STATUS OF SALT CAVERN ABANDONMENT IN FRANCE: A ROCK MECHANICS POINT OF VIEW

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Workshop: Proceedings in salt cavern uses and abandonment: Bridging the technical and social perspectives

15-16 October 2024, TNO, Utrecht, The Netherlands

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Agenda

1. **Salt cavern uses and abandonment in France**
   a. Status of salt cavern uses in France
   b. Status of salt cavern abandonment in France
   c. Carresse-Cassaber, a storage case
   d. Main physical phenomena
   e. Risks associated with salt caverns abandonment
   f. Trial and error tests in France

2. **TE02 pilot in Tersanne, France**
   a. Abandonment cavern pilot location
   b. TE02 key figures
   c. Observation in experimental phasis
   d. Equilibrium pressure – trial and error test

3. **Predictive numerical computations**
   a. Modeling salt caverns abandonment (von Mises, effective stress, permeability, porosity, …)
   b. Ongoing PhD thesis at Ineris on damage zone around salt caverns (candidate : Mrs Hajar Habbani)

4. **French procedures and regulation**
   a. Suggested abandonment plan for TE02 pilot from Storengy
   b. French regulation on salt cavern abandonment

5. **SMRI ongoing research projects on deep/tall cavern abandonment**
   a. Hbornum HV-02 salt cavern
   b. FRISIA salt cavern

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1. Salt cavern uses and abandonment in France

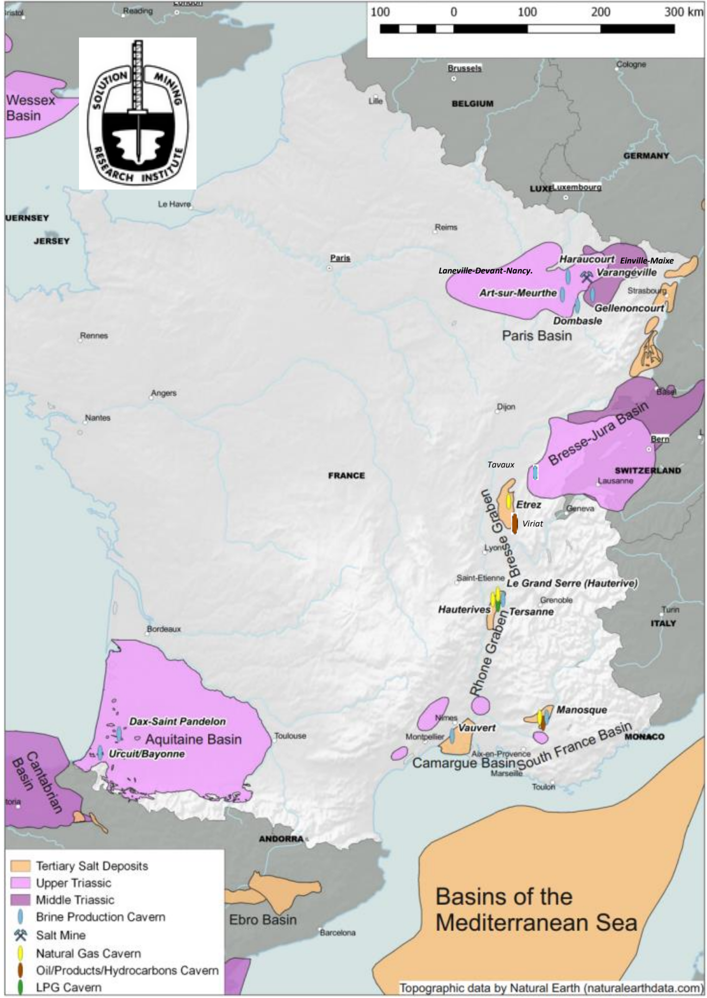
Status of salt cavern uses in France

<u>Salt production by solution mining:</u> 3.4 MT in 2021 (67% of French salt production), ~250 mining concession, more than hundreds active wells.

- **Novacarb/SEQUENS, Storengy, K+S, Geosel Manosque, Solvay Opération, Chloralp (ex Vencorex), Kem One, …**

<u>Underground storage in salt caverns:</u> 36 TWh or 26% of 138 TWh the national gas storage capacity (26% of France gas annual consumption), 78 salt caverns, 6 sites (4 for natural gas, Oil/products/hydrocarbons, LPG).

- **Storengy, Géométhane, Teréga**
    - Gradient at LCCS = 0,018 MPa/m to 0.019 MPa/m



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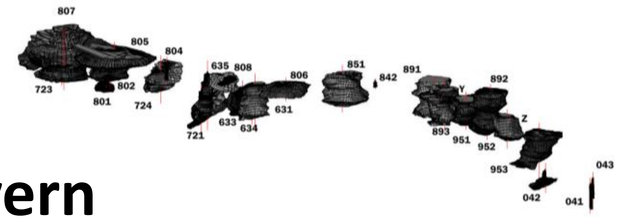
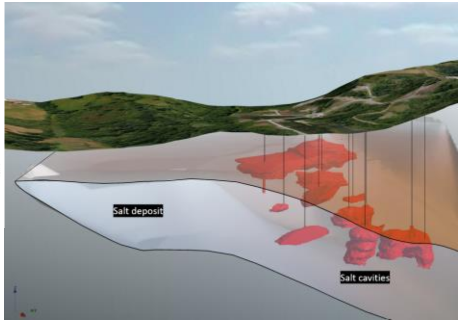
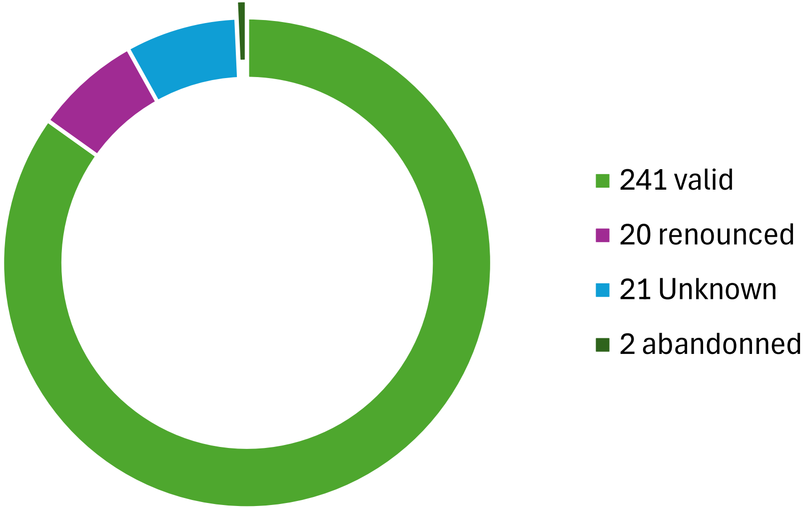




Ineris paper : Urcuit salt mine closure (Lecomte et al., 2023)

Status of salt cavern abandonment in France



Mining concession with salt as principal substance

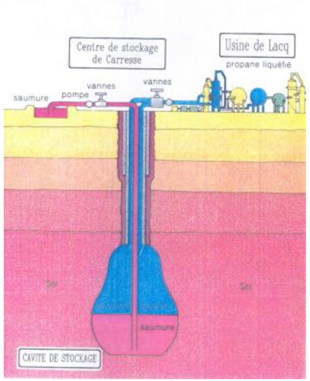
Brine production

- **Briscous-Les Salines (Saline Cerebos et de Bayonne)**
- Several sites undergoing administrative abandonment procedures : Dax (**Salins du Midi**); Urcuit, La Madeleine & Ponts Saint Phlin, Poligny (**Solvay**); …

Underground storage

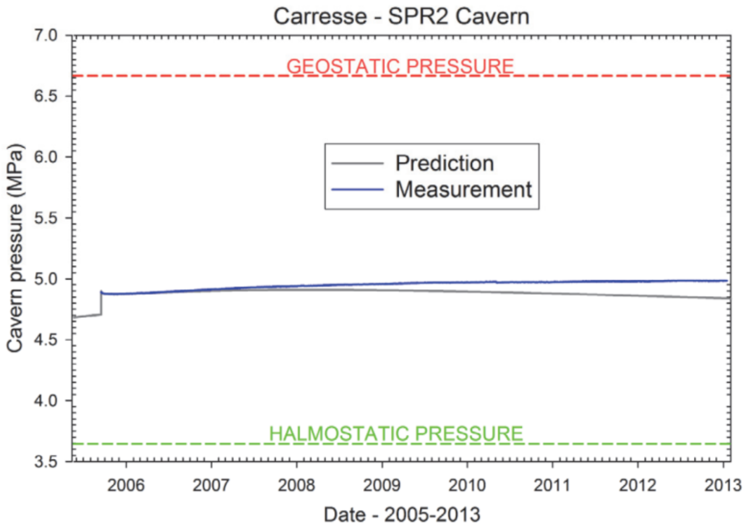
- **Carresse-Cassaber, propane (Elf, Total, 3 salt caverns, 43,350 m^3, ~310 m depth.**
- Several abandonment pilots : Gellenoncourt (**CSME**), Etrez & Tersanne (**Storengy**), Caresse-Cassaber (**Elf, Total**)

Carresse-Cassaber (an 11-year test)



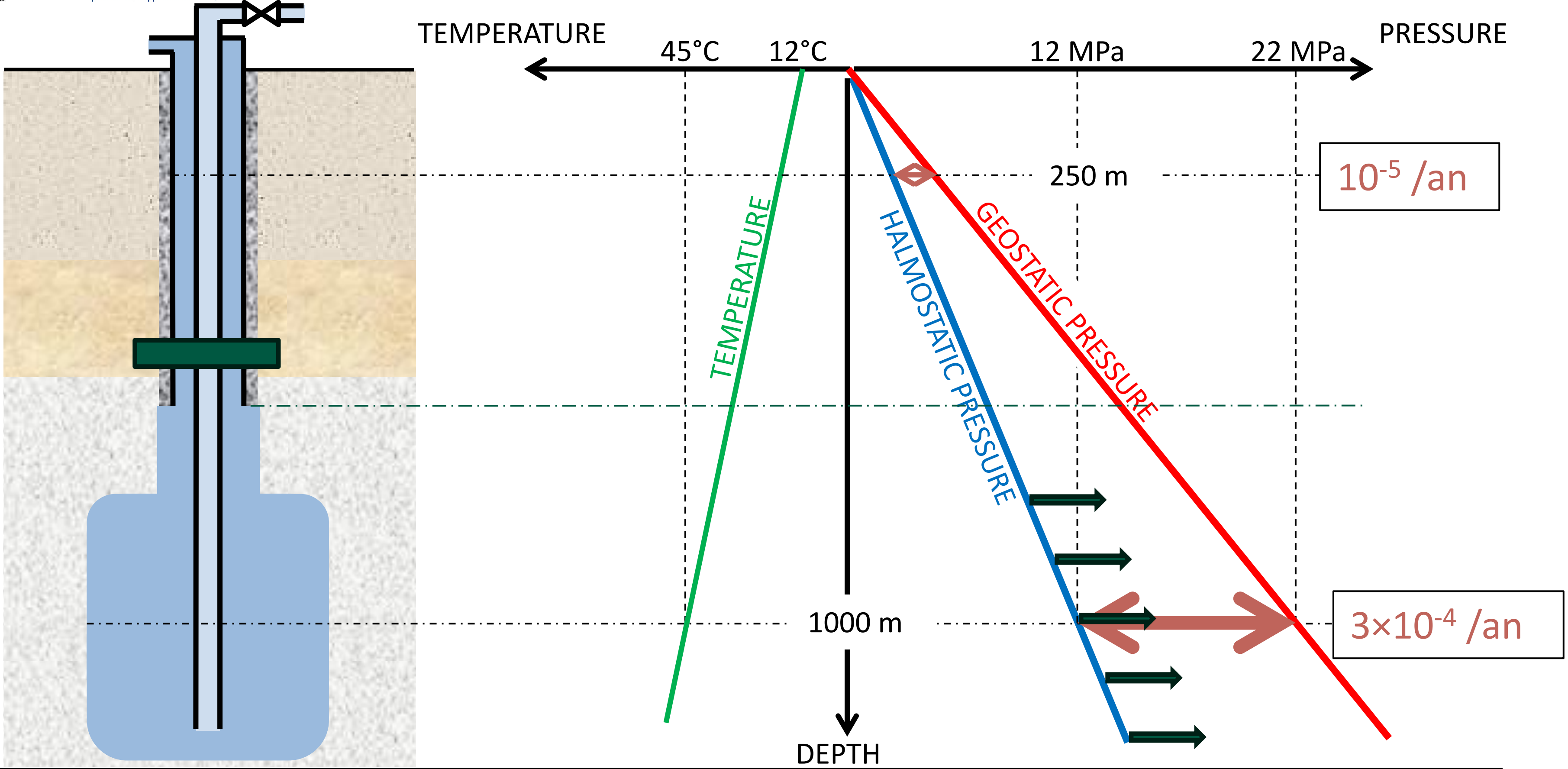
SPR2 cavern, 1960s, liquid propane, 9000 m^3, 310 m depth

- **2001 - 2002:** Complete emptying of the caverns
- **2002 - 2003**: Monitoring of brine temperature in the caverns
- **2002 - 2003:** Hydrogeological assessment, including piezometric measurements and water analyses to check for brine leakage
- **2003 - 2004:** Removal of trapped propane (de-trapping operations)
- **2002 - 2004:** Tests and study to verify long-term stability and sealing of the caverns post-abandonment
- **2004:** Validation of results through long-term pressure test on a propane cavern with pressure monitoring
- **2005:** Measurement of cavern shape using sonar
- **2005:** Inspection of well casings
- **2005 - 2006**: Complete dismantling of surface installations (pipelines, cables, buildings, brine pond) and restoration of land for agricultural use
- **2005:** Installation of cement plugs in the wells



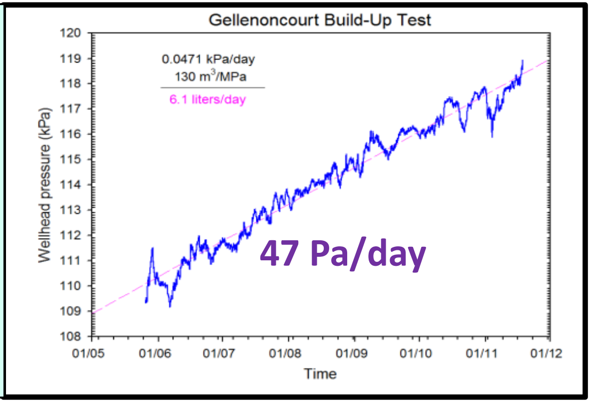
Bérest et Brouard, 2013

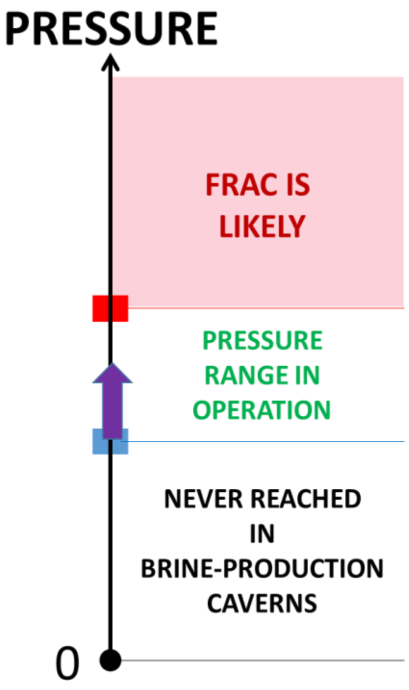
The brine **heats up** to reach thermal equilibrium with the rock mass



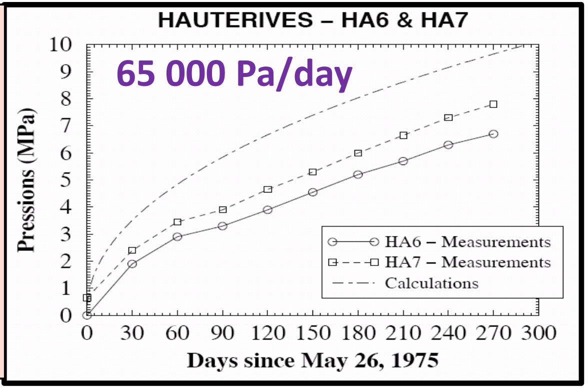
When a cavern is shut-in, cavern pressure **increases**, whatever age, depth, size, shape

Gellenoncourt, 300 m

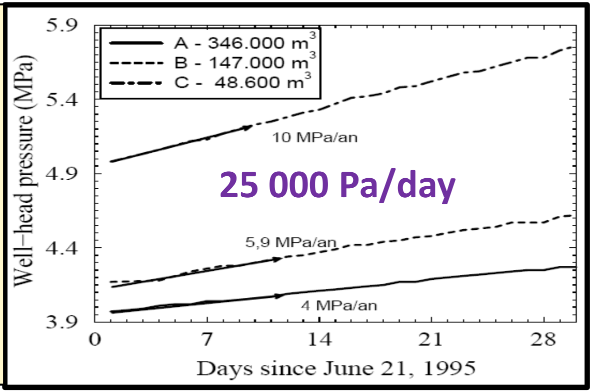




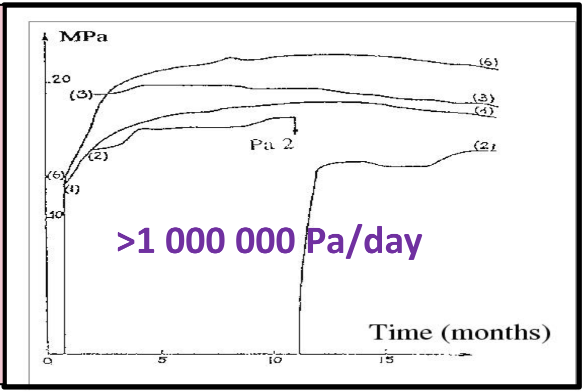
Hauterives, 1500 m



Etrez, France, 1350 m



Vauvert, 2000 m



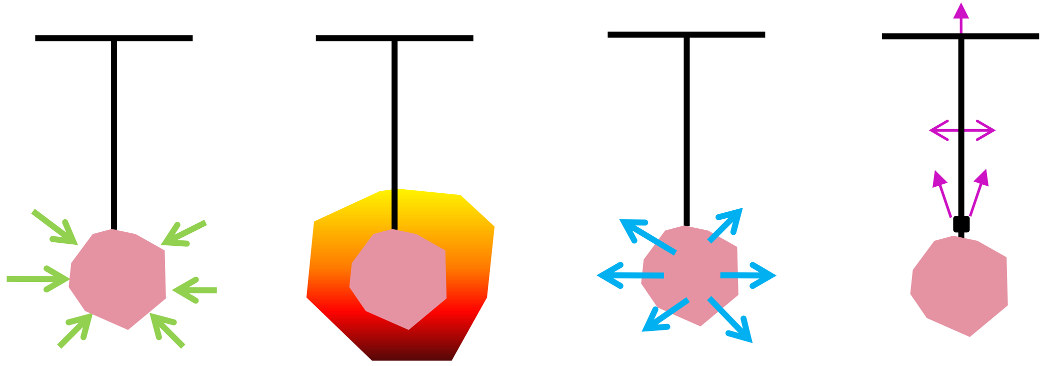
4 main phenomena for the long-term behavior

Cavern-Pressure Rate

$$\beta V \times \dot{P}_c = \boxed{\dot{V}_{creep} + \dot{V}_{therm} - \dot{V}_{perm}}$$

Volume change rate (m^3/j)

Cavern Compressibility



Creep Closure

Brine Thermal Expansion

Brine Micro-Permeation

Leaks

Risks associated with salt caverns abandonment

- **Hydrogeological disturbances**: Pollution of groundwater by brine, followed by surface resurgence.
- **Ground movement hazards**: Subsidence – spreading with a basin that expands, modification of the hydrographic network.

Risk = **Hazard** x Stakes

Hazard = Predisposition x Intensity

(green)	Not sensitive
(orange)	Sensitive
(red)	Highly sensitive

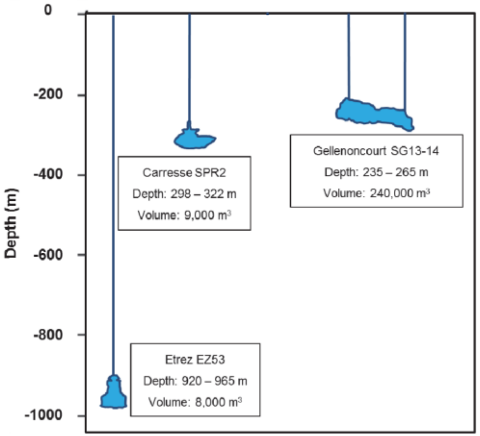
(green)	Low
(orange)	Medium
(red)	High

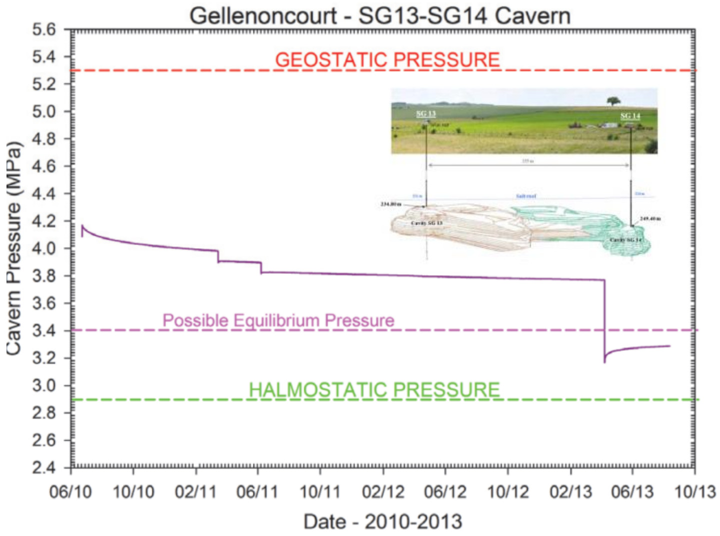
Hazards assessment is essential !

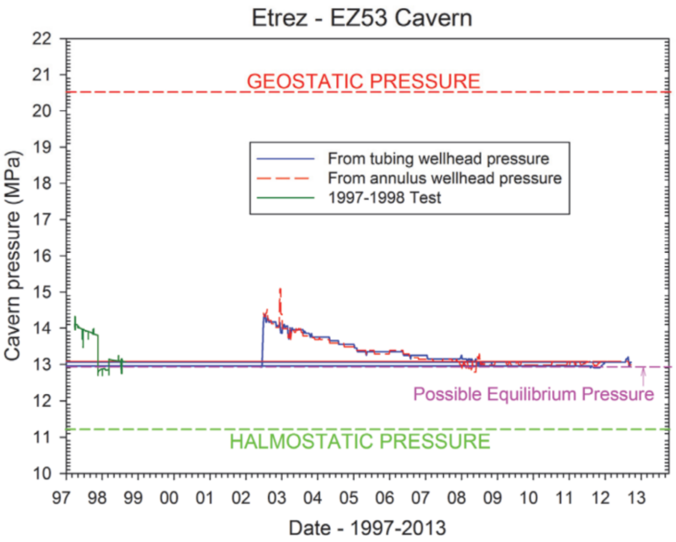
- **Progressive subsidence**
- Brittle subsidence
- **Localized collapse**
- **Generalized collapse**
- Compaction
- **Deep landslide**
- **Shallow landslide**
- Shallow slope movement
- Flow
- Landslide
- Rockfall
- Mine gas
- Heating – Combustion
- Alteration of spring flow regime
- Alteration of river flow regime
- Flooding of low-lying areas
- Flash flooding
- Water pollution
- Soil pollution
- Air pollution

Trial and error tests

Gellenoncourt (CSME) & Etrez (Storengy)



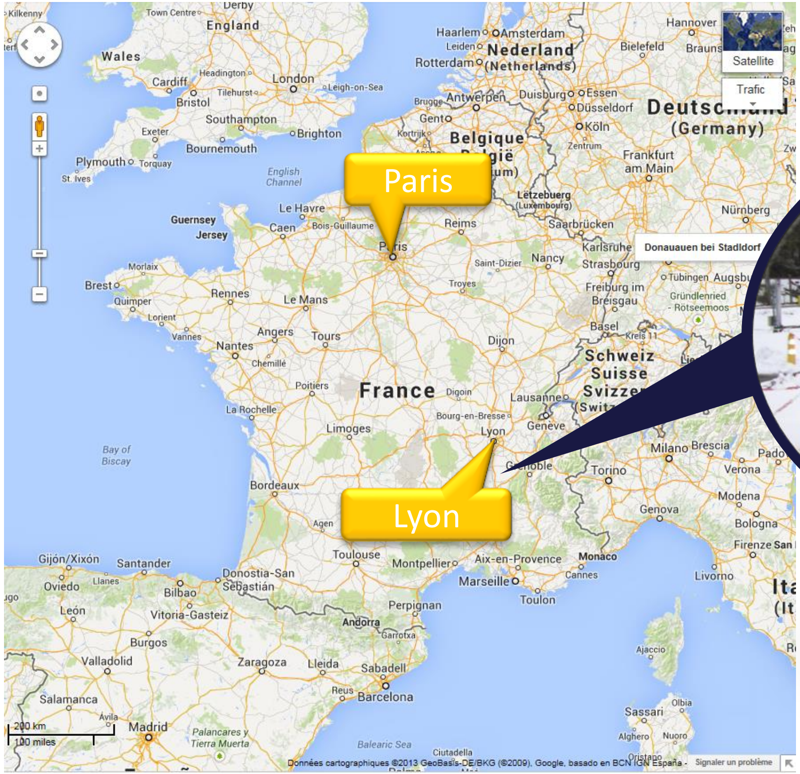




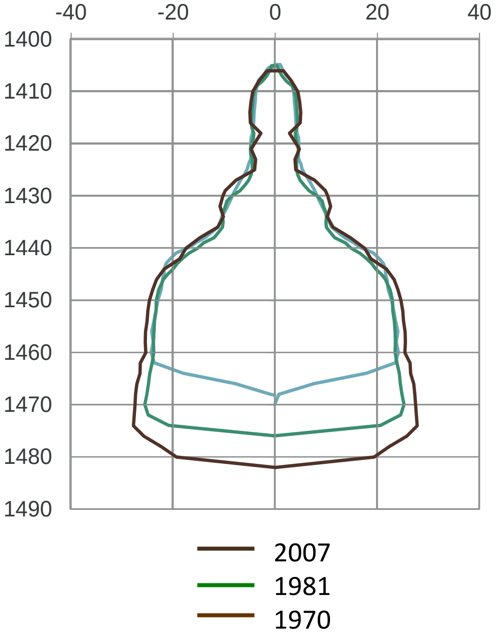
Bérest et Brouard, 2013

2. TE02 pilot in Tersanne, France

TE02 salt cavern



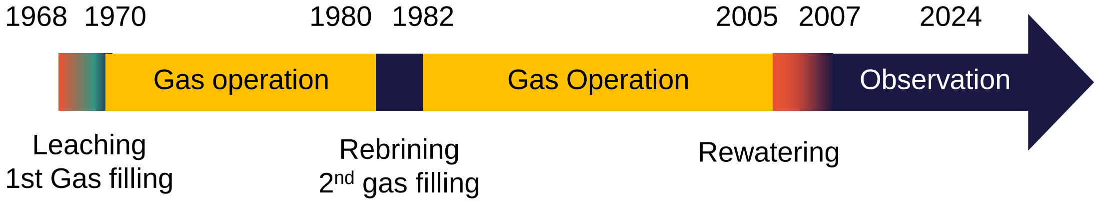
TE02 key figures



Sonars

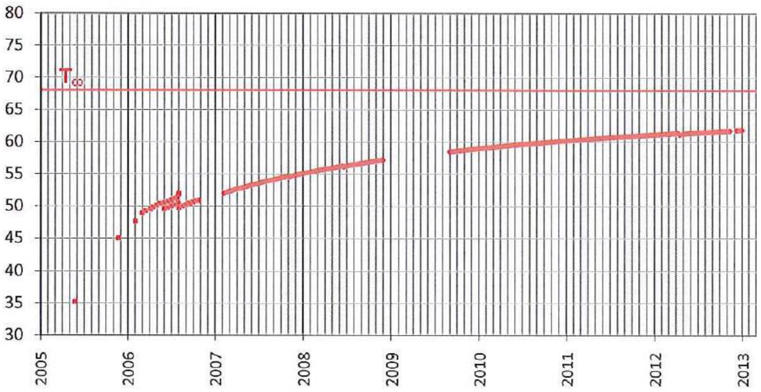
Why TE02 is an interesting pilot abandonment project:

- **Deep cavern (1,450m),**
- **Small volume (45,000 m^3),**
- **High initial temperature difference (Geothermal temperature ~68°C),**
- **High creep rate (loss of volume of 30% on the first 10 years),**
- **Low permeability (10^{-20} m² ~ 10^{-8} D).**

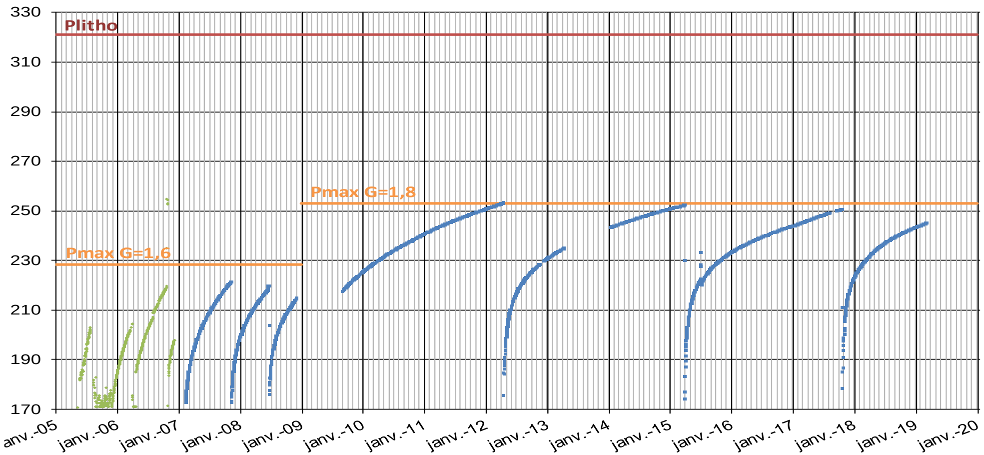


Observation in experimental phasis

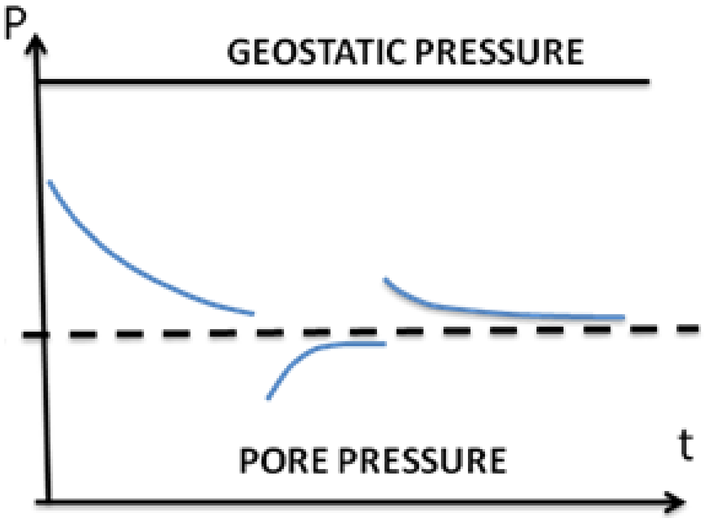
Temperature (°C)

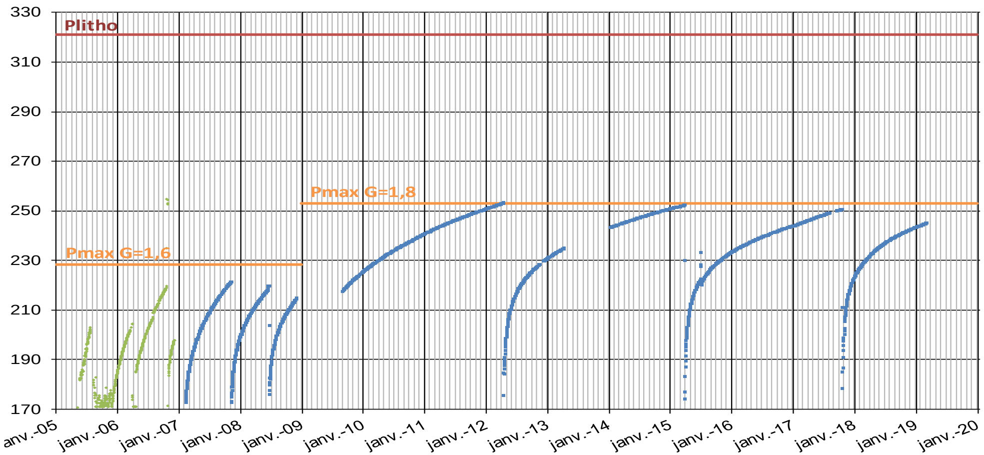


Pressure (bar)



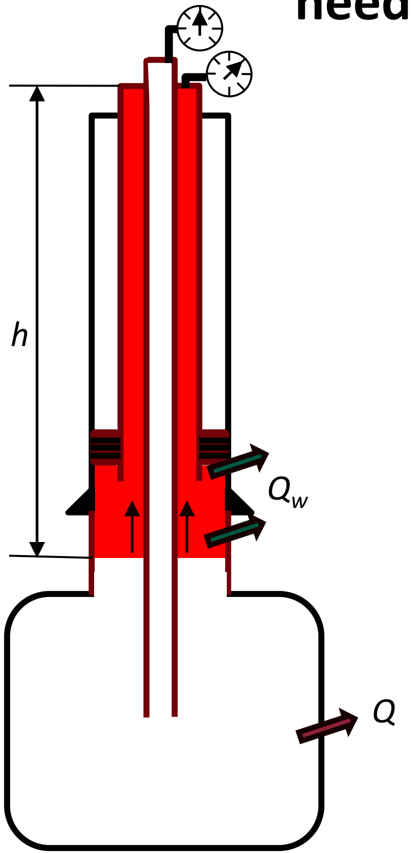
Equilibrium pressure – Trial and error test

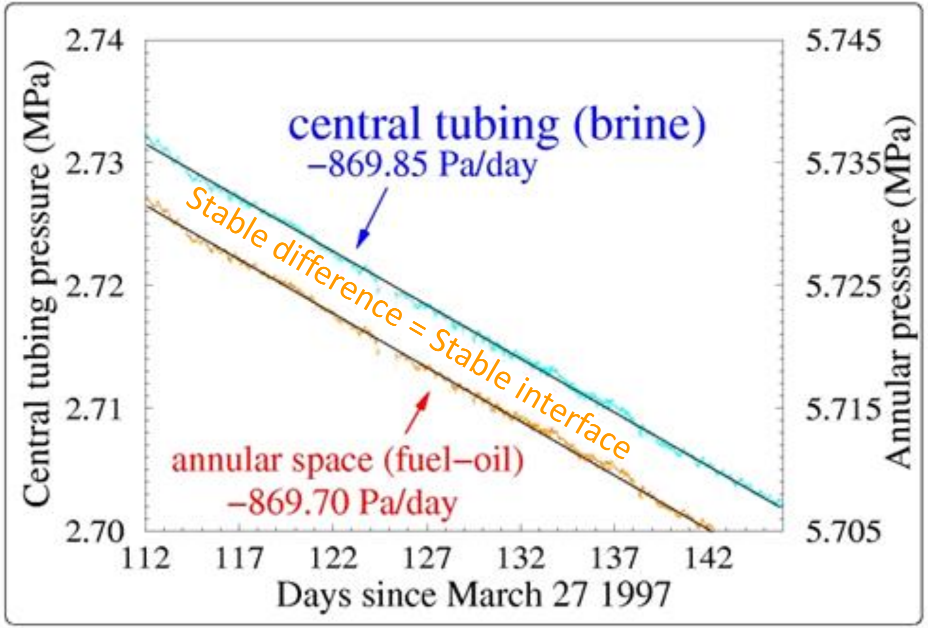




$$dV_{\text{creep closure}}\,(P_\infty - P) - dV_{\text{permeation}}\,(P - P_o) = \beta V * dP$$

Check the eventual leaks :
need of a central tubing to create a fuel/brine interface

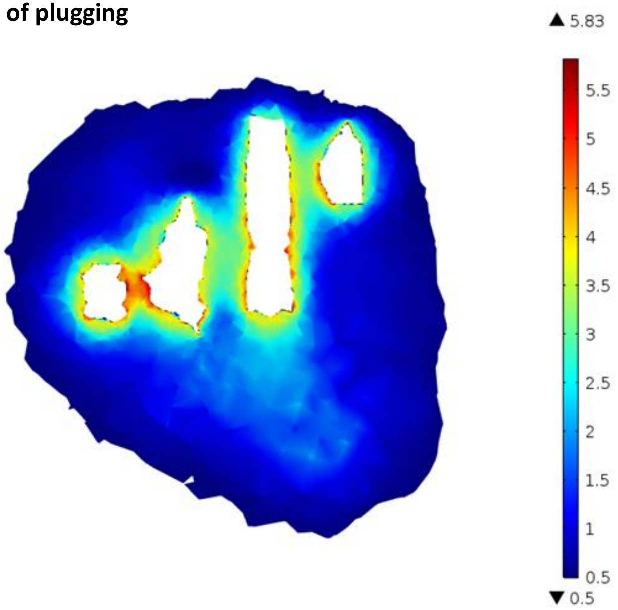




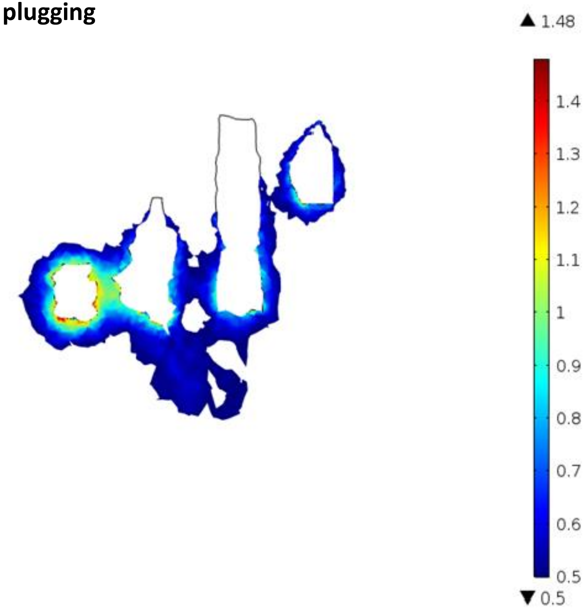
3. Predictive numerical computations

Modeling of salt caverns abandonment

At the time of plugging



100 years after plugging

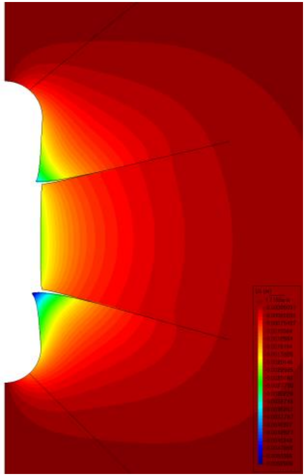


von Mises iso-stresses at the time of plugging (max: 5.8 MPa) and 100 years after plugging (max: 1.5 MPa) in a vertical cross-section plane passing through wells 5 and 7 (areas where the value is less than 0.5 MPa are masked).

2D plane numerical computations performed with COMSOL Multiphysics by Ineris (Thoraval and Renaud 2018).

Contributions of Fracture Mechanics (PhD thesis Hajar Habbani, 2024 – 2027)

Example : modeling cylindrical cavern with DISROC software developed by Pr. Amade Pouya



- <u>Theory and calculation parameters</u>

Fracture mechanics: CZFrac - Cohesive Zone Fracture with Damage-Plasticity and Unilateral Contact

$$\underline{\sigma} = [(1-\mathrm{D}).\mathrm{K}^{\mathrm{d}} + \mathrm{s}.\mathrm{k}_{\mathrm{r}}].\underline{\mathrm{u}}$$

The cohesion law describing the stress-displacement relationship at the interface (Soltanabad et al. 2023)

$$\tau = [(1-D)k_t + s\,k_{0t}]\,u_t^e \quad (2) \qquad \sigma_n = \left((1-\mathrm{D})k_n + \frac{S\,k_{0n}}{1+\frac{u_n}{e}}\right)u_n^e \ (3)$$

with :

$$\mathrm{D} = \begin{cases} 0 & ;\text{Intact initial state (i.e. a rock joint)} \\ 1 & ;\text{Damaged final state (e.g. a fracture)} \end{cases}$$

$$\mathrm{s} = \begin{cases} 0 & ;\text{if } \mathrm{u_n} > 0 \\ 1 & ;\text{else} \end{cases}$$

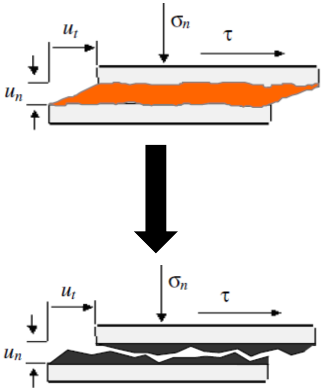
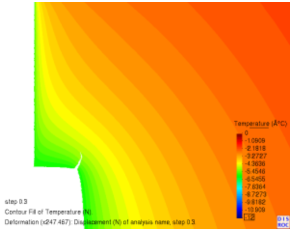
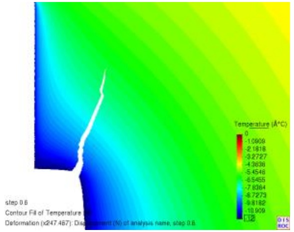


Fig1. Concept of the CZFrac law (Materials Catalogue, Fracsima)





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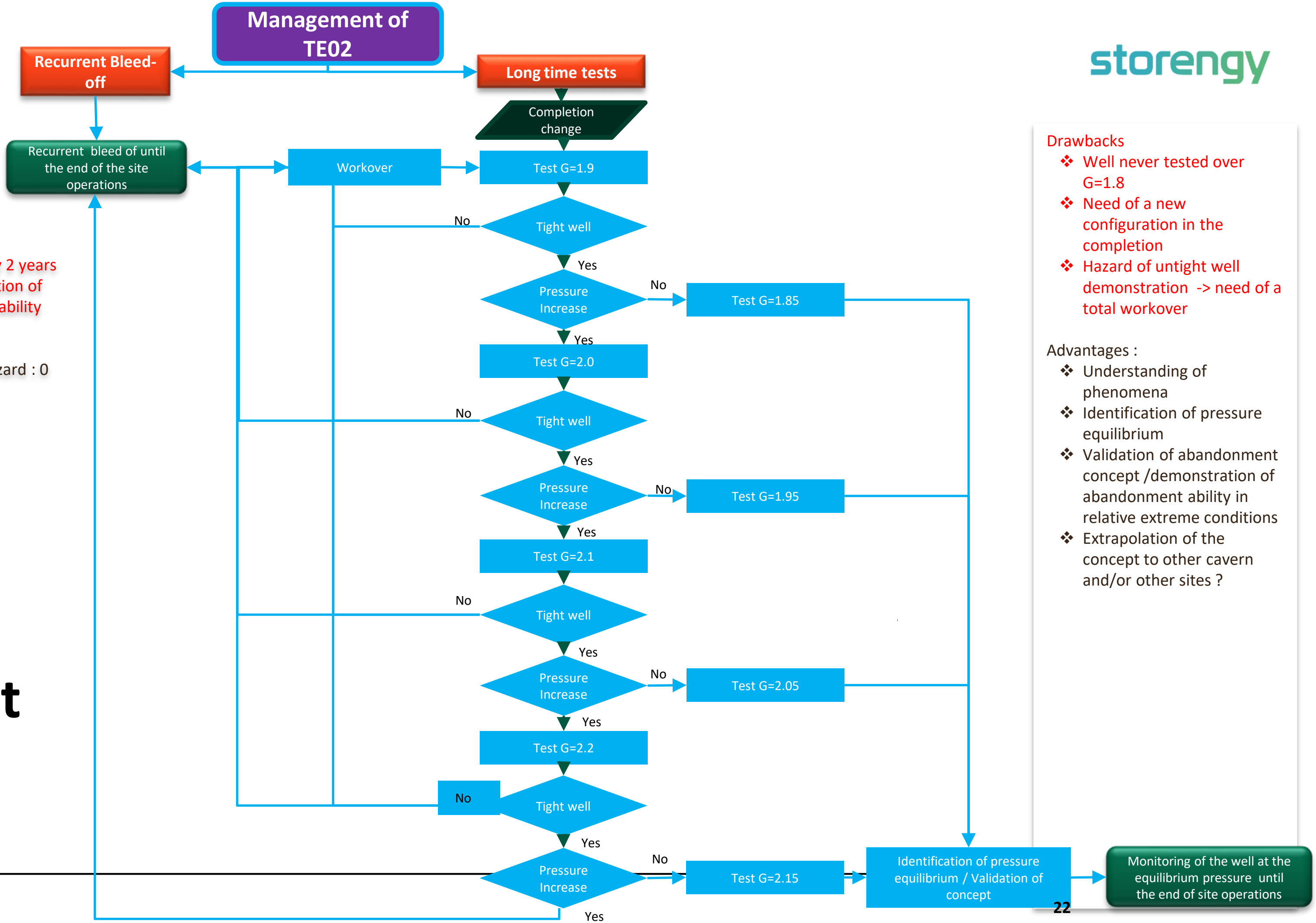
4. French procedures and regulation

Logigram of the experiment



Drawbacks

- Bleed-off every 2 years
- No demonstration of abandonment ability

Advantages

- operational hazard : 0

Drawbacks

- Well never tested over G=1.8
- Need of a new configuration in the completion
- Hazard of untight well demonstration -> need of a total workover

Advantages :

- Understanding of phenomena
- Identification of pressure equilibrium
- Validation of abandonment concept /demonstration of abandonment ability in relative extreme conditions
- Extrapolation of the concept to other cavern and/or other sites ?

Regulatory stages in the life of an underground storage in France

1. Underground Storage **Research**
2. Underground Storage **Concession** (max 50 years)
3. **Extensions** of Underground Storage (max 2! years)
   - AP1 – Definitive Cessation of work
4. **Site Restoration** (5-10 years)
   - **AP2 –** acknowledge the execution of measures
   - **Abandonment –** acceptance of the waiver of the storage title)
5. **Post-Abandonment**

OPERATOR	ADMINISTRATIVE AUTHORITY
Global presentation of the site (mining time and risks evaluation) to the DREAL Official deposition at the Prefecture	
Implementation of DADT	
	Receipt of the DADT
	Consultation, for their opinions, of concerned services
	possible prescription of additional measures
	First order given by the prefect
Implementation of measures	
	Verification of measures (minutes)
	Second order given by the prefect
End of DADT Process (end of the mine police but if important risks appear after this formality, mine police can be reactivated)	
Request approval for the abandonment of the site	
	Receipt of the request
	Inquiry of the request (review)
	Approval of the request
restitution of the site at the administration (end of operator monitoring + cash payment equal to 10 years for following monitoring)	

Admissibility of DADT/ instruction decision may take time

Monitoring measures = Operator responsability

AP1

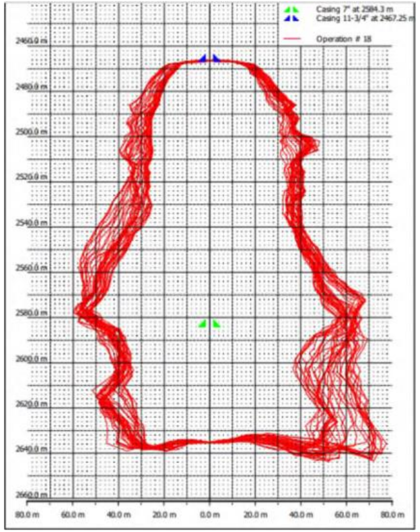
AP2

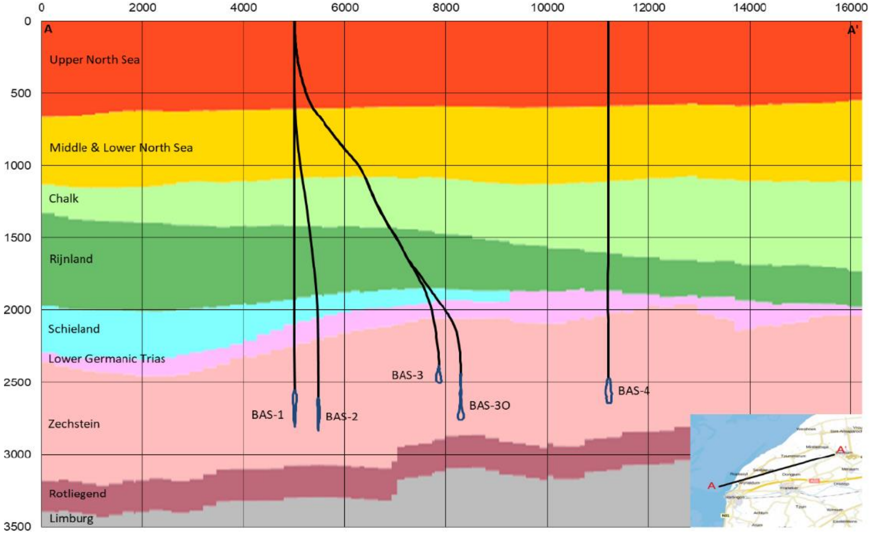
5. SMRI ongoing research projects on deep/tall cavern abandonment

Pre-abandonment – FRISIA caverns

Pre-abandonment & abandonment field data, results evaluation

- ❑ Volume: 970,000 m³
- ❑ Confirmed integrity of the LCC
- ❑ Shut-in as of 2022
- ❑ Current WHP ~ 260 bar
- ❑ Brine line not in operation
- ❑ Subsidence to be considered as a limiting factor
- ❑ Cavern not accessible
- ❑ Final sonar with temperature measurement during P&A (2027/2028)


Sonar measurement of cavern BAS-4



Vertical section of the Frisia caverns field in Harlingen

Deep or Tall Cavern Abandonment Testing and Analysis

Field testing on cavern Hvornum-02, Laboratory investigations & Numerical modelling

- ❑ Volume: 2.3 10^6 m^3
- ❑ LCCS depth : 361.5 m
- ❑ Roof depth: 778.5 m
- ❑ Sump depth: 1,438 m
- ❑ Average cavern temperature at last sonar: 26°C
- ❑ Average diameter: 78.1 m
- ❑ The well integrity was last proven by means of a USIT cement bond log in 2020.