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## Invited Article

# OVERVIEW ON HYDROGEN RISK RESEARCH AND DEVELOPMENT ACTIVITIES: METHODOLOGY AND OPEN ISSUES

AHMED BENTAIB\*, NICOLAS MEYNET, and ALEXANDRE BLEYER

Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Severe Accident Department, BP17, Fontenay-aux-Roses, 92262, France

## ARTICLE INFO

## Article history:

Received 8 December 2014

Received in revised form

18 December 2014

Accepted 31 December 2014

Available online 21 January 2015

## Keywords:

Combustion  
Distribution  
Hydrogen  
Methodology  
Mitigation  
Risk

## ABSTRACT

During the course of a severe accident in a light water nuclear reactor, large amounts of hydrogen can be generated and released into the containment during reactor core degradation. Additional burnable gases [hydrogen ( $H_2$ ) and carbon monoxide ( $CO$ )] may be released into the containment in the corium/concrete interaction. This could subsequently raise a combustion hazard. As the Fukushima accidents revealed, hydrogen combustion can cause high pressure spikes that could challenge the reactor buildings and lead to failure of the surrounding buildings. To prevent the gas explosion hazard, most mitigation strategies adopted by European countries are based on the implementation of passive autocatalytic recombiners (PARs). Studies of representative accident sequences indicate that, despite the installation of PARs, it is difficult to prevent at all times and locations, the formation of a combustible mixture that potentially leads to local flame acceleration. Complementary research and development (R&D) projects were recently launched to understand better the phenomena associated with the combustion hazard and to address the issues highlighted after the Fukushima Daiichi events such as explosion hazard in the venting system and the potential flammable mixture migration into spaces beyond the primary containment. The expected results will be used to improve the modeling tools and methodology for hydrogen risk assessment and severe accident management guidelines. The present paper aims to present the methodology adopted by Institut de Radioprotection et de Sûreté Nucléaire to assess hydrogen risk in nuclear power plants, in particular French nuclear power plants, the open issues, and the ongoing R&D programs related to hydrogen distribution, mitigation, and combustion.

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## 1. Introduction

During severe accidents (SAs) in a nuclear power plant, hydrogen can be produced from exothermal oxidation of fuel

cladding or fuel assembly canisters, other hot metallic components, and molten core–concrete interaction (MCCI) after failure of the reactor pressure vessel and melt relocation to the reactor pit if in-vessel retention measures failed. A large

\* Corresponding author.

E-mail address: [ahmed.bentaib@irsn.fr](mailto:ahmed.bentaib@irsn.fr) (A. Bentaib).

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<http://dx.doi.org/10.1016/j.net.2014.12.001>

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amount of carbon monoxide may also be produced during MCCI in addition to hydrogen and other gases. The hydrogen released into the containment via a reactor cooling system (RCS) break or through the pressurizer safety valves or during corium-concrete interaction is transported by convection loops arising essentially from the released hot steam/gas or initiated by condensation of steam on cold walls. Depending on the level of mixing in the containment atmosphere, the distribution of hydrogen can be homogeneous or stratified. If considerable hydrogen stratification exists, local concentration of hydrogen and carbon monoxide may become a safety concern because pockets of high hydrogen and carbon monoxide concentrations may lead to combustion, flame acceleration (FA), and eventually deflagration to detonation transition (DDT) if the combustible mixture is ignited. Furthermore, the hydrogen distribution may be affected by safety systems such as spray or coolers that are widely used in many reactors to reduce the containment pressure and to provide heat removal by steam condensation on water droplets or cold surfaces. These measures may homogenize the hydrogen distribution in the containment because of enhanced mixing, but they can also significantly reduce the steam concentration, which may lead to more combustible gas mixture compositions.

Several methods [1] can be proposed to reduce the hydrogen concentration in the containment: (1) deliberate ignition, (2) consumption or recombination of hydrogen by passive autocatalytic recombiners (PARs), (3) combining ignition and recombination measures, (4) replacing oxygen (air) with an inert gas [typically nitrogen ( $N_2$ )] during normal plant operation, (5) diluting the atmosphere by having, by design, a large containment volume or by injecting an inert gas, or (6) releasing hydrogen by containment venting. Hydrogen risk management can be implemented by one or a combination of the previous measures.

The choice of a mitigation strategy depends primarily on the design of the containment. For pressurized water reactors with a large dry containment, the strategy usually consists of combining a large free volume to allow dilution, a high value of the design pressure, and the use of mitigation means such as PARs to consume hydrogen. This strategy is adopted in all French pressurized water reactors. The implementation of PARs were performed following rules and criteria that allow (1) the reduction of the possibility of hydrogen accumulating to flammable concentrations, (2) the minimization of the flammable gaseous volume, and (3) the prevention of an increase in the hydrogen levels from flammable to detonable mixture concentrations. For French reactors, the adopted criteria consist of keeping the hydrogen concentration mean value below 8%vol to avoid complete combustion and the local hydrogen concentration value under 10%vol to avoid FA. These criteria were established to achieve the safety objective set for French reactors, which is to practically eliminate situations that could yield an early containment failure with large early releases. Hydrogen combustions that can challenge the containment integrity consequently have to be avoided. Therefore, for an auxiliary building, hydrogen combustion should not challenge any safety function and system.

To evaluate the efficiency of such mitigation strategies, the methodology usually adopted is based on the prediction of

hydrogen distribution inside the containment while taking into account the mitigation and safety systems effect and the prediction of pressure and temperature loads that are induced by the combustion. To cover all conceivable situations of a severe accident, including in- and ex-vessel phases, research and development (R&D) efforts are still needed to improve the methodology described in more detail in the next paragraph.

## 2. Hydrogen risk assessment methodology

To fulfill the requirements for the management of the hydrogen risk in the nuclear power plant (NPP) mitigation measures have been implemented in various NPPs containments to remove hydrogen or to control the hydrogen concentration inside the containment. The appropriate mitigation measures is then designed, based on the results of numerical simulations and dedicated experiments. The methodology usually adopted to assess the hydrogen risk in the reactor building and in the auxiliary buildings consists of the following seven steps:

### Step 1: Modeling of the plant design.

The starting point of any analysis is the selection of the plant and geometrical modeling of the containment or the auxiliary building. This step aims to describe adequately the building geometry and volumes (including compartments) and the safety system considered (e.g., PARs, spray, coolers), which influence hydrogen distribution inside the reactor containment or auxiliary building.

### Step 2: Selection of relevant accident scenarios.

The representative or bounding in terms of hydrogen-produced (mass and kinetics) severe accident scenarios for hydrogen assessment are generally identified from SA code calculations such as ACTEC calculations, Probabilistic Safety Analysis (PSA) level 1 and 2 or other analyses. The evaluation of the associated hydrogen production rates and release into the reactor building is usually derived from parametric code calculations and best estimates calculations considering remaining uncertainties on hydrogen production processes.

### Step 3: Evaluation of the containment atmosphere condition.

During the accident transient, the temperature, pressure, and gas composition in the different regions and volumes of the containments are determined, and account for the presence of the mitigation systems. For this purpose, both lump parameter (LP) and computational fluid dynamics (CFD) codes are often used to simulate the transient. The CFD codes are usually used for deeper analysis in short-term temporal windows (e.g., hydrogen release phase, scenarios with local accumulation, and expected stratification).

### Step 4: Evaluation of the time evolution of a flammable hydrogen-air-steam cloud.

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