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RockEnGe.be

INERIS
maîtriser le risque pour un développement durable

HYPSTER

1st demonstrator for green hydrogen storage

Mons, 19 février 2024 de 17h à 18h30

Hippolyte Djizanne, Eng, Msc, PhD in rock mechanics
Solution Mining Research Institute (SMRI) Research Committee member (2024-2028)

Co-funded by the European Union · Clean Hydrogen Partnership

Ineris - [CGR] - 2723046 0.1

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HyPSTER stands for Hydrogen Pilot STorage for large Ecosystem Replication

- Project start date: January 2021
- Location : Etrez (Ain 01) | France
- H_2 Production: Electrolyzer (1 MW)
- Storing capacity: 3 tons H_2 (exp. phase)
- Total budget: 13 M€ (5M€ funding)
- End of the Pilot Phase: 2024
- Perspective Phase II: 44 tons H2 (2025)

Description: Test industrial-scale renewable hydrogen production and storage in salt caverns supported by technical and economic reproducibility of the process to other sites throughout Europe.

9 partners, 4 countries

Consortium Partners

H2 & Subsurface expertise: storengy, ESK, ARMINES, BROUARD CONSULTING

Regulation & Safety: INERIS

Storage replication potential: inovyn, storengy

Technical and economic assessments: elementenergy

Bacteriology Purification: equinor

Communication: axelera

Coordination: storengy, elementenergy

2 Strategic partnerships

Schneider Electric, TechnipFMC

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Project Overview

Project Director :
Jean-François GUERIN
Storengy
https://hypster-project.eu/
jean-francois.guerin@storengy.com

- Call year: 2020
- Call topic: FCH-02-7-2020 Cyclic testing of renewable hydrogen storage in a small salt cavern
- Project dates: 01 2021 – 01 2025
- % stage of implementation 01/11/2023: 85 %
- Total project budget: 15,5 M€
- Clean Hydrogen Partnership max. contribution: 5 M€
- Other financial contribution: 10,5 M€
- Partners: Storengy, Ineris, Armines Ecole Polytechnique, ESK, Inovyn, Axelera, element energy, Brouard Consulting, Equinor

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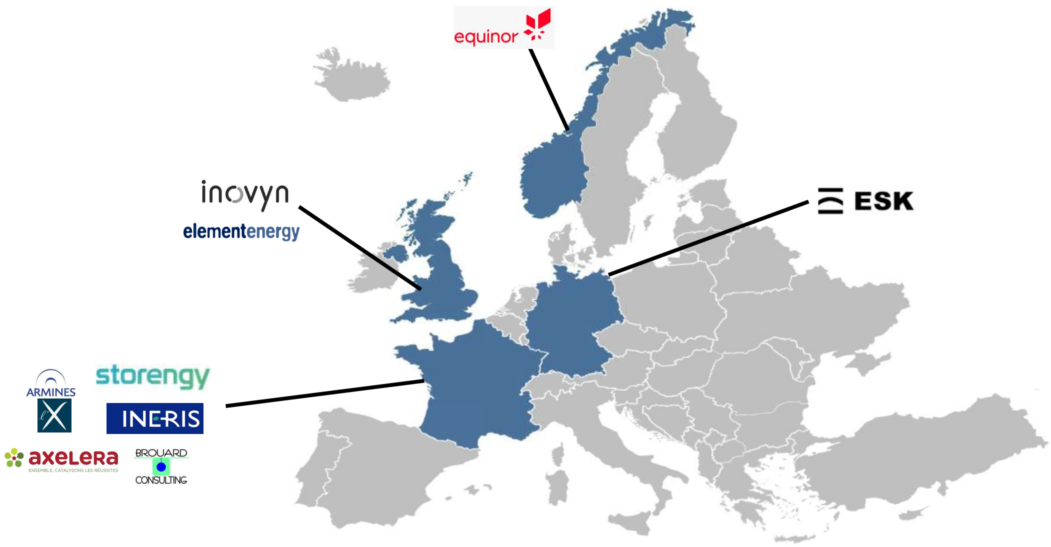
Partners



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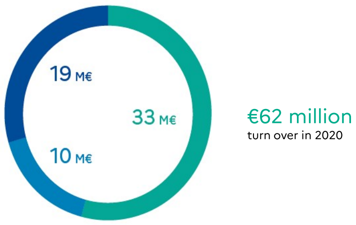
Ineris is the French public expert for industrial and environmental risk management

- Ineris model is based on three core elements:
  - support for public policies,
  - high-level applied research,
  - consulting and service activities.

- This model relies on stringent ethical standards and a regular dialogue with the civil society.

- 25 years of experience on hydrogen safety
  - Multidisciplinary skills
  - Laboratories
  - Numerical tools
  - Large-scale testing facilities

INERIS ACTIVITY



- Support
- Research
- Business Services

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Storengy as project leader

4TH
LARGEST UNDERGROUND GAS STORAGE OPERATOR IN THE WORLD

600
WELLS (in France) WITH A LARGE VARIETY OF TECHNICAL SOLUTIONS

21 UGS *
OPERATING IN FRANCE, UK, & GERMANY
+ REMOTE DISPATCHING OF THIRD-PARTY UGS

- Aquifers
- Salt caverns
- Depleted fields

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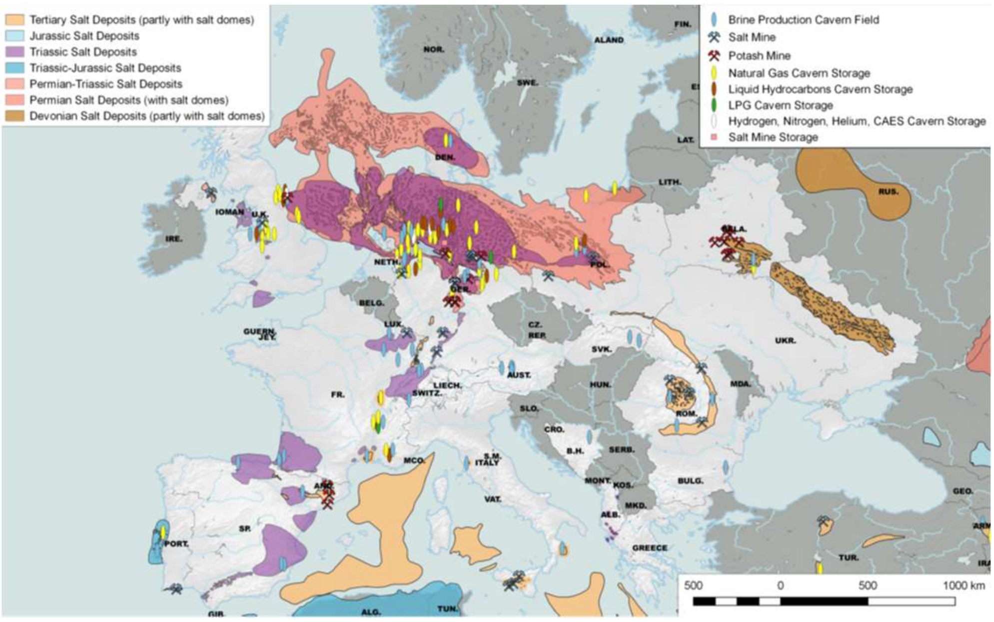

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03 Schedule and technical challenges

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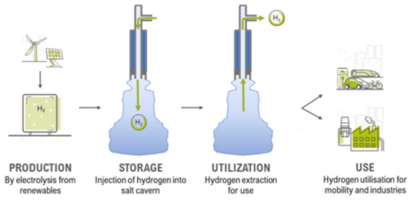
Situation map



Etrez NG Storage facility

Planned H_2 Production Platform

EZ53 Cavern Platform

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HyPSTER Project Schedule overview

2021 2022 2023 2024

Hydrogen production

Engineering design → Building & commissioning → Hydrogen production

Hydrogen Storage in salt cavern

Engineering design → Building & commissioning → Tightness tests and pressure cycling

H2 Production Platform

- *Start of the construction 18th July 2022*
- *Packages deliveries: **Stacks April 2024***
- *Commissioning: from April 2023 **to April 2024***
- *Start of H_2 production: **July 2024***

UHS EZ 53

- *Start of construction work: 22nd August 2022*
- *Cavern Workover: March - April 2023*
- *Tightness Test: October 2023 – **April 2024***
- *Cycling Test: **May to September 2024***

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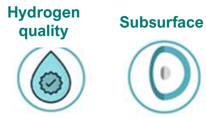
Technical challenges to be addressed

- Adaptation of equipment to hydrogen (piping, valves, pressure vessels, completion, gas treatment purification after withdrawal)

- Tightness and High Frequency Cycling of underground H2 storage (Salt cavern, completion)

- Thermodynamic behavior to H_2 during storage cycles

- Interaction inside the UHS
  - Hydrogen dissolution in brine (*in-situ*)
  - Chemical and bacteriological reaction (*in-situ*)



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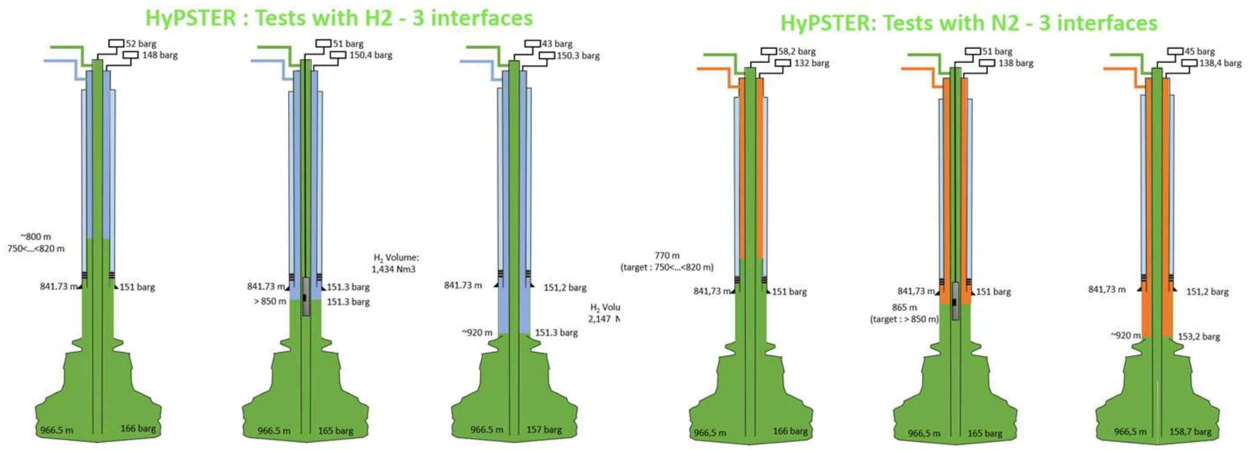
The Mechanical Integrity Test (M.I.T.)

Aim: check the tightness and the strength of the completion (tubing + packer + casing shoe)



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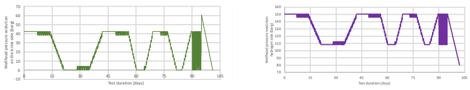
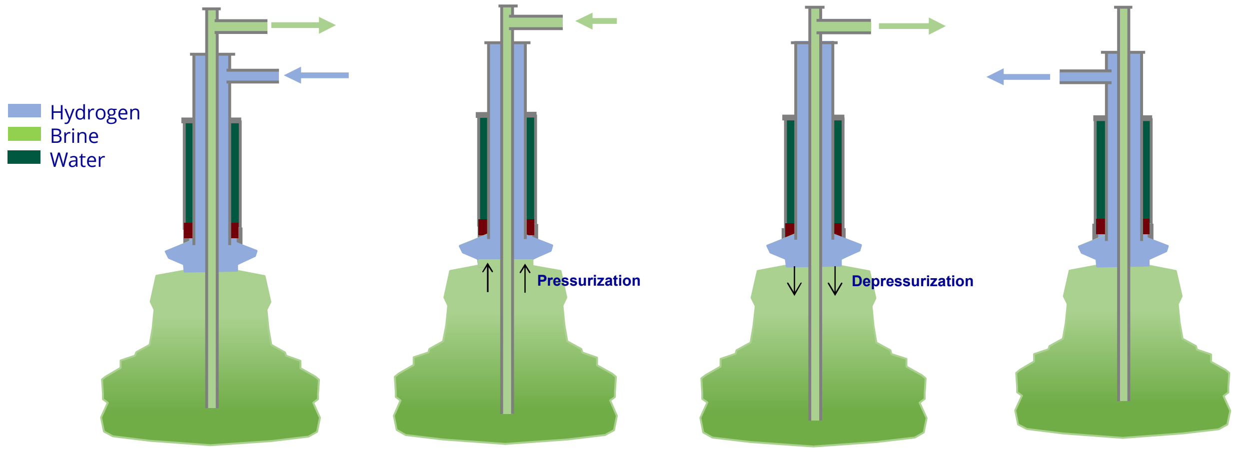


Principles of the pressure cycles in the cavern



Injection of H_2
Withdrawal of brine volume 26,910 Nm^3 of H_2
(+2,147 Nm^3 already in the well)
<=> 230 m^3 of brine
interface at 930m

Beginning of a cycle
Injection of brine
Pressurization of H_2

End of cycle
Withdrawal of brine
Depressurization of H_2

Experiment plans at least 100 cycles

End of the experiment
Withdrawal of H_2 to vent

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03 | Equipments

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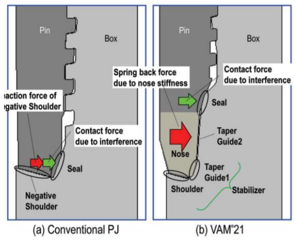
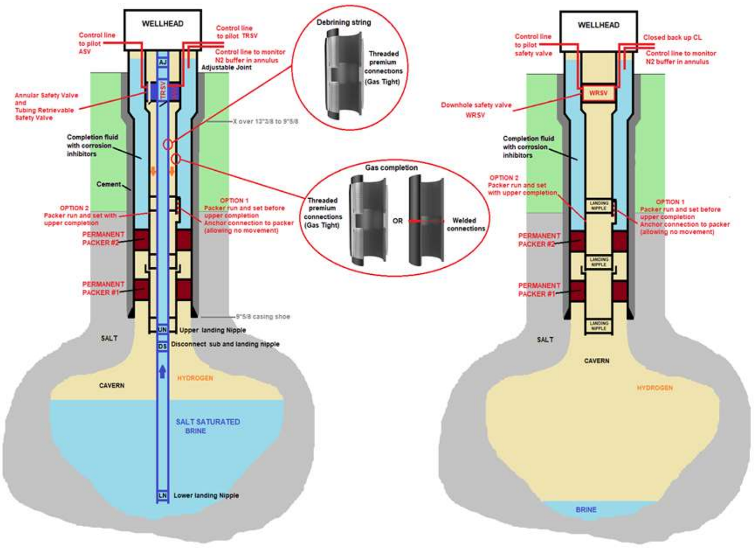
EZ53 – Completion equipment

- Wellhead provided by Technip FMC
- Completion equipment provided by Schlumberger (requirement to get annular safety valve)
- Tubulars provided by Vallourec: only supplier to have performed H2 tightness test on the VAM 21





EZ53 Completion selected

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Hydrogen storage platform

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Hydrogen storage platform

EZ53 Well head

Automatic cycling sequences tests on EZ53

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Hydrogen production platform

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Hydrogen production platform

H2 Buffer Tank

Dispenser Panel

H_2 outlet lines to buffer tank

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04 Risk control

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Challenges - Hydrogen safety and risk management

- **Risk and environmental impact assessment**

  INERIS storengy ESK

- **Contribution of numerical modelling to cavern storage risk evaluation**

  INERIS BROUARD CONSULTING ARMINES ESK storengy

- **Relation with French authority and authorization to perform the test**

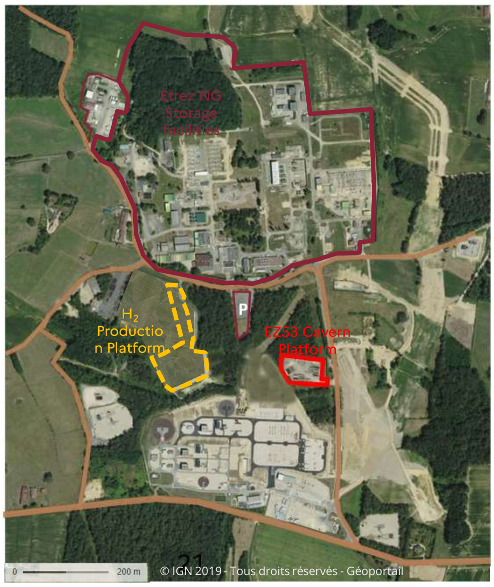
  storengy

- **Lessons learned on safety and environmental issues and recommendations for replication**

  storengy INERIS

- **Regulatory assessment and recommendations for large-scale deployment in Europe**

  INERIS storengy ESK inovyn



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Key features of hydrogen cavern storage

EZ53 cavern

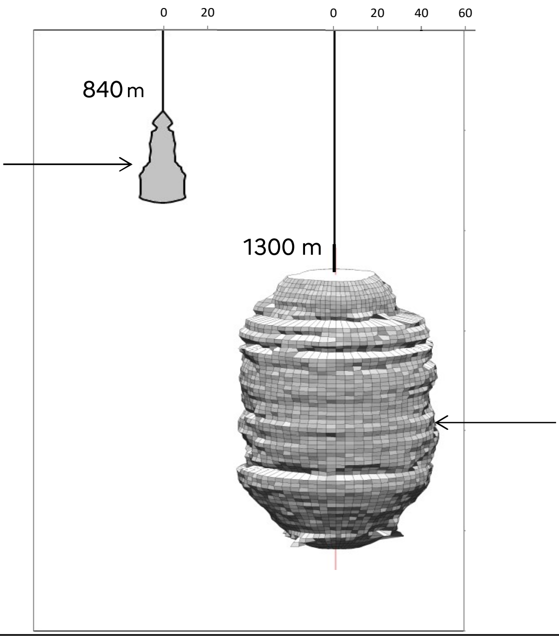
Geometric volume:

7 to 8000 m^3

Hydrogen volume

- **Total :** 900,000 Nm^3
- **Usable :**
  - 500,000 Nm^3
  - 1.7 GWh
  - 44 tons H_2

- P_{min} : 60 bar
- P_{max} : 165 bar



« Normal » cavern

Geometric volume:

570,000 m^3

Hydrogen volume

- **Total :** 100,000,000 Nm^3
- **Usable :**
  - 70,000,000 Nm^3
  - 250 GWh
  - 6300 tons H_2

- P_{min} : 60 bar
- P_{max} : 240 bar

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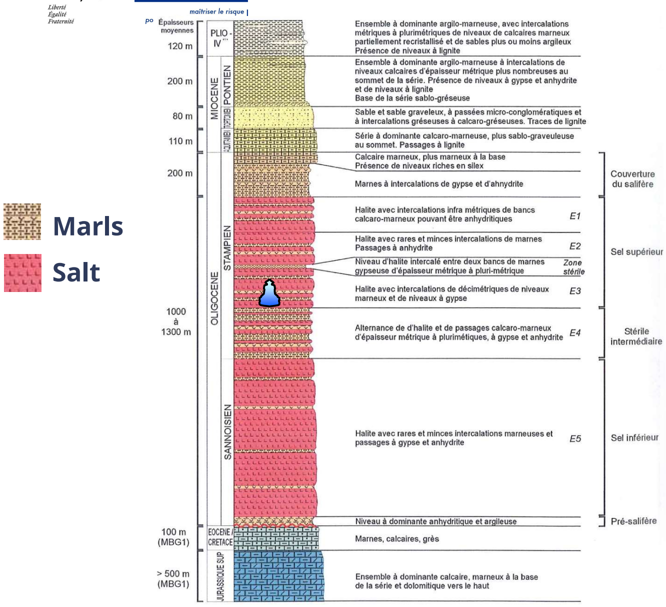

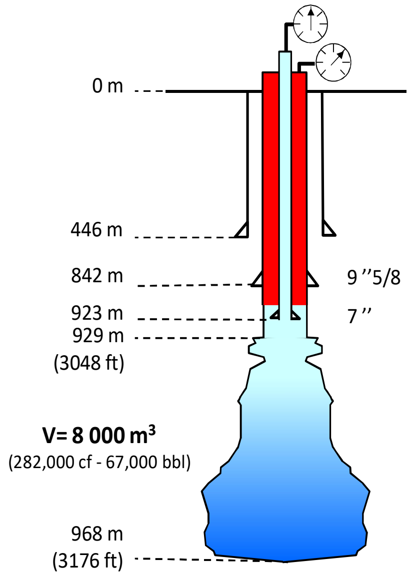

EZ53 Cavern

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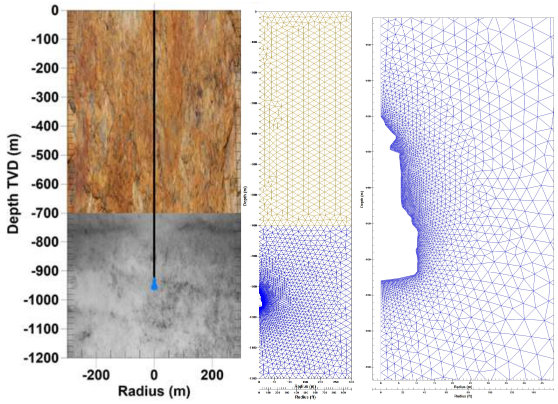
Modelling worst-case scenario

Rapid depressurization, fast cycling and blowout



RISKS

- Excessive volume loss
- Severe subsidence
- Spalling
- Cracks
- Loss of tightness
- Generalized collapse

GEOMETRY

- Depth
- Cavern and roof shape
- Safety distances

KEY FIGURES

- Minimum pressure
- Maximum pressure
- Cyclic load
- Temperature variation
- Pressure variation

THE MOST STUDIED PHENOMENA

1. Thermodynamics
2. Creep closure
3. Dissolution
4. Crystallization
5. Micro-permeation
6. Leakage
7. Atmospheric variation in P
8. Atmospheric variation in T
9. Earth tides

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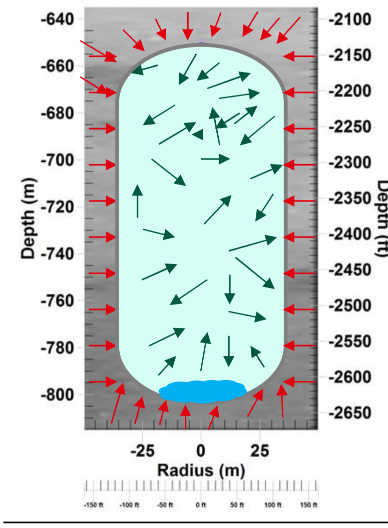
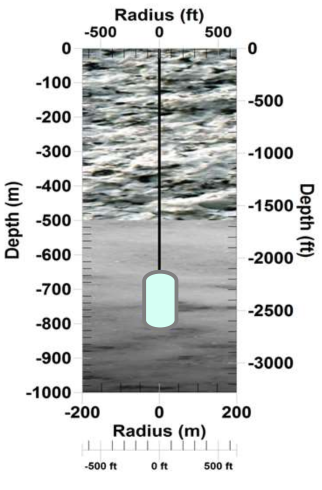
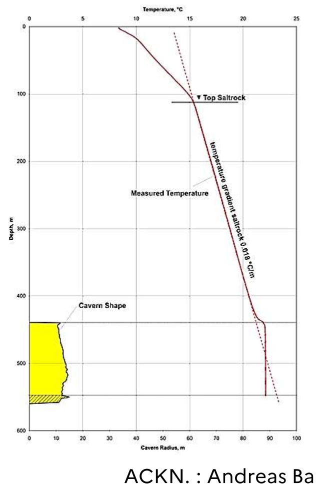
04 | Modelling blowout

Conduction – Convection - Condensation

Cavern fluid is stirred by convection and temperature is roughly homogeneous







ACKN. : Andreas Banach

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Gas Thermodynamics: Main assumptions, Model simplifications, Boundaries conditions

Energy balance

Temperature rate

Conduction heat flux

$$mC_v\dot{T} - VT\left(\frac{\partial P}{\partial T}\right)_\rho \dot{\rho} = \langle \dot{m} \rangle C_p \left(T_e - T\right) + q_c + L\dot{C}$$

Compression decompression — Gas injection — Condensation

With: Conduction heat flux: $q_c = \int_{\partial\Omega} -K_{salt} \frac{\partial T_{salt}}{\partial n} da$

L Latent heat of condensation — $\dot{C}$ Water vapor massic flow

Cavern Thermodynamics

and

Salt Rock Mechanics

are calculated <u>simultaneously</u>

Thermodynamics model validated with real data (Djizanne et al. 2014):

- Melville, Regina North n°5, Saskatchewan, Canada (Crossley, 1996)
- Huntorf NK1 salt cavern, Germany (Quast et Crotogino, 1979)

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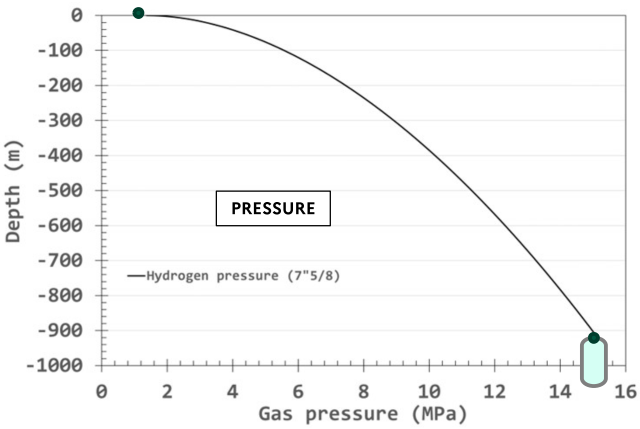
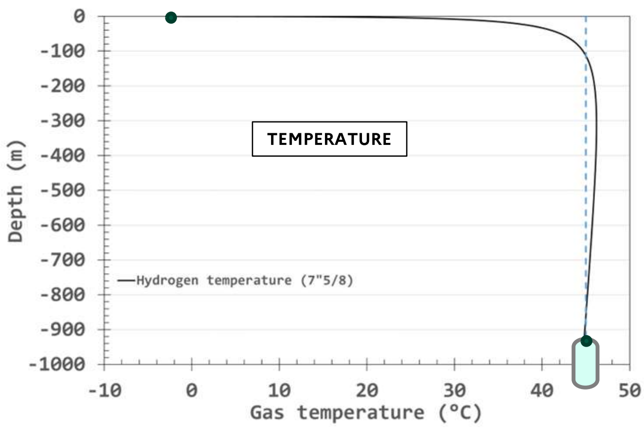
Distribution through the well from the cavern top to ground level

❑ At the very beginning of the blowout (t = 0)

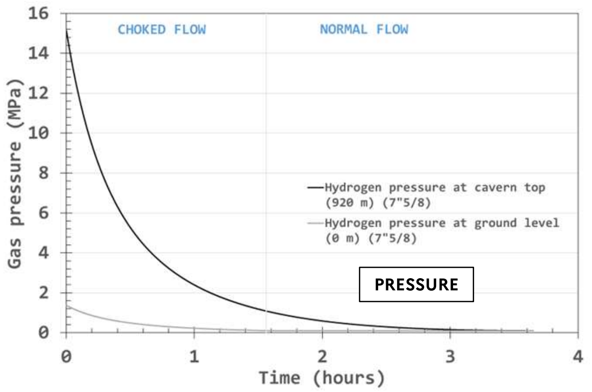


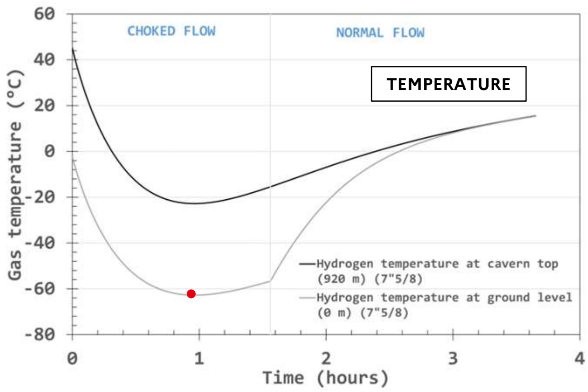


Hydrogen pressure and temperature during the blowout

Gas initial pressure	15,15 MPa
Ground level pressure at the start of the blowout	1,5 MPa
Cavern top pressure at the end of the choked flow	1,08 MPa
Ground level pressure at the end of the choked flow	0,10 MPa

Gas initial temperature	45°C
Ground level temperature at the start of the blowout	-3°C
Gas temperature at cavern top at the end of the choked flow	-16°C
Ground level temperature at the end of the choked flow	-56°C
Lowest temperature in the cavern	-22°C
Lowest temperature at ground level	-66°C

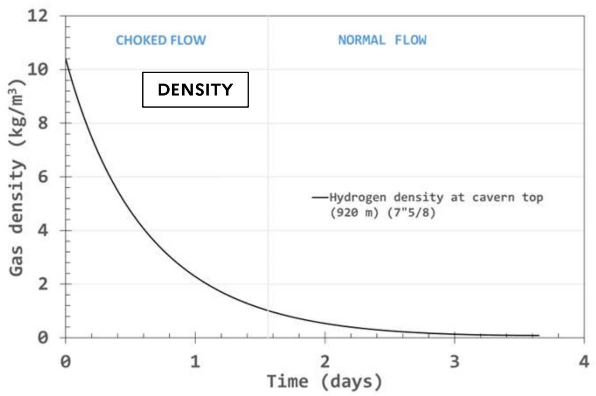


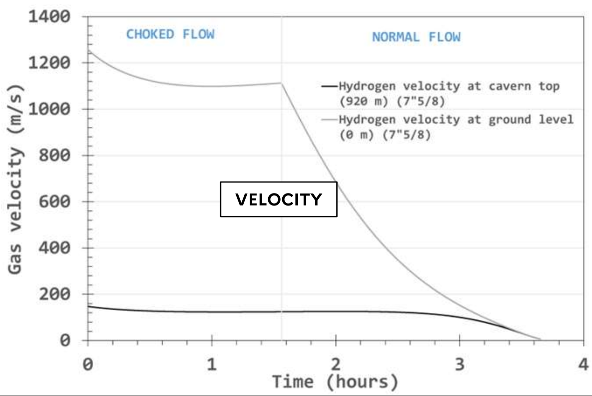


Hydrogen density and velocity during the blowout

Cavern volume	7390 m3
Gas mass	83 tons
Maximum flux from cavern wall	19 MW
Tubing diameter (internal diameter)	7"5/8

Well length or cavern top depth	920 m
Gas velocity at cavern top at the start of blowout	177, 85 m/s
Gas velocity at ground level at the start of blowout	1257 m/s
Gas velocity at cavern top at the end of the choked flow	144 m/s
Gas velocity at ground level at the end of the choked flow	1113 m/s





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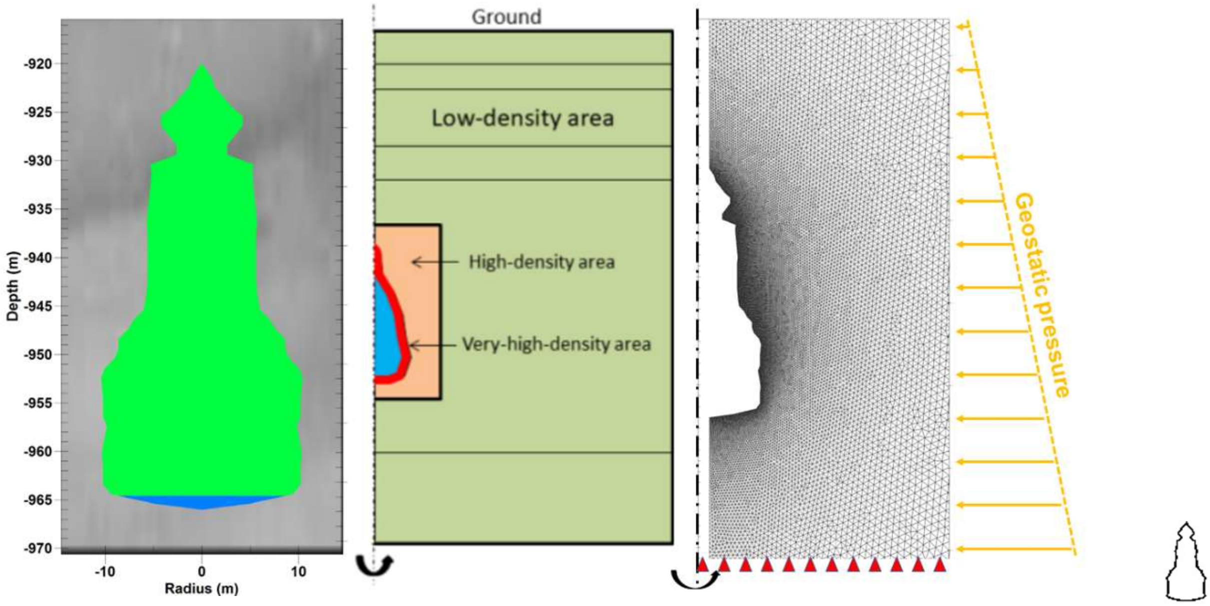
Initial and boundaries conditions



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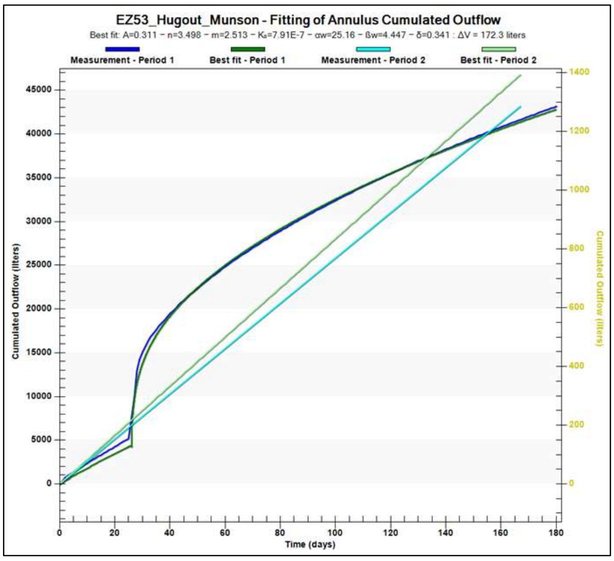
Constitutive laws for rock salt



MUNSON-DAWSON CREEP LAW

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\partial \sigma}{\partial \sigma_{ij}} F \dot{\varepsilon}_{ss} \qquad \begin{cases} F = e^{\Delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \le \varepsilon_t^* \\ F = e^{-\delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \ge \varepsilon_t^* \end{cases}$$

$$\dot{\varsigma} = (F-1)\dot{\varepsilon}_{ss} \qquad \dot{\varepsilon}_{ss} = A\exp(-Q/RT)\sigma^n$$ Steady-state

$$\sigma = \sqrt{3J_2} \qquad J_2 = \frac{1}{2}s_{ij}s_{ij}$$

$$\varepsilon_t^* = K_0 e^{cT}(\sigma/\mu)^m$$

$$\mu = \frac{E}{2(1+\nu)} \quad \text{and} \quad \Delta = \alpha_w + \beta_w Log_{10}(\sigma/\mu)$$ Transient

Set of parameters for Etrez rock salt

$A = 0.311$ /MPa^n-yr	$n = 3.498$	$Q/R = 4100$ K
$K_0 = 7.91\times10^{-7}$ /MPa^m	$\alpha_w = 25.16$	$\beta_w = 4.447$
$m = 2.513$	$\delta = 0.341$	$c = 0.00902$ /K

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The main mechanical stability criteria can be described as follow:

- the onset of salt dilation,
  - salt micro-fracturing and dilation occur when the shear stresses are significant compared to the mean stresses. These lead to a permeability increase, a drop in wave speed, an increase in acoustic emission and a loss of rock strength
- the onset of effective tensile stresses at the cavern wall,
  - when tensile stress develops at the cavern wall, there is a risk of salt fracturing and spalling. Thermal contraction of the salt near the surfaces of the cavern is likely to cause stresses to become tensile.
- the onset of tensile stresses at the cavern wall,
- the overstretching at the last cemented casing shoe,
- limited volume loss and volume-loss rate and
- limited subsidence.

Djizanne et al., 2012, Bérest et al., 2013, Brouard et al., 2022, Djizanne et al., 2023

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Spiers et al., 1988	$\sqrt{J_2} = -aI_1 + b$		a 0.27	b 1.9 (MPa)
Ratigan et al., 1991	$\sqrt{J_2} = -aI_1$		a 0.27	
Hunsche et al., 1993	$\sqrt{J_2} = \sqrt{\frac{3}{2}}\left(f_1\frac{I_1^2}{9} - f_2\frac{I_1}{3}\right)$			
Thorel, 1995	$\sqrt{J_2} = \sqrt{\frac{-I_1}{9Z(J_m)}}$	$Z(J_m) = \frac{Z_e - Z_c}{2}\sin\left(\frac{\pi}{2J_m}\right) + \frac{Z_e + Z_c}{2}$	$J_m = \frac{3\sqrt{3}J_3}{2\sqrt{J_2^3}}$	$Z_e = 0.05$ MPa $Z_c = 0.03$ MPa
Hatzor, 1998	$\sigma_1 = k_1 e^{k_2\beta}$	β 90 (°)	$k_1 = -0.0743\sigma_3^2 + 3.2223\sigma_3 + 12.9$ $k_2 = -0.0057$	
Respec, 2005	$\sqrt{J_2} = \frac{D_1\left(\frac{I_1}{\mathrm{sgn}(I_1)\sigma_0}\right)^n + T_0}{\left(\sqrt{3}\cos\psi - D_2\sin\psi\right)}$			

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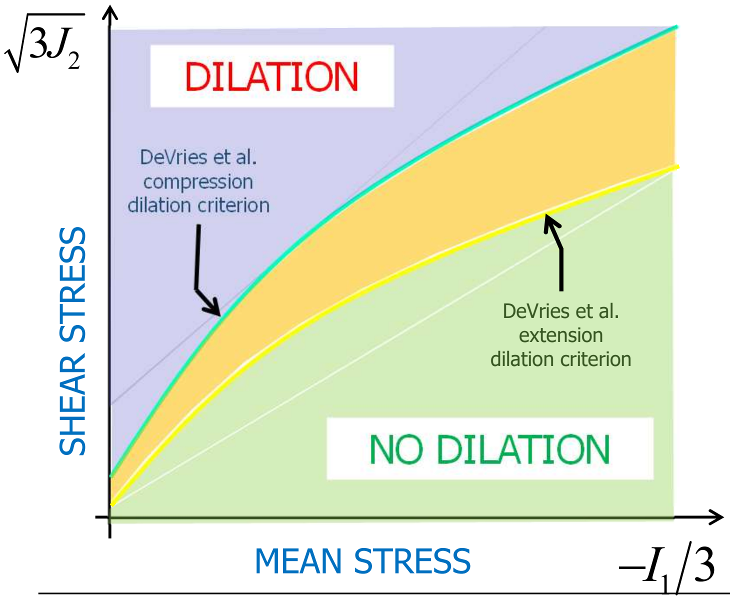
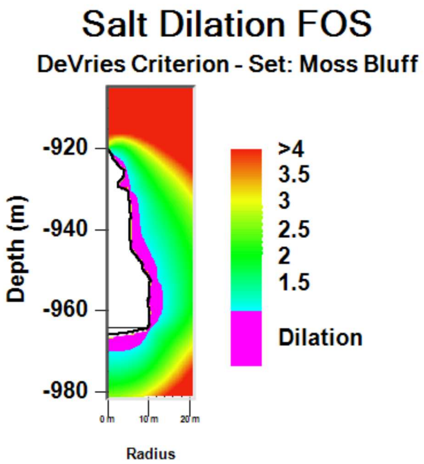
Damage zone around the salt cavern





DeVries et al. (2005)

$$FOS = \frac{\sqrt{J_{2\,dil}}}{\sqrt{J_2}} \qquad \sqrt{J_2} < \sqrt{J_{2\,dil}} = \frac{D_1\left(\frac{I_1}{\mathrm{sgn}(I_1)\sigma_0}\right)^{n_1} + T_0}{\left(\sqrt{3}\cos\psi - D_2\sin\psi\right)}$$

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Modelling the blowout on its aerial part

Objective:

Simulating its dispersion in the atmosphere to evaluate the effects of potential resulting phenomena on surrounding assets

Input data:

this subtask will involve taking as input the jet of gas flowing from the well (as modelled respectively by LOCAS and KAPVOOL in subtasks 2a and 2b)

Numerical approaches:

- **Integral approach: Unified dispersion Model**

  Process Hazard Analysis Software Tool (PHAST - v8.4)

- **Computational Fluid Dynamics**

  Fire Dynamics Simulator (FDS – v6.7.16)

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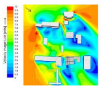
Modelling of hazardous phenomena

PHAST™ v 8.21

NIST National Institute of Standards and Technology



- Hydrogen leakage at the surface level for the scenario

Evaluation of effects associated with the combustion of leaked hydrogen

JET FIRE

FLASH FIRE

UVCE

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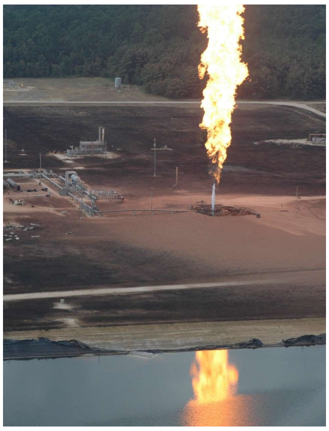
Modelling Blowout in H_2 caverns

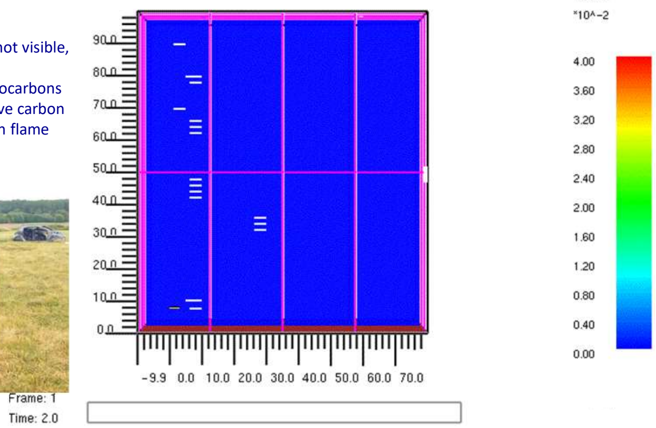


Natural Gas blowout at Moss Bluff, TX facility / Brouard et al. (2014)

Kurt Vollmacher ©
Hydrogen flame with and without a thermal camera.

There is no carbon in H_2, so the flame is not visible, and there is almost no radiation of heat.
This is a big difference compared to hydrocarbons such as Methane and LPG, where you have carbon in the flame. But be careful; the hydrogen flame has a temperature of 2,182°C

Hydrogen Gas blowout simulation for the HyPSTER project



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Unconfined Vapor explosion (UVCE)

Evaluation of hazardous events

- Irreversible effects – Dmax = 551 m – 3A = Very unstable & Sunny + Light winds
- Lethal effects (1%) – Dmax = 246 m 3A = Very unstable & Sunny + Light winds
- Significant lethal and domino effects (5%) – Dmax = 194 m – 3A = Very unstable & Sunny + Light winds

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04 | Effect of a rapid depressurisation

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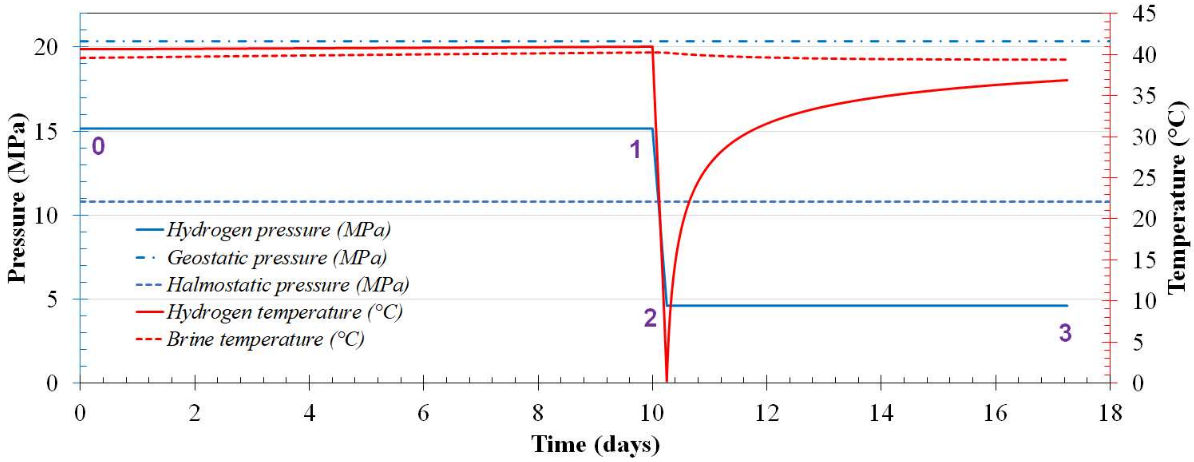
A rapid depressurization from Pmax to Pmin in 6 hours (2 MPa/h)



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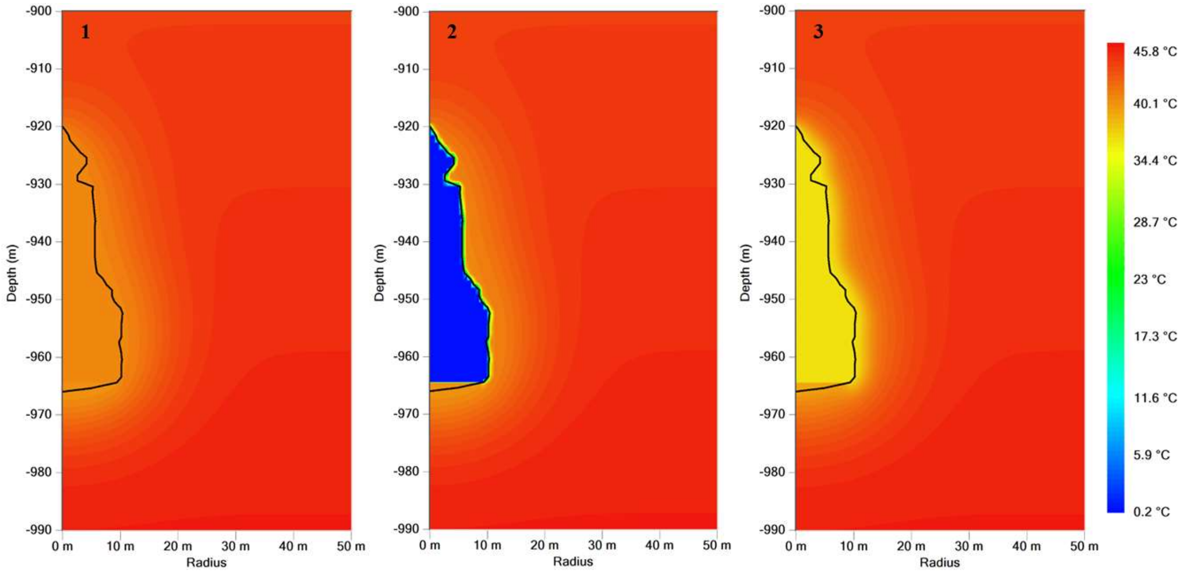
Temperature - **Before** (**1**), **at the end** (**2**) and **after** (**3**) the rapid hydrogen withdrawal



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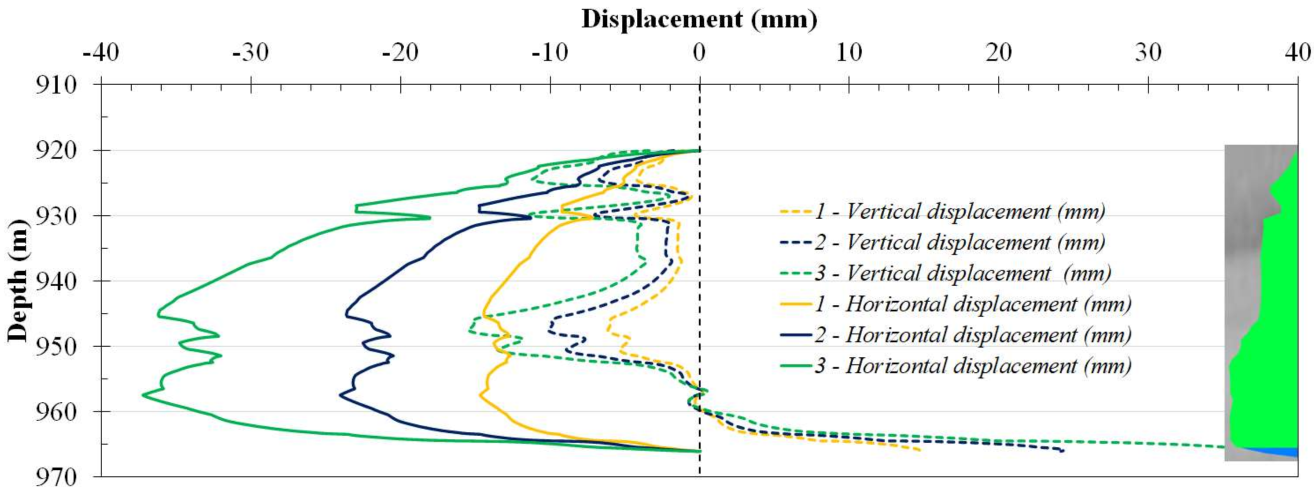
Displacements along the wall - **Before** (**1**), **at the end** (**2**) and **after** (**3**) the rapid hydrogen withdrawal



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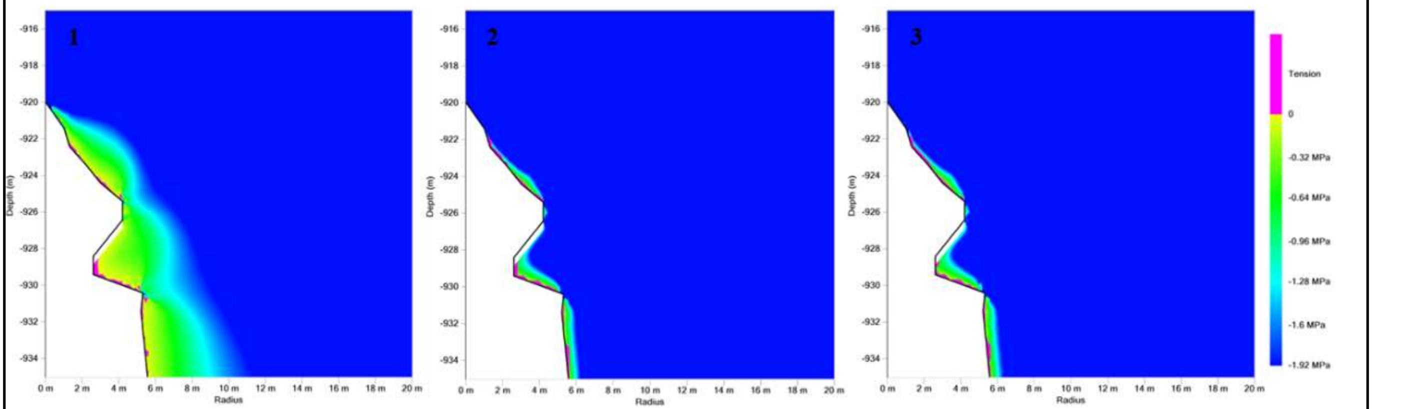
Tensile effective stress - **Before** (**1**), **at the end** (**2**) and **after** (**3**) the rapid hydrogen withdrawal



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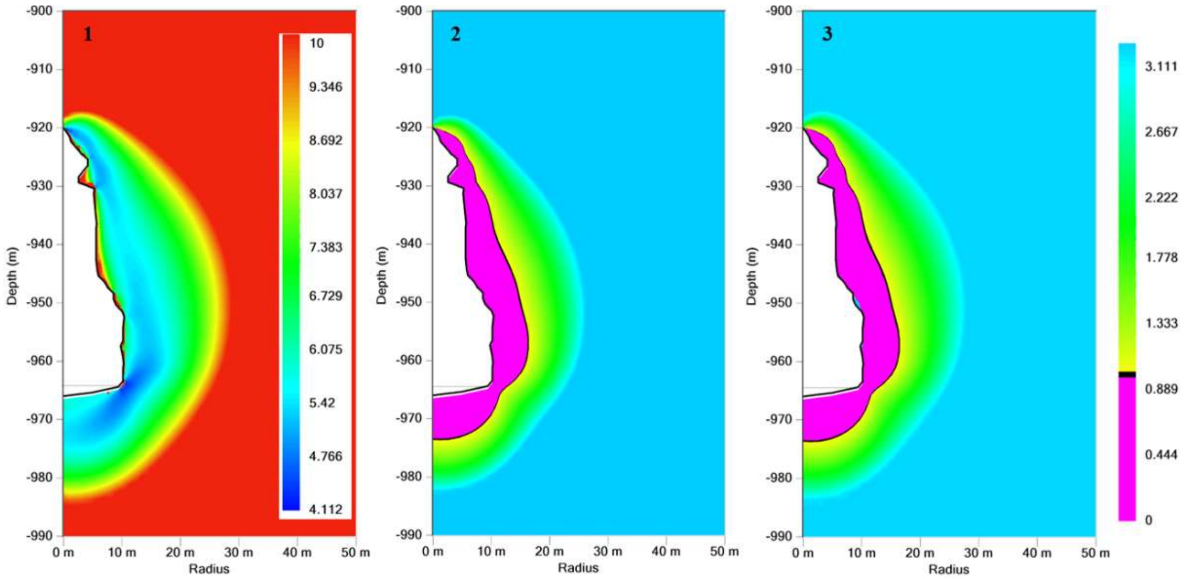
Salt dilation - **Before (1), at the end (2)** and **after (3)** the rapid hydrogen withdrawal



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- A two-dimensional axisymmetric thermomechanical finite element simulation of a cavern submitted to a fast withdrawal was performed using LOCAS.
- The case modelled here contributes to risk control and represents one of the worst-case scenarios during the operation with hydrogen.

- According to the RD criterion, dilatancy is observed at the cavern wall because of rapid pressure drop.
- Low-temperature induced microcracks must be carefully studied prospectively to ensure the tightness of salt caverns that store large quantities of hydrogen.

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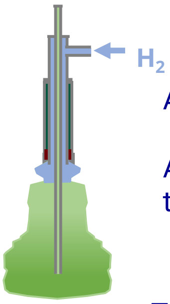
Chemical reactions / bacterial growth in the cavern

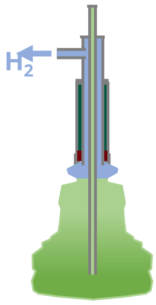
Brine sampling from the cavern before the experiment for bacteria growth to identify the bacteria population present and estimate the possible H_2 interaction.

At the end of experiment, brine in close contact with H_2 will also be sampled, analyzed and compared to the initial brine to detect an eventual evolution.



Analysis of H_2 composition before injection for reference.

Analysis of H_2 composition after withdrawal (after 3 month in the cavern) for comparison.



=> The aim: Identification of possible purification system if needed

05 | Summary

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Conclusion


Vue globale du conteneur

Hydrogen has been successfully stored in salt caverns of many years.

But only limited information is available on sub surface design and material selection.

The HyPTER Project aims to:
- Test manufactures equipment inside a salt cavern
- Prove test procedures and measure leak tightness of completion equipment
- Test material compatibility
- Understand the impact of pressure cycling
- Establish whether there is any chemical reactions / bacterial growth in the cavern.

Initial results should be available in the second half of 2024.

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hypster
Hydrogen Storage

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