathways were identified from the Reactor Pressure Vessel (RPV) to the Primary Containment Vessel (PCV) (safety relief valve gasket, core instrumentation breaches, and instrumentation sealing failures); three potential locations for the PCV leak were assumed (PCV flange; Dry-Well (DW) sand cushion leak; and Wet-Well (WW) bellows leak); two nominal leakages were set in the Reactor Building (RB), both located at the first and second floors and both open at the explosion time (24.83 h); the corium fell in the RPV cavity and distributed freely across the PCV; the suppression pool was considered axially and circumferentially stratified; water injection was assumed unsuccessful until 273 h, when the injection point was moved to the feed water line. As shown in Fig. 6, a noticeable agreement with the RPV and PCV pressures during 500 h has been achieved (Herranz et al., 2020a). As indicated in the Fig. 6, the RPV and PCV leaks/failures, as well as venting played a determining role in the short run of the accident and water injection heavily conditioned the long one.

Additionally, the qualitative comparison with dose rates data in containment show a reasonable consistency and supports the low prediction of iodine and cesium core inventories at the onset of the accident to the environment. The simulation confirmed the high relevance of the suppression pool in the trapping of fission products, although an eventual recombination from the sump due to the containment venting at about 24 h cannot be neglected. No less important, MELCOR 2.1 predicts some cesium revaporization from the upper structures in the RPV in the longrun of the accident. Based on the postulated scenario, an analysis of the long term containment cooling indicated that a reduced water injection might lead to an increase of the relative release of cesium to the environment, but the timing of the injection seemed not to significantly affect the source term (Herranz and Bocanegra, 2021).

As for the main mechanisms responsible for particle scrubbing according to MELCOR simulations, most of fission products were trapped at the inlet of the pool as a consequence of diffusiophoresis and inertial mechanisms. However, a thorough examination of the approximations underneath the corresponding models have been found to be questionable and some new formulations have been implemented within the stand-alone SPARC-90 code (Owczarski and Burk, 1991), which is the basis of the MELCOR models for pool scrubbing. However, despite that qualitative differences were found once the models were upgraded, quantitatively the models enhancement did not have a major impact.

Expectations were different as for including a jet scrubbing model. Two approaches were, in fact, taken (Herranz, 2023): an analytical one,

based on the similarities between a submerged jet and in-pipe annular flow; and an empirical one, which relied in the PASSAM jet experiments and some additional data points found in the literature at those high injection velocities. The results showed differences of up to a factor of 2 in terms of the Decontamination Factor (DF) during the fission product arrival to the suppression pool. Nonetheless, when these values are looked at from the perspective of the uncertainty associated to those DFs (around two orders of magnitude), they lack of quantitative significance. The semi-empirical correlation derived is the recommended model to estimate jet scrubbing:

$$\varepsilon = \frac{0.98}{1 + 1.0847 \hat{A} \cdot \text{Exp}(-1.0528 \hat{A} \cdot 10^8 \hat{A} \cdot \text{Stk}^{3.7885} - 0.7257 \hat{A} \cdot S)} \hat{A} \cdot 100$$

Note that the retention efficiency correlates with the Stokes dimensionless number (Stk), which accounts for the inertial impaction, and the saturation ratio (S), which captures the driving force for diffusiophoretic deposition (Herranz et al., 2018). The correlation determination coefficient (R^2), though, is considered low (0.8).

CIEMAT has persistently defended that pool scrubbing modeling lacks of a systematic validation, through which individual models first and then codes, get tested. The target, as discussed recently (Herranz and Sánchez, 2023), should be to qualitatively follow the physical trends expected with major affecting factors (i.e., gas composition; particle size; submergence; etc.), and quantitatively enhance predictions, particularly for DFs over 10 and under 100 (DF values over 100 are hard to give any credit, as they represent a very small amount of mass).

CIEMAT modeling work of specific severe accident phenomena (i.e., pool scrubbing, particle nucleation, in-containment aerosol behavior, etc.) and related databases have been reported to MELCOR developers and USNRC by technical presentations made during the annual CSARP meetings and technical reports.

CIEMAT analysis of PARs performance focused on FRAMATOME PARs. By comparing the manufacturer proposed correlation with nearly 20 THAI experiments, major deviations were noted concerning recombination onset and lean-oxygen conditions. A simplification of the correlation was proposed and compared again with data. The predictions enhancement was visible. However, when the enhanced correlation was used in several accident scenarios (LOCAs and SBO in a PWR-W 1000 MWe), the effect on combustible gases concentration evolution was just slight, even if significantly different recombination rates are estimated (Fontanet et al., 2022). This might be seen as a buffering effect, as the

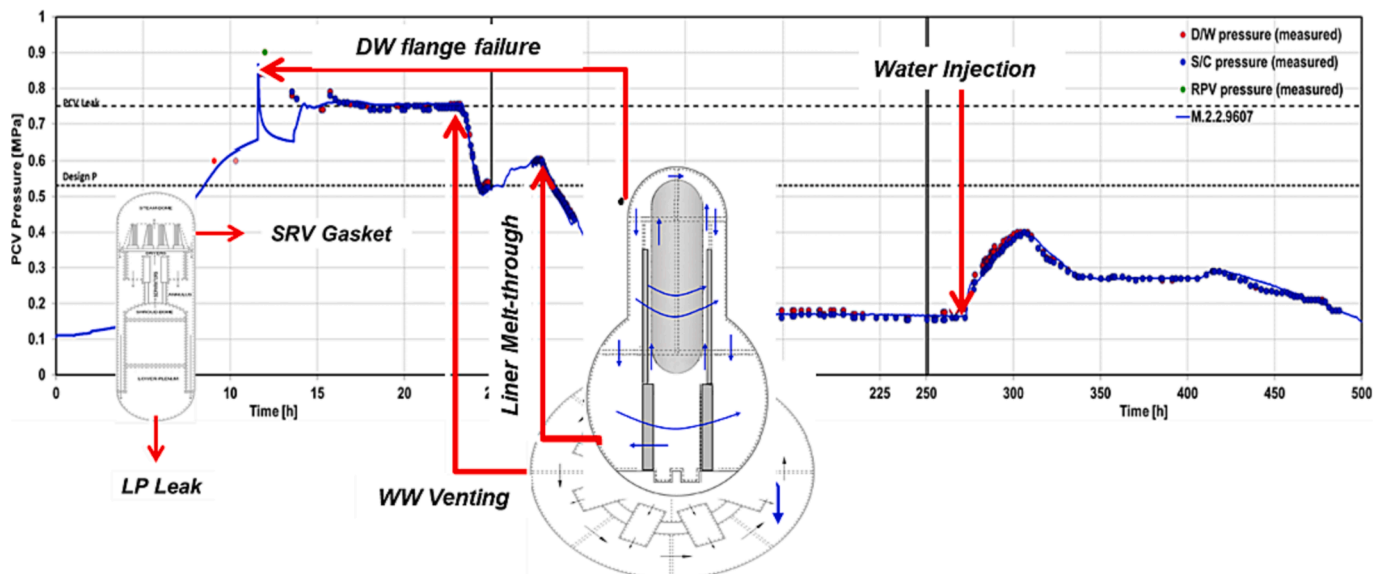


Fig. 6. Containment pressure evolution in 1F1 (MELCOR 2.1 predictions and data).

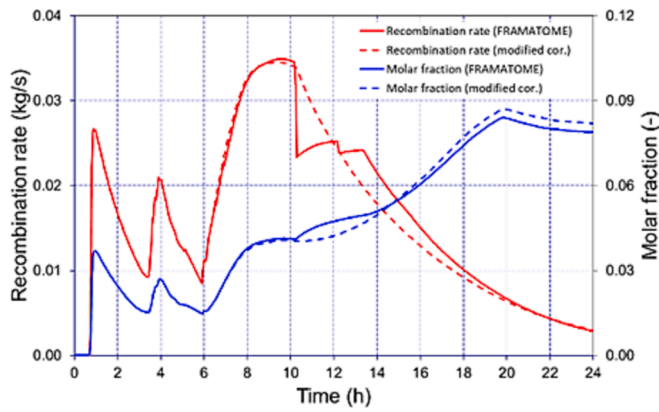


Fig. 7. Recombination rate and H2 molar fraction in a SBLOCA sequence.

recombination rate eventually depends on combustible gas concentrations. All these calculations were conducted with MELCOR 2.2 (Fig. 7).

From all the sequences analyzed in AMHYCO (Herranz et al., 2022c), in the case of CIEMAT’s analyses of a PWR-Western 1000 MWe, the LBLOCA has resulted to be the one associated to the highest risk of gas combustion (Fig. 8 – Fig. 9). These conditions, along with others from other reactor types, will be used in AMHYCO to perform the containment analysis at the three levels introduced in the previous section. CIEMAT will carry out MELCOR simulations (LP level).

3.2. UPM

Concerning the research conducted on severe accident management/ and instrumentation survivability, two high level outcomes might be withdrawn: verification of SAMGs, FLEX strategies included, is a useful tool to identify scenarios and phenomena that might play distinctive role in the severe accident unfolding; further attention should be paid to severe accident instrumentation, as an *a priori* characterization of its response under the anticipated harsh conditions, might eventually help the right implementation of accident management actions.

In particular, from the assessment of FLEX strategies, it was found out that depending on the timing of water injection and recirculation failure, it is possible to prevent or halt the degradation of the core. Additionally, the different mass flow rates explored (20–60 kg/s) delivered by the FLEX portable pump were noted to have a very limited effect on the core final state (i.e., increasing mass flow rate over 20 kg/s does not change the pace of the accident). Nonetheless, the amount of hydrogen generated during the accident does vary with different portable pump mass flow rates.

Regarding the Instrumentation assessment, it was seen that during a severe accident, it is likely to enter time periods where the

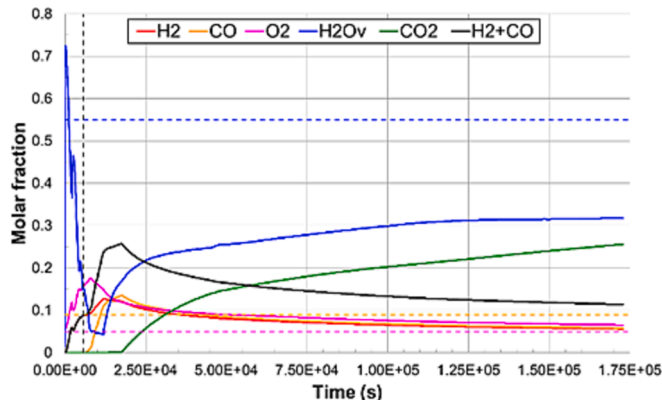


Fig. 8. Gas composition for LBLOCA in PWR-W.

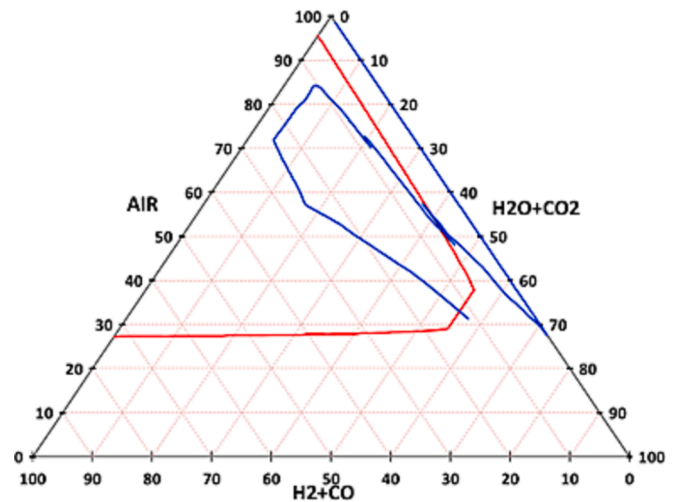


Fig. 9. Shapiro diagram for LBLOCA in PWR-W.

implementation of Candidate High Level Actions (CHLA) present in SAGs will be done in a close-to-blind manner. As the severe accident progresses, some SAGs will have all instrumentation related to the CHLA in a degraded state or even completely destroyed and therefore unreliable from the TSC point of view. The methodology developed by UPM-ETSIME precisely addresses this issue and provide an insight to the TSC.

As for the containment modeling, the 3D approach (GOTHIC) has proved to be insightful in complex containment configurations, like the Mark-III containment (Jimenez et al., 2015; Serrano et al., 2016; Díez Álvarez-Buylla et al., 2021). Specific tasks benefited from the 3D approach were PAR sizing and location and Filtered Containment Venting System (FCVS) actuation. This statement, though, may be also applied for PWR-W when studying pressure and temperature distribution in containment rooms (Jimenez et al., 2017) to assess equipment qualification requirements or the effect of FCVS performance (Fernández-Cosials et al., 2017).

The experimental testing of GOTHIC left two major insights: (1) the code might be limited to reproduce suppression pool stratification/ mixing related to different steam injections (Estévez-Albuja et al., 2020; Gallego-Marcos et al., 2019a, 2019b, 2018); (2) if properly built, GOTHIC models allow capturing the trends in a multi-phase, multi-component problem like a containment sprayed scenario, even with relative coarse meshes (Vázquez-Rodríguez et al., 2023); Fig. 10 illustrates it.

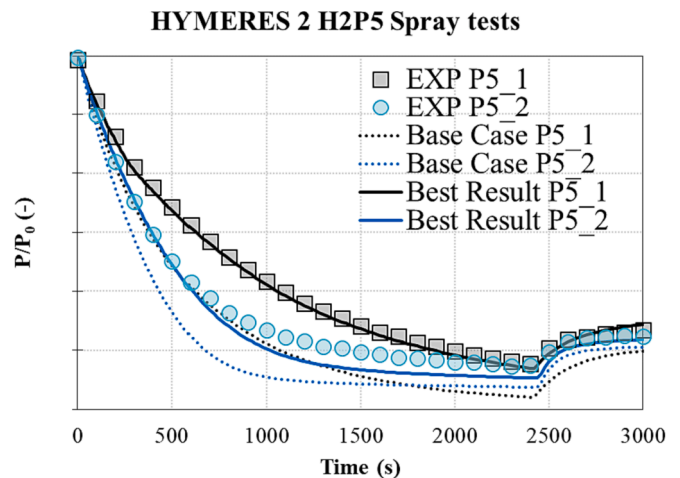


Fig. 10. GOTHIC best and base cases of HYMERES 2 H2P5 spray tests (Vázquez-Rodríguez et al., 2023).

The three-level simulation methodology is certainly very relevant for the containment modeling and has been feasible thanks to the CAD databases built by ETSII-UPM for different reactor technologies. To start with, it will allow meaningful cross-comparison of the three thermal-hydraulic resolution levels, having consistent free volumes and wall surfaces (Fig. 11). Additionally, PARUPM has been validated with the AMHYCO experimental results from REKO (FZJ) (Fig. 12) and coupled with the GOTHIC code.

4. . Expected developments of research

From the research activities described in sections 2 and 3, some present expectations should come true in the coming years:

- Enhanced national capabilities to manage severe accidents in case they ever happen. There are two facts that support such a strong statement. First, most of Spanish research on severe accidents is accident management driven; examples have been given above (i.e., FLEX strategy; instrumentation survivability; sprays performance; etc.); moreover, a significant number of plant applications are performed within the research activities. Second, given the tight connection between the Spanish research community on severe accidents and Spanish regulators and utilities, the transfer of the latest advances from research to its users is ensured. This makes the entire national system involved in such an emergency to be ready and, in case of need, to respond based on the best background feasible. The deep involvement of Spanish research teams in international frames strengthen their abilities and turn them in effective assets for the country nuclear safety.
- Sound knowledge on specific phenomena with the potential of heavily impacting the consequences of a severe accident. Examples are: combustible gases recombination and distribution throughout containment as well as their combustion regimes; and aqueous trapping of fission products. Associated to such sound knowledge it comes a thorough validation of models used in the simulation tools.
- Better and sounder assessment of risks. New modeling approaches for severe accident scenarios and phenomena (i.e., in-containment combustion) are being explored. This points straight to the ongoing international investigation to bring UaSA (Uncertainty and Sensitivity Analysis) into the severe accident domain analysis, but also to the multi-level thermal-hydraulic approach that is being currently tested; in both cases Spanish institutions are playing a leading role. In addition, modeling Fukushima Daiichi through forensic analyses has turned into an invaluable hands-on training with severe accident system codes.

As for work ahead, there are some activities towards which the Spanish teams are already paying attention to:

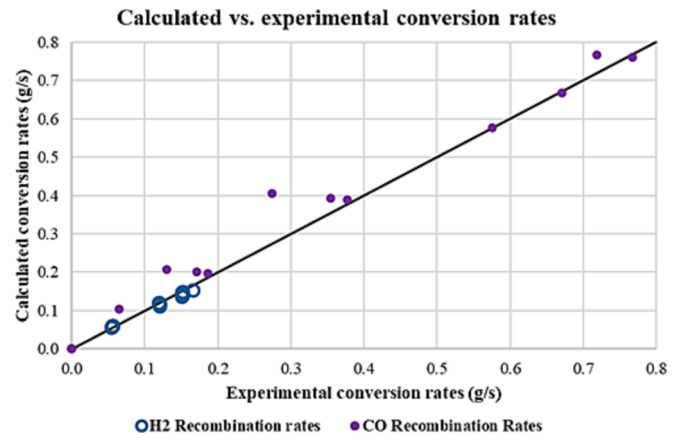


Fig. 12. PARUPM predictions of recombination rates against REKO-3 experimental data.

- Assessment of FLEX strategies and instrumentation survivability in Boiling Water Reactors.
- Verification of SAMGs in Gen. III (e.g., VVER 1200, AP1000, ...) and Small Modular Reactors (SMRs). For the latter, combustion risk management seems an area worth visiting, since many of the current designs rely heavily on safety measures that entail highly condensing environments that might result in high combustible gas concentrations.
- Investigation of unexpected observations coming out of the Fukushima Daiichi, which might affect the long-term management of severe accidents (i.e., fission products distributions; sediment nature; status of the units pedestal; etc.).
- Consolidation of the new modeling approaches under investigation and codes extension to systems other than LWRs, particularly SMRs.
- Pool scrubbing experimentation in the frame of THEMIS or the IPRESCA. A thorough critical review of available experimental data highlighted that some ranges of the governing boundary conditions anticipated in severe accidents might not have been given enough attention, like high injection flow rates, fission gas scrubbing/remobilization or presence of structures and impurities in the water bulk

Finally, the SEAKNOT project, as mentioned above, has been devised to produce a roadmap on severe accidents research in the coming ten years. The deep involvement of the Spanish research community and regulators allow foreseeing that the project outcomes will have a strong effect in shaping up the future national activities.

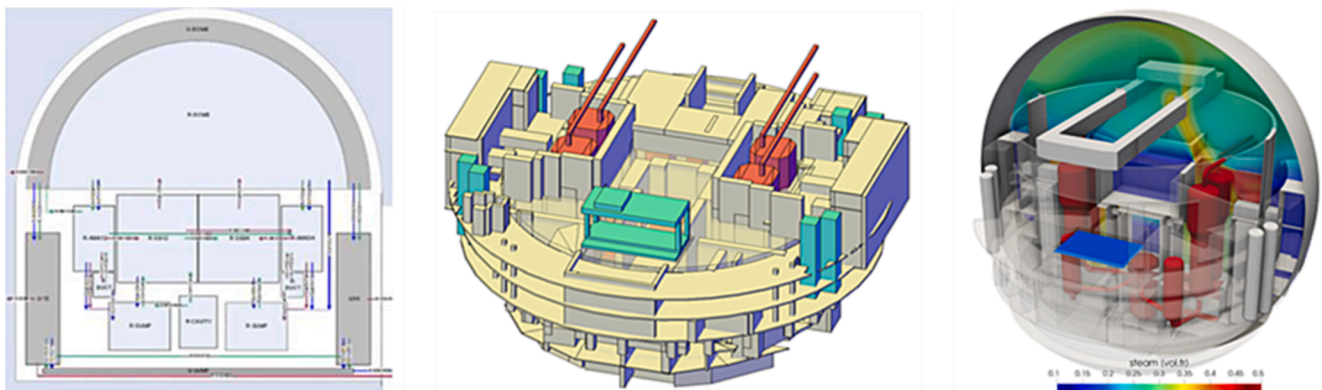


Fig. 11. AMHYCO lumped parameters, 3D, and CFD models.

5. Connection of Spanish research and the VSI framework

The current nuclear situation in Spain (phase out policy by 2035 according to the Integrated National Plan for Energy and Climate, PNIEC), affects only indirectly the Spanish severe accident research. On one side, the Fukushima Daiichi effect and the subsequent stress tests conducted, have fed the national activities. The utilities have implemented new systems in their NPPs aimed at mitigating the consequences of a severe accident (PARs, FCVS; mobile equipment; etc.) with the corresponding oversight of the regulatory body. Both roles involved launching a number of research activities by the national research center (CIEMAT) and Academia (mostly UPM), many of which have been reported here. The supporting role of the Regulatory Authority (CSN) is worth mentioning, as it allows preserving and transferring knowledge to young generations of Spanish researchers. On the other, Spanish severe accident research activities are to a good extent conducted in international frames and, hence, is not so heavily conditioned by the domestic situation. This international nature has a triple effect:

- Strengthening the national capabilities by the technical exchanges in international frames.
- Contributing to the international progress in the area, which usually means making or proving that running reactors are even safer than previously estimated.
- Looking ahead to upcoming innovative technologies (ATFs, SMRs), so that even in the case of new builds, the Spanish nuclear sector would be ready from the severe accident perspective.

Nonetheless, Spanish severe accident research might note some indirect effect, though, from different circumstances:

- The phase-out policy is a negative motivation for picking up nuclear technology as future professional career of students.
- The high activity in the nuclear sector in the last 5 years has meant a transfer of youngsters from research to utilities.

Overall, the severe accident knowledge in Spain has grown significantly thanks to the research activities and has focused particularly on different practical aspects of the accident management, and the progress is passed to the latest users to enhance safety of the still running reactors.

6. Conclusion

A number of highlights may be withdrawn from the previous sections and are here synthesized:

- Spanish research on severe accident is deeply integrated in the existing international frameworks, both in terms of agencies (i.e., IAEA, NEA, NUGENIA/TA2, etc.) and specific projects. In recent years, its visibility has grown substantially.
- CSN support through its investigation plans has been instrumental to progress in the understanding of severe accident and, no less important, to preserve the knowledge gained. The participation of CSN in international projects permit the access of the Spanish severe accident community to the experimental results and the international groups involved in them.
- Utilities and engineering companies have also contributed to this effort.
- Most research in the last decade has been driven by accident management (i.e., FLEX strategy; combustion risk in containment during the ex-vessel phase; passive systems performance; etc.) and the interest in achieving a thorough understanding of the Fukushima accidents (i.e., safety systems performance; alternate water injection; management measures in the long run; etc.).
- The nature of the investigation is massively analytical, both using codes of different scope and developing physical–chemical models.

Nonetheless, there is a specific laboratory that has been testing safety systems and contributing to specific databases of international projects.

- Complementary to the issues being investigated, huge resources are being spent on adopting new modeling approaches of severe accidents, like UaSA or multi-level containment analyses.
- The tight bond between the Spanish severe accident research community and national regulators and utilities, set a useful bridge to transfer the most significant advances to the final users of this investigation.

Despite the current nuclear situation in Spain, the severe accident workforce keeps moving at full speed, both at national and international level. However, if the situation continues, it is foreseeable that the nationally-rooted activities will decrease and the interest of young generations to join severe accident research will be hard to maintain.

CRedit authorship contribution statement

L.E. Herranz: Conceptualization, Investigation, Writing – original draft. **A. Domínguez-Bugarín:** Investigation. **K. Fernández-Cosials:** Investigation, Writing – review & editing. **J. Fontanet:** Investigation, Writing – review & editing. **G. Jiménez:** Investigation, Writing – original draft. **J.M. Martín-Valdepeñas:** Writing – review & editing. **C. Queral:** Investigation, Writing – original draft. **F. Robledo:** Writing – review & editing. **L. Serra:** Investigation. **C. Vázquez-Rodríguez:** Investigation.

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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