Transactions of the Korean Nuclear Society Autumn Meeting
Gyungju, Korea, October 25-27, 2017

Safety Perspectives to Hydrogen Control and Management Strategies for Nuclear Power Plants

Manwoong Kim *, Jungjae Lee, Ku Young Chung
Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 34142. Republic of KOREA
**Corresponding author: M.Kim@kins.re.kr*

1. INTRODUCTION

It has been well recognized that the objective of severe accident (SA) management in nuclear power plants (NPPs) is the protection of the containment integrity that is the ultimate barrier against the release of fission products to the environment. Although there are various potential challenges to the containment integrity during a severe accident in NPPs, the most significant challenge is a combustion of hydrogen, produced primarily as a result of heated zirconium metal reacting with steam. Because hydrogen combustion can create short term pressure or detonation forces that could exceed the strength of the containment structure and lead to early containment failure. For most NPPs, severe accidents lead to hydrogen release that exceed the capacity of hydrogen control measures at design basis accidents (DBAs).

Hydrogen generation, distribution and combustion in containment during accident conditions are very complex and highly plant- and scenario-specific phenomena. Moreover, hydrogen combustion can take place in a variety of forms likely mild deflagration, fast or accelerated flames, deflagration to detonation transition (DDT) and detonation. The distribution of the hydrogen released within the containment determines local and global hydrogen concentrations, which are decisive for the evaluation of the various combustion modes, such as diffusion flames, deflagration and detonation, depending on geometrical effects and concentrations. In terms of implementing effective hydrogen management measures, an understanding of all these phenomena is crucial. These measures include enhancement of mixing, deliberate combustion through igniters, use of recombiners, and post-accident inerting.

Nevertheless hydrogen combustion causes high consequences to the NPPs during accident conditions, regulatory requirements on the implementation of hydrogen mitigation measures for existing plants are limited without being restricted, while these measures have to be incorporated into the design for new build reactors that are planned or under construction after Fukushima Daiichi accident. Therefore, mitigation measures for hydrogen already exist in many NPPs on a voluntary basis. The implementation level varies considerably from country to country and also from plant to plant in an individual country.

After Fukushima Daiichi accident, the measures are installed to cope with hydrogen produced during severe accidents in many plants. Current years, the issue of mitigation measures for hydrogen is being in progress in a number of countries.

In order to share views and experiences among the countries, a report, IAEA-TECDOC-1661 on *Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants* was published in 2011 by IAEA [1] and a document entitled *Hydrogen Management and Related Computer Codes*, was published in 2014 June by OECD/NEA [2]. These two documents provide an overview of the status report, focusing on current knowledge on hydrogen generation, distribution, combustion and recombination, and approaches for hydrogen management under severe accident conditions in various NPPs.

The purpose of this paper is focused to review the current safety perspectives for hydrogen control and management in the countries aimed at enhancing severe accident management strategies.

2. POST-FUKUSHIMA ACTIONS FOR HYDROGEN MANAGEMENT

After the Fukushima accident, many countries have started to study SA conditions. A lot of actions were taken in many countries in terms of hydrogen control and management. The details are described in the following.

In Korea, special safety inspection was carried out on all the NPPs by the government. Hydrogen management was included among the recommendations for safety improvement. For example, passive autocatalytic recombiners (PARs) have been installed in all operating and under-construction plants by the end of 2013 for hydrogen management in the inner containment during SAs. The measurement of hydrogen concentrations during a SA and the management of hydrogen flammability have been included in the SAMG of the units where this strategy was not implemented. Hydrogen risks in the spent fuel pool (SFP) area or due to hydrogen leakage from the inner containment to other peripheral buildings will also be investigated.

In the United States, the current US Nuclear Regulatory Commission (NRC) regulations focus on hydrogen mitigation within the primary containment only, but the US NRC has initiated post-Fukushima actions regarding hydrogen management for (1) assessment of hydrogen control measures and potential hydrogen ingress into adjacent buildings, (2) evaluate the Fukushima accident sequences with particular emphasis on hydrogen generation from all sources and timing, (3) review information that becomes available in the near term on potential containment release pathways for hydrogen ingress into the respective Fukushima damaged reactor buildings.

In France, the French operation organization, the Electricity of France (EDF) has conducted to examine the risks linked to the build-up of hydrogen in the buildings other than the containment, especially the fuel building requested by the French Regulatory Authority (ASN) to identify: (1) the phenomena capable of generating hydrogen (radiolysis, zirconium/steam reactions), (2) the possible build-up of hydrogen, and (3) the means implemented to prevent hydrogen explosion or detonation. Regarding the SFP, an additional analysis is being initiated to assess the possible risk in the absence of ventilation. In accordance with the hydrogen risk studies, particular steps may need to be taken such as the installation of PARs in the fuel building.

In Japan, all NPPs considered to restart are required to prepare alternative power supply and cooling measures. BWRs are required to prepare a FCVS in order to suppress the containment pressure increase in early stage of the accident. Additional measures are suggested, such as (1) preventing a backward flow of hydrogen due to the common off gas system used for the primary containment venting (PCV), (2) ensuring independence of pipes belonging to PCV venting, (3) preventing hydrogen explosion in the reactor building (i.e., add openings in the top and ground floor of the building).

In Canada, the Canadian Nuclear Safety Commission (CNSC) performed inspections of all NPPs to assess the adequacy of mitigating systems, including hydrogen control system. As results, the CNSC has recommended to enhance the design of hydrogen and other combustible gases in terms of SA management.

In Germany, the existing provisions (PARs, inerting) are considered to be sufficient for accidents within the containment. However, it is being considered to install the FCVS, especially its off-gas systems related to the hydrogen combustion issue. As to the SFP located inside the containment, the existing PARs can protect the containment as well in such cases.

3. NATIONAL REQUIREMENTS AND MITIGATION MEASURES

In order to prevent the occurrence of an accident or to limit its consequences, nuclear regulatory authorities define rules and criteria for the implementation of prevention or mitigation means and elaboration of accident management activities.

IAEA

New Draft Safety Guide DS 482 Design of Reactor Containment Structure and Systems for Nuclear Power Plants was prepared under the IAEA programme for safety standards for nuclear power plants. It is a revision of the Safety Guide on Design of Reactor Containment Systems for Nuclear Power Plants (Safety Series No. NS-G-1.10, 2004), which is now superseded by this safety guide [3]. This guide recommends to prevent and mitigate threats due to hydrogen combustion in accident conditions with core melting as followings;

- Hydrogen combustion should be postulated when flammability is exceeded (e.g. for hydrogen concentration higher than 4% in volume in dry air)
- As long as conditions for flame acceleration phenomena and for high dynamic pressure loads are not reached, the Adiabatic Isochoric Complete Combustion (AICC) pressure curve calculated for all the hydrogen combustions at a slow flame regime should be retained to define the global and local pressure bounding loads
- Conditions for flame acceleration phenomena which could lead to deflagration to detonation transition (DDT) or to a detonation should not be reached to the extent possible in areas where hydrogen accumulation is possible.
- To reach safe conditions inside the containment, performance and efficiency of the means to remove combustible gases should be designed to reduce their concentration in average in the free volume of the containment below the gas flammability limit in dry air (e.g. below than 4% for hydrogen).
- An adequate number of passive autocatalytic recombiners and/or active means such as igniters should be provided and suitably distributed inside the containment for burning/removing combustible gases.
- The number and positioning of recombiners or igniters should be justified on the basis of detailed combustible gas distribution analyses resulting from different scenarios of an accident with core melting.
- The containment design either should incorporate active means (such as sprays and mixing fans qualified for operation in a combustible gas mixture) or should facilitate the action of mechanisms (such as large volume dispersion or natural circulation) to enhance the uniform mixing of the containment atmosphere within and between compartments, in particular owing to the implementation of openings and/or preventing to the extent possible dead-end zones.
- Inerting the containment atmosphere during reactor operation (usually with nitrogen) for a small containment.

Korea

According the regulatory requirements in the Nuclear Safety Act and Notice of the Nuclear Safety and Security Commission (NSSC), pressurized water reactor fueled with uranium oxide pellets within cylindrical zirconium alloy cladding shall be provided with an ECCS that shall be designed so that its calculated cooling performance following postulated LOCAs of DBAs conforms to the criteria set forth in the followings:

- Peak cladding temperature: The calculated maximum fuel element cladding temperature shall not exceed 1204ºC.
- Maximum cladding oxidation: The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
- Maximum hydrogen generation: The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel were to react.

The criteria for Severe Accident in Notice No, 2016-02 and Notice No, 2014-31 of the NSSC as followings respectively:

- The structural barrier of containment building shall be kept intact during and after significant core (fuel) degradation to prevent large release of radioactive materials due to combustion of combustible gas in containment building.
- The concentration of combustible gas in each compartment of containment building shall be low enough for preventing global FA or DDT. Containment building shall not be damaged due to combustion of combustible gas in containment building.

United States of America

The US NRC revised the hydrogen control requirements in 2003, “Combustible Gas Control for Nuclear Power Reactors” in 10CFR50.44 supersede 10CFR50.34(f) for a reactor construction permit or operating license whose application is submitted after October 16, 2003. This rule specifies requirements for combustible gas control in future water-cooled reactors which are similar to the requirements specified for existing plants in 10CFR50.34(f). However, a key difference is the need to accommodate an equivalent amount of hydrogen as would be generated from a 100 percent fuel clad-coolant reaction. Particularly, if a containment does not have an inerted atmosphere, it must limit hydrogen concentrations in containment during and following an accident that releases hydrogen (equivalent to 100 percent fuel-coolant reaction) when uniformly distributed to less than 10 percent (by volume); and maintain containment structural integrity and appropriate accident mitigating features. Consequently, the PWR large dry containments are now required to install a hydrogen control system to adhere to the above specified limits.

France

Due to the standardization of the French NPPs, the adopted hydrogen mitigation has been designed to fulfil the same following requirements:

- For all SA conditions, in case of ignition, the pressure induced by the AICC remains under the design pressure (7 bar for PWR900 , 6 bar for PWR1300 and PWR 1450),
- During the SA transient, the mean hydrogen concentration remains under 8 volume %. This limit ensures the non-completeness of hydrogen combustion in case of ignition,
- During the SA transient, the local hydrogen concentration must be below the target value of 10 volume %, which permits to avoid FA phenomena and the possibility of high dynamic pressure loads.

Canada

The design requirements to control the release of hydrogen to prevent deflagration or detonation that could jeopardize the integrity or leak tightness of the containment for a new water-cooler reactor are established in a regulatory document RD-337 [4]. It should be noted that the containment and reactor building are a single combined structure for CANDUs with a single unit, and for multi-unit CANDUs, the reactor building includes the reactor vault of a specific unit, the common vacuum building and the fuelling duct, forming the reactor containment.

- For DBA, it is considered to assess the potential adverse effects of the bounding hydrogen releases and burns. The designer needs to demonstrate the effectiveness of any introduced hydrogen mitigating measures, such as the PARs.
- For BDBA with limited core damage (such as LOCA + ECCS failures in CANDU), the designer needs to show that there are no issues with the short and long term hydrogen releases and demonstrate the effectiveness of the hydrogen mitigating measures, in precluding destructive potential hydrogen combustion modes.
- For SAs, the designer is expected to choose a set of representative scenarios and assess the corresponding flammable gas releases including the hydrogen and CO releases from MCCI. The designer then needs to demonstrate that the introduced hydrogen complementary features such as the PARS provide effective mitigation and that destructive potential combustion modes are avoided.

Japan

The new regulatory requirements are enforced on July 8th 2013 after Fukushima Daiichi accident. Requirements on the SA measures are mentioned to prevent and mitigate both core degradation and containment failure. For hydrogen explosion, it is interpreted to prevent detonation that can cause the containment failure. These national requirements are substantiated by the guidelines that show how to prove adequacy of measures against hydrogen explosion:

- An amount of hydrogen generated before failure of the reactor vessel corresponds to reaction of 75% of Zircaloy located in the core.
- After failure of the reactor vessel, generation of combustible and non-combustible gases due to MCCI is taken into account.
- Criteria for preventing the destructive detonation are interpreted as maintaining the mean and local hydrogen concentration at 13 volume % or less without steam condition or the mean and local oxygen concentration at 5 volume % or less.

Besides, the general national requirements for hydrogen management inside the containments are listed in Table 1. The hydrogen mitigation strategy depends primarily on the design of the containments, for instance, NPPs with large dry containment (e.g., PWR, PHWR, and VVER-1000), the strategy is mostly a combination of a large free containment volume with the use of many PARs, and/or glow plug igniters.

It is also observed that in some countries likely Czech Republic, there is no specific requirement, regulatory guide or other document for Nuclear Safety. However, conditions for a design of the hydrogen removal system under SAs were prepared to cover all important variants of scenarios and hydrogen concentrations, criteria for FA and DDT, and AICC pressure. Meanwhile, some countries likely France and Canada have two distinguish regulatory requirements of hydrogen control for DBA and BDBA/SA.

Nevertheless, implementation of hydrogen measurement systems has been considered (or under consideration) as a part of hydrogen management strategies in most countries, particularly following the Fukushima accident.

4. STRATEGIES BEING CONSIDERED FOR HYDROGEN CONTROL

As aforementioned, the objective of this study is focused how to harmonize requirements of hydrogen management of countries rationally and practically. Hence, following approach is considerate for enhanced hydrogen control and management of nuclear power plants during accident conditions.

- Hydrogen concentration shall be reduced either below the mean hydrogen concentration (volume %) of hydrogen flammability limit in dry air in average in the free volume of the containment (e.g. below than 4% for hydrogen) or not exceed local hydrogen concentration (volume %) in the containment (e.g. below than 8% for hydrogen) during and after accident conditions where hydrogen generated from reaction of 100% cladding metal and water under the assumption of uniform distribution of hydrogen inside containment building.
- The concentration of combustible gas in each compartment of containment building shall be low enough for preventing DDT or a detonation so that flame should not be reached to the extent possible in areas where hydrogen accumulation is possible. Facility shall be installed for protection of containment building from damage due to combustion of combustible gas in containment building. Containment building shall not be damaged due to combustion of combustible gas in containment building.

5. CONCLUSION

This study provides a summary of the status of knowledge on hydrogen control and management strategies and measures implemented by the major countries. It is observed that all countries have taken significant steps to improve the safety of their plants with various degrees of practical implementation, in particular for hydrogen control and management, high priority must be given to installing means of hydrogen mitigation designed for severe accidents so as to practically eliminate containment failure due to hydrogen combustion.

Nevertheless hydrogen combustion causes high consequences to the NPPs during accident conditions, regulatory requirements on the implementation of hydrogen mitigation measures for existing plants are limited without being restricted, while these mitigation measures have to be incorporated into the design for new build reactors with being varies from country to country and also from plant to plant in an individual country after Fukushima Daiichi accident.

REFERENCES

[1] IAEA TECDOC No.1661, Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants, 2011

[2] Hydrogen Management and Related Computer Codes, CSNI/NEA/R(2014)8, 2014

[3] IAEA draft Safety Standard No. DS 482, Design of Reactor Containment Structure and Systems for Nuclear Power Plants, (to be published)

[4] Canadian Nuclear Safety Commission Regulatory, RD-337, Design of Nuclear Power Plants, May 2008

[5] State-of-the Art Report on Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety, NEA/CSNI/R(2000)7, 2000

[6] Nuclear Safety Laws and Notice of the Nuclear Safety and Security Commission

[7] Federal Registration of USA, 10 CFR 50.44, Combustible Gas Control for Nuclear Power Reactors", Nuclear Regulatory Commission

Table 1 National requirements for hydrogen management inside the containment

Country	NPPs	National Requirements		
		For DBAs	For SAs	
		Mean H_2 vol.%	Mean H_2 vol.%	Local H_2 vol.%
Belgium	PWR 440	<4	<5	-
	PWR 1000	<4	<5	-
Canada	CANDU 6 (C6)	<6	<8	-
	CANDU (Multi-units)	<4	<8	-
	Enhanced C6	<6	<8	-
France	PWR 900	<8	<8	<10
	PWR 1300	<8	<8	<10
	PWR 1450	<8	<8	<10
	PWR 1650	<8	<8	<10
Japan	PWR[(d)]	-	<13	<13
	BWR	-	-	-
Korea	PWR (587-950)	Not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel were to react	<10	Local H_2 to avoid global FA or DDT
	CANDU 6 (Wolsung 1)		<10	
	CANDU 6 (Wolsung 2-4)		<10	
	APR 1400		<10	
	OPR 1000		<10	
USA	BWR Mark I/II	-	-	-
	BWR Mark III	-	-	-
	Large dry PWR	-	-	
	Ice condenser PWR	-	-	-
	AP 1000	-	-	-
	ALWR PWR	<10	<10	-
	ALWR BWR	-	-	-