Toward a risk informed hierarchy of hydrogen rooms in nuclear power plants

Julien Beaucourt (*)[a], Angélique Pasco[a], and Gabriel Georgescu[a]
[a] Institute of radioprotection and nuclear safety – BP17 – Fontenay-aux-Roses, France, 92262

Abstract: Gaseous hydrogen is used in nuclear power plants, especially pressurized water reactors, for several process reasons. In this paper, we present a two steps probabilistic analysis methodology proposed by the French Institute of radioprotection and nuclear safety (IRSN), which allows for a risk informed hierarchy of the rooms in the auxiliary nuclear building through which gaseous hydrogen is circulating. Based on this analysis, the different rooms within the auxiliary nuclear building may be hierarchized, according to the evaluated frequencies of hydrogen release and explosion. This analysis may be used to prioritize the in-service controls of the venting system within this building, and to identify the needs of improvements of the venting system efficiency. In this paper, the methodology and initial lessons of the study will be presented, as well as some sensitivity studies to the main parameters.
Due to the proprietary nature of the parameters (configuration of the rooms and hydrogen distribution network, operating experience feedback data, etc.) the numerical evaluations are not presented in this paper, and the discussion focus on the method.

Keywords: hydrogen explosion, Bayesian modeling, risk assessment

1. HYDROGEN IN PWR

1.1. Normal operation of the plant

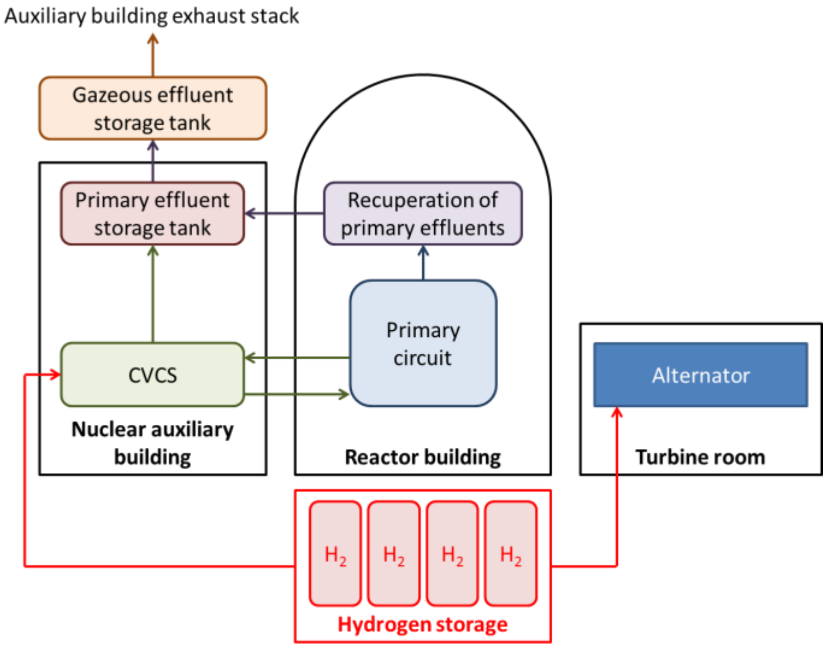
The use of hydrogen in pressurized water reactors (PWR) is twofold. Firstly, the important heat capacity of gaseous hydrogen is used for alternator cooling. Secondly, hydrogen is also used to reduce the oxygen concentration in the primary circuit. Indeed, radiolysis effects close to the reactor core lead to production of oxygen within the primary circuit. The primary circuit is then voluntarily saturated with hydrogen and complex chemical recombinations allow reducing the oxygen concentration, and therefore, the oxidation of primary components.

Gaseous hydrogen is stored outside the nuclear island buildings. It is directly injected into the alternator cooling device, and into the primary circuit through the chemical and volume control system (CVCS) (see Fig. 1). Primary effluents are collected within the reactor building and the auxiliary buildings of the Nuclear power plant (NPP), and the gaseous effluents are stored separately in a dedicated tank before release in the atmosphere (this intermediate storage before release allows for radioactive decay until the legal thresholds are reached). As a consequence, hydrogen circulation takes place during normal operation of the plant within nuclear auxiliary building, reactor building and turbine building, through dedicated circuits.

Hydrogen concentration within the involved circuit depends on the operating state, but may be as important as 100 % in volume, especially for pipes directly connected to the hydrogen storage tanks. The pressure range within the pipe is usually a few bars, but some pipes connected to the primary heat transport system pressurizer are directly at the primary pressure (around 155 bar).

* julien.beaucourt@irsn.fr

Figure 1: Main systems involving hydrogen circulation in the nuclear island buildings (PWR) – Simplified overview



Beside this voluntary use, gaseous hydrogen is also an indirect product of the electrical batteries located in the electrical building during charge or even in floating operations.

1.2. Phenomenology and modelling of accidental hydrogen release and explosion

Two situations should be considered, depending on the initiating event. Firstly, we discuss the phenomenology of hydrogen release following a leak on a pipe or a singularity (valve, flange, etc.), and secondly, we present some general features related to hydrogen production by electrical batteries.

Hydrogen is highly inflammable (the order of magnitude of the hydrogen ignition energy is 20 μJ, which is one order of magnitude lower than "classical" hydrocarbures). The non-flammable limits, as the detonation thresholds, depend on the local relative concentration of oxygen, steam and air, and is best described by the so-called Shapiro diagram. For the sake of simplicity, it may be considered that explosion is very likely to occur when the hydrogen concentration is higher than 4 %, which will be referred as the LEL (Lower Explosive Limit) in the following. Therefore, in the IRSN approach, the probability of explosion when the concentration reaches the LEL is equal to 1.

2. METHODOLOGY FOR HYDROGEN EXPLOSION RISK ASSESSMENT

The methodology used by IRSN for the analysis of hydrogen risk within French PWR may be decomposed in two successive steps:

- Firstly, an evaluation of the frequency of explosion is performed in every local where hydrogen pipes are present (the IRSN analysis also covers the batteries rooms, but they are not discussed in this paper) ;
- Secondly, the functional consequences of the explosion on the facility are evaluated : some of them are likely to initiate an accidental transient affecting the main safety function of the plant, as the protection system designed for the protection of the core in such a situation (for example, the hydrogen explosion may induce a break on a pipe connected to the primary circuit, and simultaneously makes the safety injection system unavailable: in that case, the core meltdown is more likely to occur). The conditional probability of core melt (assuming the occurrence of an explosion) is evaluated using the usual PSA modeling of the plant.

Finally, for every room of the auxiliary building, the risk induced by the presence of hydrogen pipe is the product of the two terms, the explosion frequency and the conditional probability of core melt. The global risk is then the sum of the risks calculated for every room.

3. FIRST STEP: EVALUATION OF THE EXPLOSION FREQUENCY

The evaluation of the frequency of explosion is itself performed in several successive steps:

- Evaluation of the hydrogen flowrate and the kinetic of hydrogen accumulationwithin a room: this evaluation depends on the leak size (or on the batteries properties, in the electric rooms), and is performed under the simplifying assumption that the hydrogen is homogeneously dilute within the room;
- Evaluation of the efficiency of the mitigation possibilities : typically, in a nuclear power plant, the two main protections against hydrogen explosion are the automatic isolation of the leak and venting systems (the main hydrogen pipes are equipped with isolation valves, and a closing order is automatically sent by the protection system when the hydrogen concentration is a room – permanently monitored in the rooms equipped with hydrogen detectors – reach a certain threshold, lower than the LEL);
- Quantification of the explosion frequency: this evaluation is performed using simple event trees, as described hereafter, and taking into account the reliability of mitigation possibilities that may be efficient (depending on the leak size). The key point is the evaluation of the leak frequency, as a function of its size. This evaluation is performed using a Bayesian approach, adapted from the methods used by the SANDIA laboratories [1].

3.1. Hydrogen flowrate and kinetic aspects

3.1.1. <u>Hydrogen flowrate</u>

<u>Batteries</u>

The gaseous hydrogen production in the batteries rooms is due to the charge of the batteries. Indeed, the gaseous hydrogen is the result of the water hydrolysis by the charging current. Two operating modes have to be taken into account for the gaseous hydrogen production.

<u>The floating charge</u>
This operating mode, called floating, offsets the natural self-discharge of the battery by a supply current upper than the self-discharge current. The self-discharge current of the batteries is variable in time (ageing effect) and depends on the temperature and the state of the battery; that’s why the floating current is not constant, but stays in the order of the milliampere/Ah.

<u>The battery charge</u>
This operating mode compensates the partial discharge or the full discharge of the battery after a situation like the loss of electrical power or a periodic test. As a normal way, the charge of the battery is done through two phases:

- At first, the voltage of the battery increases up to reach the sizing charging voltage. During this phase, between 60% to 90% of the charging is done and the supply current of the battery is constant;
- Then, at a constant voltage, the charging current decreases towards the floating current.

The accumulation of the gaseous hydrogen results from the failure of the venting systems in the batteries rooms. For a battery with a capacity (C, in A/Ah), comprising N elements submitted to an electrical current intensity I and with the conservative assumption that the whole current is used to produce the hydrogen, the flowrate Q_{H_2} (in $m^3.h^{-1}$) of the hydrogen production is equal to (Faraday's law):

$$Q_{H_2} = 0{,}42.10^{-3} \times I \times N \times C \qquad (1)$$

The gaseous hydrogen production of a battery depends on several parameters: electrical current intensity, ambient temperature, aging of the components and failing components.

Leaks on pipes or singularities

A leak on a singularity (valve, flange, etc.) or directly on a pipe leads to the accumulation of hydrogen within the room. In that case, the hydrogen flowrate at the break may be evaluated using simple models, and are well described by the so-called Barré de Saint-Venant relation (this equation may be derived from the conservation of energy along a fluid line in the pipe, assuming a perfect gas relation between pressure, temperature and density, and an isentropic expansion of the hydrogen at the break) [2]:

$$Q_{H_2} = S \cdot \rho \cdot v = S \cdot \rho_S \left(\frac{P}{P_S}\right)^{\frac{1}{\gamma}} \cdot \sqrt{\frac{2\gamma}{\gamma-1}\frac{P_S}{\rho_S}\left(1-\left(\frac{P}{P_S}\right)^{\frac{\gamma-1}{\gamma}}\right)} \qquad (2)$$

In this equation, the subscripted quantities refer to the source of hydrogen where the velocity is assumed to be null (typically, P_s and ρ_s are the pressure and the density of hydrogen in the storage tanks). γ corresponds to the Laplace coefficient (γ=1.4 for perfect diatomic gazes). Some corrections may be needed in order to take into account the pressure loss between the break and the hydrogen source. Moreover, for large pressure difference between the pipe and the local, a correction for supersonic effects may be added to this simple model. Some more sophisticated expression may be used, when the hydrogen pressure is important enough to have criticality conditions at the break [2].

3.1.2. Kinetic aspects

For every room, it is necessary to determine the asymptotic hydrogen concentration, in order to determine if the venting system is efficient, and also the time when the critical hydrogen concentration is reached, in order to assess the efficiency of the automatic isolation of the affected pipe (when the pipe is equipped with an automatic isolation system). Assuming an homogeneous dilution of hydrogen within the room, the hydrogen concentration C(t) may be evaluated using a simple linear model:

$$\frac{dC(t)}{dt} = \frac{Q_{H_2} - C(t)Q_{venting}}{V} \qquad (3)$$

where V stands for the volume of the local and $Q_{venting}$ for the venting flowrate in normal operation. Eq. 2 leads to an exponential evolution of the hydrogen concentration in the local. The asymptotic concentration results in a balance between hydrogen and venting flowrates. The LEL is reach after a time T_{LEL} given by:

$$T_{LEL} = -\frac{V}{Q_{vent}} log\left(1 - \frac{LEL \cdot Q_{vent}}{Q_{H_2}}\right) \qquad (4)$$

This expression is a decreasing function of the hydrogen flowrate, as expected : for a given room, increasing the hydrogen flowrate at the leak leads to a more rapid accumulation of hydrogen at the LEL. In the following, the discussion focus on the leaks on pipes or singularities, but the methodology may be applied to the batteries rooms.

3.2. Event trees for the quantification of the explosion frequencies

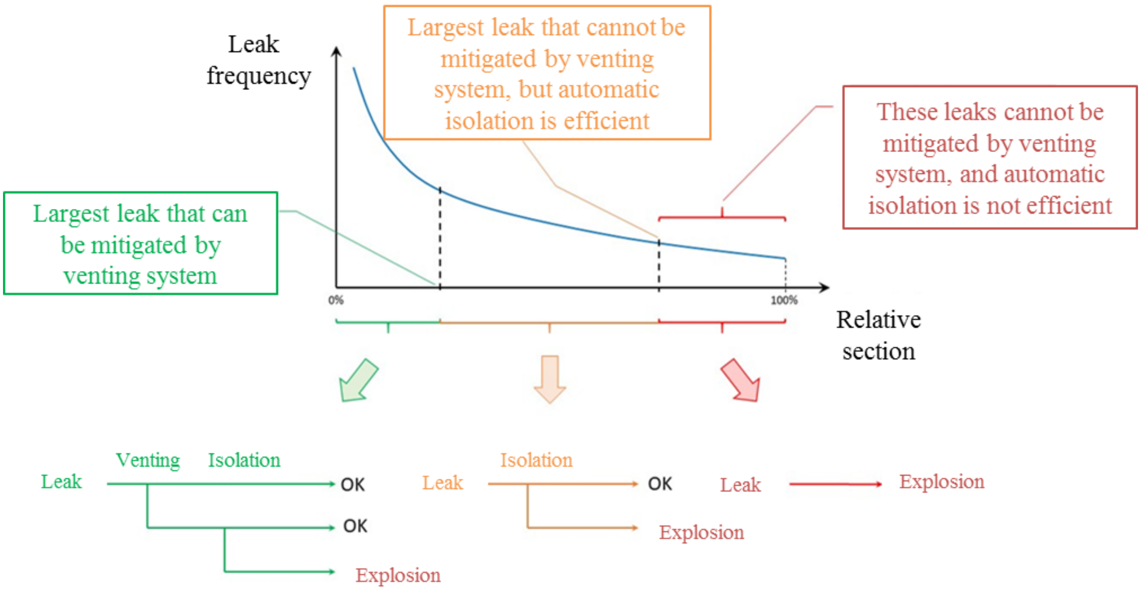
The quantification of explosion frequency within a room is performed using dedicated event trees: the initiating event is a leak, and the different mitigations are modeled using classical fault trees. For every room of the auxiliary nuclear building, three different types of event trees may be constructed, depending on the leak flowrate (see Fig. 2):

- For the smallest leaks, both venting and automatic isolation may be taken into account as protection against explosion. In that case, the LEL is reached after a very long time ;
- When the leak flowrate is more important, venting system is no more efficient (the LEL is reached in a finite time according to equation (3)) and the only protection against explosion is the automatic isolation of the line. It is important to emphasize here that the venting system of the auxiliary building has not been sized to avoid the formation of explosive atmosphere after an unexpected release of hydrogen ;
- Finally, for the largest leaks, the LEL is reach so rapidly that the automatic isolation occurs too late to avoid explosion. In that case, the frequency of explosion is simply given by the frequency of the leak. Here, the situation is slightly different since this automatic isolation has been sized as a protection against explosion. The purpose of this probabilistic analysis is precisely to demonstrate that the situations where this system is not efficient are rare, and have no significant consequence from the core point of view (see § 3.3).

Of course, depending on the local characteristics, venting system may be efficient for any leak size. For some rooms, isolation may also be efficient on the whole spectrum of leak sizes. And finally, in some particular situations, the automatic isolation cannot be taken into account (when the affected hydrogen pipe is not equipped with isolation valves, or when no hydrogen detection is present in the room). These characteristics have to be listed for every room of the nuclear auxiliary building.

The quantification of the explosion frequency depends not only on the reliability of the mitigation provisions (which is evaluated using classical fault trees), but also on the frequency of the initiating event, namely the leak, which has to be determined for any leak size.

Figure 2: Event trees for the quantification of the explosion frequency



3.3. Quantification of explosion frequency

It is necessary to determine an analytical relationship between the leak size and its occurrence frequency (see Fig. 2). As a starting point, IRSN used the data provided in the SANDIA laboratories report [1]: in this paper, a leak frequency distribution is determined for a discrete set of leak sizes (defined as the relative section of the affected pipe: 0.01%, 0.1%, 1%, 10% and 100%), using a Bayesian modeling for different categories of components (seals, valves, etc.). It is usually admitted that the determination of the prior distribution in a Bayesian modeling is a keypoint in the analysis, and in order to improve the quality of the prior, the approach retained by the SANDIA laboratories is sequential, in the following sense:

- In a first step, a Bayesian analysis is performed for data issued from different industries for hydraulic systems, denoted as "generic data" in the SANDIA report [2]. As a result, for the different relative leak sizes S_j defined here above, a leak frequency distribution LF_j is determined.
- This distribution is then used as a prior distribution for the evaluation of the leak frequency distribution for hydrogen components, using again a Bayesian modeling. As mentioned in the document [2], the hydrogen data are not fully presented in the report [2], due to their proprietary nature.

A Gaussian Bayesian linear model is used for the first step of this evaluation, as follow:

$$\begin{cases} log_{10}(LF_j) \sim \mathcal{N}(log_{10}(\mu_j), \alpha_2) \\ log_{10}(\mu_j) = \alpha_0 + \alpha_1 \cdot log_{10}(S_j) \end{cases} \quad (5)$$

For the first step (generic data), the distributions for the model parameters α_0, α_1 and α_2 are classical:

$$\begin{cases} \alpha_0 \sim \mathcal{N}(0, 10^3) \\ \alpha_1 \sim \mathcal{N}(0, 10^3) \\ \alpha_2 \sim \Gamma(1,1) \end{cases} \quad (6)$$

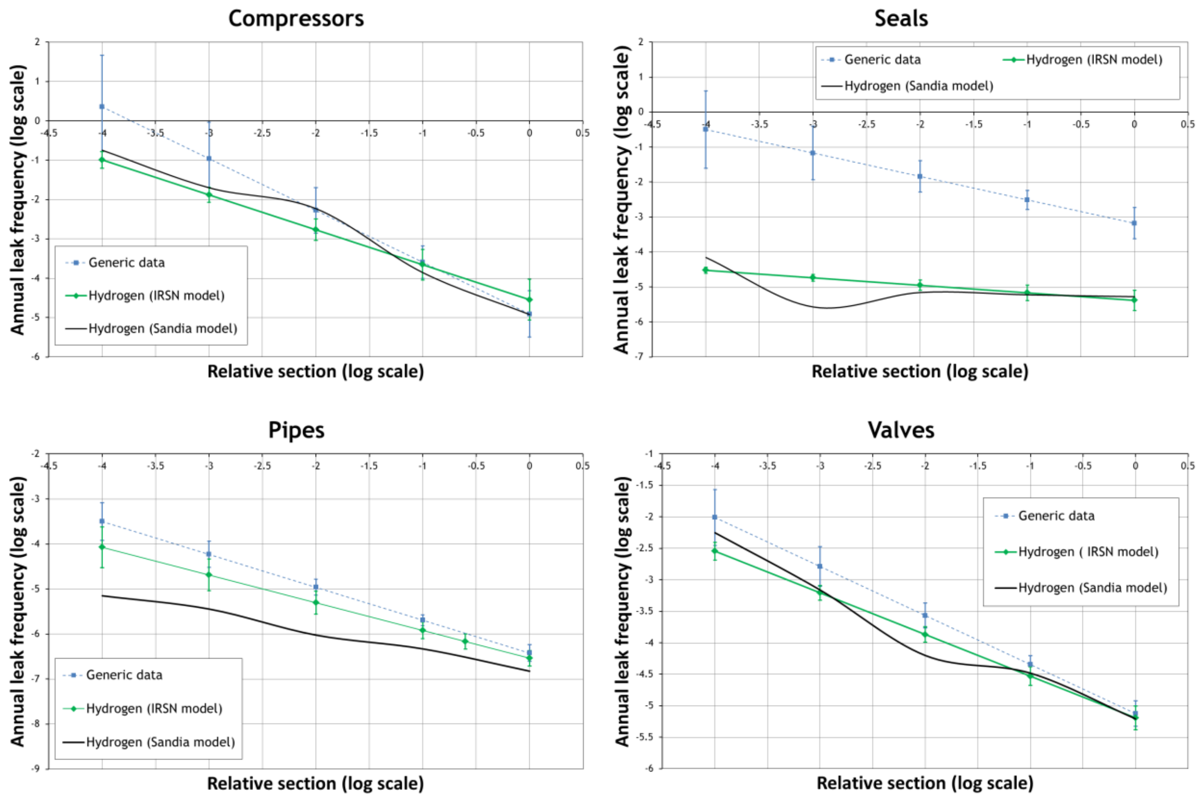
The posterior distributions for these three parameters are then used to define the prior distributions of the second step, dedicated to the analysis of hydrogen data. In the SANDIA report [1], the power law structure is not preserved in the second step of the analysis: the Bayesian update is performed independently for every leak size (the SANDIA results are presented on the Fig. 3 for compressors, seals, pipes and valves).

Based on the data presented in the report [1], and also on the operating experience feedback data available at IRSN for hydrogen leak within French nuclear power plants (for leaks on pipes), the second step of the sequential Bayesian analysis is modified: the Bayesian update is performed directly on the parameters of the linear model α_0, α_1 and α_2. As a result, a power law function is therefore obtained for every component taken into account in the SANDIA report: this analytical relation can therefore be used as an input for the quantification of explosion frequency.

The results of this analysis are presented on the Fig. 3 for pipes, valves, flanges and compressors. IRSN insists on the following point: the results presented on these graphs may be improved or modified using quantitative datasets for hydrogen leak frequencies.

Beside the qualitative differences observed between the SANDIA analysis and the IRSN approach, due to the different hypothesis taken into account in the second step of the sequential Bayesian modeling, a more important quantitative difference is observed for the pipes. The reason is the following: for pipes, no hydrogen leak has been observed within the dataset used by the SANDIA laboratories [2], and as a consequence, the second step of the Bayesian sequential model leads to the a significant reduction of the leak frequency, compared to the prior distribution issued from the generic data. In the IRSN approach, the operating experience feedback observed on French nuclear power plants are taken into account, leading to a slightly more penalizing result for these components.

Figure 3: Results of the sequential analysis modeling – Comparison to the SANDIA results



Using the curves determined in the previous step, it is possible to determine the critical leak sizes frequencies for every room of the auxiliary nuclear building. This part of the analysis is only possible if the characteristics of the rooms are known, namely the volumes, venting flowrates, number of singularities and length of hydrogen pipes. That kind of information is only possible to obtain through plant walkdowns, which have been organized by IRSN with the licensee support.

At the end of this first step, a frequency of explosion for every room in the auxiliary nuclear building is determined. The establishment of an hierarchy of the rooms, regarding the risk of explosion, is therefore possible,. The periodicity of maintenance operation and surveys may then be adjusted, in order to prioritize the most sensitive rooms.

4. SECOND STEP: CONSEQUENCES OF THE EXPLOSION ON THE FACILITY

In the context of nuclear safety, it is important to take into account not only the risk of explosion, but also the consequences of the explosion on the facility. The most sensitive rooms in that context are not necessarily the rooms where the frequency of explosion is the most important, but the rooms where the induced facility damages (following the explosion) which may possibly lead to core melt are the most important and frequent. Firstly, the extent of the zone affected by the explosion has to be determined, and secondly, it is necessary to evaluate the consequences of the explosion on the safety equipments located in the environment.

The evaluation of the impact zone is a difficult task. The simplest assumption is to consider that only the room where the hydrogen leak occurs is affected. This is obviously a non-conservative assumption, due to the fact that the rooms in the nuclear auxiliary building are interconnected: the different rooms are generally separated by fire doors, which are not necessarily designed to support overpressure resulting from the explosion of a confined hydrogen mixture. Some sensitivity analyses are performed, in order to evaluate the dispersion of hydrogen mixture in the surrounding rooms, and to determine, for some limited cases, if the LEL could be reached beyond the room where the leak occurred.

Basically, the functional analysis consists in an evaluation of the damages induced by the explosion on the facility, and more precisely, on the SSC (system, structure or component) that are taken into account in the level 1 PSA for internal events. In the impact zone defined above, all the initiating events that may be induced by explosion, as the SSC that are taken into account to cope with these particular initiating events, are listed. In principle, a mechanical analysis of the explosion consequences should be performed for all of these SSC. But this analysis is complex, since a detailed 3D modeling of the geometrical configuration of all the rooms of the nuclear auxiliary building is not reasonably achievable (several hundreds of possible sources of hydrogen release should be analyzed). Moreover, the physical modeling of the propagation of the shock wave, and the estimation of the damages induced on the SSC located in the area, is very challenging. Therefore, it is considered that all the SSC located in the impact zone are lost due to the explosion. It is believed however that this assumption is not necessarily over conservative, due to the violence of the involved phenomena (shock waves, high temperature front and fire propagation, etc.).

5. CONCLUSION

IRSN modeling of the explosion consequences in the auxiliary nuclear building and in the electrical buildings is used as a support for the review of the corresponding EDF studies, performed in the framework of the forth decennial periodic safety review (PSR) of the French 900 MWe and 1300 MWe NPP. In this paper, a general discussion on the determination of the input data has been presented. Using an analytical relation between the leak size and the occurrence frequency allows to use a more efficient approach that the one that has been presented by IRSN in a recent paper [3].

Despite some simplifying assumptions, this model captures the main features of the risks induced by the explosion of a hydrogen mixture. The most striking outcome of this analysis is that the most important contributors to the global risk induced by explosion are not necessarily the rooms where the evaluated frequency of explosion is the most important. The analysis also revealed that functional analysis is a cornerstone of the evaluation. Moreover, the analysis outcomes allow establishing a hierarchy between the different rooms, in terms of core damage frequency. As mentioned here above, one of the outcome of this analysis is to demonstrate the robustness of the protection systems, especially the automatic isolation of the hydrogen pipes when a hydrogen release is detected. The situations where this system is not sufficient and lead to an explosion and to core damage should be rare. For the most important rooms, existent deterministic analysis may be complemented, for example to evaluate the robustness of the plant for hydrogen risk when specific deterministic rules are taken into account for the mitigation systems: venting, hydrogen detection, etc. (as for example, additional failure criteria). Possibly, the general operating rules may take into account some reinforced requirements for the most important rooms (technical specifications, periodic inspection of the venting system, etc.).

Nevertheless, the IRSN PSA modeling of internal explosion consequences is based on some simplifying, and sometimes possible non conservative assumptions. In particular, the hypothesis of homogeneous dilution of hydrogen in case of pipe leak or the loss of venting in the electrical batteries room may be reviewed for some particular geometric configuration of the rooms. On the other side, the lack of conservatism of some assumptions is difficult to assess without any quantitative evaluation. Typically, the assumption that the hydrogen release do not spread to other rooms than the one where the leak is located should be, and will be, questioned. Indeed, the different rooms in the auxiliary nuclear building are usually interconnected through the venting system. This effect is not taken into account in the present study, and it is difficult to determine if this simplifying assumption is conservative or not. Dilution of hydrogen is connected rooms by the venting system may avoid the formation of explosive mixture, but on the other side, if the hydrogen leak is important, the LEL may be reached in several rooms.

In the next future, these two assumptions (homogeneous dilution and hydrogen spreading through the connected rooms) will be questioned by IRSN, in order to evaluate more precisely the dispersion of hydrogen and the extension zone of the damages.

References

[1] J. Lachance & al., "*Analyses to support development of risk-informed separation distances for hydrogen codes and standards*", SAND2009-0874, SANDIA national laboratories (2009).
[2] A. W. Cox (PhD thesis), "*Studies in support a quantitative approach to hazardous area classification*", 1989.
[3] J. Beaucourt & al., "*Modeling hydrogen explosion in level 1 PSA*", 16th international topical meeting on probabilistic safety assessment and analysis, Charleston (2019).