AMHYCO PROJECT – ADVANCES IN H_2/CO COMBUSTION, RECOMBINATION AND CONTAINMENT MODELLING

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ABSTRACT

During a severe accident in a nuclear power plant, one of the potential threats to the containment is the occurrence of energetic combustion events. In modern plants, Severe Accident Management Guidelines (SAMG) as well as dedicated mitigation hardware are in place to minimize/mitigate this combustion risk and, thus, avoid the release of radioactive material into the environment. Advancements in SAMGs are in the focus of AMHYCO, an EU-funded Horizon 2020 project officially launched on October 1st, 2020. The project consortium consists of 12 organizations (from six European countries and one from Canada) and is coordinated by the Universidad Politécnica de Madrid (UPM). The progress made in the first two years of the AMHYCO project is here presented. A comprehensive bibliographic review has been conducted, providing a common foundation to build the knowledge gained during the project. After an extensive set of accident transients simulated both for phases occurring inside and outside the reactor pressure vessel, a set of challenging sequences from the combustion risk perspective for different power plant types were identified. At the same time, three generic containment models for the three considered reactor designs have been created to provide the full containment analysis simulations with lumped parameter models, 3-dimensional containment codes and CFD codes. In order to further consolidate the model base, combustion experiments and performance tests on passive auto-catalytic recombiners under explosion prone H2/CO atmospheres were performed at CNRS (France) and FZJ (Germany). Finally, it is worth saying that the experimental data and engineering models generated from the AMHYCO project are useful for other industries outside the nuclear one**.**

1.0 INTRODUCTION

Combustible gases generated during a severe accident are among the most serious threats to the containment integrity. An appropriate management of the associated risk is paramount to prevent the potential release of significant amounts of radioactive material to the environment. Since the Fukushima accident in Japan in 2011, various additional measures to reduce the risk of containment failure have been undertaken by nuclear power plants (NPPs) within the European Union. These measures include also dedicated severe accident mitigation hardware like Passive Autocatalytic

Recombiners (PARs) and a Filtered Containment Venting System (FCVS), if not already installed previously. To this end, several projects have been recently conducted under the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) framework to address remaining gaps regarding hydrogen distribution, combustion and efficiency of PARs to prevent combustion. On the other hand, the Severe Accident Management Guidelines (SAMGs), which guide the reactor operators on how to handle the response of the nuclear power plant against severe accidents, need to be regularly updated and include knowledge gained from international research, including recent and ongoing projects.

The main objective of the AMHYCO project is to propose innovative enhancements in the way combustible gases are managed in case of a severe accident in currently operating reactors. AMHYCO will contribute to this objective by improving the understanding of H_2/CO combustion risk and incorporating this knowledge into SAMGs To reach this main objective, the project proposes a methodology that is organized in five different work packages (WPs). In the next section, the AMHYCO technical WPs will be briefly described, including outcomes obtained the first two years of the project.

2.0 AMHYCO ADVANCES

2.1 WP1: Critical review

In order to identify lack of knowledge gaps related to hydrogen and carbon monoxide recombination and combustion, the first step of the AMHYCO project was to review the status of existing methodologies and practices related to gas combustion risk management in the late phase of severe accidents. To this end, four tasks were achieved, and the main outcomes are presented in the following subsections.

2.1.1 Task 1: Overview on PAR Behaviour in Severe Accident Late Phases Conditions

The literature review showed that despite the extensive research performed in the last decades, additional experimental and theoretical investigations are needed to fill the knowledge gaps regarding the PARs behaviour in representative conditions of late phase of the severe accidents. This statement helped defining experimental performed in the framework of the AMHYCO/WP3 to address this lack of knowledge. As a conclusion of this review, several gaps of knowledge were identified regarding H2/CO/steam mixtures.

2.1.2 Task 2: Review of the Existing PWR SAMGs regarding Containment Risk Management

The performed survey identified the following:

- the adopted requirements address only in-vessel conditions; their extension to ex-vessel conditions needs to be established for the containment and the auxiliary buildings connected to the containment;
- all the adopted requirements aim to preserve the containment integrity; the availability of the safety systems, such as sprays or venting line, needed for severe accident late phases, need to be addressed in extended requirements;
- only few countries adopt quantitative criteria for the requirement;
- the mitigation means are designed for in-vessel conditions;
- only few existing SAMGs instructions about the use of safety systems (CHRS, sprays and coolers) in severe accident late phases;
- the existing monitoring systems do not measure carbon monoxide content separately.

2.1.3 Task 3: Review of the existing H_2/CO combustion risk engineering correlations

The literature review showed that the H_2/CO combustion in representative conditions of severe accident late phases is poorly investigated. Only few data are available in the open literature. Based on this statement, experimental program was suggested to AMHYCO/ WP3 (see Section 2.3).

2.1.4 Task 4: Review of the Containment Equipment Qualification Criteria and Instrumentation Surveillance under Severe Accident Conditions

This task aimed to provide a review of different approaches and main principles of the qualification of safety-related equipment and instrumentation under conditions of Design Basis Accident (DBA) and Severe Accident (SA). The objective of task was to give sufficient insight in the fields of DBA Equipment Qualification (EQ) and SA survivability assessment, and to provide parameters, namely stressors as temperature and pressure. The EQ values have been extracted from different studies performed in various PWR NPPs worldwide.

This review will serve as a reference technical document for WP4, where equipment and instrumentation surveillance under SA scenarios will be compared with the data gathered in this task, and WP5, where proposals for SAMG long-term operation improvements and guidelines for equipment and instrumentation survivability assessment will be given, considering typical containment qualification requirements as the ones described herein.

2.2 WP2: Characterization of sequences with high relevant combustion risk

The identification and characterization of high relevant combustion risk sequences has proceeded in steps along the first two years of the AMHYCO project: setting figures of merit, building a sequences matrix, and achieving sequence characterization through code simulations. As an outcome, a scenario database has been developed on which experimental investigation on recombination and combustion of H_2-CO mixtures are being planned and different analytical approaches (3D vs. LP codes; LP standing for Lumped Parameter) are started to be tested.

The selection criteria to choose safety-relevant combustion scenarios were: high molar fractions of combustible gases (H_2 + CO) within flammability limits (the Shapiro diagram [1] serving as a monitor), large amounts of combustible gases, and fast in-containment release rates of H_2 or H_2+CO. Besides, some qualitative analysis was needed with a broader assessment of the entire scenario. Among the variables considered for a comprehensive description of the scenarios were: gas molar fractions, gas injection/generation rates, enthalpy and temperature associated to the incoming gases, and some others related to the compartment boundary conditions and safety systems performance. A comprehensive list was given in [2].

Accident sequences with the potential to evolve in challenging combustion conditions were pooled for different PWR designs: PWR-W (different reactor sizes and variants included), PWR-VVER and PWR-KWU. Fig. 1 displays the complete matrix of sequences simulated. It should be mentioned that the thresholds set to consider a gas mixture flammable (embedded in the Shapiro diagram) have been:

- $X_{H2} + X_{CO} > 9$ vol.%
- $X_{O2} > 5$ vol.%
- $X_{H2O} < 55$ vol.%

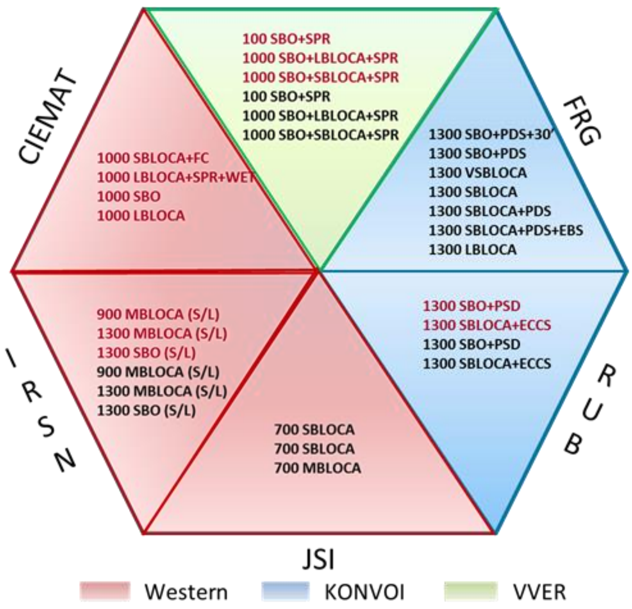


Figure 1. PWR accident sequences modelled.

As a sample of the type of results reported, those specific of the Westinghouse 1000 MWe designs are shown in Fig. 2. Two sequence were simulated: LOCA and SBO. Different pipe breach sizes and accident management actions (fan coolers, FC; sprays, cavity flooding) were considered: 2-inch SBLOCA (fan coolers on); 2-inch SBLOCA (sprays on and cavity flooding implemented); double-ended guillotine LBLOCA (both sprays and fan coolers on); SBO.

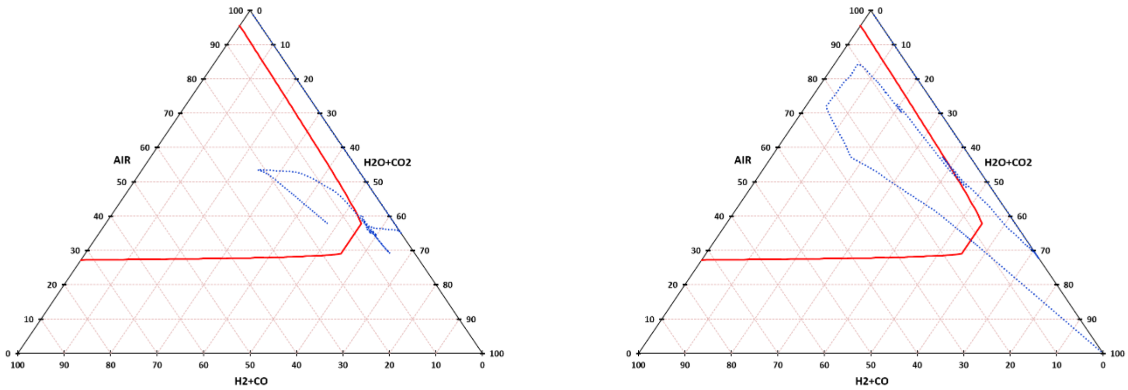


Figure 2. Shapiro diagram of PWR-W-1000 simulations (Left: SBLOCA with FC; Right: LBLOCA)

In all those sequences with systems capable of condensing steam, a higher fraction of combustible gases has been observed. As a consequence, the two sequences which represent the highest risk associated with combustible gases are the SBLOCA with fan coolers and the LBLOCA. Fig. 2 shows the Shapiro diagrams of both of them, where a deeper penetration is noted within the flammability region in the case of LBLOCA.

Both sequences lead to a high steam concentration at the beginning of the accident due to the flashing of the water loss from the RCS (LBLOCA) or to the release of steam directly through the circuit breach (SBLOCA). The sprays operation in the LBLOCA triggers a fast and large drop of steam content. Even though, for a short time the H_2 molar fraction reaches combustion limits set (9%) at the end of the in-vessel phase, it is in the ex-vessel one where further release of H_2 and CO from the Core Concrete Interaction (CCI) together with the efficient condensation of steam, make combustible gas mixture attain concentration over 25% at around 20000 s. The loss of efficiency in condensation due to recirculation mode operation of sprays and the generation of CO_2 results in a progressive dilution of such high combustible gas concentration in the long run of the sequence, but still standing over the combustion limits. For the SBLOCA sequence, the combustible gas mixture does not exceed the combustion threshold till CO is produced in the ex-vessel phase, which together with the effect of FC on steam content, make it grow to higher than 20% at about 30000 s and stay at roughly that high concentration till CO_2 is released in massive amounts to reach higher than 20% of the total gas composition.

In summary, from the twenty-five PWR SA sequences simulated the main outcomes can be summarized as follows:

- The SA sequences that posed a higher risk of gas combustion (H_2 and CO) have been found to be SBLOCA and LBLOCA, for PWR-W, MBLOCA (80 cm^2) for PWR-KWU and SBO with sprays for PWR-VVER.
- A key factor heavily conditioning sequence selection is the availability of safety systems capable of condensing steam during the ex-vessel phase since they result in a boost of combustible gas content.
- Whenever PARs are modelled, O_2 starvation in the ex-vessel phase makes gas composition exit the flammable region of the Shapiro diagram, even if combustible gas content is well over 9 vol.%.

2.3 WP3: Experimental investigations

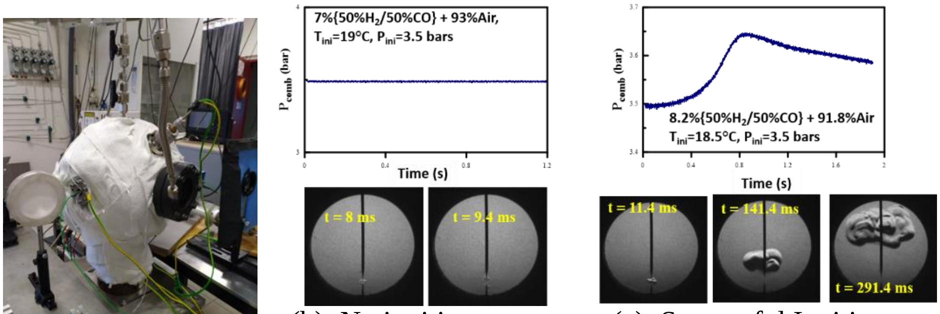
The experimental research in AMHYCO aims at obtaining knowledge and data needed for the development and validation of numerical models and simulation tools in the fields of combustion of $H_2/H_2O/CO$ mixtures in air as well as explosion risk mitigation by means of passive auto-catalytic recombiners (PARs). Following the conclusions of the review performed by WP1 and the scenarios selected by WP2, the experimental program includes separate effects, coupled effects and integral effect tests, which allow a comprehensive validation of models implemented in relevant safety tools. Based on the experimental results, numerical simulations are performed to support the development of engineering correlations to be used in safety assessment tools in WP4.

The experimental program is conducted in two laboratories: Investigations on the H_2/H_2O and $H_2/CO/H_2O$ combustion under different conditions are performed at CNRS/ICARE in Orléans/France, while the operational behavior of PARs under conditions of the ex-vessel phase of a severe accident is investigated at FZJ in Juelich/Germany.

2.3.1 Combustion

The focus of the experimental program in Task 3.1 is on H_2/H_2O and $H_2/CO/H_2O$ combustion under different conditions, considering also the interaction with the operation of containment spray and the filtered containment venting system. In the present paper, the results on H2/CO combustion will be presented on: (i) flammability limits of a 50%H2/50%CO (molar based) at different initial pressures, (ii) combustion regimes for different initial conditions in terms of %Fuel (50%H_2+50%CO) in air. To do so, 2 different facilities were used, BS-I, a spherical vessel (250 mm i.d., see Fig. 3-a) equipped with a central ignition and ENACCEF-II (vertical tube, 230 mm i.d. and 7.65 m high). Both facilities are coupled to different diagnostics including high speed imaging (Schlieren optical layout and high-speed cameras (Vision research V16), high frequency pressure transducers (Kistler and PCB), shock detectors (ChimieMétal), photomultiplier tubes with UG filters centered at 307 nm (OH^* detection).

For the flammability limits, 3 different initial pressures were investigated: 1, 2 and 3.5 bar. The distance between the electrodes were fixed to 3 mm. The synchronized recording of the ignition by the high-speed imaging and the temporal profile of the pressure signal allows to be able to use both the pressure and the visual criteria. The results presented in this paper will be based on the visual criterion. The composition of the mixture is fixed, then the spark is created between 2 tungsten electrodes. The energy provided for each test is measured via a high voltage probe and a high frequency current probe placed at the electrodes ends protruding outside of the vessel. The measured energy used is 265 ± 50 mJ. Following the spark initiation, the identification of a flammable mixture is based on the recording of a successful flame propagation (Fig. 3b&c).



(a) (b): No ignition case (c): Successful Ignition

Figure 3. Experimental facility (BS-I) for the flammability limits study (a); examples of pressure signals and flame snapshots recorded for different runs in case of no ignition (b) and successful ignition (c).

If following the spark ignition, no sustainable flame is observed after the initial flame kernel formation, then the mixture would be identified as non-flammable. Usually, more than 100 tests are performed. The flammability limit is derived from the probability of ignition using the likelihood probability. In case of a successful ignition, the probability is given the value 1, otherwise, it will be given the value 0. The determination of the flammability limit will be based on the plot of the probability of ignition versus the molar fraction of the fuel in air (Fig. 4). As one can see depending on the value of the probability of ignition adopted to define the flammability limits, different values are derived (summarized in Table 1). The errors derived from the 95% of confidence interval are reported as well. At 1bar, the lower flammability limit (LFL) was found to be 6.3±0.4 for a probability of ignition of 0.01 and increases to 7.4±0.1 when the probability of ignition is 0.5.

These values are higher than the one determined by Kilchyk [3] but in good agreement with the recent study of Shang et al. [4] who determined a LFL of 6.5%. For the upper flammability limit (UFL), at 1 bar, at a probability of ignition of 0.01, the experimental value is 72.4±0.6 and decreases to 70.6±0.2 for a probability of ignition of 0.5. These values are in agreement with our previous work [5] and the literature [6].

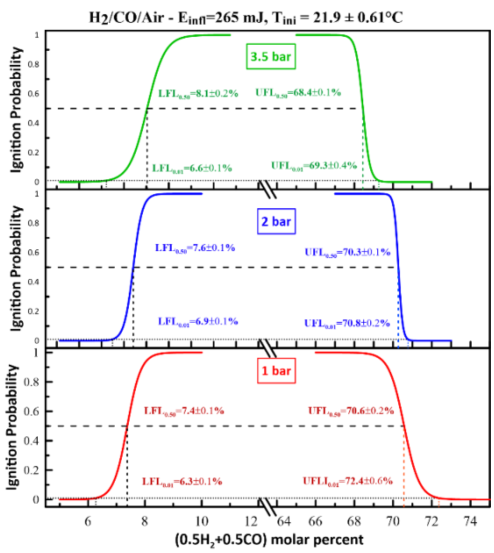


Figure 4. Probability of ignition versus the fuel/air molar percent. The binary fuel is constituted of

50 %H_2+ 50%CO. The initial temperature is 22°C and the ignition energy is 265 mJ.

As the initial pressure is increased from 1 to 2 and 3.5 bar, the flammability domain is reduced. This effect is visible at 3.5 bar at which the LFL is increased while the UFL is decreased. Jaimes et al. [7] measured the LFL for different H2/CO ratios and at different initial pressure. Their values are in a good agreement with our data.

Table 1. Experimental Flammability at different initial pressures for a binary mixture {50%H_2+50%CO) initially at 22°C.

P_{ini} (bar)	1	2	3.5
LFL at P(ignition) =0.01	6.3±0.4	6.9±0.3	6.6±0.5
LFL at P(ignition) =0.5	7.4±0.1	7.6±0.1	8.1±0.2
UFL at P(ignition) =0.01	72.4±0.6	70.8±0.2	69.3±0.4
UFL at P(ignition) =0.5	70.6±0.2	70.3±0.1	68.4±0.1

Experiments have been performed in ENACCEF-II for the study of the combustion regimes of {50%H_2+50%CO}. For this study, the tube was equipped with 9 annular obstacles with a blockage ratio of 0.63. They were installed in the lower part of the tube and evenly spaced by one diameter. The flame trajectory was derived from the 27 photomultiplier tubes installed along the tube, the pressure build-up as the flame propagates in the facility is monitored via 11 pressure transducers (2 PCB and 9 Kistler). The experiments were performed for different binary fuel content in air, namely 11, 13 and 15%. The initial pressure was varied from 1 to 3 bar. Table 2 summarizes the experimental observations: the maximum flame speed observed with the maximum pressure. The theoretical maximum pressure for an isochoric adiabatic complete combustion, P_{AICC}, the speed of sound in the fresh gases, a_{GF}, and burned gases, a_{BG}, have been estimated. If, following the literature [8, 9, 10] the combustion is defined as "fast" when the ratio maximum flame speed over the speed of sound in the burnt gases is larger than 0.5, then this regime is observed only for the mixture containing 7.5%H_2+7.5%CO in air. However, as one can see in table 2, for mixtures containing 6.5%H2 + 6.5%CO in air, although the ratio is below 0.5, the maximum pressure recorded in the facility is higher than the P_{AICC} indicating that the compressibility effects are important and shocks are formed leading to higher pressures.

Table 2. Summary of ENACCEF-II results for a binary mixture {50%H_2+50%CO) initially at 22°C. a_{FG}: speed of sound of the fresh gases, a_{BG}: speed of sound of the burnt gases.

Pini (bar)	H_2 (mol %)	CO (mol %)	$P_{exp,max}$ (bar)	$V_{flame,max}$ (m/s)	$\frac{P_{exp,max}}{P_{AICC}}$	a_{FG}	a_{BG}	V_{max}/a_{BG}
1	5.50±0.04	5.50±0.04	2.44±0.08	76±26	0.50±0.01	356.33±0.06	676.55±1.48	0.11±0.04
	6.16±0.01	6.15±0.03	4.36±0.17	230±9	0.83±0.03	357.54±0.02	702.00±0.74	0.33±0.01
	6.30±0.03	6.34±0.03	7.09±0.74	295±6	1.33±0.14	357.81±0.05	708.31±0.92	0.42±0.01
	7.25±0.04	7.25±0.08	11.96±0.51	480±26	2.06±0.09	359.57±0.07	741.63±2.01	0.65±0.03
2	5.46±0.08	5.45±0.10	5.00±0.09	72±23	0.53±0.01	356.26±0.14	674.74±3.41	0.11±0.03
	6.45±0.03	6.43±0.04	11.36±2.10	268±6.8	1.08±0.20	358.08±0.05	712.69±1.11	0.38±0.01
	7.35±0.03	7.30±0.05	20.83±1.61	482±10	1.84±0.14	359.74±0.06	744.19±1.34	0.65±0.01
3	5.41±0.07	5.41±0.12	7.84±0.14	71±7.5	0.55±0.02	356.17±0.12	673.01±3.76	0.11±0.01
	6.38±0.06	6.35±0.03	12.59±1.65	300±42	0.81±0.11	357.95±0.10	709.98±1.52	0.42±0.06
	7.21±0.09	7.25±0.15	29.21±0.54	485±19	1.72±0.03	359.49±0.17	740.72±3.78	0.65±0.02

2.3.2 Recombination

PARs are the key feature of the strategy for mitigating the hydrogen risk in many European nuclear power plants. The operational behaviour of PARs has been studied in various national and international projects in the past, starting with early test programs conducted primarily by manufacturers, such as Siemens/Germany and AECL/Canada [11]. The objective of this subtask is to provide suitable numerical PAR models which have been validated against both existing experimental data from other programs and new targeted experiments performed in the framework of AMHYCO.

PARs are supposed to continuously recombine hydrogen and oxygen once hydrogen is released into the containment. For the boundary conditions of the so-called in-vessel phase, i.e. mixtures of hydrogen, air and steam in an oxygen-rich atmosphere, numerical PAR models have proven to provide reliable results that can be confidently applied in the context of accident analyses. However, less is known about the performance of PARs in the presence of carbon monoxide. Former experimental programs have demonstrated that carbon monoxide could be converted to carbon dioxide in a heterogeneous catalytic process similar to the recombination of hydrogen. However, under certain conditions, CO has been demonstrated at different labs [12,13] to act as a catalyst poison with the potential of completely deactivating the catalyst. The boundary conditions for these different phenomena affecting the PAR performance are not yet clear.

The experimental program of sub-task allows further advancement and validation of numerical models simulating PAR operation as a function of the atmospheric boundary conditions. These models are:

- Framatome correlation, an empirical equation implemented in most of the relevant codes used for accident simulations [14]
- PARUPM (UPM), a mechanistic model involving detailed surface chemistry [15]
- REKO-DIREKT (FZJ), a mechanistic model based on a mass transfer approach [16]
- SPARK (IRSN), a 3D model involving full surface and gas phase chemistry as well as multi-species CFD [17]

The experimental setup includes three facilities located at FZJ (Fig. 5): REKO-1 to perform scoping tests with small catalyst sheets to identify the relevant process parameters, REKO-3 to obtain experimental data in full catalyst scale providing data for project partners' model validation, and REKO-4 to investigate the effect of pressure on PAR operation. Furthermore, experimental results of the OECD/NEA THAI and THEMIS projects were analysed to broaden the database.

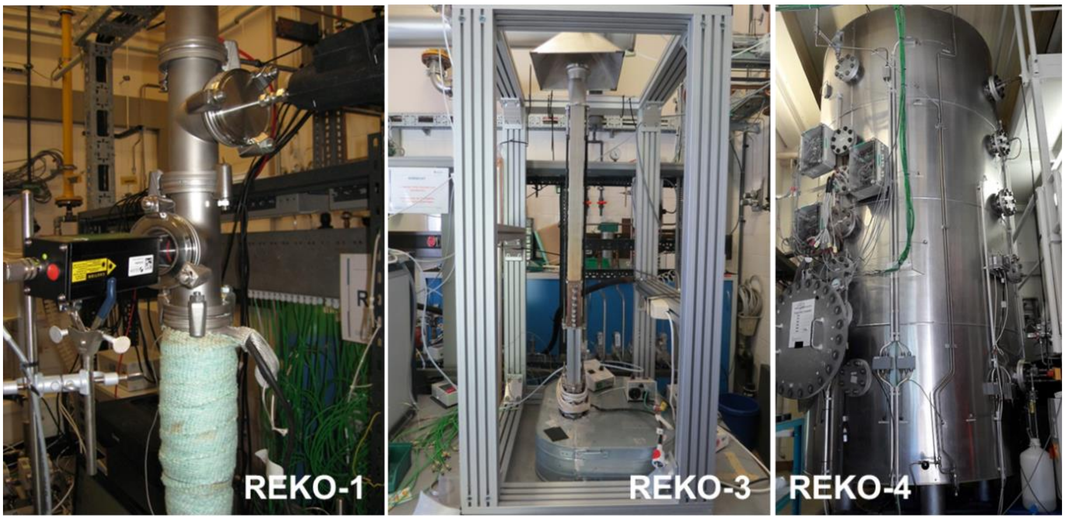


Figure 5. REKO facilities: Flow tube reactors for steady-state well-defined boundary conditions (REKO-1, REKO-3) and a pressure vessel for pressurized tests (REKO-4)

For the recombination experiments, the analysis of the accident scenarios (as performed in WP 2) led to the test matrix being focused on oxygen-lean atmospheres. Gas temperatures were predicted to range between 70 and 150 °C while pressures were estimated to range between 1.2 and 3.7 bar (It has to be mentioned that pressures above 2 bar cannot be realized in the present set-up). Furthermore, H_2/CO ratios between 1 and 3 need to be considered.

The scoping tests performed in REKO-1 revealed that catalyst poisoning effects are to be expected for oxygen-lean conditions. Pd-based catalysts are less susceptible to the influence of carbon monoxide. However, the effect depends significantly on the temperature, while Pt-based catalysts were showing deactivations independently from the temperature. The REKO-3 experiments have detailed these findings and have provided measurements of the temperature profile on the catalyst surface as well as recombination rates of both hydrogen and carbon monoxide at full catalyst scale.

Figure 6 shows two examples of the model improvements and validations that were achieved with the experimental data. The PARUPM code has significantly improved the prediction of recombination rates by adding a diffusion-based reaction model to the surface chemistry approach [15]. The graph on the left shows the comparison with experimental data before and after model enhancement. The capability to predict catalyst poisoning of the SPARK code has been advanced as shown on the right side [18]. The graph on the right shows predicted catalyst temperatures for different oxygen concentrations. Poisoning is predicted only 0.2 vol.% earlier than observed in the experiment. In a similar way, data has been used to advance REKO-DIREKT. Also the Framatome correlation model which is widely used in containment codes has been significantly improved to cope especially with oxygen-starvation conditions. For this purpose, a specific database has been developed from large scale transient experiments performed in the framework of the OECD/NEA THAI projects.

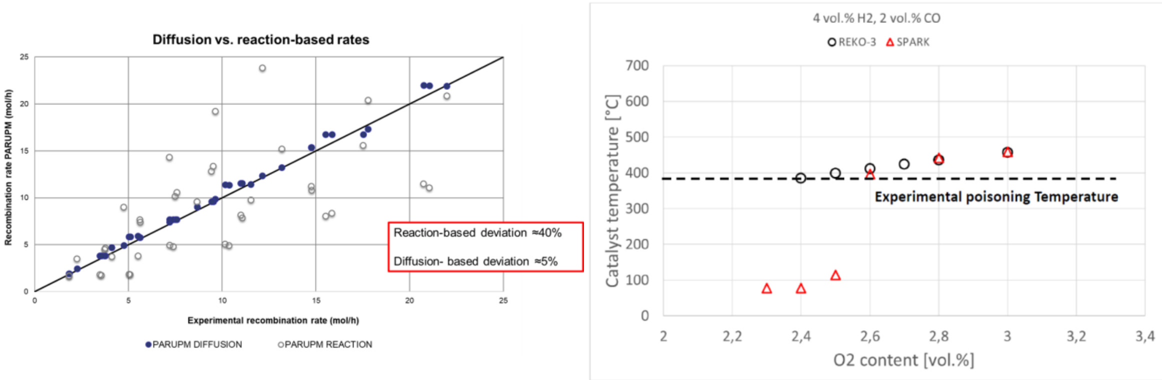


Figure 6. Examples for successful code enhancement in the framework of WP3.

Overall, the experimental program has successfully supported the further development of the computational PAR models and contributed to the availability of well-validated codes for the accident simulations in the following AMHYCO activities.

2.4 WP4: Full containment analysis

Main objective of WP4 is to employ the results obtained in WPs 1-3, to define and conduct a comprehensive analytical assessment and finally provide the insights for a review and potential extension of the SAMGs and EOPs within WP4. Following the approach of WP2, analysis is conducted for the European PWR concepts, W(estern), KWU and VVER. However, while WP2 used the available plant specific models and nodalisation schemes, in WP4 generic containments and partly scaled input tables (from WP2) are employed to prepare a common open basis of the analysis, enable a certain comparability of the simulation results as well as pave the way for obtaining generic, i.e., non-plant-specific conclusions. In a nutshell, the integration of WP4 activities in the AMHYCO project is depicted in Fig. 7.

Full containment analyses are conducted in a consecutive analysis chain, consisting of three levels of increasing detail: As a basis, the identified sequences are simulated completely with lumped parameter containment models e.g., built in ASTEC or MELCOR. On this basis, the most penalizing cases will be additionally investigated by 3D models developed in GOTHIC to address potential asymmetric / 3D conditions that may lead to higher combustion risk. As a last step, relevant compartments and/or time frames identified in the 3D analysis will be simulated in detailed CFD-grade local containment studies (e.g., using containmentFOAM or ANSYS Fluent) to substantiate GOTHIC analysis and answer remaining open issues.

The increasing level of spatial details achieved with the different codes will also be utilized to assess the view on the accident from the control room (available sensors) against the full insights provided by the simulations to propose an upgrade of the SA instrumentation.

Experimental insights achieved in WP3 on combustion risk (in terms of flammability and flame propagation characteristics) as well as PAR performance under late phase conditions was transferred into engineering correlations and criteria, which can easily be implemented in the utilized codes. Within WP4 analytical work, they will be -as far as possible- compared against the State-of-the-Art summarized in WP1 to close knowledge gaps or substantiate the understanding of combustion risk, efficiency of mitigation measures and equipment survivability in the ex-vessel phase. Concluding the lessons-learned during the analysis are summarized to pave the way for subsequent work in the future.

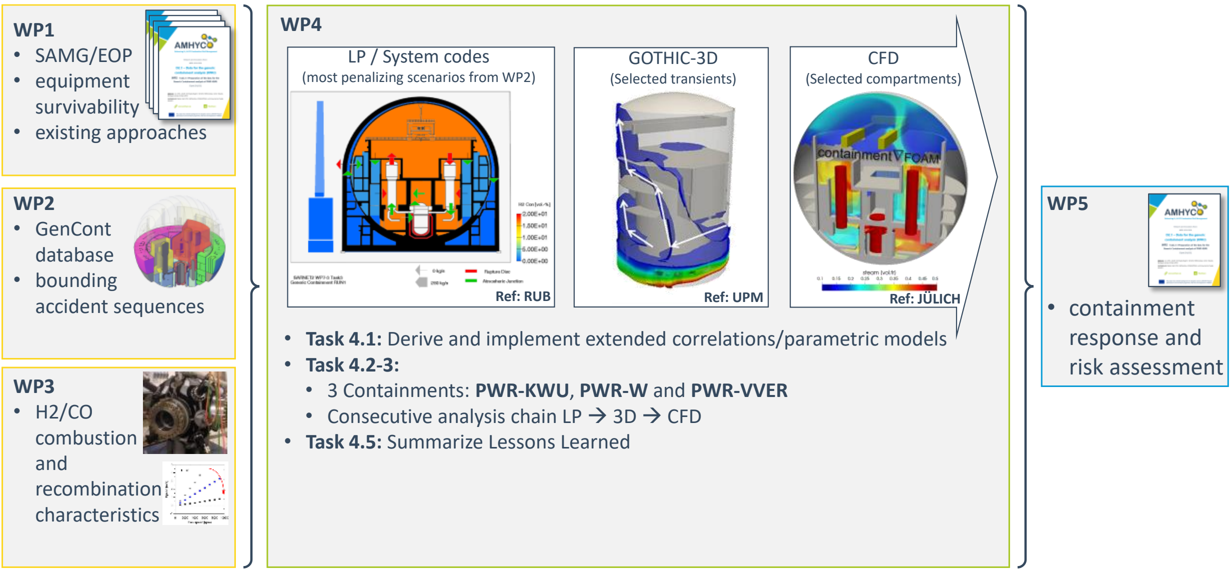


Figure 7. Integration of WP4 activities in AMHYCO

Within WP2 most penalizing accident sequences with respect to the combustion risk have been identified for the European PWR concepts. For WP4, two characteristic sequences have been selected for a detailed assessment: Unmitigated Small (S) or Medium (M) Break Loss of Coolant Accidents (LOCA) lead to a potentially flammable atmosphere in the containment and allow for studying the impact and efficiency of PARs, spray systems and fan coolers. Station Blackout (SBO) / Total loss of auxiliary power (TLAP) accidents revealed to be steam inertized throughout the transient but reach a high containment pressure up to the design limits. Thus, they enable investigating PAR efficiency at high pressure conditions, studying the effect of conducting FCVS on the combustion risk and assessing a potential recovery of emergency cooling systems in the late accident phase. A simulation matrix has been defined to systematically investigate the containment response with system codes, identify potentially challenging conditions and provide input to the subsequent analysis using 3D approaches.

2.5 WP5: Enhancement of Combustible Gas Control

The primary objectives of AMHYCO are in line with the goals described in "NFRP-02: Safety assessments for Long Term Operation (LTO) upgrades of Generation II and III reactors" of the EURATOM Work Programme 2019 with respect to the control of combustible gases present in the containment of a nuclear power plant in case of a severe accident with core damage.

When designing a combustible gas control system for a nuclear power plant, the overall system performance cannot be tested on a 1-to-1 scale due to the necessary efforts. Instead, the design and validation of the system relies on small-scale tests and full-scale numerical simulations with lumped parameter codes and CFD codes [19]. These full-scale simulations are used for optimal placement of the PAR inside the containment, and determining suitable locations of the monitoring sensors. Only at these selected monitoring sensors, the main control room can "see" the gas concentration during a real accident. The operators do not have full information about the size and shape of gas clouds within the containment. Therefore, one of the tasks of severe accident mitigation guidelines is to supply a sort of "translation" what the limited measurements available in the main control room actually tells about the real combustible gas distribution within the containment and what is the associated risk. This translation can only be gauged based on reliable containment simulations.

3.0 CONCLUSIONS

After two years of work in the AMHYCO project, several conclusions can be shared. In WP1, after an extensive bibliographic search, several useful recommendations have been arisen for both the analytical and the experimental work of AMHYCO, giving at the same time a solid documental basement for the rest of the project. In WP2, the most penalizing accident sequences with respect to the combustion risk have been identified for the European PWR concepts, being different LOCA sequences the one that posed a higher risk of gas combustion. The experimental work in WP3 is going well beyond the state-of-the-art, both in the combustion side and in the recombination side (PARs). In the combustion experiments, new mixture compositions H_2/CO have been explored, with good agreement with similar work done in other research groups. On the PARs side, the soft and complex mechanism of oxygen starvation and CO poisoning have been investigated successfully, helping to validate further simulation tools such as PARUPM or SPARK.

In WP4, an innovation proposed in AMHYCO is the creation of a methodology based on new correlations to predict the combustion risk that are adapted specifically to the LP, 3D and CFD numerical codes, testing the three approaches within the WP for different safety systems actuation. Finally, the most relevant advance of the AMHYCO project will be the creation of guidelines for the SAMGs considering combustion risk management, which will be done in the second phase of the project.

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REFERENCES

1. Shapiro, Z.M., and Moffette, T.R., Hydrogen Flammability Data and Application to PWR Loss-of-Coolant Accident, Report WAPD-SC-545, Bettis Plant, Pittsburgh, Pennsylvania, USA, September 1957.
2. Herranz, L.E., and Fontanet J., High combustion risk sequences. Identification and characterization, The 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Log Number: 339, Karlsruhe, Germany, May 16-19, 2022.
3. Kilchyk, V., Flammability limits of carbon monoxide and carbon monoxide-hydrogen mixtures in air at elevated temperatures, Department of mechanical and manufacturing engineering, University of Calgary, Calgary, Alberta, November 2000.
4. Shang, R., Li, G., Wang, Z. and Wang, Z., Lower flammability limit of H2/CO/air mixtures with N2 and CO2 dilution at elevated temperatures, *International Journal of Hydrogen Energy*, vol. 45, n° %116, pp. 10164-10175, 2020.
5. Coudoro, K., Etude expérimentale et modélisation de la propagation de flamme en milieu confiné ou semi-confiné, Thèse de Doctorat, Université d'Orléans, Orléans, 2012.

6. Wierzba I. and Kilchyk, V., Flammability limits of hydrogen–carbon monoxide mixtures at moderately elevated temperatures, *International Journal of Hydrogen Energy*, vol. 26, n° %16, pp. 639-643, 2001.
7. Jaimes, D., McDonell, V. and Samuelsen, G., Lean flammability limits of syngas/air mixtures at elevated temperatures and pressures, *Energy & Fuels*, pp. 1 - 33, 03 septembre 2018.
8. Dorofeev, S. B., Kuznetsov, M. S., Alekseev, V. I., Efimenko, A. A., Bezmelnitsun, A. V., Yankin, Y. G. and Breitung, W., Evaluation of limits fir effective flame acceleration in hydrogen mixtures, Report FZKA-6268. Karlsruhe: Forschungszentrum Karlsruhe, preprint IAE-6127/3, 1999.
9. Bentaib, A., Bleyer, A., Meynet, N., Chaumeix, N., Schramm, B., Höhne, M., Kostka, P., Movahed, M., Worapittayaporn, S., Brähler, T., Seok-Kang, H., Povilaitis, M., Kljenak I. and Sathiah, P., SARNET hydrogen deflagration benchmarks: Main outcomes and conclusions, *Annals of Nuclear Energy*, vol. 74, pp. 143-152, 2014.
10. Ciccarelli, G., Chaumeix, N., Mendiburu, A., N'Guessan, K. and Comandini, A., Fast-flame limit for hydrogen/methane-air mixtures, *Proceedings of the Combustion Institute*, vol. 37, n° %13, pp. 3661-3668, 2019.
11. Bachellerie, E., Arnould, F., Auglaire, A., de Boeck, B., Braillard, O., Eckardt, B., Ferroni, F. and Moffett, R., Generic approach for designing and implementing a passive autocatalytic recombiner PAR-system in nuclear power plant containments, *Nuclear Engineering and Design*, 221, No. 1-3, 2003, pp. 151-165.
12. Reinecke, E.-A., Allelein, H.-J., Bentaïb, A., Chakraborty, A., Chaumeix, N., Heidelberg, D., Kelm, S., Klauck, M., Maas, L. and Steffen, P.-M., Operating behavior of passive auto-catalytic recombiners under severe accident conditions, International Severe Accident Management Conference (ISAMC), Ottawa (Ontario), Canada, October 15–18, 2018.
13. Liang, Z., Gardner, L., Clouthier, T., MacCoy, R. and Gyepi-Garbrah, S., Experimental study on H2-CO combustion and recombination in severe accidents, International Severe Accident Management Conference (ISAMC), Ottawa (Ontario), Canada, October 15–18, 2018.
14. Mimouni, S., Mechitoua, N. and Ouraou, M., CFD recombiner modelling and validation on the H2-PAR and Kali-H2 experiments, *Science and Technology of Nuclear Installations*, 2011, 574514, 2011.
15. Domínguez-Bugarín, A., Jiménez, M.-Á., Reinecke, E.-A. and Jiménez, G., PARUPM: A simulation code for passive auto-catalytic recombiners, *EPJ Nuclear Sci. Technol*, 8 32 (2022). DOI: 10.1051/epjn/2022046
16. Reinecke, E.-A., Kelm, S., Steffen, P.-M., Klauck, M. and Allelein, H.-J., Validation and Application of the REKO-DIREKT Code for the Simulation of Passive Autocatalytic Recombiner Operational Behavior, *Nuclear Technology*, 196:2, 355-366, 2016
17. Meynet, N., SPARK - Logiciel de calcul pour les recombineurs catalytiques, IRSN report PSN-RES/SAG/2015-00036, 2015.
18. Nobrega, G., Reinecke, E.-A., Bentaib, A., Maas, L., Chaumeix, N., Experimental investigation on the carbon monoxide effect on platinum- and palladium-based catalysts for passive auto-catalytic recombiners, Proc. 10th European Review Meeting on Severe Accident Research (ERMSAR2022), Karlsruhe, Germany, May 16-19, 2022.
19. Cremer, I., Tap, R. and Hupp, M., Updated Modeling and Simulation of Hydrogen Recombination in Full-scale Containment Analyses, The 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) Log nr.: 35508, Brussels, Belgium, March 6 - 11, 2022.