# HYDROGEN SAFETY IN COGENERATION PROCESSES
## *Overview of methodologies and challenges*

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**Abstract**

Hydrogen could become a key enabler for the global decarbonization of relevant industrial and private sectors including energy production. Given the projected huge demand for environmentally friendly hydrogen production in sufficient quantities, nuclear energy can offer cost-efficient and $CO_2$-free supply of electricity and process heat that can be coupled with various hydrogen production technologies, e.g. steam methane reforming, electrolysis (low and high temperature), thermochemical cycles, and pyrolysis. Each of these technologies brings its own safety challenges, depending on how close the respective technology approaches the nuclear installation. As the basic thermophysical properties of hydrogen differ considerably from those of e.g. natural gas, it is important to understand the effects of these differences on the relevant safety aspects and to take them into account appropriately. While chemical and petrochemical industries have established a long-standing expertise in explosion risk management, the nuclear community has developed considerable knowledge in hydrogen safety in the context of severe accidents in water-cooled nuclear power plants. The resulting databases helped improving the validation of safety tools and the development of methodologies to assess the hydrogen risk in large-scale geometries. Moreover, the analysis of accident scenarios enabled the definition of rules and recommendations for enhancing hydrogen risk management in nuclear power plants. This combined knowledge could support the generation of an RCS framework for co-located and coupled nuclear hydrogen production. For a successful implementation, an early engagement of multiple stakeholders, such as regulatory bodies and industries, federal and local governments, R&D networks, local authorities and emergency responders is required.

## 1. INTRODUCTION

The decarbonisation of relevant processes in the energy production as well as other relevant industrial and private sectors is considered to pave the way to the global ‘Net-Zero’ objectives, which numerous governments around the world have proclaimed. In this context, hydrogen – the smallest and simplest chemical element – is widely considered as a key enabler. Today, hydrogen is mostly used as a feedstock for industrial processes. In the future, hydrogen could increasingly be applied for energy storage (compensating fluctuating renewable sources), for energy transportation (as compressed gas or liquefied), in synthetic fuels, and for both electricity and heat generation.

However, as of today, global hydrogen production is still dominated by steam-methane reforming using fossil fuels. As reported in the ‘Global Hydrogen Review 2023’ issued by the International Energy Agency (IEA), low-emission hydrogen production accounted for less than 1 % of the global production in 2022 [1]. In view of the predicted huge demand, producing sufficient quantities of hydrogen in an environmentally friendly way by electrolysis utilizing renewable energies (‘green’ hydrogen) seems illusory for the foreseeable future. In this respect, nuclear energy offers $CO_2$-free and reliable provision of electricity and process heat, which can be coupled with various hydrogen production technologies. From a technical point of view, coupling small modular reactors with hydrogen production facilities in particular can meet the demands. Nevertheless, the demonstration of the safe operation of combined nuclear and hydrogen technologies is of high relevance for public acceptance and economic benefit.

In the last decades, the continuous developments in nuclear reactor technology have found technological answers to existing safety challenges. The probability of core meltdown has been reduced through advanced passive decay heat removal systems (Gen III+), such as emergency condensers and core flooding. In addition, limiting the consequences of severe accidents has been achieved through advanced containment devices (Gen III+), such as core recuperators, containment cooling condensers, or even excluding core meltdown by nature (HTGR). At the same time, chemical and petrochemical industries have developed their own expertise in explosion risk management. Combining nuclear power generation and hydrogen production technologies poses the challenge of demonstrating the safety of the cogeneration installation. The technologies that are considered for nuclear hydrogen production include steam methane reforming using nuclear heat and electricity, electrolysis (low and high temperature), thermochemical cycles, that may involve toxic or flammable chemical substances, and pyrolysis [2]. Each of these technologies brings its own safety challenges, particularly depending on how close the respective technology approaches the nuclear installation. Furthermore, safety approaches to limit hydrogen explosion hazards developed for nuclear power plants and for hydrogen technologies differ in their design philosophies. Nuclear reactors are designed to contain accidentally released hazardous substances, such as fuel and radioactive fission products, inside the reactor building. Hydrogen technologies, on the other hand, make typically use of open designs and ventilation strategies to prevent the accumulation of combustible gases by specifically avoiding enclosures.

## 2. HYDROGEN SAFETY EXPERTISE WITHIN THE NUCLEAR COMMUNITY

The basic thermophysical properties of hydrogen differ considerably from other gases typically used in the energy sector, such as natural gas. It is therefore particularly important to understand the effects of these differences on relevant safety aspects and to properly address them. Due to its very low density (14 times lighter than air), hydrogen leaks can occur more easily than for other gases. In addition, hydrogen has a very wide ignition range (about 7 times wider than for methane), which means that flammable mixtures with air can form more easily. For stoichiometric hydrogen/air mixtures, the ignition energy is lower by a factor of 10 than for natural gas/air mixtures, for example. The high flame speed enables an easier transition to detonations and high combustion pressures [3]. However, not all properties of hydrogen contribute to an increased risk. For example, the high diffusivity ensures that hydrogen can be easily dispersed and therefore diluted more quickly. Fast combustion combined with the buoyant behaviour can even lead to less severe fire scenarios than for other fuels [4].

In the context of severe accidents, the nuclear community has developed, since the 1980s, considerable expertise in hydrogen safety for water-cooled nuclear power plants. This was motivated by considerations of the massive quantities of hydrogen produced during core degradation in the event of a severe accident, which could enter the containment via the primary circuit and form flammable gas mixtures with the oxygen present there. At least since the TMI-2 reactor accident in 1979, significant efforts have been made internationally in industry and research to understand the physical and chemical processes involved in such scenarios and to develop and implement suitable preventive and mitigative measures [5,6].

Focus of substantial R&D activities was on the behaviour of hydrogen inside the containment under the boundary conditions of a severe accident. In the field of hydrogen dispersion, code development involved initially lumped-parameter and system codes. Since the late 1990s, more detailed codes and increasingly CFD codes (computational fluid dynamics) for a better resolution of the computational domain are considered. Understanding the conditions for flame acceleration and deflagration-to-detonation-transition as well as the consequences for the containment integrity was in the focus of hydrogen combustion research. The effect that safety components, such as water spray or recombiners may have on hydrogen dispersion and combustion was also investigated through dedicated experimental programs.

Supported by the advanced knowledge of hydrogen behaviour, mitigation strategies were developed and implemented in European PWRs since the late 1990s. These developments were supported by national as well as large international research programs by EURATOM, the OECD/NEA and the IAEA involving large scale experiments, such as PANDA (Switzerland), MISTRA (France), and THAI (Germany) [7].

The resulting databases helped improving the validation of safety tools and the development of methodologies to assess the hydrogen risk in large-scale geometries. Moreover, the analysis of accident scenarios enabled the definition of rules and recommendations for enhancing hydrogen risk management in nuclear power plants [8].

## 3. RCS CHALLENGES IN COGENERATION PROCESSES

Cogeneration processes can be implemented by locating the hydrogen production installation inside the nuclear power plant fence (co-location mode) or outside the nuclear power plant fence (coupling mode). The specific siting requirements for the co-location or coupling of a hydrogen production installation with a nuclear power plant depend on the type of nuclear reactor, the hydrogen production technology, the distances between the hydrogen production plant and nearby residential areas, and the attitude of the public towards acceptance of the installation [9]. The closer the hydrogen production technology requires integration into the nuclear site, the more intense RCS for nuclear safety and hydrogen safety interact (Fig. 1). This is especially the case when nuclear process heat is involved, to keep heat losses at an economical level.

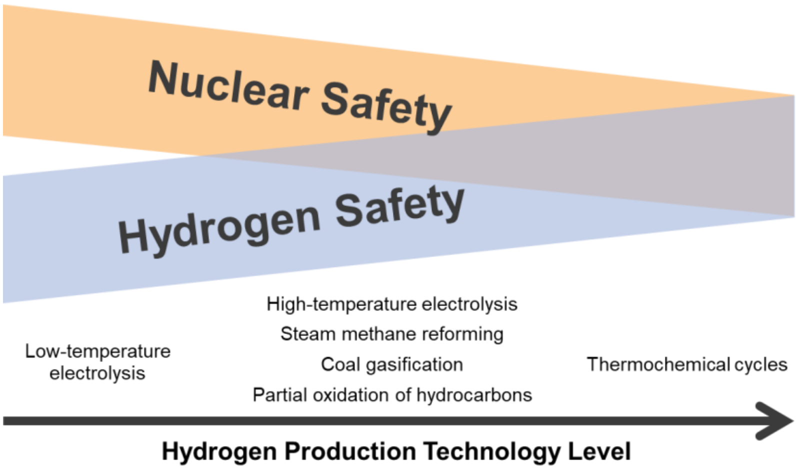


*FIG. 1. Relation of nuclear and hydrogen safety aspects depending on hydrogen production technology*

The safe production of hydrogen must consider the relevant international, national and regional regulations, codes and standards (RCS). Generally speaking, RCS aim to provide a framework for preventing accidents or limiting the frequency of potential hazardous events. The applicability of different RCS frameworks depends on national legislation. Some standards, such as ISO/TC 197 on hydrogen technologies (production, storage, transport, measurement, use), which focuses on hydrogen-related risks, are internationally accepted rules and widely disseminated at regional level. In the EU for example, further relevant standards are ATEX 2014/34/EU (Products), ATEX EC/1999/92 (Workplace) and the Seveso-III-Directive 2012/18/EU.

Further relevant standards for nuclear hydrogen production are for example ISO 22734:2019 ‘Hydrogen generators using water electrolysis’ and ISO 16110-1:2007 ‘Hydrogen generators using fuel processing technologies – Part 1: Safety’. Another illustrative example for relevant standards with regional differences are the standards for hydrogen pipelines ASME B31.12 (2019) ‘Hydrogen Piping and Pipelines’ (USA), CGA G-5.6 (2013) ‘Hydrogen Pipeline Systems’ (Canada), and EIGA IGC Doc 121/14 (2014) ‘Hydrogen Pipeline Systems’ (Europe).

Even though a significant number of RCS on hydrogen technologies already exists, it is worth bearing in mind that many of them are based on and were initially developed from natural gas standards, which need to be updated according to on-going pre-normative research and field experience. Furthermore, existing RCS have limited applicability to nuclear hydrogen production. A study entitled ‘Gaps and Considerations for Co-Locating or Coupling Hydrogen Production with a Nuclear Asset’ prepared by the Canadian Nuclear Laboratories [10] highlights the difference between RCS and requirements adopted in both coupled and co-located mode. In addition, the existing RCS identified were assessed as having limited applicability for the co-location/coupling of nuclear power plants with hydrogen production/storage facilities.

A comprehensive risk assessment based on mature standard procedures, such as Hazard and Operability Analysis (HAZOP) or Fault Tree Analysis (FTA), will be required that considers the interaction between nuclear power plant and hydrogen production facility. While potential accident scenarios on both sides may have consequences for the respective other side, also instabilities in the availability of electrical power and heat on the nuclear side and consumer load on the hydrogen production side may lead to hazardous situations that need to be assessed. As the co-location of nuclear power stations and hydrogen production and storage facilities may affect the emergency plans of both, it is necessary to review existing emergency plans to consider the effect that an accident or failure of the hydrogen production and storage facility could have on evacuation strategies in the event of a radiological emergency and/or the possible release of toxic chemicals from the hydrogen production facility [10].

## 4. CONCLUSION

Nuclear hydrogen production could be the key to provide the massive amount of hydrogen required for the decarbonization of industrial and private sectors in an environmental-friendly way. Due to the specific hazards related to the properties of hydrogen, demonstration of safety in production, storage, and distribution is essential for the widespread acceptance of combined nuclear and hydrogen plants. For this purpose, an RCS framework for co-located and coupled nuclear hydrogen production is mandatory.

Consequently, a detailed gap analysis on RCS for nuclear hydrogen production needs to be performed by engaging stakeholders, such as regulatory bodies and industries. The nuclear boundary must be clearly defined so that legal and regulatory responsibilities can be assigned unambiguously. Additionally, emergency planning considerations and strategies need to be established. To this end, an early engagement of federal and local governments is required to ensure the embeddedness in the national nuclear strategy. Regulatory and standardization bodies need to provide the required tailored RCS, where targeted pre-normative research on knowledge gaps to be defined in the RCS-developing process is mandatory for success. Nuclear regulators are specifically challenged by new reactor designs (SMR), local authorities by site-specific issues. Finally, emergency responders need to be engaged in emergency plan considerations and strategies.

## 5. REFERENCES

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