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Preliminary hazard analysis for hydrogen production by coupled High Temperature Electrolysis Facilities and Nuclear Power Plants

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Coupling of High Temperature Electrolysis Facilities (HTEFs) and Nuclear Power Plants (NPPs) is a promising solution for large-scale clean hydrogen production. A preliminary hazards analysis of the system of systems made of HTEF and NPP is presented with reference to a preliminary design in which steam and electricity are supplied by the NPP to the HTEF. The outcomes of the analysis point at the fact that hydrogen leakage, steam leakage and overcurrent events on the HTEF side may contribute to an increase in the risk at the NPP side, in terms of higher probability of Loss Of Offsite Power (LOOP), Main Steam Line Break (MSLB) and Loss of Heat Sink (LHS).

Keywords: High Temperature Electrolysis Facility (HTEF), Nuclear Power Plant (NPP), Hazard Analysis, Hydrogen Production

1. Introduction

Hydrogen technologies are expected to play a key role in the decarbonization of several sectors, including energy storage and transportation (International Energy Agency 2022; U.S. Department of Energy 2023). To accelerate the transition, the International Energy Agency (IEA) recommends implementing strategies for low-emission (i.e., clean) hydrogen-production (Moura and Soares 2023; International Energy Agency 2022). One promising solution for large-scale clean hydrogen production is the coupling of High Temperature Electrolysis Facilities (HTEFs) and Nuclear Power Plants (NPPs) (Chalkiadakis et al. 2023; Frick et al. 2022). In the U.S., NPP-hydrogen pilot demonstration projects began in 2022, with further developments anticipated over the next several years, spanning multiple design variants under consideration (Boardman et al. 2022). However, such coupling introduces new hazards, potentially leading to unforeseen accidental scenarios and a risk increase at the site level

(Vedros, Christian and Otani 2023). Risk assessment has been identified as a critical need for supporting deployment of electrolyzer technologies at scale (Al-Douri and Groth 2024; Groth et al. 2024).

In this work, we conduct a preliminary hazard analysis with reference to a preliminary design of a system of systems made of a $500\ MW$ HTEF composed of several Solid Oxide Electrolyzers (SOEs) and of a $1000\ MW$ NPP composed of 4 identical units of Small Modular Dual Fluid Reactor (SMDFR), which is an innovative fast reactor design whose high operating temperatures make it ideal for hydrogen production (Huke et al. 2015), because both the high temperature steam and the electricity can be supplied by the NPP to the HTEF (Westover and Boardman 2023).

Currently, for a system of systems made of a HTEF and a NPP, risk assessment and hazard knowledge is limited due to the lack of published system information, operational experience, and data. As a first step toward addressing these limits, in this work, we conduct a preliminary identification and preliminary hazard analysis of the most critical hazards. The most relevant hazards are identified by literature review and then quantitatively corroborated by simulation; the limited available data is used to assess by simulation their potential impact on the NPP and surrounding infrastructures. The outcomes of the analysis point at the fact that accidental scenarios arising from failures in the HTEF, such as steam leakages, overcurrent events and explosions following hydrogen leakages, are unlikely to directly damage the NPP reactor, but they can impact on the surrounding infrastructures (e.g., the power network infrastructure, the steam pipes, the turbine building) in risk-significant ways. Specifically, HTEF failures can contribute to the increase in the risk of the NPP in terms of larger probability of Loss Of Offsite Power (LOOP), Main Steam Line Break (MSLB) and Loss of Heat Sink (LHS). These findings highlight the necessity of considering the identified hazards when the Probabilistic Risk Assessment (PRA) of a NPP, if coupled with a HTEF, is conducted to assess its compliance with regulatory safety standards for licensing (US Nuclear Regulatory Commission 2018).

2. Case study

The considered site layout is shown in **Fig. 1**.

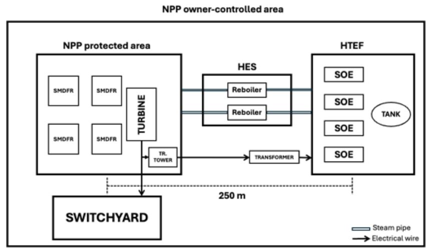

Fig. 1. Case study layout for an HTEF coupled to an NPP.

The system of systems comprises a NPP with $N = 4$ SMDFR, each with a nominal power of $250\ MW$, and a large-scale hydrogen production facility (i.e., the HTEF) with nominal rating (i.e., power input at full hydrogen production) of $500\ MW$.

The SMDFR is an innovative fast reactor design, in which the liquid fuel is a mixture of uranium tetrachloride and plutonium tetrachloride, which enters the core vessel at the bottom and spreads through a system of vertical tubes for the heat transfer before leaving the reactor from the top to enter the Pyrochemical Processing Unit (PPU). The liquid coolant is pure lead and enters the core vessel from the bottom to remove the heat from the fuel tubes by conduction before leaving the vessel from the top to enter the heat exchanger (Liu, Luo, and Macián-Juan 2021). The high operating temperature of the SMDFR allows the production of high temperature steam, which is ideal for the coupling with a HTEF. The NPP turbine is connected to the power grid through a high-voltage switchyard, adjacent to the NPP protected area, and to the HTEF through a transmission tower located inside the NPP protected area. The operating parameters of the NPP are reported in **Table 1**.

Table 1. NPP operating parameters (Liu, Luo, and Macián-Juan 2021).

Parameter	Value
Mean linear power density	$609\ W/cm$
Fuel inlet temperature	$1300\ K$
Coolant inlet temperature	$973\ K$
Steam flow rate	$75\ kg/s$
Steam temperature	$700\ °C$
Steam pressure	$0.4\ MPa$

The considered HTEF is composed by several SOEs, and is expected to produce up to

$290 \frac{metric\ tons}{day}$ of hydrogen. The HTEF is located outside of the NPP protected area, but inside of the owner-controlled area. For safety reasons, a separation distance of $250\,m$ is considered between the HTEF and the NPP and between the HTEF and the NPP high-voltage switchyard. The HTEF is equipped with a storage tank with capacity of $25\,m^3$ (Westover and Boardman 2023).

The operating parameters of the HTEF are reported in **Table 2**.

Table 2. HTEF operating parameters (Westover and Boardman 2023; Yanxing et al. 2019).

Parameter	Value
Hydrogen production	$290\ tons/day$
Steam input flow rate at full capacity	$65\ kg/s$
Steam input temperature	$700\ °C$
Steam input pressure	$0.4\ MPa$
Hydrogen storage temperature	$110\ K$
Hydrogen storage pressure	$70\ MPa$
Hydrogen storage tank volume	$25\ m^3$

The coupling of the two systems is achieved through:

- a Heat Extraction System (HES), composed by two piping lines that route the high-temperature steam from the NPP to two steam reboilers that create steam from a deionized or demineralized water source. The steam is then provided to the HTEF to be used in the HTE process. The HES is equipped with several isolation valves to isolate any steam leakages;
- a transmission tower with electrical wiring to divert electrical energy, in the form of alternating current, from the output of the turbine to the HTEF, where most of the required power is converted to rectified direct current with a transformer.

Additional details about the design can be found in (Westover and Boardman 2023).

3. Preliminary hazard analysis

With reference to the case study of Section 2, the following hazards introduced by the coupling are identified:

- hydrogen leakage or release (Vedros, Christian and Otani 2023; European Commission Joint Research Centre 2023; Wismer et al. 2024);
- oxygen leakage or release (Wismer et al. 2024);
- hydrogen and oxygen mixing (Wismer et al. 2024);
- steam leakage or release (Vedros, Christian and Otani 2023);
- overcurrent event (Vedros, Christian and Otani 2023; European Commission Joint Research Centre 2023);

In what follows, the oxygen leakage or release is not considered because it is not expected to cause accidental scenarios that can damage the NPP or its surrounding infrastructures (Wismer et al. 2024), and, despite hydrogen and oxygen mixture can result in hydrogen explosions, there is not enough evidence of such mixtures in SOEs. All the remaining hazards are relevant for inclusion in a PRA, as we shall see in what follows.

3.1. Hydrogen leakage

A hydrogen leakage or release can be caused by the failure of the HTEF piping system, the failure of one of the hydrogen storage tanks or by the toppling of the electrolyzers stack due to extreme natural events (Vedros, Christian and Otani 2023). The released hydrogen can ignite and lead to either a jet fire (in case of immediate ignition) or an explosion (in case of delayed ignition) (Groth and Hecht 2017a), which could damage the NPP and/or the surrounding infrastructures, as we shall see in what follows.

With regards to a jet fire scenario, the following conservative assumptions are made to assess its impact:

- hydrogen storage pressure equal to $P = 70\ MPa$, as in **Table 2**, being the largest storage pressure of hydrogen storage tanks (Yanxing et al. 2019);
- hydrogen leak diameter equal to $d_{JF} = 0.2\ m$, i.e., double-ended guillotine break, being d_{JF} the diameter of the pipe entering the storage tank (Kuczynski et al. 2019);

The evolution of the jet fire is simulated with the HyRAM algorithms (Groth and Hecht 2017b), and the area of the plant that can be affected by the jet fire is shown in **Fig. 2** (shadowed area). It can be seen that the flame length is such that it can reach the switchyard and/or the NPP protected area; however, as shown in **Fig. 3**, the duration of the jet fire (i.e., $t_{JF} \sim 40s$) is not enough to degrade significantly the fireproof of the walls that surround the HTEF, which are typically designed to withstand direct flames for at least 60 minutes (Sultan 2021). It is worth mentioning that smaller storage pressures and/or leak diameters may lead to a longer duration of the jet fire but with shorter length of the flames (eventually below $250\ m$), so that a jet fire cannot affect neither the NPP nor the surrounding infrastructures, provided the availability of the fireproof walls.

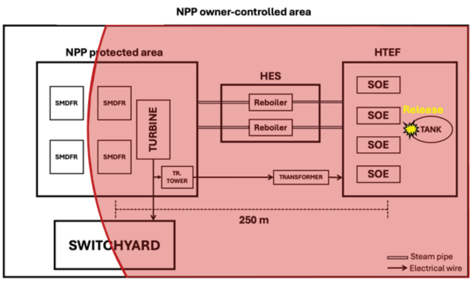

Fig. 2. Area of the plant that can be affected by the considered jet fire.

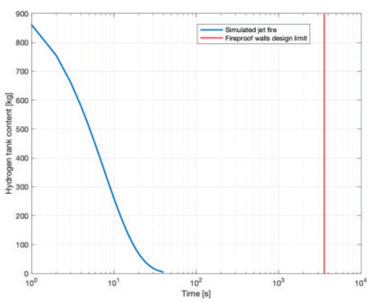

Fig. 3. Simulated duration of the considered jet fire.

With regards to an explosion scenario, we conservatively assume an undetected leakage to occur from the hydrogen piping system, so that it leads to the accumulation and subsequent delayed ignition of hydrogen. We assume, without loss of generality, a leak in the reboiler (whose pipes have a diameter equal to $d_{reb} = 0.076\ m$ and a mass flow rate equal to $\dot{m}_{reb} = 0.083\ \frac{kg}{s}$ (Glover and Brooks 2023)) with a leak diameter equal to $d_{EX} = 0.01\ m$. In such conditions, within an accumulation time in the range $t_{acc} \in [5, 120]\ min$ (Glover, Baird and Brooks 2020) which accounts for the fact that the ignition can occur randomly in time, a total mass of hydrogen in the range $m_{hydr} \in [3.2, 75.8]\ kg$ can accumulate, so that its explosion can generate an overpressure wave that propagates outward. The resulting structural damages to surrounding infrastructures are assessed by firstly modelling the overpressure wave as in (Glover, Baird and Brooks 2020) and, then, using the fragility curves showing the probability of damage to the above ground infrastructures (i.e., the power infrastructure and the turbine building) sketched in **Fig. 4** (for the switchyard), **Fig. 5** (for the transmission tower) and **Fig. 6** (for the turbine building) (Vedros, Christian, and Otani 2023). We can conclude that, under the conservative assumptions taken, the overpressure at $250\ m$ (where the above ground infrastructures are placed) can reach values $P^* \in [1.2, 5]\ kPa$ (the lower value for $t_{acc} = 5\ min$ and the largest for $t_{acc} = 120\ min$) and, thus, the probabilities of failure of switchyard, transmission tower and turbine building are $P^f_{switchyard} \in [0.20, 1]$, $P^f_{tower} \in [0.69, 1]$ and $P^f_{turbine} \in [0, 1.5 \times 10^{-4}]$, respectively.

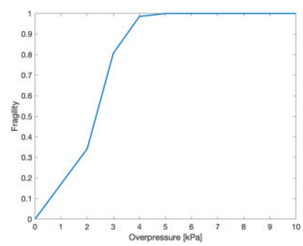

Fig. 4. Fragility curve of the switchyard.

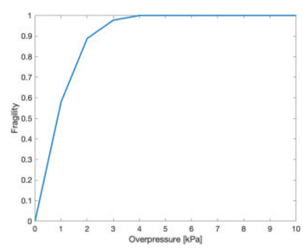

Fig. 5. Fragility curve of the transmission tower.

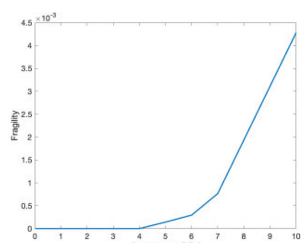

Fig. 6. Fragility curve of the turbine building.

This is a safety-relevant insight regarding the coupling of NPPs and HTEFs, because the failure of either the switchyard or the transmission tower may result in a LOOP accident for the NPP, as both failures lead to the disconnection of the plant from the electrical grid, so that the risk of severe consequences in case of LOCA or MSLB is increased, because the Auxiliary Cooling System (ACS), typically designed in NPPs to counteract the escalation of LOCAs and MSLBs by providing auxiliary coolant mass flow rate, relies on electrical power. On the other hand, the failure (i.e., collapse) of the turbine building causes the failure of the turbine, leading to a LHS accident, and the rupture of the steam pipes, initiating a MSLB accident.

3.2. Steam leakages

A steam leakage in the HES can be caused by the rupture of one of the steam pipes, the failure of one of the two reboilers, or the rupture of one of the flow control valves (Vedros, Christian and Otani 2023). The isolation valves, if functioning, are able to isolate the leakage, effectively mitigating the accident. In case of failure of the isolation valves, to evaluate the impact on the NPP of the non-isolated steam leakage, we conservatively assume a guillotine break of one of the steam pipe while the HTEF is operating at full capacity, leading to a leak flow rate $\dot{m}_{leak} = 32.5\,\frac{kg}{s}$, which is ~43% of the steam produced by the NPP. **Fig. 7** shows the simulation results of the peak cladding temperature T_w in one of the four SMDFRs, in response to the steam leakage, by means of a dynamic physical model of literature (Marchetti, Di Maio and Zio 2025) which can simulate accidental scenarios occurring in SMDFRs, i.e., the large steam leakage that causes a sudden depressurization of the steam generator, leads to a rapid increase in steam flow, which in turn causes the overcooling of the reactor coolant, an increase in its density that enhances neutron moderation, increases the core reactivity and causes fuel cladding overheating.

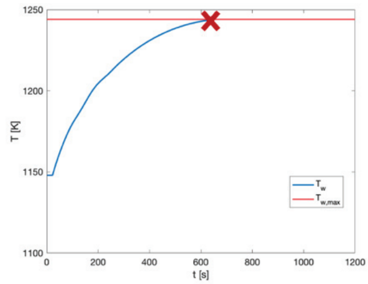

Fig. 7 Simulated peak cladding temperature evolution after a non-isolated steam leakage.

It can be seen that the cladding temperature increases over time and, if the accident is not mitigated, it reaches the failure threshold (i.e., $T_{w,max} = 1244\ K$) in less than $630\ s$, that is to be considered a too rapid surge of temperature to be counteracted and, therefore, to be accounted in the PRA, since it is lower than the time needed to drain the fuel from the reactor through the melting fuel plugs (i.e., t_{drain}~$1200\ s$) (Marchetti, Di Maio and Zio 2025).

3.3. Overcurrent event

An overcurrent event in the HTEF can be caused by the failure of the transformer. To protect the NPP turbine, three identical breakers are installed: one in the H_2 island, one within the NPP boundary and one near to the turbine (Vedros, Christian and Otani 2023). Each breaker consists of a parallel configuration of two relays in series with one high-voltage circuit breaker. In case of an unmitigated overcurrent event (i.e., failure of all breakers), the NPP turbine is damaged, leading to a LHS accident in which the heat extracted from the coolant is progressively reduced. **Fig. 8** shows the simulation results of T_w in one of the four SMDFRs, in response to the LHS, obtained with the same dynamic physical model adopted in the analysis of Section 3.2. It can be seen that, after an initial surge in temperature, the accident is successfully mitigated by the action of the ACS, which activates at $t = 257\ s$, together with the passive safety features of the SMDR (i.e., the melting fuel plugs and the large feedback coefficients of the coolant and the fuel, which decrease the core reactivity when temperature increases (Liu, Luo and Macián-Juan 2021).

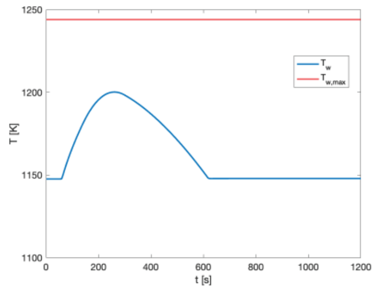

Fig. 8. Simulated peak cladding temperature evolution after a LHS event with ACS.

However, as shown in **Fig. 9**, if ACS cannot perform its safety function, the cladding temperature increases over time and reaches the failure threshold in less than 430 s which is much lower than t_{drain}: overcurrent events should, thus, also be considered in the PRA.

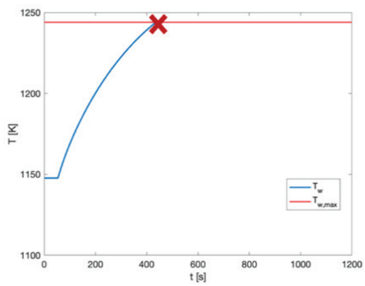

Fig. 9. Simulated peak cladding temperature evolution after a LHS event without ACS.

4. Conclusions

In this work, we conducted a preliminary hazard analysis for hydrogen production by a system of systems made of a NPP and a HTEF. The analysis is, in particular, aimed at identifying the hazards that may increase the risk at the NPP side. A preliminary expert-based hazard analysis was used to develop the list of scenarios to be considered, and the consequences on the NPP and on the surrounding infrastructures have been quantitatively evaluated by simulation. The results of the analysis point out that hydrogen leakage or release, steam leakage or release, and overcurrent events on the HTEF side may contribute to an increase in the risk at the NPP side, and must be considered when conducting the PRA of the coupled system.

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