AMHYCO

Enhancing H_2 & CO Combustion Risk Management

Research and Innovation Action

NFRP-2019-2020

Final Workshop – Key Takeaways from Madrid

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Final Technical Workshop

Workshop Overview

Date: 26-27 February 2025

Location: Madrid, Spain

Attendance: 38 in-person and 59 online

The AMHYCO Open Workshop took place on 26-27 February 2025 at the UPM as the final event of the project, showcasing key experimental results and advancements in hydrogen and carbon monoxide (H2/CO) combustion risk management in nuclear power plants. The event brought together experts from nuclear safety authorities, international organizations (IAEA, OECD/NEA), industry representatives, and academic researchers. Discussions focused on the improved Severe Accident Management Guidelines (SAMGs) and their impact on nuclear safety regulations.

Each Work Package (WP) of the AMHYCO project was presented, covering topics such as experimental investigations on combustion processes, full containment analysis, passive autocatalytic recombiners (PARs), and numerical simulations for explosion hazard evaluation. The workshop also served as a platform to discuss the integration of these findings into existing safety measures for Pressurized Water Reactors (PWRs), including PWR-KWU, PWR-W, and PWR-VVER technologies.

Beyond the technical presentations, the workshop provided opportunities for PhD students and to present their contributions, reinforcing the project's educational and training aspects. Participants also participated in networking sessions, an invited dinner, and a cultural tour in Madrid.

Workshop Agenda and Summary of Lectures

Day 1 – 26/02/2025

The AMHYCO Open Workshop began on 26 February 2025 with registration and a welcome session at the Universidad Politécnica de Madrid (UPM). During this welcome session, Gonzalo Jiménez (UPM) introduced the Workshop structure and objectives, as well as the agenda for both days. Additionally, social events like the invited dinner and the cultural tour in Madrid were presented.

Following this, Ahmed Bentaib (IRSN) presented WP1: Critical Review, offering an in-depth summary of the work performed during the Work Package 1. The in-depth analysis of H2/CO combustion risks and existing mitigation strategies, has emphasized how AMHYCO's research had

filled knowledge gaps and improved predictive modelling. This work package reviewed existing methodologies and practices related to hydrogen and carbon monoxide combustion risk in severe nuclear accidents and covered accident scenarios like Three Mile Island and Fukushima, detailing hydrogen explosion risks and mitigation strategies. It assessed existing safety guidelines, containment equipment qualifications, and instrumentation for monitoring hydrogen risks. Key findings included the impact of oxygen concentration on recombination, the effect of carbon monoxide, and gaps in current safety measures.

After that, Luis Enrique Herranz (CIEMAT) introduced WP2: Selection of Severe Accident Sequences. This work package focused on identifying accident sequences where hydrogen and carbon monoxide combustion pose a risk to containment integrity. It established a combustion-risk database and containment models (LP, 3D & CFD). The package identified key severe accident scenarios, evaluated flammability criteria, and provided inputs for experimental tests and risk assessments. Selection criteria included high hydrogen and carbon monoxide generation, fast injection rates, and containment flammability concerns.

The first day concluded with an invited dinner at Restaurante Panamera, providing an extra space for discussions among researchers, industry professionals, and regulatory representatives.

Day 2 – 27/02/2025

On 27 February 2025, the workshop resumed with WP3.1: Experimental Investigations – 'Combustion'. This Work Package, presented by Nabiha Chaumeix (CNRS) and focused on the combustion behavior of hydrogen and carbon monoxide in nuclear accident scenarios examining flammability limits, ignition energy, and explosion risks (Task 3.1). Through experimental studies in controlled environments, the flame acceleration, detonation potential, and overpressure effects were analysed. High-speed imaging and diagnostics were used to assess how flames propagate under different turbulence and oxygen conditions. The studies also explored mitigation strategies such as oxygen starvation, CO_2 dilution, and sprays to reduce combustion risk. These findings helped to refine nuclear safety protocols by improving the flammability limits and understanding on the H_2/CO behaviour under severe accident conditions.

Following this, Ernst-Arndt Reinecke (FZJ) presented WP3.2: Experimental Investigations – 'PARs'. The presentation focused on Task 3.2, detailing experiments and modelling advancements on PARs performed during the project. The presentation covered the operational conditions of PARs in various atmospheres, highlighting the challenges of oxygen starvation, and addressing catalyst deactivation due to carbon monoxide. Experiments like REKO-1 and REKO-3 aimed to provide data for PAR modelling, while REKO-4 investigated natural flow conditions. The results contributed to developing PAR operational models and validated computational tools like SPARK and PARUPM, advancing the safety protocols for hydrogen management during severe accidents.

After that, Stephan Kelm (FZJ) presented WP4: Full Containment Analysis. This Work Package focused on the analysis of the containment behavior under various mitigation strategies like PARs,

filtered venting, and emergency cooling, for PWR-KWU, PWR-W, and PWR-VVER reactors. In WP4, these reactor types were evaluated using Lumped Parameter codes, 3D modelling, and CFD simulations. The results showed how different mitigation strategies influence combustion risks and containment integrity. Key takeaways included the effectiveness of PARs in reducing hydrogen risk, the role of cooling systems in managing flammable gases, and the need for refined combustion criteria in safety assessments.

Following an invited lunch, M. Braun (FRG) presented WP5: Enhancement of Severe Accident Management Guidelines. This presentation concluded the AMHYCO project by linking the scientific findings obtained during the project for industrial applications. Key themes included the role of PARs in reducing combustion risks and the timing and consequences of hydrogen ignition. The work addressed hydrogen monitoring, containment simulations, and the effectiveness of mitigation systems like spray cooling and filtered venting. The final deliverable, D5.1, synthesizes these findings into a framework to enhance containment safety and hydrogen risk management, targeting public release by March 2025 demonstrating how AMHYCO's findings contributed to the improvement of SAMGs. This work outlined new safety recommendations specifically designed for PWR, KWU-PWR, and VVER reactors, integrating lessons learned from experimental research and computational modeling.

The workshop concluded with final remarks by G. Jiménez (UPM), summarizing the main outcomes of the different Work Packages, and emphasizing the importance of refining safety strategies through improved simulations, equipment qualification considerations, and optimized containment mitigation actions.

Finally, that evening, attendees participated in a cultural free tour of Madrid, starting at El Oso y el Madroño in Puerta del Sol, offering a unique opportunity to explore the city's historical landmarks offering a close-up to the event.

PhD Session Overview

During the PhD Session held the 26th of February, as a side event, a total of 6 PhDs and post-docs gave brief lectures summarising their AMHYCO-related current research or thesis status:

- Araceli Domínguez-Bugarín (UPM) introduced the PARUPM and GOTHIC 8.3 code coupling tests against experiments in the THAI facility. A GOTHIC 3D model of the THAI vessel was built for validation with transient experiments, such as HR-2, while the PAR component was modelled by representing its geometrical features and used a DLL extension to calculate recombination efficiency by using the advance PARUPM module.
- Luis Serra (UPM) presented an overview of the simulations performed by UPM of the PWR-VVER reactor using the GOTHIC model. Key topics included detailed CAD modelling, implementation of mitigation systems (sprays and PARs), and WP4 simulations for Loss-LBLOCA and SBO scenarios. Results highlighted temperature peaks exceeding equipment

qualification limits, hydrogen concentration heterogeneities, and combustion risk. Future work included upgrading to GOTHIC 8.5 to improve CO recombination and optimizing sensor and PAR placement.

- Alberto García-Herranz (UPM) presentation detailed the INTERCON3D project, which examines the interaction between safety and mitigation systems during severe accidents using 3D containment models in GOTHIC. It shares methodologies with AMHYCO, including air-cooling system implementation, spray system adaptation, and transient simulations. The study highlighted findings from LBLOCA cases, showing how mitigation measures impact hydrogen risk and containment integrity.
- Sofía Arfinengo (UPM) explored the impact of different variables on LBLOCA scenarios at the Almaraz NPP using a refined 3D GOTHIC model. The sensitivity analysis evaluated pressure, temperature, and velocity fields, revealing that short-term pressure values are highly dependent on initial conditions, while long-term behavior is influenced by spray system performance. The study underscored the benefits of geometric optimization and 3D modeling for containment accident analysis.

Main Conclusions

The AMHYCO Final Open Workshop successfully summarized the advancements made throughout the project, particularly on advancements in managing H_2/CO combustion risk during severe nuclear accidents.

A significant outcome of the project is the enhancement of SAMGs, which now incorporate refined protocols for deploying PARs, filtered venting systems, and emergency cooling measures. Experimental and computational research has improved predictive models for combustion behavior, flame propagation, and mitigation effectiveness, providing essential tools for decision-making in accident scenarios.

A key takeaway from the workshop was the importance of continued research and collaboration in nuclear safety. The workshop also highlighted the role of young researchers in advancing the field, with PhD presentations offering fresh perspectives and innovative methodologies.

Overall, AMHYCO findings set a new benchmark for nuclear safety by advancing risk management strategies, improving accident mitigation, and fostering international cooperation.

Participants of the Final AMHYCO Workshop held at Madrid on the 26th and 27th of February 2025.