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Developments in the Analysis and Management of Combustible Gases in Severe Accidents in Water Cooled Reactors following the Fukushima Daiichi Accident

IAEA

International Atomic Energy Agency

DEVELOPMENTS IN THE ANALYSIS AND MANAGEMENT OF COMBUSTIBLE GASES IN SEVERE ACCIDENTS IN WATER COOLED REACTORS FOLLOWING THE FUKUSHIMA DAIICHI ACCIDENT

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The generation of combustible gases such as hydrogen and carbon monoxide can occur in a nuclear power plant during a severe accident. Hydrogen is generated as a result of the oxidation of metals, especially zircaloy in the fuel cladding/assembly, and B_4C and steel in core structures/support materials and other reactor pressure vessel internals. Hydrogen and carbon monoxide can also be generated in later accident phases as a result of molten core–concrete interactions.

Combustible gases, particularly hydrogen, have long been recognized as a safety issue in water cooled light water reactors. Combustible gases and combustion processes can pose a threat to containment integrity, among other safety concerns. Maintaining containment integrity is of fundamental importance in a reactor accident to avoid the release of fission products to the environment. Safety regulations on this topic have been developed at the national and international levels, and relevant guidelines and mitigation measures are already in place in many nuclear power plants worldwide.

Since the accident at the Fukushima Daiichi nuclear power plant, where explosions of combustible gases damaged the reactor buildings of Units 1, 3 and 4, the behaviour of combustible gases and related accident management measures, as well as measures to limit fission product release to the environment, have received great attention amid calls for further studies and analyses. Analyses of the Fukushima Daiichi accident at the national and international levels have shown the need to consider a broader range of accident scenarios, including external events affecting both the containment and the surrounding reactor building, various boundary conditions, and potential new phenomena related to gas distribution and combustible gas behaviour. This requires continual development of qualified analysis tools and reliable experimental and analytical data. To ensure the effectiveness of mitigation systems, their performance behavior should be assessed under a wide range of postulated accident scenarios. Furthermore, in the light of the Fukushima Daiichi accident, additional experimental as well as analytical needs have been identified for combustible gas and fission product issues, in conjunction with the retrofitting of mitigation systems inside the nuclear power plant, such as passive autocatalytic recombiners and filtered containment venting systems, to be investigated in an integrated and optimized way.

The main objective of this publication is to review the current state of technology regarding safety issues related to combustible gases in water cooled nuclear reactors with a specific focus on developments following the Fukushima Daiichi accident. Recent results obtained in the frame of experimental and analytical research on hydrogen/combustible gas behaviour are discussed. The knowledge base developed will also be useful for validation and assessment of combustible gas modelling implemented in existing safety analysis tools, as well as for possible improvements to severe accident management guidelines.

The IAEA acknowledges the efforts and assistance provided by the contributors listed at the end of this publication. The IAEA officer responsible for this publication was T. Jevremovic of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Possible combustible gas explosions may have a significant effect on the containment or any other NPP building structure integrity and consequently on the fission product source term in case of severe accidents in water cooled reactors (WCRs). The nuclear accident at the pressurized water reactor (PWR) in Three Mile Island (TMI) in 1979 had triggered international research on severe accident phenomena and later the development of (severe) accident management programmes for nuclear power plants (NPPs) [1]. For better understanding, phenomena like combustible gas generation, release and distribution in the containment of NPPs as well as combustion and recombination have been studied first experimentally. In parallel, various codes or models have been developed and validated to analyse and assess the phenomena and to support the development of measures to prevent or mitigate challenges to the containment within various NPPs designs caused by combustions and/or explosions.

The explosions occurred during the severe accidents at Fukushima Daiichi NPP (Units 1 to 3) in 2011 damaged the reactor building of three reactor units (Units 1, 3 and 4) at the site due to combustible gas releases from the N_2 inerted containments and in case of Unit 4 due to transfer through a common ventilation system. Even so efficient hydrogen counter measures have been installed inside the containment by the N_2 inertisation, the explosions outside the containment in the reactor building could not be prevented, as no mitigation measures existed. This underlined once more the known challenges caused by hydrogen and other combustible gas accumulation to the building's integrity in general and the need to further improve the hydrogen/combustible gas mitigation measures within the containment (if nothing was implemented so far) as well as especially in surrounding reactor building.

The analyses of Fukushima Daiichi accident as well as current plant inspection results also identified the need to get more detailed knowledge of the core degradation mechanisms in the late phase of core degradation inside the reactor vessel as well as in particular to the core melt release below the reactor pressure vessel (RPV) of a boiling water reactor (BWR) where multiple structures exist. Further, the onset of and the termination of molten core-concrete interaction (MCCI) in the reactor cavity is still an issue. This knowledge is also important with regards to generation and release of combustible gases, such as hydrogen and carbon monoxide and their potential impact on combustion risk and consequently on source term [2].

Furthermore, post-Fukushima Daiichi accident action plans from regulatory bodies of several countries included directives to consider implementing the safety measures, such as passive autocatalytic recombiners (PARs) or other hydrogen mitigation measures and filtered containment venting systems (FCVS) as severe accident mitigation measures, if not done so far [3]. The FCVS has been suggested as a measure to protect the containment from over-pressure failure and to limit the fission product release from the containment. To ensure mitigation systems effectiveness, their performance behavior needs to be assessed under a wide range of postulated accident scenarios.

Another issue concerns the possibility of hydrogen/combustible gas generation within the spent fuel pool (SFP) in case the fuel assembly cooling is lost, and the event develops into a severe accident. Concerns on SFP cooling have been increasingly raised in the international nuclear community and resulted into developing common opinion papers from various international organizations, e.g. IAEA IEM report [4] and OECD/NEA SFP status report [5]. As SFPs are typically located in a building outside the containment and mitigation measures implemented in the containment may not be fully extended to SFPs, the primary focus is on preventive measures, e.g., implementation of additional or mobile water injection and heat removal systems.

To this end and in follow-up to the Fukushima Daiichi NPP accident, the need for further improvements of the mitigation means of the mentioned issues had also been highlighted in the peer review of the European Stress Tests [6] and in NRDC report [7]. In order to avoid high intensity combustion risk, installation of PARs, preclusion of vent interconnectivity in case of multi-unit NPPs and monitoring of hydrogen release rates and hydrogen concentration were identified as some of the potential measures for preservation of NPPs safety [4][5][6].

To accomplish above-mentioned goals for enhancing the safety measures, the dedicated research and development programs have already been launched at national and international levels ([8]–[12]) with the objective to improve the understanding of the phenomena associated with the distribution, mitigation and combustion hazard and to address the issues highlighted after the Fukushima Daiichi events, such as explosion hazard in venting system and the potential flammable mixture migration into spaces beyond the primary containment. The foreseen results are also committed to improve the severe accident management guidelines.

Within international framework, the Committee on the Safety of Nuclear Installations (CSNI) decided to launch several high priority activities. The Working Group on Analysis and Management of Accidents (WGAMA) proposed to write a status paper on hydrogen generation, transport and mitigation under severe accident conditions. The Status Report on Hydrogen Management and Related Computer Codes was published in June 2014 [13]. The information contained in the report covered the related information obtained in the frame of international OECD/NEA or EC programs. A new activity has been launched by the CSNI working group WGAMA in April 2019 to update this status report in the form of a state-of-the-art-report (SOAR), to disseminate the most recent findings, and to produce a consistent source of knowledge for hydrogen and carbon monoxide behavior during severe accidents in the containment and the surrounding reactor building of NPPs. The ongoing SOAR is planned to be completed in 2022.

1.2. OBJECTIVES

The objective of this publication is to provide a synthesis of results obtained in the frame of experimental and analytical research on hydrogen/combustible gas behavior and discuss their potential impact on hydrogen management and risk assessment. The focus is on work done considering Fukushima Daiichi accident. In addition to international research, findings from R&D activities at national level are also highlighted. The core issues were identified from country presentations and discussions during the IAEA Technical Meeting on Hydrogen Management in Severe Accidents held at IAEA headquarter in Vienna, 25–28 September 2018. The knowledge gaps identified during the meeting are discussed with respect to the current status of the available knowledge and ongoing efforts to close the remaining open issues.

1.3. SCOPE

The scope of this publication is an updated information on post Fukushima Daiichi accident developments in the analysis and management of combustible gases in severe accidents in WCRs. This publication is complementary to the IAEA-TECDOC-1661, Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants, published in 2011 [14].

The main focus of this publication is to provide a detailed review on hydrogen related developments by discussing the relevant analytical and experimental research work. Relevant details on carbon monoxide are provided for completion purpose by including the available details in the open literature. The inclusion of carbon monoxide is justified by the fact that in case of a severe accident (as revealed by Fukushima Daiichi accident analyses) both H_2 and CO will be generated and need to be considered in severe accident analyses and severe accident management actions. Presently, very limited amount of experimental database is available regarding CO and this publication therefore intends to underline the need for considering both H_2 and CO in future experimental and analytical activities.

1.4. STRUCTURE

Section 2 of this publication outlines the general description of combustible gas phenomena in severe accidents. Section 3 discusses different combustible gas mitigation and management strategies employed in NPPs for severe accident management. Section 4 provides information about analysis tools employed for safety analysis based on different modelling approaches. The Annex I provides examples of experimental infrastructure available in various countries for combustible gas related investigations. The Annex II provides the summary of the Technical Meeting on Hydrogen Management in Severe Accidents, while the supplementary file includes all technical papers that were presented at this Meeting (Annex III provides the content of the supplementary file).

2. GENERAL DESCRIPTION OF COMBUSTIBLE GAS PHENOMENA IN SEVERE ACCIDENTS

During severe accidents in water cooled NPPs large amounts of combustible gases typically hydrogen but as well carbon monoxide can be generated and released into the containment. The processes that are the main ones for hydrogen/combustible gas generation are core oxidation/degradation (zircaloy, steel and B_4C structures) and MCCI after RPV failure and melt release into the containment [14]. After Fukushima Daiichi accident, another process came into the focus, the possible oxidation of the cladding of spent fuel assemblies in the SFP in case cooling is lost. Other processes such as radiolysis within the reactor circuit during normal operation or in water pools in the containment contribute as well to the generation of combustible gases, but the amount or releases rates are orders of magnitude smaller [5].

Main phenomena associated with hydrogen/combustible gas behavior during a severe accident in an NPP are: generation, release and distribution and finally combustion. The latest OECD/NEA status report on Hydrogen Management and Related Computer Codes [13] contains a comprehensive summary of research programs on hydrogen/combustible gas behavior. The latest IAEA-TECDOC-1661 on Mitigation of Hydrogen Hazards in Severe Accidents in NPPs [14] contains information on hydrogen sources, hydrogen distribution within the containment, hydrogen combustion modes and loads, and hydrogen control and risk mitigation. More information on combustible gas phenomena in severe accidents can be found in other reports, e.g. [15]–[19]. A short summary of main hydrogen/combustible gas phenomena is provided in the following Sections.

2.1. GENERATION OF COMBUSTIBLE GASES

Two main processes associated with the generation of combustible gases during severe accidents with core melting are: oxidation of core and structural metals within the RPV during core heat-up and melting, and the erosion of the concrete by the molten core material after RPV failure and melt release in the containment. These two main processes are associated as well with the generation of combustible gases during severe accidents within SFPs: oxidation of spent fuel cladding and structural metals within the SFP during boil-off and spent fuel heat-up situations, and as in case of core melt accidents the erosion of the concrete of the SFP by the molten spent fuel material. Only oxidation by steam may lead to a large hydrogen production, while oxidation with air is also possible, then without hydrogen generation. Both processes would lead to significantly different reactions, as shown e.g. in experiments of the Sandia fuel programme [20].

Oxidation processes are typically exothermic processes and a large amount of additional heat is released, often being higher than the actual decay power in the fuel. The amount of hydrogen and carbon monoxide which may be produced during the MCCI depends strongly on several NPP specific parameters, such as:

- Type of concrete and aggregate used in the structure;
- Basemat thickness;
- Cavity size/geometry;
- Melt mass in the cavity;
- Melt composition; and
- Presence of overlaying water pool.

The question whether the core degradation or even the MCCI process can be terminated by flooding the degraded core or the molten pool in the containment depends on the actual situation, has still some uncertainties and is partly under further investigation including their effect on hydrogen and carbon monoxide generation. Thus, experimental programmes as CCI [21] and PEARL [22] were conducted with the objectives to reduce the mentioned uncertainties and provide recommendations to enhance severe accident management mitigation measures and guidelines (SAMGs). A review of the state-of-the-art of the progress made in MCCI phenomena investigation and related hydrogen and carbon monoxide production is provided in [23].

2.2. RELEASE AND DISTRIBUTION OF COMBUSTIBLE GASES

Hydrogen/combustible gas release and distribution in the containment or the reactor building through various release paths during a severe accident is a complex process and plant design- and scenario-specific phenomena may occur. Details on main phenomena and processes governing the hydrogen release and distribution in the containment are described in [16] and [17].

Some relevant issues are that the release of hydrogen/combustible gases typically occurs together with the release of hot steam, and that the release of non-condensable gas from MCCI is a continuous process in contrast to the release of hydrogen from the core oxidation within the RPV. The hot steam condensation on cold walls and structures induces natural convection contributing to the containment atmosphere mixing. In addition, the operating engineering safety systems such as active or passive recombiners, spray or air coolers may further enhance the atmosphere mixing. If spray and coolers operation contribute to a better mixing of the containment atmosphere, they can also significantly reduce the steam concentration and lead to more sensitive gas mixture compositions regarding the hydrogen combustion occurrence. The general layout of the containment affects the hydrogen distribution. A significant issue from the point of view of hydrogen challenge can be the formation of flammable mixtures (even explosive mixtures) in relatively small size, so-called "dead end" rooms. The ratio of walls surface to the room volume is a factor strongly influencing the described phenomena – bigger is the ratio faster will be the accumulation of incondensable (combustible) gases in a small room [24].

Flammability limits (FL) and combustion phenomena as flame acceleration (FA) or deflagration-to-detonation transition (DDT) are summarized in the following Section 2.3.

2.3. COMBUSTION PROCESS

2.3.1. Flammability limits of combustible gases

"The flammability limit is the experimentally-determined minimum molar percentage of fuel (lower limit) or maximum molar percent of fuel (upper limit) required for self-sustained flame propagation at a specified initial pressure and temperature. The flammability limit is of primary interest in safety assessments as an absolute indication of the existence of a combustion hazard and the main reference point in defining a safety margins for a combustion hazard" [19].

The ternary diagram shown in FIG. 1 exemplifies the definition of the flammability limits, upper and lower, as well as the inerting point which is the minimum inert molar percentage above which no sustained flame can be observed no matter the value of the H_2/O_2 ratio.

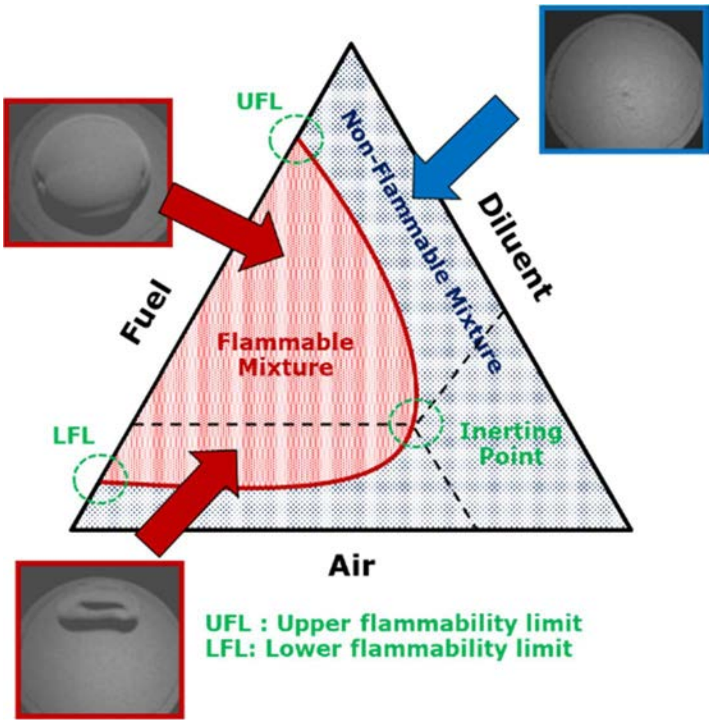

FIG. 1.Flammability limits domain definition through a ternary diagram. Flame pictures obtained at CNRS-ICARE.

For this purpose, the determination of the flammability limits of hydrogen-air-steam mixtures, representatives of in-vessel core degradation conditions, had been intensively investigated. The Fukushima Daiichi accidents, at least for Unit 1 [2][25], observed the likely production of CO_2/CO gases from MCCI, in addition to H_2 in the containment. In this case, gas composition in the reactor building is more complex and contains H_2/H_2O/air/CO_2/CO gases. The data base under MCCI conditions is available but much more limited in comparison to that for typical air/H_2 or air/H_2O/H_2 mixtures. Another important parameter that has to be considered when assessing the flammability limit is the ratio N_2/O_2. For the lower flammability limit, since N_2 and O_2 are both diatomic molecules, their thermodynamic properties are similar at standard temperature as well as their third body efficiencies. As a consequence, the ratio N_2/O_2 will have only a limited impact on the LFL (between 0 and 0.5) and only when this ratio is very high that one can see a sudden increase in the flammability limit before reaching the total inerting point as shown in FIG. 2. On the rich side, the upper flammability limit is strongly reduced when the N_2/O_2 ratio is increased.

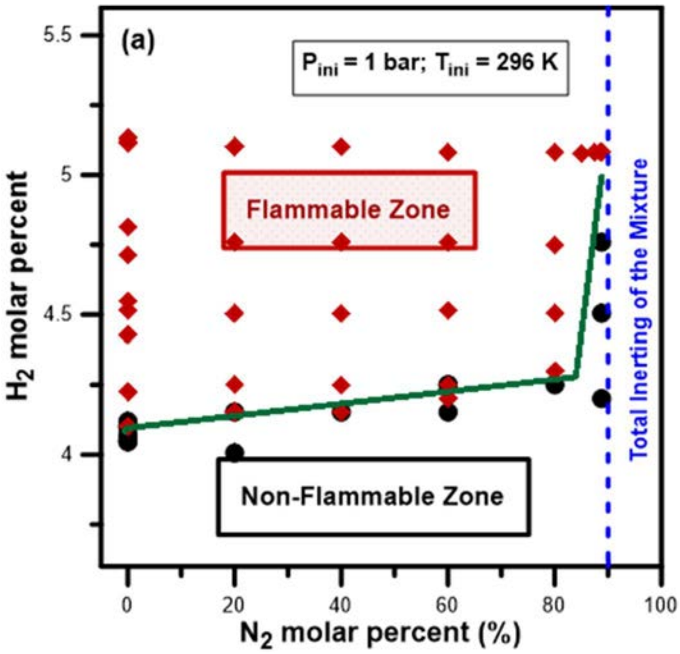

FIG. 2. Flammability limit of $H_2/O_2/N_2$ initially at 296 K and 1 bar [26],[27].

If the containment atmosphere mixture is highly heterogeneous, there may be local hydrogen concentrations that exceed the gas mixture flammability limit. The flammability of the containment gas mixture depends on the mixture temperature, pressure and composition, as well as the ignition source and mode.

The lower flammability limits for hydrogen in air are 4.1 vol. % for upward propagation, 6 vol. % for horizontal propagation and 9.0 vol % for downward propagation. The aforesaid flammability limits apply to gases maintained at atmospheric pressure and saturated with water vapor at room temperature ([28], [29]). The ternary diagram (FIG. 3) is typically used to determine whether the mixture is flammable or not. The gas composition during an accident progression may also evolve, e.g. change in N_2/O_2 ratio in air due to PAR operation. The impact of varying pressure/temperature conditions as well as gas composition is therefore necessary to be considered for flammability limits calculation during an accident progression.

The flammability limit may also be affected by the medium state in terms of turbulence and the presence of spray/water droplets. The effect of turbulence on the lower flammability limits has been examined in a spherical vessel in which an initial homogeneous and isotropic turbulence is generated. The lower flammability limit is also shown to be increased with an increase in the turbulence level [30].

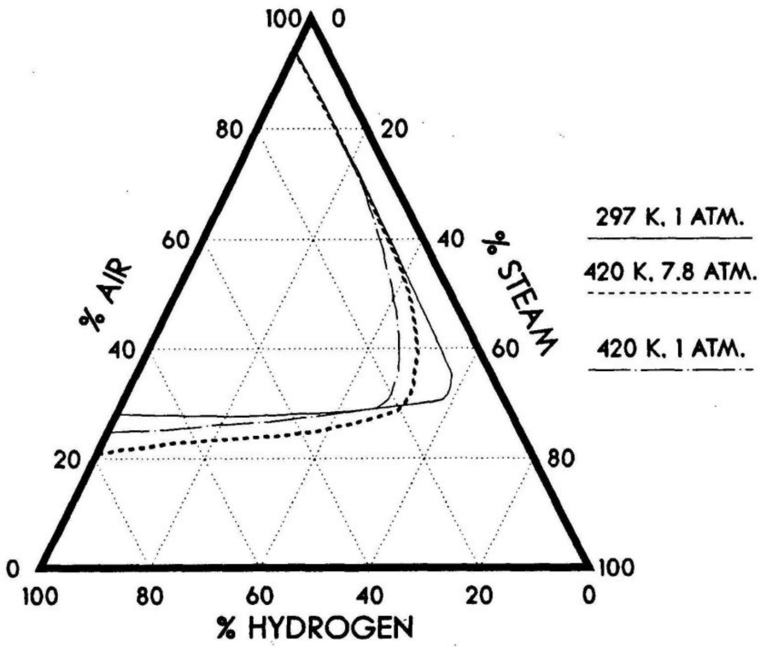

FIG. 3. Flammability limit of H_2/air /steam mixtures initially at different temperature and pressure conditions. Figure modified from [28].

As shown in FIG.4, when the turbulent velocity fluctuation increases from 0 m/s (quiescent mixture) to 2.81 m/s, the minimum percentage of hydrogen in air below which no ignition was obtained also increases from 4.4 to 5.6 %. These results show the importance of considering not only the thermodynamic conditions when evaluating the possible initiation of combustion, but also the effect of turbulence level inside containment on combustion behavior must be assessed.

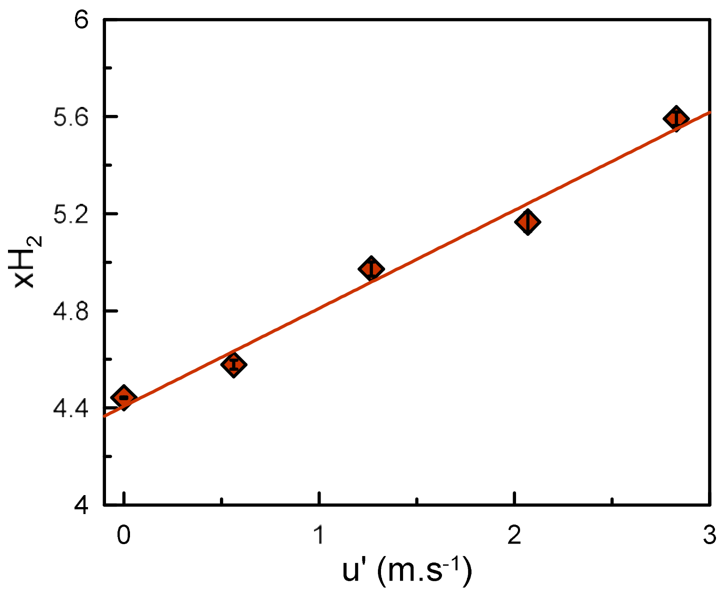

FIG.4. Evolution of the lower flammability limit with the turbulence level generated in a closed spherical vessel. The mixture was constituted of H_2+air initially at 1 bar and 293 K (u' represents the turbulent velocity fluctuation)[30]

In a similar way, the effect of spray droplets on lower flammability limit as shown in FIG. 5 had been investigated ([31], [32]). It has been shown that sprays affect: (i) the lower flammability limit, (ii) the incomplete combustion region (Z2 in Fig. 5), and (iii) the domain of complete combustions (Z3 in Fig. 5).

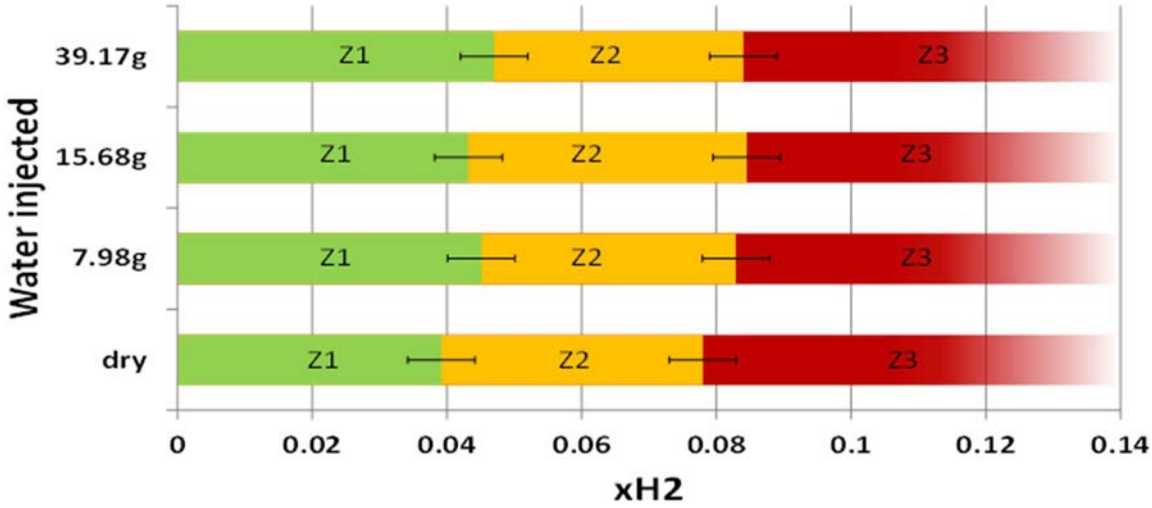

FIG. 5. Flammability limits of H_2-Air mixtures in the presence of spray water (Z1: no combustion, Z2: incomplete combustion, Z3: complete combustion) [31].

In zones directly exposed to the spray, hydrogen combustion as a slow or fast deflagration may also be moderated by spray operation depending on the prevailing conditions, such as enhanced gas turbulence generated by the falling droplets. Experimental investigation on the influence of spray droplets as well as spray induced flow conditions on hydrogen combustion have been conducted in the technical-scale THAI test facility [33]. For the investigated test conditions in THAI, spray operation particularly in tests with upward burn was determined to reduce peak pressure and temperature. Flame quenching by cooling of the reaction zone is the dominant effect of the spray. In addition, the steam produced by vaporization of water droplets acts as a heat sink which reduces peak pressure and peak temperature. An increase in peak pressure as compared to the test without spray was observed for the test with downward burn. Higher peak pressure in downward burn occurred due to spray induced large scale turbulent convection flow and the related high flame speed as compared to the reference test without spray [33].

Effect of CO

Significant amounts of CO may be released together with H_2 from MCCI (dependent on concrete composition) in the containment in the long term after RPV failure. The effect of CO on combustible gas compositions and the flammability limit is discussed in [19] and summarized there as follows:

> "The flammability limit of H_2 in air is 4 % H_2 at the lean limit for upward propagation and 75 % H_2 at the rich limit for both upward and downward propagation. Addition of

up to 12.5 % CO to a lean-limit H_2–air mixture is not expected to change the flammability limits of H_2–air mixtures. Thus, all mixtures containing >4 % H_2 or >12.5 % CO will burn provided the oxygen limit is not reached. The oxygen limit is the same, about 5 %, for both CO/air (with traces of H_2 or H_2O) and H_2/air mixtures. Karim et al. (1985)[34] have obtained flammability data in air for several binary fuel mixtures including CO and H_2. Their results indicate that Le Chatelier's Rule is surprisingly accurate in predicting the limits. In fact, the discrepancy between the measured and calculated values is less than 1 %."

Within the European HTR R&D project ARCHER (Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D), the flammability limits of two specific H_2/CO mixtures where studied with different diluents, namely carbon dioxide and He [35]. In the case of a mixture constituted of fuel {67.73 % H_2 + 32.27 % CO} in air/CO_2, the lower flammability was found to be equal to 5.22 % of the mixture. The Le Châtelier rule predicts a limit of 5.24 % when considering the limit of pure CO for dry mixtures which is 15 %. The upper flammability limit was found to be equal to 70.6 % of the mixture. The Le Châtelier rule is not valid for upper flammability limit. Finally, the flammability domain was measured at an initial pressure of 1 bar and at ambient temperature as shown in FIG. 6.

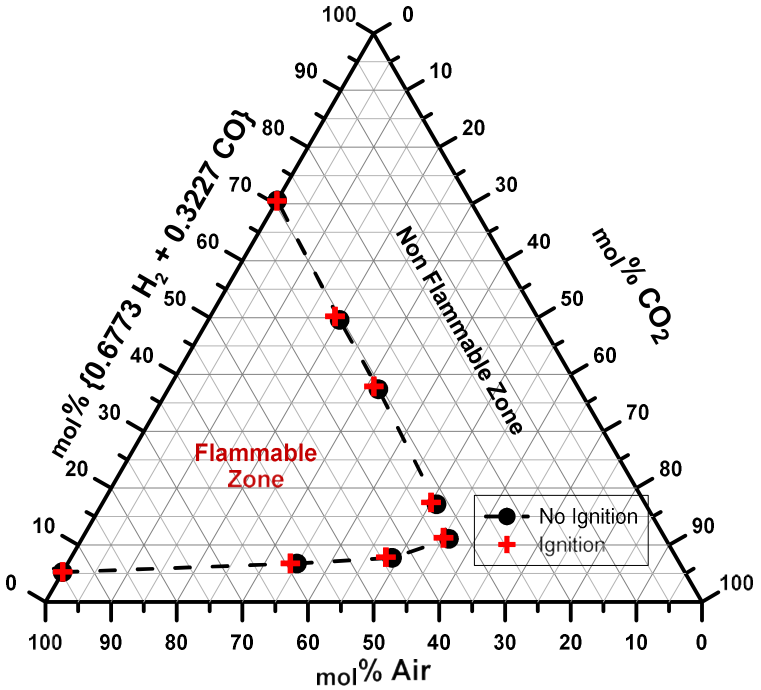

FIG. 6. Flammability limit of {67.73 % H_2 + 32.27 % CO}/air/CO_2 mixtures initially at 1 bar and 296 K [35].

Despite the effort made to characterize the flammability limits of gaseous containment atmosphere representing both in-vessel and ex-vessel phases of a severe accident, further investigations are still needed to study the effect that low oxygen concentrations, initial high temperature and pressure may have on the flammability limits.

2.3.2. Combustion regimes

In a mixture known to be flammable, combustion may be triggered by an energy source of a few millijoules. Consequently, in the presence of electrical power sources or hot points, it seems reasonable that an ignition would occur soon after the gas mixture enters the flammability domain. In contrast, a stronger energy source (at least 100 kJ) is required to trigger a stable detonation. Due to hydrodynamic instabilities and turbulence (primarily caused by obstacles in the flame's path), an initially laminar deflagration (with a flame velocity of around few m/s) may accelerate. Rapid combustion conditions may also develop, involving rapid deflagration (a few 100 m/s), DDT and detonation (over 1000 m/s) [18]. These combustion phenomena pose the biggest threat to the mechanical integrity of the containment building, reactor building and the safety components integrity, as they can produce very large, localized dynamic loads. The higher the combustion speed, the higher the pressure peak, albeit with a shorter peak application time. Nevertheless, direct detonation can be ruled out for practical purposes; the only mechanism considered likely to provoke a detonation is a flame acceleration (FA) leading to DDT. The OECD/NEA State of the Art Report on Flame Acceleration and Deflagration-to-Detonation Transition [18] as well as the IAEA-TECDOC-1196 [15] addresses the key issue of hydrogen combustion. Additional detailed information is found in the OECD/NEA report [19] related to carbon monoxide combustion.

Slow deflagration

In a quiescent medium (no turbulence, no obstacles), the flame will propagate at a speed different from the laminar flame speed, which is characteristic of the combustible mixture composition and the thermodynamic state (initial temperature and pressure). The speed, at which the flame propagates, called burning speed, depends on the geometry as well. When a planar flame propagates inside a containment, the burning speed is proportional to laminar flame speed, the proportionality factor in this case is the ratio between fresh and burnt gases densities:

$$\sigma = \rho_u / \rho \qquad (1)$$

However, in a real configuration a flame is never plane but curved and consequently it will be stretched ([36][37]). The stretch rate will also modify the burning speed. In addition, the flame will accelerate due to instabilities that can be of different nature (thermo-diffusive, hydrodynamic, buoyancy). Indeed, lean H_2/air mixtures are inherently unstable and develop a wrinkled surface as they grow in size. The onset of the flame folding occurs at a given radius of the flame and this critical radius decreases when the hydrogen content is lowered. FIG. 7 illustrates the evolution of the burning speed versus the stretch rate (which is inversely proportional to the flame radius). When the radius of the flame is below the critical one, the flame is smooth and its velocity decreases as the flame grows (and hence the stretch rate diminishes). However, as soon as the flame begins to fold (marked by the symbol © in FIG. 7, the burning speed increases drastically. The flame folding is responsible for a large increase in the flame area leading to a larger burning rate. One can then define a wrinkling amplification factor of the flame speed. This amplification factor depends not only on the hydrogen molar fraction in the mixture but also on the size of the flame [38].

As already discussed, the higher is the flame speed, the higher is the pressure induced by combustion. The combustions at low gas concentrations between 4–8 vol. % are typically incomplete processes. Experimental results showed that the completeness of combustion in quiescent mixtures increases with increasing hydrogen concentration and is near 100 % at 8–10 vol. % hydrogen. Thus, incomplete combustion of a H2–air mixture at low hydrogen concentration can be a method of consuming hydrogen without a significant increase of containment pressure [13].

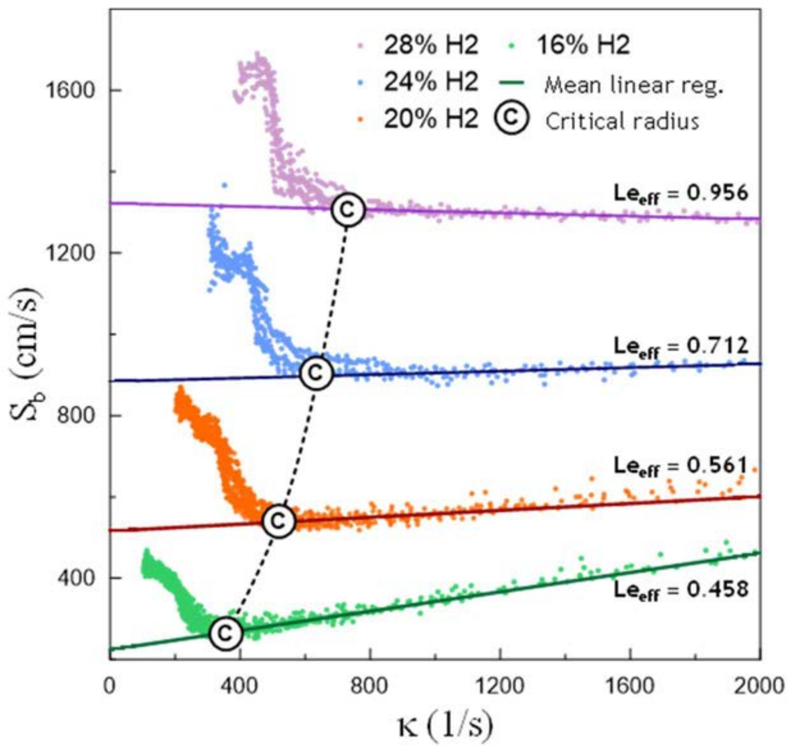

FIG. 7. Burning speed evolution versus stretch rate for H_2/air mixtures initially at 1 bar and 295 K [35]. Le_{eff} is effective Lewis number of the mixture.

Concerning the effect of geometry on slow hydrogen behavior, recent experiments conducted in THAI$^+$ facility (two-vessel configuration) have provided additional insights on hydrogen combustion behavior in a multi-compartment system [33]. As compared to the jet-ignition effect observed in multi-compartment Battelle Model Containment (BMC) test facility, which occurred at about 9–10 vol. % [38], jet ignition in THAI$^+$ was identified at much smaller hydrogen concentrations of about 6 vol. % [33]. The tests carried out in BMC and THAI$^+$ differs in terms of geometrical arrangement of the connected compartments and also in terms of distribution of the burned and unburned gases in the compartment into which flame enters. Review of experimental research on slow hydrogen deflagration with premixed and stratified atmosphere in single- and multi-compartment facilities including the scaling effect is provided in [39].

Fast deflagration / flame acceleration

Due to hydrodynamic instabilities and turbulence (primarily caused by obstacles in the flame's path), an initially laminar deflagration flame may accelerate and reach a high speed inducing then high pressure loads which may endanger the containment and the safety components integrity. The process of flame acceleration is described in [18] as follows:

"A freely expanding flame is intrinsically unstable. It has been demonstrated, both in laboratory-scale experiments and large-scale experiments, that obstacles located along the path of an expanding flame can cause rapid flame acceleration.… Turbulence increases the local burning rate by increasing both the surface area of the flame and the transport of local mass and energy. An overall higher burning rate, in turn, produces a higher flow velocity in the unburned gas. This feedback loop results in a continuous acceleration of the propagating flame. Under appropriate conditions, this can lead to transition to detonation (DDT)."

Flame acceleration criteria

To identify the conditions allowing the flame acceleration, numerous experimental programmes have been conducted on flame propagation in a premixed atmosphere containing hydrogen. Based on these programme's results and in order to identify the dangerous configurations that may lead to fast flame propagation and consequently to dynamic loads, prerequisite criteria, i.e. conditions required for the various combustion modes, have been developed. Two types of criteria have been defined as follows:

- The criterion "σ" concerns the flame acceleration. The value σ is the mixture expansion factor, i. e. the ratio between the cold gas and burnt gas densities at a constant pressure, and so is an intrinsic property of the mixture in question. The critical value σ^* above which flame acceleration is possible depends on the gases initial temperature and the flame stability and has been determined using the results of many experiments at different scales and in different geometries.
- The criterion "λ" concerns the DDT. The necessary conditions have been established for assessing the possibility of DDT. These are based on comparing a length d typical of the studied chamber geometry with the size of the detonation cells (marked λ) characterizing the mixture sensitivity.

With the mentioned criteria, it was easy to characterize gaseous mixture leading to fast combustion regimes as shown in FIG. 8 [18].

The established flame acceleration (FA) criterion was extended to multi-compartment geometry in the framework of EU project HYCOM [40]. Indeed, in cases of complex flow geometry, combustion processes can be affected by the change of cross section along the flame path, or by lateral venting. Thus, the venting decreases the effective expansion of the products, and a more energetic mixture (larger σ) is necessary for strong FA. Thus, the effect of lateral venting on σ* value is expressed as follows:

$$\sigma^* = \sigma_0^*(1 + 2.24\alpha) \quad (2)$$

where α represents the ratio of the lateral surface opening per cross section of the flame path.

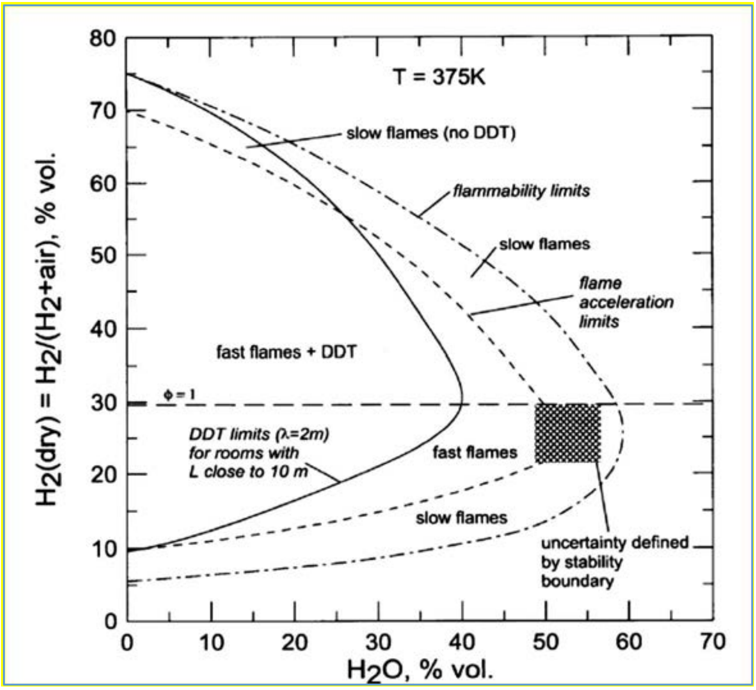

FIG. 8. Limits and possible regimes of combustion for hydrogen-air-steam mixtures at 375 K and 1,01325bar (1atm) [18].

According to [41], the σ criteria had been revised to take into account the effect that the initial temperature may have on flame propagation. Despite the accomplished work, additional investigations are still needed [42] to cover a broad range of configurations anticipated in case of a severe accident:

— Flame acceleration criteria used to discriminate a priori between (i) mixtures that have the potential to accelerate strongly, and hence induce a large pressure overload and (ii) mixtures that cannot sustain a strong acceleration and as a consequence will induce a limited overpressure if not at all. This empirical criterion based on experimental data needs to be revised 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 mixture expansion ratio, in the detonation cell size data, the laminar burning velocity, the laminar flame thickness and the turbulent flame velocity;
— Extension of the flame acceleration criteria to stratified conditions;

- Extension of the flame acceleration criteria to the ex-vessel conditions ($H_2/O_2/N_2/CO/CO_2/H_2O$ mixtures);
- Investigation of the spray initial temperature effect on the flame-spray interaction;
- Improvement of the flame-structure interaction mechanism knowledge;
- Determination of flammability domain and ignition energy/type for the ex-vessel conditions ($H_2/O_2/N_2/CO/CO_2/H_2O$ mixtures); and
- Investigation of the PAR behavior under combined conditions of lean O_2, high pressure, high temperature, high humidity, CO, CO_2, H_2.

2.4. MITIGATION OF COMBUSTIBLE GASES

Recombination of combustible gases such as H_2 and CO with oxygen will produce H_2O and CO_2, respectively. Recombination processes with oxygen can start already at concentrations below the flammability limits. Thermal recombiners as well as PARs are used in NPPs to remove combustible gases. The heat of reaction is used to produce natural convective flow over suitably arranged recombiner surfaces. While thermal recombiners are typically designed to cover the design basis accident in NPPs and require power to be operated, PARs do not need external power or operator actions and have been well established as a mitigation measure for operation under severe accident conditions especially in large dry containments. Igniter systems may be needed in case faster hydrogen release rates are expected which cannot be dealt with by PAR systems or for implementation in smaller containments. Recombiner operation in general increases convection in containment compartments, thereby promoting gas mixing. Mitigation strategies are explained in the following Chapter 3.

3. COMBUSTIBLE GAS MITIGATION AND ACCIDENT MANAGEMENT

First hydrogen mitigation measures have already been developed after the severe accident in TMI-2 in 1979 as part of the overall severe accident management (SAM) programmes being established in Europe and U.S.A. especially. Several documents exist with related information on (severe) accident management in general including hydrogen management e.g. from EU the project SAMIME [43], the IAEA TECDOC [14], the OECD/NEA CSNI SOAR on hydrogen management [13]. Further latest developments are available from national reports to the IAEA Convention of Nuclear Safety [44], or the ENSREG stress test [45] performed after Fukushima Daiichi accident and the follow-up national action plans in which the status of the implemented SAM measures is described. As well in U.S.A. many activities have been performed to reassess the SAM programs and to consider lessons learned from the Fukushima Daiichi accident for improving the safety of U.S. NPPs ([46][47]).

In the EU SAMIME project report of 2000 [43] it is stated: "In most partners' countries a certain level of severe accident management has been introduced as a means to further enhance nuclear safety, either as a utility initiative or following a regulatory requirement." It has been developed on a utility- or country-specific basis, i.e. without uniform guidance or standard. The volume and extent vary considerably: some use add-ons on their EOPs, others have systems in place primarily directed to restore lost safety functions, again others use handbooks to guide plant personnel through the accident. Most U.S. type NPPs (and some others) follow the extensive guidance set up by the U.S. Owners Groups and implemented by all utilities in the U.S. at the end of 1998.

3.1. COMBUSTIBLE GASES MITIGATION STRATEGIES

To limit the combustible gas concentration in the containment, the strategies adopted are usually based on the following methods:

- *Recombination*: For the purpose of combustible gases recombination under beyond design basis accident conditions, PARs are generally employed. While thermal recombiners require energy and mainly used to reduce hydrogen concentration below lower flammability limit of about 4.1 vol. % (at ambient pressure and temperature conditions), passive recombiners use catalysts to oxidize (recombine), combustible gases such as hydrogen, carbon monoxide and are also operable outside the lower flammability limit for hydrogen. Both thermal and passive recombiners may also act as igniters after a certain concentration of combustible gases and therefore the PAR induced ignition behavior has been subjected to experimental and analytical research in the framework of recent national and international programs, e.g. OECD/NEA THAI projects ([11], [48]).
- *Deliberate ignition*: The purpose of a deliberate ignition is to consume the flammable gas by combustion at low concentrations while distributing the energy release spatially

and temporally. Different types of igniters are available: glow plug igniters, spark igniters, catalytic igniters [14].

— *Venting*: In a venting process, containment atmosphere is vented deliberately ensuring removal of gases present in the gas mixture; so combustible gases are released as well resulting into decrease in containment pressure as well. If filters are applied, it also allows retention of fission products and thereby reduction in potential "source term" to the environment.
— *Inertization*: aims to maintain the containment atmosphere non-flammable through inert gas (nitrogen) injection. To this end, the oxygen in the gas mixture should be maintained lower than ~5 % to eliminate the risk of hydrogen combustion in the containment. This strategy is referred to as "pre-inertization" and typically nitrogen is used to replace the air in the containment. Most of the BWRs with small containments have implemented this measure already during normal operation of the plant. In some larger BWR plants (like the German BWR type 72) it is combined with a hydrogen recombination concept, as only parts of the containment are inertized. If post-inertization strategy is adopted, then inert gases are injected during the accident progression. In case of post-inertization as the amount of inert gases needs to be adjusted as per the gas-composition in containment to keep the pressure level below design pressure limits, the amount and volumetric concentration of inert gases may be lower as compared to pre-inertization.
— *Mixing of the atmosphere* (e.g., through operation of mixing fans): can be a measure to ensure the homogenization of the atmosphere in a way that local high challenging concentrations are prevented and that in all compartments of the containment the formation of flammable gas mixtures is prevented.

Hydrogen mitigation strategy can be implemented by one or a combination of the previous methods. The choice of a mitigation strategy depends primarily on the design of the containment and on the safety requirements adopted in each country [13] and different methodologies are being discussed, e.g. [49]. Thus, for BWR, strategies for maintaining "safe conditions" (are understood here as inert conditions) are typically strategies with "pre-inertization" of the atmosphere (maintaining non-flammable conditions) typically through maintaining high concentration of inertizing gases especially nitrogen respectively low concentrations of oxygen. Various other measures, such as maintaining high concentration of inertizing gases such as carbon dioxide or steam or strategies with dilution of burnable gases to limit their concentrations, are as well possible. Maintaining inertization of the atmosphere means prevention of combustion by maintaining high concentration of combustion-inhibiting gases so that the gas composition is outside the flammability zone (Section 2.3.1). Steam inertization requires more than 55 % of steam whatever the concentrations of flammable gases and oxygen is. Inertization by other gases (i.e. suppression of combustions at all hydrogen concentrations) is possible only when the carbon dioxide concentration exceeds ~60 % in air or the nitrogen concentration exceeds ~75 % ([13], [14]).

Implementation of "post-inertization" strategy could be related with different implications, since the quantity of diluent gas and the time needed to inert the containment could be quite large and the measure needs to be completed before the hydrogen / combustible gas release into the containment starts. The release of significant masses of steam from the reactor coolant system or any other source into to the containment during the progression of the accident could support those measures, however, uncontrollable condensation of steam on containment walls and structures or the use of engineered safety systems such as containment coolers or sprays can limit the applicability of such a strategy.

The possibility of employing alternative sources of steam to inertize the containment has also been explored and already established in some NPPs, e.g., the Borssele NPP, Netherlands, where auxiliary steam boilers are used [14] or the Paks NPP, Hungary, where the steam generators are considered as a source of steam in scenarios with large loss of coolant accident when the steam generator inventory of the secondary side is not exhausted [50].

The igniter technology is established as a method of preventing challenging combustions by ensuring ignition at low concentration as soon as flammable mixtures arise [14]. Igniters could deal with higher hydrogen flow rates than PARs but they have to be appropriately located, and especially a glow plug system needs external power. Therefore, reliable power supply and igniter placement are important for the effective reduction of hydrogen concentration. Implementation of igniters requires study of gas flow patterns in representative scenarios to optimize location selection. Igniters and PARs are not mutually exclusive solutions; they can be used in some combinations to improve the hydrogen control.

The PARs use platinum and/or palladium based catalysts to oxidize (recombine) hydrogen, which usually accomplish the chemical reaction at lower temperatures, in a wider hydrogen/oxygen concentration range, and even under steam inerted conditions and over longer times than it would be with gas combustion [14]. PARs are available in different designs. They vary in the shape of the reacting surfaces (flat plate, pellets contained in cartridges or honeycomb structures) and the layout of the channel box enhancing the flow natural flow conditions. The working principle of these PARs is almost identical, but the difference in the design may affect the recombination efficiency and their performance under specific accident conditions, such as low oxygen concentrations and CO/CO_2 containing atmosphere.

Regardless of the adopted mitigation strategies, the followed objective should finally result in a long-term controlled and stable state of the NPP, being one of the goals of all SAM programs.

3.2. IMPLEMENTATION OF HYDROGEN MONITORING SYSTEMS

The activation of Accident Management (AM) measures such as safety injection, containment spray or filtered venting is based on information provided in Emergency Operating Procedures (EOP) or Severe Accident Management Guidelines (SAMG) and requires insights in the hydrogen concentration inside the reactor containment. Such systems are not standard in many plants. With regard to plant updates done for SAM many countries have adopted a pragmatic approach first, i.e. to start from the plant ‘as is’ and to give guidance to the operators in order to help them manage core melt accidents with existing equipment, rather than implementing additional measures or instrumentation. This is for example the approach followed in U.S. by the plant Owners Groups, e.g. by Westinghouse Owners Group (WOG) in developing SAMG that could be generically applicable to the majority of PWR plants employing a Westinghouse Nuclear Steam Supply System. In this case alternative information might be used if e.g. the hydrogen concentration in the containment is unknown. Other countries, especially in Europe have updated their plants by several systems in addition to the implementation of SAMG [43]. The Fukushima Daiichi accident, with the expected hydrogen stratification in the reactor building and the induced combustion, illustrated the importance of being able to characterize combustible gas conditions within the containment as well as the surrounding building.

In fact, the application of SAMG illustrated the point that decision making related to accident management actions (such as containment venting or actuating containment sprays) could be better informed if the operators had knowledge of the time-dependent gas composition in containment.

Several monitoring systems exist and based mostly on gas sampling or on the use of catalytic reaction [43]. These systems suffer from significant lag times to provide information in a dynamic environment or are sensitive to poisoning (e.g. by CO or combustion products) and may exhibit cross-sensitivity with other gases.

The knowledge gap in this area is predominately equipment related. It concerns:

- Possibility to be deployed in multiple locations inside containment in order to provide an overview on the flammability propensity of the containment atmosphere;
- Survivability in-containment severe accident environmental conditions for an extended period of time;
- Ability to provide rapid response; and
- Possibility to measure overall flammability in the presence of hydrogen and carbon monoxide.

Some developments are ongoing with the aim to answer the above-mentioned knowledge gaps ([8], [42]). The development of SAM measures that includes implementation of combustible gas mitigation strategies, including monitoring systems, is based on the use of analytical tools. In the following, an overview on status of analytical tools based on different modelling approaches, such as lumped parameter (LP) and computational fluid dynamics (CFD) is provided.

4. ANALYSIS TOOLS

Traditionally, the numerical method is split into a lumped parameter (LP) method and a multi-dimensional method. In the frame of multi-scale approach proposed by Yadigaroglu [51], LP method is thought to be useful for system scale (macro scale) analysis. On the contrary, computational fluid dynamics (CFD) is applicable to component (meso scale) or detail (micro scale) analysis.

4.1. LP CODES

The LP codes, as MELCOR [52], MAAP [53], ASTEC [54] and AC^2 [55] traditionally used to simulate severe accidents in NPPs cover main aspects of in-vessel and ex-vessel severe accident phenomena, such as thermo-hydraulic response in the reactor coolant system and containment, core heat-up, core degradation and relocation, fission product release and transport, direct containment heating, MCCI, etc. These integrated codes employ simpler physics, models and calculation methods to simulate various complex severe accident phenomena over a long time period. The biggest advantage of these codes is to calculate a long time transient in an acceptable computation time. They have been widely used by the utilities, research institutions or regulatory bodies in the countries of the writing group for this report. The application involves various purposes, such as research and development, safety analysis, licensing, and periodic assessments. These codes are continuously under review and validated against new experimental data.

These codes have demonstrated, through benchmarks organized in the framework of OECD/NEA NEA projects (ISPs) and European projects, their capacity to calculate hydrogen distribution, as well as their limits, in small- and large-scale experiments, with or without the use of spray system and considering or not the effect that recombiners may have on the hydrogen distribution. They do however require a special dataset to be able to predict all the potential flows in a reactor, particularly in volumes where concentration gradients may exist (stratification, jets, etc.). These benchmarks highlighted also the importance of the “blind” exercises to assess the predictive aspect of the codes, produced a wide array of results. Actually, the outcomes from the OECD/NEA ISP-47 [56] and the OECD/NEA THAI HM-2 benchmark [57] related to hydrogen distribution reveal the strong user-dependent variability and consequently the need of “best practice guidelines” to overcome this problem.

To this end, several analytical activities had been performed in the framework of the EU-ERCOSAM [58] and the EU-SARNET projects with the aim to address the user and scaling effects. Thus, several plant calculations of severe accident sequences had been scaled down to define initial and boundary conditions for the experiments performed in TOSQAN, MISTRA and PANDA test facilities having different dimensions. The results of tests analyses were then used to derive rules for reactor application. Such rules had been investigated also in the framework of the “generic containment” benchmark performed within the EU-SARNET project [59]. The results of this benchmark indicate that, even though the problem was well defined, and the calculations were performed by experienced users, the uncertainty of calculated results due to different modelling approaches and users may be much higher than commonly expected. For this reason, it is recommended not only to verify the input models but also to perform at least two independent calculations for decision-making procedures such as licensing, safety and design support analyses. Independent calculations imply either different codes and users ('fully independent') or the use of different codes by the same user or the use of the same code by different users (both 'partly independent').

Concerning the estimation of the loads generated by hydrogen combustion, the OECD/NEA ISP-49 [60] and the EU-SARNET [61] hydrogen combustion benchmarks results show the ability of LP codes to predict loads induced by slow flame for which pressure loads can be considered as static.

4.2. MULTIDIMENSIONAL CODES

The codes that use a multidimensional approach, such as GOTHIC [62], GASFLOW [63] or TONUS [64], can model complex flows much more precisely and so can be used to complete the studies conducted using the codes listed above in the case of complex flows. They may be of limited use in some cases, however, due to the geometric complexity of the containment's internal structures as well as to the costs involved, which may be considerable.

The comparative computational exercises, such as ISP-47 [56] and ECORA [65], performed before Fukushima Daiichi accident, showed that the main limitation in the use of this type of computational code lay in the computation of large-scale slow transients. In fact, the existing means of computation were not powerful enough to allow computation convergence or mesh sensitivity over time to be studied. Moreover, the ISP-47 outcomes showed that CFD tools have not shown any significant advantages over the multi-compartment tools, possibly due to the relatively simple flow structures in the case of the TOSQAN, MISTRA or THAI tests.

The progress made through EU/ERCOSAM and OECD/NEA SETH and THAI programs as well as the improvement of the computation machine capacity, lead to a real increase of the CFD ability to address both hydrogen distribution and combustion. As evidence, these tools were used successfully to design and validate the combustible gas control system of the EPR reactor [66].

5. POST-FUKUSHIMA DAIICHI ACCIDENT REPRIORITIZATION

Based on what has been known about hydrogen behavior since 1980, the explosions and damage to reactor buildings at the Fukushima Daiichi plant should not have been that surprising. They illustrate in dramatic fashion the importance of hydrogen/combustible gas control in severe accidents in NPPs. The hydrogen explosions in Units 1, 3, and 4 at Fukushima Daiichi caused severe structural damages to reactor buildings, created pathways for radioactive material releases to the environment, and greatly impeded onsite accident responses. The explosions also caused damage to fuel handling equipment and cooling systems for the SFPs. If the integrity of the SFPs had been compromised, large additional releases of radioactive materials to the environment might have occurred [3]. The accident highlighted the need to examine the adequacy of current hydrogen mitigation measures in some types of reactor containments and triggered discussion on necessary extension of such measures to premises outside the containment, e.g. in the reactor building or the SFP area.

The Fukushima Daiichi accident demonstrated also in a dramatic way that preventing hydrogen combustions inside the containment by N_2-inertization (only) is adequate for the containment but may not be sufficient for preventing combustible gas explosions in surrounding buildings if the containment fails and results into transfer of the combustible gases in surrounding buildings initially at ambient pressure/temperature conditions (potential of steam condensation). Here, the availability of the system installed to vent the containment would be another key accident management procedure. The system must be available to the operators even under adverse environmental conditions, though setting a minimum release limit of fission products through the system is another requirement.

Thus, several research and development programmes have been launched with the objectives to fill the gap of knowledge regarding combustible gas distribution, recombination and combustion including the structure response to combustion loads. The development of new gas monitoring system was also initiated. The knowledge gained then aims to improve the SAM by enhancing the mitigation system and process.

5.1. IMPROVEMENT OF KNOWLEDGE RELATED TO HYDROGEN PHENOMENA

5.1.1. Distribution

The work performed in the framework of the THAI and HYMERES programmes provide valuable experimental data for the LP and CFD code validation. The conducted experimental investigations have been increasingly complex in nature and included coupled effect or integral tests mostly with the effect of safety system (spray, recombiner and cooler) on the hydrogen distribution. Considering safety relevance of local hydrogen accumulation in the containment building, the build-up of hydrogen stratification and its erosion due to the operation of the mentioned safety systems are investigated. The analytical work performed in the framework of THAI, HYMERES as well as by individual organizations have supported in gas distribution related model development work.

Nevertheless, further investigations are still needed to address situations related to the late phase of a severe accident progression. Indeed, only few data related to H_2/CO distribution in representative condition of MCCI phase, to H_2/CO migration into the auxiliary buildings are available.

5.1.2. Recombination

For PAR performance behavior under simplified experimental conditions representative of in-vessel accident scenario (i.e. initially quiescent atmosphere, well defined mixture of hydrogen, air and steam), a large database for model development and validation exists based on the OECD/NEA and national THAI programmes [67],[68] and the REKO programme at JÜLICH [69][70][71]. The simulation of the PAR behavior under these conditions has reached a good level of maturity.

Significant progress in knowledge has been achieved on the behavior (onset of recombination, recombination rate and ignition potential) of different PAR designs under severe accident typical conditions. The important results relevant for safety and source term concern the PAR ignition characterization, and PAR behavior in an oxygen starved atmosphere and the effect that PAR operation may have on the thermal decomposition of CsI into molecular iodine [72]. Concerning PAR ignition issue, there has been enhanced focus to consider PAR induced ignition behavior in accident modelling and PSA studies, e.g. [73][74].

Nevertheless, the boundary conditions during a severe accident include more challenges, as the gas mixture at the late phase will include not only hydrogen and steam, but also carbon monoxide and carbon dioxide from MCCI at rather low-oxygen conditions. In the THAI and REKO programmes, first studies of sequential and parallel hydrogen and carbon monoxide recombination, as well as the impact of O_2 lean conditions have been performed ([68], [71]). The potential consequences of PAR poisoning by CO has been highlighted in a numerical study considering these findings [75]. These investigations are continued in the framework of the NUGENIA/SAMHYCO-NET programme [42].

5.1.3. Combustion

After the Fukushima Daiichi events, investigations were mostly focused on the review of the flammability limits, on the characterization of the turbulent flame, on the extension of flame acceleration criteria to cover heterogeneous mixtures, multi-compartment geometry and on effect that spray may have on hydrogen flame propagation [8] [31][39].

Despite the effort made so far, there are still remaining uncertainties in the determination of the critical conditions, including critical values of mixture expansion ratio, in the detonation cell size data, the laminar burning velocity, and the laminar flame thickness.

In addition, the flame propagation in representative gas mixture of a late phase of severe accident is poorly investigated. The possible impact of reactor typical conditions (e.g. geometry, turbulence effects, gas composition), and transfer of experimental results to reactor case remain to be the topic of high priority for hydrogen combustion related experimental and analytical research. Some of the aforesaid investigations are planned to be continued in the framework of the NUGENIA/SAMHYCO-NET programme [42].

5.2. IMPROVEMENT OF TOOLS ABILITY

The analytical activities performed in the framework of the OECD/NEA and the EU programmes show an increase of the CFD maturity [57][58][76][77]. On the other hand, LP codes such as the integral codes MELCOR [52], MAAP [53], ASTEC [54], and ATHLET-CD/COCOSYS (today AC²) [55] have been continuously improved in their capabilities. MELCOR has been added convection terms in two-phase momentum equations. RELAP-3D [78], a 3D version of the RELAP code, has a multi-dimensional nodalization module similar to a CFD code. One of long-standing containment analysis codes GOTHIC [62] was developed as a LP code originating COBRA-TF [79]. Now, it can simulate a containment three-dimensionally using a Cartesian or cylindrical coordinate-based nodalization. So, it is believed that the LP codes may now resolve 3D behavior of flows in a component such as a reactor or containment.

CFD codes, as GASFLOW [63], are based on 3D nodalization but they use lumped models for PAR (passive auto-catalytic recombiner) and sink or source of mass and energy to reduce the number of nodes and efficiently simulate their thermal hydraulic phenomena.

It is not likely that LP-based code is only applicable to a system-scale analysis. Here, “turbulence-resolved method” [80] is used to distinguish the analytical methods. If GOTHIC is used for a containment analysis only with correlations or lumped model (e.g. not a localized model), it is a turbulence-unresolved approach. On the other hand, when a turbulent flow is simulated by GOTHIC with a turbulence model, it can be a turbulence-resolved approach. In the MELCOR or RELAP-3D codes, turbulence effect is lumped into the friction terms in momentum equations. So, these belong to a turbulence-unresolved approach even with a very fine nodalization.

The choice of modelling based on LP or CFD approaches must be applied carefully for an analysis of hydrogen behavior in NPPs. If turbulent characteristics in a flow field are not well resolved by the turbulence-resolved approach, the flow field may be poorly distorted, and sometimes it is worse than the correlation-based turbulence-unresolved solution. On the contrary, in the case that turbulent characteristics are well lumped into correlations used in the turbulence-unresolved approach, the solution can be better than a poorly resolved turbulent solution. Moreover, the outcomes of the performed analytical activities showed the benefit to use two-equation models to model the turbulence [57].

Concerning the hydrogen combustion, the performed analyses show that most of the existing codes are able to predict qualitatively the pressure evolution. Nevertheless, the flame speed maximum value is generally over predicted. This indicates that there are still limitations and weaknesses in the combustion models used in the different codes. These limitations concern the chemistry part, the turbulent combustion model and the coupling between the two models. An improvement of the combustion models is necessary in order to obtain consistent agreement between the flame regime and the pressure build-up predicted for a given configuration.

5.3. IMPROVEMENT OF STRATEGIES FOR COMBUSTIBLE GAS MITIGATION

Following the Fukushima Daiichi accident, the U.S. NRC issued orders requiring installation of reliable venting systems in reactors with Mark I and Mark II containments [46]. In June 2013 the U.S. NRC modified this order to require severe-accident capable venting systems. These vents should help to reduce hydrogen explosion hazards during severe accidents. It was judged that re-examination is needed of the potential hazards of hydrogen explosions within the secondary containment (i.e., reactor buildings) of Mark I and Mark II plants. Mitigation strategies such as deliberate ignition, installation of PARs, and post-accident inertization that have been previously examined for large dry containments could be re-examined for secondary containments.

The U.S. Electric Power Research Institute (EPRI) commissioned a revision to the “Severe Accident Management Guidance Technical Basis Report”. The new effort on the part of the nuclear industry was done to ensure that the existing SAMG were as effective as possible. The revised report was published in October 2012 [47]. This report is the first update of the original 1991 version, adding additional Candidate High Level Actions (CHLA) in Volume 1 and providing supporting technical information in Volume 2. New material addresses using sea water injection for reactor core cooling, common cause failures due to external events, cooling spent fuel pools, setting priorities in multi-unit events, containment isolation failure and hydrogen combustion within plant buildings. The report updates the original technical bases for SAMGs to reflect the lessons learned to date from the Fukushima Daiichi accident. The intent, as with the original report is to guide operators in developing new SAMG. Among the key findings and new material in the updated Technical Basis Report are the following:

- The Fukushima Daiichi accident also focused further attention on the management of hydrogen generated during a severe accident. The revised report provides an expanded treatment of the sources of hydrogen and of the potential need for venting of plant buildings and other measures to prevent serious hydrogen burns.
- The Fukushima Daiichi accident also focused attention on the potential for a severe accident involving the spent fuel pool. Accordingly, special attention should be given to the hydrogen management in spent fuel pool buildings.

The hydrogen combustion events at Units 1, 3, and 4 highlighted the importance of managing hydrogen in primary and secondary containments (for a BWR) as a means of limiting offsite consequences. The revised EPRI report incorporates an additional venting/ventilation CHLA for secondary containments to provide enhanced capability of coping with hydrogen in primary or secondary containments. The mentioned CHLA relates to the reactor building or the auxiliary building. It intends to provide ventilating/venting of buildings external to the primary containment that could accumulate larger amounts of combustible gases. The CHLA is intended to minimize the potential for formation and ignition of such a combustible gas mixture.

Although this CHLA deals with ventilation of secondary containment areas, the retention or controlled release of fission products from the buildings is, in many circumstances, another important issue. Its importance should be seen relative to the consequences of a sudden failure of a secondary containment structure due to combustion. Insights gained from the Fukushima Daiichi event are relevant in this respect. Following the combustion events at Units 1, 3, and 4, the damage that occurred to equipment, along with the disruption to efforts required to provide cooling to degraded reactor cores and the release of fission products, illustrated the consequences of a sudden failure of a reactor/auxiliary building. Actions to manage the challenges to plant structures are crucial to the orderly management of an accident.

If normal building ventilation is not available or is ineffective at mitigating the build-up of flammable concentrations in the reactor/auxiliary building, alternate strategies must be implemented to control the building atmospheric conditions. All those measures are to be seen in conjunction with the limitation of the fission product release from the building. Examples of alternative methods to re-establish reactor/auxiliary building ventilation are the following:

- Using alternative power supplies to re-establish power to a minimal but critical set of ventilation system components;
- Using portable power, exhaust, and recirculation equipment;
- Introducing natural circulation pathways through buildings by opening doors, windows, and other barriers at multiple levels of the building; and
- Introducing natural circulation flow using a chimney effect by creating openings at the lower and upper levels of the building.

The situation on the implementation of hydrogen / combustible gas counter measures in many European countries sometime after Fukushima Daiichi accident is summarized in the recent OECD/NEA CSNI Status report on hydrogen management published 2014 [13]:

- The report has identified that the hydrogen mitigation strategies vary from country to country and depend primarily on the design of the containments. For NPPs with large dry containment, such as PWR, PHWR, and VVER-1000, a combination of a large free containment volume, the use of PARs, and/or glow plug igniters is commonly used, whereas for NPPs with small containments, such as BWR Mark I, nitrogen inertization in the whole containment is typically applied.
- For the containment, and the reactor and auxiliary buildings, implementation of hydrogen mitigation measures is aimed in general to prevent and limit hydrogen explosion consequences. Therefore, depending on the NPP type, hydrogen mitigation measures are designed to meet specific safety criteria and requirements. In addition to mitigation measures, gas composition monitoring system is often used to check if the

requirements are satisfied and to provide relevant information to NPP operators during accident and SA conditions.

— While the deliberate ignition concept was explored especially in the USA after the TMI event leading to installation of glow plug igniters (active systems) especially into Mark III BWR containments or the US PWR and Finnish VVER-440 with ice condenser containments, effort was undertaken in Germany, France and Canada to find an alternative passive device. This led to the design of PARs by different manufacturers, especially Siemens/AREVA, NIS (Germany) and AECL (Canada) and the implementation into many plants worldwide.
— In response to the Fukushima Daiichi accidents, hydrogen mitigation systems, particularly PARs, are now required to be installed in most of the countries inside the containment if there was no mitigation concept required before. For the NPPs where the hydrogen mitigation systems are currently designed for design basis accidents (DBA) only, the existing systems are being evaluated and considered to be enhanced under SA conditions. Most countries have not yet adopted specific national requirements for hydrogen mitigation measures outside the containment (e.g., annulus, reactor or secondary building, etc.) or the spent fuel pool areas. Due to the Fukushima Daiichi accidents, many countries have started to study severe accident conditions within such areas and to consider hydrogen management outside of the primary containment (i.e., reactor building) and at the SFP area.

6. SUMMARY AND PERSPECTIVES

In the course of a severe accident, a substantial amount of combustible gases can be generated from the oxidation of zirconium and other metals or due to interactions between the molten core and concrete. The amount and composition of combustible gases may vary depending on failure vessel mode (in-vessel or ex-vessel). Appropriate provisions for the safe management of combustible gas behavior is required to ensure maintaining containment integrity to avoid fission product release to the environment (source term).

Since TMI-2 nuclear accident, combustible gas management has received special attention and safety regulations on this topic have been derived at national and international level and relevant guidelines and mitigation measures are already in place. Immediately following the TMI-2 severe accident, the U.S. Nuclear Regulatory Commission established a lessons-learned task force to analyze and evaluate the consequences of severe accidents and provide recommendations for changes to licensing requirements. Some of the changes were made related to the control of hydrogen during severe accidents included adding a hydrogen recombiner system or early venting of containment atmosphere by hardened vents to minimize fission product release to the environment.

Despite of a mature level of understanding about combustible gas management, significant uncertainty exists not only with the understanding of phenomena but with the determination of timing of different possible accident management actions. This was also demonstrated by Fukushima Daiichi accident, where the explosions occurred in Units 1 to 3 and damaged the reactor building of three reactor units at the site due to combustible gas releases from the N_2 inerted containments. Despite of combustible gas control inside the containment by the N_2 inertization, the explosions outside the containment in the reactor building could not be prevented as no mitigation measures for combustible gas control under severe accident existed. This underlined once more the known challenges caused by hydrogen and other combustible gas accumulation to the building's integrity in general and the need to further improve the hydrogen/combustible gas mitigation measures within the containment but also in surrounding reactor building.

Even though Fukushima Daiichi accident did not identify completely unknown combustible gas phenomena, the research activities based on Fukushima Daiichi accident have clearly underlined the need to investigate combustible gas behavior under broader range of accident scenarios and relevant boundary conditions. Another important aspect which requires further research and development in the light of Fukushima Daiichi accident is to put enhanced focus on long-term management of severe accident. The uncertainty on the timing of equipment recovery or mobile equipment availability result in need for comprehensive analysis considering different unfavorable conditions and assumptions to reveal all type of risk related with combustible gas generation, transport, accumulation as well as combustion potential. Due to extent of uncertainties, engineering judgement is considered as main approach for analysis of possible scenarios and phenomena, where needs to be further analyzed to lay down most relevant boundary conditions for combustible gas analysis under severe accident conditions.

Several national and international programmes have been launched in the wake of Fukushima Daiichi accident. These programmes have been performed with a specific focus to understand processes and phenomena under extended range of test conditions such as late phase of an accident (e.g. CO, O_2 lean atmosphere), interaction of safety components and their influence on containment conditions. The experimental programmes also aim to provide data for validation and further improvement of severe accident analysis codes.

In summary, future experimental and analytical research activities related to combustible gases will indeed be required to continuously enhance safety of nuclear reactors. Hydrogen mitigations systems require enhanced focus to ensure an optimal performance under extended range of severe accident conditions, e.g. carbon monoxide effect on PAR performance, in-containment source term due to high temperature produced by an operating PAR or hydrogen deflagration. The safety analysis tools based on different modelling approaches for application towards hydrogen/combustible gas behavior under severe accident conditions are being continuously improved as well as under development. Future experimental and analytical research including scaling effect and representative boundary conditions is necessary to further reduce uncertainty in application of modelling results to reactor application.

Finally, the IAEA safety standards of relevance to the scope of this publication are:

— IAEA Safety Standards Series No. SSR-2/1 (Rev.1), Safety of Nuclear Power Plants: Design, IAEA, Vienna (2016); Requirement 58, para 6.29 (b) deals specifically with the "control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment" [81];
— IAEA Safety Standards Series No. SSG-53, Design of the reactor containment and associated systems for nuclear power plants, IAEA, Vienna (2019); paragraphs 4.132–4.150 provide recommendations on how to fulfil the Requirement 58 from SSR-2/1 (Rev. 1) [82];
— IAEA Safety Standards Series No. NS-G-1.7, Protection against internal fires and explosions in the design of nuclear power plants, IAEA, Vienna (2004) [83].

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ANNEX I:
EXPERIMENTAL FACILITIES

I-1. CHINA

Name of the facility	HYMIT
Starting year of operation	2015
Organization	Shanghai Jiao Tong University (SJTU)
Brief description	The test facility HYMIT (**H**Ydrogen MItigation Test) focuses on hydrogen mitigation efficiency of ignitor and PAR under condition of spray, steam and iodine aerosols in the containment of light water reactors during severe accidents. It can be used for containment safety research under severe accident conditions too.
Dimension of the test facility	12 m^3, 4 m high, and 2 m in diameter
Design pressure / temperature	10 bar /200 °C
Main research fields	Hydrogen combustion, PAR performance, aerosols behavior
Projects/code benchmarks (selection)	Severe accident phenomenology project (Chinese national science and technology major project) ALISA project (CN-EU project)
Figure of the test facility	
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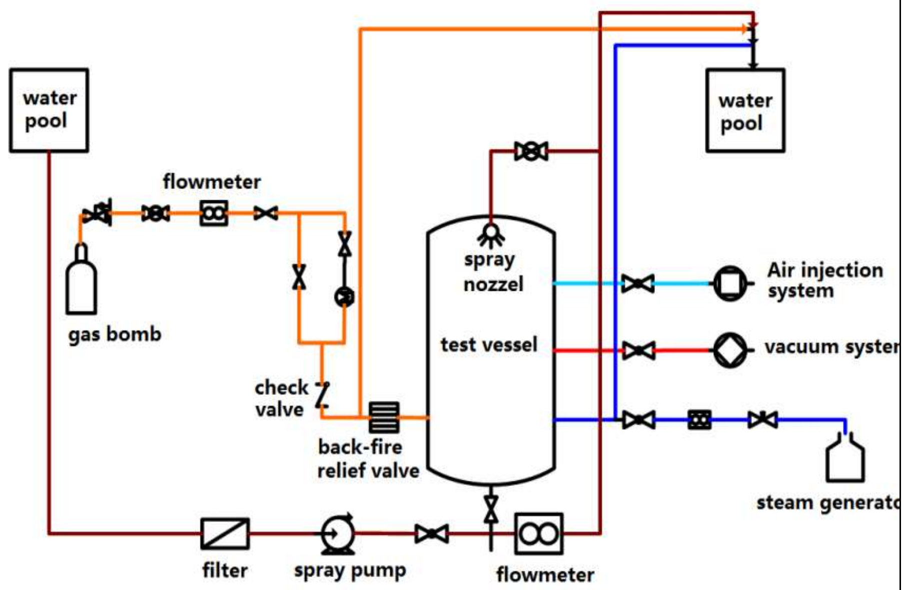
Name of the facility	MCTHBF
Starting year of operation	2014
Organization	Nuclear Power Institute of China
Brief description	The test facility MCTHBF aims at addressing open questions concerning gas distribution and combustion behavior of hydrogen in the containment of light water reactors during severe accidents. Used for containment safety research under severe accident conditions.
Dimension of the test facility	MTV (MCTHBF test Vessel): 20 m^3, 3.2 m high, and 2.8 m in diameter
Design pressure / temperature	22 bar /250 °C
Main research fields	Hydrogen distribution, hydrogen combustion, PAR performance
Projects/code benchmarks (selection)	ALISA (CN-EU) experiments of hydrogen distribution
Figure of the test facility	
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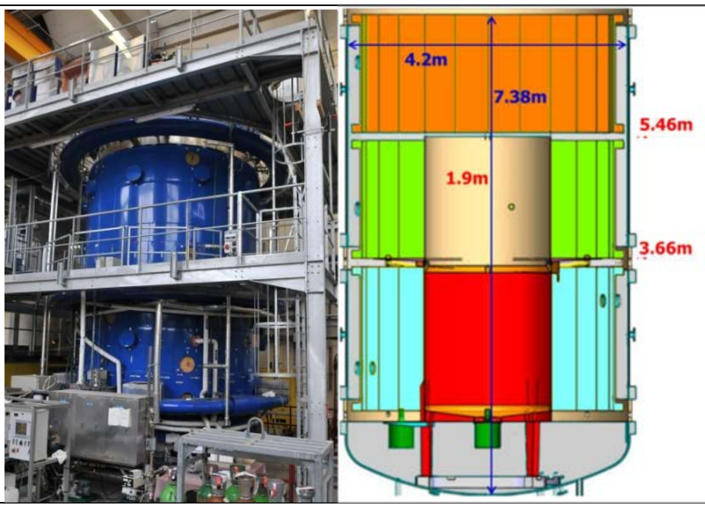
I-2. FRANCE

Name of the facility	**MISTRA**
Starting year of operation	1999
Organization	Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)
Brief description	The Mitigation STRAtification (MISTRA) facility is a medium scale pressure vessel in which several issues related to containment thermal hydraulics have been investigated i.e. film condensation in presence of non-condensable gases, containment spray efficiency, Passive Autocatalytic Recombiner (PAR) behavior, and gas mixing related to hydrogen risk.
Dimension of the test facility	MISTRA test vessel: 100 m^3, 7.4 m high, and 4.2 m in diameter
Design pressure / temperature	5 bar / 200°C
Main research fields	Containment thermal hydraulics, Hydrogen dispersion, wall condensation distribution, spray behavior
Projects/code benchmarks (selection)	OECD/NEA SETH-2, HYMERES, EC-SARNET, ERCOSAM, ISP-47
Figure of the test facility	
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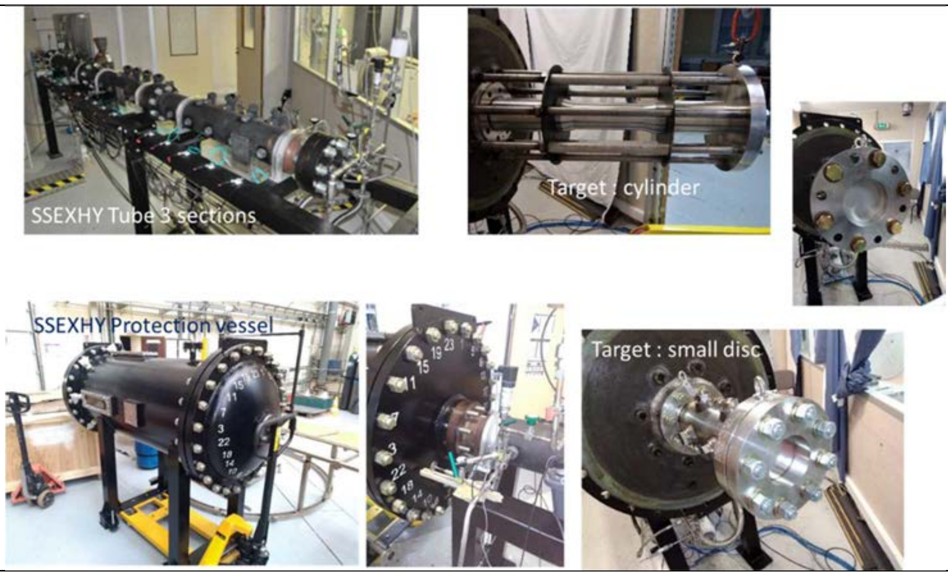
Name of the facility	SSEXHY
Starting year of operation	2012
Organization	Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)
Brief description	The Structure Submitted to EXplosion of HYdrogen (SSEXHY) facility is a medium scale pressure vessel in which several issues related to hydrogen combustions and their effects have been investigated i.e. flame acceleration process, and effects of hydrogen explosions on simple targets.
Dimension of the test facility	SSEXHY test vessel: 0.05 m^3, 5.4 m long, and 12 cm inner diameter
Design pressure / temperature	100 bar/50°C
Main research fields	Hydrogen explosion behavior from slow flames to detonations
Projects/code benchmarks (selection)	French ANR project: MITHYGENE
Figure of the test facility	
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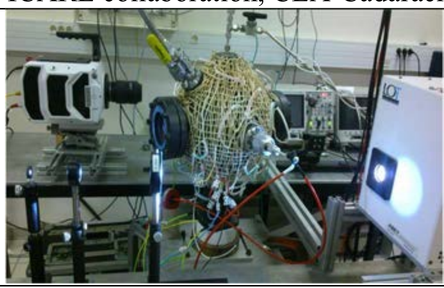
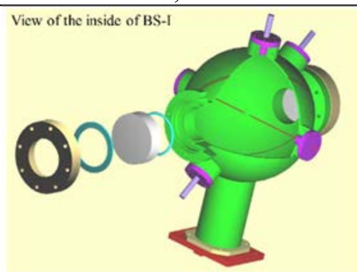
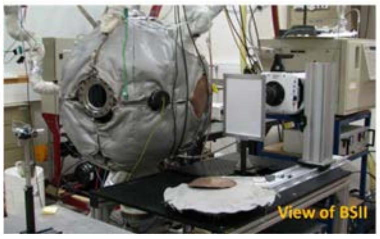
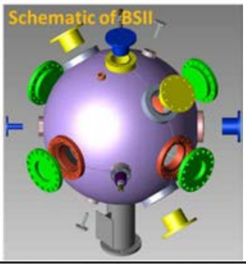
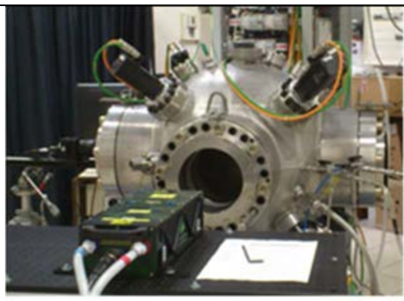
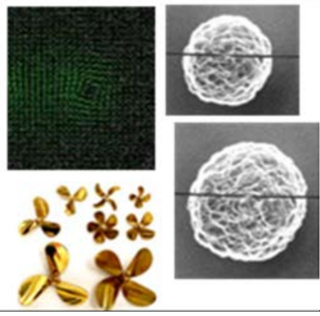
Name of the facility	**Spherical Bombs platform (BS-I, BS-II, BSIII)**
Starting year of operation	BSI- since 1996; BSII-since 2008; BSIII-since 2014
Organization	CNRS-ICARE
Brief description	The platform is composed of three spherical bombs : 1) BSI dedicated to the study of flammability limits of gases and hybrid fuels (dust/gases). The BS-I facility is a spherical vessel of 8 liters with 2 optical access quartz windows and equipped with an electrical heating to be able to vary the initial temperature up to 100°C, 2) BSII is a spherical vessel of 56 liters with 4 optical access quartz windows dedicated to the study of laminar flame properties. 3) the BSIII dedicated to study combustion, flame instabilities, turbulent flame with an initial homogeneous and isotropic turbulence and the spray effect on combustion. The experimental set-up consists of two concentric stainless-steel spheres. The inner combustion spherical combustion chamber has an inner diameter of 563 mm and a thickness of 42 mm. The outer sphere has an inner diameter of 640 mm and a thickness of 4 mm. A thermal fluid flows between the two spheres for raising the chamber temperature up to 573 K and to maintain this temperature uniform For all these experimental set-ups, the ignition energy is controlled and can be varied over a very large domain (less than a millijoule up to 2 J). Ignition system can be spark based using 2 tungsten electrodes or laser based using an Nd-YAG laser. High frequency pressure transducer and high-speed imaging are used to monitor the successful/unsuccessful ignition events. In the event of a successful ignition, the overpressure is monitored. A gas chromatographer is used to analyze the gaseous reactants and products. In case of dust, samples are collected and analyzed via TEM and SEM techniques
Dimension of the test facility	BSI: Inner diameter: 250 mm; Internal volume: 8 L; Optical windows diameter: 60 mm BSII: Inner diameter: 473 mm; Internal volume: 56 L; Optical windows diameter: 100 mm BSIII: Inner diameter: 563 mm; Internal volume: 95 L; Optical windows diameter: 400 mm; 8 fans from 100 to 12000 rpm
Design pressure / temperature	BSI: 50 bar / 100°C; BSII: 50 bar / 250°C; BSIII: 300 bar / 300°C
Main research fields	Flammability Limits, Gaseous fuels and Dust, Laminar flame speed, , Impact of Spray, dilution, temperature and pressure on the laminar flame speed and flammability limits, Flame instabilities, Turbulent flame with an initial homogeneous and isotropic turbulence,
Projects/code benchmarks (selection)	ARCHER (EU), LASECOM (National program), HYDROMEL (ANR), MITHYGENE (PIA-RSNR), SARNET-II, SAMHYCO-NET, AMHYCO IRSN/CNRS-ICARE collaboration, CEA-Cadarache/CNRS-ICARE,
Figure of the test facility	BSI  

	BSII		
	BSIII		

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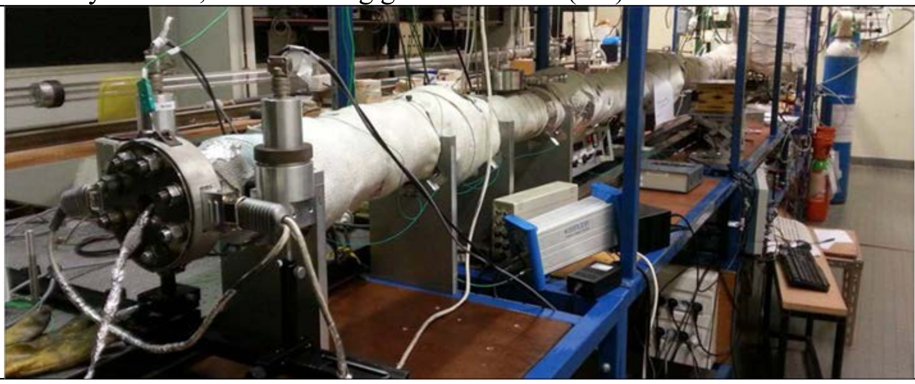
Name of the facility	**HPST-52**
Starting year of operation	1991
Organization	CNRS-ICARE
Brief description	The high pressure shock tube consists of a long cylindrical vessel (7 m long and 52 mm internal diameter for the driven section). It is equipped with several diagnostics for shock waves characterization, auto-ignition measurements and species monitoring
Dimension of the test facility	Driven section: 4 m long, 114 mm internal diameter. Driver section: 5 m long, 52 mm internal diameter.
Design pressure / temperature	60 bar / 130°C
Main research fields	Auto-ignition, Shock waves, High temperature chemistry, kinetic mechanisms validation
Projects/code benchmarks (selection)	HYDROMEL (ANR), SiA-TEAM (EU-FP7), several collaborations Industry/ICARE, ERC-Starting grant FUN-PM (EU)
Figure of the test facility	
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Name of the facility	DETO-78
Starting year of operation	2000
Organization	CNRS-ICARE
Brief description	Detonation tube is constituted of a cylindrical tube of around 6 m long. It is equipped with several diagnostics to study the dynamic parameters of gaseous detonations (Detonation speed, pressure, detonation cell size) and the Deflagration to Detonation Transition a well as the Shock to Detonation transition.
Dimension of the test facility	Length 6 m, Internal diameter: 78 mm
Design pressure / temperature	70 bar/100°C
Main research fields	Detonation, Deflagration to Detonation Transition a well as the Shock to Detonation transition, Auto-ignition
Projects/code benchmarks (selection)	HYDROMEL (ANR), IRSIS (ANR), several Industry-CNRS collaborations
Figure of the test facility	
References	[1] R. Mével, J. Sabard, J. Lei, N. Chaumeix (2016). "Fundamental combustion properties of oxygen enriched hydrogen/air mixtures relevant to safety analysis: Experimental and simulation study". International Journal of Hydrogen Energy 41 (16), 6905-6916, https://doi.org/10.1016/j.ijhydene.2016.03.026 [2] R. Mével, D. Davidenko, F. Lafosse, N. Chaumeix, G. Dupré, C.-E. Paillard, J. E. Shepherd, (2015). "Detonation in hydrogen–nitrous oxide–diluent mixtures: An experimental and numerical study", Combustion and Flame, Volume 162, Issue 5, P. 1638–1649, https://doi.org/10.1016/j.combustflame.2014.11.026 [3] N. Chaumeix, B. Imbert, L. Catoire, C. -E. Paillard (2014), The Onset of Detonation Behind Shock Waves of Moderate Intensity in Gas Phase, Combust. Sci. Technol., 186: 607–620, https://doi.org/10.1080/00102202.2014.883259 [4] R. Mével, S. Javoy, F. Lafosse, N. Chaumeix, G. Dupré, C.E. Paillard, (2009). “Hydrogen–nitrous oxide delay times: Shock tube experimental study and kinetic modeling”, Proceedings of the Combustion Institute, 32 (1), 359-366, https://doi.org/10.1016/j.proci.2008.06.171 [5] R. Mevel, F. Lafosse, L. Catoire, N. Chaumeix, G. Dupré, C.-E. Paillard, (2008). “Induction delay times and detonation cell size prediction of hydrogen-nitrous oxide-diluent mixtures”, Combustion Science and Technology, 180 (10-11), 1858-1875, https://doi.org/10.1080/00102200802261340

Name of the facility	ENACCEF-I
Starting year of operation	2001
Organization	CNRS-ICARE
Brief description	ENACCEF-I is constituted of 2 sections: the upper part is a 654 l vessel, named the dome, and it is connected to a vertical tube of approximately 65 l, referred to as the acceleration tube, in which different shapes of obstacles can be positioned. This facility is highly instrumented with 16 photomultipliers tubes for flame detection and 9 pressure sensors to measure the maximum pressure load. The dome and the acceleration tube are equipped with 3 optical windows each to allow laser diagnostics implementation. Spark ignition can be positioned at different height allowing the study of different flame propagation (upward and downward). Different type of sprays can be implemented in the facility. Homogeneous mixtures or gradient of concentration can be obtained.
Dimension of the test facility	Acceleration tube: 3.2m long, 154mm of i.d. Dome: 1.7m long, 738mm of i.d.
Design pressure / temperature	45 bar/ 25°C
Main research fields	Flame acceleration, Water sprays effect, gradient of H2, sigma criterion, Flame Dynamics
Projects/code benchmarks (selection)	HYDROMEL (ANR), MITHYGENE (PIA-RSNR), IRSN/CNRS collaboration, SARNET-II
Figure of the test facility	
References	[1] N. Chaumeix, H. Cheikhravat, A. Bentaib, A.Bleyer (2017). On the Applicability of the Sigma Criterion to Non-Homogeneous H2 Concentration Configurations, 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Sept. 3-8, 2017, Xi'an, Shaanxi, China [2] R. Grosseuvres, N. Chaumeix, A. Bentaib (2017). Pressure Profiles Measurements in ENACCEF Facility for Fast Flame Propagation, 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Sept. 3-8, 2017, Xi'an, Shaanxi, China [3] N. Chaumeix (2016), "Fundamental Studies Towards Better Assessment of Hydrogen Explosions" 8th International Seminar on Fire and Explosion Hazards (ISFEH), April 2016 [4] A. Bentaib, A. Bleyer, N. Meynet, N. Chaumeix, B. Schramm, M. Höhne, P. Kostka, M. Movahed, S. Worapittayaporn. Brähler, H. Seok-Kang, M.

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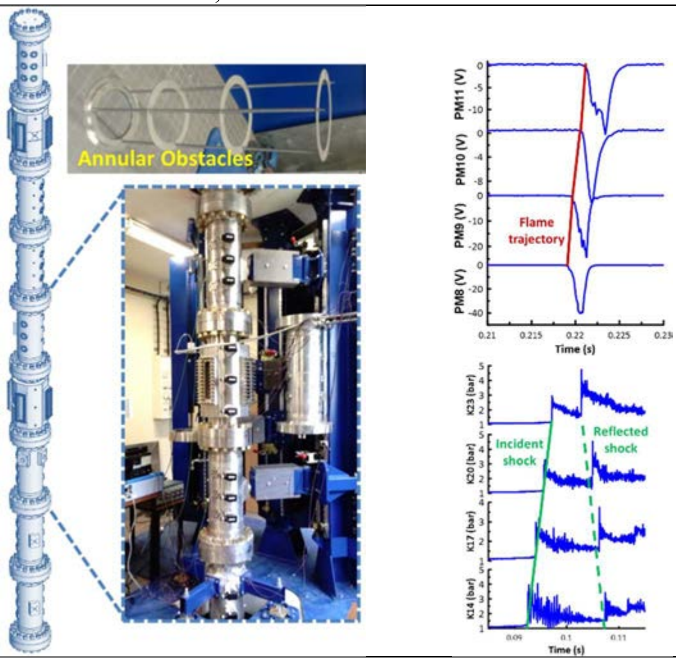
Name of the facility	ENACCEF-II
Starting year of operation	2016
Organization	CNRS-ICARE
Brief description	ENACCEF 2 facility is a vertical tube, 7.65 m high and 230 mm i.d., equipped with 27 optical ports to detect the flame passage along the tube and 12 large windows at specific locations along the tube to record the flame structure using high speed imaging techniques. These large windows allow the use of high speed particle image velocimetry to measure the velocity field ahead of the flame induced by the latter. Ten high frequency pressure sensors distributed along the tube allow the monitoring of the pressure build-up inside the facility and the characterization of the pressure loads. 27 shock detectors measure precisely the shock waves location and hence a trajectory can be derived. The ignition can be located at any position in the tube so that several flame propagation can be studied. A gradient of either composition or temperature can be easily created. Different sprays configurations can be implemented in the facility to study water spray effect on the combustion dynamics.
Dimension of the test facility	Vertical Facility: 7.65 m high and 230 mm i.d.
Design pressure / temperature	240 bar, 200°C
Main research fields	Flame acceleration, Deflagration-to-Detonation Transition, Water sprays effect, gradient of H2, sigma criterion, Combustion, Flame Dynamics
Projects/code benchmarks (selection)	MITHYGENE (PIA-RSNR), IRSN/CNRS collaboration, SARNET-II, SAMHYCO-NET, AMHYCO
Figure of the test facility	
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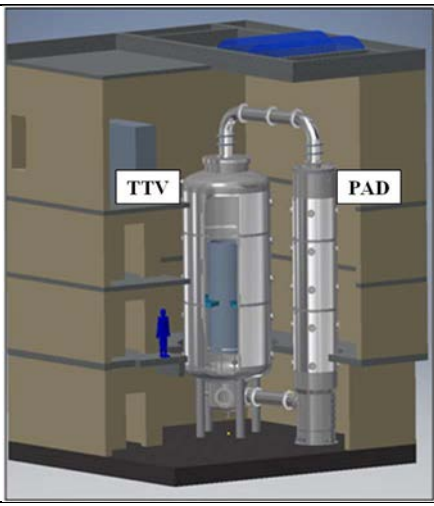
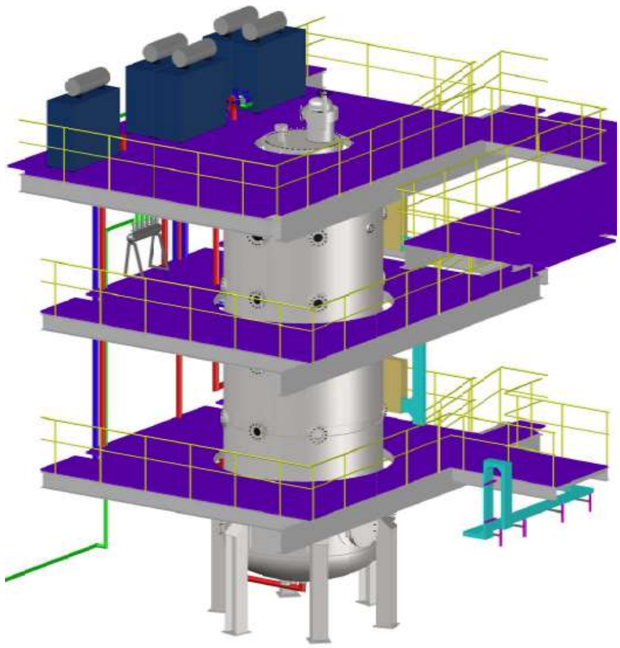
I-3. GERMANY

Name of the facility	THAI+
Starting year of operation	2001
Organization	Becker Technologies (BT)
Brief description	The test facility THAI (**T**hermal-hydraulics, **H**ydrogen, **A**erosols, and **I**odine) aims at addressing open questions concerning gas distribution, behavior of hydrogen, iodine and aerosols in the containment of light water reactors during severe accidents. Used for containment safety research under severe accident conditions. The facility is approved for the use of low-level radiotracer I-123 which enables the online measurement of time resolved iodine behavior.
Dimension of the test facility	TTV (THAI Test Vessel): 60 m^3, 9.2 m high, and 3.2 m in diameter PAD (Parallel Attachable Drum: 17.7 m^3, 9.73 m height, and 1.6 m Upper and lower connection pipes diameter: 500 mm
Design pressure / temperature	14 bar /180 °C
Main research fields	Hydrogen distribution, hydrogen combustion, PAR performance, fission product (aerosols, iodine) behavior, water pool hydrodynamics
Projects/code benchmarks (selection)	THAI National program running since 1998, OECD/NEA THAI, THAI-2, THAI-3, EC-SARNET, ISP-47, ISP-49
Figure of the test facility	
References	[1] FREITAG, M, VON LAUFENBERG, B, COLOMBET, M, KLAUCK, M., "Measurements of the Impact of Carbon Monoxide on the Performance of Passive Autocatalytic Recombiners at Containment-typical Conditions in the THAI Facility", Annals of Nuclear Energy, Vol. 141, June 2020. [2] GUPTA, S., FREITAG, M., LIANG, Z., REINECKE, E.-A., KELM, S., SCHRAMM, B., NOWACK, H., BENTAIB, A., ROYL, P., KOSTKA, P., KOTOUC M., DUSPIVA, J., "Main outcomes and lessons learned from THAI passive autocatalytic recombiner experimental research and related model development work", submitted to 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Xi'an, China, September 3-8, 2017. [3] FREITAG, M, SCHMIDT, E, GUPTA, S, and POSS, G., "Simulation benchmark based on THAI-experiment on dissolution of a steam stratification by natural convection," Nucl. Eng. Des., vol. 299, pp. 37–45, 2016. [4] GUPTA, S., SCHMIDT, E., VON LAUFENBERG, B., FREITAG, M., POSS, G., FUNKE, F., WEBER, G, "THAI test facility for experimental research on hydrogen and fission product behavior in light water reactor containments", Nucl. Eng. Des. **294** (2015) 183-201.

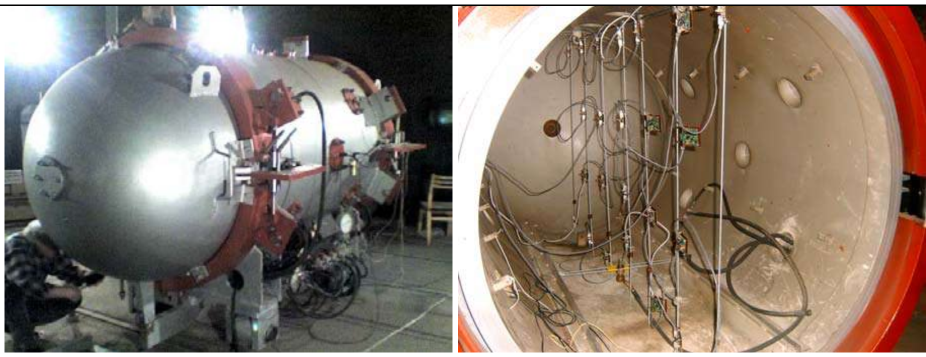
Name of the facility	**REKO-4**
Starting year of operation	2010
Organization	Forschungszentrum Jülich GmbH (FZJ)
Brief description	In addition to REKO-1 and REKO-3 facilities which allow investigation of the operational behavior of generic catalyst elements for hydrogen recombination, the REKO-4 test facility enables the investigation of the operational behavior of a passive auto-catalytic recombiner under natural flow conditions. Gases (hydrogen, air, nitrogen, etc.) are injected via mass flow controllers. Steam is provided by a direct steam generator with a maximum capacity of 10 L/h (liquid water). The vessel instrumentation includes pressure gauges, > 50 thermocouples, hydrogen sensors (> 30 mini-catharometers), oxygen sensors, and humidity sensors. Velocity field measurements are performed by means of Particle Image Velocimetry (2D-PIV). A blower can be operated to obtain well-mixed conditions and to avoid gas stratification.
Dimension of the test facility	Cylindrical steel pressure vessel with a free volume of 5.32 m^3, 32 flanges and a manhole with a diameter of approx. 60 cm, external wall heater
Design pressure / temperature	25 bar @ 280 °C (2.3 bar max. operational pressure)
Main research fields	Operational behavior of passive auto-catalytic recombiners (PAR): Chimney effect, conversion efficiency, sub-atmospheric pressure effect
Projects/code benchmarks (selection)	German National Reactor Safety Projects 1501308 (2010), 1501394 (2014), 1501470 (2018), data used to develop the in-house PAR code REKO-DIREKT, qualification of commercial (non-nuclear) recombiners
Figure of the test facility	
References	[1] Reinecke E-A, Bentaïb A, Dornseiffer J, Heidelberg D, Morfin F, Zavaleta P, Allelein H-J, A first orienting investigation of the interaction of cable fire products with passive auto-catalytic recombiners (PARs), Nuclear Technology 196/2 (2016) 367-376 [2] Klauck M, Reinecke E-A, Kelm S, Meynet N, Bentaïb A, Allelein H-J, Passive auto-catalytic recombiners operation in the presence of hydrogen and carbon monoxide: experimental study and model development, Nucl Eng Des 266 (2014) 137–147 [3] Simon B, Reinecke E-A, Kubelt C, Allelein H-J, Start-up behavior of a passive auto-catalytic recombiner under counter flow conditions: Results of a first orienting study, Nucl Eng Des 278 (2014) 317-322 [4] Steffen P-M, Reinecke E-A, Meynet N, Bentaïb A, Chaumeix N, et al., Operational behavior of a passive auto-catalytic recombiner under low pressure conditions, Fusion Engineering Design 124 (2017) 1281-1286 [5] Ono H, Takenaka K, Kita T, Taniguchi M, Matsumura D, Nishihata Y, Hino R, Reinecke E-A, Takase K, Tanaka H, Research on hydrogen safety technology utilizing the automotive catalyst, Proc. ICMST-4, Tohoku, Japan, October 23-26, 2018

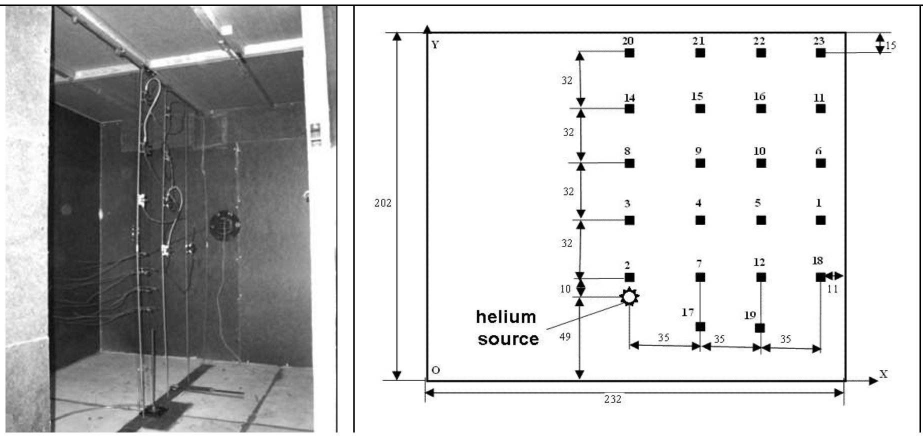
Name of the facility	REKO-Fire
Starting year of operation	2019
Organization	Forschungszentrum Jülich GmbH (FZJ)
Brief description	The REKO-Fire facility enables the investigation of the operational behavior of generic catalyst elements for hydrogen recombination in the presence of cable fire products. For this purpose, the catalyst specimens are mounted inside a vertical cylindrical flow tube and exposed to a mixture of different gases (hydrogen, air, nitrogen, steam) with cable fire emissions. Inlet conditions are controlled by means of mass flow controllers and pre-heater. Key measurements are gas and catalyst temperatures (contact and optical measurements), gas probe sampling and the composition and characterization of the cable fire products.
Dimension of the test facility	Modular set-up, typically 100 cm tube length, tube diameter ~70 mm
Design pressure / temperature	Ambient pressure, inlet gas temperature ~180 °C
Main research fields	Operational behavior of passive auto-catalytic recombiners (PAR): Effect of cable fire products (start-up delay, catalyst deactivation)
Projects/code benchmarks (selection)	German National Reactor Safety Project 1501551 (2017ff)
Figure of the test facility	
References	[1] Allelein H-J, Kubelt C, Reinecke E-A, Impact of cable fire products on severe accident processes, Proc. Int. Congress on Advances in Nuclear Power Plants (ICAPP 2017), Fukui and Kyoto, Japan, April 24-28, 2017 [2] Klauck M, Reinecke E-A, Allelein H-J, Experimental investigations on the impact of cable fire products on the start-up behavior of passive auto-catalytic hydrogen recombiners, Proc. NURETH-2019, Portland, OR, USA, August 18-23, 2019

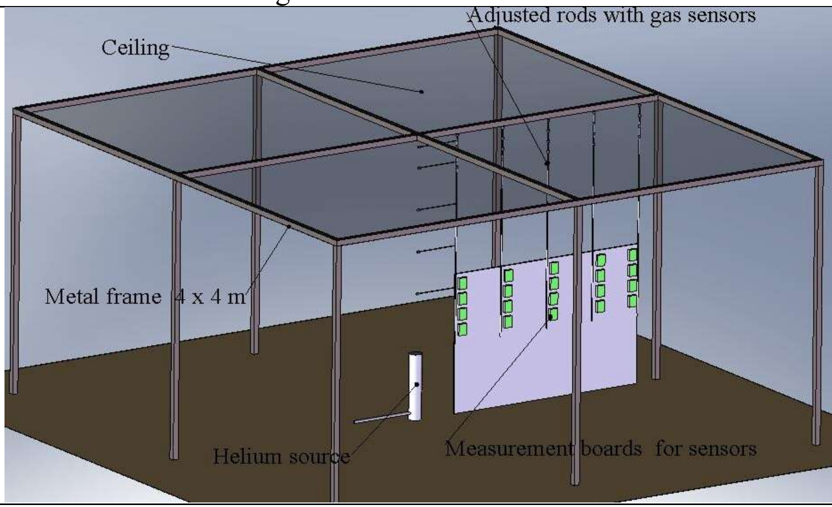
I-4. REPUBLIC OF KOREA

Name of the facility	**SPARC**
Starting year of operation	2016
Organization	KAERI (Korea Atomic Energy Research Institute)
Brief description	The test facility SPARC (Spray-Aerosol-Recombiner-Combustion test facility) was built in 2016 aiming at experimental simulation of hydrogen behaviors in a containment such as jet release and mixing of hydrogen, PAR and spray effects on the hydrogen behaviors, and flame propagation in a containment-specific geometry. It is also going to be used for an evaluation of hydrogen mitigation strategy.
Dimension of the test facility	SPARC test vessel: volume of 81 m^3, height of 9.7 m, and diameter of 3.4 m
Design pressure / temperature	15 bar /180 °C
Main research fields	Thermal-hydraulic hydrogen and aerosol behaviors
Projects/code benchmarks (selection)	Involved in National projects for hydrogen safety and mitigation
Figure of the test facility	
References	[1] NA, Y.S, KIM, J., "Introduction to Sparc Test Facility for Assessment of Hydrogen Behavior in Severe Accident," 12th International Topical Meeting On Nuclear Reactor Thermal-Hydraulics, Operation Aad Safety (Nuthos-12), Qingdao, China, October 14-18, 2018 [2] NA, Y.S, KIM, J., "Experimental Study on a Hydrogen Stratification Induced by Passive Autocatalytic Recombiners," Transactions of the Korean Nuclear Society Autumn Meeting Yeosu, Korea, October 25-26, 2018

I-5. RUSSIAN FEDERATION

Name of the installation	**Gas-tight barrel**
Starting year of operation	2006
Organization	National Research Center “Kurchatov Institute”
Brief description	The installation aims to study the basic flow patterns during hydrogen release and dispersion inside of gas-tight enclosure for the representative hypothetical accident scenarios.
Dimension of the test facility	Volume: 4 m^3, internal diameter 1,28 m, length of cylindrical part 2,22 m
Design pressure / temperature	Up to 105 bar, normal temperature
Main research fields	Hydrogen dispersion in gas-tight cylindrical enclosure
Projects/code benchmarks (selection)	HyPER
Figure of the test facility	 *External (left) and internal (right) views of the gas-tight barrel*
References	[1] DENISENKO, V.P., KIRILLOV, I.A., KOROBTSEV, S.V., NIKOLAEV, I.I., Kuznetsov A.V., Feldstein V.A., Hydrogen subsonic upward release and dispersion experiments in closed cylindrical vessel, ICHS2009, 2th International Conference on Hydrogen Safety, San Sebastian, 2007, 106

Name of the installation	**Ventilated parallele piped**
Starting year of operation	2007
Organization	National Research Center “Kurchatov Institute”
Brief description	The installation aims to study the differences in plume and jet hydrogen dispersion inside of ventilated enclosure.
Dimension of the test installation	Volume: 8,9 m^3, height 2,02 m, length 2,32 m and depth 1,9 m
Design pressure / temperature	1 atm, 25 C
Main research fields	Hydrogen dispersion in ventilated parallelepiped enclosure
Projects/code benchmarks (selection)	HyPER, grant 02.516.11.6028 from the Russian Ministry of Science and Education
Figure of the test facility	 *Internal view (left) of the experimental chamber and the representative schematic of spatial allocation of the sensors (right)*
References	[1] DENISENKO, V.P., KIRILLOV, I.A., KOROBTSEV, S.V., NIKOLAEV, I.I., “Hydrogen-air explosive envelope behavior in confines space at different leak velocities”, ICHS2009, September 16–18 2009, Ajaccio - Corsica. [2] DENISENKO, V.P., KIRILLOV, I.A., KOROBTSEV, S.V., NIKOLAEV, I.I., “Hydrogen distribution in enclosures: on distinction criterion between quasi-homogeneous mixing and stratification modes”, ICHS 2013, Brussels

Name of the installation	**Semi-confined enclosure**
Starting year of operation	2015
Organization	National Research Center “Kurchatov Institute”, Russia
Brief description	The installation aims to study different regimes of hydrogen flow interaction with ceiling from hydrogen explosion hazard viewpoint.
Dimension of the test installation	Volume: 33,8 m^3, height 2,07 m, width 4,04 m, length 4,04 m
Design pressure / temperature	1 atm, 25 °C
Main research fields	Hydrogen dispersion in semi-confined enclosure
Projects/code benchmarks (selection)	SC “Rosatom”: Complex program on R&D for hydrogen safety provision and severe accident management at NPP with VVER
Figure of the test facility	
References	[1] DENISENKO, V.P., KIRILLOV, I.A., KOROBTSEV, S.V., NIKOLAEV, I.I., “Precise experimental data for CFD codes validation: hydrogen-air stratification during jet/plume interaction with ceiling”, Technical meeting on Hydrogen management in Severe Accidents (EVT1701911), IAEA, Vienna, 28 September 2018

I-6. SWITZERLAND

Name of the facility	**PANDA**
Starting year of operation	1995
Organization	Paul Scherrer Institute (PSI), Switzerland
Brief description	PANDA is a large scale, multi-compartment thermal hydraulic facility. The facility is multi-purpose and the applications cover integral containment response tests, component tests and separate effect tests. Experimental investigations carried on in PANDA facility have been embedded in international projects, most of which under the auspices of EURATOM and OECD/NEA.
Dimension of the test facility	Volume 515 m^3 (modular structure based on 6 main vessels). Height 25 m
Design pressure / temperature	10 bar/200 °C
Main research fields	Containment thermal-hydraulics hydrogen distribution, integral containment response tests (BWR/PWR), component tests, e.g. coolers, spray, Heat sources, separate effect tests.
Projects/code benchmarks (selection)	EURATOM (e.g. NACUSP, TEMPEST, ERCOSAM)/OECD/NEA (ISP-42, SETH1-2, HYMERES1-2, etc.)
Figure of the test facility	
References	[1] D. Paladino and J. Dreier, "PANDA a Multi Purpose Integral Test Facility", Science and Technology of Nuclear Installations, Volume 2012, Article ID 239319, doi:10.1155/2012/239319 [2] D. Paladino, M. Andreani, S. Guentay, G. Mignot, R. Kapulla, S. Paranjape, M. Sharabi, A. Kisselev, T. Yudina, A. Filippov, M. Kamnev, A. Khizbullin, O. Tyurikov, Z. (Rita) Liang, D. Abdo, J. Brinster, F. Dabbene, S. Kelm, M. Klauck, L. Götz, R. Gehr, J. Malet, A. Bentaib, A. Bleyer, P. Lemaitre, E. Porcheron, S. Benz, T. Jordan, Z. Xu, C. Boyd, A. Siccama, D. Visser, "Outcomes from the EURATOM-ROSATOM ERCOSAM SAMARA projects on containment thermal-hydraulics for severe accident management", Nuclear Engineering and Design, Volume 308, November 2016, pages 103-114. [3] D. Paladino, M. Andreani, R. Zboray and J. Dreier, "Toward a CDF quality database addressing LWR containment phenomena", Nuclear Engineering and Design, Volume 253, December 2012, Pages 331-342.

ANNEX II: SUMMARY OF THE TECHNICAL MEETING ON HYDROGEN MANAGEMENT IN SEVERE ACCIDENTS

II-1. OBJECTIVE

The Technical Meeting on Hydrogen Management in Severe Accidents was organized on 25–28 September 2018 at IAEA Headquarter in Vienna. The Meeting included Member States' presentations on computer codes and models about hydrogen generation, distribution, and combustion, hydrogen management in severe accidents and support of experimental data to simulation and modelling.

The objective of the Meeting was to generate a Meeting summary of the highlights providing comprehensive conclusive recommendations to the IAEA on the Meeting topical areas, led by Meeting Chair and supported by the Session Chairs.

II-2. MEETING PARTICIPANTS

The Meeting was attended by 29 participants from 21 Member States and one International Organization. Scientific Secretary of this Meeting was Ms Tatjana Jevremovic of the Division of Nuclear Power (IAEA). The meeting was co-chaired by Mr Ahmed Bentaib, (Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France) and Mr Sanjeev Gupta (Becker Technologies GmbH, Germany).

II-3. SUMMARY OF TECHNICAL SESSIONS

The meeting was divided into three topical sessions, each followed by a Discussion Session:

- *Topical Session 1*: Hydrogen Management and Mitigation
- *Topical Session 2*: Hydrogen Safety and Risks
- *Topical Session 3*: Hydrogen Behavior during Severe Accidents and Codes Validations

The supplementary file contains all papers that are presented in the Meeting, while Annex III provides the full content of the supplementary file.

Topical Session 1: *Hydrogen Management and Mitigation*

This Session was dedicated to general descriptions and evaluations of hydrogen management and mitigation systems to minimize the hydrogen risk. The nine (9) papers were presented discussing hydrogen management strategies and hydrogen risk assessments with mitigation systems using various codes; future issues to be researched were outlined. The summary of this Session is as follows:

- The participant from Brazil evaluated the pressure by combustion of hydrogen generated by 100 % cladding water reaction condition in the LABGENE containment and proposed an inertization system using N_2 as an inert gas.
- The participant from Canada presented hydrogen risk management in Canada from a regulatory perspective reporting on the present status, challenges, future research plans and international collaboration. Canada also introduced the hydrogen computational tool CHAT used to assess hydrogen flammability in the NPP containment.
- The participant from Czech Republic presented the process of designing the hydrogen management system, consisting of PARs. A numerical model was developed using MELCOR code for two types of verified and validated PARs from AREVA and NIS. The optimized PAR locations were proposed in selected rooms of the Temelin NPP containment to satisfy established criteria in calculations by the computational severe accident code MELCOR.
- The participant from Egypt introduced the history and present the status of the Egyptian NPP planning project. The technical criteria related to severe accident phenomena and general description of hydrogen risk mitigation systems were discussed.
- The participant from France presented the contribution of recent work related to initial turbulence, spray influence on flammability limit, PARs ignition limit, and the development of flame acceleration correlation. Ongoing experimental work on flame acceleration and future projects on gas monitoring system and flame behavior in ex-vessel conditions were also introduced.
- The participant from India discussed the validation of the PACRs code and assessment results of hydrogen risk with passive catalytic recombiner devices using PACRs code.
- The participant from Mexico analyzed the hydrogen distribution and behavior in the atmosphere of the hardened containment venting system to evaluate the vulnerability of the venting pipeline due to hydrogen explosion using MELCOR and GASFLOW codes.
- The participant from Pakistan analyzed the PARs' effect on hydrogen concentration in various locations for different accident scenarios such as large break LOCA, small break LOCA and TLOFW using the MELCOR code.
- The participant from Republic of Korea presented the analytical containment code, containmentFOAM based on OpenFOAM, which is used to analyze hydrogen behavior and evaluate hydrogen safety in a NPP containment. Some modularized models have been validated by solving international benchmark problems.

The Discussion Session identified the current status and further research activities on hydrogen management, development of the hydrogen mitigation systems and practical applications to the NPPs:

- The late phase phenomena of severe accidents, such as carbon monoxide production and its effects, have not sufficiently been researched. Research on these topics should be considered and supported by national authorities and international organizations.

— When designing mitigation systems, a guideline is needed for the selection of testing conditions (e.g. homogenous or stratified atmosphere and consideration of steam condensation). A unified testing methodology and quantitative criteria of PARs startup and ignition limit should be established.
— More systematic approach and consensus methodology for nodalization in code calculations should be established, as nodalization significantly influences final results.
— Each country and institution have used different values for the flammability limit. Recommendations of unified criteria such as flammability limit, flame acceleration criterion, deflagration to detonation transition criterion are needed for reactor applications.
— There exists substantial amount of research and new findings on hydrogen management. These data should be gathered and developed as a comprehensive resource to be disseminated. The document should simplify a link between hydrogen R&D and SAMG in consideration of operators who may not have sufficient knowledge and address all related phenomena and related uncertainties.

Topical Session 2: *Hydrogen Safety and Risks*

This Session was dedicated to assessment of hydrogen safety and risk and further issues to be performed. The eight (8) papers were presentated summarizing the activities on hydrogen safety and research results to assess hydrogen risk using various numerical codes such as MELCOR, GASFLOW and ASTEC:

— The participant from Armenia presented on the assessment of hydrogen risk using MELCOR code. The hydrogen generation mass in different scenarios, hydrogen mass threatening the confinement integrity by slow deflagration, flammability of the atmosphere of a small area in the case of a gas leak and flammability of the atmosphere in the small dead-end room with different ratios of surface to volume were assessed. Further research issues related with PAR implementation and spent fuel pools safety were also introduced.
— The participant from China discussed the hydrogen safety in CAP1400 based on GASFLOW calculations. The developed model is validated by comparing with CERT test results and hydrogen generation mass, pressure and temperature of containment and flame acceleration criterion were calculated according to the presence of PARs. The participant from Indonesia presented on the hydrogen production rate due to radiolysis of water during a small break LOCA accident.
— The participant from OECD/NEA presented the past, present and future activities of the Working Group on Analysis and Management of Accidents (WGAMA) related to thermal hydraulics safety during severe accidents. The status report on hydrogen management and related computer codes published in 2014 was introduced. There are no currently ongoing activities on hydrogen risk specifically, but many are focused on severe accidents.

- The participant from Republic of Korea discussed the risk of hydrogen detonation in the In-Containment Refueling Water Storage Tank (IRWST) using the MELCOR code. The sensitivity analysis was carried out considering the factors of creep rupture at the hot leg, release ratio into the IRWST, loss coefficients at the IRWST vents, characteristic lengths of DDT and CV modelling. The installation of additional valves to prevent hydrogen release was decided as a design improvement.
- The participant from Lithuania presented on the risk of hydrogen deflagration in a dry atmosphere with different hydrogen concentrations using ASTEC code calculations. A sensitivity analysis was conducted considering the parameters of flame velocity correlation, turbulence decay coefficient, minimal turbulence length and pre-factor in the turbulence intensity.
- The participant from Russian Federation provided information on the regulation and requirements for hydrogen safety implemented in the Russian NPPs. Certified numerical codes currently used for assessment of hydrogen risk in VVER were summarized. Quantitative criteria and indicators for hydrogen safety assessment were explained and their limitation were pointed out. A second presentation from Russian Federation from Kurchatov Institute discussed the model based method for estimating the flame acceleration limit to reduce the uncertainties of an empirical-based method. Several problems for using empirical estimation were pointed out and it was found that theoretical estimation is more conservative then the empirical one.

The outputs from Discussion Session are summarized as follows:

- Much of the referenced material in hydrogen safety was developed several decades ago and in the current day may be potentially misused or used with a lack of understanding due to the lack of knowledge transfer. For example, Shapiro diagrams may be used without deep understanding, though it is necessary to understand in what scenarios these diagrams are developed and in what situations they may be applied.
- The appropriateness of nonphysical hydrogen generation being used as a conservative approach in safety analysis was identified in some Member States.
- Unified and quantitative characterization methods are needed for PAR testing.
- Methods and tools for uncertainty analysis in the assessment of hydrogen safety must be improved.

Topical Session 3: *Hydrogen Behavior during Severe Accidents and Code Validations*

This Session discussed the numerical analysis of hydrogen behavior during severe accidents and included eight (8) full papers and their presentations. The hydrogen behavior in different accident conditions were analysed using codes such as MELCOR, MAAP, RELAP/SCDAMPSIM, GASFLOW and ASTECv2.0. The validations of modelling for the code calculations were also presented. The summary of this Session is as follows:

- The participant from Egypt presented on the tools' development for modelling hydrogen generation, combustion and mitigation during severe accidents. Three developed tools were described: SATAM for severe accident analysis and management; MITIG for analysis of hydrogen behavior; SPRAY for the analysis of the effects of spray systems.

- The participant from Germany presented about the THAI experiments that are developed to study hydrogen distribution, PARs effects and hydrogen combustion. The THAI experimental programme provided many useful findings and contributed to understanding of severe accident phenomena related to thermal-hydraulics, hydrogen, aerosols and iodine behavior as well as established a data base for development and validation of LP and CFD codes.
- The participant from Mexico discussed hydrogen behavior in different scenarios using different versions of MELCOR 1.8, MELCOR 2.1 and MAAP codes. The differences of simulation results from the two versions of MELCOR code were analyzed. Hydrogen generation with various degrees of mitigation strategies in short term and long term SBO were analysed using MAAP code. A second presentation from Mexico from ININ discussed the impact of severe accident water injection at different stages of LOCA in a BWR/5 with MARK II containment that was calculated using the RELAP/SCDAMPSIM code. The hydrogen behavior in the containment during an accident was also analyzed using the GASFLOW code.
- The participant from Romania presented the ASTECv2.0 code analysis of hydrogen behavior during a severe accident due to SBO in CANDU. The hydrogen distribution was simulated considering PARs effects with simplified model based on an empirical correlation.
- The participant from Russian Federation presented on the experiments used to study the influence of hydrogen jet–ceiling interaction and hydrogen plume–ceiling interaction on hydrogen–air stratification. The correlations of concentration were also developed for the radial and vertical structures of the near ceiling gas layer.
- The participant from Ukraine presented the simulation of hydrogen behavior in a spent fuel pool and containment using MELCOR 1.8.5 code.
- The participant from Vietnam presented on an experimental study of the natural convective flow in molten corium in the lower vessel during severe accidents. The flow was simulated in a square cavity and its velocity was visualized using PIV and UVP techniques.

The discussion session included the following points:

- It will be useful to develop a maturity level model to recommend next steps for newcomer countries in developing expertise in topical areas such as the modelling and simulation of severe accidents.
- There is a need for an extension of knowledge in the late stage of severe accidents, in particular the chemistry and thermodynamics of the molten core–concrete interactions.
- There is a necessity for transfer of knowledge between Member States on the interaction between passive autocatalytic recombiners and containment and

components, with a focus on localized combustibility regimes, and the need for consideration of the effects of carbon monoxide.

This meeting provided a great opportunity to share information on hydrogen management and simulation and modelling, identify several unsolved issues and make a consensus on further activities. This Meeting helped to identify many new recommendations including the creation of a new Technical Document to provide needed and well consolidated information on the subject topic as an input for developing other relevant and, as this Meeting identified, THE NEEDED activities including the following:

- Consultancy Meeting to discuss the roadmap to support emerging countries in developing expertise in the area of modelling and simulation of hydrogen behavior during SA in WCRs;
- Organization of customized training course/seminars/workshops;
- Develop Technical Document on the harmonized view on hydrogen behavior and management;
- Potentially initiating a new International Collaborative Standard Problem such as:
  - Based on existing experimental data bases (to share knowledge on modelling and the methodology on producing experimental data bases); and
  - Code to code comparison based on SA scenario on representative reactor configurations.

ANNEX III: CONTENT OF THE SUPPLEMENTARY FILE

Technical Meeting on Hydrogen Management in Severe Accidents IAEA Headquarters, Vienna, Austria, 25–28 September 2018				
Papers presented at the Technical Meeting on Hydrogen Management in Severe Accidents				
No.	**COUNTRY**	**TITLE**	**PRIMARY AUTHOR**	**TECDOC SECTION**
1	Armenia	HYDROGEN CHALLENGE STUDY FOR ARMENIAN NPP	E. Yeghoyan	2.2 5.3 Annex II
2	Brazil	A PROPOSAL FOR HYDROGEN MITIGATION CONSIDERING SMALL CONTAINMENT	N.A. Fakhoury	3.1 5.3 Annex II
3	Canada	HYDROGEN MANAGEMENT IN SEVERE ACCIDENTS IN CANADA – A REGULATORY PERSPECTIVE	S. Gyepi-Garbrah	2. 3. Annex II
4	China	GASFLOW CODE PCS MODEL DEVELOPMENT AND CAP1400 HYDROGEN ANALYSIS	X. Huang	4.2 Annex II
5	Czech Republic	DESIGNING THE HYDROGEN MITIGATION SYSTEM FOR TEMELIN NPP: FROM NUMERICAL MODEL VERIFICATION TOWARDS PARS' DEPLOYMENT OPTIMIZATION	M. Kotouc	3.1 5.3 Annex II
6	Egypt	THE FIRST EGYPTIAN NUCLEAR POWER PLANTS H2 REMOVAL SYSTEM REQUIREMENTS AND SPECIFICATIONS	D.A.A. Eldesoky	2.3 3.2 Annex II
7	Egypt	DEVELOPMENT OF A COMPUTER TOOL FOR HYDROGEN ASSESSMENT DURING A SEVERE ACCIDENT	M. Hassan	4.1 2.2 Annex II
8	France	CONTRIBUTION OF RECENT R&D PROGRAMS TO HYDROGEN MANAGEMENT IMPROVEMENT	A.Bentaib	2.3 3.1 5.3 6. Annex II
9	India	MANAGEMENT OF HYDROGEN DURING POSTULATED SEVERE	S. K. Sharma	3.1 5.3

		ACCIDENT IN INDIAN PHWRS CONTAINMENT		Annex II
10	INDONESIA	HYDROGEN PRODUCTION IN LONG LIFE 620 MW(T) BWR DUE TO RADIOLYSIS OF WATER	A. Hidayati	2. Annex II
11	REPUBLIC OF KOREA	AN EXPERIENCE ON TREATMENT OF HYDROGEN RISK IN 1400 MWe PWRs	S. Lee	4.1 5.2 Annex II
12	REPUBLIC OF KOREA	METHODOLOGY DEVELOPMENT FOR EVALUATION OF HYDROGEN SAFETY IN A NPP CONTAINMENT USINNG OpenFOAM	J. Kim	4.1 4.2 5.2 Annex II
13	LITHUANIA	HYDROGEN COMBUSTION SIMULATIONS USING ASTEC CODE	M. Povilaitis	4.1 4.2 5.1 5.2 Annex II
14	MEXICO	OVERVIEW OF THE ACTIVITIES PERFORMED IN MEXICO FOR THE ANALYSIS OF HYDROGEN BEHAVIOR AND MITIGATION / CONTROL STRATEGIES	C. Mugica	3.1 5.3 Annex II
15	MEXICO	GENERATION AND DISTRIBUTION OF HYDROGEN IN A BWR REACTOR IN A SEVERE ACCIDENT SCENARIO	E.C. Zamora	2.1 3.1 5.3 Annex II
16	MEXICO	STUDY OF HYDROGEN DISTRIBUTION IN A BWR MARK II CONTAINMENT AS RESULT OF EMERGENCY WATER INJECTION DURING THE EVOLUTION OF A SEVERE ACCIDENT	J. Ortiz-Villafuerte	3.1 5.3 Annex II
17	OECD/NEA	OECD/NEA ACTIVITIES RELEVANT TO ADVANCING THE UNDERSTANDING OF HYDROGEN GENERATION, DISTRIBUTION, COMBUSTION AND MITIGATION DURING A SEVERE ACCIDENT	N. Sandberg	2. 3. 4. 5. Annex II
18	PAKISTAN	RETROFITTING OF PARs FOR HYDROGEN MANAGEMENT AT C-1 NPP	H. Ahmad	2.1 2.3 3.2 5.4 Annex II
19	ROMANIA	APPLICATIONS OF ASTEC CODE IN RELATION WITH HYDROGEN BEHAVIOUR ON A GENERIC	G. Radu	5.3 Annex II

		CANDU 6 REACTOR		
20	RUSSIAN FEDERATION	PHYSICS-BASED APPROACH FOR REDUCTION UNCERTAINTIES IN CONCENTRATION LIMITS OF “SLOW-TO-FAST” FLAME TRANSITION IN HYDROGEN-AIR GAS MIXTURES	I. Kirillov	3.2 5.3 Annex II
21	RUSSIAN FEDERATION	SOME ASPECTS OF HYDROGEN SAFETY ASSESSMENT FOR RUSSIA’S VVER TYPE REACTORS	I. Kirilov	4. 5. Annex II
22	RUSSIAN FEDERATION	PRECISE EXPERIMENTAL DATA FOR CFD CODES VALIDATION: HYDROGEN-AIR STRATIFICATION DURING JET/PLUME INTERACTION WITH CEILING	V. Denisenko	5.3 Annex I Annex II
23	UKRAINE	PROSPECTS FOR DEVELOPMENT OF COMPUTER MODEL FOR KHMELNITSKY NPP UNITS	M. Odiychuk	5.3 Annex II

GLOSSARY

u'	*Turbulence intensity*
SL^0	Unstrteched laminar flame speed
S_b	Burning speed
σ	Density ratio between unburned and burned gases
ρ_u	Density ratio of the fresh gases
ρ_b	Density ratio of burned gases for an adiabatic complete combustion at constant pressure
LFL	Lower flammability limit which corresponds to the lowest molar present of the fuel below which no sustained flame can be obtained
UFL	Upper flammability limit which corresponds to the largest molar present of the fuel above which no sustained flame can be obtained

ABBREVIATIONS

AM	Accident management
BMC	Battelle Model Containment
BWR	Boiling water reactor
CHLA	Candidate high level actions
CSNI	Committee on the Safety of Nuclear Installations
DBA	Design basis accident
DDT	Deflagration-to-detonation transition
EOP	Emergency operating procedure
FA	Flame acceleration
FCVS	Filtered containment venting system
FL	Flammability limits
LOCA	Loss of coolant accident
MCCI	Molten core-concrete interaction
NPP	Nuclear power plant
PAR	Passive autocatalytic recombiner
PWR	Pressurized water reactor
RPV	Reactor pressure vessel
SA	Severe accident
SAM	Severe accident management
SAMG	Severe accident management guidelines
SBO	Station blackout
SFP	Spent fuel pool
SOAR	State-of-the-art-report
TMI	Three Mile Island
TSO	Technical and scientific support organizations
WCR	Water cooled reactor

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MEETINGS

Technical Meeting on Hydrogen Management in Severe Accidents, 25–28 September 2018, IAEA Headquarters in Vienna, Austria

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No. 26

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