World Journal of Nuclear Science and Technology, 2024, 14, 165-177
https://www.scirp.org/journal/wjnst
ISSN Online: 2161-6809
ISSN Print: 2161-6795

Conceptual Strategy for Mitigating the Risk of Hydrogen as an Internal Hazard in Case of Severe Accidents at Nuclear Power Plant Considering Existing Risks and Uncertainties Associated with the Use of Traditional Strategies

Arman Grigoryan

Independent Researcher, Los Angeles, USA
Email: armangrigoryan39360@gmail.com

How to cite this paper: Grigoryan, A. (2024) Conceptual Strategy for Mitigating the Risk of Hydrogen as an Internal Hazard in Case of Severe Accidents at Nuclear Power Plant Considering Existing Risks and Uncertainties Associated with the Use of Traditional Strategies. *World Journal of Nuclear Science and Technology*, **14**, 165-177.
https://doi.org/10.4236/wjnst.2024.143010

Received: April 23, 2024
Accepted: July 28, 2024
Published: July 31, 2024

Abstract

Hydrogen challenge mitigation stands as one of the main objectives in the management of severe accidents at Nuclear Power Plants (NPPs). Key strategies for hydrogen control include atmospheric inertization and hydrogen removal with Passive Autocatalytic Recombiners (PARs) being a commonly accepted approach. However, an examination of PAR operation specificity reveals potential inefficiencies and reliability issues in certain severe accident scenarios. Moreover, during the in-vessel stage of severe accident development, in some severe accident scenarios PARs can unexpectedly become a source of hydrogen detonation. The effectiveness of hydrogen removal systems depends on various factors, including the chosen strategies, severe accident scenarios, reactor building design, and other influencing factors. Consequently, a comprehensive hydrogen mitigation strategy must effectively incorporate a combination of strategies rather than be based on one strategy, taking into consideration the probabilistic risks and uncertainties associated with the implementation of PARs or other traditional methods. In response to these considerations, within the framework of this research it has been suggested a conceptual strategy to mitigate the hydrogen challenge during the in-vessel stage of severe accident development.

Keywords

Severe Accident Management, Nuclear Power Plant, Hydrogen Risk Mitigation, Risk Management, Passive Autocatalytic Recombiner

1. Introduction

More than 50 years of global experience in operating NPPs have demonstrated that highly unpredictable combinations of some events may arise, jeopardizing the crucial function of adequately cooling the nuclear reactor core. The most critical in the nuclear power industry is to prevent the release of highly radioactive radionuclides into the environment. That is the reason why there are several layers of physical barriers surrounding and isolating nuclear fuel (the main source of radiation generation) from the environment. Highly improbable events can initiate challenges to NPPs safety systems, leading to nuclear fuel overheating with all negative and irreversible consequences.

In March 2011, the Fukushima nuclear accident illustrated how a series of events and cascading accidents can lead to the long-term loss of nuclear fuel elements cooling and the initiation of chemical exothermic reactions that generate highly combustible hydrogen gas inside the reactor and spent fuel pool as well. Without adequately addressing the issue of hydrogen generation, the fundamental objective of nuclear safety, which is to ensure that high levels of radioactivity are contained under all circumstances and cannot be released into the environment, or to *"protect people and the environment from the harmful effects of ionizing radiation,"* cannot be achieved.

The graphical representation of the Fukushima accident development is depicted in **Figure 1**, illustrating the loss of containment integrity following the hydrogen explosion. This represents the loss of the last physical barrier against

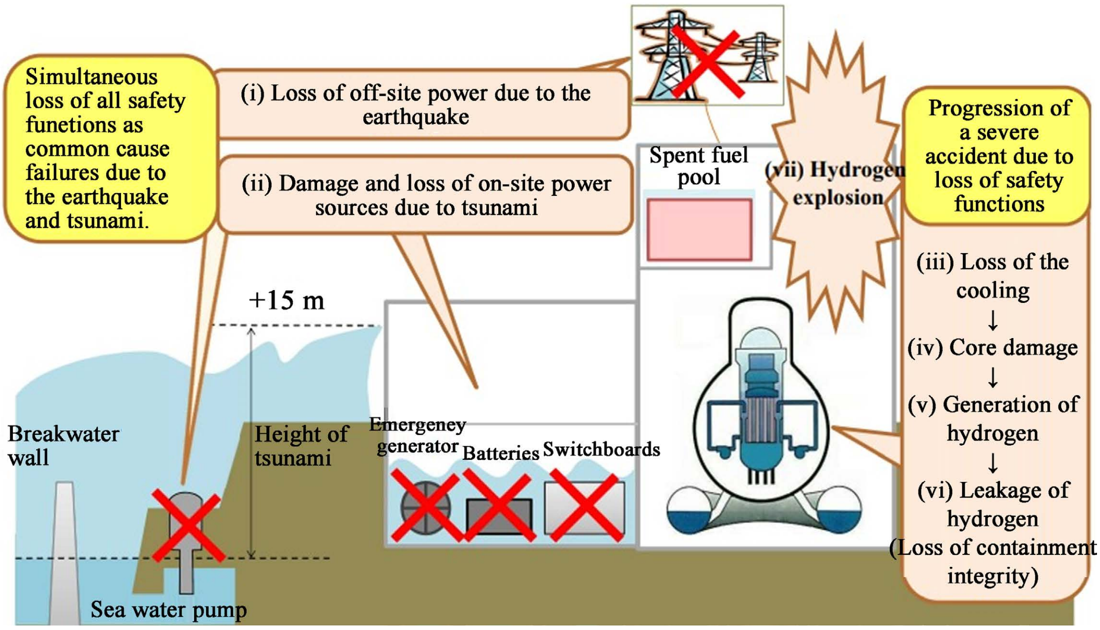

Figure 1. Progression of fukushima daiichi accident [1].

the release of radioactivity into the environment and is a key element in the concept of defense-in-depth.

The defense-in-depth principle is well known fundamental concept in ensuring nuclear safety. It involves the implementation of multiple levels of protection to prevent accidents and mitigate their consequences in nuclear facilities. These levels typically include physical barriers, redundancy in safety systems, operational procedures, and a strong safety culture. By having multiple barriers in place, each designed to prevent and mitigate different types of failures, the defense-in-depth approach aims to provide multilayer and multifunctional protection against nuclear accidents and their potential consequences (graphical representation of the physical barriers of a nuclear power plant is illustrated in Figure 2). The functionality of these barriers is constantly monitored. In case any of these barriers loses its integrity the risk of the next barrier failure increases and the potential of increasing the risk of worst-case scenarios (uncontrolled radioactive release into the environment) becoming more likely as in case of Chernobyl and Fukushima nuclear accidents. The Chernobyl explosion that demolished the reactor building and released large amounts of radiation into the atmosphere put approximately 400 times more radioactive material into the

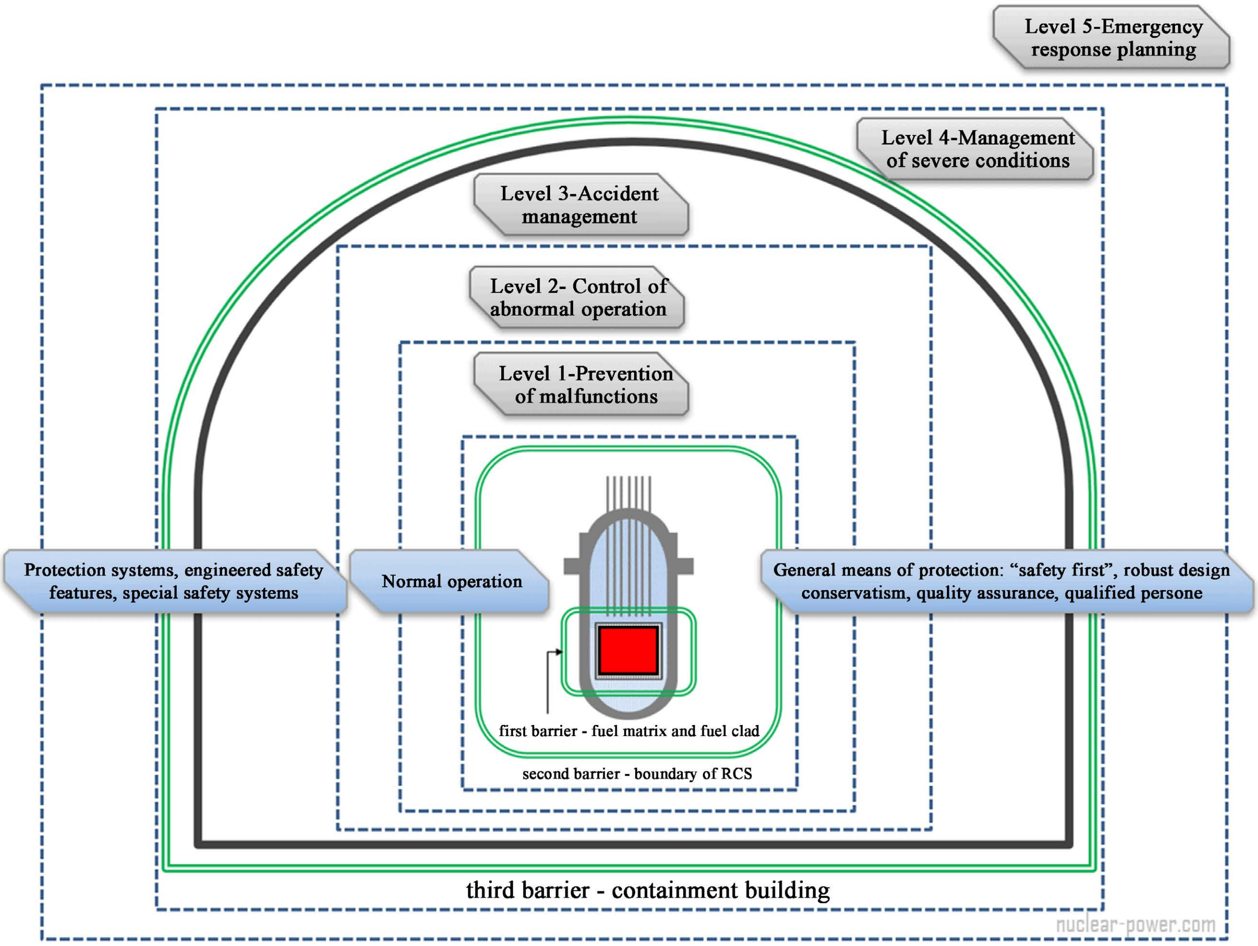

Figure 2. Nuclear safety Defense-in depth principle.

Earth's atmosphere than the atomic bomb dropped on Hiroshima, and the reason was likely to have been caused by the production of hydrogen from zirconium-steam reactions and detonation of hydrogen which threw out fragments from the extremely radioactive fuel channels and hot graphite.

In scenarios leading to a severe accident, a significant portion or all of the systems outlined in emergency operating procedures would be temporarily lost, by partially dewatering the reactor core and causing fuel and zircaloy cladding overheating, leading to extensive fuel cladding oxidation reaction. As previously mentioned, the containment boundary plays a critical role as the final physical barrier against the release of highly radioactive fission products into the environment. Due to volatile and easily airborne fission products being carried with the hydrogen and steam, venting and potential hydrogen explosions discharged a significant amount of radioactive material into the atmosphere (notably ^{133}Xe, ^{131}I, ^{134}Cs and ^{137}Cs). Hence, ensuring the integrity of containment structures stands as a strategic priority in the management of severe accidents.

During the in-vessel stage of a severe accident development, hydrogen combustion, primarily generated from overheated zirconium metal as well as reactor internal steel components reacting with steam (zirconium-steam chemical reaction process and fuel element degradation scheme is illustrated in the **Figure 3**), can exert short-term hazardous pressure forces that may surpass the containment structure's strength and integrity, leading to containment partial or total failure as it happened in Fukushima Daichi NPP (Fukushima NPP's Unit 1, Unit 3 and Unit 4 have been strongly damaged by hydrogen explosion as shown in **Figure 4**). The most damaged from hydrogen explosion was Unit 3 as shown in **Figure 5**. The figures obviously reflect the severity of hydrogen explosion inside the containment, emphasizing the importance that in the stage of hydrogen generation, ensuring the integrity of the containment becoming the number one strategic priority. This is achieved by maintaining the integrity of the containment

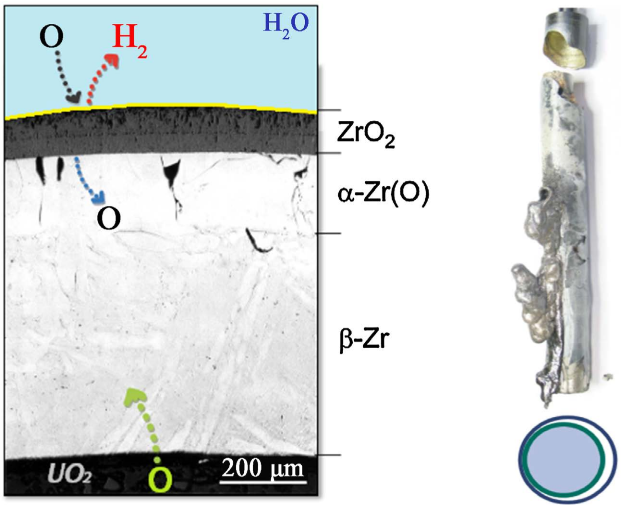

Figure 3. Zirconium-steam reaction process and fuel element degradation scheme during in-vessel stage of severe accident development.

Figure 4. The crippled Fukushima Dai-ichi nuclear power plant complex is seen in Okumamachi, Fukushima prefecture, northern Japan. From top to bottom: Unit 1, Unit 2, Unit 3 and Unit 4. (Air Photo Service Co. Ltd., Japan) [3].

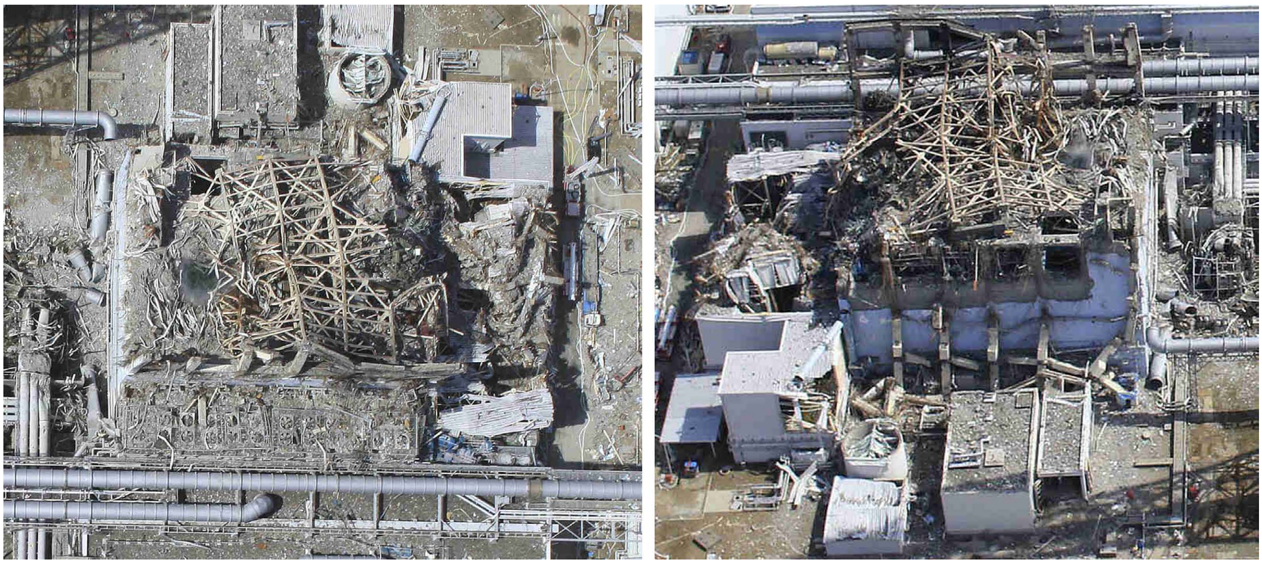

Figure 5. Unit 3 of the crippled Fukushima Dai-ichi nuclear power plant from different views is seen in Okumamachi, Fukushima prefecture, northern Japan. (Air Photo Service Co. Ltd., Japan) [3].

by preventing or mitigating the potential risk of hydrogen-air-steam combustion during the in-vessel stage of severe accident development. Consequently, measures to mitigate the hydrogen challenge must be viewed as integral components of the plant severe accident management program.

The reaction of zirconium with steam involves the formation of zirconium oxide and the release of hydrogen gas which is extremely explosive. This reaction is highly exothermic and can occur at high temperatures. The chemical equation for this reaction is:

$$Zr + 2H_2O \xrightarrow{\sim 700-1000^{\circ}C} ZrO_2 + 2H_2 \uparrow + \Delta H; \quad [2]$$

where ΔH is the heat released from the reaction of zirconium with steam to completely oxidize a unit kilogram of zirconium.

Overall, the reaction of zirconium with steam proceeds by the adsorption of water molecules onto the zirconium surface, dissociation of water molecules, oxidation of zirconium, and subsequent formation of zirconium oxide along with the release of hydrogen gas according to the scheme below.

2. Results of the Risk-Oriented Comparative Analysis of the Most Common (Traditional) Hydrogen Mitigation Strategies

The primary methods employed for hydrogen mitigation involve inertization of the atmosphere and the removal of hydrogen through controlled burning by igniters, catalytic recombination (the most common strategy currently), or venting of the containment.

Inertization, in this context, refers to achieving and maintaining an atmosphere composition where combustion becomes impossible. This objective is accomplished by either limiting the concentration of hydrogen and/or oxygen or by sustaining a high concentration of non-combustible or combustion-inhibiting gases (such as steam, nitrogen, carbon dioxide, etc.).

It is crucial to understand that inertization serves as a temporary solution and cannot be the only strategy against the hydrogen challenge due to a numerous uncertainty, and there exists a practical timeframe within which hydrogen must be eliminated from containment while maintaining an inert atmospheric condition.

Common strategies for hydrogen removal include the implementation of Passive Autocatalytic Recombiners (PARs), hydrogen igniters or controlled venting of the containment. In all cases, ensuring the inertization of the atmosphere is imperative to prevent any potential ignition of the gas mixture, which could lead to unpredictable devastating dynamic loads on the containment structures especially in case of supersonic detonation. Formation of burnable mixtures in case of existence of hydrogen mitigation methods mentioned above is permissible only when the anticipated burning mode precludes any flame acceleration, specifically deflagration to detonation transitions.

PARs are passive devices that promote the recombination of hydrogen and oxygen into water vapor. Unlike hydrogen igniters, PARs do not require external power and can operate passively, providing continuous hydrogen mitigation without the need for human intervention.

The principle of the passive autocatalytic recombination of hydrogen is shown below (**Figure 6**).

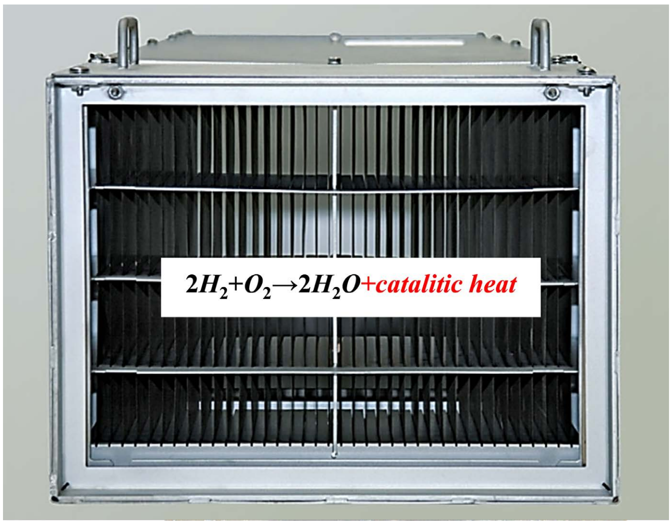

Figure 6. PAR from below with view of the catalytic plates [4].

In the presence of a catalyst, such as platinum (Pt) or palladium (Pd), the reaction of recombination of hydrogen with oxygen can occur at lower temperatures and faster rates. The catalyst provides an alternative reaction pathway with lower activation energy, facilitating the recombination of hydrogen and oxygen molecules.

When exploring approaches to address the hydrogen issue with PARs, it is crucial to take into account the following:

- PARs function as passive systems devoid of control mechanisms, rendering it impossible to mitigate associated risks, such as ignition, if the PAR operation poses a certain threat in the current conditions of the containment atmosphere.
- Depletion rates of PARs, in addition to the prevailing hydrogen concentration, hinge on various factors, including oxygen concentration, atmospheric pressure, and temperature. Within extensive convection zones of the containment, a relatively uniform distribution of steam-air-hydrogen is observed. Conversely, stagnation zones, separated by partitions or stratification phenomena, can result in diverse compositions [2]. Consequently, actual depletion rates of PARs may diverge significantly due to several uncertainties, at times being notably lower than the rated values established for specific conditions. Optimal PAR positioning within the containment varies across scenarios, precluding a one-size-fits-all approach.
- In non-inert atmosphere with specific hydrogen and oxygen content, PARs may unexpectedly become a source of hydrogen ignition due to substantial overheating of catalytic surfaces.

- Hydrogen removal by PARs is contingent upon the presence of oxygen. If any region of the containment experiences oxygen depletion due to PAR operation, hydrogen may accumulate, posing a risk of further burnable mixture formation through the intensified mixing of atmosphere in different containment sections related to certain accident management actions.
- The operation of PARs induces heightened atmospheric circulation, diminishing the natural deposition of aerosols. In scenarios lacking a spray system, natural deposition might otherwise be the predominant method of aerosol removal from the containment atmosphere.
- PAR capacities (hydrogen depletion rates) are very limited and may not cope with high hydrogen production rates in some scenarios. Consequently, during certain phases of the accident progression, there exists the potential for the accumulation of a specific hydrogen mass within the containment or its distinct sections, leading to the attainment or surpassing of flammability limits and the formation of so-called "hydrogen pockets" [2].
- PARs are devices that operate autonomously without any means for direct control over their functioning. In situations where the operation of PARs poses a specific risk, such as the potential for ignition in the current conditions of the containment atmosphere, it becomes unfeasible to mitigate this risk, conditioned to the fact that there is no direct control of mechanism because these devises are passive.
- The performance of PARs is influenced not only by the current hydrogen concentration but also by various other factors, including oxygen and steam relative concentrations, atmospheric pressure, and temperature. In scenarios where large-scale convection zones exist within the containment, a relatively uniform distribution of steam, air, and hydrogen is typically observed. However, in stagnation zones delineated by partitions or stratification phenomena, differing compositions may develop [2]. Consequently, the actual performance rates of PARs can vary significantly and may sometimes be notably lower than their rated values, which are determined under specific dynamic conditions. The optimal positioning of PARs within the containment may vary depending on the scenario, meaning that no single positioning variant can be universally optimal for a wide range of scenarios.
- In certain conditions where there is a non-inert atmosphere containing hydrogen and oxygen, PARs can potentially act as a source of ignition. This can occur due to significant overheating of the catalytic surfaces within the PARs, which may lead to the initiation of combustion reactions between hydrogen and oxygen. It's important to carefully consider and manage these risks when utilizing PARs in environments where there is a presence of hydrogen and oxygen to ensure safety measures are in place to prevent ignition events. However, the risk cannot be directly mitigated because PARs cannot be directly controlled by humans. Consequently, in the above-mentioned cases the risk associated with PARs cannot be directly eliminated.
- The removal of hydrogen by PARs is possible only in case of availability of

oxygen—if in any area of containment, the oxygen is exhausted due to the operation of PARs, hydrogen can accumulate in this area and create a risk of further formation of combustible mixture.

The removal of hydrogen by venting the containment is related to the removal of the significant volume of gas atmosphere from the containment and need of filtering of high amount of gas to minimize the radioactive releases, thus the capacity of the filtered venting system may not be sufficient to cope with high rates of hydrogen generation. The existing filtered venting systems are designed for preventing, in case of severe accidents, the overpressure failure of the containment and keeping the containment pressure to acceptable levels (by discharging steam, air and incondensable gases to the atmosphere) while mitigating the radioactivity releases. They are designed mainly for limited flow rates and cannot be used as a means for hydrogen removal to cope with the hydrogen challenge.

The efficiency of the hydrogen removal system will depend on the strategies used, the accident scenario and many different factors and associated unavoidable risks and uncertainties. It is clear and more than predictable that in different scenarios different systems can be more or less efficient and the implementation of only PARs cannot be assessed as a reliable strategy for mitigation of the hydrogen challenge first of all due to the fact that in certain conditions where there is a non-inert atmosphere containing hydrogen and oxygen, PARs can potentially act as a source of ignition after the surface temperature of catalytic plates will exceed the hydrogen-air-steam mixture ignition temperature. Consequently, a comprehensive hydrogen mitigation strategy should incorporate a blend of approaches, such as combining PARs with venting, to ensure flexibility in managing hydrogen challenge effectively and reliably across a wide range of unavoidable risks and uncertainties during a severe accident scenario.

Furthermore, it is critically important to note that severe accident management actions may yield not only positive impacts in the context of hydrogen detonation risk mitigation but also potential negative consequences due to possible deviations of predictions from reality across a wide range of unavoidable risks and uncertainties. Addressing or mitigating challenges during the severe phase of the accident can introduce new challenges as shown in the following 2 specific examples:

- **Example 1**. Inertizing the containment atmosphere primarily involves increasing steam or nitrogen or any inert gas content, leading to an increase in pressure. The elevated pressure correlates with the potential for release of radioactive materials from the containment.
- **Example 2**. Restricting radioactive releases in a severe accident necessitates minimizing the mass of radioactive aerosols in the containment atmosphere. The most effective aerosol removal method involves operating the containment spray system. However, the act of spraying within the containment results in the condensation of steam (the inert content of the mixture), leading to reduced steam concentration and consequently increases hydrogen and oxygen relative volumetric concentrations (a risk of losing atmospheric in-

ertness can sharply increase).

In this context it can be concluded that *"coping with or mitigating hydrogen risk during severe accident development can potentially generate another risk, even more unpredictable and unfavorable, parallelly increasing the uncertainty level by generating situations where the outcomes and probabilities are unknown or cannot be reliably estimated."* Moreover, consideration must be given to the fact that the implementation of technical means for a severe accident management strategy may set limits and generate higher risk with the implementation of another strategy intended to address a different challenge. For instance, the installation of PARs may present a significant limitation for the operation of the spray system, which is designed for aerosol removal from the containment and pressure reduction. The operation of sprays can lead to the loss of atmospheric inertness generating risk of ignition from PARs.

3. Concept of the Proposed Hydrogen Mitigation Strategy

The principal diagram of the concept of the proposed strategy is shown in Figure 7. The proposed strategy can be concurrently implemented with another strategy, such as the installation of PARs, to serve as an additional measure in addressing the hydrogen challenge.

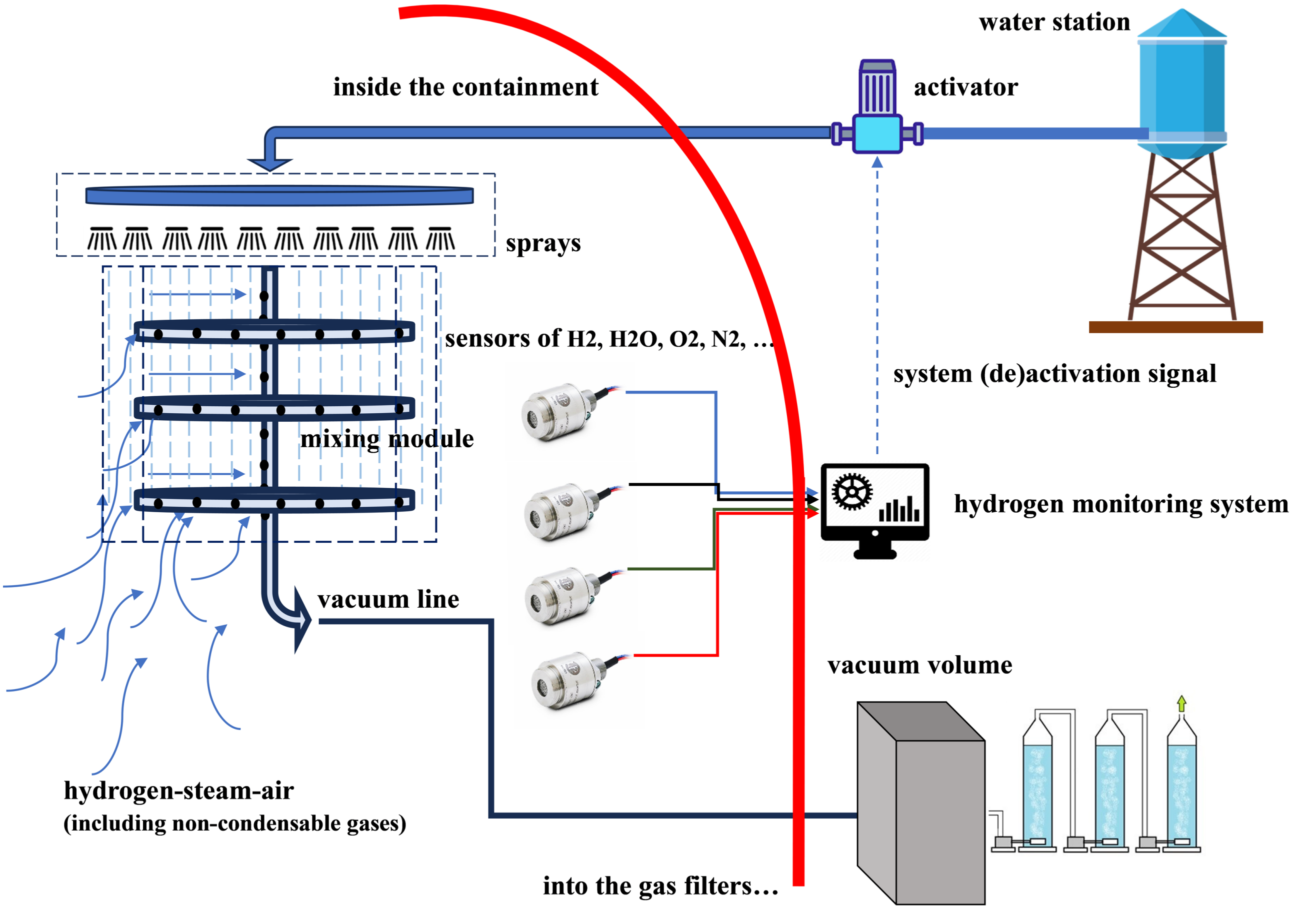

Figure 7. Principal diagram of the concept of the proposed strategy.

A specially designed and implemented spray system with special vacuum tubes covers only a small part of the containment. Due to the operation of sprays in the dedicated area and condensation of steam, a flow of gases from other parts of the containment is expected. Due to such a flow and continuous condensation of steam, accumulation of hydrogen and air will take place (increase of relative volumetric concentration) with a parallel decrease in the steam relative volumetric concentration. Venting is performed from this dedicated area through specially implemented lines. Venting from this dedicated area and operation of sprays should be done in alteration. When, during the spraying phase, the concentration of hydrogen reaches the defined maximal allowed local concentration, the spraying is stopped, and the venting is started. The removal of hydrogen is performed by portions. This alteration is performed several times before reaching non-flammable conditions in the containment. Ultimately the mixture (including hydrogen, steam, oxygen, nitrogen, and non-condensable gases) is removed to a special vacuum volume and then to the filtering plant. With this action, we are transferring the risk of a hydrogen explosion from the containment area to a more manageable volume outside of the containment.

In the context of the defense-in-depth approach, where the containment is the last physical barrier against the radioactivity release into the environment, this could be a significant step in reducing the associated risks that can lead to the hydrogen explosion and loss of containment integrity. This is one of the several advantages of this conceptual strategy.

Min advantages of the proposed strategy:

- Reducing the risk of total loss of the last physical barrier against the radioactivity release into the atmosphere by mitigating the hydrogen explosion risk,
- the integrated spray system modulates the atmospheric composition within a confined volume, mitigating the risk of extensive combustion,
- the strategy ensures aerosol removal from the containment atmosphere and facilitates containment atmosphere heat removal, contrasting with PARs that release substantial thermal energy because of the exothermic nature of hydrogen and oxygen recombination chemical reaction (as shown in **Figure 6**),
- the strategy induces a more controlled flow of atmosphere within the containment, minimizing the likelihood of hydrogen accumulation in specific areas,
- the strategy ensures the controlled accumulation and removal of oxygen, reducing the risk of flammable mixture formation and the magnitude of possible explosion,
- the likelihood of gas ignition in the sprayed area is minimal. This is attributed to low temperatures, absence of high-temperature plant system components, and no electro-powered components.

As aerosol removal is very important for severe accident management, the proposed system must be designed considering the physics of aerosol removal by sprays.

The strategy's effectiveness may be compromised in scenarios with relatively low steam concentration in the containment, where atmospheric flows to the sprayed area might not be sufficient to remove hydrogen effectively.

The main challenges in designing and implementing the described system will be as follows:

- the need for hydrogen (oxygen, nitrogen, steam) concentration sensors with an adequate measurement range and accuracy, response time, as well as qualification for environment conditions,
- the need for controlling the system operation by the plant staff or automatics,
- the possible difficulties/constraints for implementing the system components in the existing layout of the plant (availability of free space, possible restraints for maintenance works during outages).

A limited number of PARs, coupled with the proposed strategy, will facilitate the removal of most of the hydrogen as well as oxygen from the containment.

For each type of containment, a detailed analysis is imperative to assess the strategy's effectiveness, including determining the free volume available for system implementation and evaluating associated possible risks and uncertainties.

4. Conclusions

Due to specific risks and associated uncertainties of traditional hydrogen mitigation strategies, that cannot be separately considered as reliable and efficient means for mitigation of hydrogen challenge for a wide spectrum of worst case severe accident scenarios at a NPP the hybrid use of strategies will be more efficient, flexible and reliable in the context of reducing possible risks regarding unpredictable and uncertain combination of some sequencies that can generate favorable conditions in which the traditional hydrogen risk mitigation strategy could become a risk itself and generate new risks by even increasing the risk of hydrogen detonation and loss of the last physical barrier against the released of radioactivity into the environment by jeopardizing the main goal of nuclear safety, *to "protect people and the environment from harmful effects of ionizing radiation"*.

Within the framework of this research, in the light of the above an innovative conceptual strategy to cope with a hydrogen challenge is proposed. The proposed strategy is more risk oriented and is in line with the main goals of severe accident management. With this approach, we are mitigating the hydrogen risk and transferring the residual risk of a hydrogen explosion from the containment volume to a more manageable volume outside of the containment. In the context of the defense-in-depth approach where the containment is the last physical barrier against the radioactivity release into the environment, the implementation of the proposed strategy could be a significant step in mitigating the risks associated with the hydrogen accumulation and formation of combustible mixture with oxygen.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Nuclear Regulation Authority (2013) Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors. https://www.nra.go.jp/data/000067212.pdf

[2] TECDOC1661-International Atomic Energy Agency (2011) Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants.

[3] Air Photo Service Co. Ltd., Japan "High-Resolution Photos of Fukushima Daiichi" (2011). https://cryptome.org/eyeball/daiichi-npp/daiichi-photos.htm

[4] Passive Autocatalytic Recombiner (2019). https://www.framatome.com/