Hydrogen Behavior and Mitigation Measures: State of Knowledge and Database from Nuclear Community

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ABSTRACT

Hydrogen has become a key enabler for decarbonization as countries pledge to reach net zero carbon emissions by 2050. With hydrogen infrastructure expanding rapidly beyond its established applications, there is a requirement for robust safety practices, solutions, and regulations. Since the 1980s, considerable efforts have been undertaken by the nuclear community to address hydrogen safety issues because, in severe accidents of water-cooled nuclear reactors, a large amount of hydrogen can be produced from the oxidation of metallic components with steam. As evidenced in the Fukushima accident, hydrogen combustion can cause severe damage to reactor building structures, promoting the release of radioactive fission products to the environment. A number of large-scale experiments were conducted in the framework of national and international projects to understand the hydrogen dispersion and combustion behaviour under postulated accidental conditions. Empirical engineering models and numerical codes were developed and validated for safety analysis. Hydrogen recombiners, known as Passive Autocatalytic Recombiner (PAR), were developed and have been widely installed in nuclear containments to mitigate hydrogen risk. Complementary actions and strategies were established, as part of severe accident management guidelines, to prevent or limit the consequences of hydrogen explosions. In addition, hydrogen monitoring systems were developed and implemented in nuclear power plants. The experience and knowledge gained from the nuclear community on hydrogen safety is valuable and applicable for other industries, involving hydrogen production, transport, storage, and use.

1.0 Introduction

During severe accidents (SAs) with core degradation in water-cooled nuclear power plants (NPPs), a large amount of hydrogen (H_2) can be produced. The H_2 can migrate into the containment buildings and form combustible mixtures. H_2 combustion presents a challenge to containment integrity, which could potentially break the last safety barrier for release of radiative material to the environment. Since the Three Mile Island Unit 2 (TMI-2) accident in 1979 [1], there has been a great deal of interest concerning H_2 combustion in post-accident nuclear containments. Since the 1980s, comprehensive research and development (R&D) programs have been developed to address H_2 safety issues by the nuclear community. The evolution of the nuclear H_2 safety research and areas of focus in the past 40 years are summarized in Figure 1~~Figure 1~~. The R&D program is divided into four stages.

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In the 1980s and 1990s, the R&D aimed to establish the fundamental understanding of H_2 combustion behaviour. A great number of H_2 combustion tests were performed by the international nuclear community, including combustion characteristics [2-7], diffusion flame [8], deflagration-to-detonation transition and detonation [9-14]. Various large-scale facilities were constructed in these experimental programs to address scaling issues. The early studies established a foundation for the development of safety criteria and analysis tools. Most importantly, these studies contributed to the development of H_2 mitigation measures and strategy [15].

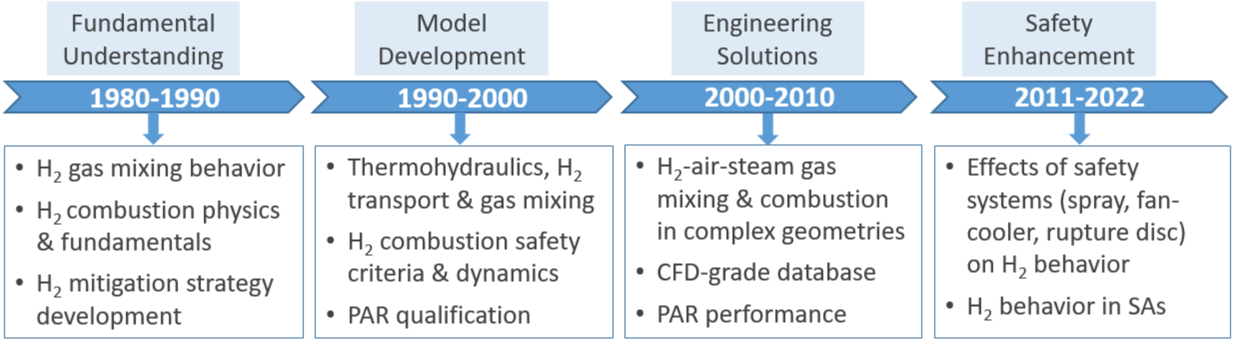


Figure 1. Evolution of H_2 safety research in nuclear community

Most of the studies conducted before 2000 were focused on capturing global H_2 behaviour and the experimental conditions were not always relevant to accident scenarios. The measurement data were obsolete and lacked spatial details. The application of three-dimensional and computational fluid dynamic (CFD) simulations for reactor safety analysis has inspired further experimental studies on H_2 behaviour in the 2000s. Various international collaborative projects were initiated by the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), and European Commission (EC), such as THAI [16], SETH [17], SARNET [18] and ERCOSAM [19]. Combining multi-national efforts allowed conducting a more comprehensive program and a more complete data analysis. These experiments were well instrumented with advanced measurement techniques (known as "CFD-grade"). Most experimental data have been used for code validations and benchmark exercises [20, 21].

The occurrence of the Fukushima Daiichi accident in 2011 triggered further analyses and assessments to support safety enhancements for the protection of containment and reactor buildings [22]. Although R&D efforts to date had already significantly enhanced the understanding of the phenomena governing the distribution of H_2 gas mixtures and their potential for combustion, effort continued to close research gaps, enhance computer codes prediction capabilities, and reduce their uncertainty. In addition, it was recognized that significant improvements were needed for national and international communications on nuclear safety, as well as information exchange amongst national nuclear regulatory organizations. Further, H_2 risk assessment methodology has been implemented in safety analysis by combining the use of CFD tools and empirical correlations to simulate the dispersion of H_2, assess the flammability and flame acceleration propensity of the resulting gas mixtures, and evaluate the pressure and temperature impacts induced by combustion.

In addition to H_2, carbon monoxide (CO) can also be produced due to molten core–concrete interaction in the late phase of SAs. The H_2 and CO combustion behaviour and performance of PARs have being studied in the EC AMHYCO project [23] and OECD/NEA THEMIS [24] project. The purpose of these projects was to enhance model predictive capabilities and accident management guidelines.

H_2 has become a key enabler for decarbonization as countries pledge to reach net zero carbon emissions by 2050. With H_2 infrastructure expanding rapidly beyond its established applications, there is a requirement for robust safety practices, solutions, and regulations. The experience and knowledge gained from the nuclear community on H_2 safety is valuable and applicable for other industries. This paper will provide an overview of the state of knowledge obtained on H_2 gas mixing behaviour and mitigation measures, describe selected experimental programs and facilities, as well as summarize the computer codes and their capabilities used for safety analysis. The intention of this paper is to increase the awareness of the existence of the database of knowledge on H_2 safety developed by the nuclear community.

2.0 Hydrogen Distribution

2.1 Overview

H_2 generated from the reactor core can be released into containment or reactor buildings through engineered pathways and breaks of reactor cooling system. Nuclear containments are confined and generally of large size (several thousand cubic meters) with internal obstacles, although most containments or reactor buildings have a large free volume in the upper dome. H_2 transport and mixing behaviour in large closed enclosures is one of the important thermal-hydraulic phenomena investigated by the nuclear industry to determine the H_2 risks. Detailed knowledge of containment thermal-hydraulics and gas distribution is essential to assess the effectiveness of H_2 mitigation measures employed in the containments or reactor buildings, such as ignitors, PARs, coolers, spray, and venting system. The experiments conducted by nuclear industry are primarily focused on investigating the following aspects:

- Effects of turbulence, buoyancy, and steam condensation on homogenously mixed or stratified H_2-air-steam atmosphere in single- and multi-compartment geometries
- Stratification break-up due to natural or forced convection (such as momentum dominated jets)
- Interaction between containment gas atmosphere (well-mixed and stratified) and operation of H_2 mitigation systems (PARs, containment coolers, spray, and venting system)

In general, the mixing of H_2 with surrounding air in containment can be influenced by the volume Richardson number Ri_V, introduced by Cleaver et al. [25] as:

$$Ri_V = g\left(\frac{\rho_0}{\rho_a} - 1\right)\frac{V^{1/3}}{{U_0}^2} \tag{1}$$

where V is the enclosure volume, U_0 is the injection velocity, ρ_0 is the injection gas density, and ρ_a is the surrounding gas density. The Richardson number compares the inertia of the discharge to the natural convection in the volume. If Ri_V is less than $(CR_1/H)^2$, where C is a constant equal to 25 for vertical upward release, R_1 is the release radius and H is the height of the enclosure, the inertia of the release can mix the gas in the entire volume, leading to a homogeneous atmosphere above the release location. Otherwise, the gas mixture is stratified with a large amount of H_2 accumulated at the upper region, which can significantly slow down the mixing process at the containment scale. The spatial extension and persistence of flammable atmosphere must be eliminated for such cases.

Since the TMI event, a great number of experiments and benchmark exercises have been carried out to understand the gas mixing and transport phenomena. Most gas mixing experiments were conducted using helium as a surrogate gas for H_2 due to safety concerns. The experimental study conducted in the OECD/NEA THAI project [16] confirmed that the transferability of helium as a replacement for H_2. Details of the experimental facilities and computers codes referred in the following sections can be found in Appendices A and B, respectively.

2.2 Experimental Programs and Benchmark Exercises

In the 1980s and 1990s, the experimental programs were focused on measuring the global gas composition in large-scale volumes (e.g., several tens of cubic meters), providing data for validation of lumped parameter (LP) codes. Most tests were conducted with limited instrumentation. A major breakthrough occurred in the OECD/NEA ISP-29 benchmark exercise for the HDR E11.2 H_2 distribution test [26]. The HDR vessel and the comparison of gas concentrations in the experimental measurements and simulation results are shown in Figure 2~~Figure 2~~. In this test, a mixture of H_2 and He was injected at an intermediate level without global homogenization. A great modelling effort was required to capture the gas mixing process using the LP codes (CONTAIN, GOTHIC and MELCOR).

Since the early 2000s, 3D codes started to be used to provide complementary analysis for H_2 mixing, although LP codes remain essential for the calculation of many accidental scenarios for probabilistic safety assessments. In the OECD/NEA ISP47 benchmark exercise [27], 3D/CFD codes demonstrated their strength for capturing local details. Figure 3~~Figure 3~~ shows the THAI vessel and the comparison of the experimental measurements with the predictions of CFX, GASFLOW and GOTHIC.

Since 2000s, experiments started to be equipped with “3D-grade” instruments and optical techniques, such as Particle Image Velocimetry to obtain the velocity field. Figure 4~~Figure 4~~ shows an example of a test conducted in the PANDA facility for the OECD/NEA SETH project [28]. Figure 5~~Figure 5~~ shows an example of the MISTRA test and benchmark exercise (CFX, GOTHIC, OpenFOAM and FLUENT) conducted in the OECD/NEA HYMERES project [29]. The experiments examined the erosion of thermal or gas stratification and impingement of jets on structures.

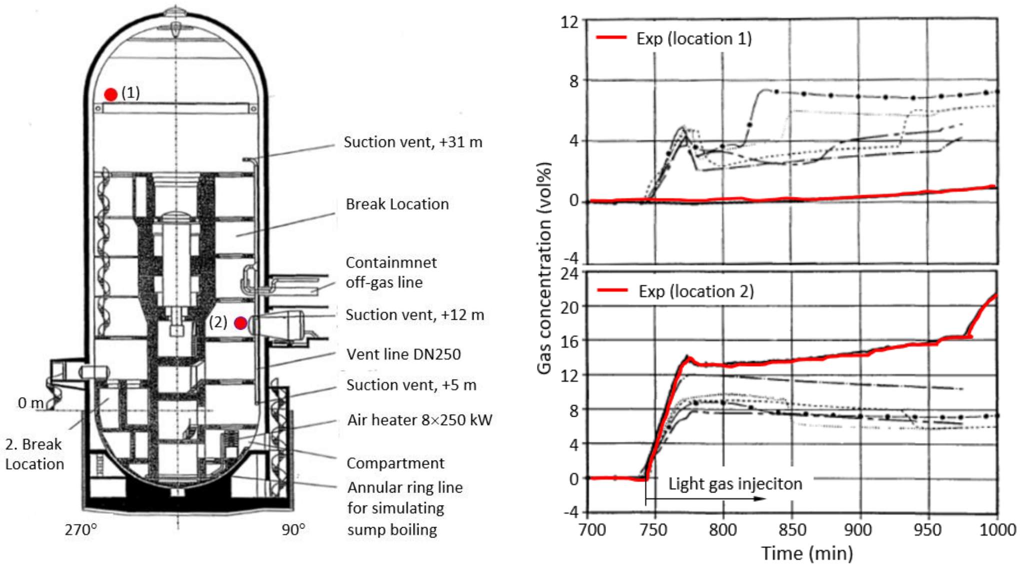


Figure 2. ISP 29 – benchmark exercise for HDR E11.2 H_2 distribution test [26]

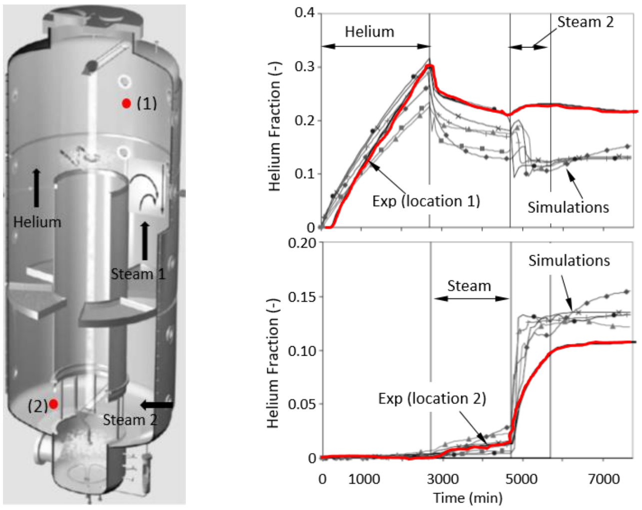


Figure 3. ISP47 – THAI benchmark exercise: evolution of helium predicted by CFD codes [27]

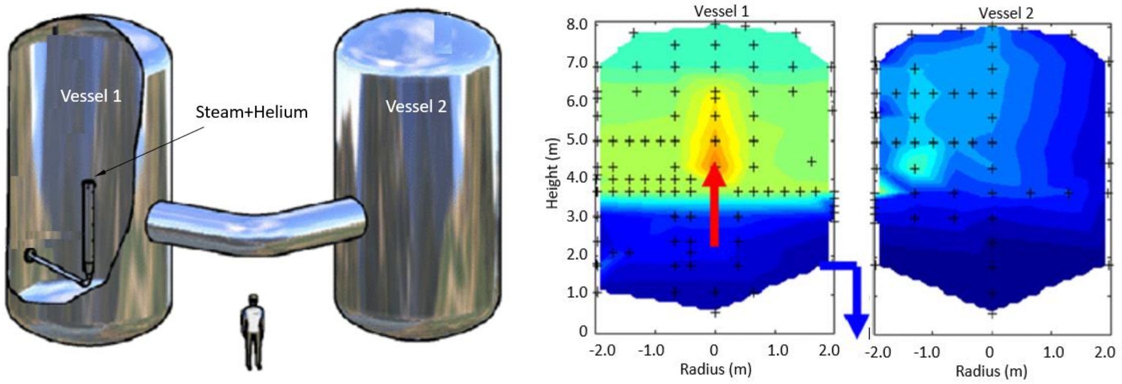


Figure 4. OECD/NEA SETH – PANDA test 25: experimental measurements of temperature fields [28]

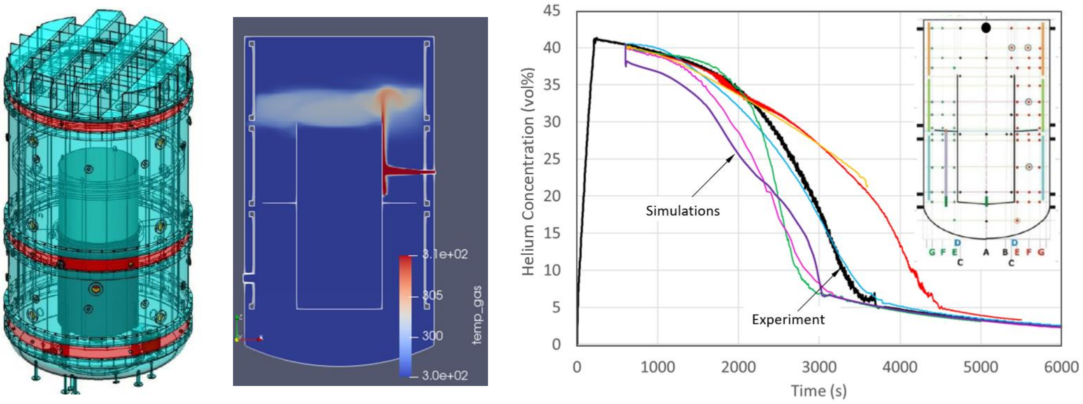


Figure 5. OECD/NEA HYMERES – MISTRA HM1-1 benchmark exercise [29]

A recent benchmark demonstrated that taking into account the radiative heat transfer in a participating medium (water vapour) allows a more accurate interpretation of the experimental results, even with small temperature differences [30]. Figure 6~~Figure 6~~ shows the comparison of experimental data with the predictions conducted with or without thermal radiation heat transfer.

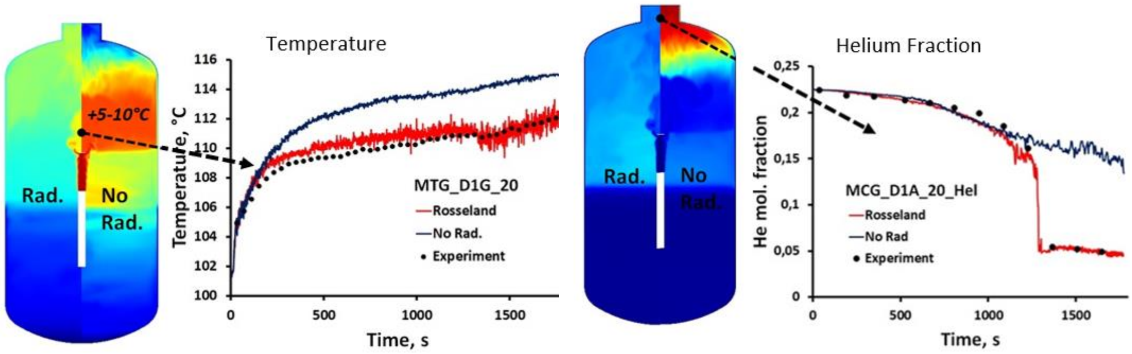


Figure 6. HYMERES – PANDA HP1_8 benchmark exercise for local temperature field (left) and stratification breakup (right) [30]

Finally, the effects of operation of mitigation measures (spray, cooler, PAR, and venting system) on H_2 mixing has been the subject of extensive research in recent years. While spray can provide an efficient mixing for a larger region, the gas mixing induced by PARs, coolers or venting is generally limited to the region close to these devices.

2.3 Open Questions and Future Investigations

There are a few issues that need to be further investigated. First, H_2 mixing and transport are primarily driven by buoyancy and turbulence, however, none of the Reynolds-Averaged Navier-Stokes (RANS) turbulence closure models have shown superiority. A hybrid of RANS and large eddy simulation approaches and extension of validation cases can be considered. Second, scaling effect remains an open issue. The height of experimental facilities present in operation is generally 8 to 10 m, whereas it is an order of magnitude larger for nuclear containments. Therefore, natural convection could be enhanced, and boundary layer thickness could be reduced in containment, which will be more difficult to capture in computer models. Third, propagation of uncertainties in the models needs to be considered for future analyses. Finally, for experiments, in addition to the ever important need for separate-effects tests, it is desirable to have more advanced parametric studies, including integral tests.

3.0 Hydrogen Combustion

3.1 Overview

Since the 1980s, the research effort of nuclear reactor safety in the combustion community has been focused on the understanding of the risk of explosion of H_2-air mixtures through specific studies related to flame acceleration [31-34] and transition to detonation [35-37]. Recently, through the French national program MITHYGENE [38], the effect of steam dilution and initial temperature on flame acceleration in a closed tube laden with obstacles (ENACCEF-2) have been addressed.

Indeed, in the evaluation of an explosion hazard with pressure effects that can threaten the containment and the safety equipment, the identification beforehand of the combustion regime is mandatory in the assessment of the different scenarios stemming from the H_2 distribution analyses. When a combustible mixture is formed and a flame is initiated, three different combustion regimes can be identified: (i) slow flame with a limited pressure increase, characterized by a flame speed on the order of m/s, (ii) fast flames with high pressure loads, characterized by flame speeds higher than the speed of sound in the unburnt gases and above half the speed of sound in the burnt gases, (iii) detonation with extremely high pressure loads and a velocity on the order of km/s. If the gas distribution analyses show that a steady detonation is highly unlikely to occur, the limit between slow and fast flames must be addressed thoroughly.

The understanding of flame acceleration phenomena relies on the following parameters identified in the literature [14, 31]:

- Laminar flame velocity and flame thickness that are intrinsic to the combustion itself
- Turbulent flame velocity that is characterized by the integral length scale and intensity of turbulence
- Flame instabilities, characterized by the Lewis number, $Le=\chi/D$, where χ is the mixture thermal diffusivity and D is the mixture mass diffusivity
- Thermodynamic and kinetic properties, characterized by the expansion ratio $\sigma=\rho_u/\rho_b$, where ρ is gas density, and the Zeldovich number, $\beta=E_a(T_b-T_u)/RT_b^2$, E_a is the global activation energy, and T is the temperature. The subscripts u and b represent the unburnt and the burnt gas.
- Speed of sound for reactant and product

The more recent work [39] illustrates the importance of the flame-stretch interaction in the subsonic stage of the flame acceleration through the proper characterization of the burned gas Markstein number and may act in the turbulent burning rate in addition to the classical variables of the Borghi diagram. Turbulent flow may be characterized by integral scales; this is generally applied to stationary turbulent flow. When considering premixed flame propagation, the involved processes are too complicated to define those scales. For example, the integral length scale, L_T, depends not only on the characteristic geometric size (such as tube diameter, obstacle shape and size), but also on the gas flow dynamics. Based on numerous experimental tests of flame propagation in tubes with different obstacles, Kuznetsov et al. [33] proposed a global expression of L_T according to the obstacle geometry, where the turbulent length scale is normalized with the laminar flame thickness.

Ciccarelli and Dorofeev [40] have pointed out that although the basic phenomena involved in flame acceleration and deflagration to detonation transition are identified, there are still deficiencies that the scientific community has to address in order to reduce the uncertainty margins within the evaluation of the potential hazard in a given scenario. These deficiencies can be attributed to remaining uncertainties in the determination of the critical conditions, including critical values of the mixture expansion ratio in the detonation cell size data, the laminar burning velocity, and the laminar flame thickness.

3.2 Experimental Programs and Benchmark Exercises

Since the 1980's, extensive experimental research has been carried out to study pre-mixed H_2 combustion behaviour. The objective was twofold: 1) characterize the transition between slow and fast regimes, and between deflagration and detonation; and 2) produce a database to validate computer codes. The OECD report [41] provides a description of the major experiments conducted for flame acceleration and detonation. These experimental programs aimed to address the postulated typical reactor conditions (e.g., geometry, turbulence effects), the gas composition and the venting on flame propagation.

The complexity of the facilities geometry and the limited instrumentation have made it difficult to validate advanced combustion models using the earlier data. Since 2000, new experimental programs were conducted on well instrumented facilities with the objective to provide complementary data for the validation of both CFD and LP codes. In the OECD/NEA ISP49 benchmark exercise [21], LP and CFD codes demonstrated their ability to predict flame speed and rate of pressure increase. Figure 7~~Figure 7~~ shows the THAI vessel and the comparison of the experimental measurements with the predictions of Fluent and COM3D codes. The ISP49 also highlighted the need of further investigations to increase the knowledge regarding turbulence effect on flame propagation, especially in stratified mixtures.

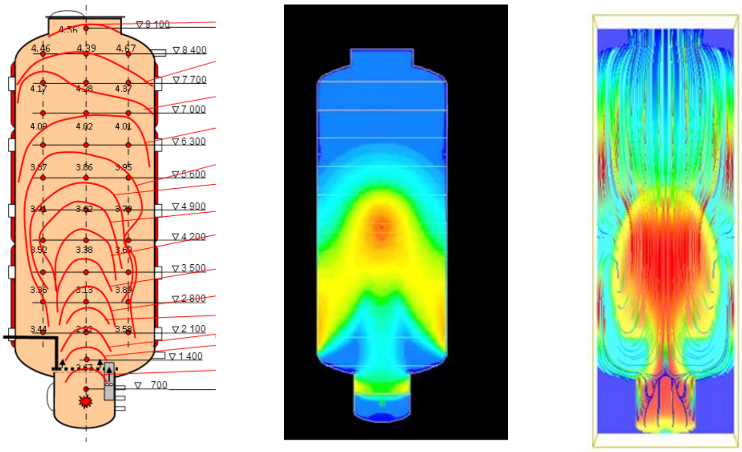


Figure 7. ISP49 – THAI flame front (left: experiment, middle: Fluent, right: COM3D) [21]

More recently, benchmarks were conducted to simulate the experiments performed in the ENACCEF2 facility, where H_2-air and H_2-air-steam mixtures were considered [42]. As shown in Figure 8~~Figure 8~~, most of the LP and CFD codes were able to qualitatively predict the pressure evolution inside the vessel. Nevertheless, the maximum flame speed was generally over predicted. This indicates that there are still limitations and weaknesses in the combustion models used in the different codes. These limitations are related to the chemistry and turbulent combustion models, and the coupling between the two models.

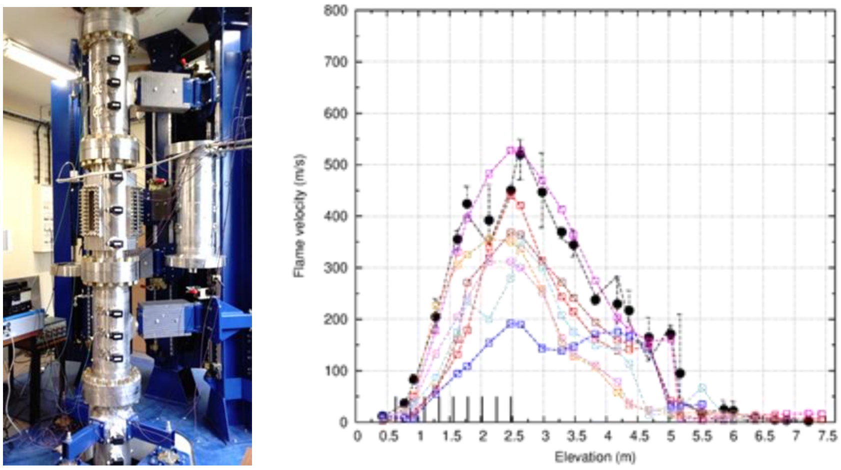


Figure 8. ENACCEF2 (left: experiment, right: experiment (solid black symbol) vs code results (coloured open symbols) [42].

3.3 Open Questions and Future Investigations

Despite the extensive effort spent on addressing the fundamentals of the H_2 explosion hazard evaluation, there are still numerous questions raised concerning: (i) the combustion regimes in oxygen starvation conditions, resulting in H_2-rich mixtures that are less studied in the literature, (ii) the limit between slow and fast flame seems to be too high and should be revised. Indeed there are conditions for which combustion regimes are identified as “slow”, but the flame is fast enough to induce pressure peaks higher than the theoretical combustion pressure for an adiabatic, isochoric complete combustion, (iii) the mitigation measures relying on dilution (inert gases) and/or water sprays are not fully understood and need further investigations, and (iv) the effect of non-homogeneous mixtures either in terms of H_2 distribution or temperature gradients on the combustion regime classification needs to be assessed and their effect on the flame acceleration criteria are not well understood nor quantified. Questions were also raised regarding the effects of vented combustion in multi-connected rooms, interaction of spray and flame and combustion in venting systems.

In the near future, it is mandatory to extend the current studies to the late phase SAs, where not only H_2 and steam are involved, but also CO, CO_2 and other minor gases. These new mixtures are also obtained under oxygen starvation. The future programs, such as the on-going European AMHYCO project [23] and OECD/NEA THEMIS [24], are addressing these specific questions. Indeed, the presence of carbonated species modifies several features in the combustion regimes, such as the completeness of the reaction in case of oxygen starvation, the radiative heat losses responsible for a modification of the heat release, the flame dynamics, and the modification of the thermo-diffusive instabilities, which in turn modify the acceleration process and the interaction of the flame with the environment.

4.0 Hydrogen Mitigation

4.1 Overview

Since the TMI-2 accident, worldwide R&D programs have focused on developing mitigation strategies to prevent fast H_2 combustion in case of SAs. Further actions have been taken to address issues raised after the Fukushima Daiichi accident. The H_2 mitigation measures commonly applied by NPPs [1] are:

- Pre-inerting of containment by replacement of oxygen with an inert gas during normal operation
- Post-accident inerting of containment by local injection of inert gas during an accident
- Dilution of the atmosphere to prevent the formation of flammable mixtures by natural convection or engineered systems (e.g., fan-cooler, spray)
- Consumption and recombination of H_2 by PARs
- Deliberate ignition of the gas mixture as soon as the lower flammability limit is reached

The principle of the above measures is to preclude flammable mixtures either by control of the oxygen concentration through inerting of the containment atmosphere or by control of the H_2 concentration through dilution or recombination (i.e., PARs). The strategy to control the H_2 concentration follows three steps: (1) reduce the possibility of H_2 accumulating to flammable concentrations, (2) minimize the volume of gas at flammable concentrations if flammable concentrations cannot be precluded, and (3) prevent the H_2 concentration from increasing from flammable to detonable levels. To allow monitoring the performance of mitigation measures and to provide relevant information for operators supporting decision making during the progression of an accident, gas composition, monitoring systems have also been implemented in many reactors.

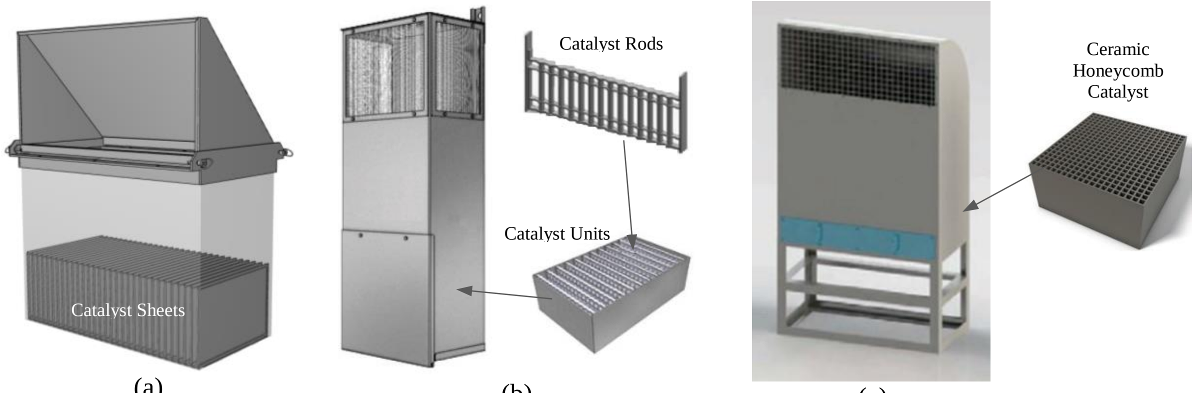
The choice of mitigation strategy depends on specific containment designs [22]. After the Fukushima accidents, PARs have become a primary choice for large containments in long-term accidents, while inerting remains commonly used for smaller containments, such as boiling water reactors. The location and size of each mitigation measure are generally determined based on plant-specific numerical simulations and dedicated assessments [22]. However, due to significant differences in regulatory requirements, safety criteria and plant conditions, the specific approach and strategy vary in different countries or reactors designs.

4.2 Passive Catalytic Recombiners

Catalytic recombiners use noble metal catalysts to recombine H_2 and oxygen (from air) to form water vapour. The catalyst elements are commonly arranged in a rectangular open-ended stainless steel housing to promote the buoyancy driven chimney effect. The PAR units are situated inside the containment building and use the heat of the oxidation reaction to produce flow through the unit by natural convection. As a consequence of their passive self-start and self-generated flows, they do not require outside power or operation actions. In contrast to combustion, the catalyst enables the oxidation of H_2 outside conventional flammability limits at room temperatures under saturated conditions.

PARs are in line with the general trend towards passive safety features in NPPs. However, the H_2 recombination rate of PARs is ultimately subject to mass transfer limitations. PARs may not be capable of removing H_2 at a rate required for fast-developing conditions. In addition, the catalysts can become a source of ignition at high H_2 concentrations (i.e., 6–9 vol.%). Further, the PAR catalysts can be temporarily poisoned due to environment contaminants.

PARs are commercially available from vendors in Canada and Europe [43]. Additional systems are under development in Korea [44] and Russia [45]. Figure 9~~Figure 9~~ shows the example of three PAR designs with catalyst coated on: (a) thin metal sheets by Canadian Nuclear Laboratories (CNL, formerly AECL), (b) cylindrical rods by Russkiye Energeticheskiye Tekhnologii (RET), and (c) ceramic honeycomb by Ceracomb Co. Ltd.



(a) (b) (c)

Figure 9. Images of typical PAR designs: (a) AECL/CNL, (b) RET and (c) Ceracomb

4.3 PAR Qualification and Testing

Extensive testing of PAR performance took place in the 1980s and 1990s in different experimental facilities, including BMC [46], KALI [47] and H2PAR [48], LSVCTF [49] to investigate the initial performance of the PAR designs and qualify the PARs for installation in NPPs. To provide an example of the extent, Table 1 summaries the qualifications of the PAR developed by AECL/CNL [49].

Table 1. Summary of Qualifications for AECL/CNL PAR.

Qualification Aspect	**Operability**
Pressure	1-4 bar(abs)
Temperature	13-108 °C (ambient), up to 750 °C (catalyst)
H_2 concentration	>0.5 vol.%
Relative humidity	Up to 100%
Radiation	2000 kGy gamma
Post-accident H_2 transient	Yes (24 h post-LOCA H_2 transient in CANDU reactor)
Seismic acceleration	Up to 9.5 g (horizontal) and 6.3 g (vertical)
Thermal aging	40 years at 50 °C
H_2 combustion	Yes
Cable/kerosene fires	Yes
Sprays (Before & after H_2 release): Water; NaOH; Na_3PO_4; $B(OH)_3$, borax, KOH; Na_3PO_4, LiOH	Yes
Low oxygen concentration	Yes (1 – 2 vol.%)
Post-accident chemicals (I_2, CH_3I, H_2N_4, Cl_2, HCl)	Yes
Long-term exposures to plant operating conditions	Yes (up to 42 months)

After the initial qualifications were performed by the manufacturers, several institutions started more scientific experimental programs in order to further consolidate and understand the operational behaviour under specific accident-related boundary conditions. In the framework of the OECD/NEA THAI project [16], PAR units provided by three manufacturers (AREVA, AECL, NIS) were tested under accident-relevant boundary conditions. These tests provided fundamental information on the PAR start-up behaviour, H_2 recombination rate and gas-phase ignition to enable further development and validation of numerical PAR models [50]. In more advanced experiments, specific accident conditions such as the release of aerosols, atmospheres with very low oxygen concentrations, occurrence of local counter flows, and the presence of carbon monoxide were investigated. In parallel with the THAI project, PARs have also been tested in national programs, including FZJ (Germany) and CNL (Canada) to understand the PAR operation in more detail and to develop advanced numerical PAR models beyond the existing correlation models. Experiments conducted in the REKO facilities at FZJ enabled the development of FZJ's REKO-DIREKT code, which is a geometry-independent PAR model [51], and IRSN's SPARK code [52], which is a detailed PAR model involving full surface and gas-phase chemistry.

Research at CNL on PARs has been driven by the Canadian nuclear utilities, the Canadian nuclear regulator and AECL's Federal Science and Technology program to facilitate the understanding of PAR behaviour and explore the use of PARs for the H_2 economy. Some examples of CNL's research on PARs include investigating the gas-phase ignition [53], behaviour in the presence of carbon monoxide [54], improving the catalyst to resist carbon monoxide poisoning [55], and PAR behaviour with continuous H_2 release. Figure 10~~Figure 10~~ provides an example of a test performed in CNL's 60 m^3 large-scale vented combustion test facility. In this test, H_2 was continuously released at approximately 5 g/min from the side wall at the 1.5 m height, which was above the PAR inlet (1.3 m height). Under quiescent conditions, the H_2 accumulated in the in the upper portion of the facility. The PAR didn't begin to function until the PAR inlet H_2 concentration reached 0.5% (at approximately 36 min). Once operational, the PAR reduced the overall H_2 concentration in the facility and mixed the gases within minutes. The H_2 concentration was maintained at fairly low concentration afterward.

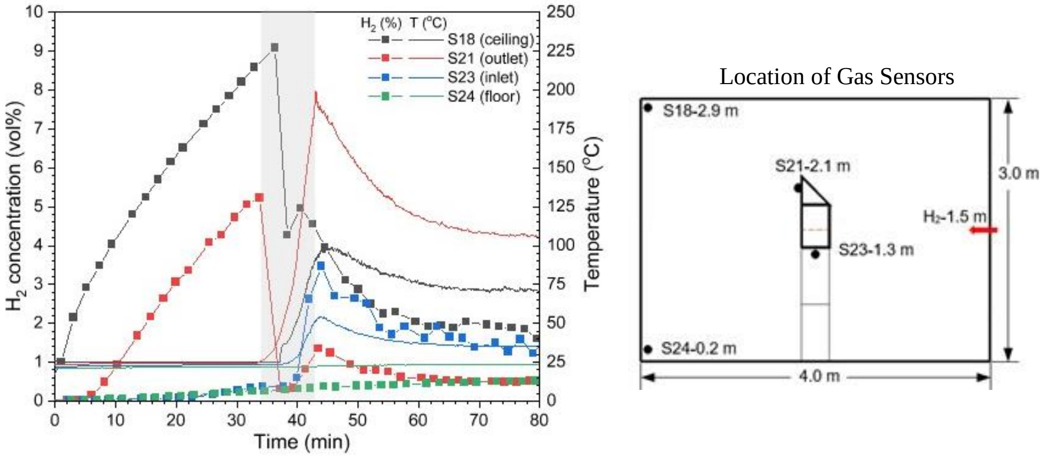


Figure 10. Example of continuous H_2 injection PAR experiment with gas stratification conducted in CNL's large-scale vented combustion test facility

At present, research projects are focusing on the late phase of SAs, when the gas mixture contains H_2 and CO. Predicting the effect of CO on H_2 mitigation has proven to challenge the capabilities of existing simulation tools. The open issues being studied include the combustion properties of the resulting H_2/CO mixtures, as well as the effect on H_2 recombination. The identification of the boundary conditions resulting in the deactivation of the PAR (i.e., catalyst poisoning) are the specific focus in the on-going EC AMHYCO project [23] and are part of the OECD/NEA THEMIS project [24].

5.0 Summary and Implication for Other Industries

There is a fundamental difference in the safety design philosophy between NPPs and H_2 facilities. The safety regulations and mitigation measures implemented for NPPs are aimed to limit the consequences of an accident, such as combustion loads and possible fission product releases. In contrast, the mitigation strategy for H_2 facilities is to prevent the accumulation of flammable gas by allowing ventilation and dilution, thus avoiding confinement and congestion. Further, the H_2 release pressure in a nuclear accident is much lower than a non-nuclear accident, but opposite for the release temperature. Despite the difference stated above, H_2 risk assessment in both nuclear and H_2 facilities presuppose the use of validated computer codes to predict H_2 dispersion and evaluate the explosion-induced pressure and temperature loads, and the use of empirical correlations to identify flammable clouds and assess the possibility of flame acceleration and detonation.

A large amount of data for hydrogen safety has been produced by the nuclear community. Continuous validation of computer codes along with the experimental progress is ongoing in many organizations. Some of the above-mentioned experimental results and computer codes have been applied to strengthen the capabilities of modelling H_2 mixing in the H_2 economy. It is important to maintain this strong link to progress towards safer systems. As mentioned above, a number of projects have been carried out at national and international level to develop and validate advanced LP and CFD simulation tools taking into account a wide range of conditions. These tools and the associated safety assessment methods have been successfully used in the licensing process (such as EPR-Flamanville in France). As a result, the knowledge and experience gained in nuclear applications can be easily used to assess the risk of H_2 explosion in industrial installations.

In the future, the realization of nuclear reactor technologies, such as the molten salt reactor and high temperature gas cooled reactor, and the coupling or co-locating of a nuclear reactor with H_2 production installations will drive further development and research on hydrogen toward safety, risk assessment, demonstration, and licensing.

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Appendix A: List of Experimental Facilities for Hydrogen Research Used by the Nuclear Community

A number of experimental facilities have been built at different scales to study hydrogen behavior (distribution and combustion) and safety systems installed in NPPs as countermeasures for hydrogen risk management. These facilities aim to provide data for development and validation of hydrogen analyses codes. This Appendix provides a list of selected facilities for hydrogen research used by nuclear community. Some of them have ceased operation, but the database can be useful for code validation. Considering the broad range of initial and boundary conditions covered by these facilities, the available database and the experimental infrastructure provide a useful link to non-nuclear hydrogen research.

Organization /Country	Facility (Period of Operation)	Geometry				Range of Tests			Investigated Mitigation Systems
		Shape	Volume (m^3)	H (m)	D or L (m)	T_0 (°C)	P_0 (atm)	Gases	
Hydrogen Distribution									
CNL, Canada	LSCF (2003-present)	Rectangular	275	9.7	5.6	20-95	1	Air. He, Steam	Air coolers
		Rectangular	1400	9.7	10	20-60	1	Air. He, Steam	
PSI, Switzerland	PANDA (1995 -present)	Cylinder	Up to 515 (6 vessels	25	4	20-140	1-4	Air. He, Steam	Fan, Coolers, Spray,
CEA, France	MISTRA (1999 – present)	Cylinder	100	7.4	4.2	20-140	1-4	Air. He, Steam	Spray, Heaters
BT, Germany	THAI (2000 -present)	Cylinder	60	9.2	3.2	20-140	1-3	Air. He, H_2, CO, Steam	Spray, PARs, Fan
BT., Germany	THAI$^+$	Cylinder	80 (two vessels)	9.73	3.2 & 1.6	20-140	1- 4	Air. He, H_2, CO, Steam	Spray, PARs, Fan
Hydrogen Combustion & Mitigation									
CNL, Canada	LSVCTF (1996-2017)	Rectangular	120	3	10	20-100	1	Air. H_2, CO, Steam	PAR, Fan
CNL, Canada	CTF(1985-2017)	Cylinder	10.3	5.7	1.5	20-100	1	Air. H_2, CO, Steam	PAR, Fan
		Sphere	6.3	-	2.3	20-100	1	Air. He, Steam	
BT, Germany	THAI/THAI+ (2000 – present)	Cylinder	60/80	9.2/9.73	3.2/1.6	20-140	1-5	Air. H_2, CO, Steam	Spray, PAR, Fan

FZJ, Germany	REKO-4 (2010-present)	Cylinder	5.32	3.7	1.4	20-140	1-2.3	Air, H_2, CO, Steam	Fan
CNRS-ICARE, France	ENACCEF-I (2001-present)	Cylinder	0.72	3.2/1.7	0.154/0.738	20-200	1-3.5	Air, H_2, Steam	Spray
CNRS-ICARE, France	ENACCEF-II (2016-present)	Cylinder	0.41	8	0.254	20-200	1-3.5	Air, H_2, CO, Steam	Spray
KAERI, Korea	SPARC (2016-present)	Cylinder	81	9.7	3.4	20-120	1-2	Air, H_2, Steam	Spray, PAR
JAEA, Japan	CIGMA (2015-present)	Cylinder	50	11	2.5	20-120	1-2	Air, H_2, Steam	Spray

Note: the P_0 and T_0 conditions refer to the range of experimental conditions. The design P and T values are much higher, particularly for the facilities designed to operate at elevated P and T conditions.

Appendix B: List of Selected Computer Codes for Hydrogen Safety Analysis by Nuclear Community

Different simulation software tools are maintained and further developed in the context of nuclear safety research, assessment, demonstration, and licensing. They can be categorized by their governing equations and spatial resolutions in three categories:

- 1D lumped parameter, system or integral codes: Solve integral equations for large control volumes, connected by flow paths. They cover all relevant physics or technical systems, which are integrated via empirical correlations or simple mechanistic models.
- CFD codes: solve the differential form of the governing equations primarily using the finite volume method. Closure models are formulated based on local (cell) quantities and their gradients, e.g., to compute turbulent heat and mass transfer or reaction rates. The computational effort still limits the detail and extent of the physical modeling and geometrical representation of a multi-scale application. Both, tailored codes developed within the nuclear community as well as add-on model packages to commercial multi-purpose software are available.
- 3D codes can be considered as ‘coarse mesh CFD’ codes, tailored for a specific application: Computational efficiency is gained by utilizing comparably large control volumes along with empirical sub-grid models, structured Cartesian/cylindrical meshes are employed instead of body-fitted unstructured meshes. They cover a broader range of physics, but lack spatial resolution, physical modeling detail and geometrical representation.

This Appendix provides a list of selected codes used in the context of hydrogen research by nuclear community and can or is already be used in the non-nuclear sector.

Country	Developer	Code	Type	Capabilities related to H_2 safety		
				Containment Thermal-hydraulics/Gas Mixing	**Combustion**	**Mitigation**
Germany	GRS	AC^2 (COCOSYS)	LP /system codes	√	√	√
France	IRSN	ASTEC (CPA)	LP /system codes	√	√	√
USA	SNL	MELCOR	LP /system codes	√	√	√
USA	ZNE	GOTHIC	LP /system codes	√	√	√
USA	EPRI	MAAP	LP /system codes	√	√	√
The Netherlands	NRG	SPECTRA	LP /system codes	√	√	√
Finland	VTT	APROS	LP /system codes	√	√	√
Japan	IAE	SAMPSON (CV)	LP /system codes	√	-	-
Germany	KIT	GASFLOW	3D	√	√	√
USA	ZNE	GOTHIC	3D	√	√	√
Germany	FZJ	containmentFOAM	3D/CFD	√	√	√
Germany	TUM	ddtFOAM	3D/CFD	-	√	-
France	EDF	Code Saturne / Code Neptune	3D/CFD	√	√	√
Korea	KAERI	CUPID	3D/CFD	√	√	√