

Looking ahead to severe accident research

Luis E. Herranz^{1*,**}, Bastien Poubeau^{2**}, Lionel Chailan³ and Fulvio Mascari^{4**}

¹ Centre for research on Energy, Environment and Technology (CIEMAT), Avda. Complutense, 40, 28040 Madrid, Spain

² Autorité de Sûreté Nucléaire et de Radioprotection (ASNR), PSN-RES, F-92262 Fontenay-aux-Roses, France

³ Autorité de Sûreté Nucléaire et de Radioprotection (ASNR), PSN-RES/SAM, F-13115 Saint-Paul-lez-Durance, France

⁴ Agenzia nazionale per le nuove tecnologie, l’energia e lo sviluppo economico sostenibile (ENEA), Via dei Mille n. 21, Bologna (BO), Italy

Received: 21 November 2024 / Received in final form: 29 March 2025 / Accepted: 5 May 2025

Abstract. Severe Accident (SA) research is currently facing new challenges coming from changes in the energy and computer science sectors. Therefore, it is imperative to reassess the current status in the area to optimize where the research resources should go to reach even higher safety standards both in the running Nuclear Power Plants (NPP) and the upcoming new designs, particularly Water-Cooled Small Modular Reactors (WC-SMR). Three Horizon Euratom projects stand out in such context. SEAKNOT (Severe Accident research and KNOWledge management) is progressing in setting a SA research roadmap by ranking the major phenomena involved in terms of knowledge and safety significance in LWRs (large water-cooled reactors) and SMRs, at the same time that it is strengthening paths for Education & Training (E&T) on SA for forthcoming generations of researchers and engineers. SASPAM-SA (Safety Analysis of SMR with PASSive Mitigation strategies-Severe Accident) is supplying valuable information on phenomena, boundary and accident conditions that might prevail in WC-SMRs, specifically integral PWR (iPWR). The project allows the assessment of the applicability of the current state-of-the-art simulation codes and the relevance of large reactor experiments to iPWRs. Different SA mitigation strategies, like In-Vessel Melt Retention (IVMR), are being explored. Finally, ASSAS (Artificial intelligence for Simulation of Severe AccidentS) is working to prove the possibility to develop fast-running SA simulators thanks to Artificial Intelligence, to support training, engineering and emergency response. This paper discusses the major progress made in the three projects and their complementarity contributes to a safer nuclear energy production.

1 Introduction

The international research agenda on Severe Accidents (SA) [1] moved towards new directions right after the accidents at the Fukushima Daiichi site on March 11th 2011. In the short-term, some initiatives targeted a thorough understanding of the accident progression [2], while some others focused on investigating phenomena playing a substantial role in the accident scenarios [3,4] and/or to explore the potential of specific actions that might significantly enhance Accident Management (AM). In the mid-term, without abandoning earlier research lines, interest expanded to new simulation approaches bringing sounder bases for Accident Management (AM) [5,6] and supporting the implementation of

new mitigation systems in operating Nuclear Power Plants (NPPs) worldwide [7,8], where they had not already been installed.

Building on this Fukushima-driven research and noting the change experienced by nuclear energy in terms of innovative technologies solutions (i.e., Small Modular Reactors, SMR; and Advanced Tolerant Fuels, ATF) and modelling techniques (i.e., artificial intelligence, AI; and Machine Learning, ML), a new research agenda is needed. This agenda should address remaining knowledge gaps with significant safety implications, incorporating these new technologies and modelling approaches. This is the investigation space that the Horizon Euratom SEAKNOT, SASPAM-SA and ASSAS address. In the coming sections a synthesis of these projects and the major achievements made half a way from their start is given.

* e-mail: luisen.herranz@ciemat.es

** These authors contributed equally to this work.

2 SEAKNOT: optimizing resources

2.1 Motivation

After several decades of research on SA in Nuclear Power Plants (NPPs), major safety enhancements have been made based on databases and codes built. Some of the most recent ones came from the Fukushima-Daiichi crisis and the subsequent stress tests conducted in European NPPs. As a result new safety systems, like Passive Autocatalytic Recombiners (PARs) and Filtered Containment Venting Systems (FCVS) have been massively implemented, once their positive effect on accident scenarios was proved through numerical simulations [2–5]. At present, there is a need to look back with perspective and project future research on sound bases that consider both the knowledge heritage and future challenges. In this context, knowledge preservation is a must. Senior scientists and engineers who started their careers after the accident at the TMI-2 accident have retired or are currently unavailable. It is indispensable that their non-written knowledge and know-how is passed onto those who will be responsible for responding the upcoming safety demands. This circumstance is even further aggravated by the huge transformation experienced in the physical support that archiving has undergone in last decades, which makes a good fraction of the oldest files not being accessible anymore or being at risk of being lost forever. SEAKNOT was devised to pave the way that inter-generation knowledge/knowhow transfer takes place as extensively and efficiently as feasible.

Nuclear technology and safety environments are notably changing and pose new challenges that should be responded with sound and scientific arguments. Innovation in nuclear technology has brought up Advanced Technology Fuels (ATFs) and Small Modular Reactors (SMRs) on the scene (in the next section, the SASPAM-SA will be described)), which even if targeting higher safety standards, would require a proper demonstration for them to become an industrial reality. AI and ML have also reached nuclear technology, and multiple applications are being explored, even in safety (in the next section, the pioneer work attempting AI use in ASSAS will be described). Additionally, application of Uncertainty and Sensitivity Analysis (UaSA) in SA analysis [6] is bringing new insights into the traditional Best Estimate (BE) analysis and should be on board of any future projection of SA research. All these elements are within the SEAKNOT scope and will be assembled in the SA research roadmap currently under development.

The factors discussed above highlight the need of SEAKNOT, particularly when resources in SA are decreasing. By critically reviewing the existing knowledge to project a SA research roadmap, a strengthening of the understanding of accident unfolding and an optimization of AM is being pursued. A key element to achieve the goal is to involve and enable young scientists and engineers by conducting a proper transfer of both knowledge and knowhow. These are the major drivers underneath the EURATOM SEAKNOT project (GA 101060327; [https://ec.europa.eu/info/](https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101060327/program/43298916/details)

[funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101060327/program/43298916/details](https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101060327/program/43298916/details)), which is coordinated by CIEMAT (Spain) and participated by a total of 16 European organizations plus 1 associated partner.

2.2 Resources articulation

The SEAKNOT project relies on two fundamental pillars: expertise and state-of-the-art. As said above, SEAKNOT aims to produce the means to make the SA related research as efficient as possible in the coming decade by identifying what should be addressed, by enabling the capabilities of those who plan to be involved in it, and by stating which existing or non-existing experimental infrastructures would be needed for such a purpose. This means that reaching a “critical expertise” by gathering senior experts with diverse perspectives (i.e., researchers, regulators, industry. . .) and mind-sets into the project is fundamental to conduct a non-biased critical assessment. At the same time, it is of utmost relevance to bring in young researchers and engineers and make them part of this venture on the best feasible grounds.

The backbone of the SEAKNOT project is the Phenomena Identification and Ranking Table (PIRT). It will be produced together with consolidated information on the SA experimental database as well as critical experimental infrastructure. Based on outcomes from previous full-scope PIRT exercises [9] and from international research projects conducted in the last two decades under the frame of EC, OECD/NEA and IAEA, particularly those on Fukushima Daiichi accidents [2], the periodic analysis of research priorities such as formulated by SNETP/NUGENIA/TA2 [10] will be updated and extended, if necessary. As additional elements to consider, progress made in nuclear technology, such as Water-Cooled (WC) SMRs and ATFs, will bring new SA scenarios to explore and will be also addressed.

Figure 1 shows a sketch of the workflow that will articulate the whole SEAKNOT project through the different Work Packages (WPs). Aside WP5 (Project coordination), there are 4 technical WPs. The PIRTSA WP (WP1) aims at developing the PIRT, with a specific sub-WP (WP1.1) devoted to set a methodology and the other sub-WPs (WP1.2-WP1.5) to its application in the in-vessel, ex-vessel, containment, and source term domains. The Validation Database Directory (VADD) WP (WP2) structure is practically identical to WP1 but its focus is the SA database (DB) to finally provide a sort of DB directory for SA codes validation. Note the strong interaction of VADD and PIRTSA, as input on available representative data is one of the pillars of the PIRT. WP3 SAINET (Severe Accident experimental Infrastructure NETWORK) plans to build a map of experimental infrastructures in Europe with potential to be used in the coming years, as well as to identify what sort of facility should be set up to address some of the primary PIRT issues, if none of the existing ones can do it. Finally, WP4 KNOS (KNOWledge Spreading) responds to the SEAKNOT need

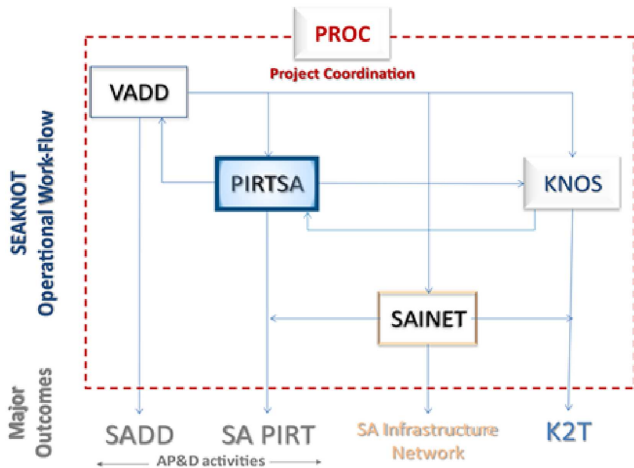


Fig. 1. SEAKNOT work-packages and major outcomes.

of a powerful WP for dissemination, communication, and exploitation of the project results, also in the view of an effective K2T (Knowledge and Knowhow Transfer) to young generations of researchers and technicians.

The SEAKNOT central activity is the PIRT. Once the fundamental SA library, which consists of a list of the references used for the individual PIRT in each severe accident domain (i.e., in-vessel, ex-vessel, containment and source term) is gathered, the main sources of relevant data will be identified and employed to characterize the existing knowledge. Both the safety significance as well as the existing modelling capabilities of the phenomena under study will be assessed according to the PIRT methodology [11]. The domain PIRTS will be disseminated at different levels, from the lectures in the Severe Accident Phenomenology (SAP) course and hands-on training sessions in SASCamp (SA Summer Camp) to potential papers in the next editions ERMSAR conferences, passing through the updates in the SA textbook that was published by SARNET [12]. In turn, the PIRT process will be given specific support by the mobility programme for young researchers and engineers. The SA database evaluation and the consideration of WC-SMRs and ATFs will highlight necessary experimental infrastructures to be used by the SA young workforce when addressing the issues ranked on top in the PIRT. As a final outcome, SEAKNOT will outline a SA research roadmap capable of enhancing nuclear safety records, including WC-SWRs and ATFs.

Under CIEMAT coordination, 16 European organizations are investing 260 person-month in the SEAKNOT endeavors (<https://seaknot-project.eu/>).

2.3 Major progress

The PIRT methodology, born in the field of thermal-hydraulics and Design Basis Accidents (DBA) [11], has been adapted for a “full-scope” PIRT in SA. This is a major step and has required extensive and thorough discussions. The specific problem the PIRT addresses is the

identification of the SA issues which research would lead to better characterize, reduce uncertainties and efficiently enhance mitigation of SA consequences. The focus is on the potential issues effect on source term, i.e., radiological releases from the NPP, specifically on Figures Of Merit (FOMs): onset time, rates and composition of the releases to the environment of a selection of radionuclides (I131; I132; Cs137; Ru106; Te132; Kr88; Xe133; Xe135). The drastic difference expected in source term between the in-vessel and the ex-vessel phases recommends splitting accident sequences accordingly.

Ranking consists in assessing the relative importance of processes and phenomena with respect to the evaluation criteria selected as parameters of interest. The research priority is being assessed based on existing knowledge and safety significance of each phenomenon; each of these concepts split in three levels (i.e., low, L; medium, M; high, H). Knowledge is weighed on data availability and representativeness, and modelling maturity; as in the case of priority, three levels are given to both data and models. Figure 2 shows how knowledge and safety significance combine to define priority. It is high priority (H) whenever knowledge is poor (L) and safety significance is high. Low priority is attributed whenever safety significance is low and/or existing knowledge is high. The rest of cases (3), is given a medium ranking level but ordered by priority: the maximum (M1) given to high safety significance and the minimum (M3) to mid-impacting phenomena on which there is some knowledge.

At present phenomena has been listed in the in-vessel, ex-vessel, containment and source term domains and have been orchestrated in the two accident phases mentioned above (i.e., each “phase list” will include phenomena from its domain plus from the containment and source term ones, whenever they occur during that specific accident phase). The criteria set to bring a phenomenon in the list have been: (1) playing a role in an accident scenario of interest and, (2) potential effect on the Figures Of Merit (FOMs) chosen. It is considered that evaluation of some phenomena might require conducting ad-hoc sensitivity studies.

Validation databases play a pivotal role in enhancing the accuracy and reliability of the computer codes employed for nuclear safety analysis by validating the underlying physics and mathematical models incorporated into these codes. A Validation Database Directory (VADD) of “relational data” prepared by conducting critical analyses of the existing SA database is ongoing. A comprehensive literature review has been performed to collect SA database information as per pre-defined SA research sub-domains (i.e., in- and ex-vessel, containment and source term). In parallel, database information has also been collected on verification & validation matrices implemented in several of the existing safety analysis codes, such as MELCOR, ASTEC, AC², and GASFLOW. A variety of criteria were set in the review: relevance of experimental data; applicability to various reactor designs; validation at different scales; data used in code benchmarks; and documentation.

A methodology to assess and consolidate the SA database to finally select data as part of VADD has been

		Safety Significance		
		Low	Medium	High
Knowledge	Low	L (Poor understanding; irrelevant)	M2 (Poor understanding; mild effect)	H (Poor understanding; impacting)
	Medium	L (Some understanding; irrelevant)	M3 (Some understanding; mild effect)	M1 (Some understanding; impacting)
	High	L (Sound understanding; irrelevant)	L (Sound understanding; mild effect)	L (Sound understanding; impacting)

Fig. 2. PIRT ranking.

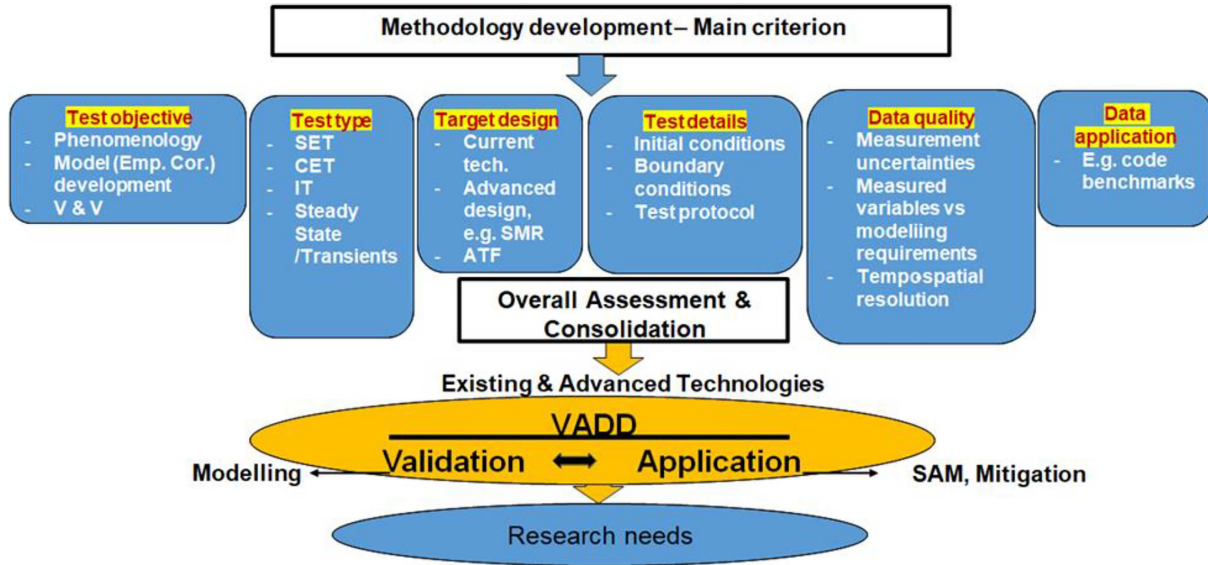


Fig. 3. Elements of the database assessment methodology (SET stands for Separate Effect Tests; CET, Combined Effect Test; IT, Integral Test).

also set. Lessons learned from the related database collection and evaluation activities, such as OECD/CCVM [6] and SAPIUM [12] and SNETP-NUGENIA IPRESA [13] have been considered as a good basis to develop a larger scope methodology suitable for the assessment of the entire SA domain. The main elements of the database assessment methodology are shown in Figure 3. This adequacy check involves assessing representativity and completeness of data, covering factors, such as spatial and temporal scales, boundary conditions, and relevant phenomena.

To facilitate broader outreach of the relational “database” beyond SEAKNOT, an analytical tool “website” is being developed. This relational database, inspired by existing thermal-hydraulic tools, e.g. OECD/NEA THIETYS [7], will serve as a valuable resource for code validation and mitigation strategy assessments.

In order to be capable to point the most suitable facilities to address the specific issues that will be ranked high in the PIRT, a mapping of the current European experimental facilities investigating SA has been built. By surveying the entire European SA community, information has been collected on facilities (characteristics and materials), running teams (expertise and professional situation), data provided for SA codes validation, current and planned activities in the coming years, and open references including their contribution in recent years. As

an illustration of the outcome from this activity, Figure 4 gives an overview of the phenomena that have been experimentally investigated in the recent past: source term & fission products, ex-vessel, in-vessel, pool scrubbing, and containment and H₂-risk. Some key insights have been highlighted: more than 20 European facilities do not have any planned activity ahead in the coming years; “critical competences” are threatened to get lost with no chance to transfer them in about 10 of them; and, currently few facilities are being used for WC-SMRs and ATFs research under SA conditions.

In the axis of knowledge spreading, significant progress has also been achieved:

- the first SEAKNOT SAP course was held in the Madrid premises of UPM on June 19–23, 2023. The technical program mostly focused on key phenomena governing SA unfolding, ended with a few lectures on application in SA management, decommissioning of accidented NPPs, Probabilistic Safety Analysis (PSA), etc. A total of 60 attendees from about 20 nationalities participated in SAP, 27 professional and 33 students. Next SAP 2025 edition will be organized from 23 to 27 June 2025 at Forschungszentrum Jülich (FZJ) and will be followed by the first edition of the SASCAMP (Severe Accident Summer Camp), where attendees will face with practical assignments under the supervision

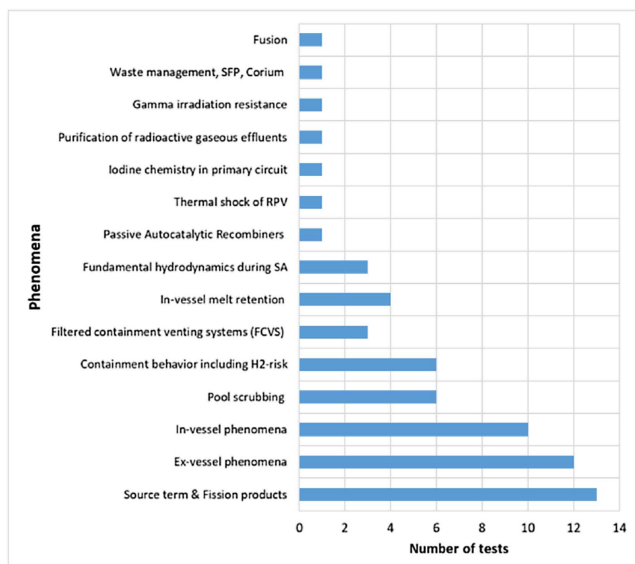


Fig. 4. Number of facilities involved in a severe accident topic.

of instructors that will lead them to find out solutions to the challenges posed.

- The first ERMSAR (European Review Meeting on Severe Accident Research) Conference in the SEAKNOT framework is the current 11th edition, hosted by KTH Stockholm, was attended by 160 professionals, which meant an increase of 20% over the previous edition, both in attendees and in number of papers submitted. The proceedings of the conference are already available [14]. The next edition will be held in Madrid (18–22 May, 2026).
- The textbook “Nuclear Safety in Light Water Reactors - Severe Accident Phenomenology”, edited in 2011 by Bal Raj Sehgal [12], under the frame of the SARNET FP6 project, is being reviewed by previous authors and experts to identify chapters and sections that might need an update and/or an extension. Presumably, part of the progress made after the Fukushima-Daiichi accident and some innovative aspects brought in by nuclear technology (i.e., installation of new engineering safety systems, new insights into accident management, ATFs, and WC-SMRs, among others) might be considered.
- A mobility program is allowing young students and researchers to attend international conferences, workshops, and seminars to present some SEAKNOT results. Since the onset of the project, actions have been supported, including one long mobility, and several further actions are on the pipe for approval.

2.4 Perspectives

Based on the accomplishments of the first two years of the project, SEAKNOT is facing an interesting and exciting phase on its way to meet the project goal. To name a few

of the upcoming milestones along the third year of the project:

- the individual domain PIRTs (i.e., in-and ex-vessel, containment and source term) will be produced and merged into what has been called “phase-based PIRT”, where source term impacting phenomena requiring further research will be identified and classified as “in-vessel” and “ex-vessel”.
- The relational database is to be set, providing the necessary feedback to assess the existing knowledge of the issues considered in the PIRT, and the input to know what is experimentally needed to be “hunted” and whether the facilities available could be used for the purpose.
- A potential network of SA experimental research infrastructures will be proposed, based on the existing facilities and the needs outstanding in the PIRT. The framework to host it must still be identified and discussed with stakeholders.
- The activities on communication and dissemination will be further strengthened by holding a new edition of SAP (SAP2025), complemented with SASCAMP, updating the SA textbook issued more than 12 years ago with new relevant sections, preparing the last edition of ERMSAR within SEAKNOT (ERMSAR2026), and encouraging organizations to embark in an ambitious program of mobility actions.

Finally, although SEAKNOT has already set bonds with other international projects and activities, it is expected that this year such interactions become more and deeper, so that the SEAKNOT messages easily reach any entity performing research on SA.

3 ASSAS: moving forward in modelling

The ASSAS project has started on 1st November 2022 for a duration of 4 years. It gathers 14 partners from the European Union, Switzerland and Ukraine, who will employ 492 person-month during the project. It will develop a basic principles simulator featuring a 1300-MWe four-loop Pressurized Water Reactor (PWR). This simplified simulator will show the possibility to connect ASTEC (Accident Source Term Evaluation Code, the severe accident code developed by ASNR [15]) with the commercial simulation platform TEAM.SUITE® developed by Tecnatom, to demonstrate the feasibility of industrial severe accident simulators. ASSAS will also prepare the extension of severe accident simulators to other designs and severe accident codes.

3.1 Motivation

Simulators are user-friendly and immersive tools that are widely used for education and training, reaching out students, reactor operators, emergency responders and other nuclear professional [16]. Their detailed description of specific NPPs also makes them an asset to support procedure development and safety assessment. The graphical

user interface, the computer-aided design tools and data analysis functionalities that they incorporate help nuclear engineers become more rapidly proficient in the use of thermal-hydraulic system codes. However, most simulators are limited to DBA, because of the lack of knowledge about SAs and the prohibitive calculation time required by SAs codes at the time of their design [17]. The increasing scientific maturity concerning SA phenomenology make them now more relevant. The deployment of additional SA mitigation systems in response to the Fukushima-Daiichi accidents also calls for adequate training that simulators can offer [18]. One remaining scientific challenge concerns the ability to run SA codes in real time, to give a realistic experience. ASSAS will address this limitation to open the way for diverse types of SA simulators.

Like many legacy scientific calculation codes, especially in nuclear science, SA codes cannot efficiently exploit recent computational hardware with a parallel architecture. SAs are by nature multi-physic and sensitive, due to possible positive feedback effects between different phenomena. They also require the management of large material and isotopic databases for an accurate modelling. This makes their optimization particularly tricky. Even with a software more adapted to modern hardware, some computationally intensive applications of SA codes may remain out of reach, like uncertainty propagation or the development of diagnosis-prognosis tools in support of emergency response [19,20]. ASSAS will investigate two strategies to improve the performance of severe accident codes: numerical optimisation (limited to ASTEC) and the development of data-driven surrogate models (for ASTEC and MELCOR), which have the potential to speed-up calculations more drastically.

All concepts will be assembled to develop a SA simulator, to prove the feasibility of the approach. It will give a deterministic answer to the user, depending on the selected scenario and the operator actions. At this stage, only best estimate physical parameters will be used to simplify the development of AI-models.

3.2 Resources articulation

To achieve these objectives, ASSAS has gathered different types of expertise:

- SA researchers from ASNR, KIT, JSI, ENEA, Ciemat, PSI, KTH, IVSTT, Energorisk and BelV,
- Scientific calculation code experts from CS Group and ASNR,
- Tecnatom, a company designing simulators for the nuclear industry,
- Artificial Intelligence researchers from KIT, Phimeca, JSI and TU Delft.

The project is divided in 7 WP. The first is dedicated to the coordination of the project. The second WP provides methodological support for the development of efficient physical and data-driven models for severe accident simulation, including their validation [21]. WP3 is dedicated to the creation of a large SA calculation database

fitted for the training of fast data-driven surrogate models. Data will be generated with ASTEC for the PWR design included in the simulator and for a VVER-1000 (Water-Water Energetic Reactor) design. Data for a Nordic BWR (Boiling Water Reactor) design will be produced with the severe accident code MELCOR by KTH. The focus of WP4 is to develop ML models according to the recommendations of WP2 and thanks to the data generated in WP3. Different machine-learning models for ASTEC and MELCOR will be considered, to show the applicability of the approach to different severe accident codes with different reactor designs. Surrogate models will be trained on data generated by a specific severe accident code for a specific design. The optimisation of ASTEC and of the corresponding reactor input decks will be carried out within WP5. The trade-off between performance and accuracy will be constantly monitored. WP6 is dedicated to the development of the simulator, which includes the definition of the scenarios proposed by the simulator [22], the development of the human-machine interface, the interfacing of ASTEC with TEAM.SUITE®, and tests and documentation. The last WP is dedicated for communication and dissemination.

The project has been designed to allow partners to work in parallel on the development of the simulator, the optimisation of ASTEC and the development of AI models. This was made possible by an early and precise definition of the specifications of the simulator. Various options will be explored in parallel to speed up calculations, increasing the chances of success. Only the most performant ones will be integrated into the simulator, to reach the computational architecture described in Figure 5.

3.3 Major progress

The main innovation in ASSAS is to bring together two communities with different backgrounds to apply AI methodologies to severe accident simulation: nuclear scientists and data scientists. The first achievement has been to mutually acculturate them and develop a common language and understanding of the stakes of the project. A detailed ASTEC training has been organised by ASNR to explain the numerical structure of the code in depth. Brainstorming sessions between ASTEC developers and data scientists as well as tests carried out on small data samples [23,24] enabled partners to define a modelling strategy [25], summarised in Table 1. Several aspects have been considered to select the models of interest, which may be combined with native physics-based models in the case of ASTEC (called “hybrid” models in Tab. 1). Such hybridisation is made possible by the modular structure of ASTEC. First, the models to be replaced and to contribute to the computation time significantly. Results provided by detailed profiling tools have been exploited to identify the computational bottlenecks in ASTEC. Second, it was checked that data could be extracted without substantial modifications of ASTEC’s source code. Third, the possibility to easily interface the new models with ASTEC or the simulator was checked. Finally, partners decided to respect the physical modelling of ASTEC and

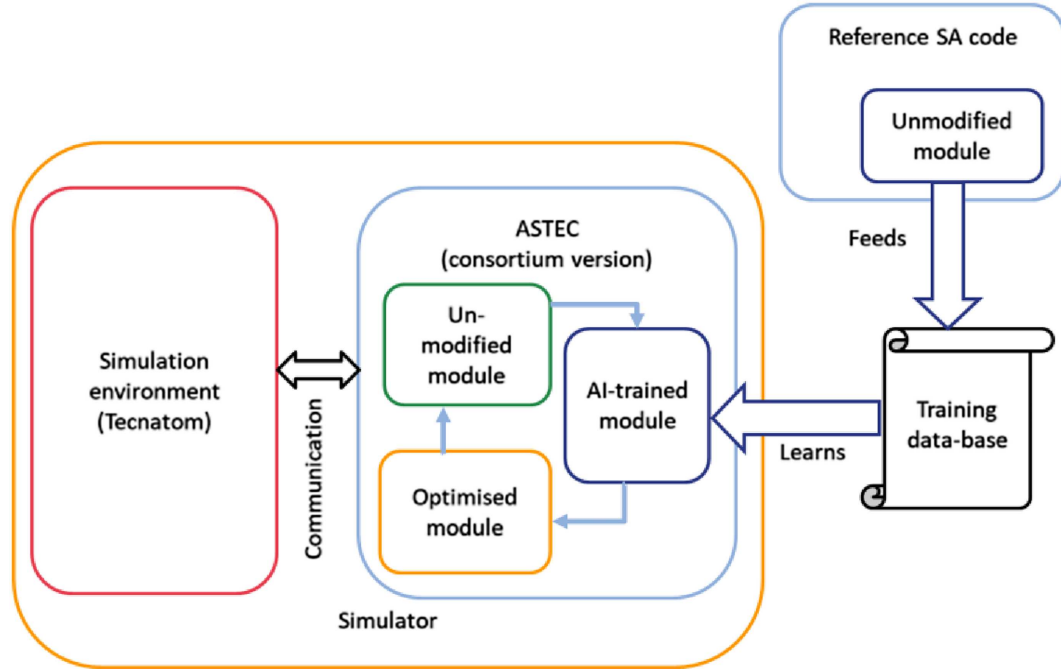


Fig. 5. Computational structure of the ASSAS simulator.

to group together phenomena known for being strongly coupled, like thermal-hydraulics and core degradation in the primary vessel. Hybrid approaches combining data-driven and physics-based models were not considered for MELCOR, since the consortium has not access to its source code. So, only a global approach was possible.

Column 2 of Table 1 presents the physical model(s) of the severe accident codes that will be replaced by a surrogate model. With global approaches, all physical models that are relevant for the selected phase of the accident will be substituted the machine-learning model. With hybrid approaches, the AI model will be limited to specific systems and physical phenomena and communicate data with other modules of ASTEC. Line 2 of Table 1 corresponds to a specific interconnection between an AI and a physical model. Indeed, the solver of the ASTEC module dedicated to thermal-hydraulics uses a Newton-Raphson method to solve a set of coupled non-linear partial differential equations. The machine-learning model will improve the initialisation of the iterative solver to converge to the solution with fewer iterations, possibly enabling the use of longer timesteps.

Data generated in ASSAS will be hosted by the datahub developed by KIT. It allows partners to upload ASTEC binary savings, from which synthetic data will be extracted in HDF5 format, which is widely used in data science. Data scientists will be able to download data generated by all partners to develop the surrogate models, gaining thus in statistical power. With at least 10 TB of available storage at the Large-Scale Data Facility (LSDF), the project plans to simulate and upload up to 10 000 severe accident sequences. The strategy to sample scenarios will be iterative. First, partners will focus on the actions available to the operator at each time of the sim-

ulation. The timing of each action will be sampled more precisely when it is expected to have more impact on the response of the reactor. This first sample database relying mostly on expert judgement for the sampling strategy will be used to train AI-models, whose performances will be assessed. Additional data will be generated for reactor states for which the surrogate models behave poorly. It must be checked that the database is representative of all the situations encountered with the simulator, to ensure the reliability of the surrogate models.

In parallel, data scientists have identified candidate methodologies for the development of surrogate models, inspired for example by the successes of weather forecasting models [26], whose underlying physics is also governed by coupled non-linear partial differential equations. They focused on advanced neural network architectures that may be used in combination. Recursive Neural Networks like Transformers [27] or Long/Short-Term Memory Neural Networks [28] have initially been developed for natural language processing. Their ability to identify correlations in time-series can be used to model dynamic physical systems. They are often associated with non-linear dimension reduction methods like Autoencoders [29], which map the high-dimension input and output parameter spaces to a small-dimension latent space with controlled accuracy loss. Indeed, Recursive Neural Networks can more efficiently learn the dynamic of the system directly on the latent space [30]. Physics Informed Neural Networks [31] are other appealing architectures because they can impose physical constraints to the surrogate models (like the conservation of mass and energy), which improves their robustness and may limit the amount of training data. They usually include first principle physical equations in their loss function, to penalise any non-physical

Table 1. Summary of the AI-models developed in ASSAS.

Data generated with	Physical model(s) replaced by a data-driven surrogate model	Type of model	Systems of the reactor	Phase of the accident	Reactor design
ASTEC	Thermal-hydraulic	Hybrid	Steam Generators, hot and cold legs, pressurizer	In-vessel phase	PWR 1300
ASTEC	Initialisation of the numerical solver for thermal-hydraulic	Hybrid	Vessel, primary and secondary circuits	In-vessel phase	PWR 1300
ASTEC	Thermal-hydraulic and core degradation	Hybrid	Reactor pressure vessel	In-vessel phase	PWR 1300
ASTEC	All active models for this phase of the accident: Containment thermal-hydraulics, transport of fission products, core-concrete interaction	Global	All active systems for this phase of the accident: reactor containment building	Ex-vessel phase	PWR 1300 and VVER-1000
MELCOR	All	Global	All	In- and ex-vessel phases	Nordic BWR

behaviour of the network. Their applicability to SA codes that extensively rely on empirical correlations (especially for thermal-hydraulics) is still an open question. Neural Operators like Fourier Neural Operators or DeepONet [32] have recently been applied to complex physical systems. One of their key features for ASSAS is their ability to work with unstructured domain discretisation, which are very common in nuclear safety system codes. Besides, ASSAS will evaluate the resources required to adapt the global model for the ex-vessel phase of the accident from the PWR 1300 to the VVER 1000 designs. This strategy is called “transfer learning” [33] and consist in training on new data a model which has already been pretrained on similar data. This approach now becomes standard in image recognition, but may be applied to engineering problems.

In the frame of the classical optimisation of ASSAS, different strategies have been explored. The first tackles the simplification of the nodalization of the PWR 1300 and the VVER 440 input decks. Results with the PWR 1300 reactor show that acceptable results can be generated with a significant gain in performance thanks to a coarser discretisation. The main drawback is the increased sensitivity of the result to numerical noise, despite the long-term efforts dedicated by ASTEC developers to this issue. Nevertheless, it has been decided to use the simplified description for ASSAS, to save computational resources, which are already significant. The other strategy investigated concerns the simplification of physical models. For example, it is assumed that all the corium will be slumped into the cavity at the time of the vessel rupture. Therefore, thermal-hydraulics and core degradation models are turned-off during the ex-vessel phase of the accident. The effect on result accuracy has been evaluated and considered as acceptable. Finally, efficient programming techniques have been tested to enhance the performances of ASTEC without affecting the results, including OpenMP parallelisation [34], optimised memory management, and state-of-the-art linear algebra solvers. The combined effects of these strategies resulted in a three-fold

decrease in computation time, making ASTEC almost as fast as real time for the in-vessel phase, and several times faster than real time for the ex-vessel phase. The requirements of the simulator seem within reach in the frame of the project. AI models may push performances one step further.

The development of the simulator started with the definition of its specifications, to find a compromise between competitive objectives. First, the simulator must show the main phenomena involved in SAs, including high-pressure and low-pressure scenarios, in-vessel and ex-vessel phases. Very energetic phenomena like steam explosions, direct containment heating or containment rupture are out of the scope of the simulator and will lead to the end of the simulation. Second, the simulator must show the complexity of severe accidents without overwhelming the user with information. This lead for example to selecting approximately 20 variables and to summarise the source term to the environment. Third, the simulator must run in real time, which requires some simplifications, especially for the development of AI-models. Indeed, data-driven models are affected by the so-called “curse of dimensionality” [35], which means that the complexity of such models increases exponentially with the number of independent variables. Therefore, multiplying the number of input and output variables in the simulator could make the development of surrogate models intractable. This called for a careful selection of data to be displayed. They were summarised in synthetic SA dashboards that will show the core degradation, corium-concrete interaction and the release of fission products into the containment building and the environment. The simulator will also include an overview of the plant systems, an alarm display and, if possible, a 3D representation of the reactor. Balance-of-plant systems will be drastically simplified to focus on the severe accident sequence. The user will be able to interact with the simulation: load sequences, actuate systems, plot and extract data.

In parallel, ASTEC has been interfaced with TEAM_SUITE® without major problem. The smooth

integration was made possible by the modularity of both software that already contained the most important functionalities. The communication is established thanks to the ASTEC database that contains all variables used by the code. This architecture allows a seamless integration of AI-models that will read and write in the database without interacting with the HMI.

3.4 Perspectives

Results obtained to date gives a reasonable assurance that ASSAS will be able to deliver the basic principles simulator with acceptable performances. The optimisation of ASTEC and its connexion with TEAM_SUITE® are successful. Tecnatom's simulation platform allows to develop an ergonomic interface including numerous functionalities with reasonable efforts. The ASSAS simulator should be ready to be used for educational activities at the end of the project. It is hoped that this success will give confidence to nuclear utilities to extend the scope of their simulators to severe accidents.

The feasibility to develop fast surrogate models to speed-up SA calculations still needs to be proven. At this stage, ASSAS has gathered the human expertise and the computational resources to make considerable progress about this scientific challenge, exploring various approaches, each one opening exciting perspectives. Global surrogate models would be game changers for emergency response, uncertainty quantification and level 2 Probabilistic Safety Assessment (PSA), by providing fast and accurate SA sequence evaluation. Hybrid methods may not reach as high acceleration factors, but they would improve the modularity of SA codes. For example, a surrogate model for a steam generator could be trained on Computational Fluid Dynamics (CFD) data, to use high-fidelity models in SA codes without impacting their performance. Generally speaking, the experience gained in ASSAS will be valuable for diverse multi-physic legacy codes in nuclear science and beyond. Hybrid machine learning attracts growing interest to support fast, accurate and reliable simulations in science and engineering.

4 SASPAM-SA: enhancing safety of small modular reactors

4.1 Motivation

SMRs are one of the key options for the near-term deployment of new nuclear reactors. Currently in Europe there is a growing interest towards the deployment of SMRs, and several activities are underway in many countries preparing for possible licensing needs. In particular, Integral Pressurized Water Reactors (iPWR) are ready to be licensed as new builds because they start from the well-proven and established large LWR technology, incorporate their operational plant experience/feedback, and include moderate evolutionary design modifications to increase the inherent safety of the plant. However, despite the reinforcement of the first three levels of the Defence-in-Depth

(DiD), e.g., with the adoption of passive safety systems, a sound demonstration of iPWR ability to address SA should be carried out (DiD levels 4–5) [36,37]. Considering this, independent features for preventing and mitigating a SA sequence have to be included in its design (DiD level 4) together with the offsite emergency response (DiD level 5). Therefore, scenarios leading to SAs need to be postulated and deterministically studied throughout the reactor design and the safety review process.

By looking at the current initiatives that are already finished or are on-going in different fora it appears clear, along the preparation of SASPAM-SA, that the iPWRs SA investigation with best estimate methods are limited. Therefore, the systematic analyses of the applicability and transfer of the current available SA experimental database (developed for current large-LWR) for iPWR safety assessment studies, and the analyses of current codes capabilities to simulate SA phenomena in iPWRs are novel topics of current high interests for TSOs, regulators, research centers, universities, industries and operators.

The Horizon Euratom SASPAM-SA project [36–39] responds to the above needs. It aims to speed-up the European licensing/siting process for iPWRs by leveraging the operational experience and knowledge from large LWRs. Specifically, the main objective of the SASPAM-SA project is to investigate the applicability and transfer of the operating large-LWR reactor knowledge and know-how to the near-term deployment of iPWR, in the view of SA and EPZ European licensing analyses needs. In order to maximize the knowledge transferability and impacts of the project, two generic design-concepts, characterized by different evolutionary innovations in comparison with larger operating reactor, have been selected for the analyses. These two generic reactor concepts include the main iPWR design features, considered in the most promising designs ready to go on the European market, allowing to assess in a wider way the capability of codes (SA and CFD) to simulate the phenomena typical of iPWR. It is not the project's objective to assess the generic reactor designs selected but, based on the project findings, allow a more general statement on the code's applicability to currently favoured designs under postulated SA conditions. No PSA considerations will be done in the project due to the generic nature of the reactor concept considered, then the scenarios identified will be characterized in terms of severity but not in terms of probability. The specifications of both generic designs are based on open literature and engineering assumptions.

The project is coordinated by ENEA (Italy) and 23 organizations from 14 countries are involved, involving 502 person-month [38].

4.2 Resources articulation

To address the ambitions of the project, it is structured in 5 technical WPs (from WP2 to WP6), plus one for the coordination (WP1) and one for the dissemination (WP7), as shown in Figure 6. The different WPs are strongly interconnected to address the WP objectives. In particular, WP2 (Input deck development and

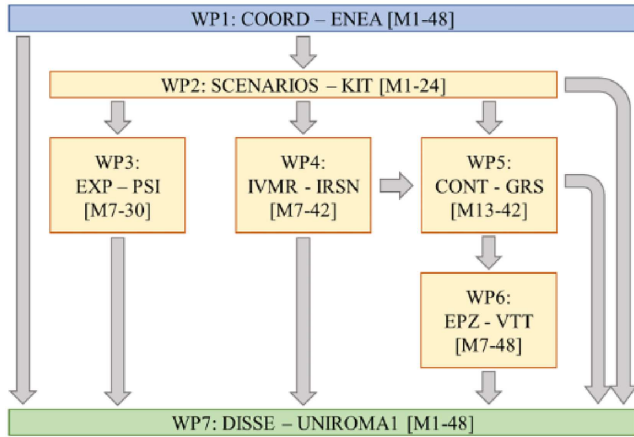


Fig. 6. Graphical representation of the SASPAM-SA project.

hypothetical SA scenarios assessment – SCENARIOS) is the common ground because it identifies the plausible iPWR SA scenarios and the phenomena and conditions needed to develop the other WPs activity. WP3 (Applicability and transfer of the existing SA experimental database for iPWR Assessment – EXPeriments) is directly linked to WP2 because it is feed with the SA phenomena and SA conditions needed to characterize the experimental data applicability to iPWR. WP4 (Assessment of code capabilities to simulate and evaluate corium retention in iPWRs -In-Vessel Melt Retention) and WP5 (Assessment of the code capabilities to simulate iPWR containment and characterize mitigation measures efficiency – CONTainment) are detailed plant applications done to characterize the code capabilities to address IVMR and containment phenomena, characterizing IVMR feasibility and containment mitigation features efficiency. From WP5 the source term needed to develop WP6 (Characterization of iPWR Emergency Planning Zone – EPZ) analyses of EPZ will be developed. The graphical representation of the project is shown in [Figure 6](#).

4.3 Major progress

SASPAM-SA project has already made significant progress in advancing the safety analysis practice for iPWRs along the last 2 years of activity. In the following, the main insights are reported referencing papers and deliverable to have more detailed information. As previously underlined, two generic design-concepts, have been selected for the analyses. The generic designs considered are called Design 1 and Design 2: Design 1 is a generic iPWR characterized by a submerged containment and electric power of about 60 MWe; Design 2 is a generic iPWR characterized by the use of several passive systems, a dry containment and an electric power of about 300 MWe. The generic layouts of the iPWR Design 1 and 2 are shown in [Figure 7](#). A common database has been created for the two generic iPWR designs based on open literature and engineering judgment [40]. A fuel inventory and decay heat analysis were conducted using CASMO5 on a 2D

fuel assembly [41] and input decks for both state-of-the-art European and non-European integral codes, as well as CFD tools, were developed, assessed, and shared for the two generic designs. A CFD model has been developed for the Design 1 with ANSYS CFX (preliminary mesh of about 370000 nodes) and with containment FOAM for Design 2 (preliminary mesh using between 200000 and 750000 mesh for representing one quarter of the containment).

DBA and BDBA scenarios were identified and simulated to evaluate the codes capabilities in modeling the main features of the selected generic iPWRs. These scenarios were carefully selected based on a literature review, engineering judgment, and expertise. Since functional failures [35,42] were not investigated in the project, due to the SA focus, scenarios were set by postulating the failure of passive system valve activation. Multiple DBA and BDBA scenarios were simulated and analyzed, and the most representative scenarios were chosen as reference cases to capture key phenomenological behaviors and the transient kinetics. The selected scenarios were further evaluated based on their severity to identify the reference SA scenarios. The codes were tested for their ability to predict thermal-hydraulic and degradation phenomena in iPWR conditions. The analysis has demonstrated that integral SA codes are generally able to qualitatively predict the main thermal-hydraulic and degradation phenomena in iPWRs across the different scenarios investigated; the results of the codes have been compared to underline differences as reported in [?]. Across all simulations of the postulated SA scenarios and using all SA codes, no lower head failure was observed for both generic designs. The first CFD results show rather stable simulation and good qualitative assessment of the expected phenomenologies. The conditions in the containment and in the vessel that characterize iPWR scenarios have been identified, and a dedicated scenarios database, including corium layering transients, has been fully developed to be used in to assess the applicability of existing experimental data to iPWRs. Based on these calculated scenarios database, the main boundary conditions, the transient conditions and the specific features of iPWRs are determined and compared to those of large LWR. Based on this comparison, the applicability of the existing experimental data to iPWR is assessed for in-vessel, containment, source term and ex-vessel phenomena (if any ex-vessel phenomena are observed in the identified scenarios).

The specific experimental data to be evaluated extend over the entire SA domain. In particular, the datasets currently analysed include, e.g., natural circulation and passive systems, debris bed formation, liquid melt spreading, in-vessel steam explosion, re-flooding of an overheated core, in-vessel melt pool formation, corium cooling under water, hydrogen distribution, combustion and mitigation, wall condensation, aerosol transport and hygroscopic growth, iodine speciation and mitigation, pool scrubbing, and fission product composition. This work was started by developing a methodology to assess the applicability of existing data to iPWRs, as described in [43]. Comparison between calculated data and experimental data is done using the main parameters and dimensionless

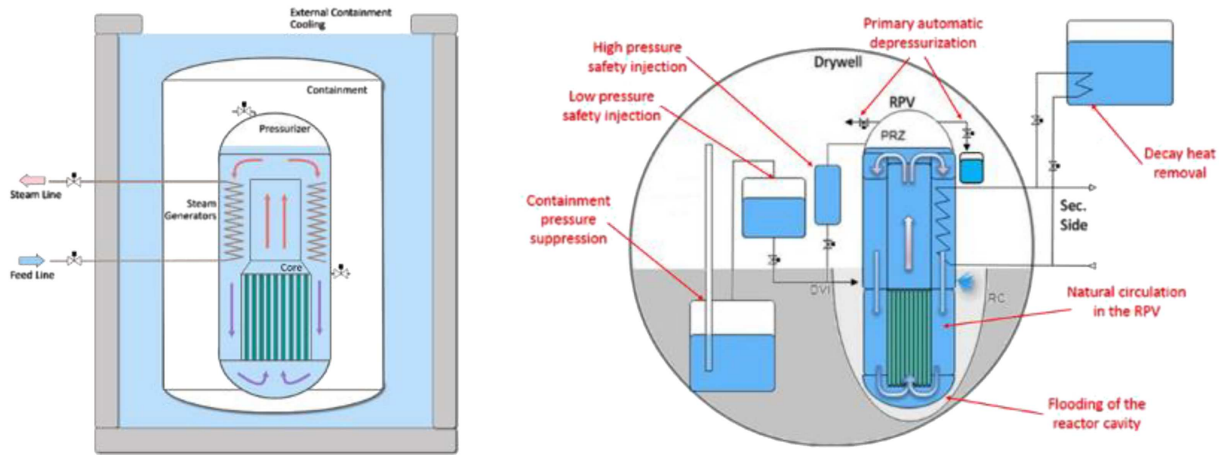


Fig. 7. Generic reactor concept layouts: Design 1(left), Design 2 (right).

numbers determined based on the governing equations for each phenomenon. Based on the comparison of the existing experimental data with the iPWR designs calculated data, the assessment of the applicability of the experimental data to iPWRs is on-going. Based on this comparison, the experimental data will be divided into three categories: (1) data which are directly applicable to iPWR; (2) data which can be used by developing extrapolation methods, and (3) data which are not applicable to iPWRs. The first results of this comparison have been discussed in [44]. Since no lower head failure has been identified in all the scenarios simulated, no new ex-vessel data needs have been identified. Experimental data needs were identified for, e.g., natural circulation tests using advanced instrumentation, hydrogen risk and mitigation to extend the validity of data above 1.0 MPa and high temperatures, and iodine chemistry under reducing conditions.

In relation to IVMR, a 0D Corium Model has been developed to preliminarily investigate the IVMR phenomenology for iPWR [45]. The first results show that IVR strategy appears feasible, with enough safety margin. Maximum heat flux is small enough to be extracted by pool boiling, in principle, and the residual vessel thickness is large enough to ensure mechanical resistance. Some specific features of IVMR in iPWRs (e.g. a larger fraction of power transferred to the top of the oxide pool because of the low aspect ratio – shallow pool-, existence of a rather thick oxide crust and the occurrence of a thin metal layer but a limited focusing effect because of a large fraction of power lost by radiative heat transfer, etc) have been already identified and are detailed in [45,46]. However, detailed data and complete calculations with integral SA codes are necessary to go further. Initial applications of SA integral codes provide physically acceptable results that align with independent evaluations performed using the 0D model. Few modeling improvements appear necessary to achieve more accurate, physically and accurate predictions by SA codes. Coupled vessel/containment calculations are expected to provide valuable insights into the plant's stabilized configuration.

From the foundation laid by this work (core inventories, SA scenarios and phenomena, including those in the containment) the purpose of the project in its last step is to proceed from possible accidental atmospheric releases to the actual potential harm to the health of the off-site population. Generally, for iPWRs and many other SMRs, it is claimed that they are inherently safer than operating large NPPs, partly because of the smaller radioactive inventory and partly because of advanced passive safety systems. Consequently, lower radiological impact and smaller EPZ are expected. The main objective is to provide recommendations for a rigorous and justified iPWR EPZ size (single unit is currently considered in the SASPAM-SA). So far, the work has started with a review phase investigating the present methods and regulations for offsite dose projection and EPZ determination in various countries or proposed by the IAEA.

4.4 Perspectives

Following the significant progressed achieved over the first 2 years, SASPAM-SA is now transitioning into a new phase. The first next activities will contribute to develop the know-how in relation to the use of ATF in iPWR. Currently, analyses of the postulated scenarios are ongoing incorporating ATF cladding materials, specifically FeCrAl as studied in the QUENCH-19 experiment at KIT [47]. These analyses aim to further explore the behavior of ATF materials under SA conditions and assess their potential benefits in enhancing reactor safety. This will help to enhance ATF application in iPWR and develop code capability to simulate it. Currently, the relevance and applicability of the existing experimental database to iPWR is under evaluation; at the end of this process the new experimental needs will be identified. In relation to IVMR, the next SA integral code applications will contribute to the assessment of code capability to simulate the main phenomena characterizing the IVMR in iPWR. Starting from the 0D Corium Model conservative analyses, the next steps will compare the results obtained by

each partner with SA codes after achieving corium stabilization in the lower plenum. This comparison will allow assessing the differences and similarities among the various SA codes. Following this, it will extend to the determination of uncertainty in input parameters. Additionally, IVR calculations will be developed with some enhanced features, including coupling with external cooling calculations, containment coupling, and accounting for water present at the beginning of the scenario. Finally, the activity will aim to extend the results up to the evaluation of the mechanical safety margin. In relation to the containment, the related behavior in postulated SA scenarios in iPWR will be studied in detail. Through these analyses the capability of the codes to simulate the main phenomena characterizing the containment behavior will be assessed and the efficiency of the existing and advanced containment mitigation measure characterized; currently partners are defining the reference scenarios and SA integral calculation are going to start. As last step, it will be provided evaluations of size and extension of EPZ for postulated SA scenarios coupling the results of best estimate source term codes to radiological consequences tools. Currently the practical, quantitative work for EPZ estimation is proceeding in two successive phases: first the participants are doing dispersion, dose and EPZ calculations using simple, but also then by necessity more conservative methods. Conservativeness is a subject of debate, and it is well recognized that differing choices may lead to a spectrum of results. A subsequent best-estimate phase will be carried out, in a mechanistic fashion by dedicated SA codes. Not having to resort to conservative expert judgement, it remains to be seen whether source terms and consequently offsite doses and EPZ sizes will turn out smaller than in the first phase. At the end of the activity, evaluations of code suitability, recommendations on appropriate EPZ determination methodology, and also some numerical values for Design 1 and Design 2 accidental offsite doses and EPZ sizes will appear [48].

5 Preliminary remarks

Given the time still remaining until the end of the projects, the remarks here synthesized are preliminary and kept at a high level until they can be more detailed and consolidated with the work coming in the next two years.

- SEAKNOT is proposing directions for a sound research agenda based on an efficient enhancement of nuclear safety at the same time as it is strengthening the instruments for E&T on SA of the next generation of researchers and engineers. The roadmap that is being shaped up identifies the issues to be addressed on the basis of lack of knowledge and safety importance, specifies the boundary conditions of major interest, and discusses the capability of the current SA infrastructures available and/or needed. New elements in E&T are being brought, as the update of the textbook on SA published in 2013 and the SA Summer Camp, which first edition will be held in 2025.

- ASSAS aims at developing a fast, accurate and user-friendly SA simulator based on ASTEC and the commercial simulation platform TEAM.SUITE®. Computational optimisations brought ASTEC close to a real-time execution. More drastic improvements are awaited from machine learning models that could be run autonomously or be hybridised with physics-based models. A large database of SA calculations hosted by a dedicated infrastructure will be generated to train state-of-the-art neural networks, to assess the applicability of the approach.
- SASPAM-SA project has made significant progress in advancing the safety analysis practice for iPWRs. DBA and BDBA/SA scenarios have been identified, assessing the capability of advanced codes to simulate the main features of iPWR, characterizing containment and in-vessel conditions. The first results show that in-vessel retention strategy appears feasible, with a good safety margin. A dedicated calculated database has also been created to be used to assess the applicability of existing experimental data to iPWRs. Currently, rigorous and justified methodology is under discussion to support the evaluation of the EPZ for SMRs. These efforts highlight the project's contribution to iPWR safety demonstration and supporting a possible future licensing review in Europe. In general, the research activity outcome will enhance safety analyses practice but also, will contribute to build expertise among code users for SA in iPWRs and to train new code users (e.g., younger generations) and, on the other hand, to assess code guidelines and best practices for the simulation of iPWRs.

Acknowledgments

The authors acknowledge the support of the projects WP leaders in reviewing the material used in this work. For SEAKNOT: S. Gupta (BT), P. Piluso (CEA) and S. Paci (UNIP); for ASSAS: F. Fichot, M. Barrachin and J-M. Ricaud from ASNR and S. Dzeroski (JSI), F. Gabrielli (KIT), D. Grischchenko (KTH), I. Parrado-Rodriguez (Tecnatom), Fulvio Mascari (ENEA); for SASPAM-SA: F. Gabrielli (KIT), T. Lind (PSI), F. Fichot (ASNR), N. Reinke (GRS), M. Ilvonen (VTT), F. Giannetti (UNIROMA1).

Funding

SEAKNOT, ASSAS and SASPAM-SA are funded by the European Union under the grant agreements no. 101060327, no. 101059682 and no. 101059853. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission-Euratom. Neither the European Union nor the granting authority can be held responsible for them.

Conflicts of interest

The authors declare having no conflict of interest related to the work presented in the article.

Data availability statement

This manuscript does not have specific data. The individual projects, though, do have them. However, what described and discussed in this article is not associated to such data.

Author contribution statement

L. Herranz (CIEMAT): article coordinator and responsible for the SEAKNOT description. B. Poubeau and L. Chailan (ASNR): responsible for the ASSAS description and the article review. F. Mascari (ENEA): responsible for the SASPAM-SA description and the article review.

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Cite this article as: L.E. Herranz, B. Poubeau, L. Chailan, F. Mascari, Looking ahead to severe accident research, EPJ Nuclear Sci. Technol. **11**, 28 (2025). <https://doi.org/10.1051/epjn/2025025>.