CNSC Expectations for Resolution of Hydrogen Related Safety Issues

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Abstract

The TMI and Chernobyl severe accidents of 1979 and 1986 demonstrated the containment crucial role in preventing radioactive releases and highlighted the hydrogen combustion safety challenges.

The CNSC issued the containment regulatory document R-7 and initiated Generic Action Item GAI 88G02 to resolve the hydrogen challenges, following the R-7 approach.

In the early 2000-s, the IAEA issued in response its NS-R-1 NPP design standard. Many countries followed suit. They established rules to protect the containment and installed passive autocatalytic recombiners (PAR) to reduce the hydrogen risk.

In 2002, the CNSC started updating its documents based on the IAEA standards. Because the R-7 design basis rules could not be fully met by current NPP, the CNSC decided to use the new RD-337 NPP design document to address the hydrogen risk.

In this paper, we describe the current CNSC expectations for reducing the hydrogen risk in new, operating and refurbished NPP over the full spectrum of accidents including severe accidents for adequate containment protection.

1. Introduction

Hydrogen is generated in containment during normal operating conditions and in more appreciable amounts following accidents. Hydrogen gas mixtures are flammable over a wide range of hydrogen concentrations, and can be ignited by very small sparks (milli- joules). Once ignited, hydrogen burns may lead to significant challenges to plant systems, in particular, the containment.

The Three Mile Island (TMI) Severe Accident (SA) of 1979 proved that ignition of the hydrogen could lead to substantial pressure loads. There were no fatalities caused by the TMI accident because of its strong containment and, thus, very small radio-nuclide releases. This was not however the case following the Chernobyl SA of 1986 where the absence of a containment resulted in a significant release of radioactivity and ensuing fatalities.

To reduce the residual risk and protect the containment from the challenges posed by potential hydrogen releases and burns, R&D programs were initiated to better understand behaviour of the hydrogen in the containments following accidents, in particular, severe accidents. Development and implementation of suitable mitigating features for hydrogen removal such as igniters and Passive Autocatalytic Recombiners (PAR) was an important outcome of these efforts.

To reflect the important role of the containment in protecting persons on and off various countries including Canada enhanced their containment regulatory requirements. During the 1990-s, the initiated intensive R&D programs on Beyond Design Basis Accidents (BDBA) lead to significant progress in understanding the accident progression and post-accident behaviour of the hydrogen and radio-nuclides released into containment. In the recent years the IAEA published several safety standards which served as the basis for the CNSC regulatory documents for design on nuclear power plants, and which consider explicitly the full spectrum of reactor operating and accident conditions, including SA.

This paper discusses the technical and regulatory basis and the history of the generic approach and current station specific activities in Canada addressing the safety challenges posed by potential hydrogen combustion in nuclear power plants.

2. Generic Approach to Resolution of the Hydrogen Issue

It was evident after TMI (1979) and Chernobyl (1986) that the loads induced by potential combustion of the post-accident hydrogen releases could challenge the containments as well as the necessary equipment and systems located within the containments of existing CANDU.

CNSC staff issued therefore a Generic Action item GAI 88G02 asking the industry to develop an R&D program to be able to assess and address the hydrogen related safety issues.

Early CNSC Regulatory Approach Used for Resolution of the Hydrogen Issue

To recognize the crucial safety role played by the containment in protection of the public following an accident, the CNSC issued in 1991 the regulatory document R-7 [1] that specified the containment design and operation requirements to be met.

R7 [1] addressed BDBA by including a number of postulated duel-failure accidents with limited core damage such as LOCA with dual/multiple ECCS failures in the design basis to enhance the containment and NPP margins to safety. As a result, measures were to be provided to control the hydrogen concentrations in containment and prevent destructive combustion modes for the most bounding conditions induced by the postulated BDBA, namely LOCA with total loss of ECCS with bounding leakage (trace) flow to the primary heat transfer system and bounding containment configurations.

Hydrogen R&D Program

During the early stages of an accident (minutes and hours) the hydrogen releases to containment are mainly generated by zirconium-steam reaction and degassing. The hydrogen releases from water radiolysis by the radio-nuclides located in the core and sumps and by corrosion become however dominant in the longer term (days-weeks).

The processes of hydrogen generation by oxidation and water radiolysis by radio-nuclides are complex. The transport of the hydrogen and radio-nuclide releases in containment is similarly governed by complex processes and could lead to non-uniform hydrogen distribution in the containment volume and development of hydrogen pockets of high concentrations.

Hydrogen combustion can involve wide time scales (milliseconds in case of detonations and several seconds for slow deflagrations) and pressures (between 4 and 30 times the initial pressures depending on shock wave reflections). The mode of hydrogen combustion: slow deflagration, fast turbulent deflagration, detonation or standing flame - governs 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 determines 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 necessary SSC via proper design.

Extensive international effort was dedicated to resolution of the hydrogen issues in 1980-1990-s. In Canada, the industry developed a broad R&D program to address GAI 88G02. This included participation in an international NEA working group on hydrogen behaviour for information exchange and collaboration in international research projects. The national and international R&D activities resulted in the development of a solid knowledge base, as demonstrated for example by the NEA State of the Art Report (SOAR) on containment thermal-hydraulics and hydrogen distribution [5], the NEA report on Flame acceleration and DDT [6], and similar COG reports such as [7-8].

AECL Passive Auto-catalytic Recombiners (PAR) for hydrogen removal via hydrogen and oxygen recombination were also developed and commercialized, with installation, as early as 2001, in an NPP in Belgium.

Original Generic Closure Criteria for Resolution of the Hydrogen Issue

In the 1990-s the ongoing national and international R&D programs on the hydrogen related issues lead to a significant progress in the understanding and modelling of hydrogen generation and transport [5] as well as of the combustion modes such as slow deflagrations and standing flames. In addition, criteria to preclude destructive FA and DDT hydrogen combustion modes, [6-7] and the DDTINDEX code were developed [8]. Hydrogen mitigating measures such as igniters and PAR were further improved and modelled.

To reflect these new R&D developments CNSC staff developed in 2000 a set of specific closure criteria for resolution of the hydrogen generic issue.

These criteria were based on the regulatory document R7 [1], and required the consideration, assessment and resolution of the hydrogen related safety issues, namely:

- The industry was asked to consider both short and long term hydrogen and radio-nuclide source terms induced by the BDBA with limited core damage postulated in R7 [1]. This included consideration of the long term hydrogen releases from water radiolysis in the reactor core, sumps and atmosphere.

- The industry was also asked to assess the transient flammable gas distributions in containment, assess the corresponding potential combustion modes (such as FA, DDT, standing flames, slow deflagrations) and loads that might develop and their consequences and show that they do not challenge safety. Destructive FA and DDT combustion modes were to be precluded via suitable mitigating measures such as the PAR. Credited post-accident systems, structures and components (SSC) were to be protected from standing flame loads. The containment and other necessary post-accident SSC were to be Environmental Qualified (EQ) to withstand the generated bounding conditions in containment.

Difficulties Encountered in Application of the Original Closure Criteria for the Hydrogen Issue

The bounding hydrogen and radio-nuclide source terms from the postulated BDBA with limited core damage assessed using the methods based on R-7 [1], were found to lead to large hydrogen and radio-nuclide releases, severe potential combustion modes/loads and challenging environmental conditions in containment.

The containment and other necessary post-accident SSC of existing CANDU NPP were not however originally designed to address such effects. As a result the design changes necessary to address these more severe conditions, prevent destructive combustion modes, protect the containment and other systems, and meet the regulatory requirements of R-7 [1] as well as the hydrogen closure criteria of GAI 88G02, were found to be quite extensive and sometimes prohibitively expensive.

Furthermore, providing large safety margins for protection of the containment and other necessary SSC for BDBA with limited core damage, while enhancing the NPP safety margins, does not necessarily lead to better protection from the larger safety threat posed by SA, because the governing phenomena are substantially different and can lead to more severe consequences.

3. Current Regulatory Approach to Resolution of the Hydrogen Issue

In view of the difficulties encountered in meeting the originally established closure criteria for the hydrogen issues, the licensees put forward a position on resolution of the hydrogen issue and associated EQ issues for the postulated BDBA with limited core damage. It was proposed, on probabilistic grounds, to essentially exclude consideration of dual-failure events from the design basis. The postulated dual failure events with limited core damage, identified in R-7, were to be re-categorized as BDBA. For analysis of such events more relaxed analysis and design rules would be developed. In addition, the industry deferred their decision on the installation of AECL PAR in CANDU NPP because of newly identified concerns related to the delayed self-start of the PAR when subjected to pollutants.

Internationally, the crucial safety role played by the containment for SA and the results of the significant R&D effort dedicated to understanding of hydrogen behaviour and control are reflected in the modern IAEA safety standard NS-R-1 on the requirements for design of new NPP [2]. Its companion safety guide NS-G-1.10 on design of the containment was issued in 2004 [3].

Nationally, the CNSC decided in 2002 to update its regulatory documents using as basis the internationally accepted IAEA safety approach. This approach was chosen because it is cohesive, systematic and comprehensive, covers the full spectrum of reactor operating and accident conditions and, addresses explicitly BDBA with limited and severe core damage. It includes single failure events only in the design basis. It also specifies the design and analysis rules to be used for DBA and BDBA/SA respectively. A draft version of the CNSC document that was eventually to become RD-337 was issued for discussion in 2004.

Around that time, New Brunswick Power (NBP) and Bruce Power (BP) initiated the refurbishment of a number of reactor units. Both NBP and BP performed a clause by clause comparison against the IAEA NS-R-1 [2] to identify non-conformities with the modern international expectations. That was done using the IAEA PSR approach [9] to systematically identify the necessary and justified design and operational improvements.

In view of the above, CNSC staff informed the licensees of its intention to update the hydrogen closure criteria based on the safety approach of the IAEA NS-R-1 [2].

4. Current Station Specific Approach to Resolution of the Hydrogen Issue

The new CNSC regulatory document, RD-337, was issued in 2008 [4].

Also in 2008, the utilities informed CNSC staff that tests had shown that the adverse effects of pollutants from normal operating conditions on the PAR delayed self-start could be resolved by installing a new PAR plate at regular time intervals [10]. It was also established that the hydrogen mitigating effectiveness of the PARS, was not challenged by the releases of aerosols from both DBA and BDBA/SA.

CNSC staff decided to close the hydrogen generic action item, GAI-88G02, based on:

- The merits of the significant R&D development of the last two decades in the domains of hydrogen behaviour, mitigation and modeling,
- Application of the new IAEA/CNSC [2, 4] safety approach and associated cohesive and well-defined design and analysis rules over the full spectrum of accidents. It was also noted that this approach had already being applied by the licensees in their refurbishment activities.

To address the outstanding issues related to station specific activities such as analyses and installation of the requisite number of PAR, the station-specific action items were initiated. Closure criteria for these action items are elaborated below; it is important to note here that CNSC staff believes that at this time there are both a well establish overall safety framework as well as a sufficient experimental knowledge base and analytical capabilities to successfully close this issue.

Strictly speaking, NS-R-1/RD-337 containment design expectations apply only to new NPP. In recognition of this, the CNSC action items and expectations with respect to the hydrogen issue for new, refurbished and existing NPP are not exactly the same, as discussed in further details below.

CNSC Expectations for Resolution of the Hydrogen Issue for New NPP

To outline the current regulatory expectation with regard to the hydrogen issue, we will start outlying the case for the new plants, since this is the most straightforward case. From there we will then explain our position for the existing plants, either undergoing refurbishment or not.

To demonstrate resolution of the hydrogen issues in new NPP the focus is on meeting the RD-337 high level safety and design expectations applicable to the containment, the containment system specific expectations as well as the hydrogen management system expectations over the full spectrum of reactor operating and accident conditions, including BDBA and SA, using appropriate design and analysis rules.

- The designer (and the licence applicant) is expected to adopt the safety approach of RD-337 and containment design and analysis expectations, including those applicable to hydrogen assessment and mitigation.

- For DBA, the designer is expected to consider and assess the potential adverse effects of the bounding hydrogen releases and burns. The designer then needs to preclude destructive global/local hydrogen combustion modes, demonstrate the effectiveness of any introduced hydrogen mitigating measures, such as the PARS and establish compliance of the containment post-accident performance with the applicable RD-337 deterministic expectations via appropriate design and analysis rules. Appropriately validated codes and models (e.g., GOTHIC-IST, DDTINDEX, etc) need to be used.

- 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. The designer also needs to establish compliance of the containment post-accident performance with the RD-337 containment performance expectations applicable to BDBA, albeit with different design and analysis rules more relaxed than those from DBA. Mechanistic models are expected to be used to assess the hydrogen challenges.

- For SA, 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 molten core concrete interactions (MCCI). The designer then needs to demonstrate that the introduced hydrogen complementary feature such as the PARS provide effective mitigation and that destructive potential combustion modes are avoided. The designer also needs to establish compliance of the containment post-accident performance with applicable RD-337 containment performance expectations for BDBA/SA using appropriate design and analysis rules. Use of integrated models, such as MAAP to assess the hydrogen challenges, is acceptable.

- The designer is expected to show that the containment probabilistic safety goals, such as the large release frequency, are met, with the adverse effects of hydrogen combustion considered.

- For defence in depth of the containment design for BDBA/SA, the designer (and the licence applicant) is required to develop a Severe Accident Management (SAM) program in addition to complementary design provisions for hydrogen mitigation. RD-337 requires the installation of a hydrogen monitoring and sampling system to manage the potential hydrogen challenges to safety and to the containment via SAM [4].

CNSC Expectations for Resolution of the Hydrogen Issue for Refurbished NPP

It is generally expected that refurbished plants would approach the level safety similar to that of new NPP. Hence, to demonstrate resolution of the hydrogen issues for refurbished NPP the focus is on meeting, to the extent practicable, the RD-337 safety and design expectations applicable to containment and the hydrogen control system. More specifically [11-12]:

- For DBA, the licensee is expected to assess and address the potential adverse effects of hydrogen releases and burns. Particular attention is to be paid to demonstrating, before plant restart, that the finalized PARS design provides the expected protection from potential hydrogen burns.
- For LOCA + ECCS impairments considered as BDBA the licensee needs to demonstrate that there are no issues with short term hydrogen sources and that the number of PAR units to be installed is adequate to control accumulation of hydrogen.
- For BDBA with severe core damage the hydrogen issue is expected to be addressed under the SAM program. This includes consideration of the potential combustion effects of the flammable gas releases from BDBA/SA such as the hydrogen and CO releases from molten core concrete interactions (MCCI), for the chosen representative set of SA. It also includes installation of a hydrogen monitoring and sampling system for use with SAM.

In a gist, the CNSC expectation is that the licensee meets, to the extent practicable, the modern requirements applicable to the containment and hydrogen control systems. This expectation is no different with regard to other modern codes and standards to which a refurbished plant is being compared. The so-called Integrated Safety Review approach has been established and applied to several CANDU plants; an important component of this approach is the gap dispositioning process which allows making a decision with regard to which safety improvements are practicable.

CNSC Expectations for Resolution of the Hydrogen Issue for Operating Non-Refurbished NPP

To resolve the hydrogen issue for operating NPP not planned to be refurbished in the near future (or at all), the industry is expected to conduct a gap assessment against the modern expectations applicable to the containment and hydrogen control systems (e.g., references 2-4). The identified gaps then would need to be dispositioned. It is important to acknowledge, of course, that the extent of justified modifications could be different than those for the refurbished plants. Practicability may significantly limit the options available; nevertheless, the effort that went into advancement of the hydrogen behaviour knowledge base and development of PAR does provide acceptable ways to improve safety. Hence, as has been communicated to the industry, CNSC staff expects that:

- Each plant is to demonstrate that the PAR design, number and location within containment provide adequate hydrogen mitigation capability.
- The analysis to evaluate the hydrogen source term and distribution, as well as combustion modes is to use validated models and computer codes and to employ:
  - conservative assumptions for design basis accidents;
  - a best estimate approach for BDBA with limited core damage.
- Severe accident management provisions are to explicitly include hydrogen control and mitigation measures.

The intent is demonstrate that the risk posed by hydrogen combustion to containment has been adequately addressed over the full spectrum of reactor operating and accident conditions including BDBA/SA, with due consideration given to the remaining unit life and the practicability of design changes.

5. CNSC Assessment for Closure of the Hydrogen Issue in Refurbished and Operating Non-Refurbished NPP

As already stated above, CNSC staff considered that the conditions are ripe for successful closure of the hydrogen issue. This conviction is based on several factors. First, the passive autocatalytic recombiners have been demonstrated to offer an efficient means of controlling the hydrogen concentration, at least in a significant portion of cases. Second, sufficiently detailed and validated analytical models and computer codes have been developed and are available for use. Third, the industry is already well into implementing severe accident mitigation and SAM programs which include protection of containment as a key objective, by controlling the hydrogen concentration, among other things. In preparation for closure of the station specific action items, CNSC staff has developed certain success criteria to be applied in regulatory assessments:

Success Criteria for DBA and BDBA with Limited Core Damage

a) 3-D assessments of hydrogen mixing and transport are carried out, using validated models, in order to determine the short/long term local distributions in critical containment regions with considered mitigating measures, including the PARS and igniters during their respective mission time.

b) The envelope of hydrogen combustion modes is determined, which:

- takes into account all relevant sources of hydrogen, including long term hydrogen releases from radiolysis of the water in the calandria and sumps for both in-core and out core PHTS failures
- shows that local pockets of sensitive gas mixtures (combustible clouds) cannot lead upon ignition to Deflagration to Detonation Transitions (DDT) and fast deflagrations with potentially unacceptable combustion loads in any region of containment.
- shows that gas mixtures outside the DDT and fast deflagration envelope but within the “slow deflagration” domain do not have, if ignited, consequences detrimental to the containment and supporting systems, taking into account turbulence and flame acceleration by obstacles.
- demonstrates that potential standing flames/flammable break jets do not threaten the containment SSC or other credited/necessary SSC and take appropriate protective or mitigating action, if necessary.

c) Hydrogen releases into containment extensions and appurtenances caused by random containment isolation failures, maintenance errors or containment procedures, and the associated consequences are considered and assessed.

d) The hydrogen mitigating effectiveness of the selected PARS (their capacities and location) is demonstrated. This includes demonstration that the PARS can prevent the flow of potentially damaging flammable gas mixtures via the credited venting system.

e) Threats posed by hydrogen are included into the program of Environmental Qualification for containment.

As was said earlier, the analyses for DBA are, as per standard practice, bounding and maximize the short and long term release of hydrogen and radio-nuclides, whereas analysis for BDBA with limited core damage can use best estimate models with realistic assumptions.

Success Criteria for Severe Accidents

The hydrogen success criteria for resolution of the hydrogen issue for severe accidents are quite different.

a) The key expectation is to adequately maintain the containment function for the chosen representative set of severe accidents taking into account the hydrogen challenges to safety and to the containment. Based on RD-337 [4], enhanced SAM mitigating measures such as PAR may be needed to address the challenges posed by the hydrogen releases and combustion to the containment. This is to be supplemented by SAM actions. In operating non-refurbished NPP, the focus is currently on SAM actions/procedures to control the hydrogen (and other combustible gases) concentration in containment.

b) The licensee needs also to assess the practicability of installation of a containment atmosphere monitoring/sampling system at locations where hydrogen is expected to accumulate, especially at the inlets to the venting system. In view of uncertainty associated with SA analysis, this provision may be necessary to give the operator sufficient information for judicious management of the containment pressure and combustible gases via SAM to prevent post-accident damage to the containment or venting systems, especially in existing NPP.

c) As part of substantiation of the effectiveness of the considered hydrogen mitigating features and/or SAM actions/procedures, the licensee is also expected to perform calculations of the global concentrations and, where allowed by state of the art, of the local combustible gas mixture distributions in critical containment regions for the chosen representative set of SA. Integral system models such as MAAP4-CANDU may be used, but where applicable, it is recommended to use the GOTHIC-IST code to assess the hydrogen distributions and combustion modes/loads.

6. Conclusions

This paper has presented the expectations to be met to maintain the integrity of the containment barrier, the last line of defence in protecting persons in case of BDBA/SA. The international consensus is that it is important to take into account the challenges posed by potential hydrogen accumulation and combustion inside containment. This requires adequate assessment and mitigation of the challenges posed by potentially destructive hydrogen combustion modes over the short and long terms, which has lead to the development of an extensive hydrogen R&D program both nationally and internationally.

We presented, in broad terms, the original generic CNSC closure criteria which were based on the CNSC regulatory document R-7 [1] and the difficulties encountered in meeting them. We then presented the current CNSC expectations for reducing the risk to safety posed by the hydrogen releases, based on the CNSC RD-337 [4] safety approach and discussed their application to new and refurbished NPP in some detail. This included presentation of the success criteria associated with single failure event DBA, BDBA with limited core damage and severe accidents that define the scope of the assessments to be performed.

7. References:

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