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Review Article

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Towards an optimized management of accidents

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Abstract. Nuclear safety has been one of the main research domains in EURATOM programs for decades, and accident prevention and mitigation have drawn much of the attention paid over the years to this framework. In the essence of this interest are designs of reliable systems, accurate methods to estimate risk, and a permanent search for optimizing accident management. This is the focus of PIACE, MUSA, and AMHYCO projects. A fully passive system for decay heat removal in off-nominal conditions based on the concept of isolation condenser is the subject of PIACE. A harmonized approach for analyzing uncertainties and sensitivities associated with severe accidents, particularly with the source term to the environment, is the final aim of MUSA. And finally, AMHYCO is exploring the potential for enhancing the management of combustible gas risk. Despite the project's diversity, they all will converge on the same outcome: an optimization of nuclear safety from better safety systems, risk estimating methods, and in-accident guidelines. These projects have received funding from the H2020 EURATOM research and training program under grant agreements 847715 (PIACE), 847441 (MUSA), and 945057 (AMHYCO).

1 Introduction

Nuclear safety relies on several aspects, such as the Defence-in-Depth approach, which identifies Nuclear Power Plant (NPP) conditions progressively degraded from nominal to postulated severely deteriorated in five levels, and articulate means (standards, engineering safety features, and guidelines) to minimize risk to public and environment. For decades, Euratom has brought nuclear safety up as one of the key targets for research. With a broad scope, which ranges from testing more reliable and efficient systems to enhancing procedures, guidelines, and measures on robust knowledge and know-how, research nuclear safety projects have been awarded under the HORIZON 2020 framework. PIACE, MUSA, and AMHYCO are good examples of them.

The high standards set for NPPs get its top in nuclear safety systems that are supposed to operate in harsh conditions. Their performance needs to be demonstrated before being implemented in any reactor design, particularly if they are based on an innovative passive approach. The challenge is multiple. On one side, suitable facilities capable of setting representative initial and boundary conditions as well as being scalable to NPPs should be built and/or adapted, if already existing. On the other, the system should be properly modeled so that its effect is soundly assessed under any anticipated condition. PIACE integrates all these aspects for a specific proposal to remove decay heat based on the concept of isolation condenser.

Numerical simulation tools are widely used to assess the behavior of NPPs during postulated accidents, including Severe Accident (SA). In other words, they are a central element of the safety demonstration where the compliance of the main safety features of an NPP is checked against the actual safety requirements reflecting the state-of-the-art. In addition, the development and optimization of Accident Management (AM) measures aiming at preventing and mitigating the consequences of SA strictly rely on numerical simulations with SA codes. Since the SA tools predict important parameters such as the time of failure of safety barriers, on the one hand, and the potential radiological Source Term (ST) to be released to the environment if the safety barriers fail, on the other hand, it is of paramount importance to be aware of and enhance their accuracy. To do so, MUSA brings uncertainty quantification into SA analyses and provides insights that might change the perception of the current precision of SA codes and highlight areas where further research would be more beneficial.

One of the priority areas of SA research has been analyzing the risk of combustion of H_2 and CO, as it might

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jeopardize containment integrity. The Fukushima Daiichi accidents that occurred in Japan in 2011 just strengthened the need to properly manage such risk and practically eliminate the consequential dynamic phenomena. By keeping the containment integrity, the potential release of a significant amount of radioactive material to the environment would be prevented. Despite the numerous research projects and activities conducted in different frameworks, some of their outcomes have not been fully exploited in the form of actions to be taken for accident management, particularly in the ex-vessel phase of accidents when H_2 and CO coexist in a containment atmosphere. AMHYCO fills this gap by using a comprehensive approach involving analytical methods, systems testing, and SA management procedures.

Euratom has always paid due attention to communication and dissemination of the research results and outcomes of the projects sponsored in its frame. This aspect has been particularly emphasized in H2020. Consequently, in each of the above projects, a specific Work Package (WP) deals with these aspects. It is a common feature nowadays to host project websites for internal communication, as storing and share-points of the material produced or used as a background in the project. Newsletters, LinkedIn, and Facebook accounts are among the instruments used by these projects to reach the public. No less important, these WPs foster the education and training aspects by facilitating the participation of young researchers and engineers in scientific and technical events as well as financially supporting their mobility across European laboratories.

2 PIACE: an efficient system for decay heat removal

2.1 Project overview

The PIACE (Passive Isolation Condenser) project will provide a significant contribution to the safety improvement of the present and future technology of nuclear reactors. The project aims to demonstrate the feasibility, shortening the time to market, of an innovative Decay Heat Removal (DHR) system, based on an isolation condenser with non-condensable gases, to manage the variable decay heat in a passive way, verifying and validating the concept of a patented passively controlled safety system for decay heat removal [1]. The innovative concept has the important peculiarity of being completely passive by making use of simple physical phenomena, limiting the use of energy sources or movement of mechanical parts only at the actuation stage (category D of passivity according to IAEA [2]) without human intervention, and have the flexibility to be adapted both to the liquid metal and water-cooled reactors.

The project has received funding from the Euratom research and training program 2014–2018 under grant agreement No. 847715. The total cost is in the order of 3 M€ with human resources involved in the order of 400 person-months, over 3 years (2019–2022). It is an international collaboration involving 11 European partners, research centers, and private companies (ANN, EAI, ENEA, GEN ENERGIJA, JSI, RATEN, SCK-CEN, SIET, SINTEC, TRACTEBEL, and UPM), and is led by ENEA. In addition, an external advisory committee, specialized in different types of plants, as well as safety and licensing aspects, is supporting the project; and an exploitation manager is defined to guarantee the process of exploitation and dissemination of the results reducing the risks associated with technological innovation.

The ultimate goal of the PIACE project is the finalization of specific designs of the innovative DHR concept, ready for industrial implementation on several reactor technologies ranging from currently operating plants to innovative energy systems, namely: Lead-cooled Fast Reactor (LFR) Accelerator Driven System (ADS), Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR) and Pressurized Heavy Water Reactor (PHWR).

Two main branches can be identified in the project, a design assessment, with the support of numerical codes, to analyze the applicability of the concept to the different reactor technologies of interest, and an experimental investigation to test the feasibility and the performance of the system during accident scenarios. The experimental tests will take advantage of the facility SIRIO located in Italy in the SIET laboratories [3]. The facility is conceived for feasibility testing on this new DHR system applied to LFR technology, and it will be easily adaptable for the tests in PIACE. A simplified scheme of the SIRIO facility, along with a photo of the steam generator, is reported in Figure 1. The system mainly consists of Steam Generator (SG), Isolation Condenser (IC), Non-condensable Gas Tank (GT), and By-pass Heat Exchanger (HX), each equipped with isolation valves.

The facility can simulate the transient operation of the IC starting from a steady state condition of the system. During the steady state condition, the valves (V3) and (V4) are open, and the water circulates, in two-phase flow and natural circulation, between the steam generator and the bypass heat exchanger. The valves (V1) and (V2) are closed, and the IC and the GT are filled with nitrogen at a lower pressure than the waterside. Later, the (V4) is closed, and the pressure of steam in the upper branch increases up to the automatic opening of the valve (V1). The steam enters the IC, "pushes" the non-condensable gas in the gas tank, and condenses along the IC tubes. After a certain delay with respect to (V1), the condensate isolation valve (V2) opens, and a natural circulation occurs, providing heat transfer from the SG to the water of the IC pool. Then, the electrical heater power in the SG is modulated to simulate the decay heat. When the power removal capacity of the IC exceeds the power generated in the SG, the condensation of steam in the IC increases, and consequently, the pressure of the system (SG+IC) decreases. In this condition, the non-condensable gas flows back from the GT into the IC tubes, decreasing its condensing capacity. Consequently, the pressure remains almost constant and the system can passively align the power removed from the isolation condenser with that produced by the steam generator.

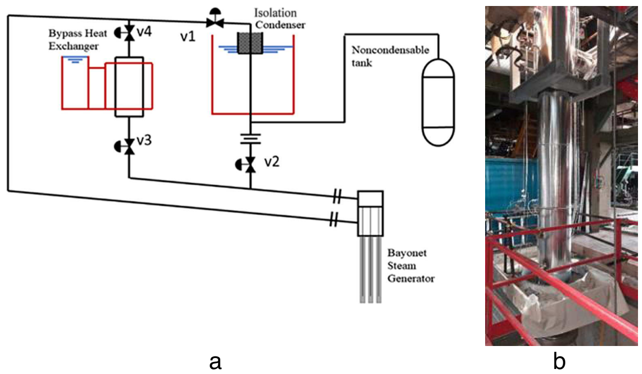

Fig. 1. The SIRIO facility. a. Schematics, b. Steam generator.

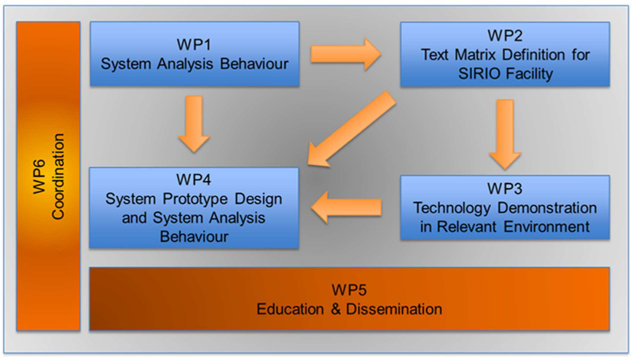

Fig. 2. PIACE Functional structure.

2.2 Project structure

The project is structured into 6 distinct work packages (WP), as reported in Figure 2.

WP1 is devoted to implementing the innovative system to the different reactor technologies and analyzing the plant response for a reference full-scale system through modeling and analyses by system codes. The result consists of a first feasibility study highlighting the potential benefit of the safety system applied to a specific reactor technology. The WP1 is concluded.

In WP2, the main phenomena controlling the system behavior are identified. Then, a pre-test phase with numerical models is used to analyze the scalability of the system to be tested on the SIRIO facility once the facility is adapted to reproduce the reactor technology under investigation. Finally, the test matrices are defined, for each reactor technology, to identify the minimum set of experimental runs necessary to catch the controlling phenomena. The WP2 is concluded.

The WP3 is devoted to the experimental campaigns on the SIRIO facility. The first run planned is relevant for LFR technology. Further tests will then be performed, considering the other two reference cases, with an upgrade of SIRIO. The WP3 is ongoing. The selection of the two reference cases is concluded. The test campaign for the LFR technology is ongoing, and the preparation of the SIRIO facility for the two further reference tests is started. Delays are accumulated on these text campaigns due to the forced long inactivity of the laboratories caused by the pandemic situation of Covid-19. An extension of the project of six months is indeed requested.

The WP4 activities will be devoted to the comparison of the experimental data with the pre-test analyses to understand any difference or scaling distortions, as well as to validate the computational tools and provide "best practices" guidance to capture the main underlying phenomena. Moreover, a technical specification of the safety system will be developed for each of the nuclear technologies under study, covering aspects like, but not limited to, system functions, system criteria, interface requirements, system performances, and validation basis. The activities outcome will represent a perspective improvement in Technology Readiness Level (TRL) and bring the innovation closer to the market. The preparation of the structure of the documentation is already done.

The WP5 deals with dissemination and training activities. In addition to the classic dissemination activities, webinars, workshops, and hands-on training on the SIRIO facility are planned during the project to inform young researchers and students about the issues of interest in passive safety systems.

As expected, one WP (WP6) deals with coordination activities related to both project management (quality plan, risk management, interface management, administrative matter, reporting) and technical coordination (project execution plan, technical interfaces, technical review). This can also be applied to MUSA (WP1) and AMHYCO (WP6).

2.3 Preliminary results

The WP1 relates to the selection of enveloping accidental transients, and the most representative results obtained through the system codes simulations for each of the reference technologies are reported in [4]. Just to illustrate the work done, a couple of examples are succinctly described next:

- in the liquid metal reactor technology, the activities are based on ALFRED design [5], a pool-type concept with all the components installed inside the reactor vessel. The analyzed operating condition of ALFRED is related to a thermal power of 200 MWth and a thermal cycle between 400 °C and 480 °C. On the secondary side, the water enters the steam generators at 335 °C and flows out as superheated steam at a temperature of 435 °C and 175 bar. The passive DHR interfaces with the secondary system through the feed water and the steam line, and each steam generator has its safety system loop. The accidental transient studied in the PIACE project was taken from the list of accidental events developed during the LEADER project [6]. The enveloping event that was identified for the numerical study is the Protected Loss Of Offsite Power (PLOOP) and accounts for the loss of electricity (resulting in loss of all pumps), containment isolation, SCRAM, and actuation of the safety system. The transient was analyzed by means of the system code RELAP5-3D [7]. Two main phases of the transient are identified. At first, the safety system operates

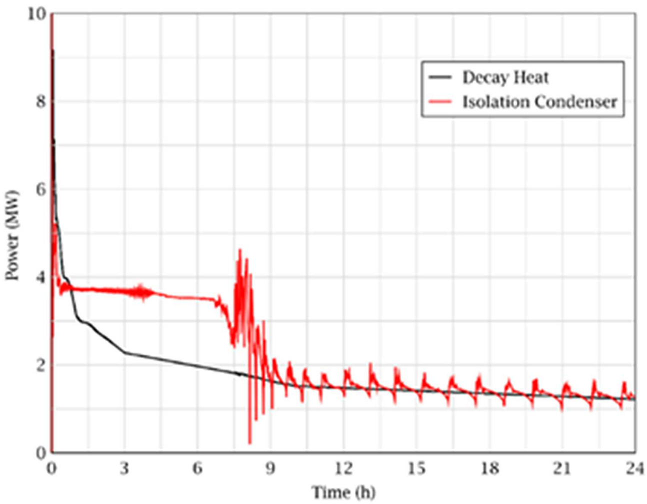

Fig. 3. IC power removal by IC in ALFRED during a PLOOP.

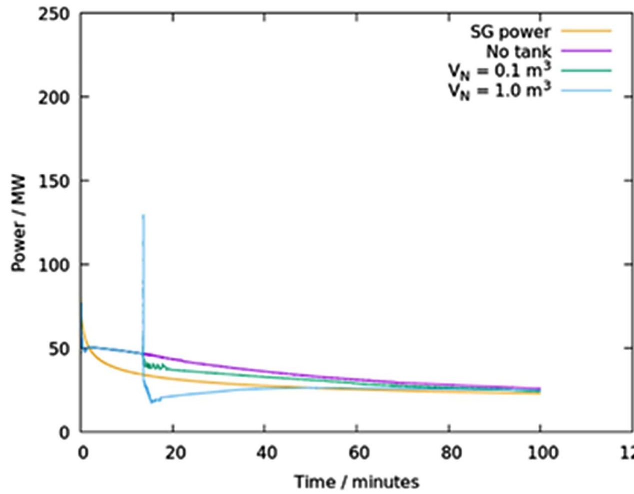

Fig. 4. Power removal by IC in a PWR configuration (effect of the N_2 tank).

at maximum power while maintaining the non-condensable gases trapped inside the tank, with a total power of around 4 MW. Over time, the temperatures of the reactor coolant system decrease, and once much of the heat capacity has been removed, non-condensable gases migrate from the tank to the isolation condenser, and the power balance is achieved. In parallel, the temperatures of the reactor coolant system stabilize to a value greater than 350 °C, about 20 °C above the freezing temperature. The system maintains this safe condition for the entire 24-hour period studied in this case. The results indicate an increase in the grace time against reactor coolant freezing (which would be otherwise reached in approximately 10 hours), and temperatures are kept within the safety conditions. Figure 3 shows the trend of power absorbed by the coolant and removed by the isolation condenser.

ADS transients and accidents based on MYRRHA design [8] have also been analyzed.

- On the water-cooled reactor technology, the considered plant, in the case of PWRs, was a two-loop Pressurized Water Reactor (PWR) with thermal power of 2000 MWth. The enveloping scenario assumed is a station blackout, where the electrically powered components are not available, and only passive components and systems remain functional. The proposed conceptual design of the passive isolation condenser consists of cylindrical headers and vertical tubes. The condenser was modeled as being part of a separate, closed loop that includes a heater, which simulated the heat flow due to the decay power. The transient involving the functioning of the condenser was simulated with the system code RELAP5/MOD3.3 [9]. A parametric analysis was performed with different values of the nitrogen tank volume and different initial decay power, highlighting their impact on transient behavior and the most suitable parameter selection for accident mitigation. Figure 4 shows the trend of power removed by the isolation condenser with different nitrogen tank volumes.

In addition, transient and accident analyses have also been conducted in BWR (particularly ESBWR) [10] and PHWR (particularly CANDU 600) [11].

The scalability of the systems under investigation has been analyzed, and the representativeness of the SIRIO facility has been delineated in terms of upgrading needs related to instrumentation, layout, volumes, main components, and logical controls. In addition, the test matrix of each reactor technology relevant for the experimental characterization of the SIRIO facility has been set (Tab. 1). The study provided the basis for selecting the experimental campaigns of the two additional reference cases.

The selection of the two further reference cases to be tested on the SIRIO facility is concluded. The choice made concerning BWR and PWR technologies has been made based on the scientific value of the test, technical feasibility, economic sustainability, and time needed for the modifications compared to the project time schedule. The test campaign on the LFR technology is started, and the first results are under analysis.

3 MUSA: empowering severe accidents predictability

3.1 Project overview

The MUSA (Management and Uncertainties of Severe Accidents) project aims to quantify the uncertainty in SA codes when modeling accident scenarios to predict the radiological ST [12]. Uncertainty Quantification (UQ) methodologies are being applied to initial and boundary conditions, model parameters, and even accident management measures. ST-related Figures Of Merit (FOMs) have been set for each scenario in which the Best Estimate Plus Uncertainties (BEPU) is being applied.

The project has received funding from the Euratom research and training program 2014–2018 under grant

Table 1. Tests conditions for SIRIO experimentation.

	LFR (SIRIO as it is)	ADS		PWR		BWR		PHWR	
		Proposal 1	Proposal 2	Proposal 1	Proposal 2	Proposal 1	Proposal 2	Proposal 1	Proposal 2
Layout & components modifications required	None	Direct connection of the non-condensable tank to the HX upper header		Heat transfer surface of HX increased by a factor 1.82	Heat transfer surface of HX increased by a factor 1.82 Gas Tank volume increased by a factor 1.2	Extra vessel on Steam line. $6'' \times 5.86$ m	None	Modification of the diameters of the most piping of the loop	
Operation parameters									
Power (kW)	55	28.3	3.25	55	55	55	110	30	55
Pressure primary circuit (bar)	180	16.0	16.0	60	60	72.52	72.52	46	46
Pressure gas tank (bar)	110	12	12	50	50	50	69	30	30
Water inventory (kg)	38	38	50.7	38	38	57.1	57.1	38	38

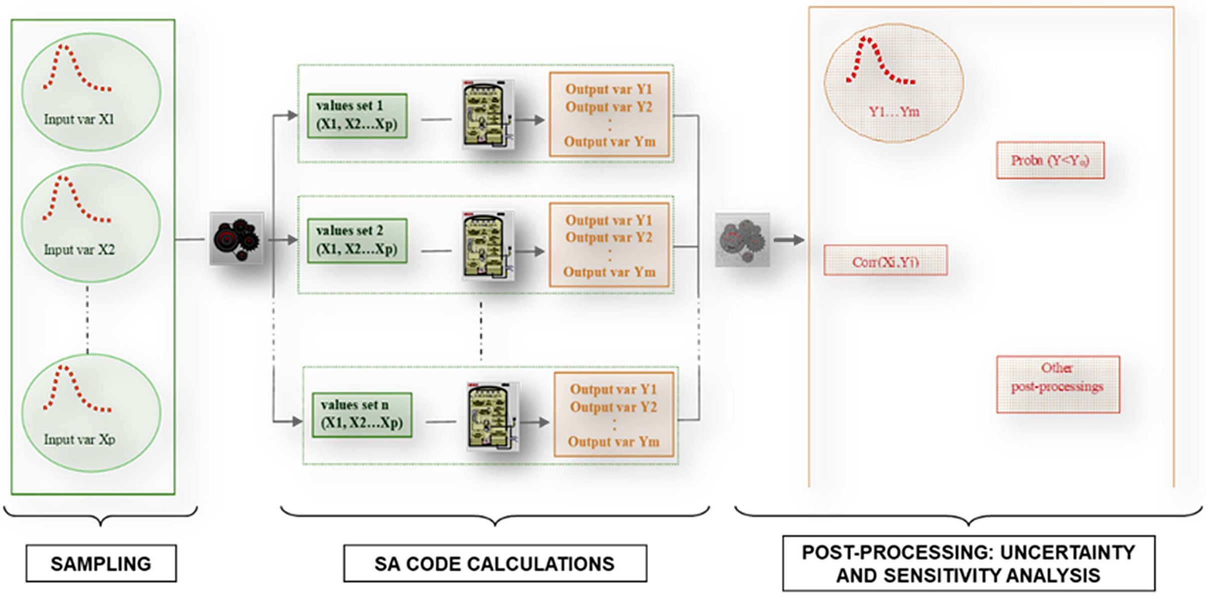

Fig. 5. Sketch of uncertainty propagation being applied in MUSA [13].

agreement No. 847441. The total cost is in the order of 5.9 M€, with human resources involved in the order of 625 person-months over 4 years (2019–2023). MUSA is an international collaboration that involves 28 partners led by CIEMAT. The rest of the partners are mostly European, but there are institutions from America and Asia as well (Bel V, CEA, CNPRI, CNSC, ENEA, Energorisk, EPRI, Framatome, GRS, INRNE, IRSN, JAEA, JACOBS, JRC, KAERI, KIT, LEI, LGI, NINE, PSI, SSTC, Tractebel, TUS, UNIPI, UNIRM1, USNRC, VMU, VTT). This large participation ensures the involvement of a wide range of competencies and approaches (i.e., Technical Support Organizations (TSO), utilities, research centers, and academia) and effective dissemination of major project outcomes worldwide.

Numerical simulation tools are a central element of the safety demonstration where the compliance of the main safety features of an NPP is checked against the actual safety requirements reflecting the state-of-the-art. In addition, the development and optimization of AM measures aiming at preventing and mitigating the consequences of SA heavily rely on numerical simulations with SA codes such as ASTEC, AC2, MAAP, MELCOR, etc. However, although statistical tools are available worldwide, few investigations have been focused on SA and UQ. Therefore, MUSA goes beyond the state-of-the-art regarding the predictive capability of SA analysis codes by combining them with the best available UQ tools. By doing so, not only the prediction of the timing for the failure of safety barriers and the radiological ST in the case of a SA in an NPP will be possible, but also the quantification of the uncertainty bands of selected analysis results, considering any relevant source of uncertainty, will be provided. A schematics of the uncertainty propagation is given in Figure 5 [13].

MUSA is not restricted to reactor accidents, including GEN II and GEN III designs (PWR and BWR ones). Spent Fuel Pool (SFP) accidents are also addressed. In addition to including AM in the uncertainty analyses, MUSA intends to develop some innovative AM strategies for SFP accidents. It is worth noting that the project has strong links with the communities dealing with Probabilistic Safety Assessment (PSA) level 2, emergency response, environmental consequence analysis, and AM, all of which have been undertaking deep reviews since the Fukushima Daiichi accident.

3.2 Project structure

As shown in Figure 6, the technical WPs (i.e., WP2-WP6) distribute in two blocks (WP1 and WP7 deal with coordination and dissemination, respectively). The first one, including WP2 and WP3, is meant to prepare everything necessary to conduct the second block, which can be referred to as the "application WP block" (i.e., WP4, WP5, and WP6). The "application block" represents roughly two-thirds of the total workforce anticipated in MUSA.

WP2 (Identification and Quantification of Uncertainty Sources, IQUS) identifies and partially quantifies the major sources of uncertainties of any type of processes and phenomena during SAs affecting the ST. This would entail both uncertainties in the existing models and uncertainties due to the lack of specific models in the codes. A preliminary "knowledge-based matrix" containing the selected variables, parameters, and models and their uncertainty ranges has been set. To do so, a list of FOMs was previously developed consistent with the focus of MUSA on ST.

WP3 (Review of Uncertainty Quantification Methodologies, RUQM) aims to review and assess methodologies and codes used for uncertainty quantification and sensitivity analyses and their applicability to the analysis of SA. In particular, the strengths and weaknesses of each methodology/code to be applied have been identified, and by the end of the project, a report on guidelines for the best use of UaSA (Uncertainty and Sensitivity Analysis) codes/methods in the SA domain is planned to be delivered. Among the uncertainty quantification tools, partners are using SUSA, DAKOTA, URANIE, RAVEN, and data assimilation tools (NEMM, MOCABA); additionally, the coupling and post-processing require PYTHON scripting.

WP4 (Application of UQ Methods against Integral Experiments, AUQMIE) was outlined to get some experience and insights into applying the RUQM methodologies against internationally recognized integral ST-experiments. Since its onset, it has become a drill for other application WPs (WP2 and WP3) and an opportunity to provide some early feedback to RUQM. The test PHEBUS FPT-1 was selected for this purpose. The work has already been practically finished and the main outcomes are gathered in [14].

WP5 (Uncertainty Quantification in Analysis and Management of Reactor Accidents, UQAMRA) aims at demonstrating the applicability and the level of readiness of uncertainty assessment in a broad range of set-ups. In addition to uncertainty bands affecting ST estimates, two other major outputs are to be produced: a best-practice protocol for applying UaSA methods to SA codes (as feedback to WP3) and identifying areas where further research would efficiently reduce ST estimates. Four subgroups have been set up according to the reactor technology (PWR Gen II; PWR Gen II; VVER/CANDU; BWR). The work is undergoing, and preliminary insights

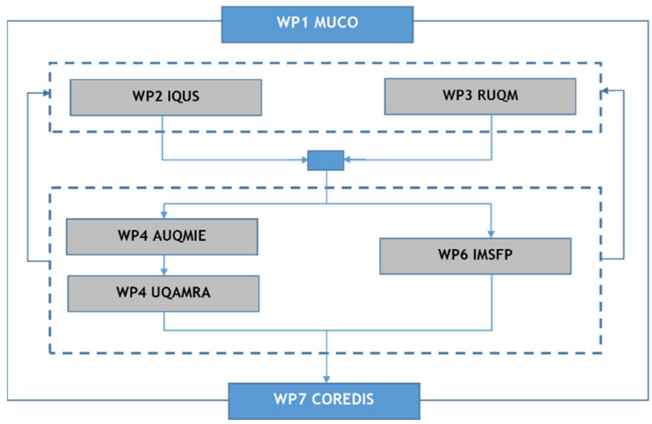

Fig. 6. MUSA Work Package interlink.

into BEPU application to SA have already been gained [15].

WP6 (Innovative Management of SFP Accidents, IMSFP) follows the same orientation as WP5 with respect to RUQM methodologies application to SFP SA scenarios, but a special emphasis has been placed on AM mitigation measures. The same scenario (a loss-of-cooling accident inspired in the SFP of Unit 4 of the Fukushima Dai-ichi NPP) is being simulated by all the partners. Given the differences with WP5, FOMs have been somewhat adapted. Preliminary results of the UaSA exercise are being obtained, and major observations have already been delivered [13].

3.3 Preliminary results

Once over the MUSA half-life time, some preliminary results, particularly from the application packages (WP4-WP6), are worth noting:

- identification and characterization of the input uncertain parameters has resulted/is resulting in a key and challenging task. On one side, the huge complexity of a SA scenario involves a tight phenomenological interlink that, even when just focused on a few FOMs, results in an overwhelming number of potentially influencing input variables subject to uncertainty (easily over hundreds or even further). On the other, the lack of characterization (lower and upper bounds, probability density function) data for many of those variables make their definition uncertain by itself.
- A review is ongoing to identify if input parameters are lacking. But the input uncertainty quantification, which has been identified as an important step in the UQ phase [13], is a long task that is out of the scope of this project.
- Highly demanding computation costs have been found in all the application WPs, although a noticeable variability among partners has been reported (from a few hours to several days per single run). Using multi-core processors or PC clusters might help overcome this challenge (particularly with UQ exercises over 100

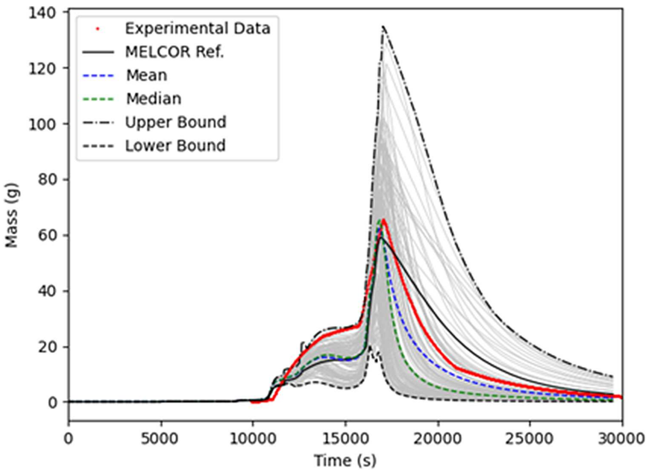

Fig. 7. Airborne particle mass in containment (FPT1) [14].

runs). Figure 7 shows an example of the type of results obtained within WP4.

- Code crashes look practically unavoidable when addressing "full-scope" scenarios for the first time, and there is no systematic way to handle them. Extending the number of runs with respect to the minimum required by the Wilks' formula to ensure having enough computations is an option but does not guarantee a proper FOM distribution without biases. All this said some codes appear to be more resilient to failures than others.
- Systematization of SA code/UQ-tool coupling, as well as post-processing through scripting, is an essential step to better accommodate the long time required by this application and to address the best way to analyze the huge numerical data resulting.
- The application of regression techniques entails no minor challenges. At this time, it seems unlikely to define an optimum correlation coefficient; what is considered essential is the accurate meaning of the chosen coefficient. This is an area where several project partners are working on. Using the physical understanding of the scenario to figure out the rationale behind the significance/non-significance of any sampled variable is indispensable.

4 AMHYCO: optimizing management of combustible gases

4.1 Project overview

The project AMHYCO (Towards an Enhanced Accident Management of the Hydrogen/CO Combustion Risk) will consider practical issues to reduce further (as much as possible) the threat posed by the combustion of gases generated during accidents on containment integrity [16]. Specifically, it will improve the Severe Accident Management Guidelines (SAMGs) for both in-vessel and ex-vessel phases using numerical and experimental results. It will also experimentally study the phenomena that are difficult to predict numerically (such as H_2/CO/H_2O distribution and combustion). A third goal will be to improve the predictability of the numerical tools used for explosion hazard evaluation.

The project has received funding from the Euratom research and training program 2019–2020 under grant agreement No 945057. The total cost is in the order of 4 M€ with a human resource involved in the order of 490 person-months, over 4 years (2020–2024). It is an international collaboration that involves 10 European partners, research centers, and private companies (CIEMAT, CNL, CNRS, ENERGORISK, FRAMATOME, FZJ, IJS, IRSN, LGI, NRG, RUHR U., UPM), and is led by UPM. In addition, an external advisory committee and an end-user group have been set up to count on some external consultancy and to ensure the optimum exploitation and dissemination of the results.

Appropriate management of the associated risk to combustible gases is paramount to avoid the potential release of radioactive material to the environment due to the containment loss of integrity. SAMGs must be regularly updated and include knowledge gained from international efforts, including recent and ongoing research projects. AMHYCO will contribute to this objective by improving the understanding of H_2/CO combustion and incorporating this knowledge into SAMGs. The AMHYCO project intends to respond to practical questions, such as the right timing and mode for actuation of containment safety systems (i.e., Filtered Containment Venting System (FCVS), sprays, fan coolers) to reduce as much as feasible the threat posed to containment integrity. To do so, all the available tools to enhance the present status (i.e., LP, 3D, and CFD codes, together with experimentation and the best use of engineering judgment) are to be applied.

The scope of this project is outlined by the most common reactor technology in the EU: PWRs. The three existing designs are being addressed: PWR-Western type (PWR-W), PWR-KWU type (PWR-K), and PWR-VVER type (PWR-V). When feasible, diversity in reactor size (power) is also being considered.

4.2 Project structure

In order to meet the above objectives, the project proposes a working method based on five different work packages (WPs), as illustrated in Figure 8, which are at the same time successive and interlinked.

The WP1 aims at reviewing the status of existing methodologies and practices related to gas combustion risk management in the late phase of severe accidents. As most of the mitigation strategies adopted in European countries to prevent this risk are based on the use of Passive Autocatalytic Recombiners (PARs), a critical assessment of the PAR behavior in the late phases of severe accidents is performed. Similarly, a survey of the available experimental data and engineering combustion models is provided. The lessons learned will help identify knowledge gaps related to hydrogen (H_2) and carbon monoxide (CO) recombination and combustion. In addition, a review of

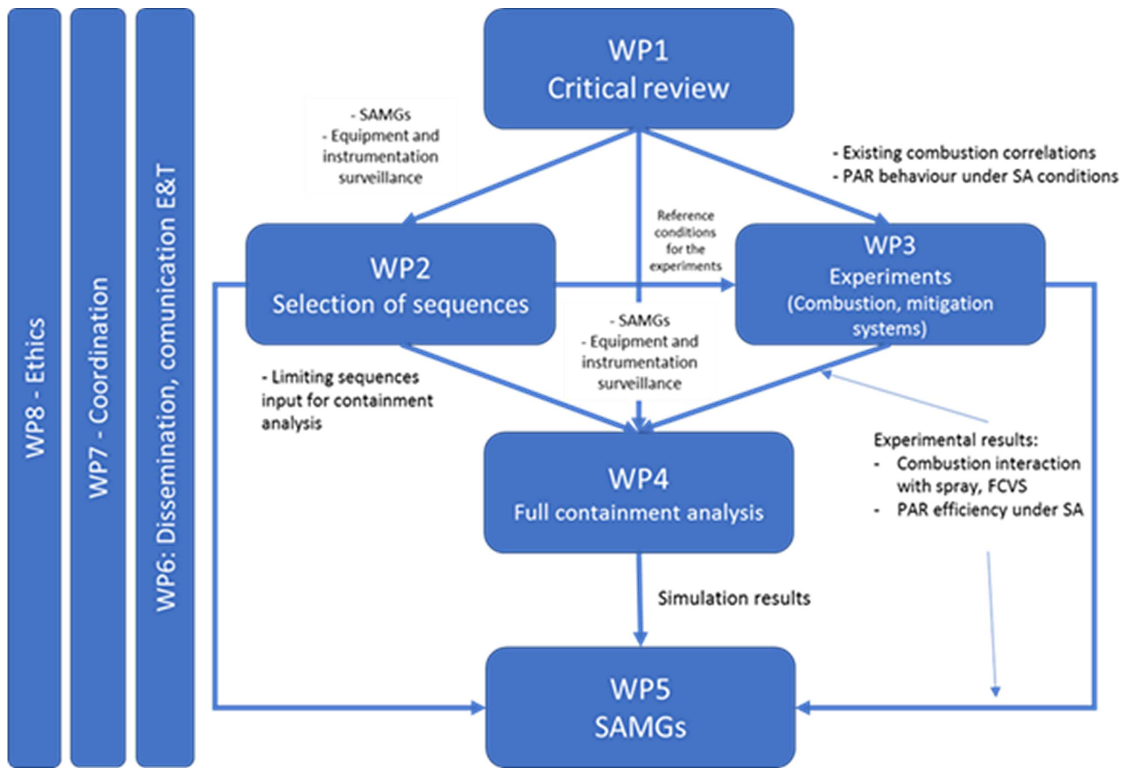

Fig. 8. AMHYCO project outline.

the safety equipment qualification criteria and gas monitoring systems, as well as the existing SAMGs, is established with the aim of paving the way toward SAMGs enhancement.

The intention of the WP2 is to identify accident sequences in which H_2 and CO combustion risk might jeopardize containment integrity. Given the current European nuclear reactor fleet, the three PWR reactor designs have been modeled (PWR-W; PWR-K; PWR-V), and the most relevant sequences have been chosen according to a set of agreed criteria: high molar fractions of combustible gases ($H_2 + CO$) in control volumes which conditions are within flammability limits; large total mass of combustible gas ($H_2 + CO$) within the containment; and, fast combustible gas ($H_2 + CO$) release rates. Besides, this WP includes a specific task to produce "Generic Containments (GC)" databases based on containment descriptions available and/or reachable by the AMHYCO team [17]; from the 3D description (CAD file), lumped-type nodalizations are agreed among partners to be later used in WP4.

The objective of WP3 is to experimentally investigate phenomena related to hydrogen and carbon monoxide combustion and mitigation, which are still not covered by existing numerical models. The focus is set on the combustion of hydrogen/carbon monoxide/steam mixtures as well as on the operational behavior of PARs under boundary conditions representative of the late phase of severe accidents. Hence, following the conclusions of the review performed in WP1 and the scenarios selected in WP2, WP3 will provide specific experimental data to assess and enhance the numerical tools used in WP4.

The most penalizing sequences identified in WP2 for the PWR containment designs will be further analyzed within WP4. The focus of the analysis will be to investigate the late phase containment response in terms of containment pressure build-up, H_2/CO combustion risk, efficiency, and options/timing of individual mitigation measures (in particular PARs, fan cooler or spray systems, and FCVS), and equipment and instrumentation surveillance. For this purpose, the sequences for each plant design will be generalized and harmonized as far as possible in WP2 to enable comparability, and the RCS is simply represented by source terms (energy and mass; fission products will be neglected).

Finally, WP5 aims to identify room for improvement of SAMGs with respect to the management of combustible gases within the containment. The basis for this evaluation is the experimental and computational efforts carried out in the above-mentioned WPs. Thereby, the insights from the calculations, including the late phase with CO present in the containment, will be transferred into SAMG considerations. Recommendations are foreseen for all large-dry PWRs containments explored in the project.

4.3 Preliminary results

For the time being, the results have come from the insights gained from WP1 reviews, the calculations conducted in the frame of WP2 and the GC databases built up, and the early phase of experimentation concerning PARs performance and combustion of combustible gas mixtures. All of them may be summarized as follows:

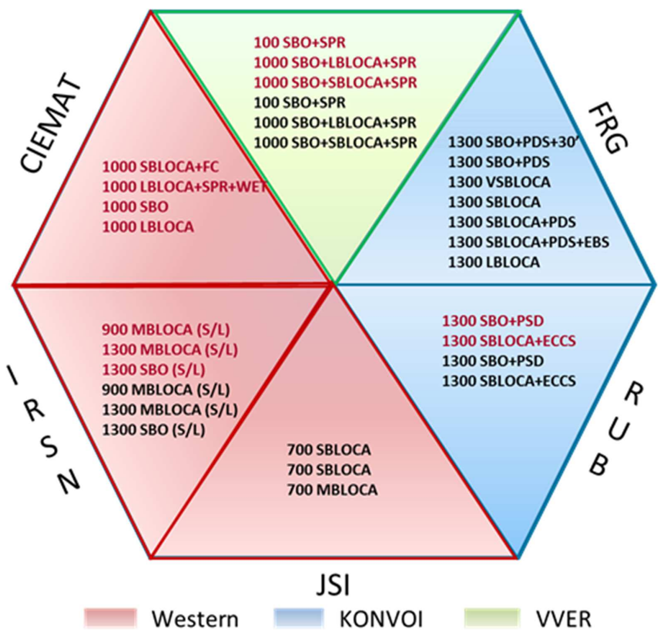

Fig. 9. Severe accidents sequences modeled.

- additional experimental and theoretical investigations are needed to fill the knowledge gaps regarding the PARs behavior in representative conditions of severe accidents in late phases. Given that the different nature of existing models (from engineering correlations to CFD models accounting for phenomena such as thermal radiation, superficial and bulk chemical reactions on the surface and in the gas) was validated on experiments dealing with H_2, data with gas combustible mixtures are necessary to extend the domain of the model's validation. WP3 will supply the data for such a purpose, and the resulting enhanced equations will be implemented in safety codes to simulate the containment of severe accident scenarios in WP4.
- The requirements for combustion risk management and mitigation measures address only in-vessel conditions and aim to preserve containment integrity; their extension to ex-vessel conditions needs to be established. In addition, most times, they have a qualitative nature. This focus on the in-vessel phase extends to monitoring systems, which are not designed to measure CO. Finally, just a few SAMGs instruct on how to use other safety systems (i.e., sprays, FCVS) to handle the combustion risk in the late phases.
- H_2/CO combustion in representative conditions has been poorly investigated. Few data are available in the open literature, and, consequently, the application of existing modeling is restricted to a limited validation. Part of the work underway in WP3 is dealing with this issue and will provide data on laminar and turbulent flame speed, flammability limits, and flame acceleration criteria. These data are expected to contribute to the enhancement of the existing engineering correlations and combustion models.
- A number of accident sequences have been modeled for each reactor type addressed (Fig. 9). The accident selection has been fundamentally based on the resulting Shapiro diagrams, samples of which for PWR-W are shown in Figure 10. In the case of PWR-KWU reactors, the sequence selected has been an SBLOCA (80 cm^2). Despite the diversity of reactor size in PWR-W (i.e., 700 MW, 1000 MW, and 1300 MW), it was agreed that the selected sequences were an SBLOCA (120 cm^2) and a double-ended guillotine break (LBLOCA). As for VVER reactors, the decision is still to be made.
- The flammability limits for a mixture of $\{50\%H_2 + 50\%CO\}$ in air ($O_2/N_2 = 0.264$) and in starvation conditions ($O_2/N_2 = 0.11$) for an initial pressure ranging from 1 to 3.5 bar were determined in the ENACEFF facility. The effect of CO_2 and H_2O is currently being investigated [18,19].
- Scoping tests were performed with different catalysts (platinum- and palladium-based) to define the boundary conditions of more complex experiments to be conducted in the REKO-3 facility [16]. Specific focus was set on identifying the conditions for catalyst poisoning, which could be highly significant for late-phase PAR operation. For Pt-based catalysts, the catalyst poisoning temperature (i.e., the threshold value of the catalyst temperature below which the catalyst gets poisoned) was shown to be independent of the gas temperature, while Pd-based catalysts were found to be less sensitive to poisoning at elevated gas temperature.

5 Final remarks

This paper illustrates the ongoing support from Euratom to further strengthen the nuclear safety of NPPs through investigating innovative, reliable safety systems (PIACE project), enhancing predictive analysis of SA scenarios (MUSA project), and optimizing guidelines to manage combustible gas risk in containment (AMHYCO project).

The PIACE project focuses on the designs of the innovative DHR concept, ready for industrial implementation on several reactor technologies ranging from currently operating plants (L- and H-WRs) to innovative energy systems (including FRs and ADSs). The innovation lies in the ability of the system to control passively the power exchanged with the heat sink by using non-condensable gases. The activity developed so far showed: the applicability of the system to the different reactor technologies, the scalability of the system to be tested on the SIRIO facility, the necessary testing of each reactor technology, and the selection of the reactor technologies as reference cases for the test campaign. The experimental campaign is ongoing.

The MUSA project is facing the challenge of bringing uncertainty and sensitivity analysis into the SA simulations as a means to better assess the potential source term to the environment, encompassing both Gen. II and Gen. III reactors and SFP accidents. So far, a database on input deck uncertainties has been built and applied to the simplified scenario of PHEBUS-FPT1, and the first challenges and difficulties of a systematic application of UaSA into SA analyses have been experienced, and ways

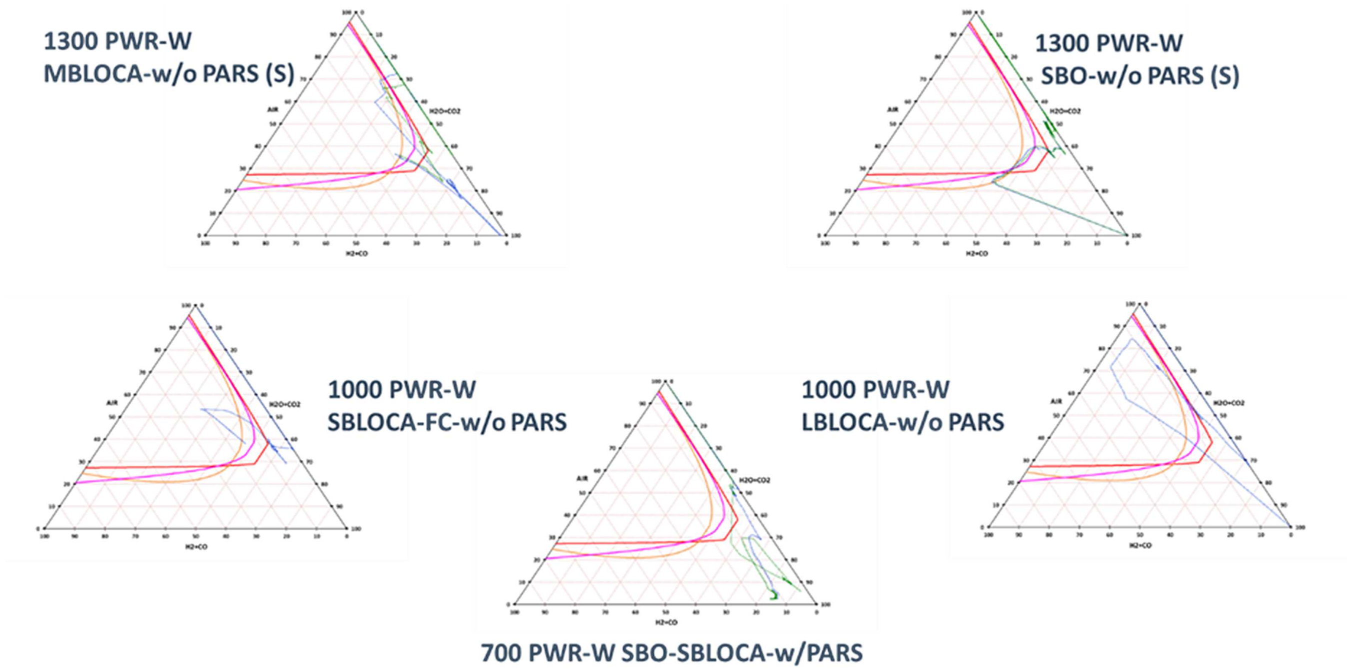

Fig. 10. Shapiro diagrams of the PWR-W accident sequences analyzed.

to overcome them are being proposed. Currently, the practical application to reactor and SFP scenarios is underway, and the lessons learned from the FPT1 training experience are being tested in these "full-scope" simulations. From these exercises, feedback on BEPU methodologies application in SA analyses is being settled.

The AMHYCO project is addressing practical issues to further reduce (as much as possible) the threat posed by the combustion of gases generated during accidents on containment integrity. Specifically, it will propose improvements to the SAMGs for both in-vessel and ex-vessel phases using numerical and experimental results. It will also experimentally study the phenomena that are difficult to predict numerically (such as $H_2/CO/H_2O$ combustion and recombination). The progress done so far has paved the road to the full containment simulations and SAMGs feedback that will take place in the second phase of the project; in addition, experimental investigations on PARs performance and gas combustion under conditions barely explored earlier are ongoing.

Finally, despite the harsh COVID conditions that have prevailed since early 2020, the three projects are deeply committed to young researchers' and engineers' education and training through powerful mobility programs already being executed.

Conflict of interests

The authors declare that they have no competing interests to report.

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