PRELIMINARY RISK ASSESSMENT (PRA) FOR TESTS PLANNED IN A PILOT SALT CAVERN HYDROGEN STORAGE IN THE FRAME OF THE FRENCH PROJECT STOPIL-H2

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ABSTRACT

The STOPIL-H_2 project, supported by the French Geodenergies research consortium, aims to design a demonstrator for underground hydrogen storage in cavern EZ53 of the Etrez gas storage (France), operated by Storengy. Two types of tests are planned in this cavern: a tightness test, with nitrogen and hydrogen, then a cycling test during which the upper part of the cavern (approximately 200 m^3) will be filled with hydrogen during 6 to 9 months.

In this paper, the PRA for the cycling test is presented comprising the identification of the major hazards and the proposed prevention and protection measures. The implemented methodology involves the following steps: data mining from the description of the project; analysis of lessons learned from accidents that occurred in underground gas storage and subface facilities; identification of the potential hazards pertaining to the storage process; analysis of external potential aggressors.

Resulting as one of the outcomes of the PRA, major accidental scenarios are presented and classified according to concerned storage operation phases as well as determined preventive or protective barriers able to prevent their occurrence of mitigate their consequences.

1.0 INTRODUCTION

Context

Hydrogen (H_2) molecule is emerging as an alternative energy vector to fossil fuels and one of the levers for combating climate change. Indeed, hydrogen is easily transportable and can be produced from renewable (solar, wind) or low carbon (nuclear) electricity so called low carbon energies [9]. One central condition for the development of the hydrogen sector is its ability to address the questions of safety over the whole H_2 value chain: production, transport, storage, distribution and usages end-use.

Regarding storage, the underground environment offers a favourable environment for massive hydrogen storage: large volumes potentially available, small impact on surface occupation, enhanced kind of intrinsic safety due to the distance of the product from vulnerable assets.

Objective of the STOPIL-H_2 project

The STOPIL-H_2 project (2019-2020) is part of the first phase of development of an industrial flagship demonstration unit for renewable hydrogen storage in a salt cavern. It is intended to demonstrate the tightness of underground storage with regard to H_2 leaks as well as its mechanical integrity under severe cycling. Two types of tests are planned in this cavern: a nitrogen and hydrogen leakage test of the well, followed by a cycling test during which the upper part of the cavern (about 200 m^3) will be filled with hydrogen. The amount of hydrogen for these tests will be of the order of 2.5 tonnes and the total duration of the tests is estimated at approximately 6 to 9 months. The STOPIL-H_2 project aims to study the feasibility of this demo unit and acquire useful data for its implementation.

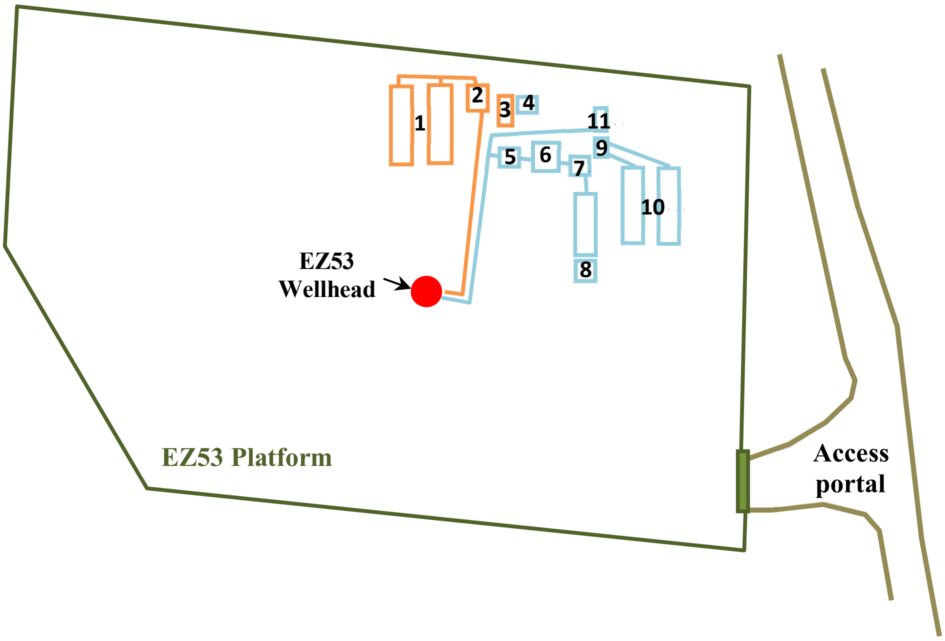
Scope of risk assessment

This study aims to conduct a preliminary risk analysis (PRA) of the test programme implementation: it notably focuses on the establishment of all the accident scenarios that could develop during the operation of the demo storage facility and on the definition of adequate prevention and protection measures planned to reduce the probability of occurrence (prevention measures) or the severity of the consequences (protection measures). The major hazardous phenomena that are key aspects to the related accidental scenarios are also identified. Indeed, these phenomena will require for which further analysis in terms of a quantitative assessment of the distances of potential subsequent effects neds to be performed at later stage. This risk analysis covers the whole testing programme, but this paper focuses on the cycling test.

2.0 EXPERIMENTAL STORAGE SITE PRESENTATION

Presentation of the platform of Etrez

The project is planned on the EZ53 platform of the Etrez underground storage facility, located on the town of Etrez - Bresse Vallons, in the department of Ain in France. This storage is operated by Storengy. A first draft of the equipment layout on EZ53 platform is given on *Figure 1*.



N°	Equipment	N°	Equipment N°
1/2/3	Brine facilities	4/5/9/11	Gas facilities (Nitrogen and hydrogen gas)
6/7	Cryogenic facilities (Liquid nitrogen)	8/10	Trailers areas

Figure 1: Zoom on the EZ53 platform

Presentation of cavern EZ53

Cavern EZ53 was created between depth levels 920 m and 966 m, in the E2 salt level, which is a good quality rock salt (10% insoluble), with intercalated levels of marls and anhydrites. The upper salt roof is encountered at a depth of 684.5 m. The well crosses two aquifer levels: a set of shallow aquifers (between levels -3 m and 5 m) in the Plio-quaternary, between the surface and level ~ -140 m and the Tortonian aquifer, which is of little economic interest and is generally not exploited for human consumption or agricultural uses.

Since its creation in 1982, the EZ53 cavity has always remained in brine and has been used to carry out in situ measurements and tests for scientific purposes [1, 4, 10, 11]

2.0 DESCRIPTION OF THE CYCLING TEST

A simplified scheme of the well, as planned during the cycling test, is provided in *Figure 2*.

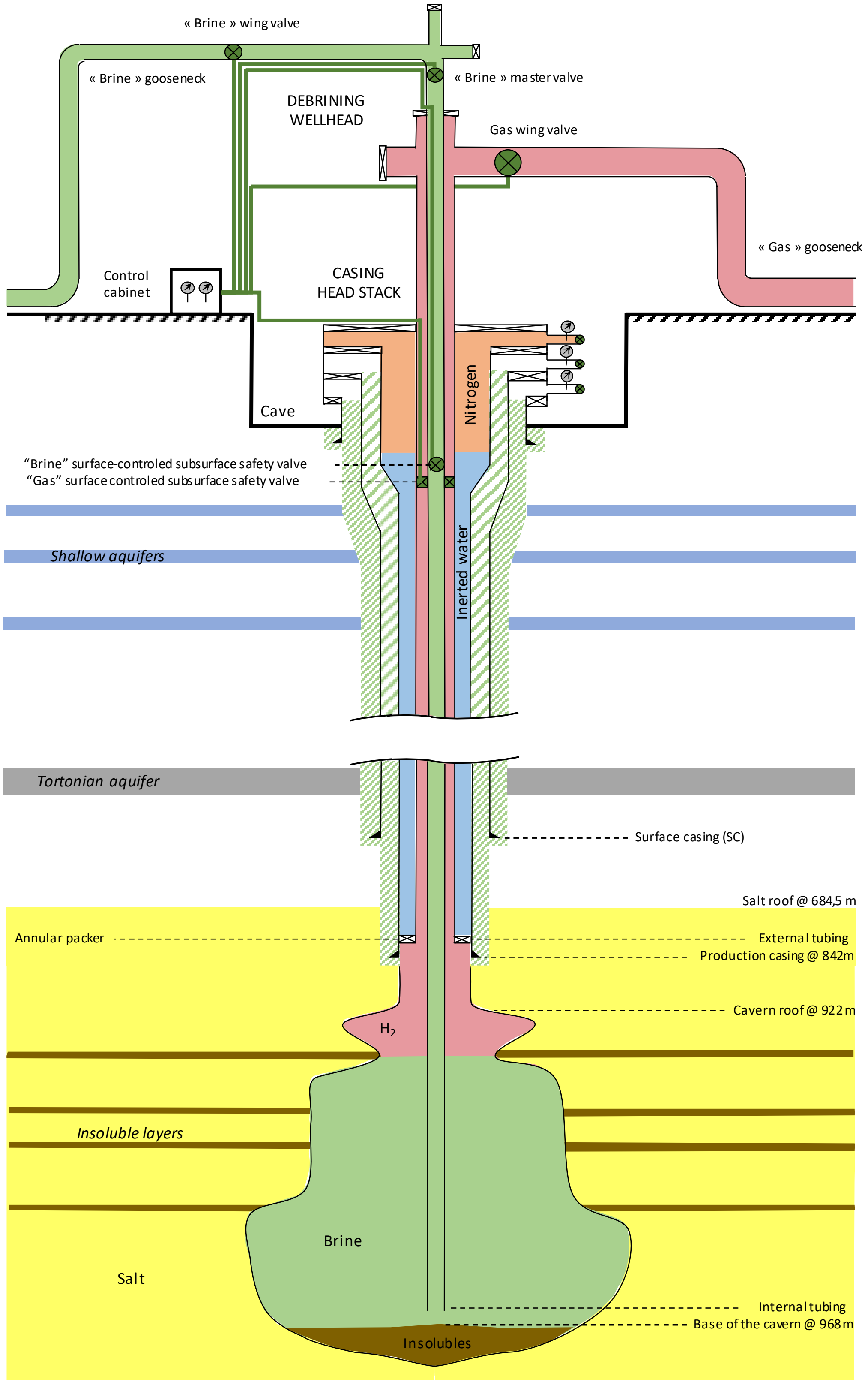


Figure 2: Predicted configuration of the EZ53 well during the cycling test

This scheme specifies the various components of the well and the wellhead, namely:

- the internal tubing inside which the brine circulates (shown in green); the external tubing inside which hydrogen circulates (shown in pink); the different casings that widen near the surface, as well as the associated cemented sheaths;
- the valves used to regulate the circulation of fluids (brine and gas), distinguishing remotely controlled valves (connected to the control and regulation system) and manually activated valves;
- the casing head stack buried just below surface to avoid any potential external aggression;
- the "gas" (respectively "brine") wellheads subsystems which include the part of the external (respectively internal) tubing located above the surface and the associated antenna valves;
- the "gas" (respectively "brine") gooseneck between the "gas" (respectively "brine") manual antenna valve and an isolation valve located on the other side of the S.

The "cycling" test will consist of filling the upper part of the EZ53 cavern (approximately 200 m^3) and then performing injection / withdrawal cycles representative of those that a salt cavern could experience when used for the storage of low carbon hydrogen. The objective of the cycling test is to determine whether it is possible to operate a salt cavern with short and intense pressure cycles without generating significant mechanical disorders or any significant loss of storage volume capacity in the cavern.

The main operation phases planned for the cycling test are listed below:

- Initial set-up stage: external tubing filled with hydrogen down to level -910 m - internal tubing filled with brine – high pressure gradient at the shoe- hydrogen gas semi-trailer still connected;
- Filling of the upper part of the cavern with hydrogen until the gully is reached: filling carried out by successive phases of brine withdrawal (through the internal tubing) and hydrogen injection (through the external tubing) - several semi-trailers will be necessary to inject the quantity of hydrogen needed for this filling - interface measurement (head pressure/ Soundwell) - departure of the last semi-trailer
- Rapid cycling at high pressure by injection / withdrawal of brine: several daily cycles consisting of 8 h of injection and 4 h of withdrawal, interrupted by a 6 h pause - interface measurement;
- Low pressure waiting stage assessment: gradient at the shoe of 0.6 bar/m - expansion carried out by withdrawing brine through the internal tubing then injecting nitrogen into this same tubing in order to be able to follow the depth of the interface via the reading of the pressures at the head - the pressure record should be: pressure decreased during 7 days; minimum pressure during 10 days; pressure increase during 7 days - interface measurement;
- Final stage: withdrawal / venting of the hydrogen through the external tubing and brining of the well with atmospheric pressure at the top - end of the test.

As during the leakage tests, the injection / withdrawal operations (of brine, hydrogen or nitrogen) will be carried out at a flow rate not exceeding 10 bar/hour. With a safety margin to account for contingencies, the cycling test should last between 60 and 80 days.

3.0 HAZARD POTENTIALS

At this stage of project, the following potentials hazards has been identified.

Hazard potentials in the cavern

The main hazard potentials are the following:

- Product present into the cavern: hydrogen, nitrogen, brine
- Gas pressures: A too high pressure in the cavern can cause ruptures and may drive hydrogen out of the cavern.

- Cavern: The cavern itself is a potential hazard. If the cavern pressure is too low, the cavern can close in on itself (by rupture or excessive creep of wall salt), leading to a risk of deformation (or even rupture) of the overburden formations and, consequently, subsidence (or even collapse) of the ground surface.
- Presence of geological formation that could form toxic gases by interaction with H_2 [6, 15]:
    - *Insolubles fixed onto the walls of the cavern:* Hydrogen stored in a salt cavern could, over the long term and under certain pressure and temperature conditions, react with wall accessible insoluble materials to form secondary gases, as H_2S;
    - *Geological formations located in the cover:* The geological log of well EZ53 shows that there are sulfur-containing minerals such as calcium sulfate ($CaSO_4$) as well as pyrite (FeS_2) present in the cover of the cavern.

  In the case of EZ53 cavern, given the small amount of hydrogen introduced into the cavern (200 m^3), the expected temperature conditions at the depth of the cavern (maximum 45°C) and the duration of the planned tests (< 6 months), the amount of toxic gas created into the cavern is likely to be very limited. The amount of H_2 likely to leak through the geological formation will be extremely limited (this is what the planned leakage tests are intended to verify), as well as the quantity of secondary gas created by interaction with the cover formations

Other hazard potentials could exist (present of brine aquifer, water-sensitive formations) that could lead to pollution or movements of the ground surface. However, those risks are not unique to the project or to the EZ53 well. Consequently, risk management of those risks requires a regular control of the integrity of the wells throughout their life.

Hazard potentials on the surface storage demo plant subsystems

Surface equipment and facilities can be classified by hazard category, shown in Table 1.

Equipment	Operating conditions	Associated hazards
Hydrogen gas tube trailers	Unloading, in parking space	Loss of containment of a cylinder or on the connection circuit => hydrogen leakage Burst due to increase of pressure following an external fire
Hydrogen Pipes	Operating phase Maintenance	Burst due to pressure regulation fault Loss of containment of a pipe => hydrogen leakage
Gas expansion panels and control valves	Operating phase Maintenance	Burst due to pressure regulation fault Loss of containment => hydrogen leakage

Table 1: Hazards identified at surface level of the demo plant facility

Reduction of hazard potentials

To limit the hazard potentials, present on the site, the following reduction measures have been taken:

- it was decided to limit the amount of hydrogen stored in the cavern by filling only the upper part (200 m^3) of an 8,000 m^3 cavern;
- it was decided to supply hydrogen in gaseous rather than liquid state in order to reduce (by a factor of about 5) the quantity of hydrogen present on the surface and the number of equipment on site (for example without liquid hydrogen supply and buffer storage capacity, no need of

additional piece of equipment like a hydrogen vaporiser): this is favouring inherently safer design (ISD) of facilities according to the “simplification” keyword, as advocated by Kletz [12];
- it was decided that the hydrogen pressure in the semi-trailers would be maintained at high pressures in order to avoid the use (and therefore the presence on site) of a compressor.

Other factors that were considered as drivers of risk reduction associated with the testing procedure itself are:

- the relatively short duration of the tests (6 to 9 months maximum);
- the good knowledge of EZ53 cavern, which has been used as an experimental cavern for 40 years already;
- the fact that the EZ53 well has already been proven to be nitrogen tight and that this gas proof property already evidenced from past testing will be tested again before introducing hydrogen;
- the fact that the cavern is in thermal equilibrium, allowing an accurate characterisation of potential leaks and the possibility to act quickly.

4.0 ANALYSIS OF LESSONS LEARNED FROM ACCIDENTS

Lessons learned in the field of underground hydrogen storage

Feedback from accidents or incidents related to the storage of hydrogen in salt caverns is very limited, if any at all. Indeed, at present, there are only 6 hydrogen storage caverns in the world: 3 large caverns in the United States (Texas) operated by Conoco Philips, Praxair and Air Liquide and 3 small caverns in United Kingdom operated by Sabic. It should be noted that these caverns store hydrogen intended for industrial use (chemical industry), with much longer cycling frequencies than those anticipated in the case of storage of hydrogen of renewable origin (weekly or even daily).

To our knowledge, there are no documents in the public domain mentioning incidents or accidents relating to such storage. This absence of any significant accident occurrence may be perceived as a first indicator that hydrogen can be stored in salt caverns under reasonably good safety conditions and over long periods of time, at least for caverns subject to low frequency hydrogen filling/withdrawing cycles.

Lessons learned in the field of underground storage of gas and hydrocarbons

The low level of feedback specific to underground hydrogen storage leads us to extend our analysis of external REX to the field of underground gas and hydrocarbon storage. Based on the published literature on the subject [2, 3, 4, 7, 7, 8, 14, 14], a database of 85 significant accidents or incidents in the field of gas and hydrocarbon storage to date.

From inventory analysis of these 85 accidents, 11 seem relevant in the context of the Etrez pilot facility. In order to establish this selection, the focus was put on the examination of accidents that occurred in salt cavern gas storage. Then selection refinement leads to collect data from the sole incidents in which root event originated from the well or cavern itself. These accidents can be classified into 5 risk categories, namely: risks related to the gas column (4 cases); risks related to the brine column (3 cases); wellhead risks (2 cases); risks related to cemented section (1 case); risks related to the cavern (1 case).

These accidents show that in the case of a completion composed of 2 columns for gas and brine (i.e. during the first gas filling phase or in the case of operations by balancing brine as we can see on *Figure 2*), leaks can occur at the gas completion level (through the casing, cementing or wellhead) but also at the brine completion level, following an accidental passage of gas in this completion.

The main causes resulting from the selected accidents are: casing corrosion; bad cementing; an overfill or leak in the central column; excessive cavern pressure with subsequent geomechanical disorders.

The main measures put in place after these accidents were: the implementation of checking procedures of the state of the casing and cemented section before the caverns are put into operation; the standardization of leakage tests (MIT); the setting of a pressure limit to ensure a safety margin versus the maximum working pressure; the implementation of a dedicated safety procedure regarding brine completion in case of gas intrusion.

Lessons learned in the field of surface hydrogen storage facilities

This part of the risk assessment was performed on the basis of some incidents reported in the open scientific literature as well as from learning accessed from known accident databases such as h2tools.org and ARIA (from BARPI [Bureau for Analysis of Industrial Risks and Pollutions]). Lessons learned from this search are summarized by equipment hereafter:

- piping (9 cases); the main causes of accidents identified were corrosion and external aggression (especially thermal) with the consequences such as leaks and fire. Subsequent field learnings mainly led to the implementation of guidelines for choosing the right materials and to the installation of thermal and physical protective shields;
- “tube-trailers" (truck transporting H_2) during loading/unloading operations (4 cases): the main causes of accidents are: failure of equipment due to hydrogen embrittlement, lack of control procedures. The consequence of this type of failure were: H_2 leaks, or even explosion of the truck (1 death and 10 injured in one case). The corrective measures essentially put in place consisted of a) improving training of personnel, b) setting inspection of equipment and procedures prior to and during handling (filling, unloading) of H_2;
- “tube-trailers" on the road (3 cases): the main causes of accidents were collisions or poorly secured trailer, resulting in fires, explosions and collateral damage. The measures put in place reported were a) better training of personnel b) securing the trailer and c) improving the materials resilience of equipment;
- TPRD issues [Thermal and Pressure Release Device], the databases identify very few cases specific to hydrogen. From a survey that was carried out in 1997 on 703 GNV buses which identified 132 gas leaks, including one with a subsequent serious fire, the causes of TPRD failures were classified as follow: a) wear and tear, b) misuse, c) design failure, d) material defects, e) ice in the vent, and f) refuelling malfunction.

5.0 PRELIMINARY RISK ANALYSIS

Risk Analysis: Organization and Methods

The STOPIL-H_2 project (2019-2020) is part of the first phase of development of an industrial pilot for "green" hydrogen storage in a salt cavern. For this reason, preliminary risk analysis (PRA) was adopted as the preferred risk analysis method. Its objective is to rank the severity of all the dangerous phenomena feared according to a rating scale determined in terms of intensity degree and considerations of critical dangerous phenomena that can have effects out the site.as described by C. Lenoble [13].

The PRA was carried out by holding meetings involving all STOPIL-H_2 partners. During the PRA, each Central Feared Event (CFE) was analysed in terms of: a) root causes, b) initiating events, c) suitable preventive measures, d) associated dangerous phenomena and e) its *a priori* intensity degree, potentially protective measures. CFE were also discussed in terms of additional safety recommendations.

Exclusion of underground specific hazard

Some underground-driven hazardous phenomena which did occur in rare occasions in the past in very specific conditions are very difficult to quantify in terms of kinetics and/or distance of effects or have a negligible probability of occurrence in given contexts. Such rare phenomena are namely:

- the risk of ground collapse due to geomechanical disorders in the cavern;
- the risk of fire or explosion on the surface due to flammable gas rising from the ground following a leak in the well or cavern.

A French circular (dated 10 May 2010) proposes a specific treatment of these risks for the storage of gas, hydrocarbons and chemicals for industrial use (including hydrogen for industrial use) in the operating phase: these risks can be neglected actually , as soon as a number of criteria are fulfilled or a number of barriers are implemented. Following this legal recommendation, we have excluded the following risks in the context of the project through the following reasoning:

- Ground collapse: The roof of the Etrez cavern is located at a depth P = 922 m, thus beyond the critical depth of 700 m mentioned in the cited circular. The risk of localised collapse can therefore be excluded. Cavern EZ53 is the only cavern created in Etrez upper salt layer. The risk of generalised collapse of a group of caverns can therefore also be excluded.
- Risk of gas rising from the ground: The main causes would be leakages of H_2 due to salt fracturing or permeable cemented casing. We have checked that in the case of EZ53 cavern:
    - the chimney height (distance between the roof of the cavern and the shoe of the last cemented casing) is high enough (80m). This ensures that the shoe of the last cemented casing is neither in an area of high deviation stress nor in a traction zone.
    - As we can see on *Figure 2*, the distance between the salt roof and the shoe of the last cemented casing is very important (157 m), which subsequently limits the risk of a significant amount of H_2 rising to the surface;
    - Eventually, additional computations have been performed to make sure than other geometrical criteria pertaining to the underground storage cavity still qualify the cavity as a geomechanically resilient underground structure, according to the cited circular

  Besides, since it is not possible to guarantee in advance the tightness of the H_2 cemented sheath of well EZ53, some actions are planned before and during the cycling test:
    - prior to cycling test: monitoring the integrity of the cemented zone by CBL-VDL and ultrasonic tools during the change of completion; performing a leak test of the cemented section (MIT test), first with nitrogen, then with hydrogen
    - during the cycling test: monitoring of hydrogen leaks along the well (in particular through the cemented layer) by two redundant methods (monitoring of head pressure + soundwell), previously set on a direct measurement of the interface.

  Moreover, the following preventive barriers will be implemented:
    - the cemented sheath will be protected from pressure and temperature variations linked to gas movements by the existence of the annular space between the external tubing and the production casing.
    - conservatively, the pressure gradient at the shoe that should not be exceeded is 0.22 bar/m, or a pressure of 185 bar at the shoe. On the hydrogen line, a valve with a set pressure of 190 bar will be positioned downstream of the expansion system between the exchanger and the flowmeter;
    - It is planned to set the minimum pressure within the cavern at 60 bar to avoid the occurrence of excessive deviation stresses in the wall which could damage the salt and increase convergence by creep. Note that this value is the one fixed by prefectoral decree for the exploitation of the caverns of the lower layer of Etrez. Compliance with this minimum pressure will be monitored by checking the pressures at the wellhead.

Synthesis of main root causes identified

The main root causes retained from the PRA are summarized below:

- mechanical deterioration of material used in the process for instance due to hydrogen embrittlement or corrosion or wear,
- process design errors for instance leading to unexpected opening of vent or tubing permeation on well,
- occurrence of natural hazards such as lightning,
- mechanical abuse conditions such vehicle impacts,

- causes bound to human factors such as inappropriate work organisation or management, misleading start and shutdown phases or malicious intents,
- domino effect onto the facility having internal or external origin.

Major hazardous events

As a result of the preliminary risk analysis, the central feared event (CFE) and major dangerous phenomena (PhD) were identified. They are detailed by equipment in Table 2.

Equipment		CFE				PhD				
		Loss of H_2 containme	Increase of pressure[2]	Formation of ATEX	Release	Torch fire[3]	UVCE[4]	Flashfire[5]	VCE[4]	Burst[6]
Subface equipment	Tube Trailer	X	X			X	X	X		X
	Hose	X	X			X	X	X		X
	Piping	X	X	X		X	X	X	X	
Well	H_2 Wellhead	X				X	X	X		
	Gooseneck	X				X	X	X		
	Brine wellhead	X				X	X	X		
	Airlock	X				X	X	X		
Safety equipment	Pressure safety valve				X	X	X	X		
	TPRD				X	X	X	X		
	Vent				X	X	X	X		

[1] The loss of containment is considered outside. The dangerous phenomena depend of the size of the leaks. It is considered only torch fire for small and medium and add UVCE and flashfire for major leak.

[2] In this project, the cause of the increase of internal pressure is due to the heating of the hydrogen in the equipment following an external fire or pressure regulation default.

[3] The torch fire is the result of the direct ignition of accidental leaks of hydrogen. These leaks produce jets ignited. The main effect of this dangerous phenomenon is thermal.

[4] The UVCE/ VCE is a fast combustion of a cloud of flammable gas conducting to an explosion. Unlike torch fire, the UVCE and VCE are linked to delayed ignition. The difference between UVCE/ VCE is the confinement. The VCE is linked to the ignition of an ATEX inside a capacity or a confined area.

[5] The flashfire is a slow combustion of a cloud of flammable gaz. Flashfire can also be called cloud fire. The main effect of this dangerous phenomenon is thermal.

[6] The burst is due to an increase of internal pressure to a pressure in hydrogen equipment greater than the rupture pressure of the capacity. The main effect of this dangerous phenomenon is overpressure.

Table 2: hazardous events associated to CFEs potentially affecting

Selection of prevention and protection measures

Some key prevention and protection barriers were determined that are detailed below per piece of equipment in Table 3 and for natural hazards in Table 4.

Hydrogen gas tube-trailer and unloading hose	
Prevention barriers	• Protect parking areas from shock (concrete block; speed limits; circulation plan), • Implement a non-return device between the semi-trailer and the wellhead • TPRD system on trailers • Consider installing an anti-tearing system on hose • Train operators in hose connection • Carry out a leak test with nitrogen before unloading
Protection barriers	• Hydrogen flame detection on unloading area (UV detector) with report to the monitoring station • Monitoring of the trailer by an operator and low-pressure control system during unloading operations connected to emergency stop and shut off valves closing • Electrical grounding of the facilities
Hydrogen injection devices	
Prevention barriers	• Limitation of the number of fittings on pipes • Choice of materials compatible with hydrogen • Pressure resistant piping implementation • Pressure test before commissioning
Protection barriers	• Hydrogen flame detection on hydrogen injection area with report to the monitoring station • Carry out an ATEX study to prevent the ignition
Wells	
Prevention barriers	• Tightness test before a first filling of hydrogen, • Presence of pressure safety valve and event before the wellhead, • Ensure that the high-level sensing and safety valve pressures are adjusted to not exceed the estimated fracturing pressure • Pressure safety valve and event before the wellhead
Protection barriers	• Automatic isolation of the installations if the low or high-pressure threshold or gas sensor detector is reached on surface or underground facilities, • Hydrogen flame detection on wellhead area with report to the monitoring station
Vent line	
Prevention barriers	• Provide an isolation valve that closes when atmospheric pressure is reached on the vent line, • Pressure monitoring on wellhead • Calibration test of the safety valve • Protect the pipe from water and impurities inlet • Regular monitoring of the vent pipe.
Protection barriers	• Limit flow rate of release • Position vent outlet so that the effects of dangerous phenomena remain on the platform
Utilities	
Prevention barriers	• Reliability of the inerting system to guarantee its operation during the starting and stopping phases. • Ensure that the facilities are positively secured.

Table 3: Prevention and protection barriers per piece of equipment

Natural hazards	
Prevention barriers	• Calculation of the structures and ground anchorages of equipment from regulations • Lightning risk assessment
Protection barriers	• Consider natural hazards as possible event in emergency plans

Table 4: Prevention and protection barriers for natural hazards

6.0 CONCLUSION

The STOPIL-H_2 project globally aims to demonstrate the feasibility of safe storing hydrogen in a cavern. In this context, a preliminary risk analysis (PRA) was carried out in order to secure a cycling test to be operated in the upper part of the experimental cavern which is used in the project. This cycling test is planned over a period of 6 to 9 months.

The analysis is based on a) the detailed description of the project, b) lessons that can be learnt from accident records in salt cavern gas storage, c) the identification of the potential hazards linked to the storage process as well as those arising from external potential aggressors. As Resulting as the outcome of this PRA, major accidental scenarios associated with the different operation phases as well as a list of preventive or protective barriers against these scenarios are presented.

A first result from our accident survey is that no emerging accidentology seems to appear so far for this type of very specific hydrogen storage (salt cavern storing), a conclusion that must however be somewhat mitigated by the fact that today only 6 such caverns among those used for gas storing are currently operated for hydrogen gas). When considering more broadly existing feedback from underground storage of gas and hydrocarbons in general, 11 accident records were further considered as relevant for underground hydrogen storage safety considerations. The corresponding incident records analysis highlights that the main causes of potential incidents could be: a) corrosion of the casings; b) bad cementing; c) an overfill or leak in the centre column; d) excessive cavern pressure. Relating to surface equipment, we found relevant cases concerning pipes, tube-trailers and TPRD. The main causes for surface level equipment are failures of equipment due to hydrogen embrittlement or climatic conditions or poor design, wear and lack of control procedures.

The risk analysis dedicated to cavern EZ53 to be used in the project STOPIL-H_2 highlights the importance of paying attention to the losses of containment but also to the overpressure which can generate dangerous phenomena such as torch fire, UVCE or flashfire as well as the bursting of equipment. Therefore, measures must be put in place to prevent so far as possible the occurrence of such phenomena or protect equipment against their effects its. Given the rapid kinetics of the scenarios, technical barriers should be favoured even if it is also necessary to ensure the training of stakeholders in specific hydrogen risks. The analysis highlights the importance of implementing preventive or protective barriers to reduce the probability of risks and reduce their severity. The main ones are as follows:

- ensure the tightness of the cavity before a first filling,
- take measures in order to be able to isolate surface to underground installations,
- manage overpressure by pressure safety valves, vents and pressure detection systems associated with the isolation of installations,
- early detect ATEX formation (sensor or explosimeter) and implement fire detection (by UV).

This analysis will be further completed by the company STORENGY encompassing a detailed risk assessment in which the probability and severity of accidents considered as major scenarios that could be feared will be estimated in order to position them in a criticality grid. The STOPIL-H_2 project will be continued in the HYPSTER project, where the coupling of cavity storage to a system for producing hydrogen by electrolysis will be evaluated.

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