HYDROGEN MANAGEMENT STRATEGIES AND ANALYSIS CODES IMPLEMENTED BY THE OECD/NEA MEMBER COUNTRIES

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ABSTRACT

In the follow-up to the Fukushima accident, the OECD/NEA CSNI initiated an activity within its member countries to review and assess their hydrogen management strategies under severe accident conditions and the associated computer codes used for the hydrogen safety analysis. A CSNI report, titled *Hydrogen Management and Related Computer Codes*, was thereafter published by OECD/NEA in 2014 June, consisting of information contributed by 15 OECD/NEA member countries. This paper summarizes the major findings obtained in the activity. The state of knowledge on hydrogen generation, distribution, combustion and mitigation is presented. The corresponding computer codes that are used by the member countries for hydrogen safety analysis are discussed, including code capabilities and validation status assessed against the hydrogen behavior associated with generation, distribution, combustion and mitigation. The hydrogen management strategies are presented based on the literature findings. The status of hydrogen management systems implemented by the member countries are discussed, including national requirements, mitigation measures and their implementation status, and considerations regarding the interaction of engineering safety systems with hydrogen behavior during severe accidents. The CSNI report provided a basis for assessing severe accident management strategies, identifying gaps in code capabilities and validation, and providing insights for model enhancement and application. It is expected to be a useful handbook for nuclear safety authorities, research institutions, and utilities.

KEYWORDS
Hydrogen management, generation, distribution, combustion, mitigation

1. INTRODUCTION

In the course of postulated severe accidents (SAs) in water-cooled nuclear power plants (NPPs), large amounts of hydrogen can be generated and released into the containment. The formation of hydrogen inevitably accompanies the core degradation process or molten core-concrete interaction (MCCI). It is well known that hydrogen combustion can cause high pressure spikes and high temperatures, leading to potential damage of mitigation equipment or failure of the NPP containment, and thus breaking the last safety barrier for release of fission products to the environment. Since the TMI-2 accident, considerable research efforts have been undertaken to better understand the associated concerns. A large number of experimental programs have been developed to examine various aspects of hydrogen behaviour, including generation [1], distribution [2], combustion [3] and mitigation [4]. The test results have been extensively applied to analytical assessments and model development [2] [5]. A number of hydrogen mitigation measures had already been developed and implemented in many NPPs in the early 90's [6].

During the Fukushima Daiichi NPP accident, hydrogen explosions occurred in three units, resulting in severe damage of the reactor buildings. This has again triggered extensive analyses and assessments to support safety enhancements for the protection of the containment and the building structure containing the spent fuel pool (SFP), and to cope with events that go beyond the design basis. In addition, it has been recognized that significant improvements are needed for national and international communications and information exchange amongst national regulatory organizations. In the follow-up to the Fukushima accident, the Organization of Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) developed a working document, "*Considerations and Approaches for Post-Fukushima Daiichi Follow-Up Activities*", as referenced in [7], which identified R&D areas in response to the accident. The underlying technical phenomena associated with the Fukushima accident, including such matters as fuel and system performance, hydrogen generation, venting of the containment, and behavior of the SFP, were identified as high priority for future research programs. In 2012 December, CSNI approved a proposal, prepared by CSNI's Working Group on Analysis and Management of Accidents, for compiling a status report on hydrogen generation, transport and mitigation under SA conditions. The purpose was to review the existing approaches implemented before or after the Fukushima accident for hydrogen management under SA conditions within the OECD/NEA member countries, including safety requirements, mitigation systems and their implementation status, and analysis codes and their validation status.

Representatives from 15 OECD/NEA countries, consisting of Belgium, Canada, Czech Republic, France, Finland, Germany, Italy, Japan, Korea, the Netherlands, Poland, Sweden, Switzerland, Spain, and USA, prepared a report on *Hydrogen Management and Related Computer Codes*, which was published by CSNI in 2014 June [8]. In the report, experimental and benchmark studies are reviewed on hydrogen generation, distribution, combustion and mitigation performed by the international nuclear communities in the past three decades. The containment design features and accident management systems are summarized for four types of reactors, including pressurized water reactors (PWRs), boiling water reactors (BWRs), Russian type PWR reactors (VVERs) and pressurized heavy water reactors (PHWRs). The hydrogen management strategies are described, including mitigation measures currently implemented or to be applied, particularly, the post-Fukushima actions undertaken by the member countries. A number of computer codes used by the member countries are assessed for their capabilities and validation status in modeling hydrogen phenomena.

This paper provides an overall summary of the CSNI report [8] and presents the major findings obtained in the assessment of the hydrogen mitigation strategies, and the relevant hydrogen analysis code capabilities and their validation status. The purpose is to provide a basis for assessing severe accident management strategies and to identify gaps in model capabilities and validations, and to provide insights for model enhancement and application.

2. HYDROGEN BEHAVIOR AND RELATED COMPUTER CODES

The hydrogen behavior in the containment under accident conditions is plant and scenario specific. A good understanding of phenomena associated with generation, distribution, combustion and mitigation is crucial for planning and implementing effective hydrogen management measures. Over the past 30 years, significant advances in the understanding of hydrogen behavior have been gained through various experimental programs. The accompanying analytical activities have significantly enhanced the code capabilities by continuous model improvement.

Eleven computer codes, including five lumped parameter - LP (ASTEC, MAAP/MAAP-CANDU, MELCOR, SPECTRA, COCOSYS) and six 3D/CFD codes (TONUS, GOTHIC, GASFLOW, and ANSYS CFX/FLUENT/AUTODYN), are evaluated in the status report [8]. It is known that the LP codes employ simpler physics and calculation methods, thus they are capable of simulating long time transients with acceptable computation times, but assumptions and model simplifications can lead to larger uncertainties. In contrast, the 3D/CFD (Computational Fluid Dynamics) codes are capable of modeling local details, but they usually require a relatively large computational effort. In particular, they don't have models to simulate all phenomena associated with SAs. It has become a common practice nowadays to apply 3D/CFD codes as a complement to LP codes for hydrogen safety analysis.

ASTEC, MAAP/MAAP-CANDU, MELCOR, SPECTRA are often referred to as integral or system code, which cover all aspects of in-vessel and ex-vessel SA phenomena. COCOSYS is mainly developed for containment analyses. TONUS, GOTHIC and GASFLOW are also special purpose 3D codes designed for containment analyses. GOTHIC's control volumes can be modeled with a LP approach or subdivided into 2D or 3D grids. CFX and FLUENT are commercial multipurpose CFD codes. AUTODYN is specially designed for simulations of detonations and the resulting interaction between pressure waves and the structural behavior.

In general, a certain degree of validation is performed by code developers before the codes are released for use. Users often perform their own independent validation to increase their knowledge and confidence for appropriate code application. In the recent decade, significant effort has been made in executing numerical benchmarks on hydrogen behavior through various International Standard Problems (ISPs) or analytical activities incorporated into the international collaboration projects. These activities have provided a good understanding of code performance in modeling hydrogen behavior under accident related thermal-hydraulic conditions. They also have helped development of user guidelines for both the LP and 3D codes.

2.1. Hydrogen Generation

During severe accident scenarios in water-cooled NPPs, the primary hydrogen source can come from zirconium-steam reaction during the in-vessel core degradation process and MCCI during the ex-vessel processes [1]. The amount of hydrogen produced and the production rate depends largely on boundary conditions, including available mass of zirconium, water and steam, and temperature. For a typical 1,000 MW(e) PWR, the Zr mass is on the order of 30,000 kg and the average hydrogen production rate is ~0.2 kg/s without core reflooding [1] [5], and the value is sufficiently accurate as long as the fuel bundle geometry remains intact. The in-vessel hydrogen release is also highly variable, but it can reach the order of 1000 kg, although most severe accident sequences lead to a range of 100 to 800 kg. Other sources of hydrogen can come from oxidation of steel and B_4C (an absorber material used in BWRs, VVERs and some western type PWRs) with steam during the in-vessel process, and water radiolysis and metal corrosion (mainly during the ex-vessel phase), but these are secondary hydrogen sources and their contributions are significantly smaller than the primary sources. In addition, in case of loss of cooling for a spent fuel pool, oxidation of the fuel cladding by steam may lead to a large amount of hydrogen production. Following the Fukushima accident, spent fuel pool cooling has been assessed by almost all member countries and actions have been undertaken to address the concerns.

The four LP codes, ASTEC, MAAP, MELCOR, and SPECTRA, are capable of calculating hydrogen generation within the reactor core during core degradation and within the reactor cavity during MCCI. For these four LP codes, validation exists for hydrogen generation from metal-steam and metal-oxygen reaction, but some codes lack validation for oxidation in molten pools or debris bed and MCCI. The LP code, COCOSYS, includes a model to calculate hydrogen generation due to MCCI and validation has been performed. All of the other codes assessed in this paper have no capability to model hydrogen generation. The hydrogen source term is generally calculated by other means and implemented as boundary conditions for these codes. The ISP-31 benchmark, performed against the CORA-13 experiments in 1993, investigated the behavior of PWR fuel elements during early core degradation and fast cool-down due to refill [9]. MELCOR was one of codes used in the benchmark. The hydrogen generation was over-predicted in the early transient, but under-predicted in the later pre-quench phase. None of the codes used in the ISP-31 benchmark could predict the intensive hydrogen generation during the refill. However, significant progress has been made in the model development for most codes since then, and the prediction accuracy has been significantly improved.

It is commonly agreed that hydrogen generation during the in-vessel processes is the main factor influencing the hydrogen risk, which is generally well understood when the core geometry is still intact. Modeling of oxidation of metals in the molten pool or in a debris bed still needs some improvement in some codes. Additional information is required for the late phase of the core degradation during reflooding, and therefore it was addressed by the former CORA experiments and is being studied by the on-going QUENCH experiments at KIT, Germany [10].

When molten corium enters the reactor cavity after the reactor pressure vessel has failed, MCCI may start. Various gases, especially hydrogen and carbon monoxide, can be generated due to concrete ablation and is released into the containment atmosphere. Although the exact impact of the noncondensable gases produced in the course of MCCI on the containment remains uncertain, the major influencing factors for noncondensable gas generation include the concrete composition, content of metals in the corium and concrete basement by reinforcing steel bars. Typically such parameters can be defined in the LP codes discussed here.

None of the assessed codes have models to calculate hydrogen production from radiolysis within the containment sump water. Metal corrosion (i.e., low temperature Zr oxidation by water) is modeled in MELCOR and SPECTRA based on a user input for the reaction coefficients, and it is under development in other codes, but no validation has been performed for the corrosion model. However, since the hydrogen source from water radiolysis and metal corrosion are generally considered to be negligibly small during SAs, the model capability for these phenomena is not a significant concern.

2.2. Hydrogen Distribution

The hydrogen generated can be released from the reactor circuit or cavity into the containment or reactor buildings through engineered pathways, breaks, leaks or other pathways. Hydrogen distribution can be significantly affected by the containment layout, hydrogen release location and mass flow rate, its mixing with other gases [5], and safety systems used (i.e., spray and fan coolers). The hydrogen release characteristic depends strongly on the accident sequence. After the initial blow down, transport of hydrogen in the containment is mostly driven by convection loops due to the release of hot steam/gas mixture or steam condensation on cold walls and structures, if no other source of forced flow exists.

A large experimental database has been generated by numerous experiments at various scales to examine the hydrogen-steam-air mixing behavior. Specific interest was devoted to long-term natural-convection experiments including mixing and thermal stratification [2]. Recent research is directed to provide data for model development and validation [11], and to examine the interaction of engineering systems (i.e., spray, local air cooler, passive autocatalytic recombiners - PAR) with hydrogen distribution [12].

Hydrogen distribution in the containment is a general transport process such that all the assessed codes, except AUTODYN (dedicated for detonation calculation), have been used for containment thermal-hydraulic and hydrogen distribution analysis. The accuracy depends to a large degree on the user's choice of an appropriate nodalization scheme and the consideration of plant specific features (i.e., doors, burst membranes, spray systems, fan coolers). This is particularly true for the LP codes because the properties of a fluid are averaged within a given control volume. It is thus challenging for the LP codes to capture stratification, momentum or buoyancy induced mixing originating from plumes of steam and non-condensable gases, but satisfactory results can be obtained by following the available best user practices developed based on the international benchmark activities [13]. In contrast to the LP codes, the 3D codes have shown certain advantages for modeling hydrogen mixing in complex geometric structures, but large discrepancies still exist due to limitations of the codes and user effects, particularly in using the commercial CFD codes (e.g., FLUENT, CFX). It is also highly recommended that the best practice guidelines for the use of CFD codes be closely followed in modeling hydrogen behavior [14].

Hydrogen distribution in the containment is quite well validated for almost all the codes used for this purpose and much experimental data relevant to SA conditions are available. Since 1990, several ISP benchmarks have been performed against many thermal-hydraulics and hydrogen mixing experiments, including ISP-23, 29, 35, 39, 42, and 47 [2]. It has been found that, although the LP codes have some inherent limitations due to simplification of physical processes, appropriate user modeling experience can often overcome these limitations. In addition, combined use of both LP and 3D codes was recommended, where the LP codes can be used as the basic tool for containment analyses, whereas the 3D codes can be used for local detailed analyses for selected accident scenarios. Furthermore, for the commercial CFD codes, improvements in modeling condensation and wall treatment are needed. Even though these CFD codes allow simulation of multi-phase flows, their application to hydrogen mixing and mitigation in containment compartments is still limited to a single (gas) phase approach in most cases due to enormous computational requirement. Consequently, heat and mass transfer for the liquid phase (i.e., fog, condensate on walls and structures) is often neglected. The condensate is often removed from the system and not able to be automatically included in case where re-evaporation takes place. However, many CFD users have developed approaches to improve the condensate/liquid water balance using user defined wall/film functions based on the governing laws/correlations.

Density variation due to temperature difference or mixture composition can lead to stratification. If considerable hydrogen stratification exists, pockets of high hydrogen concentrations may become a concern. Operation of engineering safety systems (i.e., spray and local air coolers) can affect the local hydrogen concentration and global distribution. The spray and local air coolers can significantly reduce the local steam concentration, leading to more sensitive gas mixture compositions by removing steam inerting, but they may also homogenize the hydrogen distribution in the containment due to enhanced mixing. All the LP codes (and GOTHIC) have models or components to simulate spray systems and air coolers and validation exist for most codes. Similar approaches can be used in the CFD codes, but no applications have been performed. A general spray model is available in CFX, but it has not been applied for containment spray modeling. Some users have developed their own spray model in FLUENT and validations are in progress.

It is also important to note that production, transport and dissipation of turbulence are not generally considered by the LP codes, but they are taken into account by the 3D codes. In general, the code developers performed fundamental qualification of the turbulence models of their codes against small scale tests with turbulence characteristics measured, and the users performed benchmarks against large scale integral tests where turbulence played a significant role in mixing. Although the turbulence characteristics were not specifically quantified, the agreement in gas mixing behavior sometimes relies on a good prediction of turbulence. The local turbulence level is an important factor for the prediction of 3D hydrogen mixing and a critical initial condition for flame propagation and acceleration.

2.3. Hydrogen Combustion

Hydrogen combustion can occur in different regimes and modes depending on various conditions. If oxygen and ignition sources (i.e., igniters, static electricity, or accidental sparks from electric equipment) are present in the vicinity of the break, the hydrogen can ignite and burn as a standing flame at the release location, which is possible over a large range of jet exit diameters, jet velocities and environmental conditions. The hydrogen that does not burn close to the source can mix with steam and air, and be transported in the containment building to increase global or local concentrations and create possibly flammable conditions. If ignited at high enough hydrogen concentration, the mixture could burn as a fast deflagration, creating a transient pressure and temperature that could possibly challenge the containment integrity and equipment. In regions of higher hydrogen concentration and under special geometric conditions, an accelerated flame (FA) or even a local deflagration-to-detonation transition (DDT) may occur, which would produce higher dynamic loads than a deflagration and pose a more serious threat to equipment and structures. Should it occur in spite of its low probability, a global detonation, following prolonged and extensive accumulation of hydrogen in the containment atmosphere, would be a major threat to the containment integrity.

Over the past three decades, significant advances have been gained in the understanding of hydrogen combustion characteristics through various R&D programs. Early studies conducted in the 80's and 90's established the foundation for development of FA and DDT criteria [15]. The recent studies are primarily motivated by the need for new 3D data for model development and code validation [16].

None of the codes assessed can simulate the entire range of combustion events or regimes. All the LP codes (and GOTHIC) use simplified parametric methods to simulate deflagrations without modeling the actual reaction kinetics or tracking the actual flame front propagation. The combustion rate is determined by the flame speed, the volume characteristic dimension, and the combustion completeness. These parameters are either constant values or calculated based on built-in empirical correlations or user-defined functions. The flame speed strongly depends on the initial turbulence level and the turbulence generated during the flame propagation. Since turbulence is not computed by the LP codes, it is commonly simulated by implementing a user defined burn enhancement factor to mimic the flame surface area increase due to turbulence effect. Turbulent combustion is not treated in a specific way by any of these codes. For the diffusion flame, most of the LP and 3D codes employ a simple model that allows for the burning of hydrogen-rich mixtures upon entry into volumes containing oxygen.

During MCCI, a significant amount of carbon monoxide can be produced in addition to hydrogen. The combustion with a mixture containing H_2 and CO is modeled with the same approach as H_2 combustion by ASTEC, MAAP, MELCOR, COCOSYS and TONUS, but no validation has been performed due to lack of experiments.

In TONUS, different types of models have been developed to cover slow deflagrations, accelerated flames and detonation and implemented in a fully compressible flow solver to simulate shock wave propagation. In GASFLOW, a one-step global chemical kinetics model based on a modified Arrhenius law accounts for local hydrogen and oxygen concentrations. In CFX and FLUENT, several options are available to model deflagrations using the similar approaches as implemented in the LP and other 3D codes. With continuous model development, for instance, CFX-14 is able to model combustion with hydrogen-air-steam mixture (hydrogen-air mixture only for previous CFX versions). AUTODYN is specially designed for simulation of detonation only. In GASFLOW and SPECTRA, the potential risk of FA can be calculated based on the built-in engineering criterion. In most codes, flammability limits are calculated as functions of gas composition as well as gas temperature and pressure based on the Shapiro diagram.

A large number of experimental data exist for hydrogen deflagration and the codes are widely validated against this phenomenon, but validations are limited or large uncertainty exists for fast deflagration and FA. The ISP-49 benchmark [17] was performed against the hydrogen combustion tests covering slow deflagration and the FA range. The experience acquired in the ISP-49 revealed that the contemporary level of the numerical tools developed for combustion analysis under SA conditions in NPPs requires further improvement to provide high quality blind predictions. The existing combustion models demonstrated that the quality of the prediction for FA reached moderate level of accuracy in the tube-like geometries with the regular obstruction, however, in other geometrical configurations (i.e., partially enclosed volumes with the irregular obstruction, flat layer of hydrogen-air mixture, or large volumes with walking grids), there is no clear proof of their conformity to the numerical code validation requirements.

2.4. Hydrogen Mitigation

For the containment and the reactor and auxiliary buildings, implementation of hydrogen mitigation measures is to prevent and limit hydrogen combustion consequences. Details of hydrogen mitigation measures are discussed together with the hydrogen management strategies in Section 3. Installation of Passive Autocatalytic Recombiners (PARs) has become one of the primary hydrogen management measures adopted by most countries. A large number of experimental data exist on PAR performance under a wide range of conditions relevant to SAs, for instance the latest data collected during the OECD-THAI project for three commercially available PARs (AREVA, AECL and NIS) [16]. The recent research is directed towards examining PAR performance under specific conditions (i.e., extremely low oxygen concentration in the late phase of SAs) [18].

The PAR behavior is modeled with different approaches. The simplest one is the so-called black-box model, where the hydrogen or H_2-CO (during MCCI) recombination efficiency or recombination rate is calculated using manufacturer correlations and implemented by means of volumetric sinks and sources of energy, mass and momentum. All the codes, except FLUENT, CFX and AUTODYN, have simple built-in PAR models and validation has been performed using the well-known experiments performed at various facilities, but no validation exists for CO recombination. The same approach has been applied by FLUENT and CFX users with user defined functions. Some codes (e.g., ASTEC, COCOSYS) have implemented a one-dimensional detailed PAR model for box-type PAR components based on a diffusion approach [19]. The heat transfer between the surrounding gas and the structures is calculated by means of free and forced convection, condensation and radiation. A mechanistic PAR model with complete description of relevant heat and mass transfer process has been developed by JUELICH, Germany and implemented in the CFX code. This user model is capable of handling H_2 and H_2-CO recombination.

It has been recognized that hot catalytic plates of PAR can cause combustion under specific condition (i.e., >6-8 vol.% H_2 in air). Since the ignition occurs at low hydrogen concentrations, the combustion pressure is relatively small [18], thus PAR induced ignition can have a beneficial effect. There is no model built into any of the assessed codes to predict the onset of PAR operation and hydrogen ignition by PARs. Most codes allow users to start or stop the hydrogen recombination at a defined hydrogen concentration and to initiate combustion in the zone containing a PAR at a given hydrogen concentration, but no validation has been performed for ignition by PAR. A SPARK code, developed by IRSN, France, considers a full description of the gas-phase and surface chemistry and is dedicated to evaluating PAR efficiency and hydrogen ignition limit for any operating conditions [20].

3. HYDROGEN MANAGEMENT STRATEGIES

The goal of hydrogen mitigation measures is aimed to prevent hydrogen combustions which may threaten containment integrity and, in case of occurring, to limit its consequence,. Comprehensive R&D programs have been developed in many countries since the TMI-2 accident to develop appropriate severe accident management (SAM) strategies. The risk of containment failure depends on several factors [6], including overall hydrogen concentration, containment structure and design, geometrical configuration, hydrogen release rate, and containment thermal-hydraulic conditions. The hydrogen concentration can be affected by several factors, including the amount of hydrogen released, containment volume, steam and other non-condensable gases. The containment design pressure is extremely important to sustain the combustion pressure, which highly depends on the hydrogen concentration and ambient conditions. Geometrical shape is also very important as significant accumulation of hydrogen in sub-compartments may create high local concentrations within the detonable range or closed (or partially closed) long pathway may favor flame acceleration.

If designated safety systems and preventive accident management measures have failed to prevent core heat-up from occurring and hydrogen is generated and released to the containment atmosphere in large amounts, three steps are generally recommended [6]:

(1) Reduce the possibility of hydrogen accumulating to flammable concentrations,
(2) Minimize the volume of gas at flammable concentrations if flammable concentrations cannot be precluded, and
(3) Prevent further increasing hydrogen levels from the flammable to detonable mixture concentrations.

As a result, hydrogen management strategies can be developed based on the following mitigation measures [6]:

- Preclude flammable mixtures by oxygen control
  - Dilute or replace the containment atmosphere with inert gas to maintain conditions outside the oxygen flammable limit (<5 vol.%) by either inerting the containment under normal operation (pre-inerting) or injecting inert gas during an accident (post-inerting).

- Preclude flammable mixtures by hydrogen control
  - Dilute hydrogen with available containment air from mixing by natural convection or engineered systems,
  - Dilute hydrogen and oxygen from post-accident by local inert gas injection,
  - Remove hydrogen and oxygen by catalytic recombiners (i.e., PARs or thermal recombiner in case small amounts of hydrogen are expected), or
  - Release hydrogen by filtered containment venting systems.

- Avoid unacceptable combustion pressures and temperatures
  - Induce local slow deflagration in the near hydrogen flammable limit region (4 vol.% in air) by deliberate ignition (igniters), or
  - Suppress detonable mixtures in selected locations by post-accident inert gas injection.

As concluded in [4], the choice of hydrogen mitigation measures depends strongly on the containment design. There is no single strategy or technique that is universally appropriate for all designs and accident scenarios, or even, for all phases of an accident in a particular design. Different measures may be more appropriate at different locations and at different times during an accident. For instance, a combination of deliberate ignition and catalytic recombination, known as the dual concept, has been implemented in some NPPs. It is recognized that recombiners cannot cope with high release rates, and therefore igniters are used for initiating combustion at the flammability limits and to prevent formation of rich mixtures.

A completed safety assessment for the particular plant is the only valid context for judging the adequacy of safety systems and accident management measures, including hydrogen countermeasures. In general, the following strategies have been used by different reactors:

- For NPPs with large dry containment (i.e., PWR, CANDUs, and VVER-1000), the strategy is predominantly on a large free containment volume and/or a high mechanical load capability, combined with the use of many PARs, and/or glow plug igniters.
- For BWRs with Mark III containments, US PWR and Finnish VVER-440 both with ice condenser containments, multi-unit CANDU stations, and some single-unit CANDU stations, deliberate ignition systems have been installed to cope with SA conditions to limit hydrogen concentration by early ignition.
- For NPPs with small containments with pressure-suppression systems (i.e., BWRs with Mark I and II containments, and BWR type 69 in Germany), the containments have been filled with nitrogen during normal operation to prevent any hydrogen combustion during all types of accidents. PARs are used in addition if the dry-well cannot be inerted as the German BWR type 72.
- For VVER-440 different means exist depending on the containment design (bubble condenser tower, ice condensers), which can affect the hydrogen mitigation concept.

The containment design features and accident management systems of various PWRs, BWRs, VVERs and PHWRs are described in details in the status report [8]. They are briefly summarized in Table 1.

Table 1
NPP design features related to hydrogen management [8]

Type	**PWR**	**BWR**	**VVER**	**PHWR**
Power [MWe]	~365 - 1,650	~370 - 1,360	~500 - 1,000	~700 - 1,000
No. of Loops	2, 3, 4	-	4, 6	2
Types of Containment	steel, pre-stressed concrete with steel liner, double concrete with inner wall pre-stressed, or reinforced concrete with steel liner	steel, pre-stressed concrete with steel liner, or reinforced concrete with steel line	steel with ice condensers, pre-stressed concrete with steel liner, or concrete with bubble condenser	pre-stressed concrete with steel liner, or pre-stressed concrete with epoxy or polymer coating
Volume of Containment (m^3)	~34,000 - 90,000	~7,000 - 39,000	~55,000 - 61,000	~50,000 for single unit; ~130,000 for multi-units
Design Pressure [bar (a)]	2 - 6.4	2 - 5.8	1.7 - 5.1	2.24 for single unit
Reactor Building	reinforced concrete or steel/concrete composite, or without reactor building	reinforced (or partially reinforced) concrete	with or without or partially reinforced concrete	containment and reactor building are a single combined structure

4. REQUIREMENTS AND STATUS OF HYDROGEN MANAGEMENT SYSTEMS

The national requirements for hydrogen management in SAs vary in details. Some countries tend to provide a general guideline, such as "avoid global combustions or eliminate possibility of FA and DDT to challenge the containment integrity". Some countries define maximum means and local hydrogen concentrations (typically PWR), and the adiabatic, isochoric complete combustion (AICC) pressure for the design of igniter or PAR concepts, or a maximum oxygen concentration (typically BWR) for the N_2 inerting-concept. Some countries require mitigation systems to accommodate a prescribed amount of hydrogen source (i.e., metal-water reaction involving 75% active cladding for the BWRs in USA). Some criteria are not defined by authorities, but by the utilities. In most countries, regulatory requirements on the implementation of hydrogen mitigation measures are required for reactors that are under construction or new designs, but there are no prescribed rules for existing plants. Therefore, the level of mitigation measures implemented varies significantly from country to country and even from plant to plant for the same country.

Depending on the NPP type, various hydrogen mitigation measures have been implemented to meet specific safety criteria and requirements. Since the 90's, installation of PARs has become favored for hydrogen management in most countries, especially for large dry containments. PARs are also seen as a promising alternative to older thermal (active) recombiners which are installed for long term hydrogen control following design basis accidents. Installation of PARs has become the preferred option for future upgrading too.

In response to the Fukushima accident, the European Council requested a comprehensive safety and risk assessment performed on all EU nuclear plants, including "stress tests" performed at a national level complemented by a European peer review [21]. It has been concluded that all countries have taken significant steps to improve the safety of their plants with various degrees of practical implementation, in particular for hydrogen management, high priority must be given to installing means of hydrogen mitigation designed for SAs to eliminate containment failure due to hydrogen combustion. Almost all the member countries have conducted evaluations of the existing hydrogen mitigation systems and considered to enhance them under SA conditions. Most countries now require hydrogen mitigation systems, particularly PARs, to be installed inside the containment if there was no mitigation concept required before. The optimal number and installation location for PARs may be plant and scenario specific. General recommendations and guidelines only exist in some countries (i.e., PAR system implementation procedure in Germany for large dry PWR containments).

After the Fukushima accident, many countries also started to investigate SA conditions outside of the primary containment, including the annular space between the reactor building and the containment in a PWR, the multiple rooms inside a BWR reactor building, or other non-accident containments for multi-unit stations, and at the spent fuel pool area. However, most countries have not yet adopted specific national requirements. Question remains open regarding the need of hydrogen management outside the containment and decision has to be made whether additional mitigation measures are required. In France, it is now required that the mean hydrogen concentration must stay below the lower flammability limit (4 vol.% in air) outside the reactor containment. In Japan, it is required to prevent damage to the reactor building and containment vessel annulus due to accumulation and explosions of hydrogen in the event of severe core damage.

Various engineering systems (e.g., spray, containment ventilation, local air cooler, suppression pool, latch systems) have been installed in many NPPs to reduce containment pressure and temperature during an accident. Operation of these systems can have an impact on hydrogen distribution and combustion if ignition occurs. Requirements have been defined by some countries for use of these systems in their severe accident management guidelines (SAMG). For instance, in order to keep the containment atmosphere inert during the in-vessel hydrogen production phase, the French SAMG recommends postponing the spray system activation at least 6 hours after the beginning of core degradation. During this time, hydrogen concentration would be reduced by recombination. It is expected that the SAMG of other countries will be updated to establish deliberate operational procedures for the operation of these engineering systems during a severe accident.

For the containment venting system, measures are taken to limit the risk of hydrogen combustion in the venting line by nitrogen or steam inerting, but for a long term operation, hydrogen build-up may occur due to inflow from the containment and slow but steady generation by radiolysis inside a scrubbing pool. It has been required to prevent hydrogen explosion inside a filter and at discharge paths connected to the outside the containment vessel by many countries. A containment depressurization limit is also sometimes defined to avoid high hydrogen concentrations when depressurizing the containment by venting.

The suppression pool is a general design feature for BWRs. The hydrogen released into the suppression pool can exit from the pool surface into the wet-well region. It may migrate into the drywell region through the opening of vacuum breakers. If the hydrogen release rates are high enough, mitigation measures (i.e., nitrogen inertisation, igniters or PARs) must be considered.

Implementation of hydrogen measurement systems has been considered (or is under consideration) as a part of hydrogen management strategies in many countries, particularly following the Fukushima accident. Hydrogen concentration measurements can be useful for the administrative authorities to be aware of the accident progression, and most importantly to assist the crisis teams in SAM, for instance to avoid an inadvertent spray actuation that may lead to an escalation of the hydrogen risk in case of hydrogen deflagration. In most countries, active measurement for hydrogen concentration are applied in the accident management concepts, but the implementation details vary, such as the number of samples and their locations. Some NPPs install the hydrogen measurement system inside the containment, but analyze it outside the containment. In some countries, measurements for oxygen concentrations, gas temperature, pressure and dose rates are also monitored as part of the accident management plan. In France, thermocouples are instrumented on selected PARs to obtain indication of hydrogen recombination. Nevertheless, questions remain open on reliability of limited sampling locations for monitoring non-uniform hydrogen distribution and how the measurements can be used to direct the SAM operation during an accident progression.

5. CONCLUSIONS

It has been identified that the hydrogen mitigation strategies vary from country to country and depend primarily on the design of the containments. The national requirements for hydrogen management also vary in details. In response to the Fukushima accidents, hydrogen mitigation systems, particularly PARs, are required to be installed in the containment by most countries, but most have not yet adopted specific requirements for hydrogen mitigation measures outside the containment (e.g., annulus, reactor or secondary building, etc.) or the spent fuel pool areas.

It is also evident that most countries tend to use lumped parameter codes for full plant long term analysis combined with 3D codes for detailed short-term analysis. It has been recognized that quantification of code uncertainties is challenging, thus a large degree of user experience on code application is necessary to obtain realistic results.

R&D efforts to date have already significantly enhanced the understanding of phenomena governing the hydrogen behaviour during an accident. Although none of the assessed codes have been fully validated for the entire list of hydrogen phenomena, considerable efforts have been made for model development and code validation. The computational tools have reached a reasonable degree of maturity, although engineering judgment is sometimes still required. Further efforts are still needed to close research gaps and properly apply the knowledge to SAMG, such as:

- There have been gaps identified in hydrogen measurement strategies. In most NPPs, measurement is performed only at a single or a few (e.g., up to 10) points. More studies are needed to understand how an accident progression can be determined based on the limited number of hydrogen measurements, and how to provide guidance for SAM decisions.

- Progress has been made to examine the effect of engineering systems (spray, local air coolers) on hydrogen behaviour, but implementation of the knowledge to SAMG has not been finalized.

- PSA Level 2 studies performed by some countries show that FA cannot be ruled out even with PARs installed. Therefore, the effect of pressure loads due to combustion of hydrogen and/or carbon monoxide mixture on containment and equipment needs to be assessed under in-vessel and ex-vessel conditions.

- Various international benchmarks on hydrogen behavior have been performed and showed encouraging results, but uncertainties in modeling fast (or turbulent) combustion (FA and DDT) in mixtures with non-uniform hydrogen concentrations remain large by both LP and 3D codes.

- Strong user effect on simulation results has been observed for both the LP and 3D codes. User training is as important as code validation. The best practice guidelines are highly recommended for both the LP and 3D code users.

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