Severe Accidents research in the frame of SNETP/NUGENIA: Recent major achievements (2019-2023)

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Abstract – *Severe accident research is the only way to achieve the best possible management in case such unlikely events eventually happen. Early this century, the Severe Accident Research NETwork (SARNET) was born as an EC project and about 10 years later it became the technical area 2 of NUGENIA, the SNETP (Sustainable Nuclear Energy Technology Platform) pillar devoted to research on Gen. II and Gen. III Light Water Reactors (LWRs). This paper describes the most relevant outcomes from NUGENIA/TA2 research in the last five years concerning coolability of in-vessel and ex-vessel corium/debris, in-containment phenomena, and source term; besides, the progress made and underway on severe accident modelling is outlined. Finally, the NUGENIA/TA2 commitment to knowledge dissemination through courses and conferences is highlighted.*

Keywords: Severe Accident, SNETP, NUGENIA

I. Introduction

No matter how unlikely they are, severe accidents (SA) may happen and, then, the best management possible of an incredibly complex scenario is needed. Both preventive and mitigating actions are articulated in Severe Accident Management Guidelines (SAMGs), whose development requires an in-depth knowledge of both SA phenomena and their interaction, as well as management measures (i.e., efficiency, modes of implementation, side effects, etc.). Consequently, investigation on SA has been ongoing for decades.

Even though SA research started with the development of nuclear power, it was after the Three Mile Island accident, in 1979, that it took off and drew major attention among nuclear technology scientists with particular emphasis given to fission product release and transport. Roughly a decade later, in the 1990's most research focused on the international PHEBUS-FP project [1]. In 2004, the search for an efficient use of the still available technical and human resources in Europe ended up with the launch of the Severe Accident Research NETwork (SARNET) under the 6th and 7th Framework Programmes (FP) of the European Commission (EC) from 2004 to 2013 [2]. It was coordinated by IRSN, mostly with participation of European institutions, although prominent Asian and American organizations in SA research also joined the network. SARNET self-sustainability was achieved through integration in the NUGENIA European association in 2013, which had been created two years before to foster R&D on fission technology of Gen. II and III reactors. Since then, SARNET turned into what is known as NUGENIA Technical Area 2 (NUGENIA/TA2) of the Sustainable Nuclear Energy Technology Platform (SNETP) (https://snetp.eu/technical-area-2-severe-accidents).

This paper presents the major developments and achievements on SA research accomplished in the last five years by NUGENIA/TA2.

II. Major achievements

The issues investigated have been inspired by periodic prioritization of SA research needs [3-4], which aimed at reducing the uncertainties in current analytical tools and enhancing the capability of accident management. In all the cases, the projects enlarged the existing database and enhanced the modelling capability at the time. Table I gathers the full list of projects recently ended or still ongoing.

Table 1: List of NUGENIA/TA2 projects

Acronym	Domain	Duration	Coordinator	Funding
SAMHYCO-NET	H2 risk	2017-22	IRSN	In-kind
ASCOM	SA modeling	2018-22	IRSN	In-kind
IPRESCA	Pool scrubbing	2018-23	BT	In-kind
MUSA	Modeling / Source Term	2019-23	CIEMAT	H2020
R2CA	Modeling	2019-23	IRSN	H2020
AMHYCO	Risk combustible gas	2020-24	UPM	H2020
SEAKNOT	Cross-cutting	2022-26	CIEMAT	H-Europe
ASSAS	Modelling (AI)	2022-26	IRSN	H-Europe
SASPAM	Modeling (SMRs)	2022-26	ENEA	H-Europe

The technical domain of NUGENIA/TA2 (Severe Accidents) is split in several sub-domains: in-vessel corium/debris coolability; ex-vessel corium; containment phenomena; source term; and, accident scenarios. Specifics in each of them are given in the next sub-sections.

II.A. In-vessel corium/debris coolability

The objective of the research activities has been the analysis and the assessment of strategies for the corium retaining in the Reactor Pressure Vessel (RPV) as well as the minimization and the delay of the material transfer to the containment. Therefore, by focusing on the cooling of degraded in-vessel components and the in-vessel corium behaviour, such strategies aim at impacting the definition of the Severe Accident Management (SAM) for the current Nuclear Power Plants (NPP) as well as for the innovative concepts, i.e. Small Modular reactors (SMRs).

Many research activities have been launched in the EU and NUGENIA framework in the period 2019-2023. Such projects have been significantly triggered by the activities launched in the previous time period, which allowed opening and identifying new research paths. One example is the H2020 EC IVMR (In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs) project [5], coordinated by IRSN. The project, launched in 2015, provided new experimental data on the corium behaviour within the RPV lower head in different conditions. One of the main outcomes of the IVMR project was the assessment of a new methodology based on the residual thickness of RPV as a safety criterion for the In-Vessel Retention (IVR). Other than the potential for the improvement of the SAM of large and mid-size (VVER) power reactors, the IVMR project provided insights to improve the capability of the Accident Source Term Evaluation Code (ASTEC) [**¡Error! No se encuentra el origen de la referencia.**], developed by IRSN, to model the corium behaviour in the RPV lower plenum as well as the IVMR. As this strategy is one of the main safety issues in SMRs, the new ASTEC features linked to IVMR are being widely used in the research activities carried out as part of the ongoing SASPAM-SA European project. (Safety Analysis of SMR with PAssive Mitigation strategies - Severe Accidents) [**¡Error! No se encuentra el origen de la referencia.**]. This project aims at investigating the applicability and transfer of knowledge on SA in the operating large-LWR reactor knowledge to the near-term deployment of integral PWR (iPWR), with the emphasis given to needs concerning management and Emergency Planning Zone (EPZ) licensing analyses

Moving to the research facilities, the 7th FWP of EC: SAFEST (Severe Accident Facilities for European Safety Targets) [**¡Error! No se encuentra el origen de la referencia.**] and ALISA (Access to Large Infrastructures for Severe Accidents) [**¡Error! No se encuentra el origen de la referencia.**] projects, both led by KIT, provided an important impulse to develop new large experiments. As an example, the LIVE3D test vessel at KIT [**¡Error! No se encuentra el origen de la referencia.**] for investigating the evolution of the in-vessel late phase of a SA has been further developed to investigate the cooling effect of control rod guide tube (CRGT) in the lower head of a BWR (LIVE-BWR) [**¡Error! No se encuentra el origen de la referencia.**]. Furthermore, experiment have been performed to better understand the debris melting behaviour in the late in-vessel process of the Fukushima Unit 2 (LIVE-J1) [**¡Error! No se encuentra el origen de la referencia.**], in order to accomplish safe decommissioning of the Fukushima Daiichi NPP. A sketch of the LIVE-BWR facility and the LIVE-J1 experiment performed in the framework of the KIT/JAEA collaboration are shown in Figure 1.

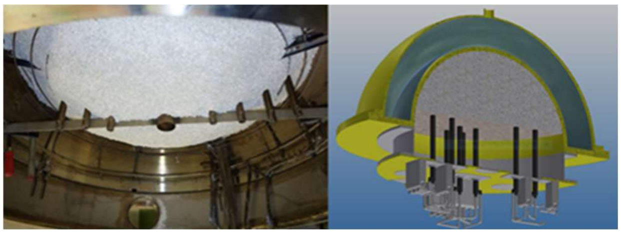


Figure 1. LIVE3D-BWR (left) [**¡Error! No se encuentra el origen de la referencia.**] and the LIVE-J1 (right) [**¡Error! No se encuentra el origen de la referencia.**] test vessel facilities.

The results obtained in the framework of the CoreSOAR [**¡Error! No se encuentra el origen de la referencia.**] and QUESA (QUEnch experiment with Steam and Air) [**¡Error! No se encuentra el origen de la referencia.**] in-kind projects are expected to provide significant insights to the on-going SEAKNOT (SEvere Accident Research and Knowledge ManagemenT) project (2022-2026) [**¡Error! No se encuentra el origen de la referencia.**]. **C**oordinated by CIEMAT, SEAKNOT aims at building a roadmap for Severe Accident (SA) research for the next decade (innovative technologies, as SMRs and ATFs are within the project scope)

Being focused on updating the previous state of the art on core degradation, the CoreSOAR project (2016-2018), coordinated by IRSN, revised the major experimental programs in the last 20 years (Phébus FP, QUENCH, LIVE-2D/3D, HEVA/VERCORS, VERDON, PRELUDE/PEARL, and KROTOS), updated the material properties database and modelling, and highlighted research priorities like the need for further data on debris coolability. At the same time, several air ingress bundle experiments were carried out, e.g. AIT-1, AIT-2, QUENCH-10, PARAMETER SF4, QUENCH-16, and QUENCH-18, in the framework of the QUESA project (2016-2018), coordinated by GRS, aiming at investigating the effect of air ingress into RPV on the oxidation and degradation of the in-vessel materials [**¡Error! No se encuentra el origen de la referencia.**].

Under most of the above projects, the analytical tools have been significantly enhanced and the field of application has been extended. In particular, in the frame of the ASCOM in-kind project (2018-2022), coordinated by IRSN, the field of application of the ASTEC code has been widened to Spent Fuel Pools (SFP), SMRs, and BWRs, and the validation matrix has been further expanded.

One may, therefore, recognize a continuity among the different research projects in line with the strategy of the NUGENIA TA2. The new methodology developed for the IVMR strategy as well as the corresponding validation against experiments allows a significant improvement of the performance of the integral codes for the safety assessment of SMRs, which are used in the on-going SASPAM-SA project. The research activities currently on going as follow-up of the SAFEST and ALISA projects are expected to further improve our knowledge on the corium and debris behavior in the lower plenum and is expected to be employed in the currently going-on SEAKNOT project. Furthermore, the activity in the QUESA project allowed the increase of the validation matrix of the SA codes [16] and contributed to trigger the currently going-on activities focused on the analysis of the behavior of ATF cladding materials, i.e. FeCrAl, in high-temperature steam environment [17**¡Error! No se encuentra el origen de la referencia.**] and the development of the corresponding physical models in the integral codes [16]. Finally, the tight exchange among the users and developer of the ASTEC code in the ASCOM project allowed a significant improvement of the robustness and the stability of the latest versions of the code as well as the enlargement of the ASTEC capabilities to be successfully employed in innovative technologies, i.e. SMRs.

II.B. Ex-vessel corium

Research on ex-vessel phenomena during 2019-2023 has decreased in the frame of SNETP/NUGENIA (SAFEST and ALISA projects were ended), but some domestic European activities are still existing: in case of flooded or partially flooded reactor pit, Fuel Coolant Interaction and its possible consequence Steam Explosion, spreading under water are topics of high interest; for dry reactor pits, corium spreading, corium-concrete interaction and corium/debris bed coolability, are also being investigated. Since the Fukushima Daiichi accidents, long term processes in damaged reactors have drawn the attention of the research community, as they might entail the release of fission products through potential leaching phenomena [18], and they seem to be essential for a thorough understanding and modelling of the accident unfolding. Besides, corium thermophysical properties measurements at liquid state, needed for reliable modelling, is also a topic of interest (see Figure **2**) [19]. In the frame of OECD/NEA, an international project- COPS (COrium Properties for reactor Simulation and uncertainties)- devoted to thermophysical properties and their impact on corium phenomenology should start in 2024 with CEA as operating agent.

In the frame of SAFEST project, the improvement of post-test analyses for ex-vessel conditions: a MCCI corium sample coming from a previous FRAMATOME test has been chosen as representative of the complexity and heterogeneity of corium concrete samples. Four European laboratories were involved using classical tool post-test analyses. This task has allowed to qualify for the first time experimental uncertainties on corium composition. As a consequence of these activities, it has been built the Intra-European Network for Corium Analysis (INCA), which is a consortium of European laboratories which collaborate in the thorough characterization of corium samples. Knowledge of solid state for corium debris coolability and for corium decommissioning of severely damaged NPPs, like Units 1-3 of Fukushima is a key issue. The latter has been one of the goals of the OECD Pre-ADES project [20]. More recently fundamental studies of final corium solid state have been performed using instruments located around synchrotron radiation sources (SOLEIL or ESRF) or the ILL neutron source and has been able to give important information on the solid solution $U_{1-x}Zr_xO_{2+/-y}$[21].

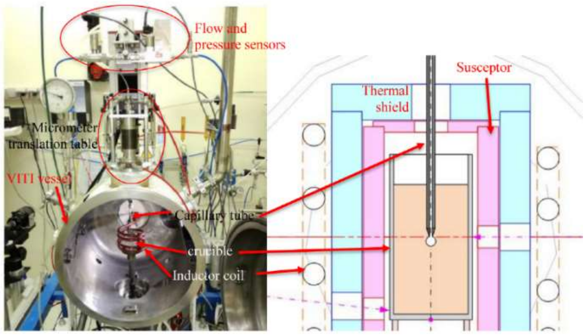


Figure 2. VITI facility- PLINIUS platform- Corium Thermophysical properties measurements-Maximum Bubble Pressure configuration

Recent work to better modelling of premixed layer in stratified fuel–coolant configuration has been done showing the possibility of higher steam explosion energetics in this configuration [22].

Modelling for Gen III+ reactor have been performed to assess core catcher concepts and the ability but also limitation of the current modelling [23].

As for other severe accident topics, SEAKNOT (2022-2026) [**¡Error! No se encuentra el origen de la referencia.**] will be able to identify the remaining important open issue for ex-vessel management and the necessary experimental efforts needed for Gen. II, Gen. III reactors, and SMRs.

At last, in the frame of the European program OFFERR (2022-2026), some severe accidents experimental activities are proposed such as the PLINIUS platform at CEA-Cadarache, IRESNE institute [24].

II.C. Containment phenomena

Within SNETP/NUGENIA, research on containment phenomena resumed within the in-kind project SAMHYCO-NET (2017-2022), coordinated by IRSN. Following that, within the AMHYCO H2020 project (2020-2024), coordinated by UPM, the knowledge gained on hydrogen distribution and combustion is being brought into the practical arena of accident management and lessons learned have been published under the IAEA [25-26] and the OECD [27] auspices.

II.C.1 Containment atmosphere behaviour

A Generic containment benchmark, coordinated by FZJ, was performed to discern the differences between lumped-parameter codes that might have a significant influence on simulations in safety analyses of actual NPPs [28]. A generic scenario based on the German KONVOI containment (Figure 3), with uniquely defined modelling of containment geometrical characteristics and materials, as well as initial and boundary conditions, was proposed. The first step tracked down fluid flows and heat/mass transfer in the system, with particular attention to H_2 distribution, whereas the second step addressed the same scenario, but with added PARs (Passive Autocatalytic Recombiners). The results were much more similar to each other than at the start of the previous benchmarks organized in the years 2010-2012, which revealed the increased expertise in the use of lumped-parameter codes.

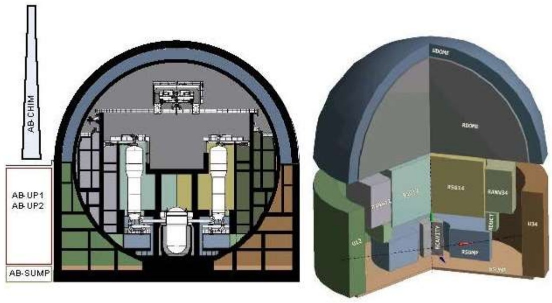


Figure 3: Schematic of generic containment.

Another benchmark exercise, focused on modelling PARs performance, was coordinated by FZJ, with both CFD and lumped-parameter codes used for simulations [29]. The exercise consisted of three steps: a preparatory phase devoted to the assessment of removal models for H_2 in oxygen-rich and oxygen-lean atmospheres; a second phase, based on REKO-3 tests (Figure 4), aimed to analyse the PAR performance in steady conditions with H_2 and CO present in oxygen-rich atmospheres; and, finally, modelling PAR performance in transient conditions with both H_2 and CO present, in the THAI HR-51 test. The results obtained by different benchmark participants were then compared.

In the course of the three validation steps, hydrogen recombination rates have been in general well reproduced under oxygen-rich conditions. However, under oxygen-lean conditions all models show significant deviations from the experimental data, mostly overpredicting the recombination rates. The exercise has helped the participating partners to perform first steps in enhancing PAR models towards the interaction with carbon monoxide in the late phase of a severe accident. Not all phenomena could be considered, though, due to lack of experimental data. Further model enhancements are expected to take place in the future based on new experiments performed in the framework of the AMHYCO project.

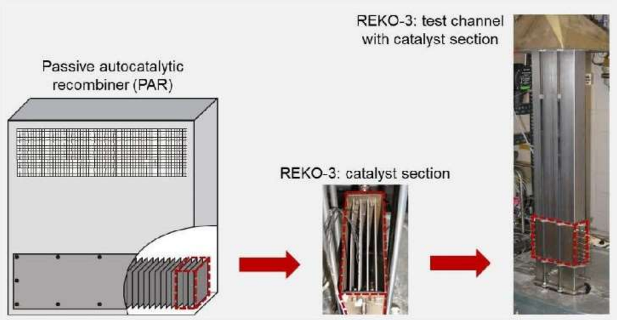


Figure 4: Principle of REKO-3 experiment.

Both the Generic containment benchmark and the PAR benchmark were suitable bases to continue research activities within the AMHYCO project. With the aim to eventually propose modifications of Severe Accident Management guidelines based on new research and resulting new insights, simulations of hydrogen distribution are being performed in a generic containment, using both lumped-parameter, 3D, and CFD codes with subgrid modelling. The generic containment model is based on CAD files built upon public information and recommendations from experts who are very familiar with the specific containment-type modeling. The hydrogen source was determined from simulations of severe accidents in different European NPPs using system severe accident codes. Both unmitigated and mitigated (that is, with the use of PARs) scenarios were simulated. For the later, the modelling of PARs uses insights from earlier benchmarks as well.

The major progress in the field of containment atmosphere behaviour has been in the development of lumped-parameter modelling which can, contrary to the modelling on the local instantaneous scale, be applied to real nuclear power plants. This applies both to accident scenarios with and without hydrogen mitigation.

II.C.2 Hydrogen combustion in containment

A hydrogen deflagration benchmark exercise [30] has been organized in the framework of the SAMHYCO-NET project and with the support of ETSON with the aim to assess the ability of CFD and LP codes to predict the effect of the steam, the initial temperature and the initial pressure on hydrogen premixed combustion flame propagation.

The benchmark consisted of simulating experiments, performed in the ENACCEF2 facility (see Figure **6**), in which hydrogen-air and hydrogen-air-steam mixtures were ignited at the tube bottom, and the subsequent flame and pressure wave propagation were observed.

During the first step, the effect of initial temperature had been investigated. The second step was dedicated to study the combined effect of steam and high temperature on flame propagation in initial homogenous atmosphere. The third step aimed to analyze the flame propagation in homogenous (H_2/H_2O/O_2/N_2) mixture under high initial pressure and high temperature.

The benchmark blind results showed that most of the used codes are able to predict qualitatively the pressure evolution inside the vessel. Nevertheless, the flame speed maximum value is either over or under predicted (see Figure **5**).

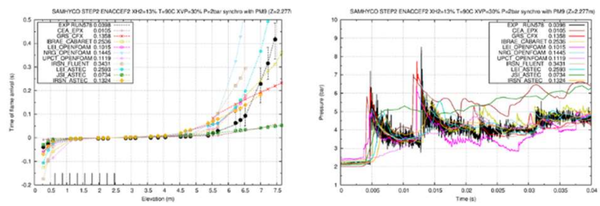
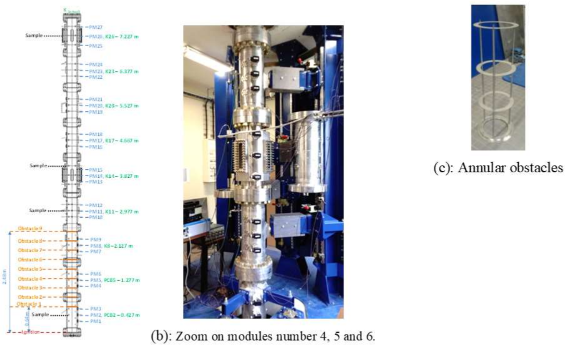


Figure 5: (left) flame position along the facility height-comparison of numerical results vs experiments; (right) Pressure peak at level 5.527m

This indicates that there are still limitations and weaknesses in the combustion models used in the different codes. These limitations concern the chemistry part, the turbulent combustion model and the coupling between the two models. An improvement of the combustion models is necessary in order to obtain consistent results between the flame regime and the pressure build-up predicted for a given configuration. Consequently, further studies are still needed to investigate, in particular, the configurations expected in SMRs with flame propagation in a highly congested geometry and hydrogen-rich mixtures.



(a): Schematic (b): Zoom on modules number 4, 5 and 6. (c): Annular obstacles

Figure 6: ENACCEF2 facility.

II.D. Source Term

The objective of the source term related activities within TA2 has been the prevention and/or mitigation of SA consequences (i.e., radioactivity release to the environment). A synthesis of source term research activities falling within TA2 scope and conducted in the timeframe of 2015 – 2020 has already been reported in Herranz et al [31]. In the timeframe of interest for the present paper, the international workshop on source term organized by OECD/NEA WGAMA [32] played a key role. The workshop was organized with strong involvement of TA2. More recently, the 10th edition of the ERMSAR [33] conference organized by TA2 facilitated to assess the progress made since WGAMA workshop and took stock of complete domain of severe accident research including recent outcomes as well as perspectives of source term research. The aforesaid two activities allowed to discuss high priority topics originated from Fukushima accident analyses towards reliable safety assessment, such as remobilization (delayed releases) of fission products from surfaces, water pools, or by fission products leaching or processes governing release of fine particles in containment atmosphere, high temperature iodine chemistry, organic iodine release etc. Performance testing of engineering safety and mitigation systems towards source term mitigation as well as the role of scenarios specific conditions in defining experimental and modelling activities has been further strengthened and being increasingly considered in various national and international projects.

On remobilization behaviour, important insights have been obtained in OECD/NEA joint safety projects ESTER [34] and THAI-3 [35] and other Fukushima related projects like ARC-F. In ESTER project, the focus has been on RCS relevant conditions and some of the tests investigated CsI aerosols revaporization mechanisms and quantified iodine revaporized species in varying temperature and oxygen partial pressure conditions. For containment specific conditions, OECD/NEA THAI-3 [35] provided relevant experimental data by investigating re-entrainment of aerosols and gaseous iodine from water pools under representative accident conditions. As an example, in case of aerosol re-entrainment (Fig.1), effect of surface tension (mimicking impurities in water pools during an accident) was investigated, and the tests on iodine entrainment (mass transfer) considered different water saturation state (sub-cooled and boiling) and pH effect covering both alkaline and acidic conditions.

Phase a3) Phase a4) Phase b1)

Figure 7. Primary bubbles leaving the downcomer during different test phases a3) Airflow rate: 19 kg/h, Steam mass flow: 70 Kg/h, Pool temperature: 60 °C r, a4) same air and steam mass flows, pool temp. 90 °C, and b1) no air, same steam mass flow, boiling water pool **[5]**

On pool scrubbing aspects, IPRESCA [36] project has shown significant progress in experimental and analytical research by carrying out specific tasks, such as critical analyses of exiting pool scrubbing experiments, consolidation of experimental research, CFD and LP code benchmarking, and other specific efforts directed towards pool scrubbing modelling improvements. As an example, pool scrubbing validation database matrix worked out in IPRESCA framework [37] provided the basis for developing new pool scrubbing correlations [38]. These correlations are now available to potentially use as "analytical data" for comparison against pool scrubbing models and codes. New well-instrumented experiments and the associated analytical work being done by IPRESCA partners is also supporting reassessment of previously developed simplified pool scrubbing models. As an example, recent experimental work and it's use for correlation development for pool scrubbing under jet regime [39] provided additional physical insights to previously developed jet-regime modelling work done, e.g. by Berna et al [40]. It was shown that by adopting the correlation developed by Berna et al [40], by use of droplets size distribution instead of an average droplet size resulted into better comparison between experimental and calculated DFs. A lognormal distribution with an upper limited hypothesis was adopted to predict droplets size. [39] A new pool scrubbing modelling is also currently under development by several IPRESCA partners, e.g. by IRSN for implementation in ASTEC [41].

Although, application of CFD codes is still a way from addressing the pool scrubbing conditions as anticipated during an accident in an integral manner, activities launched by partners on assessing application of CFD codes provided useful insights and framework for future activities focussing on pool scrubbing calculations, e.g. by supporting LP calculations with local information or implementing correlations derived from CFD calculations into LP codes [36]. There are still ongoing efforts on new experimental data to support code validation towards reactor application as data remains sparse, especially under key boundary conditions for reactor analyses, e.g., water impurities, jet-regime flow, boiling conditions, organic iodine release from water pools. The efforts towards completion of missing database are currently underway. Some of these open issues are being considered by IPRESCA partners in their respective national programs or part of international projects, e.g. pool scrubbing under jet-regime is considered in OECD/NEA THEMIS project [35].

Participation of TA2 co-ordination group in other international activities facilitated optimisation of the efforts on investigating topics of common interest by various international agencies. As an example, IPRESCA task related to reactor application has a strong link to other related ongoing CSNI/WGAMA activity BCAPFIS (boundary conditions of scrubbing and remobilization of fission products in aqueous pools during severe accidents). This allows development of common understanding and sharing of relevant information in the frame of two ongoing activities. The BCAPFIS activity aims to develop database (based on reactor analyses calculations performed by the task group members) on representative pool scrubbing scenarios and boundary conditions in different accident scenarios and for different reactor design.

In the context of advanced technologies, like SMR and ATFs, there is increased interest in source term domain to understand phenomenology and potential releases of radionuclides. The database is needed for assessment of the safety and mitigation systems installed in advanced reactor technologies under a broad range of accident conditions. As an example, in case of ATF aimed for near term deployment compared to conventional fuel, there is lack of experimental data on fission product speciation & chemistry, e.g. due to use of different cladding material.

The overall source term research activities linked within TA activities are expected to provide high confidence in predicting radiological source term calculations for different designs of NPPs. Recent H2020 projects, like MUSA (Management and Uncertainties in Severe Accidents, led by CIEMAT, 2019-2023) [42], provided important insights towards systematic assessment of the uncertainty and sensitivities embedded in different severe accident codes and R2CA project (Reduction of Radiological Consequences of Design Basis and Design Extended Accidents, led by IRSN, 2019-2023) [43] made efforts on developing methodologies aiming towards reducing conservatisms for source term calculations under DBA and DEC-A conditions, respectively. The ongoing projects launched in the year 2022 in the framework of EC Horizon like ASSAS [44], SASPAM-SA [**¡Error! No se encuentra el origen de la referencia.**], and SEAKNOT [**¡Error! No se encuentra el origen de la referencia.**] aim to provide necessary input on the emerging source term issues relevant for management and mitigation of severe accidents in both operating fleet as well as advanced reactor designs.

II.E Accident scenarios

Past activities in the area of accident scenarios have been carried out mainly in the framework of the Horizon 2020 Euratom project FASTNET (2015-2019), dedicated to the development of fast and reliable tools for source term prediction during emergencies [45]. In order to validate these tools and to provide the European emergency preparedness and response community with reference data, several accident scenarios were identified for the main NPP types installed in Europe (ideally including SFPs) and then analyzed with best-estimate codes like ASTEC, MELCOR or MAAP. The results were stored in a dedicated database, which was the basis of the verification of fast deterministic and probabilistic (based on Bayesian Belief Networks) approaches intended in fast running tools. Such a database was finally transferred to the IAEA Incident and Emergency Center for future uses. In parallel, the ASTEC COMmunity (ASCOM) NUGENIA project nucleates the ongoing activities to validate the European SA code ASTEC [6] and to extend its NPP models database, including SMRs, while the NUGENIA AIR-SFP project [46] was an analytical exercise of SA codes application to Spent Fuel Pools (SFP) accident scenarios. This last project highlighted as a straightforward application of codes developed for reactors is not allowed and some approximations and/or even new developments were needed to apply the tools out of a non-radial topology, as the reactor one.

The accidental scenarios for SFPs have been further investigated in the MUSA project, one of the Horizon 2020 Euratom projects with NUGENIA labels. MUSA (Management and Uncertainties in Severe Accidents, led by CIEMAT, 2019-2023), and R2CA (Reduction of Radiological Consequences of Design Basis and Design Extended Accidents, led by IRSN, 2019-2023) clustering most of the recent efforts in SA modelling. The former was aimed at systematically applying the Best Estimate Plus Uncertainties (BEPU) approach in SA analysis [**¡Error! No se encuentra el origen de la referencia.**]. The latter was focused on reducing radiological consequences of Design Basis Accidents (DBAs) or Design Extended Conditions (DEC) by enhancing the current modelling capabilities in severe accident codes and evidences the efficiency of updated tools and evaluation methodologies to optimize the evacuation plans as well as their usefulness to quantify the gains that can be expected from innovative devices, passive systems and advanced technological cladding and fuel concepts under development worldwide [43].

The MUSA major tangible achievements have been the creation of an extensive database of Uncertainties Parameters (UP), where more than 400 UPs, substantiated by expert judgments, are identified and characterized, the use of a vastly diverse and tested range of UQ methods & tools, the large variety of reactor & scenarios UQ database and the "first-of-a-kind" UQ application to SFP scenarios. To be highlighted also the MUSA attention for E&T actions oriented to young researchers exploring this "new" field of UQ for SA scenarios.

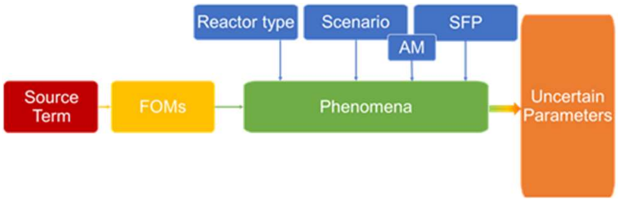


Figure 8: MUSA database for UPS**.**

In the more recent Horizon Europe framework, a critical analysis of the knowledge on Severe Accidents acquired in the last 15 years will be carry out in the SEAKNOT project (SEvere Accident research and KNOwledge managemenT for LWRs), led by CIEMAT (2022-205) [15], with the following objectives:

a) Make recommendations for further reduction of risks associated with existing and forthcoming nuclear technologies (SM-LWRs & ATFs);

b) Identify experimental research needs to optimize SA mitigation measures;

c) Strengthen the transfer from senior scientist and engineers to the young generation of researchers and workers in SA field.

A focus on the possible accident scenarios for forthcoming technologies is also given in the other NUGENIA TA2 project SASPAM-SA (Safety Analysis of SMR with PAssive Mitigation strategies – Severe Accident), led by ENEA (2022-2025) [7]. The key objective of SASPAM-SA is to investigate the applicability and transfer of the operating large-LWR reactor knowledge and know-how to the near-term deployment of integral PWR (iPWR), in the view of SA and Emergency Planning Zone (EPZ) European licensing analyses needs.

III. Beyond research

NUGENIA/TA2 (formerly SARNET) has always been sensitive to its main objective: improving nuclear safety. From the outset of SARNET, it was conceived that the network should not be limited to the acquisition of knowledge, but should go beyond it. Lack of knowledge should not be the only motivation for investigation. This idea inspired two working principles that still drive NUGENIA/TA2 activities:

- Focus on missing knowledge that is relevant to safety and has the potential to effectively reduce remaining uncertainties in safety analyses. This has been guided by the periodic review of severe accident research priorities [3-4].
- Disseminate information through open communication within the severe accident community (ERMSAR conferences) and, in particular, articulate tools (SAP courses and a textbook) that allow nuclear engineers and students to access a solidly based understanding of SA and the latest insights from research.

IV. Conclusions

The NUGENIA/TA2, presently embedded in the SNETP Association, has been functional for more than 10 years to articulate research projects on severe accidents and to foster internationally recognized education and training (Severe Accident Phenomenology Course, SAP) and dissemination activities (European Review Meeting on Severe Accident Research, ERMSAR conference series).

Over the past five years, European as well as non-European organizations got meaningful outcomes from in-kind projects, which achieved substantial progress on: management of combustible gases (SAMHYCO-NET), quenching of degraded reactor cores (QUESA), pool scrubbing (IPRESCA), and modeling of severe accident scenarios (ASCOM).

In addition, the NUGENIA/TA2 networking has strengthened the ability to build sound, consistent projects that have been awarded by the European Commission as worth being financially supported. These projects articulate activities in the following domains: risk of combustion in the late phase of accidents (AMHYCO); application of the UaSA approach in severe accident modelling (MUSA); investigation of severe accident scenarios in water-cooled SMRs (SASPAM-SA); advanced modelling of radiological consequences of DBA and DEC-A scenarios (R2CA). More importantly, the SEAKNOT project has been running for one year to build a sound roadmap for severe accident research in the coming decade (including innovative technologies, like ATFs and SMRs) and to transfer knowledge and know-how to those who will be responsible for it in the future.

In the search for an optimum use of resources in the severe accident domain, NUGENIA/TA2 is seeking new avenues of collaboration with international initiatives related to the subject, such as OECD projects and the activities of the Working Group on Accident Management and Analysis (WGAMA) within the framework of the Nuclear Energy Agency (NEA) and/or the Coordinated Research Projects (CRP) within the framework of the International Atomic Energy Agency (IAEA).

References

1. B. Clement, R. Zeyen, "The objectives of the Phébus FP experimental programme and main findings", Annals of Nuclear Energy, vol. 61, pp. 4–10, November 2013, https://doi.org/10.1016/j.anucene.2013.03.037.
2. J-P. Van Dorsselaere et al., "Recent severe accident research - Synthesis of the major outcomes from the SARNET network", Nuclear Engineering and Design, vol. 291, pp 19-34, September 2015.
3. W. Klein-Heßling et al., "Conclusions on severe accident research priorities", Special number of Annals of Nuclear Energy on ERMSAR 2013 Conference, vol. 74, pp. 4-11, December 2014.
4. D. Manara et al., "Severe accident research priority ranking: A new assessment eight years after the Fukushima Daiichi accident", Proceedings of the 9th European Review Meeting on Severe Accident Research (ERMSAR 2019), Prague, Czech Republic, March 18-20, 2019.
5. F. Fichot, L. Carénini, J. M. Bonnet, "Main Physical Questions Raised by In-Vessel Melt Retention," Proc.s of the International Workshop on In-Vessel Retention, Aix-en-Provence, France (2016).
6. P. Chatelard, et al., "ASTEC V2 Severe Accident Integral Code Main Features, Current V2.0 Modelling Status, Perspectives," Nuclear Engineering and Design, 272, 119-135 (2014).
7. https://cordis.europa.eu/project/id/101059853
8. A. Miassoedov, et al., "SAFEST Project on Corium Behavior in Severe Accidents,“ Proc. of the 12th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (Nuthos-12), Qingdao, China (2018).
9. A. Miassoedov, et al., "ALISA Project: Access to Large Infrastructures for Severe Accidents in Europe and in China,“ Proc. of the 12th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (Nuthos-12), Qingdao, China (2018).

10. X. Gaus-Liu, et al., "Experimental Study and Analytical Analysis on the Global Heat Transfer of Stratified Corium in LWR Lower Head," Nuclear Engineering and Design, 372 (2021).
11. B. Fluhrer, at al., "LIVE-BWR Experiments to Study the Effect on CRGT Cooling on In-Vessel Melt Retention Strategy," Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), Brussels, Belgium, March 6 - 11, 2022.
12. H. Madokoro, et al., "LIVE-J1 Experiment on Debris Melting Behavior Toward Understanding Late In-Vessel Accident Progression of the Fukushima Daiichi," Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), Brussels, Belgium, March 6 - 11, 2022.
13. T. Haste, et al., "CoreSOAR Core Degradation SOAR Update: Summary," Proc. of the 9th European Review Meeting on Severe Accident Research (ERMSAR 2019), Prague, Czech Republic (2019).
14. T. Hollands, "First Results of the QUENCH-18 Post-Test Benchmark in the Frame of the NUGENIA QUESA Project," Proc. of the 24th International QUENCH Workshop, November 13-15, KIT, Karlsruhe, Germany (2018).
15. SEAKNOT, https://seaknot-project.eu/
16. T. Hollands, "Status of Benchmark Exercises in the Frame of the NUGENIA QUESA Project," Nuclear Engineering and Design 399, 112011 (2022).
17. J. Stuckert, et al, "Post-Test Analyses of the CORA-15 Bundle Test with the System Codes ATHLET-CD and SOCRAT," Nuclear Engineering and Design, 342, 320 – 335 (2019).

18. C. Jegou, P. Piluso, F. Audubert, M. Autillo, S. Miro, S. Peuget, A. Denoix, J. Delacroix, A. Bachrata Kubic, L. De Windt, P. Bros, "Methodology to address the liquid radionuclides source term from corium leaching after severe accident", The 7th Fukushima International Forum on the Decommissioning of the Fukushima Daiichi Nuclear Power Station, 2023, to be published.

19. P. Piluso, C. Journeau, A. Denoix, J. Delacroix, V. Bouyer, C. Mattassoglio, A. Bachrata, "Severe accident research on corium at CEA for generation 2, 3 and 4 reactors", SNETP-2023.

20. A. Nakayaoshi et al., "Current situation of OECD/NEA - Preparatory Study on Analysis of Fuel debris (PreADES) project, Proceedings of the International Workshop on Post-Fukushima Challenges on Severe Accident Mitigation and Research Collaboration", Daejeon, Korea, 2019.

21. M. Jizzini, "Etude des phases solides métastables et stables de corium issus de trempe par approche multi échelle, étude d'un chemin réactionnel", Ph-D, Limoges University, May 2022.

22. J. Kokalj, M. Ursic, M. Leskovar, "Modelling of premixed layer in stratified fuel–coolant ", The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), 2022.

23. C. Spengler, I. Bakalov, "A simplified core catcher model for the containment code ac2 /cocosys" The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), 2022.

24. https://snetp.eu › offerr
25. IAEA, Developments in the Analysis and Management of Combustible Gases in Severe Accidents in Water Cooled Reactors following the Fukushima Daiichi Accident, IAEA-TECDOC-1939 (2020).
26. IAEA, Hydrogen Phenomena During Severe Accidents in Water Cooled Reactors, IAEA-TCS-72 (2021).
27. OECD/NEA, Status Report on Hydrogen Management and Related Computer Codes, NEA/CSNI/R(2014)8 (2014).
28. St. Kelm et al., "Generic Containment: Detailed Comparison of Containment Simulations Performed on Plant Scale", Annals of Nuclear Energy, 74, 165-172 (2014).
29. E.-A. Reinecke, "PAR Model Development Exercise in the Framework of SAMHYCO-NET", Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), Brussels, Belgium, March 6 - 11, 2022.
30. A.Bentaib et al, "ETSON-SAMHYCO-NET Benchmark on Simulations of Upward Flame Propagation Experiment in Representative Hydrogen-Air-Steam Mixtures of Severe Accidents Containments Atmosphere", Proc. of the 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), Brussels, Belgium, March 6 - 11, 2022.
31. L.E. Herranz, A. Bentaib, F. Gabrielli, S. Gupta, I. Kljenak, S. Paci, P. Piluso, F. Rocchi, "NUGENIA/TA2 Achievements in Severe Accidents Research (2015-2020)", Journal Nuclear Espana (2020).
32. OECD/NEA, "CSNI/WGAMA Source term workshop", Paris, France, January 2019, report number NEA/CSNI/R(2020)4 (2021).
33. Proceedings of the 10th European Review Meeting on Severe Accidents Research (ERMSAR2022): Severe Accident Research Eleven Years after the Fukushima Accident, Akademie hotel, Karlsruhe, Germany, May 16-19, DOI: 10.5445/IR/1000151444 (2022).

34. E. Le Fessant, C. Gregoire, C. Tornabene, G. Bourbon, L. Cantrel, J. F. Paul, S. Mamede, “Experimental study of CsI revaporization behavior in RCS condition after a SA”, The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Akademie hotel, Karlsruhe, Germany, May 16-19 (2022).
35. S. Gupta, M. Freitag, G. Poss, “THAI experimental research on hydrogen risk and source term related safety systems”, Front. Energy 15, 887–915 (2021).
36. S. Gupta, L. E. Herranz, L. S. Lebel, M. Sonnenkalb, M. Pellegrini, C. Marchetto, Y. Maruyama, A. Dehbi, D. Suckow, T. Karkela, “Integration of pool scrubbing research to enhance Source-Term calculations (IPRESCA) project – Overview and first results”, Nuclear Engineering and Design, vol. 404 (2023).
37. L.E. Herranz, S. Gupta, “Validation matrix for pool scrubbing models”, Nucl. Technol., 2022, https://doi.org/10.1080/00295450.2022.2122679
38. L. E. Herranz, F. Sánchez, “New pool scrubbing correlations based on reliable data”, Annals of Nuclear Energy, vol 183 (2023).
39. X. Yan, Y. Zhou, H. Diao, H. Gu, Y. Li, “Development of mathematical model for aerosol deposition under jet condition”, Annals of Nuclear Energy, vol. 142 (2020).
40. C. Berna, A. Escrivá, J.L. Muñoz-Cobo, L.E. Herranz, “Enhancement of the SPARC90 code to pool scrubbing events under jet injection regime”, Nuclear Engineering and Design, Vol 300, 563-577 (2016).
41. C. Marchetto and F. Cousin F., “Proposal of a pool scrubbing modelling for ASTEC: Bubble hydrodynamics and Thermal hydraulic aspects”, Proceedings of the 9th European Review Meeting on Severe Accident Research (ERMSAR 2019), Prague, Czech Republic, March 18-20 (2019).
42. L. E. Herranz et al., “The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status”, Energies, 14(15), 4473 (2021)
43. N. Girault et al., “The R2CA project for evaluation of radiological consequences at design basis accidents and design extension conditions for LWRs: Motivation & First Results”, The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Akademiehotel, Karlsruhe, Germany, May 16-19 (2022)
44. ASSAS project website, https://cordis.europa.eu/project/id/101059682
45. F. Rocchi, I. Devol-Brown, W. Raskob, “Nuclear and radiological emergency management and preparedness”, EPJ Nuclear Sci. Technology, vol. 6, No. 37, May 2020. https://doi.org/10.1051/epjn/2019011.
46. Coindreau O. et al., Severe accident code-to-code comparison for two accident scenarios in a spent fuel pool, Annals of Nuclear Energy, vol. 120, pp. 880-887, October 2018, https://doi.org/10.1016/j.anucene.2018.06.043.