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TECHNICAL REPORT ON ETSON MEMBERS' CURRENT APPROACHES TO HYDROGEN RISK ASSESSMENT IN LWRS

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FOREWORD

This report is the outcome of a collaborative effort by the ETSON Expert Group EG4, which specializes in severe accident analysis. We extend our sincere appreciation to all individuals and organizations who contributed—either directly or indirectly—to the development of this report.

The primary aim of this survey is to gather and assess the current practices and approaches adopted by ETSON members in evaluating the risks associated with hydrogen and other combustible gases. The ultimate goal is to support the development of a Technical Safety Assessment Guide by identifying key issues relevant to the evaluation of nuclear power plant safety cases concerning hydrogen-related hazards during both the in-vessel (In) and ex-vessel (Ex) phases of a severe accident. The report addresses both operating and new water-cooled reactor designs.

This report presents a survey covering the following aspects:

- Requirements for hydrogen management during severe accidents, along with the hydrogen mitigation measures implemented (or under consideration) in operating nuclear power plants, particularly those employing pressurized water reactor (PWR) technology.
- The role of engineering systems such as sprays, containment venting, local air coolers, suppression pools, and latch systems in severe accident management strategies.

The survey highlights several important points:

- Current requirements primarily focus on in-vessel conditions. Their extension to ex-vessel scenarios, including containment and connected auxiliary buildings, remains to be addressed.
- All existing requirements aim to preserve containment integrity. However, the availability and function of safety systems such as sprays and venting lines for managing the later phases of a severe accident must be considered in extended requirements.
- Only a few countries apply quantitative criteria to define these requirements.
- Mitigation measures are typically designed based on the established requirements for in-vessel conditions.
- Few existing Severe Accident Management Guidelines (SAMGs) provide recommendations on the use of safety systems (such as Containment Heat Removal Systems (CHRS), sprays, and coolers) during the late phases of a severe accident.
- Current monitoring systems do not include measurements of carbon monoxide concentration.

Finally, it should be mentioned that the effectiveness of hydrogen mitigation is still being investigated in the H2020/AMHYCO and the OECD/THEMIS projects. The lessons learned from these projects will be used together with the present Technical Report to develop a dedicated ETSON Technical Safety Assessment Guide on hydrogen and combustible gases risk assessment.

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1 INTRODUCTION

In the case of an accident in a nuclear facility, dedicated actions and strategies are designed to be taken to avoid or minimize core damage and, eventually, the release of radioactive material into the environment. For these purposes, three main categories of actions and strategies were developed and implemented in all nuclear power plants (NPP):

The Emergency Operating Procedures (EOPs) to prevent or delay the core damage (i.e. to prevent severe accident conditions) and to mitigate the consequences of transients and accidents (before reaching core damage conditions). (Level 3 of Defense in Depth - DiD)

The Severe Accident Management Guidelines (SAMGs) to mitigate the accident consequences according with the following objectives (Level 4 of DiD):

to terminate the progression of core damage once it has started and retain the core within the reactor vessel;

to preserve the containment integrity[1] as long as possible;

to minimize on-site/off-site radioactive releases;

to achieve a long-term safe and stable condition;

The on-site & off-site Emergency Response Plans (REP) is designed to limit the consequences to the workers and the general public. (Level 5 of DiD)

The SAMGs objective is to maintain the containment integrity as long as possible by providing guidance for a best use of the existing plant equipment to limit the consequences of phenomena such as: steam explosion, direct containment heating, hydrogen combustion, containment pressurization and molten core-concrete interaction.

Regarding the hydrogen combustion risk, as it may endanger the containment integrity and lead then to significant radioactive releases, dedicated actions and procedures were developed, as part of the SAMGs, to address this issue. The development of such actions and guidelines depends on the nuclear facility design, on the considered safety equipment and on the adopted requirement in each country.

The aim of this report is to provide a survey on ETSON member's practices and approaches to analyse the risks associated with hydrogen and other combustible gases.

The objective is to help improving the common understanding and safety practices between ETSON members and to anticipate the analysis of the results of the ongoing R&D programs, as the OECD/Themis and the EU-AMHYCO projects, in view to develop an ETSON Technical Safety

[1] Keep the containment pressure within the design domain

Assessment Guide (TSAG) dedicated to hydrogen and combustible gases risk assessment by identifying the key issues to be considered when reviewing a power plant safety case for hydrogen and other combustible gas hazards in the In-Vessel and Ex-Vessel phases of a severe accident.

To carry out the survey, a questionnaire (see Appendix A) was sent to ETSON members. The responses received stay available.

This document encompasses the responses received and provides the key statements highlighting the similarities and differences between the hydrogen risk mitigation processes of ETSON members in support of the development of ETSON TSAG for hydrogen risk mitigation.

Before presenting the findings of the survey, the following section briefly reviews hydrogen risk mitigation strategies commonly adopted in Western countries.

2 OVERVIEW ON HYDROGEN RISK MITIGATION MEASURES

During severe accidents (SA) in a NPP, 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 an in-vessel retention strategy is not considered. A large 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 flame acceleration (FA) or deflagration to detonation transition (DDT) if the combustible mixture is ignited leading then to pressure exceeding the containment pressure design.

Moreover, the hydrogen distribution may be affected by engineering safety systems as sprayers or coolers which are widely used in many reactors to limit 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 due to enhanced mixing, but they can also significantly reduce the steam concentration and increase the containment atmosphere turbulence intensity, as it is the case with spray activation, which may lead to more sensitive gas mixture compositions promoting then the occurrence of FA and DDT.

To prevent hydrogen combustion and mitigate its potential consequences, several strategies can be implemented, including: (1) intentional ignition, (2) hydrogen removal through recombination, (3) a combination of ignition and recombination techniques, (4) enhancing mixing within the containment atmosphere, (5) inerting the containment atmosphere and (6) venting the containment to release hydrogen.

In addition, monitoring systems can be implemented to help emergency teams assess the risk of combustion and therefore make an appropriate decision about spray activation, for instance.

2.1 Hydrogen mitigation strategies

In the following sections, a short presentation of each of the mentioned mitigation strategies is given:

2.1.1 DELIBERATE IGNITION SYSTEMS

To prevent the build-up of hydrogen, many NPPs use igniters inside the containment to keep hydrogen concentrations relatively low, so that the pressure and temperature loads induced by combustion cannot jeopardise the integrity of the containment. To this end, the number of igniters, their location and the timing of their activation are appropriately designed to effectively control the concentration of hydrogen.

Three main ignition technologies are used in NPPs:

1. glow plug igniters, based on electrical resistors with hot surface temperatures of around 800-900°C, which can be operated manually (on and off), automatically (in response to LOCA signals) or semi-automatically (automatically but switched off by the operator),
2. spark igniters that do not require high external power and are battery-powered, and
3. the catalytic igniter, which uses the heat of the catalytic hydrogen-oxygen reaction to initiate combustion.

The advantages and disadvantages of each of these technologies are outlined in Table 1

Type	Advantages	Drawbacks
Glow plug igniters	- ignite over widest range of compositions, - continuous availability - robust - operator controlled	- rely on AC power, - high-power requirement -containment penetration
Spark igniters	- battery powered, do not rely on AC power - easily back-fitted, no connections required	- intermittent operation (in 5s intervals), - not operator controlled, - weaker ignition source than for glow-plug igniters, - unavailable in long term - rely on triggering from LOCA[2] signals
Catalytic igniters	- self powered, use heat of H2-02 reaction to produce ignition temperature - easily back-fitted, no connections required	- operates over narrower range of compositions than do either spark or glow-plug igniters; - response to changing conditions not instantaneous; - potential for poisoning or fouling - combined with recombiners, subject to common cause failure. - not operator controlled

Table 1: Types, advantages and drawbacks of igniters (Bentaib & Gupta, 2021)

[2] Loss of Coolant Accident

2.1.2 PASSIVE HYDROGEN RECOMBINATION

To cope with hydrogen production rates in a severe accident with core damage, passive autocatalytic recombiners (PARs) were back-fitted within the containment. The PARs recombine hydrogen and carbon monoxide with oxygen at concentrations below the flammability limit. In common PAR designs, catalytic materials (platinum and palladium on ceramic washcoat) are housed in a metallic structure whose purpose is to optimize the circulation of gases in contact with the catalyst (see Figure 1 below).

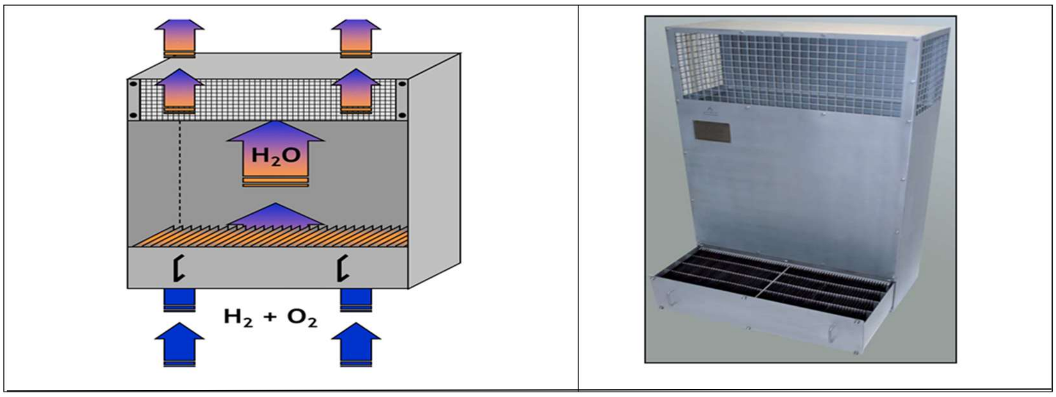

Figure 1: left: Sketch of PAR operation; right: picture of Framatome recombiner

Typical nominal rates for hydrogen depletion for the PARs are in the range up to 100 to 200 kg/h for the whole containment building. Nevertheless, studies of representative accident sequences indicate that the hydrogen release may exceed the PARs depletion capacity. In these cases, the installation of PARs is focused on preventing or minimizing the possibilities of containment integrity challenges due to flammable gases explosions.

2.1.3 ATMOSPHERE MIXING SYSTEM

The PWR-KWU[3] and EPR[4] containments are accessible during power operation. Consequently, the containment is divided into two parts: accessible service compartments and non-accessible equipment compartments. These two types of compartments are separated into two ventilation system zones. The ventilation system maintains the equipment compartments at a lower pressure. This creates a defined direction of airflow from compartments with a low risk of fission product release to compartments with a higher risk. In the event of a severe accident, the increase in pressure and temperature inside the internal containment leads to ventilation openings and then to the distribution of the hydrogen released throughout the containment, which contributes to its dilution and the lowering of its local concentration. These mixing systems are generally associated with additional means of attenuation such as PARs and igniters.

[3] PWR from Kraftwerk Union AG (KWU)

[4] European Pressurized Water Reactor

2.1.4 INERT GAS INJECTION

One way of preventing the formation of a flammable mixture is to reduce the oxygen concentration inside the containment below a critical value of 5%vol.

Thus, inert gas, nitrogen, is injected homogeneously to maintain the containment atmosphere non-flammable. This hydrogen risk mitigation strategy is mainly adopted in small containments (BWR s[5]), as they easily allow homogeneous gas distribution.

2.1.5 CONTAINMENT VENTING

Although venting the containment may help to reduce the hydrogen content inside the containment, the gas released may explode outside the containment, as was the case at Fukushima Daichi. Furthermore, venting could not be considered in the event of a severe accident, as fission products could also be released into the environment.

2.2 Containment atmosphere monitoring

The emergency procedures such as safety injection, spraying or activation of a filtered venting system may depend directly on insights about the hydrogen concentration within the reactor containment. Thus, hydrogen monitoring systems had been implemented in several NPPs. The typical number of used sensors is between 5 and 12. Their implementation inside the containment depends on the reactor design and the safety requirements.

Two measurements techniques are mainly used: gas sampling or measurement based on catalytic reaction.

When the techniques of catalytic reaction measurement are considered, the hydrogen concentration is deduced based on the increase of temperature induced by the catalytic reaction on Pt/Pd sensors.

The second mostly used hydrogen measurement technique is based on sampling. Generally, the sample extraction monitors that draw a gas sample through a sampling line are located outside the containment, where the gas sample is analysed and then returned to the containment. Sampled gases are analysed using mass spectrometer or thermal conductivity detectors outside the containment. The table 2 below summarizes advantages and drawbacks for each of the two measurement techniques.

Table 2: Types, advantages and drawbacks of gas monitoring systems for hydrogen control in NPP (Bentaib & Gupta, 2021)

Type	Advantages	Drawbacks
Catalytic	- ignite over widest range of compositions, - continuous availability - robust - operator controlled	- do not operate under conditions of the late phases of a severe accident, where oxygen is lacking, and the carbon monoxide is present in the containment atmosphere. In fact, the oxygen lack leads to the catalytic reaction reduction

[5] Boiling Water Reactor

		and consequently to the temperature increase limitation. - The simultaneous presence of carbon monoxide and hydrogen in the containment atmosphere make difficult the deduction of the hydrogen and carbon monoxide concentration based on temperature measurement
Samplings	These methods are accurate and have been used in several NPPs in Germany and in Japan. These systems allow long-term availability during a severe accident as the hydrogen monitors are located outside containment and not exposed to the hostile conditions inside the containment	- The need of containment penetration which increases the risk of containment leakage. - The gases sampling process which may lead to hydrogen dilution. Actually, gas difference pressure between the pipe inlet and outlet may affect the measurement accuracy. - The time delay induced by sampling process analysis. - The need to protect the sampling system installed outside to avoid any radiation exposure to personnel

3 SUMMARY OF HYDROGEN RISK MANAGEMENT PRACTICES OF ETSON MEMBERS

The purpose of this section is to provide a summary of the questionnaire responses received from ETSON members. To this end, the responses received are grouped into four main sub-sections covering (1) regulations and mitigation strategies, (2) qualification and maintenance of mitigation measures, (3) safety assessment methods and (4) use of SAMGs and gas monitoring.

The detailed received answers are available for the ETSON Members.

3.1 Regulations and hydrogen mitigation strategies adopted by ETSON members.

The choice of a mitigation strategy depends primarily on the containment design and on the related safety objectives. To this end, national requirements are defined to achieve the expected safety goals of preserving the containment integrity and to avoid large fission products to be released to the environment. Table 4 summarises the national requirements and mitigation measures and strategies adopted in each country for hydrogen management inside the containment for ETSON's members.

Table 3: Mitigation strategies and adopted requirements in the reactor containment: Adopted requirement per country

Country/NPPs	Mitigation strategy	Adopted Requirements/ expectations for hydrogen management during SA including In and Ex vessel phases until reaching stable state

Belgium	PARs implementation (AREVA/Siemens KWU PARs (FR90-1500) for all fleet	The threats due to combustible gases shall be managed to ensure safety functions in DEC and confinement functions Avoid combustions challenging the containment integrity.
Czech Republic	The management of hydrogen risks inside containment facilities at Czech NPPs is primarily achieved through PARs. For the Dukovany Nuclear Power Plant (EDU), hydrogen management during severe accidents relies on a network of AREVA PARs installed throughout the containment. The Temelín Nuclear Power Plant (ETE) uses a similar approach, utilizing NIS Siemens recombiners.	In the Act No 263/2016, section 46 is not directly mentioned the requirements for hydrogen and combustible gas management but it refers to the requirements for nuclear installations against the hazards resulting from the site characteristics of the site for a nuclear installation and from external influences and in the Annex 1 it is mentioned the documents need to licensed activities related with the use of nuclear energy.
Finland	Olkiluoto 1&2 (BWRs): inerting with Nitrogen Looviisa 1&2: Combination of PARs and glow plug igniters Olkiluoto 3: Areva PARs In addition latch doors opening automatically with specific pressure difference or elevated temperature are installed between the lower and upper part of the containment to enhance atmospheric mixing Hanhikivi 1: Currently the design is for 58 PARs	Item 311 states that the leakthightness of the containment in severe reactor accidents shall be demonstrated using the containment temperature and pressure obtained from the severe accident analyses performed in compliance with Guide YVL B.3 by increasing the maximum pressure (gauge pressure) by a 50% safety margin and by pressure increase due to hydrogen combustion calculated according to the AICC principle. Item 341 requires that the containment structure and systems used for managing accidents shall prevent such gas burns, gas explosions or other energetic phenomena that may Item 342 states that combustible gases shall be primarily managed by systems and components that are located inside the containment and do not require an external power supply
France	PARs for PWR900, PWR1300, PWR1450 PARs and mixing setup for EPR Flammanville	For the whole fleet, it is important to avoid the combustion of hydrogen, which could lead to pressure loads that could compromise the integrity of the containment. - PAICC[6] should stay below the containment pressure design - average H2 concentration < 8 vol.% to avoid complete combustion - local H2 concentration <10 vol.% to avoid flame acceleration
Hungary	60 NIS type PARS were installed in each unit of Paks NPP (VVER-440/213)	The threats due to combustible gases shall be managed to ensure to avoid combustions challenging the containment integrity. Eliminate the possibility of detonation and deflagration which may cause early containment failure.

[6] Pressure Adiabactic Isochoric Complete Combustion

Romania	Following the post-Fukushima stress tests, for Cernavoda NPP (both for Unit 1 and Unit 2) safety measures to resist in condition of severe accidents were identified and implemented. One of them consists of the installation of PARs for hydrogen management.	The NSN02 Norm of Romanian regulatory body (CNCAN) stipulates in Art 74, al. 2: "the design of the containment must include devices for the control of hydrogen concentration after an accident to prevent an explosion".
Slovakia	Hydrogen management and strategies are based on PARs with ignition function and possible cooperation with a dedicated containment spray system.	There are no specific requirements for hydrogen management by the regulatory authority or legislation (acts or degrees). But there are strict requirements for 4th level in depth measures, dedicated equipment and guidelines incorporated into acts and degrees in Slovak legislation. As hydrogen combustion was assessed to be of the highest risk to capability of NPPs to mitigate radionuclide releases during an accident, hydrogen mitigation measures/strategies are thoroughly checked by the regulatory body. The extent of measures or strategy of approach or equipment type was not specified or required in any way by the authority
Slovenia	The implemented safety equipment to mitigate the risk of hydrogen explosion in the only NPP in Slovenia are PARs.	PARs and other safety upgrade equipment/structures are installed upon Slovenian Nuclear Safety Administration Decree No.: 3570-11/2011/7 from September 1st, 2011, following the Fukushima accident as a step for upgrade of safety measures to prevent severe accidents and to improve the means to mitigate their consequences
Switzerland	Each Swiss NPP has PARs. One of them additionally has passively working igniters (and form the main basis to control the hydrogen hazard for beyond design basis accidents).	Eliminate the possibility of deflagration or detonation that threaten the containment integrity Guideline ENSI-B12, Sec. 8.3 generally requires that SAMG shall account for the phenomena of severe accidents and specifically requires the measurement of hydrogen in the containment. Guideline ENSI-G02 addresses requirements (design, assessment) concerning the prevention of H2 explosions in the containment venting system. Decrees released in 2013 address plant-specific requirements including passive measures for the prevention of H2 explosions and the prevention or mitigation of paths (e.g. through penetrations or vent lines) of H2 releases outside the containment
Ukraine	Hydrogen mitigation strategies for VVER-1000 rely on PARs operation (ignitors are not installed), restrictions on the containment spray operation, potential use of design ventilation system for containment air mixing	Requirements / expectations for hydrogen management during SA include the following. NPP units should be equipped with the technical means that prevent reaching explosive and fire-

	and/or filtered containment venting system. For VVER-440 installation of additional PARs for DEC is planned along with Long Term Containment Cooling System (currently in the design stage)	hazardous concentrations of gases released into containment during accidents. Such systems (measures) should exclude detonation and deflagration of explosive and fire-hazardous gases in case of design accidents. For beyond design accidents including severe accidents (DEC A and DEC B) detonation should be prevented. Local deflagration in individual compartments is allowed provided that containment integrity function is preserved. NPP compartments with presumed flammable gas accumulation should be provided with gas concentration monitoring and alarm equipment

From the survey presented in Table 3, it can be concluded about requirements and mitigation strategies:

- **the adopted mitigation strategies are based mostly on the use of PARs. Few of them are using either igniters or inerting gas,**
- **the adopted requirements address only in-vessel conditions,**
- **only few countries adopt quantitative criteria for the requirement,**
- **all the requirements aim to preserve the containment integrity; preserving safety components needed to manage severe accident are not clearly mentioned.**

Moreover, and after Fukushima accidents, the risk of gas explosion in the spent fuel building and surrounding compartments and buildings, had been highlighted. Safety assessment had been conducted in some countries. Table 5 summarizes the status of the mitigation strategies adopted in each country for hydrogen management inside the spent fuel building for ETSON's members.

Table 4: Mitigation strategies and adopted requirements in spent fuel building: Adopted requirement per country

Country/NPPs	Status of mitigation strategy in spent fuel building
Belgium/PWRs	In Belgian NPPs, the annular space between the inner containment and the reactor building is not equipped with hydrogen mitigation measures. The risk of hydrogen explosion in the annular space has been assessed as negligible as long as the containment is intact, and the design leakage is not exceeded. The spent fuel pool (SFP) is located in a peripheral building (i.e. outside the reactor containment) and threats due to combustible gases are currently managed by avoiding accumulation of such gases through (forced or natural) ventilation of that building. In some units, in case of Complete Station Blackout (CSBO), power to this ventilation can be restored using an "ultimate diesel generator"; if this ultimate diesel generator is also unavailable, openings to the outside environment are created to allow steam and hydrogen release. In other units, fail-safe positions of valves of the SFP building ventilation system ensure open flow paths to the outside environment in case of CSBO (since the original design).

Czech Republic		No PARs are installed in any room around containment. There are no PARs in the reactor hall (room in which the SFP is located). Though there is a dedicated ventilation system in the rooms bordering the containment boundary that considers that the leakage from the containment can contain hydrogen gas (leading to a potentially combustible mixture in the bordering rooms around the containment).
Finland	Hanhikivi 1	Lessons learned from Fukushima are taken into account in the design of the Hanhikivi-1 plant. Fuel pool management can be done with many systems and fire trucks. Severe accident in the fuel pool is demonstrated to be practically eliminated by deterministic and probabilistic analyses as well as with design solutions. Subcriticality is provided with design, and non-borated water can also be used. Containment conditions can be handled with containment passive heat removal system (>72h).
	Olkiluoto 1&2	Hydrogen release and distribution analyses with Computational Fluid Dynamics (CFD) for reactor building and reactor hall with SFPs have been simulated. The performed simulations indicated that combustible clouds near the ceiling can be prevented by opening the existing hatch door at the upper elevation on the reactor hall wall. The venting efficiency will be enhanced by opening the access pathway to the transport shaft at the ground level. The outermost access doors open to the plant yard. Any SAMGs for opening the reactor hall and transport shaft vent paths in severe accident. No PARs or igniters were implemented in Olkiluoto 1 and 2 for SAM.
	Loviisa 1&2	Each unit has one in-containment SFP and hydrogen is not a specific issue. There are also two spent fuel storages outside the containment. After Fukushima additional systems/arrangements have been implemented to prevent fuel uncovery by adding water into all fuel pools. In this way hydrogen generation is prevented. Possible leaks from the containment can bring also hydrogen in these rooms. Use of ventilation is part of the guidance and a way to get rid of the hydrogen.
France		The hydrogen risk is managed through ventilation systems. No additional mitigation means were implemented.
Hungary		Paks NPP: The risk of hydrogen explosion in the reactor hall (where are the SFPs) has been assessed as negligible, because after Fukushima additional systems/arrangements have been implemented to prevent fuel uncovery by adding water into all fuel pools.
Romania		In post-Fukushima context, a detailed safety assessment for the SFP was performed. Based on it, accident management provisions for events in the SFP were implemented (natural ventilation for vapors and steam evacuation, seismically qualified firewater pipe for water makeup) [CNCAN 2021] Improvement of the existing provisions to facilitate operator actions to prevent a severe accident in SFP (water level and temperature monitoring from outside the SFP building). Design improvements have been implemented at both units. Water level gauges were installed to allow operators SFP level measurement in case of severe accident from an accessible location. Portable devices will be used for water temperature measurement. [CNCAN 2021] No information on the introduction of PARs, or igniters.
Slovakia		No PARs are installed in any room around the containment. There are no PARs in the reactor hall (room in which SFP is located). Though there is a dedicated ventilation system in rooms bordering the containment boundary that considers that the leakage from the containment can contain hydrogen gas (leading to potentially combustible mixture in the bordering rooms around the containment).
Switzerland		Post-Fukushima activities at ENSI led to upgrades of the equipment serving the mitigation of the risk from H2 generated in the containment. The risk of H2 generated in an SFP outside the containment has been investigated as well for the Swiss NPPs. The results of the investigations indicate that the production rate of hydrogen generated in the pool water by hydrolysis is too small to generate sufficient amount of hydrogen for an ignitable gas mixture. Accordingly, further investigations focused on maintaining the cooling of the fuel pools in order to avoid impermissibly high hydrogen production through Zr-oxidation. Upgrading's of special protected fuel pool cooling systems for some plants have been implemented as well as additional AM-measures for all plants.
Ukraine		In VVER-1000 units the SFP is located inside the containment, i.e. the same PAR system is used for the reactor accidents and SFP accidents. The PAR system characteristics are selected taking into account accident scenarios that affect both the reactor core and nuclear fuel in the SFP during full power operation and in shutdown modes.

	In VVER-440 units, the SFP is located in a non-hermetic part of the reactor building, which is not equipped with PARs. However, the hydrogen monitoring system is installed. The hydrogen concentration control relies on using the regular ventilation system.

From the survey presented in Table 4, on mitigation strategies and adopted requirements in the spent fuel building, it can be concluded:

- **The risk of hydrogen explosion in the spent fuel building has been assessed negligible.**
- **Threats due to combustible gases are mainly managed by avoiding accumulation of such gases through (forced or natural) ventilation of that building.**
- **After the Fukushima Daiichi accident, dedicated systems were implemented in some countries to maintain the cooling of the fuel pools and to avoid impermissibly high hydrogen production through Zr-oxidation.**

3.2 Qualification and maintenance of Mitigation measures adopted by ETSON members

To ensure the full operationality of the implemented safety components, their qualification and their periodic maintenance are required. The following table summarizes the ETSON member's practices regarding the qualification and maintenance of hydrogen mitigation means.

Table 5: Qualification and maintenance of mitigation measures

Country/NPPs	Qualification & Classification	Maintenance practices
Belgium/PWRs	Confidence in adequate operation of Belgian NPP PARs under SA conditions is based on the verification (in 1992) of the applicability to Doel and Tihange NPPs of the Siemens KWU qualification program for the type of PARs installed in Belgian NPP. In addition to development tests on model and full-size Siemens catalytic recombiners, an extensive test qualification program was conducted to measure depletion rates under a range of hydrogen concentrations, steam/pressure conditions and various potential adverse poisoning conditions. Some tests were conducted in the Battelle multi-compartment facility. Independent organizations have participated in and/or performed qualification testing of the Siemens design, such as TUV, CEA (spray impact, qualification in DBA and BDBA conditions), IPSN (qualification of the recombiner in presence of aerosols, ignition tests), EPRI and EdF, etc. Moreover, for each recombiner the efficiency was tested in the factory for a non-radioactive gas mixture corresponding to post-accident conditions and the efficiency of 5% of the	Except for in-service inspection tests of the catalytic plates and visual inspection of the PARs and remediation actions in case test results do not show a satisfying recombination efficiency of catalytic plates, no maintenance is foreseen. All recombiners were tested during the first two outages after installation; afterwards the inspection concerns only 5% of the recombiners at each outage. The inspection of an equipment comprises both a visual inspection and a performance test applied to 2% of the catalytic plates in accordance with the above-described principle. The catalytic plates are extracted from the drawers and transported to the hot laboratory in separate envelopes, each being identified by its PAR number, batch number and running number. A report is produced which clearly identifies the operator, the conditions of the test, the plates and the results.

	recombiners has been tested on site upon receipt. However, applicability of the aforementioned Siemens KWU qualification program to severe accident environmental conditions determined from most recent DEC B studies for Belgian NPP remains to be verified (request of safety authority to licensee). The PARs in Belgian NPP have no formal safety classification	
Czech Republic	There is no mission time strictly established for the PARs. However, the SÚJB (Czeck Safety Authority) is aligned with international guidelines and requirements where Mission time requirements are particularly strict, with PARs required to demonstrate a minimum of 72 hours of active operation. PARs, essential for hydrogen management during severe accidents are designated as Safety Class 2 equipment, in accordance with the safety classification requirements specified in Section12 of Decree 358/2016.	Maintenance frequencies are governed by the requirements in Decree 358/2016, which establishes the minimum intervals for safety-related equipment inspections. For Safety Class 1 equipment, this includes mandatory full inspections annually and functional tests every 3-6 months, as specified in Section 15 of the Decree. Safety Class 2 equipment, including PARs, follows a maintenance schedule defined by both the national regulatory requirements and manufacturer specifications, typically requiring full inspection every 18-24 months. The maintenance program is further detailed in the plant-specific documentation that must comply with the Quality Assurance Requirements specified in Decree 408/2016.
Finland	Both the PARs and the hydrogen measurement system are classified as SC3, as they are used to bring the plant to the controlled state after a severe accident. The glow plugs PAR's are qualified for environmental conditions in severe accidents (Radiation, temperature, pressure). Also following were considered: hydrogen deflagrations, Chemicals and Spray (For PAR's in the upper part of containment) In general all qualifications are time limited due to normal operation radiation doses and ageing. Actions are taken if needed. The environmental tolerance for 72 h is considered for glow plugs. For PAR's the radiation or other environmental conditions are not an issue even in a long term, as long as there is no plate poisoning.	Glow plugs are periodically tested. PAR plates are periodically taken from PAR's and tested in a separate testing station, that uses bottled air with 2 % hydrogen. After the tests and when needed plates are regenerated (heated in oven) that removes possible impurities from the plate surface. Ex vessel scenarios are not considered as Loviisa NPP has implemented in-vessel melt retention *Detailed plans for maintenance are still being developed continuously. Most PARs will be in locations that allow testing to be performed during outages by sampling plates and testing them in a mobile workbench or in the laboratory for more detailed study.*
France	Both Framatome (Siemens) and AECL PARs test qualification programs were first conducted by the manufacturers and through national (KALIH2, H2PAR) and international programs. aerosols, ignition tests), EPRI and EdF There is no specific classification for PARs	During long outages, PARs inspection comprises both a visual inspection and a performance test.
Hungary	PAR's are qualified for environmental conditions in severe accidents. Measurement equipment's and PARS are in safety class 3 : systems, structures or system components to provide such functions that mitigate the radiological consequences of DEC1-2 plant states, prevent or hinder their evolution, and provide information in the case of DEC1-2 plant states. Seismic class 1 – equipment fully functional during and after an earthquake	PAR plates are periodically taken from PAR's and tested in a separate testing station. After the tests and when needed plates are regenerated (heated in oven) that removes possible impurities from the plate surface.

Romania	Some improvements to the reliability of existing instrumentation by qualification to SA conditions and extension of the measurement domain were introduced for both U1 and U2 Cernavoda NPP [CNCAN2021]. The implemented design changes aimed to improve survivability to SA is addressing the following parameters: (1) R/B pressure, (2) Calandria Vault level, (3) Moderator level, (4) Heat Transport temperature. There is no information available for the survivability of PARs, Igniters, Coolers	During annual outage, the mitigation equipment may be maintained according with the maintenance Plan. No information available on it
Slovakia	Hydrogen sensors survivability: Long term operation (min. 144 hours) +150°C, pressure 0,35 MPa abs., humidity 100%, steam mixture Short term operation (min. 30 minutes) +270°C, pressure 0,35 MPa abs., humidity 100%, steam mixture PAR survivability parameters provided by the producer AREVA were sufficient to meet plant equipment requirements for severe accident conditions. Equipment cabinets were required to withstand total dose of 960 kGy. PARs are safety class 3f. Equipment essential for maintaining environment conditions within nuclear facility. Seismic class 1a – equipment fully functional during and after an earthquake.	Maintenance is performed according to results of testing of the catalytic plates once per 5 years. Regeneration of plates is done according to procedures and using equipment provided by the PAR supplier. Operator of all units, Slovenské elektrárne, have a testing equipment for periodic inspection of catalytic plates of installed recombiners. Inspection of recombiners capability is performed once per 5 years according to dedicated procedure and equipment.
Slovenia	A total of 22 PARs are provided, of which 20 PARs are non-safety-related	One cartridge from each of 2 safety-related PARs should be tested during each outage. One cartridge from each of 4 non-safety-related PARs should be tested during each outage. The tested PAR modules rotate at each outage so that after 5 cycles all PARs have been examined for functioning. During tests, the cartridges are exposed to a mixture of 3 vol.% hydrogen in air. The temperature increase of the cartridge over time is measured. The success criterion is either a temperature increase of 10 °C in 20 minutes or 20 °C in 30 minutes. Inspections consist of at least once per refueling interval to verify through a visual examination that there is no evidence of abnormal conditions within the PAR enclosure (i.e., loose structures, deposits of foreign materials, etc.).
Switzerland	The PARs are designed for In- and Ex-vessel scenarios and for CO decomposition. The PARs do not have mission time restrictions The safety classification of the PARs follows the requirements of ENSI-B06 and ENSI-B14. They have a high safety class which includes requirements on the seismic qualification.	PARs and igniters are regularly tested. Moreover, PARs and igniters are covered physically according to the procedural guidance of the shut-down and outage process, and are recovered according to the procedural guidance of the restart of power operation. All hydrogen mitigation systems have specified test procedures covering the functionality and specified test intervals.
Ukraine	The qualification characteristics of PARs are defined in the respective technical specifications based on the results of SA analyses. For VVER-1000 the PARs should perform their functions under the following accident conditions:	As recombiners are fully passive, they do not require maintenance during fuel campaign. The maintenance is conducted during regular reactor outages and involves visual inspections and performance tests of selected catalytic elements using dedicated testing equipment. If

	- temperature up to 250 ·C; - absolute pressure up to 0.7 MPa; - relative humidity of steam-gas mixture up to 100%; - absorbed dose rate up to 2.0×104 Gy/h; - accident duration up to 72 hours. The catalytic element should remain functional under the impact of smoke (soot) from burning oil and cable insulation. The PAR system is classified according to Ukrainian regulatory documents as the localization safety system with safety class 2 (specified as "2L" system). Seismic class (category) 1 (systems for preventing or limiting the release of radioactive substances generated during accidents).	design recombination rate is not confirmed, the special measures (e.g., cleaning, thermal heating) should be performed to recover the catalytic properties of the element. The scope of measures is specified in the operation manuals. For RVK PARs, for example, the performance tests are conducted for the randomly selected catalytic elements once every 5 years.

Based on the survey results presented in Table 5 regarding the qualification and maintenance of mitigation measures, the following conclusions can be drawn:

- **•When the qualification of adopted mitigation measures is carried out using manufacturer qualification programs and international verification campaigns (involving factors such as pressure, temperature, humidity, radiation, and seismic activity), their classification varies depending on the country.**
- **•The adequacy of the adopted mitigation measures should be assessed under DEC-B conditions.**
- **•Maintenance procedures are governed by country-specific regulations**

3.3 Safety assessment methodologies adopted by ETSON members

To assess the mitigation strategies' ability to fulfil the safety objectives, the adopted methodologies are mainly based on the use of computational codes and pre-request criteria allowing the identification of situations leading to flame acceleration and transition from deflagration to detonation regimes. Those methodologies are mainly based on 6 steps:

(1) containment modelling,

(2) selection of relevant scenarios,

(3) hydrogen distribution simulation taking into account the effect of safety systems as PARs and spray,

(4) identification of dangerous configurations based on the use of sigma-criteria,

(5) identification of potential ignition sources, and

(6) evaluation of pressure and temperature loads induced by combustion.

The selection of accident scenarios to be considered, as well as the rationale for the safety equipment implementation and their availability (possible PARs poisoning, active equipment availability…) are summarized in the following table.

Table 6: Assessment methodologies

Country/NPPs	Assessment methodology and main assumptions
Belgium/PWRs	Considered scenarios for PARs design assessment: - scenarios with the highest computed instantaneous release rates of flammable gases. Hence, attention was focused on scenarios initiated by a small break LOCA because they lead to high release rates of hydrogen at vessel breach. A SBLOCA scenario with early timing of core melt (speeds up hydrogen release) and available containment cooling system (reduces partial steam pressure) was found to lead to highest containment loads. - Calculations were performed for two 900 MW plants with different concrete compositions. One of them is of the siliceous type (corresponding to Doel NPP) which releases limited quantities of carbon monoxide, while the second one (corresponding to Tihange NPP) is made of limestone common sand and produces large quantities of that gas during the decomposition process. Safety computational tools: Since the installation of the PARs, the licensee's architect-engineer also developed a catalytic model for the MELCOR code in order to allow integrated calculations taking into account the atmosphere composition and the hydrogen distribution in the different compartments of the containment. These calculations have been used as confirmation for the sizing of catalytic recombiners. Sensitivity analysis: Sensitivity calculations were performed in the probabilistic safety assessment (PSA) level 2 study in order to investigate the influence of various severe accident management actions on containment performance. The use of catalytic recombiners was shown to reduce the hydrogen concentration in the containment and prevent large hydrogen burns leading to containment failure. Recent DEC B studies for Belgian NPPs (which however focus on Doel 4 and Tihange 3 in a first time) that were performed using MELCOR confirmed that during the accident progression, due to the presence of the PARs inside the containment (which combine almost all the O2 RB initial inventory with H2 and CO in the first 30 hours of the accident) the RB atmosphere composed by hydrogen, air, and steam never reaches flammability limits. The possibility of PARs ignition is considered in the severe accident safety analysis of Belgian NPP.
Czech Republic	The implementation of hydrogen mitigation systems in Czech nuclear facilities follows a defense-in-depth approach, supported in both deterministic and probabilistic safety analyses. This implementation strategy is driven by multiple factors, including fulfillment with post-Fukushima safety requirements, adherence to WENRA reference levels and fulfillment of SÚJB regulations. The selection of safety equipment is based on extensive analysis of various accident scenarios, ranging from Design Basis Accidents (DBAs) such as Loss of Coolant Accidents and steam line breaks, to Beyond Design Basis Accidents (BDBAs/DECs) including station blackout scenarios and severe accidents with core damage. The PARs implementation is mainly justified by their passive operation capability. The location of PARs throughout the containment is determined through detailed CFD analyses, ensuring effective hydrogen removal in multiple compartments. The implementation strategy takes into account potential catalyst poisoning by fission products, incorporating regular testing and maintenance requirements, along with conservative efficiency calculations in the design basis. The analytical support for these implementations utilizes various sophisticated tools and methodologies. MELCOR is employed for severe accident progression analysis. Regarding equipment availability assumptions, PARs are generally considered to have 100% availability due to their passive nature, though regular inspection and maintenance requirements are established to ensure this high reliability.
Finland	Considered scenarios and safety tools: The design of the hydrogen management strategy is supported by analysis performed with Socrat and Kupol-M codes. Some selected scenarios have also been analysed with the CFD code STAR-CCM+. The risk of hydrogen combustion from these scenarios is further evaluated by the Limits-V code, specialised in prediction of combustion loads and detonation risks. The results show that the planned strategy does not lead to situations with a risk of hydrogen

	detonation in the containment. Hydrogen management systems are also part of the probabilistic risk assessment (PRA) level 2. As the project continues the analysis are also further developed with more specific plant data. Analyses are also verified by Fennovoima's own comparative MELCOR analyses. Sensitivity analysis: PAR's ignition possibility is not considered in detail at this stage of the Hanhikivi-1 project. However, analyses are performed for AICC[7] plus margin and the resulting pressure increase remains below the structural limit for the containment. As the ignition point is not be rigidly specified, these analyses also cover PAR self ignition. Structural analyses are made to justify the integrity of the containment for those rooms where conditions could lead to hydrogen burn (for most limiting walls/structures).
France	Considered scenarios for PARs design assessment: Based on PSA studies, representative scenarios are considered to assess the PAR design efficiency. Extreme scenarios with the highest computed instantaneous release rates of flammable gases are considered to check the robustness of the PAR design. Safety computational tools: The design was initially assessed using the LP ASTEC code. For the EPR, CFD analysis were performed. Sensitivity analysis: Sensitivity calculations were performed in the PSA level 2 study in order to investigate the influence of various severe accident management actions on containment performance. The use of catalytic recombiners was shown to reduce the hydrogen concentration in the containment and prevent large hydrogen burns leading to containment failure. The possibility of PARs ignition is considered and its contribution to avoid flame acceleration conditions is shown.
Hungary	Considered scenarios for PARs design assessment: Based on deterministic assumptions (LBLOCA, MBLOCA, SBLOCA SBO) and PSA studies, representative scenarios are considered to assess the PAR design efficiency. Safety computational tools: The design was initially assessed using the MAAP code for hydrogen source and 3D analysis were performed for gas distribution in the containment. Sensitivity analysis: Sensitivity calculations were performed to select the best hydrogen mitigation strategy and to investigate the number of the PARs. Level 2 PSA showed that the use of PARs reduce the hydrogen concentration in the containment and prevent hydrogen detonation and hydrogen burns leading to early containment failure.
Romania	Severe accident deterministic simulation (LOCA, SGTR, SBO) was used to stimulate the conditions in the containment. Due to the risks associated with the resulted high concentration of hydrogen in the containment PAR equipment solution was implemented.
Slovakia	A complex hydrogen study was done to consider various hydrogen mitigation strategies for Mochovce 3/4 units. The emerging winning strategy was the implementation of hydrogen recombiners with dual function (recombination and ignition). The same strategy was used then for Mochovce 1/2 and Bohunice 3/4. The number of PARs and the preferable location of PARs was performed in the complex study considering deterministic analyses, probabilistic assessment and CFD calculations. Ignition capability of PARs was provided by dedicated tests by the equipment supplier. Evaluation of acceptance criteria in the area of hydrogen were performed as integral code studies using MELCOR code. Evaluation of location of respective PARs within a containment room was done using CFD code FLUENT. The number of recombiners/recombination capacity was based on both deterministic and probabilistic approach considering also available studies from other VVER440 units.
Slovenia	The PAR sizing is based on ex-vessel accident progression (MCCI) during SBO accident since the presence of PARs has little impact on peak hydrogen concentration during the in-vessel accident phase. The accident is analyzed using the MAAP code. The sizing of PARs (determination of number of PARs) is based on oxygen depletion (oxygen starvation). Taking into account the effect of oxygen concentration, the effect of stack and the uncertainties, the actual number of PARs installed is 22 (NIS Type 44 with full stack). All 22 PARs are required for mitigation of severe accident (DEC B). Two PARs are safety related and are required for design-basis accident (they replaced electrical hydrogen recombiners).

[7] Adiabatic Isochoric Complete Combustion

Switzerland	The status of the equipment serving hydrogen management reflects the state of the art. The status has been adapted to the insights from the 2011 Fukushima accident. The efficiency of the PARs and igniters has been investigated in detail. The results indicate that their design ensures that the H2 inventory which may remain in spite of their operation will not cause a severe damage of the containment
Ukraine	The justification of the PARs number and locations is performed by comprehensive analysis with application of specialized computer codes (MELCOR, COCOSYS). The scenarios for the analyses of hydrogen hazard mitigation include a total station blackout (SBO) with and without operator actions, as well as primary circuit LOCAs ranging from large to small breaks. PRISE[8] events are typically not considered as bounding scenarios. The combination of reasonably conservative assumptions is used to maximize potential hazard. In base case analyses, no ignition is assumed to be initiated by the PARs, allowing for the highest possible hydrogen concentrations in the containment air. In the analyses with ignition, it is assumed to be triggered at the most unfavorable time of the accident, based on the pressure and temperature rise in the containment (taking into account the combustion rate and the extent of gas accumulation). The resulting pressure and temperature values are used to estimate the pressure load on containment. The activation and operation of the spray system is also taken into account, to confirm that no conditions for detonation are reached.

Based on the survey results presented in Table 6 concerning the assessment methodologies adopted by ETSON members, the following conclusions can be drawn:

- **Both probabilistic and deterministic approaches are employed to evaluate the performance of mitigation measures against the specified requirements.**
- **Accident scenarios involving significant hydrogen releases are typically taken into account.**
- **•Assessment methods utilize both lumped parameter codes and computational fluid dynamics (CFD) codes.**
- **Some ETSON members also consider the potential ignition of passive autocatalytic recombiners (PARs) and their interactions with other safety systems, such as spray systems.**

[8] Pressure Release Induced Severe Event

4 SAMG AND GAS MONITORING USE BY ETSON MEMBERS

Mitigation measures are often employed to avoid severe damage when the atmosphere of NPP containment is combustible during an accident. NPP operators need information on the current status of the gas mixture inside the containment to select suitable and timely measures. Therefore, combustible gas concentration monitoring systems are important in supporting personnel to make appropriate decisions. Usually, gas monitoring systems are based on few (less than 10) sensors located in different area of the containment. Based on these gas concentration measurements, operators may take decisions as postponing the spray activation, venting line opening …

Moreover, the possibility and the necessary hardware is foreseen to protect (in case of severe accident) the reactor building against failure by overpressure by venting (filtered or unfiltered) part of the gaseous inventory of the containment into the atmosphere. Performing such severe accident management actions might (because of e.g. condensation of inertizing steam and/or contact with a rich oxygen atmosphere) result in combustible gas related threats to the integrity of the hardware ensuring venting, confinement and/or fission product retention functions.

Table 7: SAMG & Gas monitoring

Country/NPPs	Gas monitoring	SAMG & Venting management
Belgium/PWRs	Tihange NPP: All Tihange NPPs are equipped with 4 hydrogen concentration measurement chains, the probes of which are distributed over the height of and inside the reactor building. Those measurement chains have been designed to allow for the verification of the degree of homogenization of the containment atmosphere and the determination of the average hydrogen concentration after DBA (with hydrogen production resulting from radiolysis and from oxidation of metallic surfaces in the containment, not from the zirconium in the core). The working principle of those probes is as follows. The hydrogen is oxidized on a catalyst and the oxidation temperature is	Belgian NPP containments are protected from slow over pressurization by filtered containment venting systems (FCVS). In case of use of those venting systems during a severe accident in accordance with the foreseen severe accident management strategy (which implies that the venting operations could be started and subsequently stopped several times during the accident) the formation of deflagrable gas mixtures in some limited areas of the FCVS and for some short times cannot entirely be excluded. No deflagrable gas mixtures can form during the first venting cycle as the FCVS piping and filters are inerted with nitrogen when the plant is in normal operation. However, after the first venting cycle oxygen-rich air from the outside atmosphere can penetrate into the FCVS, enabling for some short time the formation of deflagrable (but not detonable) mixtures during subsequent venting

	transmitted to a thermos-resistor which acts on the balance of a measuring bridge. A second thermos-resistor, which is inactive towards hydrogen, compensates for variations in pressure, temperature and humidity of the gas. These two thermos-resistors are placed side by side inside a gas-permeable envelope. Together they form the detection probe. In principle, all of those measurement chains, as long as they operate properly, can be used during a severe accident to determine the hydrogen concentration in the reactor building. However, the probes situated lowest in the reactor building will likely be flooded during a severe accident. The survivability under severe accident conditions (corresponding to representative severe accidents) and for an extended period of time after vessel failure of the measurement chains with probes located highest in the reactor building (i.e. in the reactor building dome) has been verified for the Tihange 1 and Tihange 3 units. Doel NPP: In Doel NPP, the H2 concentration is measured by a "Comsip"-type detector in a containment atmosphere sample outside the containment. Depending on the unit, samples can be taken from 1 to 6 different locations in the reactor building. In the analyser, oxygen is first added to the sample from an external oxygen cylinder. The analyser thus uses an oxygen source that is independent of the O2 concentration in the containment, which allows H2 measurements to be carried out in an inert atmosphere. The sample is then separated into two parts; the first goes into a cell that does not contain a catalyst (the reference cell) and the other goes to a cell with a catalyst (the measurement cell). The oxidation of hydrogen in the measurement cell causes a different chemical composition and consequently a different thermal conductivity between the two compartments. The latter is due to the much (7x) higher thermal conductivity of hydrogen compared to the other components. The change in thermal conductivity induces an imbalance in a Weathstone bridge and the resulting signal indicates the volumetric concentration of hydrogen in the mixture. The survivability under severe accident conditions (corresponding to representative severe accidents) and for an extended period of time after vessel failure has been verified for all Doel units. For all NPP, in the context of severe accident management, the H2 measurement instrumentation is used to monitor the H2 concentration in the containment as input to SAMG application. For Tihange NPP, as long as this concentration is not lower than 5%, SA	cycles if the inertising steam in the vented gas mixture is to a sufficient extent condensed on cold surfaces and/or the scrubbing liquid (that might be replenished in between venting cycles). The extent to which this phenomenon can occur depends on the outside temperatures during FCVS use as well as the time between venting operations. To deal with this threat, -the risk of combustion of hydrogen, which cannot be excluded (after AtEx methodology assessment) for the following possible sources of ignition - static electricity (air movement in the stack); - radio frequency (RF) electromagnetic waves (104 - 3x1011 Hz); - stray electric currents (High voltage electrical equipment or lines); has been minimized by fulfilling the following recommendations: -all conductive parts should be bonded and earthed; -periodic check of the bonding and earth connection system should be done; -high voltage electrical equipment / lines should be installed as far as possible from the stack in the future. - the pressure loads that could result from a hypothetic hydrogen deflagration in the CFVs have been assessed (using a RELAP model to determine duration and location of deflagrable mixture formation) and verified not to threaten the integrity of CFVS components.

	management guide "Control Hydrogen Flammability" (SCG-3) will be applied by the SA management team. This guide provides guidance (including possible strategies) on increasing the steam pressure inside the containment to reduce the containment atmosphere flammability. For Doel NPP, as long as this concentration is not lower than 4%, SA management guide "Control conditions in the reactor building" will be applied by the SA management team. This guide provides guidance on managing (increasing/decreasing) the pressure in the reactor building as a function of both hydrogen concentration and containment pressure, including possible strategies for achieving the desired reactor building pressure.	
Czeck Republic	The hydrogen monitoring system for ETE utilizes 16 Oldham hydrogen sensors strategically positioned throughout the containment structure, each contributing to a redundant monitoring network that ensures reliable detection and measurement of hydrogen concentrations. (Location cannot be disclosed) These sensors operate through a sophisticated thermos-catalytic principle, where a measuring cell detects changes in hydrogen concentration through temperature variations. The system provides continuous monitoring capabilities across a range of 0-10 vol % hydrogen, with accuracy tolerances of 2.5% in the lower range (0-4 vol%) and 5.0% in the higher range (4-10 vol%). All measurements are directly integrated into the Post-Accident Monitoring System (PAMS), ensuring real-time data availability and processing.	For Dukovany NPP (EDU): Regarding the Investigation of Combustible Gas Threats: The question about combustible gas threats during containment venting is NOT APPLICABLE to Dukovany NPP because: •EDU is a VVER-440/213 design that utilizes a bubbler condenser system for pressure suppression •The plant does not have a dedicated containment venting system. Actual Hydrogen Management Strategy at EDU: Instead, the plant approach to combustible gas management during severe accidents consists of: a) Main Systems: •Passive Autocatalytic Recombiners (PARs) installed throughout containment •Bubbler condenser system that provides passive pressure suppression •Containment mixing systems to prevent local hydrogen accumulation b) Supporting Measures: •Hydrogen concentration monitoring systems •Severe Accident Management Guidelines (SAMGs) specifically addressing hydrogen risk •Post-Fukushima safety enhancements for hydrogen management. For Temelín NPP (ETE): Investigation of Combustible Gas Threats: For Temelín NPP (VVER-1000 design), the possibility of combustible gas threats has been investigated and found to apply. The plant has: •A large dry containment design •Filtered containment venting capability •Hydrogen management strategy Implemented Equipment and Measures: The following systems and measures have been implemented to deal with such threats: a) Main Systems: •Passive Autocatalytic Recombiners (PARs) strategically placed throughout containment •Filtered Containment Venting System (FCVS) with specific design features to handle hydrogen •Containment mixing systems to prevent local hydrogen accumulation b) Supporting Equipment: •Continuous hydrogen concentration measurement system

		•Multiple hydrogen monitoring locations throughout containment •Specific Severe Accident Management Guidelines (SAMGs) for hydrogen control •Procedures for filtered venting operations considering hydrogen risks
Finland	Hydrogen measurement system with 2 redundant subsystems, capable of measuring: hydrogen conc., oxygen conc., temperature and pressure. The system also provides information of steam concentration calculated from the other measurements. The exact placement of the measurement devices is being developed in the detailed design phase, currently the design is for 8 different locations in the containment. The information from the sensors is used to monitor the situation in the containment and no automatic safety functions are activated due to the measurements. In the late stage of a SA when moving to SA safe state the data can used to verify the possibility to activate spray systems	The containment utilizes passive containment cooling system that handles the pressure increase in the containment in SA events. The initial pressure increase due to for example a LBLOCA is not high enough to threaten the containment. The Hanhikivi-1 design does not include filtered venting as there is no need for it. Safe state following a severe accident can be reached with other systems than specific SAM systems. The core catcher and fuel pool cooling can be arranged when these other systems are restored. This will end up boiling inside the containment and heat can be removed and pressure decreased. Non-condensable gases can be handled if necessary with ventilation system with filter qualified to these conditions. However, high concentration of hydrogen is managed before possible venting with PARs and no combustible gas problems are foreseen.
France	French fleet is not equipped with containment atmosphere gas monitoring	SAMG recommends delay spray actuation during SA conditions FCVS is equipped with a heater that avoid steam condensation and flammable atmosphere formation.
Hungary	All units of Paks NPP have gas monitoring systems installed, the sensors providing information about hydrogen, oxygen concentrations and temperatures (for steam concentration together with pressure measurement system) in containment rooms. The sensors are manufactured by VUJE (Slovakia), a total of 8 were placed in the hermetic building	SAMG addresses the Hydrogen treatment, assumes that the recombiners will most likely treat the Hydrogen properly, and that the hydrogen concentration will be kept at a sufficiently low value. If this does not happen, based on the SAMG, the operators try to cause a hydrogen ignition by operating various electrical devices in the hydrogen concentration range that is not yet dangerous. A sprinkler, long-term cooling sprinkler and containment venting start-up can cause a sudden increase in hydrogen concentration. In the case of these systems, this is therefore handled by SAMG. Filtered vent or vent appears in the SAMG, but its purpose is to reduce pressure.
Romania	Additional instrumentation for SA management e.g. hydrogen concentration monitoring in different areas of the reactor building was introduced. [CNCAN2021]. Information on sensors number not available	Installation of dedicated emergency containment filtered venting system for each NPP unit was reported [CNCAN2021].
Slovakia	All units in Slovakia have gas monitoring systems installed providing information about hydrogen and save Mochovce34 also oxygen concentrations in rooms of containment. The measurements are as follows: Mochovce 3-4: 24 measurements of hydrogen 0 - 30% volumetric concentration. Mochovce 1-2: 8 KAMOS430 detectors in two subsystems (4 for each subsystem) measuring concentration of hydrogen and oxygen in the central rooms of containment. Bohunice 3-4: 16 measurements of hydrogen and oxygen 0 - 30 % volumetric concentration.	The data are evaluated according to severe accident guidelines (SAG) dedicated to hydrogen mitigation. The hydrogen risk is evaluated using computational aids within SAMGs considering total pressure and hydrogen concentration. Update of SAMG is being prepared to benefit from the oxygen measurement inside of the containment. There is no severe accident dedicated venting system in the units. Although containment venting using existing venting systems is included in SAMG strategies. The venting is filtered, but filters' capacity is not adequate to severe accident conditions. Possibility of hydrogen combustion in the containment venting system is not considered.

Slovenia	H2 monitoring in containment dome (X2), above reactor vessel (X2) and close to primary loop (X2). H2 monitors are qualified for severe accidents.	The Passive Containment Filtered Venting System contains Nitrogen atmosphere and, after the actuation, nitrogen is passively injected into the system. Also, due to adiabatic expansion during venting, there is low potential for steam condensation, so the system stays inerted.
Switzerland	H2 is measured in different locations of the containment. Moreover, measurement by sample taking is provided and foreseen in the SAMG.	In each Swiss NPP, the SAMG presents a combustibility diagram on dangerous constellations of H2 concentration and containment pressure together with the related implications for the control of containment venting and cooling. CO is considered in the design of the PAR & passive ignitors, in the Swiss SAMG, and in the post-Fukushima studies. In the context of venting, the SAMG of each Swiss NPP has a combustibility diagram on constellations of H2 concentration and containment pressure (see response to Question no. 9) where venting should be avoided.
Ukraine	The hydrogen monitoring system is already installed at all NPP units or is under final stage of installation. Systems include few subsystems. One is used for normal operation and DBAs. It has 4 points of hydrogen measurements via sampling piping for half height and under dome points with the range 0-5% and alarm setpoint of 3% of H2 concentration. Additional subsystem of H2 monitoring has wider range 0-8% with alarms 4% and has 12 measurement points in the containment in all elevations (lower, middle, upper dome). Additionally, the system for DEC is implemented that can supply information to main and reserve control rooms and power-independent storage device. The ranges of the sensors are 0-5% (low H2 concentration), 0-30% (high H2 concentrations), 0-25% oxygen concentration and 0-100% for relative humidity. It has 8 locations in the containment starting from lower middle part up to the dome. Also, the system measures the temperature (0-300oC) and pressure (0-10 bars).	The hydrogen and oxygen monitoring system is used to determine the flammability point of the containment/compartment atmosphere. This information is provided to the operator through direct measurements, or in the form of tertiary or rectangular diagrams. These indications are used for SAMG actions and directly involved in diagnostic flowcharts and even special guideline in the case of high H2 concentration (SAMGs). The operation of containment spray system is allowed only with low H2 concentration as additional backup measure to decrease combustion hazard after following steam condensation. The spraying can be even temporarily interrupted if the flammability increases. Containment design ventilation system can be used for mixing of environment in the containment. Filtered containment venting system can be used during late phase of the accident for the decreasing of the mass (but not the concentration) of flammable gases in the containments.

Based on the survey results presented in Table 7 regarding SAMG implementation and gas monitoring practices among ETSON members, the following conclusions can be drawn:

- **Most ETSON members have implemented specific SAMG actions to manage spray or CFVS activation and mitigate hydrogen-related risks.**
- **Gas monitoring systems are widely used, typically employing either catalytic or sampling technologies to measure hydrogen (H_2) concentrations; some systems also provide oxygen (O_2) concentration measurements.**
- **Gas stratification is monitored using between 6 and 24 sensors distributed along the height of the containment.**
- **Water vapor (H_2O) and carbon monoxide (CO) are generally not monitored.**

5 CONCLUSIONS

As mentioned previously, the hydrogen mitigation strategies were developed to preserve the containment integrity. The related measures were designed to satisfy the regulatory requirements adopted in each country. They were designed and validated based on severe accidents considering mainly in-vessel phases.

From the survey, we can conclude that:

- **the adopted requirements address only in-vessel conditions.**
- **all the adopted requirements aim to preserve the containment integrity. The availability of the safety systems, as sprays or venting line, needed to manage the severe accident late phases need to be addressed in the extended requirements,**
- **only few countries adopt quantitative criteria for the requirement,**
- **the mitigation means are designed accordingly to the adopted requirements for in-vessel conditions.**
- **the existing monitoring systems don't measure carbon monoxide content,**
- **only few existing SAMG recommendations concern the use of safety systems (CHRS, sprays and coolers) in case of severe accident late phases.**

As a second step, the assessment will be extended *to ex-vessel conditions*, focusing on the containment and the *auxiliary buildings connected to it*. To support the extension of the existing SAMG to cover *late-phase severe accident management,* we will incorporate key lessons learned from the *EU-AMHYCO* and the *OECD/Themis* projects, particularly regarding:

- The performance of PARs under typical late-phase severe accident conditions, characterized by low oxygen availability and the presence of carbon monoxide. Specifically, the focus is on conditions that may lead to PAR deactivation due to carbon monoxide interference.
- Flammability limits and flame acceleration criteria relevant to representative containment and auxiliary building atmospheres during late accident phases. These insights will contribute to refining the requirements for late-phase accident scenarios.
- Insights on combustible gas migration from the containment to auxiliary buildings during containment pressurization in the late phase. These

data will inform requirements and strategies such as venting procedures to prevent gas explosions in auxiliary structures.

- Guidance on the use of gas monitoring systems for the timely activation of safety systems like sprays, coolers, and the Containment Heat Removal System (CHRS).

APPENDIX 1

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APPENDIX 2

QUESTIONNAIRE SENT TO THE ETSON MEMBERS

QUESTIONNAIRE

Question 1:

Background

The regulatory requirements and expectations for hydrogen (and combustible gas) management depend on the nuclear power plant technologies and on the adopted safety approach in each country. Expressing the background and the rationale of the adopted requirements will help understanding the adopted mitigation measures and strategies.

Question

What are the regulatory requirements / expectations for hydrogen management during SA including in and Ex vessel phases until reaching a stable state?

Question 2:

Background

The mitigation measures and strategies are designed to satisfy the requirements adopted in each country. Safety equipment's are used to achieve this target. Among them, Passive Autocatalytic recombiners, igniters, Coolers…

Question

Could you please indicate the implemented safety equipment's (PARs, Coolers, Igniters, …) in each of your NPP?

For your information, a first survey had been made in the framework of the OECD Status report on hydrogen management

https://www.oecd-nea.org/jcms/pl_19516/status-report-on-hydrogen-management-and-related-computer-codes?details=true

Question 3:

Background

The implementation of such mitigation measures supposed that they are "qualified" to severe accident conditions.

Question

Could you please indicate the rationale for the Qualification or survivability Test of equipment's as PARs, Igniters, Coolers… for both In and Ex-vessel conditions. Could you please indicate also the considered order of testing, the environment and the required mission time?

Question 4:

Background

Usually, the implementation of such mitigation measures is supported by both deterministic and probabilistic studies that allow assessing their efficiency

Question

Could you please indicate the rationale for the safety equipment (PARs, Coolers, Igniters,) implementation? (Example: selected scenarios, tools used for the simulation, assumptions on the availability of the active equipment (igniters, coolers,), availability of PARs (assumptions on their possible poisoning,)

Question 5:

Background

The mitigation equipment's (example: PARs, Coolers, igniters,..) maintenance frequency is linked to their safety classification.

Question

Could you please indicate the Safety Classification for each of the mentioned safety equipment and their maintenance frequency?

Question 6:

Background

The availability of the mitigation equipment's (PARs, Coolers, igniters, PARs, ..) is ensured by means of periodic test, inspections and maintenance. …

Question

Could you please indicate the adopted approach to ensure the availability of these safety components in your country? And how these safety equipment's inspection is performed?

Question 7:

Background

Under dedicated conditions, PARs may be behave as igniters. In these cases, the induced combustion is expected to be slow and allow reducing the hydrogen (combustible gas) inside the containment.

Question

Could you please indicate if the PARs ignition possibility is considered in your safety analysis? Could you please indicate if the PARs ignition is considered in deterministic assessment? In probabilistic studies?

Question 8:

Background

Mitigation measures are often employed to avoid severe damage when the atmosphere of NPP containment is combustible during an accident. NPP personnel need information on the current status of the gas mixture inside the containment to select suitable and timely measures. Therefore, combustible gas concentration monitoring systems are important in supporting personnel to make appropriate decisions.

Question

Could you please indicate if implemented gas monitoring system in your NPP? Their types, numbers and location?.

Question 9:

Background

Most the gas monitoring systems are based on few (less than 10) sensors located in different area of the containment. Based on these gas concentration measurements, operators may take decisions as postponing the spray activation, venting line opening …

Question

Could you please indicate how the information provided from few sensors is used by the operators? How these measurement is used to assess the containment atmosphere flammability, for example?

Question 10:

Background

During plant outage, protected measures are taken to avoid any malfunction of the safety equipment (PARs, Coolers, igniters,). Maintenance and check procedure are used before NPP restart.

Question

Could you please indicate the used protected measures during plant outage, if any, and

the checks before restart?

Question 11:

Background

After Fukushima accidents, the risk of gas explosion in spent fuel building and surrounding compartments and buildings, had been highlighted. Safety assessment had been conducted in some countries.

Question

Could you please indicate if such safety assessment had been conducted in your country? Did some safety equipment (PARs, igniters, coolers,) had been implemented in your NPP.

Question 12

Background

For many plants, the possibility and the necessary hardware is foreseen to protect (in case of severe accident) the reactor building against failure by overpressure by venting (filtered or unfiltered) part of the gaseous inventory of the containment into the atmosphere. Performing such severe accident management actions might (because of e.g. condensation of inertizing steam and/or contact with an oxygen rich atmosphere) result in combustible gas related threats to the integrity of the hardware ensuring venting, confinement and/or fission product retention functions.

Question

If applicable for your NPP, could you please indicate

- if the possibility of such combustible gases threats has been investigated and found to apply?
- what equipment and/or measures have been implemented to deal with such threats?

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