Hydrogen Mitigation - CNSC Focus and Expectations Following Fukushima

S. H. Gyepi-Garbrah
Canadian Nuclear Safety Commission, Ottawa, Ontario, Canada
(samuel.gyepi-garbrah@cnsc-ccsn.gc.ca)

Abstract

This paper revisits CNSC expectations for resolution of hydrogen safety in the light of the CNSC Fukushima task force's recommendations. Focusing on CANDU NPPs, present strategies for reduction of hydrogen in containment and steps to mitigation, assumptions, interpretation and modeling codes are discussed. Ensuring greater robustness for BDBAs rather than detailed modeling, PSA and calculation of margins is perceived to be the preferred approach. Proposed recommendations that should be the focus for future resolution of hydrogen safety and mitigation are related to present gaps and uncertainties.

1. Introduction

Hydrogen is generated in containment during normal operation, accidents and in more appreciable amounts following a severe accident (SA). Hydrogen gas mixtures which are flammable over a wide range of hydrogen concentrations can be ignited by milli-joules of energy. The resultant combustion may lead to significant challenges to plant systems, as witnessed in March 2011 at the Fukushima Daichii Plant (FDP) due to the SA created by the great earthquake of Japan.

In the event of a Loss-Of-Coolant Accident (LOCA) with Loss Of Emergency Core Cooling (LOECC), generation of large amounts of hydrogen is possible from various sources ranging from short-term production from fuel sheath Zircaloy oxidation, to long-term generation from water radiolysis by dissolved fission products. The hydrogen may migrate to the containment compartments and form flammable gas mixtures in the post-accident containment atmosphere.

Hydrogen combustion inside a post-accident containment is recognized as a safety concern for CANDU reactors [1]. In considering hydrogen generated in containment, provisions have been made in most plants to maintain the local hydrogen concentration below its flammability limit (4%-6% of volume) through mixing and thermal recombiners. However, SA, involving large scale core degradation with possible molten core concrete interactions, increase the probability of hydrogen release rates greatly exceeding the capacity of conventional hydrogen control measures.

While the processes of hydrogen generation due to oxidation and water radiolysis by radio-nuclides are complex, similarly its transport in containment is also governed by complex processes. This could lead to non-uniform hydrogen distribution in the containment volume and development of hydrogen pockets of high concentrations that could challenge the intergrity of the containment.

The modes of hydrogen combustion: slow deflagration, fast turbulent deflagration, detonation or standing flame - govern the amplitude and time scale of the containment pressure and thermal loads. The mixture composition, initial pressure and temperature, geometrical configuration and physical size (scale) of the reactive system determine whether Flame Acceleration (FA) or Deflagration to Detonation Transition (DDT) will take place. Identification of the potential combustion mode is difficult but crucial for mitigation of the combustion loads and protection of the containment and post-accident systems, structures and components (SSC) needed for accidental mitigation.

This paper revisits Canadian Nuclear Safety Commission (CNSC) expectations for resolution of hydrogen related safety issues a [1] and updates them based on the developments in the last years.

2. Hydrogen Control and Risk Mitigation Worldwide

To reduce risk and protect containment from challenges posed by potential hydrogen releases, burns and thus avoid severe damage of containment and loss of the confinement function for radioactivity release, various hydrogen control and risk mitigation measures exist. The main countermeasures used depend on the reactor design [2]. Some common measures are briefly described below.

2.1 Conventional Mixing

Various convection regimes (forced/mixed/natural) associated with normal operation and post-accident conditions are also known to help mitigate hydrogen in containment. Mixing of hydrogen with the containment air by natural convection or forced convection (e.g., fans, local air coolers, sprays) is the most common. Other important phenomena identified with hydrogen are usually studied and modelled with hydrogen mixing codes such as GOTHIC [3] and others [4].

2.2 Inertization

Inertization can be used during normal operation or post-accident. Pre-inertization of containment is the countermeasure used in most BWRs because they have small containments which are easily inertized before normal operation. Post-accident inertization involves injection of non-combustible or combustion-inhibiting gases into the containment atmosphere following the onset of an accident that has the potential of producing significant quantities of hydrogen. Post accident dilution attempts to gain some benefits of complete inertization while strategically injecting smaller amounts of gas. Complete post accident inertization has disadvantages in terms of containment pressurization and uncertainties in procedures and criteria for activating the system.

2.3 Hydrogen removal

Deliberate ignition: A deliberate ignition system initiates combustion of flammable mixtures when they arise, removing hydrogen by slow deflagration while distributing the energy release spatially and temporally. Igniters are unable to ignite if the containment atmosphere is not flammable. Various types of igniters include glow plugs, spark and catalytic igniters. They have been installed in various Nuclear Power Plants (NPPs) all over the world including some CANDU reactors in Canada.

Venting: The containment is vented deliberately when the combined pressure of steam, air and possible hydrogen combustion exceeds the containment pressure limits. In order to avoid radioactive releases, filtered venting is preferred compared to unfiltered venting. An engineering design to avoid venting flammable hydrogen needs to be performed for each individual case.

Spontaneous ignition: Due to the small amount of energy which is needed to ignite a hydrogen air mixture, a small spark produced by any electrical or mechanical equipment is sufficient to initiate hydrogen burns. Even if no igniters are installed there remains a high probability that the hydrogen will ignite once the atmosphere is flammable. Hot surfaces can also serve as igniters as well as static electricity.

Passive Auto Catalytic Recombiners (PARs): Catalytic recombiners oxidize hydrogen and are operable outside the limits of flammability. PARs are simple devices, consisting of catalyst surfaces arranged in an open-ended enclosure. In the presence of hydrogen (with available oxygen), a catalytic reaction occurs spontaneously at the catalyst surface and the heat of reaction promotes natural convection flow through the enclosure, exhausting the warm, humid hydrogen depleted air and drawing fresh gas from below. PARs do not need external power or operator action. For example, Atomic Energy Company Limited (AECL), AREVA and others have developed and commercialized PARs since 2001.

2.4 Strategic combinations

Catalytic recombiners and igniters (dual concept): A combination of deliberate ignition and catalytic recombination, also known as the 'dual concept' was developed and tested in Germany [3]. The results indicated such a combination is effective in controlling the hydrogen concentration under both inerted and non-inerted conditions in containment. Generally, 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. This concept is being used in multi-unit CANDU stations in Canada.

Catalytic recombination and post-CO_2 Injection: Carbon dioxide can be injected into containment so that DDT and detonation onset is prevented while recombiners remove the hydrogen over time. Therefore, containment structures and equipment only have to withstand the static loading caused by relatively benign deflagration as opposed to detonation loads. It is important that the injection of carbon dioxide be limited so that the combined pressure load does not exceed the containment pressure capability.

2.5 Hydrogen control in SA management guide approaches

Hydrogen control and risk mitigation is an inherent part of the various SA management approaches. The actual control of hydrogen depends on the method chosen. For example, if PARs are present, only limited guidance may be needed, as these devices work reliable and automatically. Presently the Canadian nuclear industry is performing an assessment to address adequate mitigation measures for hydrogen generated in CANDU reactors in case of a SA.

3. History of CNSC Regulatory Approach for Resolution of Hydrogen Issues

Assessing the impact of a post-accident hydrogen release in a CANDU reactor and the implementation of appropriate mitigation measures are included in licensing requirements by the CNSC. In 1988, the CNSC issued a Generic Action Item (GAI-88G02) [5] on hydrogen, requiring the nuclear industry to develop a deeper understanding of hydrogen behaviour and its impact on the safety of CANDU reactors. To recognize the crucial safety role performed by containment in protection of the public following an accident, the CNSC issued in 1991 the regulatory document R-7 [6] which specifies containment design and operation requirements.

The nuclear industry in Canada developed a broad Research and Development (R&D) program to address GAI-88G02. The national and international R&D activities resulted in the development of a solid knowledge base, as demonstrated for example by the Nuclear Energy Agency (NEA) State of the Art Report (SOAR) on containment thermal-hydraulics and hydrogen distribution [7], the NEA report on FA and DDT [8], and various CANDU owners group (COG) reports [9-11. Over the past two decades, the collaborative R&D activities by international organizations, and AECL and COG on behalf of the CANDU industry provided the hydrogen knowledge and technology base [7-11] which formed the basis for the current approach for the resolution of hydrogen issues. Due to a well established overall safety framework [12-15], sufficient experimental knowledge base and analytical capabilities to address hydrogen issues, GAI-88G02 was closed and station-specific action items (AIs) were initiated to address unique outstanding issues. The details of closure criteria have been presented at numerous CNSC-Industry meetings, working groups, workshops and conferences [16] and are not the focus of this paper.

4. Present Regulatory and Station Resolution of Hydrogen Issues

4.1 CNSC Position

In response to the SA at the FDP, the CNSC established the CNSC Fukushima Task Force (FTF) in April 2011 to review licensees' responses to the CNSC request to re-examine the safety cases of their NPPs. Further to the CNSC FTF Report (INFO-0824) [17], the CNSC Management Response to CNSC FTF Recommendations (INFO-0825) [18] and the CNSC Staff Action Plan on the CNSC FTF Recommendations (INFO-0828) [19], a number of Fukushima action items have been proposed. Although some FAIs depend on the outcome of others, each of the action items will only be closed when the stations have produced the required deliverable and it has been accepted by the CNSC. Station-specific AIs may be opened to track further deliverables for the long-term.

It is important to note that Canadian NPPs' were found to be safe and pose very small risk to the health and safety of Canadians and the environment. The Action Plan [19] was designed to map out the strategy and expectations upon which stakeholders will fulfill the requirements of each recommendation within the short-, medium- or long-term timeline, while enhancing the safety of these facilities through

- Part 1 - Strengthening reactor defence in depth
- Part 2 - Enhancing emergency response and
- Part 3- Improving regulatory framework and processes

In the lessons learned from FDP event, hydrogen explosion was one of the consequences that challenged containment for two or three units at FDP. In the recommendations and action items (AI) the following outlined are related to hydrogen and combustible gases issues in containment:

- Recommendation 1 – detailed by
  - AI 1.3.1 - Assessments of adequacy of the existing means to protect containment integrity and prevent uncontrolled release in BDBA including SAs. (long term)

- AI 1.4 - A plan and schedule for the installation of PARs to control capabilities for management of hydrogen and other combustible gases in a SA.(medium term)
- AI 1.5 - Preclusion of hydrogen and its mitigation in the Spent Fuel Bays and other areas (e.g., the Vacuum Building)
- AI 1.8 - Equipment survivability for Severe Accident Management

- Recommendation 3 – detailed by
  - AI 3.2.1 - Deterministic analyses for SA in multi-unit stations and Spent Fuel Bay accidents.

4.2 Industry Efforts and Response

NPPs in Canada have provided safe, reliable electricity for decades as safety culture drives the industry to continually improve ongoing programs. The nuclear industry in Canada has also worked closely to share best practice and make improvements, following the events of Fukushima. The industry sought to build on lessons learned by actively participating in the World Association of Nuclear Operators (WANO) and to assure the interested public that all lessons learned are implemented in an appropriate and timely manner.

Prior to the implementation of actions from the CNSC FTF as discussed in section 4.1 above, the industry had made efforts to address some of the lessons learned from the FDP hydrogen explosions. Present industry plans (not detailed in this present paper) identify strong commitment by all utilities in Canada to continue to operate to the highest standards by strengthening reactor defence in depth to prevent hydrogen risk that will challenge the integrity of containment in the event of severe core damage.

5. International Community - Regulatory and Station Resolution of Hydrogen Issues After Fukushima (Stress tests performed on NPPs)

All the details of hydrogen assessment and mitigation for the International Community cannot be presented in this paper; however, a summary of mitigation activities restricted to some selected countries is presented in Table 1. FDP events confirmed that despite the precautions taken in the design, construction and operation of the nuclear facilities, an accident is always possible. In this context, European countries recommended that a complementary safety assessment of their nuclear facilities, with regard to the type of events leading to the FDP event, should be initiated without delay, even if no immediate emergency measures were necessary. These assessments were to be carried out in addition to the safety review performed in the routine licensing of their NPPs. The safety assessments followed a two-fold approach: first, performance of a nuclear safety audit on nuclear facilities in the light of the FDP event, and second, the organization of "stress tests" requested by the European Council at its meeting in March 2011.

To ensure consistency between the European approaches, most countries performed assessments and drafted their reports on the basis of European specifications approved by European Nuclear Safety Regulators Group in May 2011 [18]. The specifications consisted of a targeted reassessment of the safety margins of their NPPs. Three main aspects that were included in this assessment were:

1. The steps taken in the design of the facility and its conformity with the design requirements applicable to it;
2. The robustness of the facility beyond the level for which it was designed; the licensee in particular identifies the situations leading to a sudden deterioration of the accident consequences ("cliff-edge effects") and presents the measures taken to avoid them;
3. All possible modifications liable to improve the facility's level of safety.

With our main focus on hydrogen safety assessment and mitigation, Table 1, provides a summary of the mitigation strategies implemented, recommended and/or currently being assessed by some selected countries compared to the regulatory position by the CNSC. It is worthy to mention that the Canadian nuclear industry is strongly committed to take actions as required. As Table 1 outlines, virtually all countries on the list are taking or have already taken action concerning containment monitoring, thermal recombiners (Igniters or PARS or both), filtered venting, and analyses of events in the spent fuel bay or pool, among others. Apart from containment inertization which is not used in the CANDU industry in Canada, the rest of the mitigation strategies are similar to the other countries albeit accounting for different designs of reactors. Based on this comparison it is intuitive to state that CNSC's regulatory position is strong in demonstrating its mandate and vision to assure NPP safety for all Canadians. One exception from the strong position taken by Canada and other countries is the Indian Regulatory position. India is not requiring any of the known mitigation strategies for their PHWR design, but their BWR design has containment inertization as a mitigation strategy.

6. IAEA Integrated Regulatory Review Service

CNSC hosted an IAEA Integrated Regulatory Review Service (IRRS) team mission that encompassed a review dedicated to CNSC actions on the regulatory implications of the FDP accident for Canadian NPPs. The IRRS findings indicated that CNSC actions and responses to the FDP accident were prompt, comprehensive and robust. The IRRS team rated CNSC response to the FDP accident as good practice, and that the CNSC had systematically and thoroughly reviewed the lessons learned from the SA and made full use of available information, including the review of actions taken by other international regulators. The IRRS team mentioned that the CNSC has an effective and pragmatic regulatory framework in place to continue follow-up to the FDP accident. No observations were made that impacted the CNSC Action Plan.

7. Future Focus

Hydrogen control and mitigation is possible if appropriate measures are taken and implemented as detailed in section 2. In the case of the AIs specific to hydrogen, the Canadian nuclear industry is expected to install PARs in containment as a safety measure to mitigate any flammable hydrogen concentrations that may be produced in the event of an accident. In the time frame shortly after an accident, hydrogen mitigation is dependent on natural convection mixing and igniters. In the long term, PARs are used to mitigate hydrogen risk. There are two issues that need to be addressed with respect to existing hydrogen mitigation technology. Firstly, investigation into the resultant pressure and temperature transients from igniter burns is needed to ascertain their impact on containment.

Secondly, the performance of PARS needs to be assessed when hydrogen production exceeds the PAR's recombination rate; in particular during BDBAs In this later case, the consideration of complementary design features such as containment inertization may provide an improvement to mitigation of hydrogen during BDBAs.

Hydrogen behaviour during an accident including dispersion, key combustion phenomena, source term and impact of combustion is predicted by analytical models and tools. Computer models for the analyses of hydrogen behaviour and distribution in a reactor containment use assumptions to construct a best-estimate simulation with no known bias toward conservatism of various accident scenarios. Despite their important role and maturity, the uncertainties in the use of these models and codes are sometimes difficult to define and may inadvertently reduce safety margins. For example, present day codes [10-11] used for hydrogen analyses in CANDU reactors are not able to clearly elucidate and/or identify some critical combustion phenomena and mixing behavior in containment. There also exist uncertainties in hydrogen source term dominated by unknown zirconium oxidation during in-vessel core degradation. It is envisaged that code refinement and enhancement may provide improvements to analytical assumptions and results.

8. Conclusions

This paper has outlined CNSC expectations for resolution of hydrogen related safety issues. Focusing on the CANDU NPPs, this paper considers presently known strategies for hydrogen management in containment. To reduce uncertainties and their impact in the treatment of hydrogen issues in containment, this paper mentions the uncertainties or gaps at present and recommends strategies for future resolution of hydrogen issues. In addition, paper considers the Canadian approaches to hydrogen risk in containment and compares them to a summary of some regulatory positions of the international community. Based on the comparisons, it can be concluded, the CNSC is in a strong regulatory position to focus on the path forward and oversee the resolution of hydrogen safety and mitigation issues in containment.

9. References:

1. Khosla, J.K. and Rizk, M., "Hydrogen Mitigation System – A Canadian Regulatory Perspective", AECL-11762, NEA/CSNI/R (96)8, 1997.
2. Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants, IAEA-TECDOC-1661, Vienna, July 2011.
3. International Standard Problem, ISP 47 on Containment Thermal Hydraulics, NEA/CSNI/R(2007)10, September, 2007
4. International Standard Problem, ISP 49 on Hydrogen Combustion, NEA/CSNI/R(2011)9, January, 2012.
5. Ferch, R.L., "Hydrogen Behaviour in Containment - Generic Action Item 88-G-02", AECB file #26-1-00-0-0-0, 1988.

6. “Requirements for Containment Systems for CANDU Nuclear Power Plants”, AECB Regulatory Document: R-7, 1991.
7. “State of the Art Report on Containment Thermal-hydraulics and Hydrogen Distribution”, Nuclear safety NEA/CSNI/R(99)16, October 1999.
8. “Flame Acceleration and Deflagration to detonation Transition in Nuclear Safety”, Nuclear safety NEA/CSNI/R (2000)7, August 2000.
9. C.K. Chan, "A State-of-the-Art Report on Flame Acceleration and Deflagration-to-Detonation Transition", AECL, COG-00-246, March 2001.
10. DDTINDEX User’s Manual, NAI-1003-02, Revision 1, September 2000.
11. “A State-of-the-Art Report on Hydrogen behaviour Associated with CANDU Reactor Accidents", AECL, COG-07-2066, February 2010.
12. Safety of Nuclear Power Plants: Design Requirements”, IAEA Safety Standard Series NS-R-1, 2000.
13. “Design of Reactor Containment Systems for Nuclear Power Plants”, IAEA Safety Standard Series, Safety Guide: NS-G-1.10, 2004.
14. “Periodic Safety Review of Operational Nuclear Power Plants”, IAEA Safety Guide, Safety Series No. 50- SG-O12, 1994.
15. Expectations for Resolution of Hydrogen Related Safety Issues: Technical Paper Presented at the 31st Conference of the Canadian Nuclear Society, Montréal, Québec, Canada May 24-27, 2010.
16. CNSC Fukushima Task Force Report - INFO-0824, October, 2011.
17. CNSC Management Response to CNSC Fukushima Task Force Recommendations INFO-0825, October, 2011.
18. CNSC Staff Action Plan on the CNSC Fukushima Task Force Recommendations INFO-0828, December, 2011.
19. Actions Taken by Regulatory Bodies Following the Fukushima Daiichi Nuclear Accident, Nuclear Energy Agency Website, Paris, France: http://www.oecd-nea.org/nsd/fukushima/#3.

Country	Containment Monitoring	PAR Installation	Igniters Installation	Natural or Forced Mixing	Preclude Unfiltered Venting	Inertization of Containment	Spent Fuel Bay Assessment	Ongoing Assessment /Modeling
Belgium	√	√			√		√	√
Bulgaria	√	√			√		√	√
Canada	√	√	√	√	√		√	√
Czech Republic	√	√	√		√	√	√	√
Finland	√	√	√	√	√	√	√	√
France	√	√		√	√		√	√
Germany	√	√	√	√	√	√	√	√
Hungary	√	√			√		√	√
India						√	√	√
Netherlands	√	√			√		√	√
Romania	√	√	√	√	√	√	√	√
Slovakia	√	√			√		√	√
Slovenia	√	√	√	√	√		√	√
South Korea	√	√	√		√		√	√
Spain	√	√	√		√	√	√	√
Sweden	√	√			√	√	√	√
Switzerland	√	√	√	√	√	√	√	√
United Kingdom	√	√			√		√	√
United States	√		√	√	√	√	√	√

Table 1: Regulatory Position for Hydrogen Mitigation in Place and/or Proposed for Some Selected Countries