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Detailed assessment of combustion risk and PAR efficiency in the late phase of a severe accident within the European AMHYCO project☆

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A R T I C L E I N F O

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A B S T R A C T

The European AMHYCO project aims at enhancing the understanding of H_2/CO combustion risk within the containment of a light water reactor nuclear power plant during the in- and ex-vessel phase of a severe accident. The goal is to incorporate this knowledge into severe accident management guidelines (SAMG) and give recommendations for long-term operation upgrades. Based on a critical review of established methodologies and practices related to combustion risk assessment, as well as the identification of accident sequences where the containment integrity may get challenged, experimental investigations were conducted to close knowledge gaps related to combustion characteristics and the operation of passive autocatalytic recombiners under late phase conditions.

To prepare the basis for the further assessment and refinement of existing SAMGs, systematic and detailed analyses of the most challenging scenarios and possible mitigative measures were conducted for three generic European pressurized water reactor (PWR) containment designs, namely KWU, Westinghouse, and VVER. For each reactor type, one Loss of Coolant Accident and one Station Blackout scenario were selected for detailed analyses with a variety of different numerical codes. Both scenarios cover a range of in-containment atmospheric conditions from potentially flammable at medium pressure to a steam-inerted atmosphere at high pressure, including the late phase with an active filtered containment venting system (FCVS).

This paper outlines the employed methodology using a consecutive analysis chain consisting of three levels with increasing level of detail (system codes, 3D GOTHIC™ and CFD) to assess containment pressurization,

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efficiency and/or options of individual mitigation measures regarding H_2/CO combustion risk and equipment and instrumentation survivability. As a common basis, the system code nodalization schemes and 3D models are developed from detailed CAD geometries. On the basis, the paper summarizes the outcome of the work with a focus on the comparative assessment of the impact and effectiveness of mitigative measures (passive autocatalytic recombiner, containment sprays, FCVS) on the combustion risk in the accident.

The analyses highlight that without combustible gas mitigation, containment atmospheres develop combustible pockets and may even become globally flammable, highlighting the need for control systems to preserve integrity. PARs proved effective across all scenarios in preventing large clouds with flame acceleration conditions, with their capacity mainly influencing depletion rates and timing. Oxygen removal by PARs also enables safe operation of containment and core cooling systems without increasing combustion risk in the late phase.

1. Introduction

The severe reactor accident at the Fukushima Daiichi Nuclear Power Plant in 2011 has confirmed the need to develop a more profound understanding of the generation and distribution of combustible gases. Their combustion can lead to dynamic loads on the containment structures and equipment and challenge containment integrity. Consequently, the risk of combustion inside the containment has been identified as a high-priority issue under different frameworks, such as the Nuclear Generation II & III Association (NUGENIA) Research & Development Roadmap (Al Mazouzi et al., 2015). Additionally, the European Stress Tests report (ENSREG, 2012) emphasized the importance of considering potential combustion hazards. Furthermore, according to International Atomic Energy Agency (IAEA) requirements, new and upgraded reactor designs should include safety features for core melt scenarios (severe accidents) (International Atomic Energy Agency, 2016). One objective is the practical elimination of dynamic phenomena that may lead to a loss of containment integrity. At the time of the launch of the European AMHYCO project (Euratom 20192020, Grant Agreement No 945057) (Jiménez et al., 2022), primarily the risk associated with H_2 combustion during the in-vessel phase was considered (Liang et al., 2014).Consequently, AMHYCO aimed at enhancing the understanding of $H_2 + CO$ combustion risk within the containment of a nuclear power plant during the in-vessel (H_2) and during the ex-vessel ($H_2 + CO$) phases of a severe accident (SA).

As a preparation, within its work package (WP) 1, a comprehensive and critical assessment of regarding available experimental data, existing models on PAR behavior under ex-vessel conditions, and H_2/CO combustion correlations and models was conducted and revealed the need for further dedicated experiments (later performed in WP3). Furthermore, combustible gas management requirements and mitigation measures in PWRs worldwide, with emphasis on severe accident management strategies and potential adverse effects of engineering system actuations (e.g., sprays, venting, coolers, suppression pools, latch systems) were assessed. Main criteria and principles of Environmental Qualification (EQ) and Survivability Assessment (SA) from PWR qualification programs in Europe and beyond, were screened to obtain equipment survivability criteria covering both DBA and DEC-B conditions. For the sake of brevity, the reader is referred to the public deliverable (Bentaib, 2022).

This paper focusses on the comprehensive analytical assessment of the containment behavior is conducted in AMHYCO WP4 concerning:

- The H_2/CO combustion risk, i.e. the potential of flame acceleration in in- and ex-vessel phase.
- The effect and options/timing of individual mitigative measures, including passive autocatalytic recombiner (PARs), FCVS, or spray systems activation regarding the combustion risk.
- And the equipment and instrumentation survivability and ‘operators/control room view’ on the containment status.

The analysis is performed for three generic European PWR concepts, W (French and Westinghouse designs), KWU (German PWR design), and VVER (former Soviet design), to establish a database for a review and identification of potential extensions of the Severe Accident Management Guidelines (SAMGs) within WP5. For that purpose, WP4 utilizes scenarios selected in WP2 (Herranz and Fontanet, 2023), existing empirical criteria and correlations supported by the WP1 literature review (Bentaib, 2022), and new correlations derived from experimental data on H_2/CO combustion (Desclaux et al.) and PAR efficiency (Reinecke et al., 2023; Reinecke et al., 2024) in the ex-vessel phase, developed in WP3. The integration of WP4 within the AMHYCO project is illustrated in Fig. 1.

The preparative work in WP2 aimed at screening combustion risk in potential accident scenarios by using existing integral (in part non-public) plant models. As a follow-up, WP4′s objective is to assess the containment response in more detail based on an open containment database. For that purpose, generalized nodalization schemes are employed to enable sufficient comparability of the simulation models for the participating organizations/codes and results and to enable obtaining generic, i.e., non-plant-specific conclusions. Analyses of the containment response are conducted in a consecutive analysis chain, consisting of three levels of increasing detail:

1. As a basis, the identified sequences are fully analyzed with lumped parameter (LP) containment models e.g., built in AC^2/COCOSYS, SPECTRA, ASTEC, or MELCOR codes.
2. The most penalizing cases (in terms of combustion risk) are additionally investigated with 3D models developed in GOTHIC™ to address potential gas cloud formation that may lead to higher combustion risk.
3. Finally, relevant compartments and/or time frames are simulated in detailed CFD-grade local containment studies to substantiate GOTHIC™ analysis and answer remaining open issues.

The different levels of spatial resolution are also used to assess the perspective on the accident from the control room (available instrumentation) against the full insights provided by the simulations to motivate upgrades of the SA instrumentation and their utilization within the SAMG.

The AMHYCO methodology relies for the first time on a common basis, namely detailed 3D CAD models, for this comparative approach using different computational approaches. The generic LP nodalization schemes proposed in WP2 and 3D models built in WP4 were developed on the same basis to ensure their fundamental comparability. Their consistent transfer to the employed LP codes together with the implementation of the mass and energy injection tables have been systematically verified using the unmitigated scenarios (Kelm et al., 2024). The converged containment models are used for the quantitative assessment of the impact and effectiveness of mitigative measures (PARs, sprays, FCVS) on the combustion risk in the ex-vessel phase. This paper summarizes the outcomes of the work. Section 2 briefly introduces the characteristics of the SA scenarios selected from WP2. Within Section 3, the employed methodology is outlined. The combustion risk is assessed in Section 4 to provide a set of reference cases that will be used in the future to assess the impact and effectiveness of the mitigative measures on the combustion risk in the late phase. Concluding, Section 5 summarizes the current results and lessons learned from the analysis and outlines the possible future work.

2. Scenarios and parametric studies

Within WP2, different sequences of the three European PWR designs, PWR-W, PWR-KWU, and PWR-VVER, were simulated by participating organizations, using different severe accident codes and integral models (including primary and containment). These simulations cover several initiating events and involve diverse engineered safety features and severe accident management measures. The integral simulations of WP2 were screened regarding the prevailing combustion risk to identify bounding scenarios for the detailed analysis of the containment response in WP4 (Herranz and Fontanet, 2023). For each containment type, two classes of scenarios were prioritised:

(1) A Loss of Coolant Accident (LOCA) characterized by a comparably early core damage and a large H_2 release, resulting in flammable conditions in the containment with a potential of flame acceleration when no mitigative measures or hardware are in place.
(2) A Station Blackout (SBO)/Total Loss of AC Power (TLAP) sequence, which results in delayed core damage and release of H_2, and relatively higher containment pressures due to the unavailability of active containment cooling.

For the LOCA scenarios, the size and break location were varied, and for the transient SBO accident, the boundary conditions, such as primary loop depressurization, were varied to determine the accident sequence bounding regarding combustion risk. The in-vessel H_2 release path into the containment is quite different in both types of sequences. In the case of a LOCA, H_2 is released through the break location whereas for the SBO, the release path is via the pressurizer relief tank to the containment. After Reactor Pressure Vessel (RPV) lower head failure, the molten corium-concrete interaction (MCCI) generates additional H_2 and CO. The main characteristics of the selected sequences for the specific PWR designs are briefly summarized in the following (Herranz and Fontanet, 2023):

PWR-KWU design:

- Medium-break (MB) LOCA (80 cm^2, behind the main coolant pump in the cold leg of the pressurizer loop) with a limited water injection by the extra borating system (MBLOCA + ECCS). For this sequence, all active emergency injection systems, which would prevent the escalation into a nuclear accident, are postulated to fail. Only the hydro accumulators can inject their inventory. After the water level inside the pressurizer falls below a threshold, the extra borating system starts injecting water with a limited injection rate over a period of 2.5 h, which slightly delays the core uncovery but is insufficient to stop the accident. Core degradation begins after approx. 5.3 h. The delayed accident progression (Müer et al., 2022) poses a slightly higher combustion risk due to increased condensation in the containment. With a predicted RPV failure after ~6.5 h, the release of H_2 and CO due to MCCI starts. Up to the end of the simulated problem time of 72 h, a total amount of ~1500 kg H_2 and ~7500 kg CO are released.
- TLAP with delayed Primary System Depressurization (PSD). The primary system is depressurized 30 mins after reaching the SAMG criterion "Core Outlet Temperature >650 °C" by opening all three pressurizer safety valves. This results in a large mass of H_2, which is initially stored within the primary loop and then released rapidly to the containment. RPV failure occurs after approx. 10 h. Within the considered problem time of 72 h, a total amount of ~2300 kg H_2 and ~25000 kg CO are released.

PWR-W (Framatome and Westinghouse designs):

- Large-break (LB) LOCA in the hot leg (PWR-W-1000) without availability of auxiliary feed water and safety injections, except for accumulators. Due to the fast core uncovery and depressurization of the reactor cooling system, the core degradation already begins 20 mins after the initiating event. The RPV failure occurs at ~2.7 h and at about 6 h the corium in the cavity gets completely oxidized. Activating the containment spray systems (fan coolers are not used in the reference case) significantly reduces the pressure before the generation of non-condensable gases by MCCI leads to continuous pressurization. At about 2 h, the spray system is switched from injection to recirculation mode, which reduces its containment cooling efficiency. The high release rate of H_2 in the in-vessel phase and the suppression of steam due to the operation of the spray systems lead to

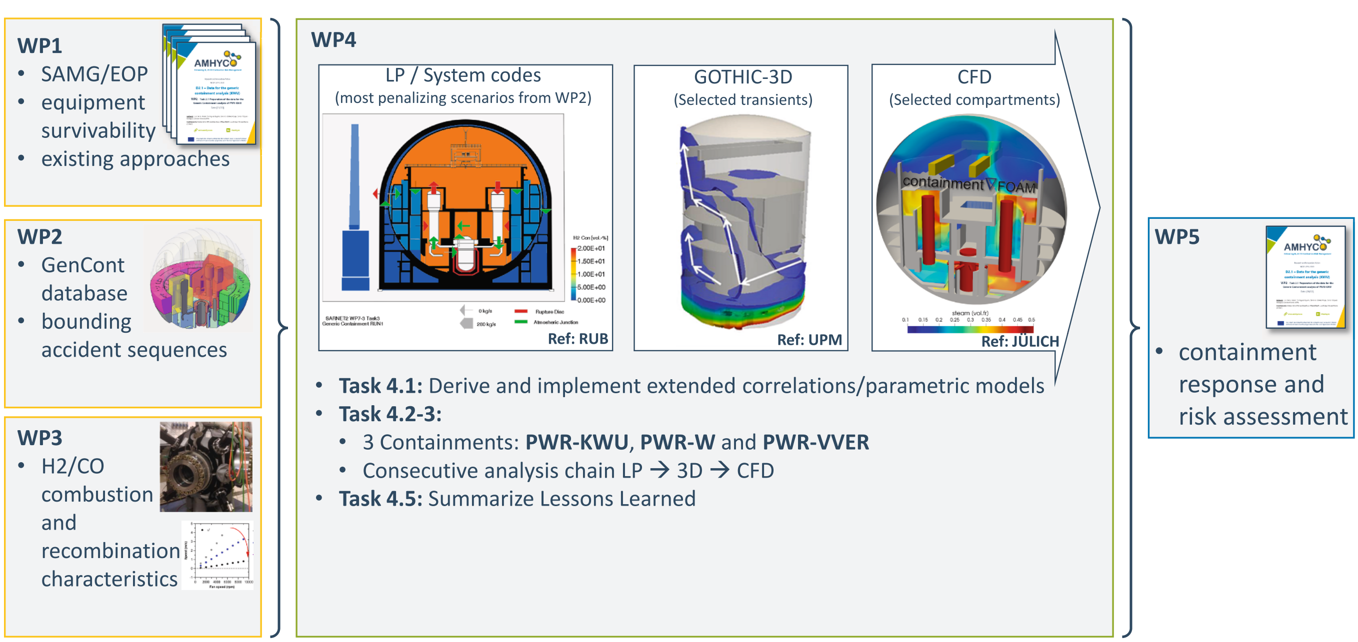


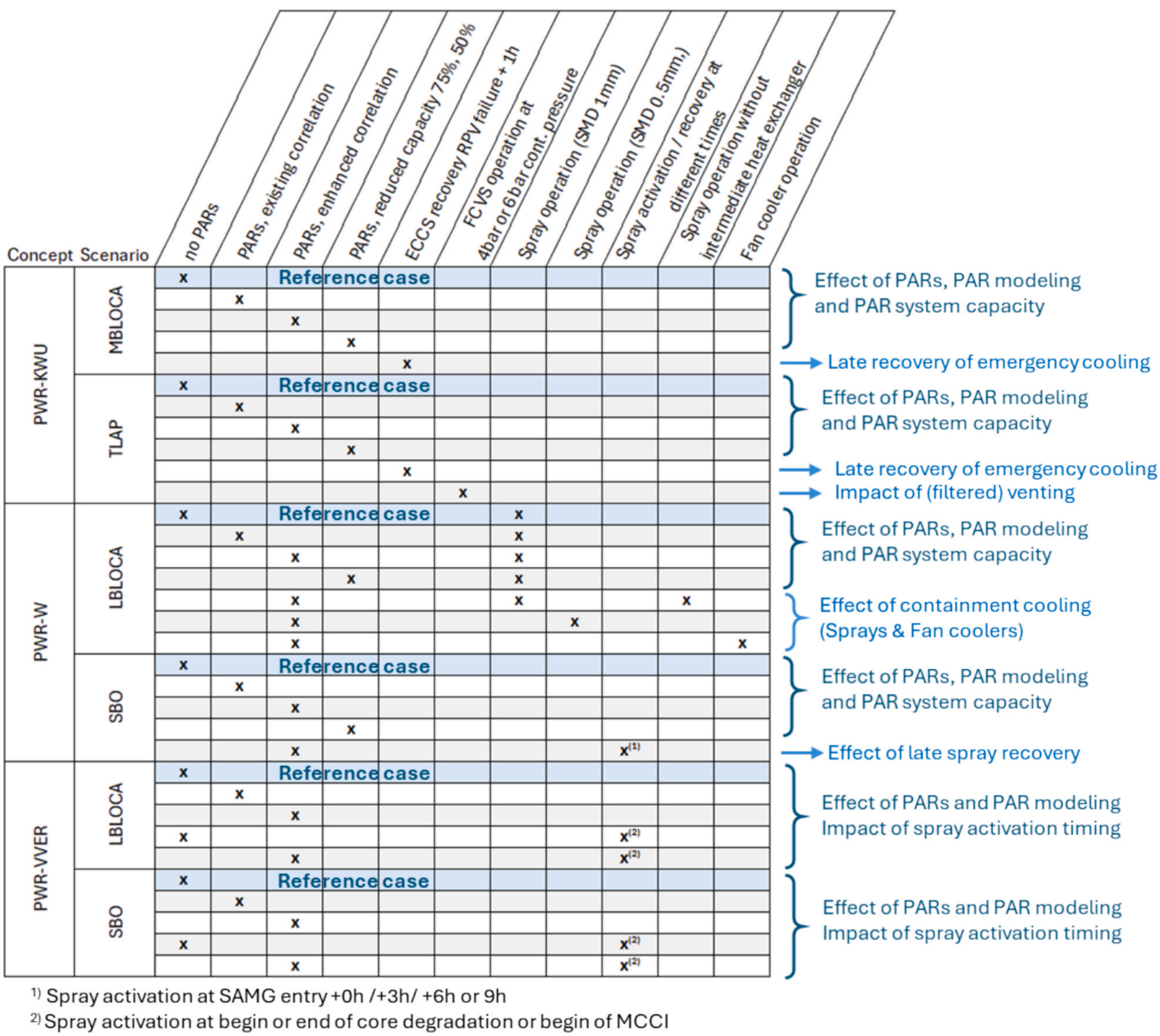
Fig. 1. Integration of WP4 in the AMHYCO project.

flammable conditions at the end of the in-vessel phase. The further release of combustible gases during the ex-vessel phase leads to a concentration maximum at about 6 h, while the subsequent CO_2 generation results in a certain dilution of the mixture. Within the considered problem time of 48 h, a total amount of 1000 kg H_2 and 13000 kg CO are released.

- SBO with loss of all offsite power (scaled from PWR-W-1300 to the generic PWR-W-1000). All active safety systems (e.g., sprays, emergency core cooling, cavity flooding) are unavailable. Steam and H_2 release to the containment occurs after rupture of the pressurizer relief tank burst discs at about 2.5 h. The pressurizer relief valves get locked open after approx. 4.5 h. The loss of coolant is partly compensated by accumulator injection at 4.75 h. The ex-vessel phase begins with RPV failure and melt relocation to the cavity at 11.5 h. Here, silicious concrete is considered so that the H_2 release is maximized. Within the considered problem time of 48 h, total amounts of 4900 kg H_2 and 1900 kg CO are released.

PWR-VVER:

- LB LOCA at the cold line weld at the reactor pressure vessel with complete loss of power supply and failure to start all emergency diesel generators (SBO). Due to the loss of power supply, water injection from the spray system does not take place. Two of the four hydro accumulators inject water into the upper plenum of the RPV, while the other two inject it into the leak zone. Due to the loss of power supply, water injection from the low pressure ECCS does not take place. The core materials and water in the PRV begin to heat up rapidly, and the water boils. Cladding oxidation and H_2 release into the containment begins after 20 min. The continuous degradation of the core leads to RPV failure and melt relocation to the cavity, followed by MCCI. More than 2900 kg H_2 and 8000 kg CO are released during the considered problem time of 44 h to the containment.
- SBO: A complete loss of power supply and failure to start all emergency diesel generators is considered. Consequently, water injection from the high-pressure ECCS does not take place. At the initial stage of the accident, heat is removed for the first hour from the RPV due to the boiling of water in the secondary side of the steam generators. Thereafter, the primary coolant starts boiling, and the steam is released to the bubbler tank and then to the containment. The bubbler tank membrane breaks in 1.7 h and releases steam to the containment with moderate pressure and temperature increase in the containment. Cladding oxidation and H_2 release into the containment starts 3.5 h after the beginning of the accident. Continuous



Concept	Scenario	no PARs	PARs, existing correlation	PARs, enhanced correlation	PARs, reduced capacity 75%, 50%	ECCS recovery RPV failure + 1h	FCVS operation at 4bar or 6bar cont. pressure	Spray operation (SMD 1mm)	Spray operation (SMD 0.5mm)	Spray activation / recovery at different times	Spray operation without intermediate heat exchanger	Fan cooler operation	
PWR-KWU	MBLOCA	x	Reference case										Effect of PARs, PAR modeling and PAR system capacity
			x										
				x									
					x								
						x							Late recovery of emergency cooling
	TLAP	x	Reference case										Effect of PARs, PAR modeling and PAR system capacity
			x										
				x									
					x								
						x							Late recovery of emergency cooling
							x						Impact of (filtered) venting
PWR-W	LBLOCA	x	Reference case					x					Effect of PARs, PAR modeling and PAR system capacity
			x					x					
				x				x					
					x			x					
				x				x			x		Effect of containment cooling (Sprays & Fan coolers)
				x					x				
				x								x	
	SBO	x	Reference case										Effect of PARs, PAR modeling and PAR system capacity
			x										
				x									
					x								
				x						x(1)			Effect of late spray recovery
PWR-VVER	LBLOCA	x	Reference case										Effect of PARs and PAR modeling; Impact of spray activation timing
			x										
				x									
		x								x(2)			
				x						x(2)			
	SBO	x	Reference case										Effect of PARs and PAR modeling; Impact of spray activation timing
			x										
				x									
		x								x(2)			
				x						x(2)			

1) Spray activation at SAMG entry +0h /+3h/ +6h or 9h
2) Spray activation at begin or end of core degradation or begin of MCCI

Fig. 2. Simulation matrix of parametric analyses.

degradation of the core leads to RPV failure and MCCI in the cavity. More than 3000 kg H_2 and 7800 kg CO are released during the simulated duration of 47 h.

Based on the selection of bounding scenarios in WP2, systematic parametric studies of these scenarios are conducted in WP4 to assess various effects on mitigative effects/efficiency, and combustion risk (see Fig. 2). In general, the following main aspects are considered:

- The efficiency of PAR operation in the late phase, where CO may lead to PAR poisoning.
- A reduction of the installed PAR system capacity from 100 % to 75 % and 50 %.
- The impact of cooling systems (re-)activation, e.g.
  - o ECCS system reactivation after PRV failure (PWR-KWU MBLOCA and TLAP).
  - o Spray system recovery during an SBO (PWR-W-SBO).
  - o Spray system droplet diameter, injection temperature and fan cooler operation (PWR-W-LBLOCA).
- The effect of containment venting on the combustion risk (PWR-KWU TLAP).

3. Methodology

3.1. Computational approach

The computational approach employed in WP4 is based on the experiences gained during the European SARNET-II Generic Containment benchmark series (Kelm, Dec. 2014) and its continuation in the frame of SAMHYCO-net. Though a code-to-code benchmarking is explicitly not the objective of the work, a certain consistency of the codes results is required to obtain a quantitative database for further assessment and extension of SAMG in WP5. Moreover, several codes ranging from system to CFD codes (see Table 1) are employed and consistent transfer of the information obtained from WP2 is the fundamental step.

The Generic Containment nodalization schemes were derived from 3D CAD models (Serra et al., 2023; Serra et al., 2021), generating a consistent and freely usable data basis for all code users to develop their LP, 3D, and CFD containment models. Material properties were defined using a best-estimate concrete density of 2500 kg/m^3 – upper end of typical values due to the high rebar content of nuclear concrete, the upper limit of the concrete thermal conductivity as defined by EUROCODE 2 Chapter 3.3.3(2) (EN 1992-1-2, 2004) – to be bounding regarding steam condensation, and a specific heat as given by EUROCODE 2 Chapter 3.3.2(1) without considering evaporation of crystal water, which is prevented by the pressurization of the containment. The generic PAR system design is based on IAEA recommendations (International Atomic Energy Agency, 2011) and publicly available data on Framatome type PAR units (Framatome GmbH, 2019). It includes about 40 Framatome recombiners (20 × FR960 and 20 × FR1500), distributed in all control volumes (CVs) except for the reactor cavity, and with an increased number close to the potential release points and in spaces where flammable gas may accumulate.

Table 1
Codes used in WP4.

	PWR-KWU	PWR-W	PWR-VVER
System codes	COCOSYS 3.1 (RUB) MELCOR 2.1 (Framatome) SPECTRA23-12-0000 (NRG) COCOSYS 2.4 (FZJ)	ASTEC (JSI) ASTEC v2.2 (ASNR) MELCOR 2.2_r2023.0 (CIEMAT)	MELCOR 1.8.6_RL_2011 (Energorisk)
3D codes	GOTHIC 8.3(Q.A) (UPM)		
CFD codes	ANSYS FLUENT (ASNR)	ANSYS FLUENT (NRG) containmentFOAM (FZJ)	–

Different verification steps were taken to assess the created code input decks and ensure consistent use of the database. e.g., a comparison of the compartment volumes and the associated steel mass/surface and concrete mass/surface. The second step was a comparative evaluation of a scenario with the lowest modeling complexity, i.e., the ‘unmitigated reference’ cases. In these cases, neither PARs nor other mitigative measures (except sprays for the LB-LOCAs to avoid unrealistically high pressurization) were considered. Fig. 3 compares the pressure evolution obtained for the unmitigated PWR-KWU MB LOCA and TLAP sequences with different codes.

The predicted pressurization is generally quite consistent among the codes for the early accident phase. An increasing spread is visible over time for the late ex-vessel phase, when sump water ingression leads to cavity flooding and codes predict the pressurization rate with systematic difference in both scenarios. This observation is to be expected, e.g., since the codes use different models for heat transfer from gas to structures and for heat conduction within these structures. The resulting differences accumulate over time so that the spreading increases with problem time. Given the fixed nodalisation, injection tables and structure properties among all LP simulations, other sources of deviations such as code specific modeling assumptions, transient scenario variations or input uncertainties are not further considered as contributors to the spread among the results in the context of this work. In final applications, however, they should be carefully discussed. Consequently, in the context of the ongoing quantitative assessment, the individual results are considered with equal probability and representativeness, which leads to a band of possible results. In the following, those bands are compared instead of the individual results within the following parametric assessment of the accident sequences and mitigative measures or actions.

3.2. Combustion risk assessment and quantification

Within the simulations of WP4, combustion events are not analyzed. Instead, the combustion risk is evaluated in post-processing at each point in time in terms of the evolution of a flammable cloud and its potential to undergo flame acceleration in the case of a combustion process. While the combustion of H_2 in an air–steam mixture was well understood, the additional release of carbon monoxide due to the MCCI introduces additional challenges to assessing the flammability of the containment atmosphere. The usually employed conservative approach is to replace the carbon monoxide with a comparable amount of H_2, mostly on a molar fraction base, and continue to employ the flammability limits of H_2. The flammability limits of H_2 derived by Martín-Valdepeñas et al. (Martín-Valdepeñas et al., 2007), using the data of Stamps and Bearman (Stamps and Berman, 1991), were employed based on WP1 review (Bentaib, 2022) as a reference in AMHYCO. Using H_2 flame acceleration criteria for a fuel mixture is, however, difficult due to the broad variation of the different reaction heat release and flame speed of CO and H_2. To overcome this limitation and avoid simplifications, within WP3, refined criteria were developed, which consider the flammability and potential of flame acceleration for a H_2 + CO mixture and explicitly for late phase conditions, i.e., low O_2 and high dilutant concentrations (e.g., (Desclaux et al.; Nyrenstedt et al.). These criteria were transferred into engineering correlations (see (Chaumeix et al., 2025) and finally allow to obtain more realistic assessment of flame acceleration conditions in the ex-vessel phase.

To quantify the combustion risk, first the flammable cloud volume and mass evolution is determined using the flammability limits, given for the following conditions:

- Fuel composition: pure H_2 and fuel ratio $0.1 < \frac{x_{CO}}{x_{H2}} < 0.75$,
- Gas temperature: 20 °C < T < 100 °C,

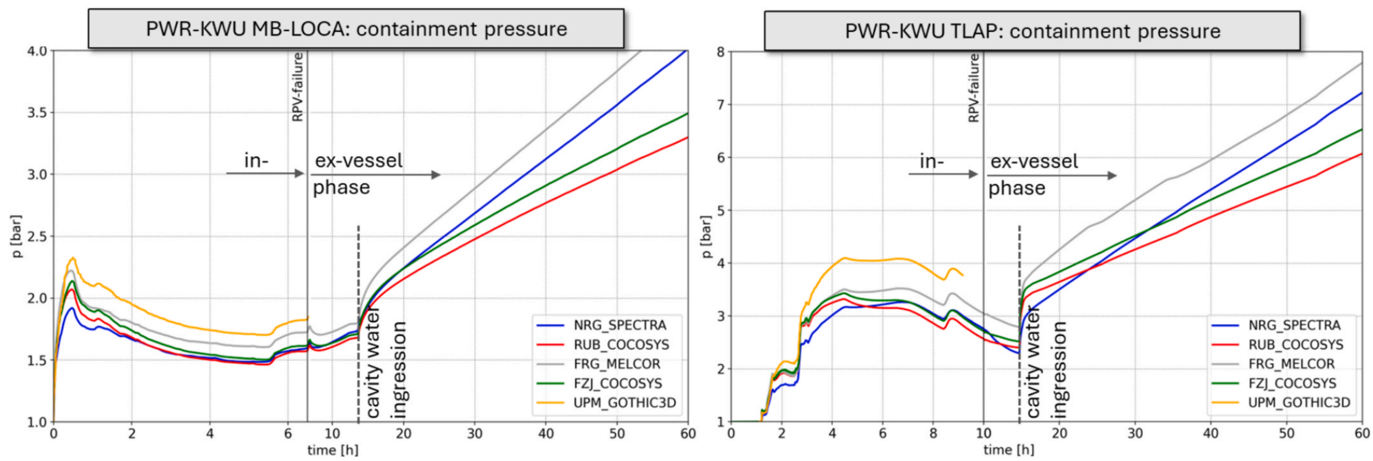


Fig. 3. Pressure evolution for the unmitigated PWR-KWU sequences.

- Pressure: 1 bar $< p <$ 5 bar,
- Diluent (here: N_2, CO_2) fraction: $0 < x_{diluent} < 0.9$ vo.fr,
- Oxidizer: Air ($\frac{x_{O2}}{x_{N2}} = 0.2658$), O_2 starvation ($\frac{x_{O2}}{x_{N2}} = 0.11$).

On this basis, its part, which can undergo a flame acceleration and thus lead to dynamic loads on the containment structures is evaluated using the flame acceleration criteria given for the following domain:

- Fuel composition: pure H_2 and fuel ratio $\frac{x_{CO}}{x_{H2}} = 0.5$, $0.085 < x_{fuel} <$ 0.15vol.fr
- Gas temperature: T = 25 °C, 90 °C,
- Pressure: 1 bar $< p <$ 3.5 bar,
- Diluent fraction: $0 < x_{CO2} < 0.467$ vol.fr, $0.05 < x_{H2O} < 0.30$ vol.fr
- Oxidizer: Air ($\frac{x_{O2}}{x_{N2}} = 0.2658$), O_2 starvation ($\frac{x_{O2}}{x_{N2}} = 0.1111$).

Compared to established criteria, the effect of initial pressure and temperature as well as H_2/CO fuel mixture and oxygen concentration is now considered. As a basis for the following discussion, these correlations were implemented into the post-processing and clipped to the definition bounds of the corresponding input parameters to enable the evaluation of a full transient.

To provide a quantitative insight into the transient behavior of the flammable cloud, and enable a comparability with established criteria, the flammable H_2-equivalent mass (i.e., adding CO conservatively as additional H_2) is integrated over all control volumes, and its transient evolution is compared in Fig. 4 (top) for the unmitigated reference MB-LOCA scenario in a PWR-KWU (without considering the installed PARs).

These integral curves do not reveal the specifical CV which is flammable but allows to compare the evolution of combustion risk in the whole containment among different codes and later for different mitigative actions. While the different codes and criteria generally predict the formation of a flammable cloud in the early phase of the SA quite consistently, the results spread after sump water ingress to the cavity when a large part of the containment (primarily the dome CV) becomes steam inerted again, while smaller compartments close to the release remain inerted.

Compared to the new AMHYCO flammability limits, the established flammability limits revealed to be conservative, i.e., provide a larger flammable cloud mass and longer existence of a flammable cloud in the late phase.

Generally, the flammability of a gas mixture is not of direct concern as during slow combustion energy is transferred primarily into heat. Only if the flame accelerates, more dynamic pressure loads can occur and lead to a containment challenge. Consequently, Fig. 5 compares the evolution of the flammable cloud volume and H_2-equivalent mass, which indicates potential for undergoing flame acceleration (using the AMHYCO criteria).

In the present scenario, the potential of flame acceleration arises primarily only in the ex-vessel phase and reduces after sump water ingression. In comparison with total containment volume of around 70.000 m^3 and the flammable mass (cf. Fig. 4 right), it becomes obvious that in the ex-vessel phase, the flammable cloud extends nearly to the full containment and has a potential for flame acceleration. These

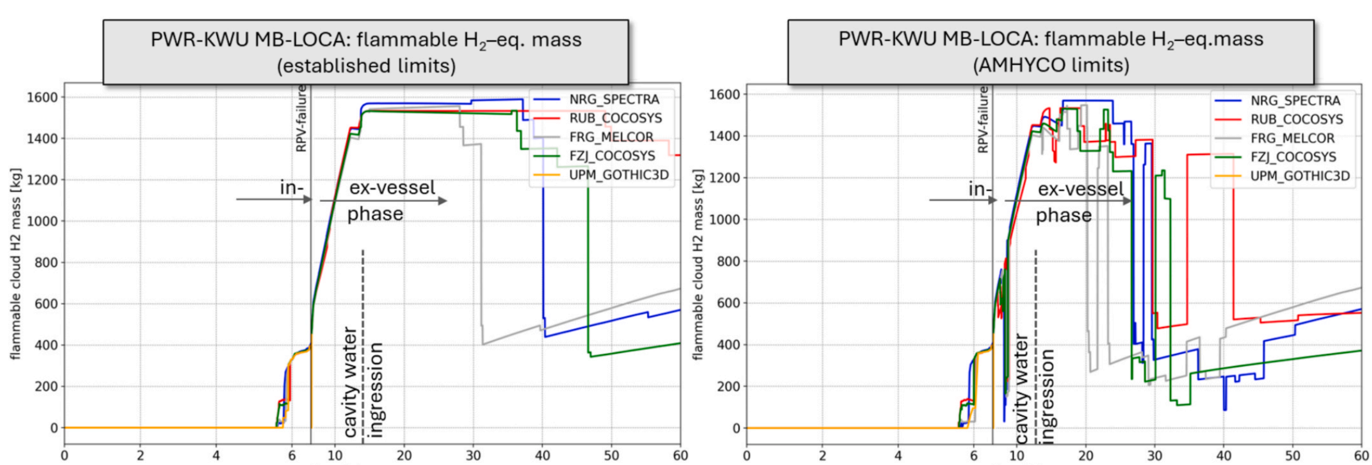


Fig. 4. PWR-KWU MB-LOCA (unmitigated): comparison of flammable cloud H_2-equivalent mass for existing (left) and new flammability criteria (right).

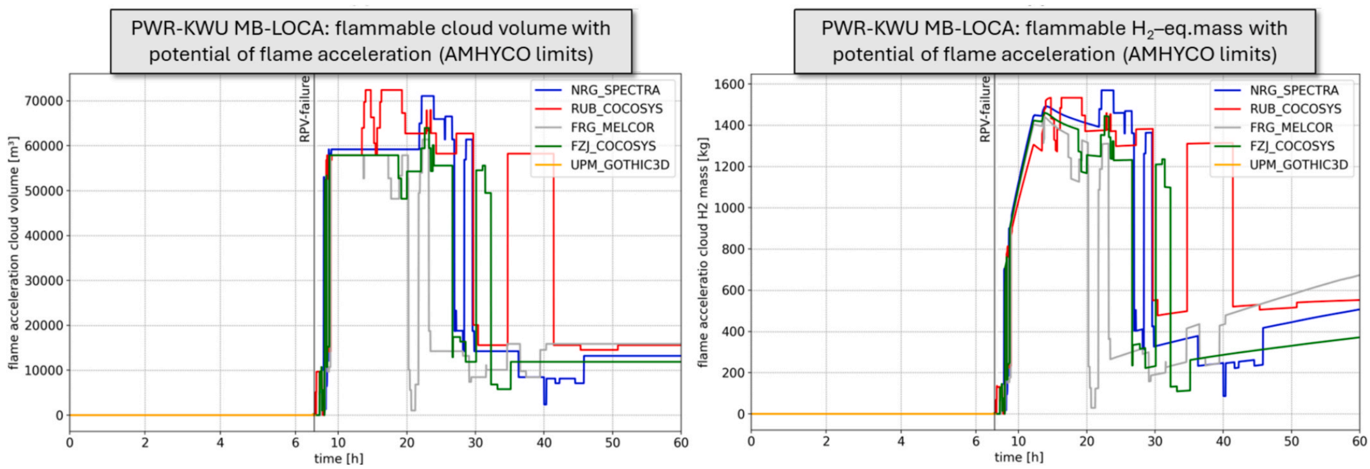


Fig. 5. PWR-KWU MB-LOCA (unmitigated): comparison of flammable cloud volume (left) and H_2-equivalent mass with potential of flame acceleration (right).

heterogeneities which can be observed between the different LP codes motivate a closer look with 3D and CFD models in the future.

As has been already explained for the pressure results, the combustion risk figures presented in section 4 will be represented by bands for each parametric run. The bands are defined by the minimum and maximum values of the results obtained from the simulations with different codes, indicated by the curves.

4. Results of the mitigated transients

In the following, characteristic results obtained in parametric studies (compare Fig. 2) are presented.

4.1. PAR performance in the late accident phase

In the frame of AMHYCO WP3, experiments and model development have been conducted to enhance the validity of established approaches of incorporating PARs into containment simulations. In particular, the

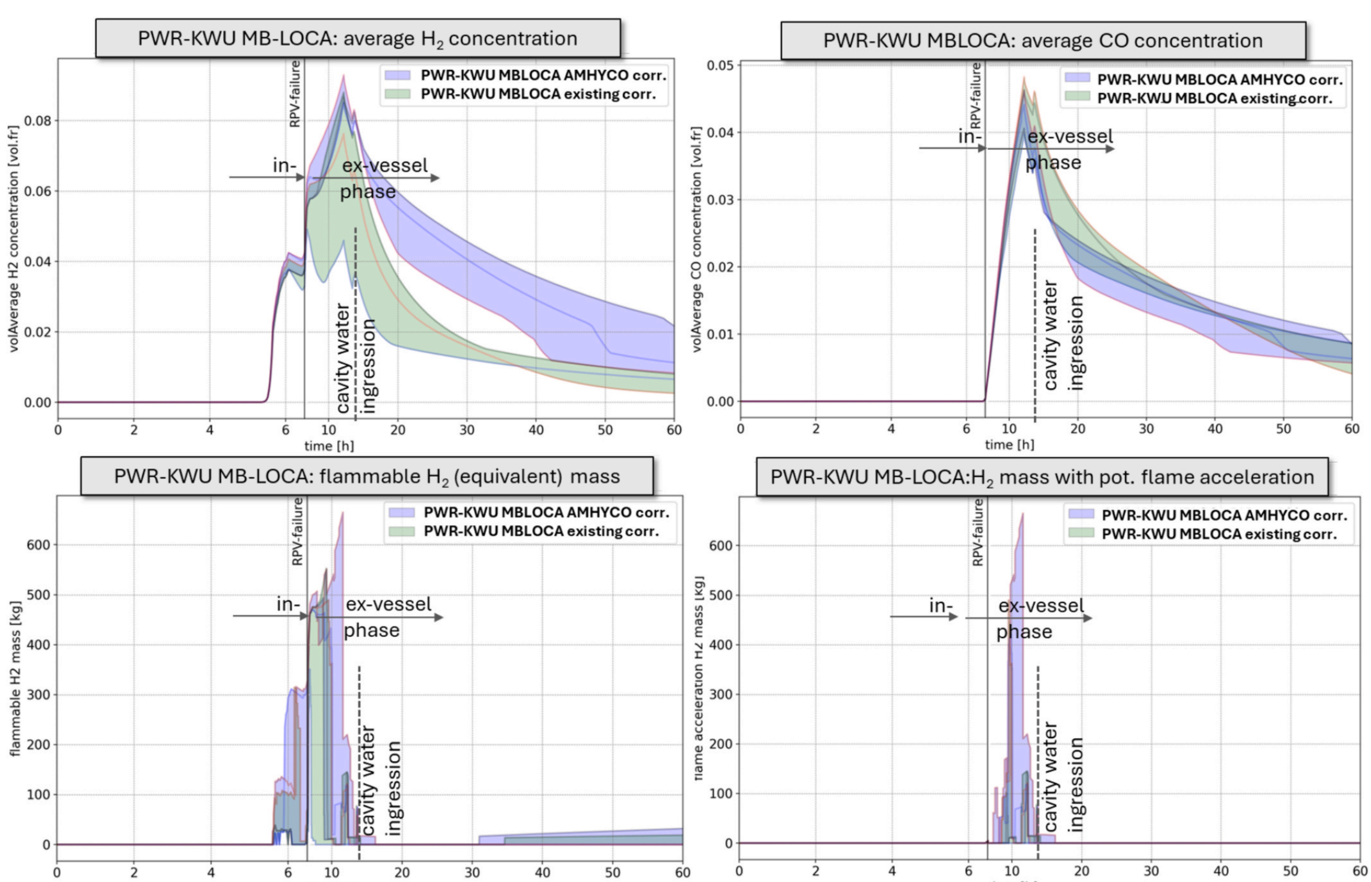


Fig. 6. PWR-KWU MB-LOCA: average H_2 and CO concentrations in the containment (top) and integral flammable H_2 mass and its part with potential for flame acceleration (bottom) with PAR for the existing and new AMHYCO correlation.

SAMHYCO-NET PAR modeling exercise revealed a visible overestimation of the H_2 recombination rate under the oxygen lean conditions (Reinecke et al., 2022) prevailing in the late accident phase. Furthermore, new experimental data from the REKO-3 and THAI facilities allowed to understand the impact of carbon monoxide on the PAR performance and to derive criteria for catalyst poisoning (Reinecke et al., 2024). An new enhanced generic correlation for plate-type recombiners (called 'AMHYCO correlation') (Braun and Reinecke, 2025), based on the original empirical Framatome/AREVA engineering correlation (denoted as 'existing correlation'), implemented in many codes (e.g., (Braun and Reinecke, 2025) was derived and implemented in the employed codes (see Table 1). Fig. 6 exemplarily compares the evolution of the mean H_2 and CO concentrations as well as the flammable H_2 equivalent mass and its part which can undergo flame acceleration in the containment for both approaches based on the PWR-KWU MB-LOCA sequence.

While in both cases PAR operation leads to a continuous depletion of H_2, CO and O_2, the new AMHYCO PAR correlation yields a reduced H_2 conversion rate in the late phase, while the CO recombination is slightly higher in the early ex-vessel phase and reduced again in the late phase. The H_2 risk in terms of the flammable H_2 equivalent mass (that is considering CO as additional H_2) is significantly reduced compared to the unmitigated case (refer to Fig. 4 top right). Considering the flammable cloud with a potential for flame acceleration, the new AMHYCO PAR correlation yields even more conservative results than the existing correlation in the ex-vessel phase with a H_2 equivalent fuel mass of up to a few 100 kg.

During a plant outage, a representative sample of the catalytic sheets from various PARs are tested in a mobile test facility. In case the tested catalytic sheets show a start-up delay longer than specified, the affected PAR undergo "regeneration". These periodic inspections are supposed to ensure the long-term availability of the system. Even though unlikely, for nowadays unknown reasons, the PAR system may be impaired to perform as specified. Therefore, a parametric study was conducted to investigate a hypothetical PAR system performance degradation to 75 % or 50 % of the installed capacity for all scenarios. Characteristic results are depicted in Fig. 7. As expected, a reduced PAR system capacity leads to higher peak H_2/CO concentrations in the containment. The dependency of peak gas concentrations on the assumed PAR performance impairment appears to be continuous, not exhibiting a cliff-edge effect. While the resulting difference in terms of average H_2/CO concentration and flammable mass are comparably small in the in-vessel phase, when the release rate is in the order of or exceeds the recombiner capacity in the ex-vessel phase, the deviations become more apparent. Here, the recombination rate is primarily limited by the previous consumption of oxygen in the in-vessel phase.

Consequently, a larger flammable H_2 mass is to be expected for a reduced PAR capacity, i.e. slower depletion of the available oxygen. Similarly, the combustible H_2 equivalent mass, which has a potential to undergo flame acceleration, visibly increases for reduced PAR capacities. Besides, the overall flammability of the gas mixture also depends on steam inertization and thus on containment heat losses/cooling measures.

4.2. De-inertization of the containment atmosphere by cooling means

In the case of the PWR-KWU concept, the steam release after the (designed) sump water ingress to the cavity and MCCI leads to a rapid steam inertization of the containment atmosphere. A reactivation of the emergency cooling systems by the operators one hour after the RPV

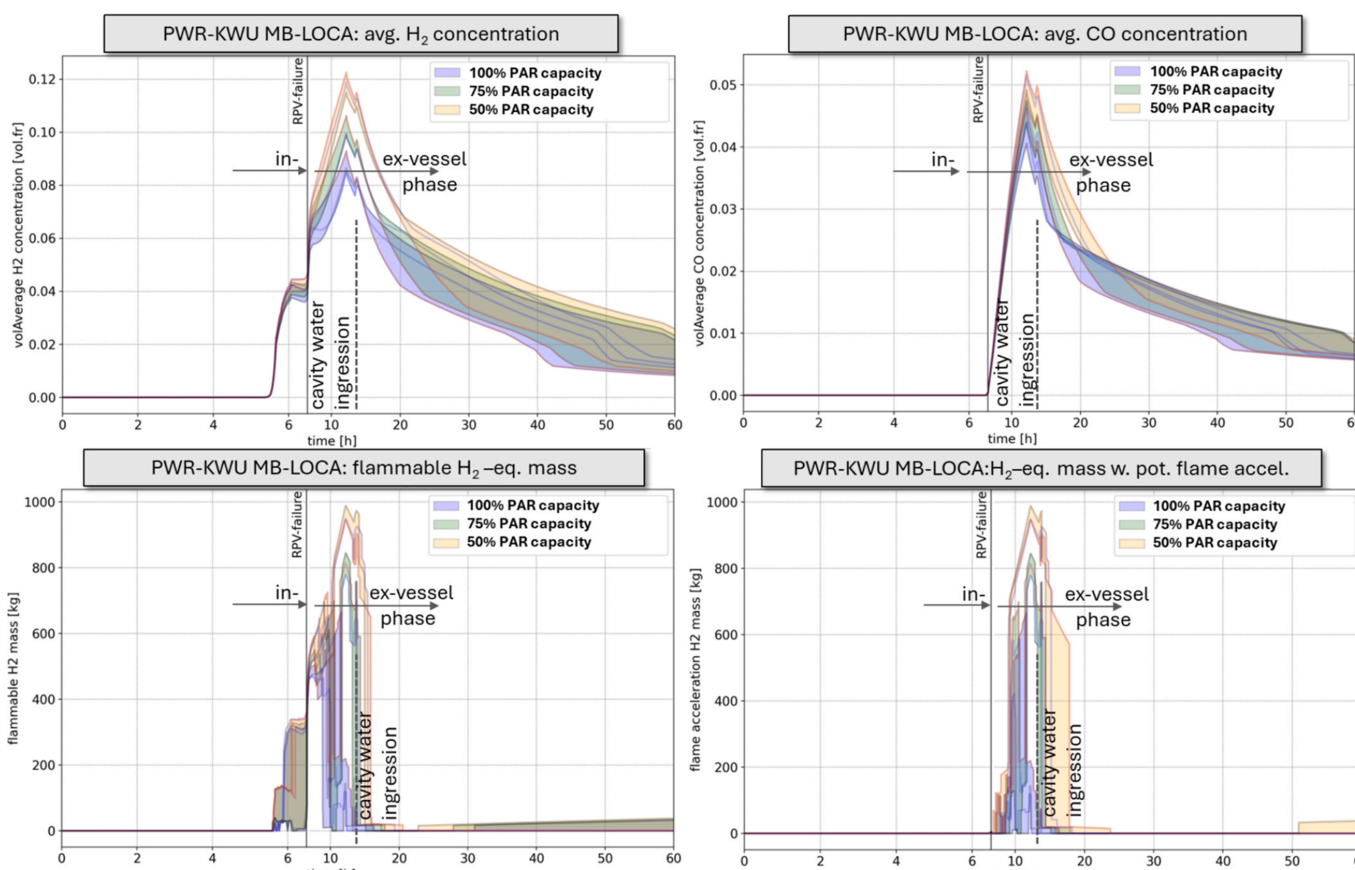


Fig. 7. PWR-KWU MBLOCA: average H_2 and CO concentrations in the containment (top) and integral flammable H_2 mass and its part with potential for flame acceleration (bottom) for different PAR system capacities.

failure was also investigated. While this action may help to stabilize the MCCI, the injected cold water forms a subcooled pool on top of the core melt and prevents a further release of steam but does not efficiently cool down (deinertize) the containment atmosphere. Subsequently, only due to heat losses into the containment concrete structure, the steam-inertization of the containment weakens with time. In the case of a full PAR system capacity, however, the early depletion of O_2 by the PARs prevents a significant effect of the reduced quantity of steam on the flammability.

The PWR-W concepts rely on containment spray systems to homogenize the containment atmosphere and reduce internal overpressure by steam condensation. In the fast LB-LOCA sequence, the direct spray operation is activated nearly immediately after the break and switched to recirculation mode later. In this case, different possible configurations were studied, including a reduction of the spray droplets Sauter Mean Diameter (SMD) from 1000 μm to 520 μm, which leads to increased condensation. On the contrary, parallel operation of fan coolers and a failure of the intermediate heat exchanger (between the sump and the spray nozzles) were considered, which resulted in lower spray flow rates or higher spray temperature during recirculation mode, respectively and thus less condensation. The results are depicted in terms of the evolution of the average pressure, steam concentration in the containment as well as the integral flammable H_2 equivalent mass and its part which can undergo a flame acceleration in Fig. 8.

The major combustion risk occurs in the early phase of the ex-vessel phase of the accident, when PAR operation did not yet consume a significant part of the oxygen in the containment. Considering the steam concentration in the containment, it is clear that for all options, the steam concentration is far below the steam inertization limit (~68 vol %), and thus, the effects of different cooling means on the flammability are small. However, the difference in the steam concentration is visible for the case without available decay heat removal and yields an earlier inertization towards the end of the in-vessel phase. Within the ex-vessel phase, the flammable cloud and its potential to undergo flame acceleration is also slightly reduced. This indicates that spraying with higher temperatures can be utilized to balance depressurization and combustion risk within the SAMG.

Considering the PWR-W-SBO sequence, sprays were assumed to be unavailable due to the lack of power supply. A recovery of AC power, which would enable the operators to activate the sprays to reduce the containment pressure, was postulated at the time of SAMG entry (depressurization of the primary system) and +3 h, +6 h and +9 h later (see Fig. 9).

Even though the steam concentration remains below the inertization limit (<68 vol%) in the reference case, spraying reduces the steam concentration and thus increases the relative concentrations of non-condensable gases. This leads to the formation of flammable clouds in all spray activation cases, while the strongest effect on the flammability is observed for the spray recovery 3–6 h after SAMG entry, when the highest H_2 concentrations are present. Flame acceleration conditions are, however, not reached. In the case of a later spray recovery, the flammable mass is reduced due to the previous consumption of H_2/CO and oxygen by the PARs.

4.3. Effect of containment venting

Based on the PWR-KWU TLAP sequence, the effect of FCVS operation on the combustion risk was investigated. Two set points for FCVS activation, i.e., when reaching containment design pressure (6 bar) and an early venting (4 bar), were investigated and compared against the case

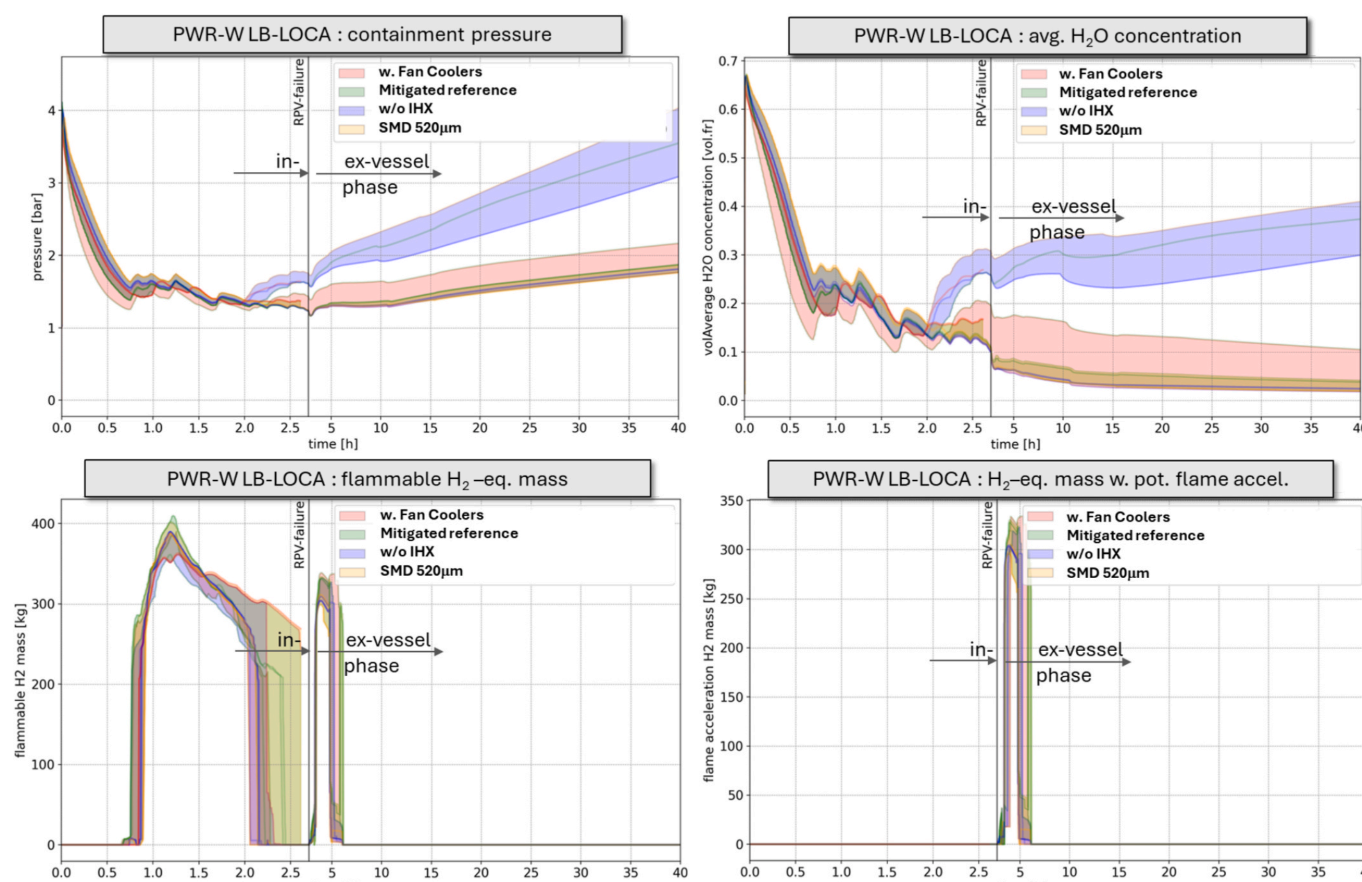


Fig. 8. PWR-W LB-LOCA: average pressure and steam concentrations in the containment (top) and integral flammable H_2 mass and its part with potential for flame acceleration (bottom) spray configurations.

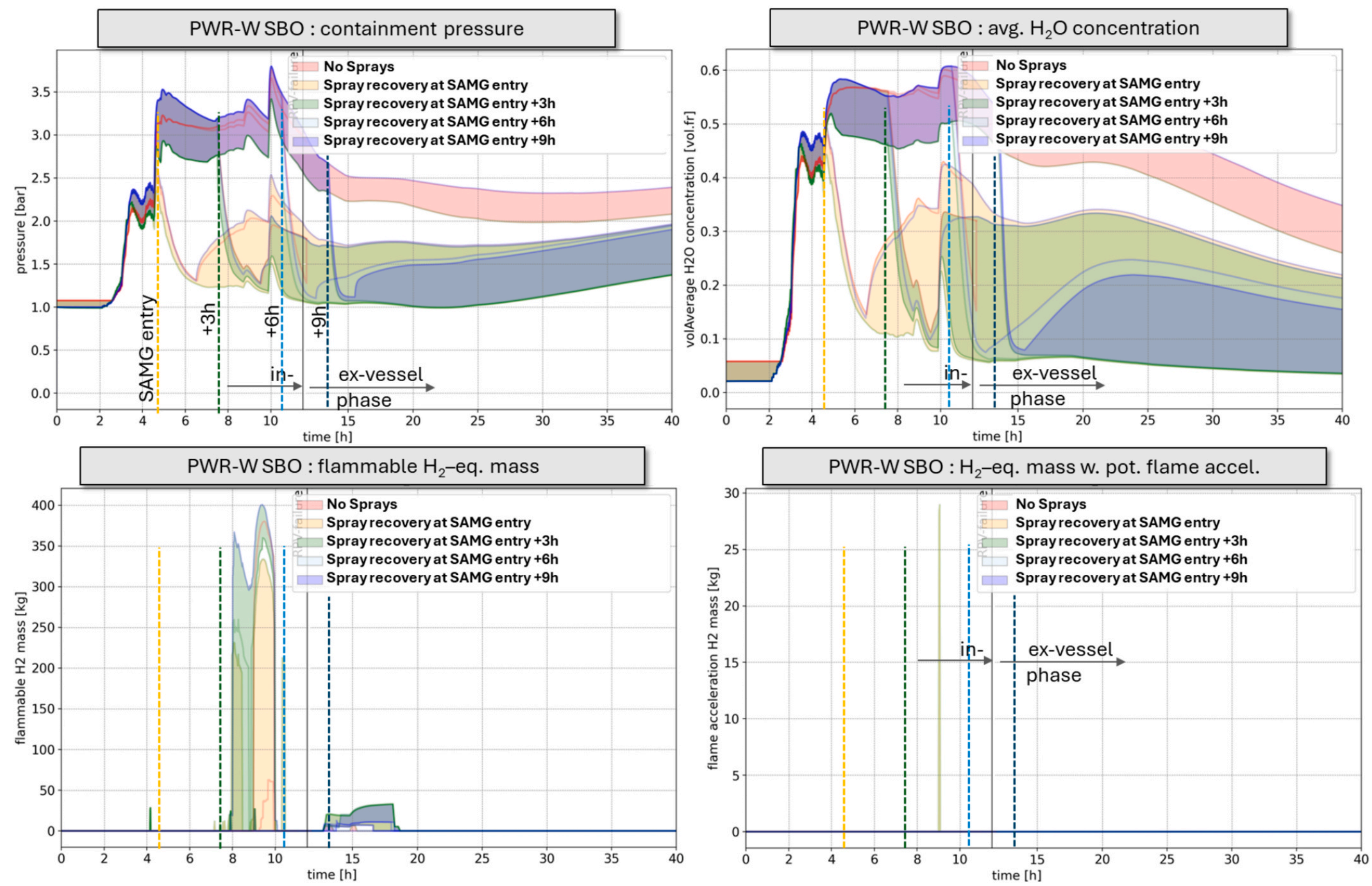


Fig. 9. PWR-W SBO: average pressure and steam concentration in the containment (top) and integral flammable H_2 mass and its part with potential for flame acceleration (bottom) for different spray recovery times.

without venting (Fig. 10).

Since the activation criteria limit venting to the ex-vessel phase, where additional pressurization results from the release of steam and non-condensables from the decomposition of concrete, the effect on combustion risk is low. At that time, PAR operation already consumed most of the available oxygen. The FCVS effectively removes both remaining O_2 and H_2/CO, as well as steam, from the containment and thus further reduces the flammable cloud. Local flammable conditions could only be observed in dead-end compartments and sum up only to up to 100 kg of H_2 equivalent flammable mass. Mixtures, which could undergo flame acceleration, were not reached. Since the vented gas mixture can be flammable, mitigative measures against combustion in the venting line need to be considered, as stated in (Löffler and Braun, 2014). The later the FCVS is operated, the more the inertization of the containment atmosphere due to PAR operation also reduces the risk of a combustion event in the first or subsequent operations of the FCVS system.

4.4. Assessment of 3D effects and heterogeneities

To complement and substantiate the system code analysis, the full 3D analysis of the in-vessel phases conducted with GOTHIC™ has been further evaluated to identify potential heterogeneities in the containment compartments and their effect on the combustion risk (Serra et al., 2025). On this basis, selected time windows were further analyzed using tailored CFD models built by ASNR with FLUENT for PWR-W or FZJ's containmentFOAM package (Kelm et al., 2021; Kelm et al., 2022) and by NRG with FLUENT (Visser et al., 2014; Pangukir et al., 2025) for the PWR-KWU.

The 3D and CFD analyses revealed generally comparable trends for the CV averaged quantities to the system code analysis (cf. Fig. 11 by example of the H_2 concentration in the containment dome compartment).

Nevertheless, flammable jet flows, local stratifications and stagnation zones, especially in dead-end compartments, were identified. Those can result e.g., in potentially standing flames or locally flammable conditions or e.g., which cannot be identified by using the coarse system code nodalisation (e.g., in Fig. 12) by example of the H_2 rich release plume within the break compartment of the PWR-VVER.

Practically, this confirms that safety equipment located close to the potential release locations but also within dead-end compartments where flammable gases can accumulate might be unavailable and should not be credited in the safety assessment.

Similarly, the jets and plumes emerging from the break introduce a heterogeneity of gas concentration, which affects the sensor readings available to the control room. Fig. 13 compares the control-volume-averaged H_2 concentration against the pointwise readings at the sensor location within the equipment rooms.

When, during an SBO, H_2 gets discharged via the pressurizer relief tank into the containment, the sensor "S9" close to the release location (top of the pressurizer) picks up high peak values compared to the remaining sensors. These peaks are significantly higher than the average combustible gas concentrations averaged over the respective control volumes, indicating a localized cloud or plume. Such readings must be anticipated for the sensors close to release locations and should be considered for the development of guidance and definition of threshold values. However, Fig. 13 also shows that these peak values rapidly relax to average values when the direct discharge of H_2 is interrupted. This variability in time may be useful to evaluate if the reading in the main control room shall be interpreted.

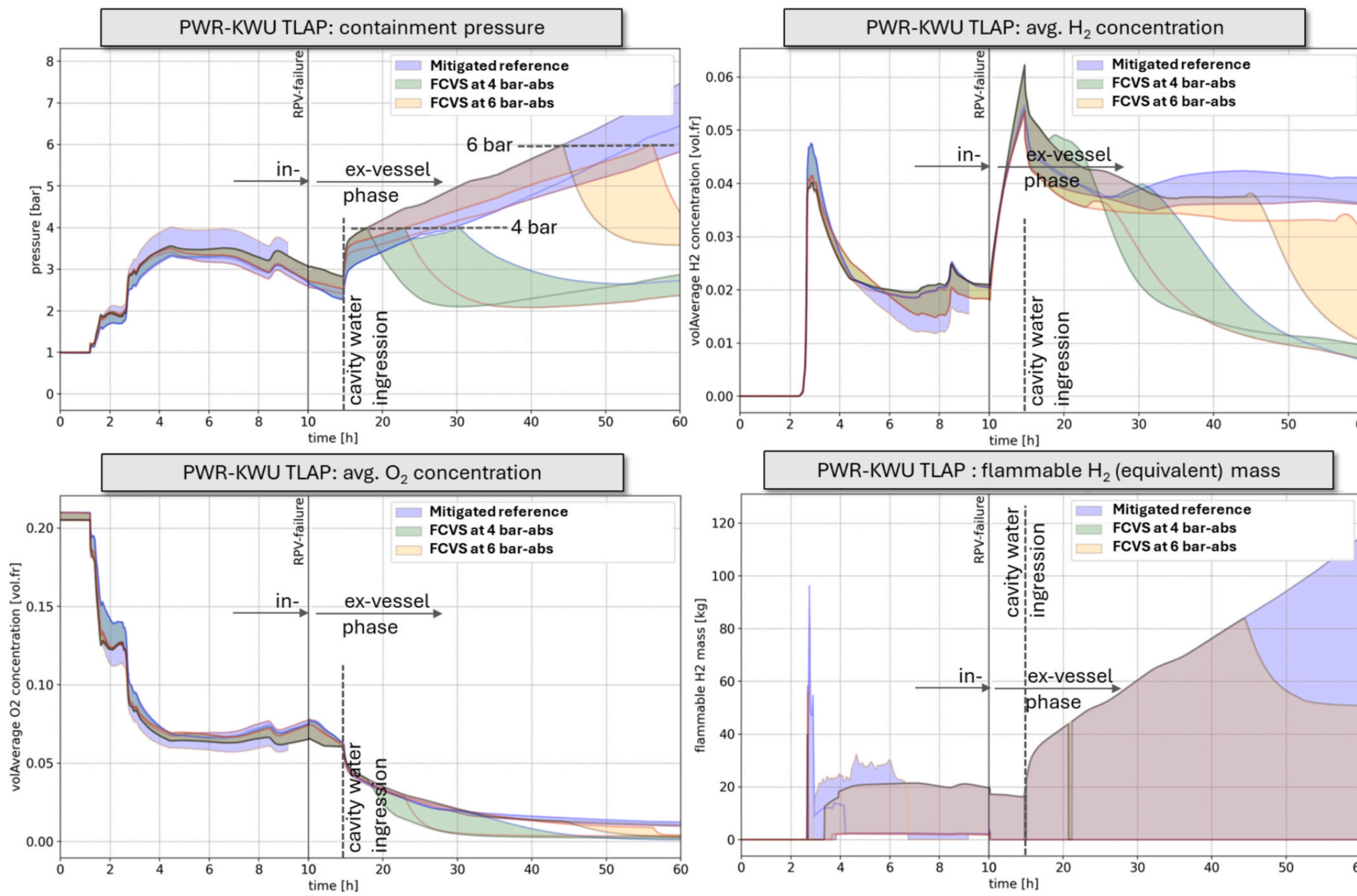


Fig. 10. PWR-W SBO: average pressure and steam concentration in the containment (top) and average oxygen concentration and integral flammable H_2 mass (bottom) for different FCVS activation times.

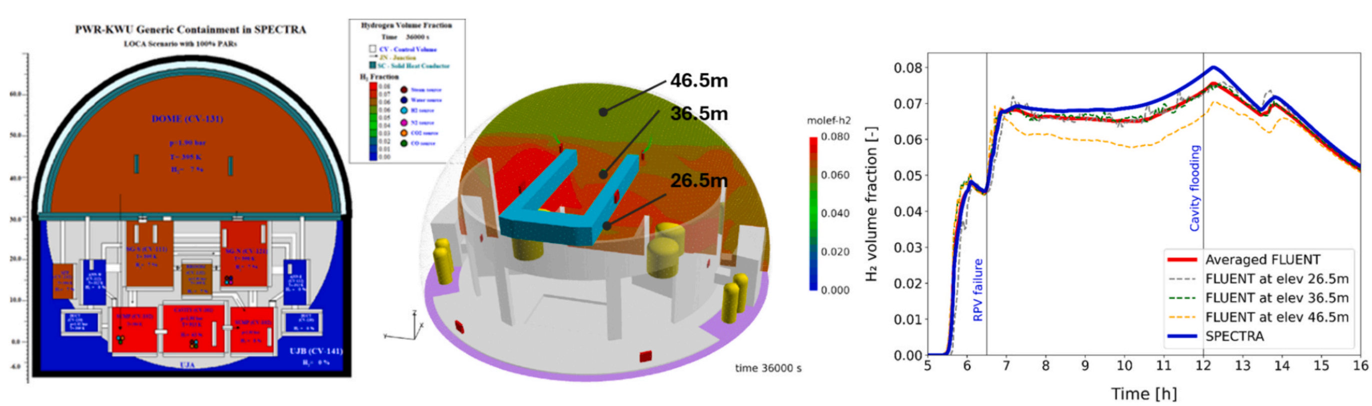


Fig. 11. PWR-KWU MB-LOCA: H_2 distribution at t = 10 h predicted by SPECTRA (left), NRG's FLUENT model (middle) and comparison of the transient evolution (right).

3D and CFD codes consider momentum transfer and thus reveal a different mixing mechanism close to the break. While system codes homogeneously 'dilute' a large CV's mixture by adding gas from the release, GOTHIC[TM] and containmentFOAM rather displace the existing mixture with the injected one. In the case of the equipment rooms of PWR-KWU during the TLAP with a high release location at the pressurizer relief tank, this leads to a less complete mixing in the equipment rooms and formation of an oxygen and H_2 rich layer near the sump region, where no PARs are mounted (see Fig. 14).

Equipment survivability (here according to standard IEEE 323-1974: $T_{gas} > 149.8\ ^{\circ}C$, $P < 4.82$ bar) can be challenged in scenarios without containment cooling and with high pressures, i.e., SBO sequences. All 3D and CFD simulations revealed a strong heterogeneity of the gas temperature, in particular when PARs are active. Fig. 15 shows, using ASNR's FLUENT analysis of a PWR-W SBO, the broad bandwidth of gas temperature in the containment DOME compartment observed with FLUENT while the gas compositions are rather comparable to the system code predictions.

Clearly, equipment qualification criteria can be exceeded locally. Consequently, 3D or CFD models should be employed to quantify potential thermal stratifications and substantiate LP code analysis.

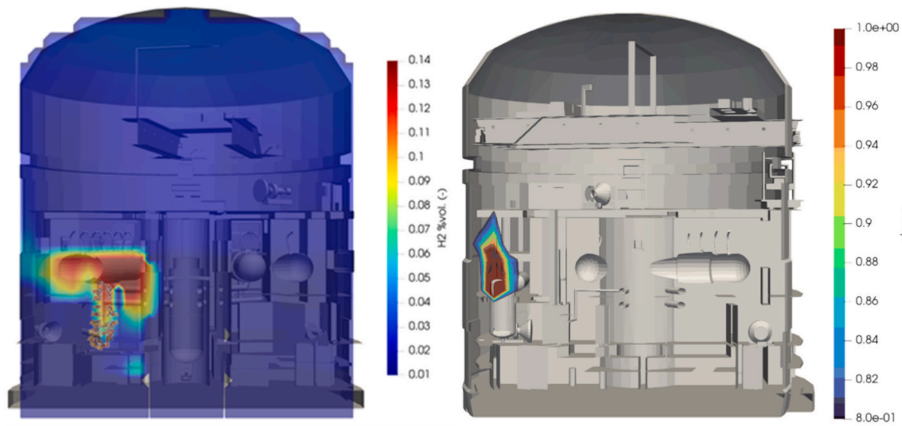


Fig. 12. PWR-VVER: H_2-rich release from break (left) and associated flammable gas cloud with potential of flame acceleration (right) evaluated with UPM's GOTHIC™ model.

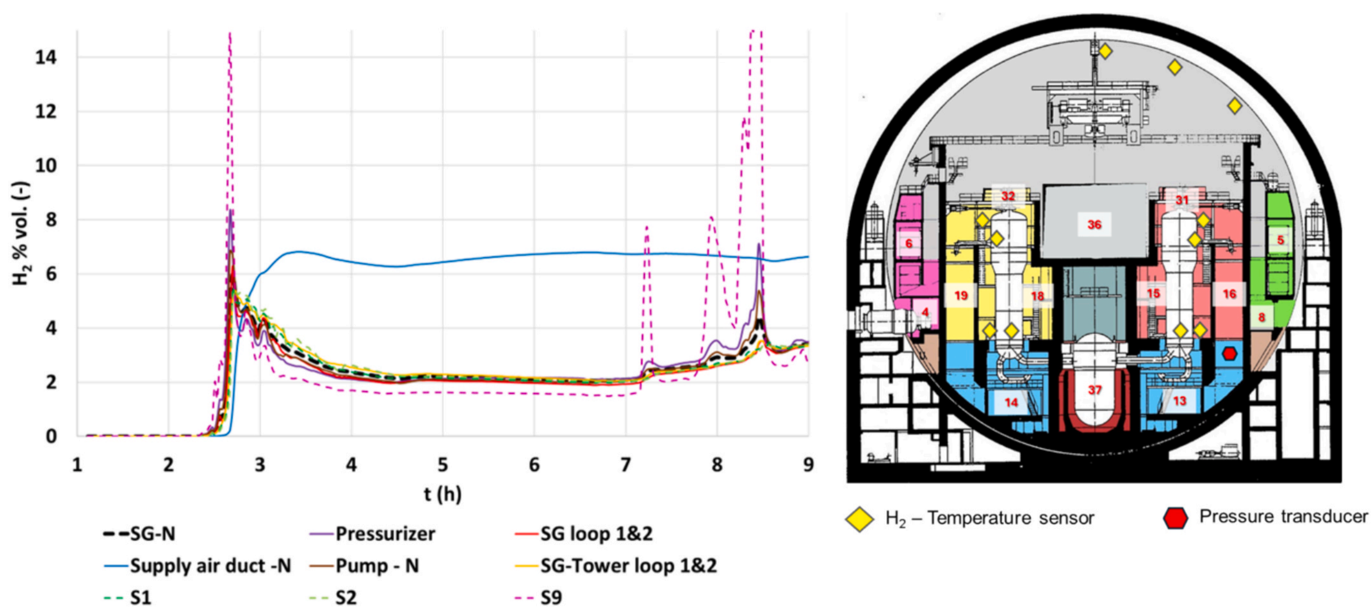


Fig. 13. PWR-KWU SBO: control volume averaged H_2-concentrations and pointwise measurements at the specified sensor positions evaluated with UPM's GOTHIC™ model.

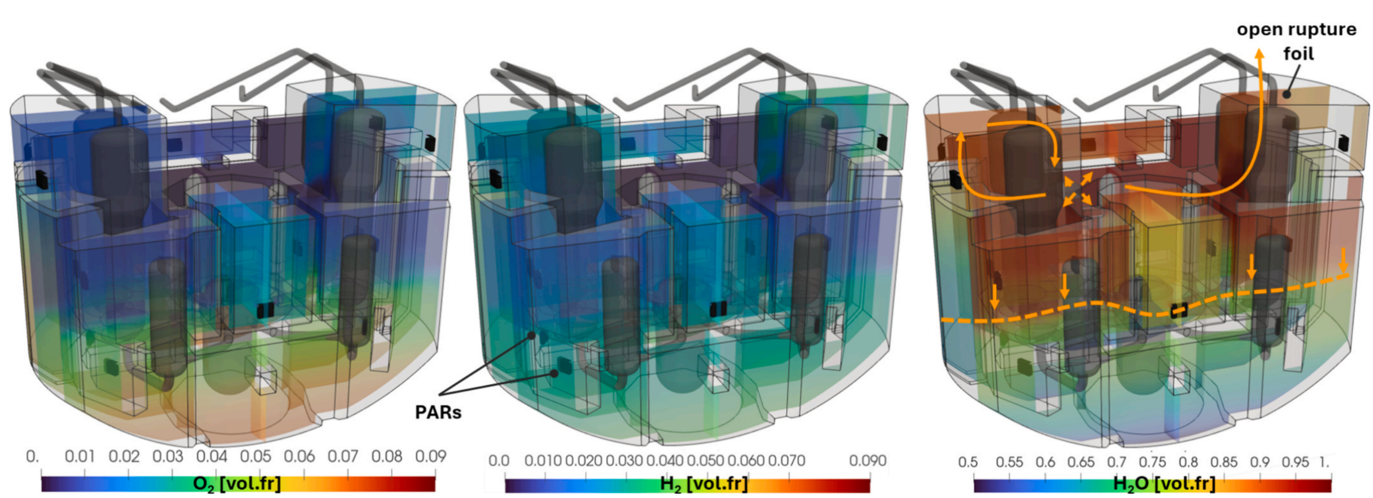


Fig. 14. PWR-KWU TLAP: gas mixing in the equipment rooms and formation of a H_2-O_2 rich bottom layer evaluated with containmentFOAM.

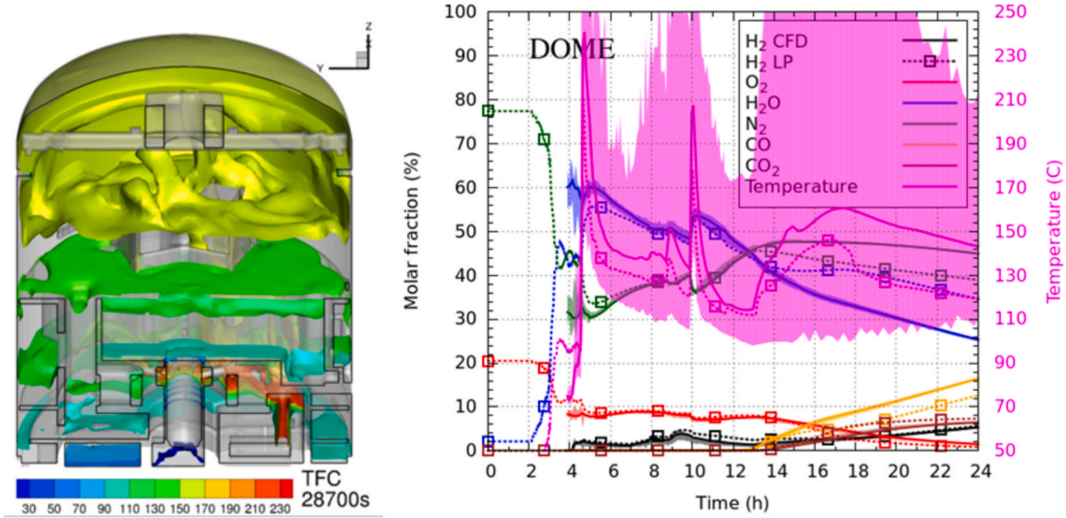


Fig. 15. PWR-W-SBO: gas temperature field at t = 8 h (left) and DOME CV conditions (right) calculated with ASNR's FLUENT model.

5. Summary and conclusions

In the frame of the European AMHYCO project, the behavior and response of the containment to various mitigation measures during two selected severe accident transients—Station Blackout/Total loss of AC Power and Loss of Coolant Accident were analyzed systematically, using generic models representing three European PWR designs: German KWU, Western (French and Westinghouse), and Eastern European VVER. The simulations were performed using different system codes and were supplemented by dedicated 3D and CFD analyses. The confirmed comparability of the different codes and models, sustained by a common geometrical database, paved the way for a detailed and systematic assessment of the effectiveness or impact of mitigative measures like passive autocatalytic recombiner, fan coolers, sprays, and filtered containment venting systems regarding the in-containment combustion risk. The latter was evaluated in terms of the evolution of flammable gas cloud as well as its potential of flame acceleration conditions, rather than by conducting combustion analyses to exclude the definition of ignition source and timing from the parameter space. Enhanced criteria were derived from new experimental data considering gas mixtures involving H_2/CO as fuel and lean O_2/high dilutant concentrations. They proved to yield a more realistic assessment of the flammability than the established and more conservative treatment of CO as additional H_2. Regarding the potential for flame acceleration, the new criteria allowed to assess also the conditions of the ex-vessel accident phase, where the simple treatment of CO as additional H_2 is not possible.

The simulations consistently show that without any H_2 mitigation measures (e.g., passive autocatalytic recombiner), the containment atmosphere always develops pockets where an ignition followed by combustion could occur. In some of these bounding scenarios in terms of combustion risk, the containment atmosphere even became globally flammable, with the potential of evolving to fast dynamic combustion processes. Furthermore, the mass of combustible gas increases with time due to the ongoing MCCI. This emphasizes the need for combustible gas control hardware to protect the containment integrity and prevent potential loads resulting from a flame acceleration during both in- and ex-vessel phases for all containment designs.

The experimental work as well as the comparison of the extended generic 'AMHYCO PAR correlation' against the established manufacturer's correlation (in this case, the AREVA correlation) confirm that PAR operation in the late accident phase is impaired stronger by oxygen starvation and parallel recombination of CO. The 'AMHYCO PAR correlation' revealed to be conservative compared to the existing manufacturers' correlation, i.e., resulting in a slower depletion of H_2, CO and O_2 in the late phase. Besides limiting the H_2 mass in the containment, the main effect of PARs is the consumption of O_2 and thus the inertization of the containment atmosphere in the late phase. The capacity and efficiency of the PAR system primarily affect the peak concentration of H_2 and the time until this inertization is reached, but PAR systems can deplete the combustible mixtures effectively even with reduced capacities in exchange for longer depletion times. In all analyzed scenarios and across all containment designs, the implementation of PARs effectively prevented the global formation of gas mixtures capable of inducing flame acceleration. Nevertheless, localized accumulations of combustible clouds with the potential to promote flame acceleration were still observed.

Furthermore, thanks to the O_2 removal, cooling systems (i.e., spray and containment coolers) to decrease the containment pressure in the late phase of the accident can be started without increasing the risk of combustion. The reactivation of the reactor emergency core cooling system likely does not further increase the combustion risk, as it primarily cools the core melt and not globally the containment atmosphere. In the specific case of containment venting, the combustion risk was further reduced by the removal of combustible gases by the PARs. The later the FCVS is operated, the more the inertization of the containment atmosphere due to PAR operation also reduces the risk of a combustion event in the first or subsequent operations of the FCVS system.

Equipment survivability (here according to standard IEEE 323-1974: $T_{gas} > 149.8$ °C, $P < 4.82$ bar) can be challenged in scenarios without containment cooling and with high pressures, i.e., SBO/TLAP sequences. 3D simulations revealed a strong heterogeneity of the gas temperature, especially when PARs are considered. They might be used to substantiate LP code analysis and allow quantifying thermal stratifications.

While the 3D and CFD analysis generally reveal comparable trends for the CV averaged quantities to the system code analysis, local stratifications and stagnation zones were identified. Those can result in locally flammable conditions or, e.g., standing flames, which cannot be identified by using the coarse system code nodalisation. Furthermore, pointwise evaluation of possible sensors locations showed stronger oscillations with high peak values compared to the rather smooth monotonous evolution of the CV mean values. Consequently, for decision-making, it should be accounted for that sensor readings might be affected by local heterogeneities and/or cannot capture local accumulations (e.g., dead-end compartments). Furthermore, while a global combustion event is most likely prevented by PARs, local combustion (e.g., in dead-end compartments) is possible and should be evaluated or conservatively treated, e.g., by assuming the unavailability of the equipment in these areas under certain circumstances.

A major advance in the state-of-the-art resulted from the use of the extended PAR correlation that captures the effects of oxygen starvation and CO poisoning in the late phase (Braun and Reinecke, 2025), as well as the application of new criteria for the H_2/CO combustion risk (Chaumeix et al., 2025). The databases and experience gained were finally transferred into a review of the SAMGs and recommendations for their extension (Braun, 2025).

Following the completion of the AMHYCO project in March 2025, an integrated computational methodology combining LP, 3D, and CFD codes has been established for the detailed assessment of in-containment atmosphere mixing and combustion phenomena. Supported by enhanced correlations, this framework was applied to generic representations of operating European containments. Future research should extend this methodology to Gen III+ and LW-SMR designs to advance the scientific basis for combustion risk assessment and to inform the development of regulatory guidelines.

CRediT authorship contribution statement

Stephan Kelm: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Michael Klauck:** Writing – review & editing, Investigation, Formal analysis. **Carlos Vázquez-Rodríguez:** Writing – review & editing, Investigation, Formal analysis. **Gonzalo Jiménez:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis. **Luis Serra:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Araceli Domínguez-Bugarín:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Luis Enrique Herranz:** Writing – review & editing, Investigation, Formal analysis. **Joan Fontanet:** Writing – review & editing, Investigation, Formal analysis. **Leticia Vitores:** Methodology, Formal analysis. **Ahmed Bentaib:** Writing – review & editing, Investigation, Formal analysis. **Ludovic Maas:** Writing – review & editing, Investigation, Formal analysis. **Alexandre Bleyer:** Writing – review & editing, Investigation, Formal analysis. **Nabiha Chaumeix:** Writing – review & editing, Methodology. **Matthias Braun:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Johannes Hoffrichter:** Writing – review & editing, Investigation, Formal analysis. **Miriam Müer:** Writing – review & editing, Investigation, Formal analysis. **Ivo Kljenak:** Writing – review & editing, Investigation, Formal analysis. **Oleksandr Sevbo:** Writing – review & editing, Investigation, Formal analysis. **Andriy Iskra:** Writing – review & editing, Investigation, Formal analysis. **F.S.L. (Fajar) Pangukir:** Writing – review & editing, Investigation, Formal analysis. **D.C. (Dirk) Visser:** Writing – review & editing, Investigation, Formal analysis. **Zhe (Rita) Liang:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The AMHYCO project has received funding from the Euratom research and training programme 2019–2020 under Grant Agreement n°945057. The content of this paper reflects only the authors' view. The European Commission is not responsible for any use that may be made of the information it contains. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

References

Al Mazouzi, A., Gruna, G., Resse, S. (Eds.), 2015. NUGENIA Global Vision Version April 2015: Revison 1.1. TheNUGENIA Association, Brussels.

Bentaib, A., 2022. Critical assessment of key elements of combustible gases management in containment, AMHYCO, Deliverable D1.1.

Braun, M., Reinecke, E.-A., 2025. Amhyco Engineering Correlation to Describe the Conversion of Flammable Gases in Framatome Passive Autocatalytic Recombiners, Elsevier BV. doi: 10.2139/ssrn.5199266.

Braun, M., Reinecke, E.-A., 2025. AMHYCO engineering correlation to describe the conversion of flammable gases in Framatome passive autocatalytic recombiners. Nucl. Eng. Des. 442, 114206. https://doi.org/10.1016/j.nucengdes.2025.114206.

Braun, M., 2025. Lessons Learned of the AMHYCO Project and Guidelines for SAMG Development, Minimizing the H_2/CO Combustion Risk in a Containment, AMHYCO, Deliverable D5.

Chaumeix, N., Ballossier, Y., Hamadi, A. 2025. Engineering Correlations, AMHYCO, Deliverable D4.1.

Desclaux, A., Nyrenstedt, G., Idir, M., Chaumeix, N., Bleyer, A., Bentaib, A. Turbulent flame speed of H_2-CO-Air mixtures for conditions relevant to late phase accident scenario. In: Proc. 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), March 6–11, 2022, p. 14.

The European Union Per Regulation 305/2011, *Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design*, The European Union Per Regulation 305/2011, EN 1992-1-2 (2004), Dec. 2004.

Peer Review Report - Stress tests performed on European nuclear power plants, ENSREG, Apr. 2012. [Online]. Available: https://www.ensreg.eu/sites/default/files/EU%20Stress%20Test%20Peer%20Review%20Final%20Report_0.pdf.

Framatome GmbH, 2019. Passive Autocataliytic Recombiner - Combustible Gas Control System. Accessed: Feb. 14, 2024. [Online]. Available: https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a0642-p-ge-g-en-201908-par.pdf?sfvrsn=748c9be2_2.

Herranz, L.E., Fontanet, J. 2023. Identification and analysis of accident sequences with posing high H_2/CO combustion risk, AMHYCO, Deliverable D2.2.

Mitigation of hydrogen hazards in severe accidents in nuclear power plants. in Tec-Doc, no. 1661. Vienna: International Atomic Energy Agency, 2011.

International Atomic Energy Agency, 2016. Consideration on the application of the IAEA safety requirements for the design of nuclear power plants. In: IAEA TECDOC Series, no. 1791. Vienna, Austria: International Atomic Energy Agency.

Jiménez, G., et al., 2022. AMHYCO Project – Towards and Enhanced Accident Management of the H_2/CO Combustion Risk. In: Proc. 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19).

Kelm, S., et al., Dec. 2014. Generic containment: detailed comparison of containment simulations performed on plant scale. Ann. Nucl. Energy 74, 165–172. https://doi.org/10.1016/j.anucene.2014.07.006.

Kelm, S., et al., 2021. The tailored CFD package 'containmentFOAM' for analysis of containment atmosphere mixing, H_2/CO mitigation and aerosol transport. Fluids 6 (3), 100. https://doi.org/10.3390/fluids6030100.

Kelm, S., et al. 2022. Technical Scale CFD Analysis of the Pressurization and Transport Processes in the Battelle Model Containment during the ISP 37 VANAM M3 Test, presented at the 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS 13), Hsinchu, Taiwan.

Kelm, S., et al. 2024. Assessment of the Unmitigated Combustion Risk in the late Phase within the AMHYCO Project. In: Proc. 11th European Review Meeting on Severe Accident Research (ERMSAR-2024), Stockholm, Sweden.

Liang, R., Sonnenkalb, M., Sangiorgi, M., Bentaib, A., 2014. Status Report on Hydrogen Management and Related Computer Codes, OECD/NEA, NEA/CSNI/R(2014)8.

Löffler, M., Braun, M. 2014. Evaluation of filtered containment venting systems with MELCOR for extended operating conditions in German PWR, In: Proc. EMUG-Meeting, Bratislava, Slovakia.

Martín-Valdepeñas, J.M., Jiménez, M.A., Martín-Fuertes, F., Fernández, J.A., 2007. Improvements in a CFD code for analysis of hydrogen behaviour within containments. Nucl. Eng. Des. 237 (6), 627–647. https://doi.org/10.1016/j.nucengdes.2006.09.002.

Müer, M., Hoffrichter, J., Bratfisch, C., Koch, M.K., 2022. Analyses of the combustible gas release into the containment during a SBO and a SBLOCA scenario in a generic PWR using the code package AC2. *Proc. 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety (NUTHOS-13)*.

Nyrenstedt, G., Chaumeix, N., Bleyer, A., Bentaib, A. H_2-CO-Air Combustion under MCCI Conditions. In: Proc. 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), p. 14.

Pangukir, F.S.L., Siccama, N.B., Stempniewicz, M.M., Tajfirooz, S., Visser, D.C. 2025. Comparison between System Thermal Hydraulic and CFD Analyses of Atmospheric Mixing in the Dome of a Generic PWR Containment during a Severe Accident Transient. In: Proc. 21st International Topiccal Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-21), Busan, Korea, 8.-5.9 2025.

Reinecke, E.-A., et al., 2022. PAR model development exercise in the framework of SAMHYCO-NET. Nucl. Eng. Des. 399, 112035. https://doi.org/10.1016/j.nucengdes.2022.112035.

Reinecke, E.-A., Domínguez-Bugarín, A., Nobrega, G. 2023. Synthesis and outcomes of performed experiments and numerical results related to PAR behaviour, AMHYCO, Deliverable D3.2.

Reinecke, E.-A., et al. 2024. Outcomes of the Experimental and Numerical Work on the Operational Behavior of Passive Auto-catalytic Recombiners in the late Phase of a Severe Accident in the Framework of the AMHYCO Project. In: Proc. 11th European Review Meeting on Severe Accident Research (ERMSAR-2024), Stockholm, Sweden.

Serra, L., et al., 2025. From the plant layouts to optimized LP and 3D PWR-KWU containment models for combustion risk assessment with GOTHIC 8.3(QA). Nucl. Eng. Des. 445, 114459. https://doi.org/10.1016/j.nucengdes.2025.114459.

Serra, L., et al. 2021. Development of a detailed 3D CAD model of a generic PWR-KWU containment as a basis for a better assessment of H_2/CO combustion risk. In: European Nuclear Young Generation Forum (ENYGF'21), Tarragona, Spain.

Serra, L., Domínguez-Bugarín, Vázquez-Rodríguez, Jiménez, G. 2023. Data for the generic containment analysis (PWR-W, PWRVVER, PWR-KWU), AMHYCO, Deliverable D2.1.

Stamps, D.W., Berman, M., 1991. High-temperature hydrogen combustion in reactor safety applications. Nucl. Sci. Eng. 109 (1), 39–48. https://doi.org/10.13182/NSE91-A23843.

Visser, D.C., Siccama, N.B., Jayaraju, S.T., Komen, E.M.J., 2014. Application of a CFD based containment model to different large-scale hydrogen distribution experiments. Nucl. Eng. Des. 278, 491–502. https://doi.org/10.1016/j.nucengdes.2014.08.005.