ASSESSMENT OF UNMITIGATED COMBUSTION RISK IN THE LATE PHASE WITHIN THE AMHYCO PROJECT

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ABSTRACT

The European AMHYCO project (Euratom 20192020, GA No 945057) aims at enhancing the understanding of H_2/CO combustion risk within the containment of a nuclear power plant in the late phase of a severe accident. The goal is to incorporate this knowledge into severe accident management guidelines and recommendations for long-term operation upgrades. Based on a critical review of existing methodologies and practices related to gas combustion risk, as well as the identification of accident sequences in which the H_2/CO combustion risk might challenge containment integrity, experimental investigations are conducted to close knowledge gaps related to combustion characteristics and the operation of passive autocatalytic recombiner under late phase conditions. To prepare the basis for the further assessment and refinement of existing SAMGs, systematic detailed analyses of the most challenging scenarios and possible mitigative measures were conducted for three generic European 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. Both scenarios cover a range of in-containment atmospheric conditions from potentially flammable at medium pressure up to a steam-inertized atmosphere at high pressure, including the late phase with an active filtered containment venting system.

This paper outlines the employed methodology using a consecutive analysis chain consisting of three levels with increasing detail (system codes, 3D GOTHIC™ and CFD) to assess containment pressurization, efficiency and/or options of individual mitigation measures with respect to 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 CADs and a shared geometry database. The paper discusses the status of the work with a focus on the comparative assessment of unmitigated reference cases that will be used in the future to assess the impact and effectiveness of mitigative measures (PARs, sprays, FCVS) on the combustion risk in the late phase. Concluding, challenges and lessons-learned are summarized.

KEYWORDS

AMHYCO, combustion risk, in-vessel phase, ex-vessel phase, Passive auto-catalytic recombiners, containment response, SAMG

1. INTRODUCTION

The severe reactor accident at the Fukushima Daiichi Nuclear Power Plant in 2011 has confirmed the need to develop a deeper understanding of the generation and distribution of combustible gases within the containment and connected compartments since their combustion can lead to dynamic loads on the containment structures and equipment and challenge containment integrity. While up to now primarily the risk associated with H_2 combustion during the in-vessel phase was considered [1], the European AMHYCO project (Euratom 20192020, GA No 945057) [2] aims at enhancing the understanding of H_2+CO combustion risk within the containment of a nuclear power plant both in the in-vessel (H_2) and ex-vessel (H_2+CO)phases of a severe accident (SA). Consequently, a comprehensive analytical assessment of the containment behavior is conducted in its Work Package (WP) 4 to investigate

- the H_2/CO combustion risk, e.g., flammability or potential of flame acceleration,
- the efficiency and options/timing of individual mitigative measures, including PARs, FCVS, or spray systems activation.
- and the equipment and instrumentation survivability and ‘operators/control room view’ on the containment status.

The analysis is conducted for generic European PWR concepts, W(French and Westinghouse designs), KWU (German PWR design), and VVER (Soviet/Russian design), to provide a database for a review and potential extension of the SAMGs and EOPs within WP5. For that purpose, WP4 utilizes scenarios selected in WP2 [3], existing empirical criteria and correlations, supported by the WP1 literature review [4], and new correlations derived from experimental data on H_2/CO combustion [5] and PAR efficiency [6] in the late phase, developed in WP3. In a nutshell, the integration of WP4 in AMHYCO is depicted in Figure 1.

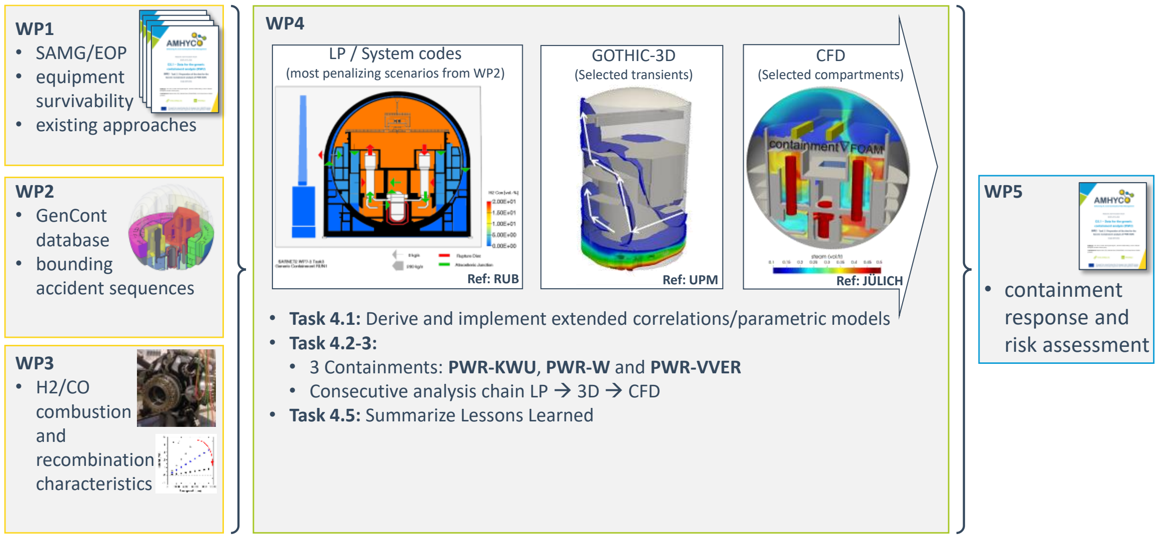

Figure 1. Integration of WP4 in the AMHYCO project

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 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 a certain comparability of the simulation results as well as to pave the way for obtaining generic, i.e., non-plant-specific conclusions. Full containment analyses are conducted in a consecutive analysis chain, consisting of three levels of increasing detail:

- As basis, the identified sequences are simulated completely with lumped parameter (LP) containment models e.g., built in COCOSYS, SPECTRA, ASTEC or MELCOR.
- The most penalizing cases are additionally investigated with 3D models developed in GOTHIC™ to address potential asymmetric / 3D conditions that may lead to higher combustion risk.
- 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 increasing level of spatial resolution achieved with the different codes will also be utilized to assess the perspective on the accident from the control room (available instrumentation) against the full insights provided by the simulations to propose an upgrade of the SA instrumentation and the SA Management Guidelines (SAMG).

This paper aims to summarize the status of the work with a focus on the methodology and comparative assessment of the unmitigated reference cases. This was found to be a necessary step to ensure a consistent implementation of the generic containment nodalization schemes and definition of the mass and energy injection tables. After convergence of the unmitigated cases the assessment of the impact and effectiveness of mitigative measures (PARs, sprays, FCVS) on the combustion risk in the ex-vessel phase. Section 2 briefly introduces the characteristics of the SA scenarios selected from WP2. Within Section 3, the employed methodology and preparative steps including the comparative assessment of unmitigated reference cases are 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 summarized the first results and lessons learned from the analyses of unmitigated reference cases and outline the future work.

2. SCENARIOS

Within WP2, different sequences of the three European PWR designs, PWR-W, PWR-KWU, and PWR-VVER, were simulated with different system codes and hypotheses, including the nodalization schemes used. These simulations cover different initiating events and involve diverse engineered safety features and SA management measures. The simulations were screened regarding the prevailing combustion risk to identify bounding scenarios for the detailed analysis of the containment response in WP4 [3]. For each containment type, two classes of scenarios were analyzed:

(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 is in place.
(2) A Station Blackout (SBO)/Total Loss of AC Power (TLAP) sequence, which results in a delayed core damage and release of H_2.

Thereby, for the LOCA scenarios, the size and break location were varied and for the transient SBO accident, the boundary conditions like primary loop depressurization were varied to determine the accident sequence bounding with regards of hydrogen risk. Additionally, the in-vessel hydrogen release path into the containment is quite different in both types of sequences. In case of a LOCA hydrogen is released through the break location whereas for the SBO the release path is via the pressurizer release tank to the containment. After 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 [3]:

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 could prevent accident progression, 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 of 4x2 kg/s over a period of 2.5 h and thus slightly delays the core uncovery but is insufficient to stop the accident. Core degradation begins after approx. 5.3 h. The delayed accident progression [7] 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 by the MCCI starts. Within the transient 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 is 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 begins already 20 min after the initiating event.

The RPV failure occurs ~2.7 h and at about 6 h the corium in the cavity gets completely oxidized. The large water and steam release through the RCS breach leads to a sudden pressure peak. Activating the containment spray systems (fan cooler are not used in the reference case) significantly reduces the pressure before the generation of non-condensable gases by MCCI leads to a continuous pressurization. At around 2 h, the spray operation is switched to recirculation mode, which reduces their efficiency. The high release of hydrogen in the in-vessel phase and the important drop of steam molar fraction due to the actuation of the safety systems lead to 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 1008 kg H_2 and 13396 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 hydrogen release to the containment after rupture of the pressurizer relief tank burst discs after around 2.5 h. The pressurizer relief valves lock 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. Within the considered problem time of 48 h, a total amount of 4880 kg H_2 and 1905 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 HA inject water into the upper plenum of the RPV, while the other two inject 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 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 and MCCI. More than 2875 kg H_2 8000 kg CO are released during considered problem time to the containment.
- SBO: A complete loss of power supply and failure to start all emergency diesel generators is considered. Consequently no, water injection from the high pressure ECCS does not take place. At the initial stage of the accident, heat is removed from the RPV due to the boiling off water from steam generators in 1 hour. The core materials and water in the PRV begin to heat up and relief steam to the bubbler tank and then to the containment. The bubbler tank membrane breaks in 1.7 h and release steam to the containment with moderate pressure and temperature increase in the containment. Cladding oxidation and H_2 release into the containment starts in 3.5 hours after the beginning of the accident. Continuous degradation of the core leads RPV failure and MCCI in the cavity. More than 3000 kg H_2 and 7800 kg CO are released during the simulated duration.

3. METHODOLOGY AND PREPARATIVE STEPS

The computational approach employed in WP4 is based on the experiences gained during the SARNET-II Generic Containment benchmark series [8] and its continuation in the frame of SAMYCO-net. Though a code-to-code benchmarking is explicitly not 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 fundament step.

Table 1. Codes used in WP4

Mesh	PWR-KWU	PWR-W	PWR-VVER
System codes	COCOSYS 3.1 (RUB) MELCOR 2.1 (Framatome) SPECTRA 23-12-0000 (NRG) COCOSYS 2.4 (FZJ)	ASTEC (JSI) ASTEC v2.2 (IRSN) MELCOR 2.2_r2023.0 (CIEMAT)	MELCOR 1.8.6_RL_2011 (Energorisk)
3D codes	GOTHIC8.3 Q.A (UPM)		
CFD codes	ANSYS FLUENT (IRSN)	ANSYS FLUENT (NRG) containmentFOAM (FZJ)	

For the sake of clarity, the flowing discussion focuses on the work performed for the PWR-KWU type of plants. Similar evaluations were also performed for PWR-W and PWR-VVER.

The Generic Containment nodalisation schemes were derived from 3D CAD models [9], [10] (see Figure 2), generating a consistent and freely usable data basis for all code users to develop their LP, 3D, and CFD containment models.

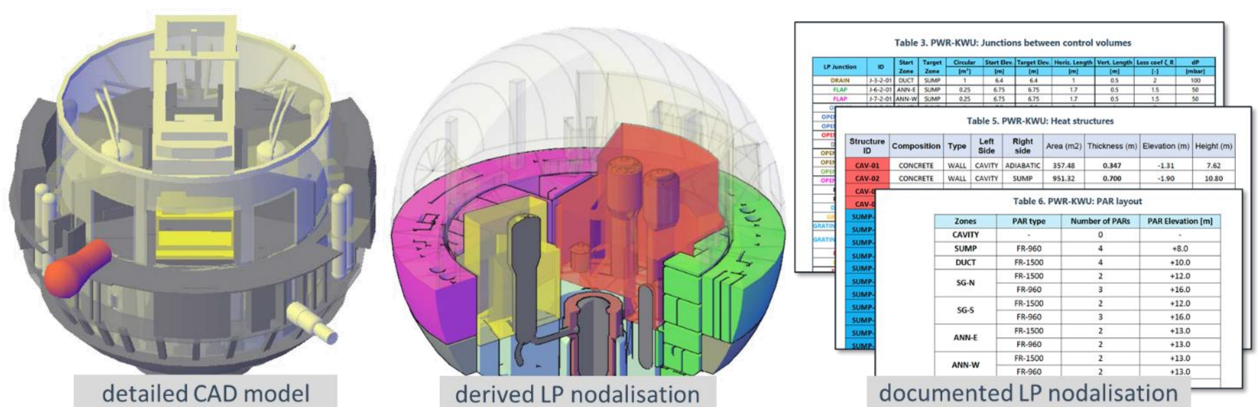

Figure 2. Definition of the generic nodalization (here PWR-KWU)

The way of extracting and documenting the nodalization scheme (surface areas, heat structure thickness, junction length etc.) still requires a ‘translation’ into different code input deck structures as they have deviating input requirements. This adaption led to ambiguities in the interpretation of the data. Therefore, 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, see Figure 3 (as example for the PWR-KWU). In the analysis of the input verification, the identified deviations were understood and are considered as justifiable.

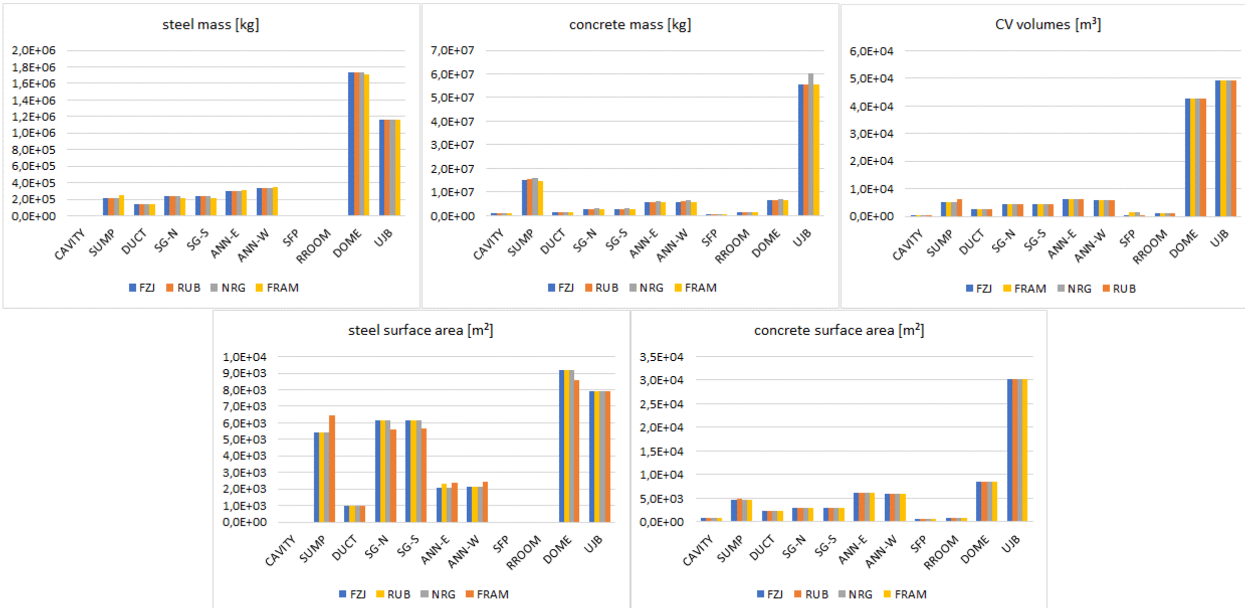

Figure 3. Comparison of the nodalization statistics for PWR-KWU

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) were considered. Figure 4 compares the pressure evolution obtained for the unmitigated PWR-KWU MB LOCA and TLAP sequences with different codes. The predicted pressurization is generally highly 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 the cavity flooding. The same tendencies are visible for both scenarios, i.e. the strongest pressurization is predicted by MELCOR, followed by SPECTRA, and the weakest by COCOSYS The visible differences between both COCOSYS results were found to result from different versions (RUB 3.1, FZJ 2.4).

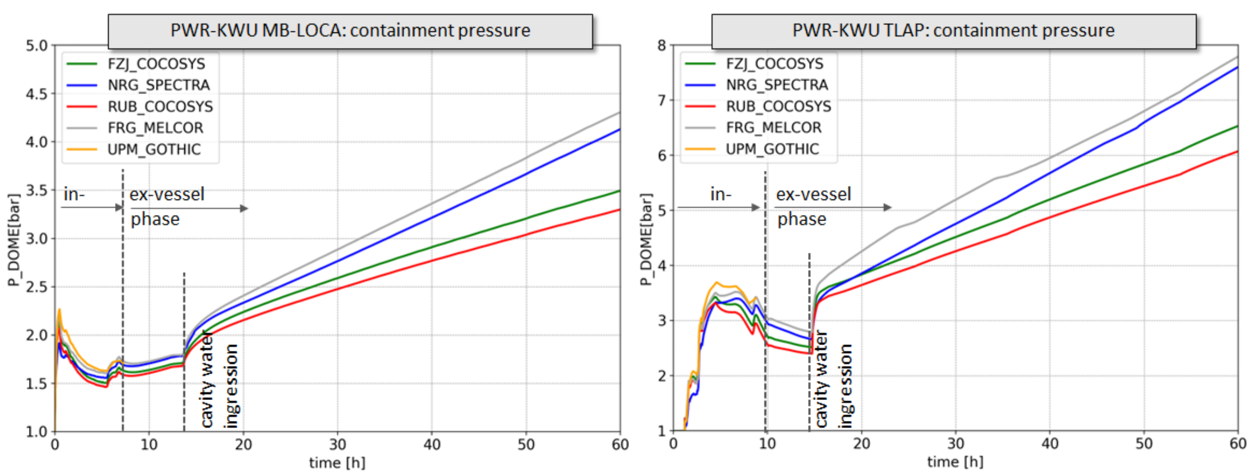

Figure 4. Pressure evolution for the PWR-KWU sequences

The observed spreading is kind of expected, since these codes use different models for heat transfer from the gas to structures, and different models for heat conduction within these structures. The resulting differences accumulate over time so that the spreading increases with problem time. Currently, additional evaluations are ongoing to further understand the differences in containment pressurization and possibilities to reduce this uncertainty of the simulation results.

The main impact parameter for the containment pressurization turned out to be the assumed thermal conductivity of the in-containment concrete structures. The concrete structures absorb heat, and thus condense steam. After a lengthy discussion, devaluating different proposals, the common conclusion for AMHYCO was to use a best-estimate concrete density of 2500 kg/m3 - 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) [11] - to be bounding with regard to 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.

Concluding, the LP code and GOTHIC™ 3D input decks are considered applicable for a quantitative assessment of the combustion risk and efficiency of mitigative measures in the further project work.

4. ASSESSMENT OF COMBUSTION RISK

Within AMHYCO WP4, combustion events are not analyzed, i.e. the combustion risk is evaluated in terms of the evolution of a flammable cloud and its potential to undergo flame acceleration in case of a combustion process. The flammability limits of H_2 derived by Martín-Valdepeñas et al. [12], using the data of Stamps and Bearman [13], are employed based on WP1 review [4].

$$x_{H2}^{LFL} \geq 0.037 + 0.011 x_{H2O} - 4.16 \cdot 10^{-5}(T - 373) \tag{1}$$

$$x_{H2}^{UFL} \leq 0.772 - 1.087 x_{H2O} - 2.71 \cdot 10^{-4}(T - 373) \tag{2}$$

$$x_{Inert} \leq 0.63 + 3 \cdot 10^{-4}(T - 373) \tag{3}$$

Here, *x* denotes molar fractions, and *T* is the gas temperature in Kelvin. The lower flammability limit (LFL) considers upward flame propagation conditions for the sake of conservativeness.

While the combustion of hydrogen in an air-steam mixture is well understood, the additional released of carbon monoxide due to the molten corium-concrete interaction introduces additional challenges to assess the flammability of the containment atmosphere. The usually employed conservative approach is to replace the carbon monoxide by a comparable amount of hydrogen, mostly on a molar base, and continue to employ the flammability limits of hydrogen. This approach is also used in the remaining part of this paper. However, to avoid this simplification, within AMHYCO WP3, refined criteria are 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.

Based on the performed numerical simulations (compare Chapter 3), the evolution of the mixture flammability in the containment dome is evaluated in a ternary diagram in Figure 6. The involved codes provide relatively comparable trajectories in the ternary diagram. As steam is an inerting / diluting gas species, it is usually expected that the codes predicting the highest containment pressurization (see Figure 4) usually also yield the lowest flammability.

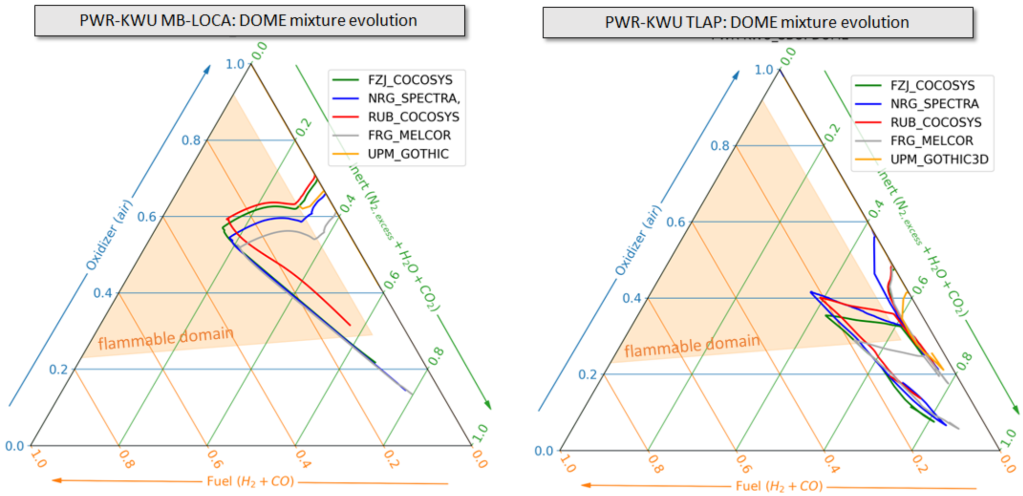

Figure 5. Shapiro-Diagram of the containment dome

To provide a more quantitative insight to the transient behavior of the flammable cloud, the flammable volume and flammable H_2 mass are integrated over all control volumes, and their transient evolution is compared in Figure 6. While the different codes 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 region) becomes steam inerted again, while smaller compartments close to the release remain inerted. These heterogeneities motivate a closer look with 3D and CFD models.

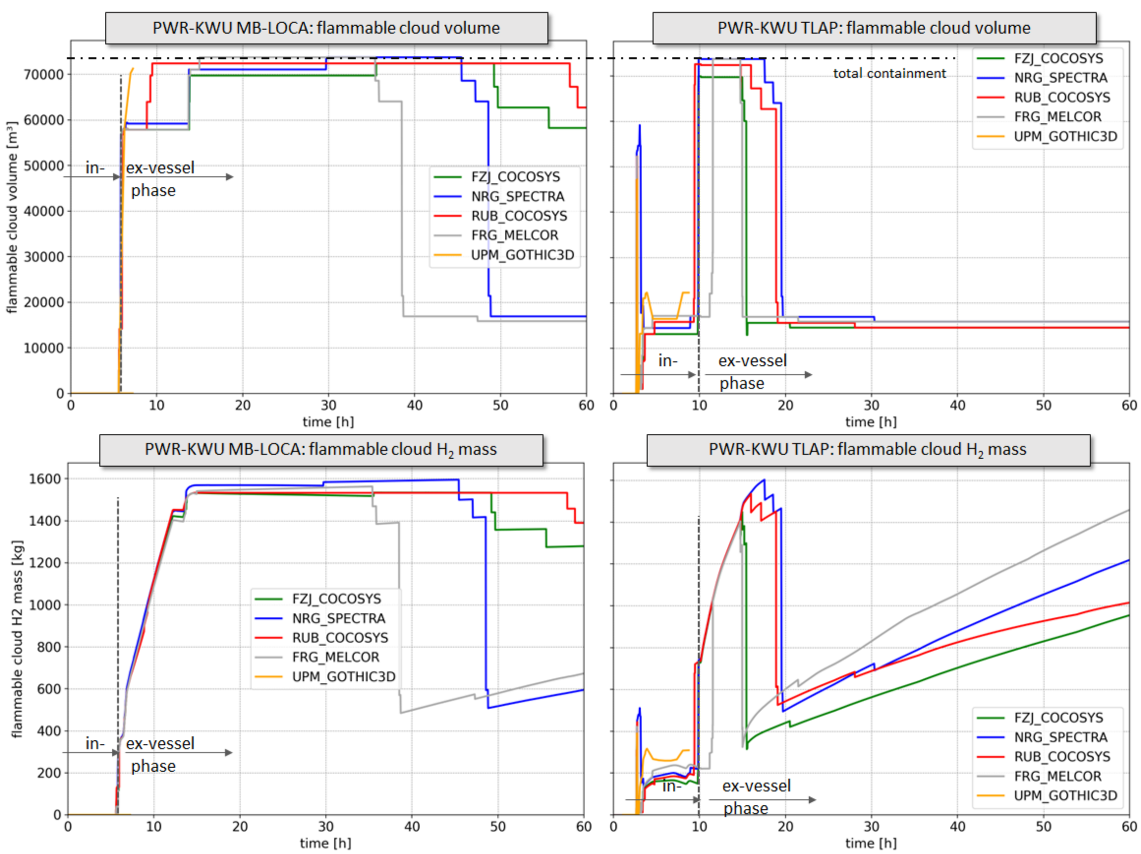

Figure 6. Evolution of the flammable cloud volume and H_2 mass for the PWR-KWU sequences

The simulations consistently show, that without any hydrogen mitigation measures, the containment atmosphere always has pockets where an ignition and flame propagation could occur. Further, the mass of combustible hydrogen increases with time due to the ongoing MCCI, see Figure 6 bottom. This emphasizes the need for combustible gas control hardware to protect the containment integrity.

In conclusion, the verification of the nodalization transfer and analyses of the unmitigated reference cases confirmed the general comparability of the input decks and simulation results, but also highlighted visible differences in the combustion risk in terms of mixture flammability. These findings need to be considered for the on-going assessment of the effect of different mitigative measures and be substantiated by 3D and CFD models. Consequently, to enable a common conclusion based on different code results, the approach considered is to involve the reference cases and evaluate a relative impact of the mitigative action instead of comparing absolute values.

5. LESSONS LEARNED AND FUTURE WORK

Even though the methodology was developed based on the experiences of the SARNET-II and SAMHYCO-NET generic containment benchmark [8], and the results discussed before already indicate a general comparability, several hurdles were encountered within the AMHYCO project up to now.

The generic containment definitions are based on a unique approach starting from a 3D CAD geometry. Nevertheless, the conversion of this database into input decks for different codes architectures (with different input requirements) caused ambiguities. Furthermore, the definition of the gas mass sources injected into the containment introduces additional uncertainties - as example the specification of an injection table in terms of mass flow rate and temperature or enthalpy does not necessarily yield the same simulation result. Only a systematic assessment and comparative evaluation of a comparably simple scenario helped to identify and clarify these issues.

Additionally, not all codes have the same capabilities to model plant -specific details, such as the sump water ingress to the cavity, require a dedicated implementation in different codes. One such example is the sump water ingress to the cavity in PWR-KWU after erosion of the Biological Shield by the core melt. Such an event requires a dedicated implementation in different codes. Another example is the representation of the core melt in a decoupled containment model, i.e. a heat source towards the atmosphere in case of dry conditions and towards the submerging water in case the melt is flooded. This is possible by a heated surface or by a volumetric energy source, each implementation possibility showing certain advantages and disadvantages. Finally, a common understanding of the material properties, especially of the concrete structures, was needed between the AMHYCO partners to obtain comparable simulation results.

These challenges required several iterations and incremental adaptions of both specification and input decks to reach the presented agreement of the containment simulations. This achievement now paves the way for a detailed and systematic assessment of the effectiveness or impact of mitigative measures like PAR, fan coolers, sprays, and filtered containment venting systems on the challenge of the flammability of the containment atmosphere.

The comparative evaluation of LP, 3D, and CFD models is expected to provide an insight into the control room view on the containment conditions based on the SA instrumentation and the full phenomenology and thus allow to review and extend the existing SAMGs and EOPs. Major advance in the Stare-of-the-Art is expected to result from the use of an extended PAR correlation that captures the effects of oxygen starvation and CO poisoning in the late phase as well as the application of new criteria for the H_2/CO combustion risk.

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REFERENCES

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

[2] G. Jiménez *et al.*, "AMHYCO Project – Towards and Enhanced Accident Management of the H2/CO Combustion Risk," in *Proc. 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, 2022.

[3] L. E. Herranz and J. Fontanet, "Identification and analysis of accident sequences with posing high H2/CO combustion risk," AMHYCO, Deliverable D2.2, May 2023.

[4] A. Bentaib, "Critical assessment of key elements of combustible gases management in containment," AMHYCO, Deliverable D1.1, Jan. 2022.

[5] A. Desclaux, G. Nyrenstedt, M. Idir, N. Chaumeix, A. Bleyer, and A. Bentaib, "Turbulent flame speed of H2-CO-Air mixtures for conditions relevant to late phase accident scenario," in *Proc. 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, 2022.

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

[7] M. Müer, J. Hoffrichter, C. Bratfisch, and M. K. Koch, "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," in *Proc. 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety (NUTHOS-13)*, 2022.

[8] S. Kelm *et al.*, "Generic Containment: Detailed comparison of containment simulations performed on plant scale," *Ann. Nucl. Energy*, **vol. 74**, pp. 165–172, Dec. 2014, doi: 10.1016/j.anucene.2014.07.006.

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

[10] L. Serra *et al.*, "Development of a detailed 3D CAD model of a generic PWR-KWU containment as a basis for a better assessment of H2/CO combustion risk," in *Proc. European Nuclear Young Generation Forum (ENYGF'21), Tarragona, Spain*, 2021.

[11] The European Union Per Regulation 305/2011, "Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design." Dec. 2004.

[12] J. M. Martín-Valdepeñas, M. A. Jiménez, F. Martín-Fuertes, and J. A. Fernández, "Improvements in a CFD code for analysis of hydrogen behaviour within containments," *Nucl. Eng. Des.*, **vol. 237**, no. 6, pp. 627–647, Mar. 2007, doi: 10.1016/j.nucengdes.2006.09.002.

[13] D. W. Stamps and M. Berman, "High-Temperature Hydrogen Combustion in Reactor Safety Applications," *Nucl. Sci. Eng.*, vol. 109, no. 1, pp. 39–48, Sep. 1991, doi: 10.13182/NSE91-A23843.