KEM-17: Over-pressured caverns and leakage mechanisms

Gerco Hoedeman
Senior Inspector – State Supervision of Mines
KEM-17 - Two questions

1. What leakage mechanism is dominant when a salt cavern is closed?
   
   Permeation, hydraulic fracturing, localized leakage path?
   
   What happens when the brine pressure reaches the minimum principal stress?

2. How certain or uncertain can you be?
KEM-17 Team

Micro-scale

Prof. Dr. Janos L. Urai
Dr. Joyce Schmatz
Dr. Job Klaver

Cavern-scale

Dr. Benoit Brouard
Prof. Dr Pierre Bérest

Salt dome-scale

Dr. Tobias Baumann
Prof. Dr. Boris Kaus
Dr. Anton Popov

Conclusions and Recommendations
1. With the current knowledge it can not be predicted with certainty if a deep cavern will leak via slow permeation, a localized leakage path or hydraulic fracture.

2. Knowledge of micro-, cavern- and salt dome-scale is not integrated enough. Processes on all three levels influence the leakage mechanism.
KEM-17 - Two recommendations

1. Integrate knowledge of micro-, cavern- and salt dome-scale.

2. Improve knowledge in areas with uncertainty. Mainly the upscaling of micro-scale behavior to cavern- and dome-scale.
Three thoughts about caverns

Safe abandonment is the future of salt caverns

Be honest about uncertainty and deal with it

Think about caverns as a cavern system

#full-life-cycle
#energy-transition
#all-realistic-scenarios
#salt-heterogeneity
#leakage-mechanisms
#anistropic-stress
#cavern-interaction
#jungle-in-the-undergrond
Content

- State Supervision of Mines
- Salt mining in NL
- Why KEM-17?

- KEM-17 results
  - Micro-scale
  - Cavern-scale
  - Salt dome-scale
  - Conclusions

- KEM-17 implications
- Final thoughts
Staatstoezicht op de Mijnen

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
SodM Regulator:

**Sector**

- Production oil, gas and salt
- Geothermal energy
- Gas transportation network
- Underground storage
- Wind energy offshore

**Where?**

- Onshore and offshore
- Above ground, shallow subsurface and deep underground
Toezicht en handhaven

› Independent supervisor on compliance to the laws and rules for mining and energy production.

› Inspections on safety and environment from a technical and social perspective.

› Goal is positively improving behavior of operators. If necessary SodM can enforce compliance.
Handhaven

› Warning
› Last onder dwangsom
› Shut-down installation
› Advice minister to withdraw license
› Administrative fine
› Criminal investigation by prosecutor ‘Openbaar Ministerie’
Advise minister EZK

› SodM has the assignment to advise the minister when asked or when SodM deemes it necessary.

› Asked: Assess competency of operator and risks in operational plans.

› When deemeed necessary: new insights in risks, suggestions to change policy/law.

› Minister in the final authority who takes the decision.
Scientific research

Coordinate research:
› SodM pays for specific research at institutes like TNO, KNMI, CBS, RIVM, etc...

› The ‘Kennisprogramma Effecten Mijnbouw (KEM)’ is a cooperation with the ministry EZK.

› KEM-17 in this presentation is one of those projects.
Salt mining in the Netherlands

- State Supervision of Mines
- Salt mining in NL
- Why KEM-17?
- KEM-17 results
- KEM-17 implications
- Final thoughts
Q1: Salt mining Netherlands?
Q2: How small are the smallest caverns?

A 25 m

B 50 m

C 100 m
Q3: How large are the biggest caverns?

A. Euromast (185 m)

B. Eiffeltoren (324 m)

C. Burj Khalifa (829 m)
Q4: What is the price of a kilo salt?
Halite - NaCl

- Minder dan € 1 /kilo
- € 10 /kilo
- € 70+ /kilo

Alternative Silvite (KCl)

- € 0,20 /kilo
- € 80-95 /kilo
Magnesium salts

Bischofite: MgCl₂·6H₂O
Carnallite: KMgCl₃·6H₂O

€10 /kilo
€16 /kilo
Minder dan €1 /kilo
Caverns in the Netherlands

- **1919 Twente**
- **1964 Zuidwending**
- **1994 Frisia**
- **1952 Heiligerlee**
- **1972 Veendam**
- **2011 Gas storage Zuidwending**
- **2016 Strategic diesel storage Marssteden**
- **2012 Nitrogen storage Heiligerlee**
- **202? Hydrogen storage**
- **202? Compressed air storage**
Salt caverns in the Netherlands
Why KEM-17 Research?

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
Operators need:

- A concession ('winningsvergunning')
  - Show they are a capable operator
  - Area containing the salt
Solution mining – Legal requirements

Operators need:

- Mining plan (‘winningsplan’)
  - The way salt is mined
  - The risks: instability, seismicity, subsidence
  - How risks are taken away/minimized
  - The way caverns are abandoned

**Mijnbouwbesluit, article 25, 1f**

“... a description of the way caverns are abandoned after the end of production.”

“...een beschrijving van de wijze waarop de holruimte na beëindiging van de winning buiten gebruik wordt gesteld.”
Cavern closure – Leakage mechanism

› Long-standing controversy in salt-solution mining community:

› What happens to a brine pressure in a cavern reaches local minimum principal?
  – Permeation/percolation
  – Preferential leakage path
  – Hydraulic fracturing

“Will it fizz or will it bang?”

Braniac, Discovery Channel
Cavern closure – Leakage mechanism

Salt operators & consultants 2017

SodM 2017

Hope for 2019

Status 2021
April 2018: outflow ~100,000 m³ in ~2 days
Most likely frack from cavern to overburden
Reality catches up - Frisia

2018-2019: pulsing inflow from 1 to 100 m³. Brine migration through carnallite and halite
KEM-17 Micro-scale

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
KEM-17 Micro-scale

› Questions
  - What are the initial mechanical properties of the salt?
  - How do mechanical and flow properties evolve during cavern life time?
  - How does the stress field evolve over time?
  - What is the role of heterogeneity/impurities?
Micro-scale – Creep rate

Micro-physical understanding required

- Extrapolation of strain rates to much lower than laboratory.
- Contribution of deformation mechanisms:
  - Dislocation creep
  - Pressure solution creep
  - Microcracking, dilatancy, permeability increase

- Microstructure evolution is reasonably understood, but not integrated with large scale cavern behavior

Top: SMRI Research Report RR2020-1: Very slow creep tests – A basis for cavern stability analysis – Phase 2
Micro-scale – Permeation

- Challenge permeation
  - Dependent on microstructure and impurities.
  - Permeation may be strongly heterogeneous and localized.

![Image of permeation process](image.png)
Micro-scale – Summary

1. A homogeneous permeation zone is not the most obvious leakage mechanism.

2. A localized leakage path seems more realistic based on differences in grain size and heterogeneity in composition.

3. Micro-physical understanding is required to upscale creep and flow properties to cavern and dome-scale.
KEM-17 Cavern-scale

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
KEM-17 Cavern-scale

Questions

- How quickly does the pressure build up after closure?
  - Salt creep
  - Thermal expansion brine
- Can permeation keep up with pressure build up?
- What is the minimum principle stress?
Why does pressure increase?

- **Reason 1: Brine warming**
  - Large influence 1 MPa per 1 °C!
  - In large caverns it takes long time (low area vs volume)
  - Long waiting period is needed.
Why does pressure increase?

 › Reason 1: Brine warming
   - Characteristic time for equilibrating 75% of temperature gap.

   - Cavern X:
     ▪ H= 700 m, D= 100 m
     ▪ Time = 40 years

   - Cavern Y:
     ▪ H= 30 m, D= 100m
     ▪ Time = 7 years

\[
t_c \approx a \cdot \left[ \frac{V_c (m^3)}{100,000} \right]^{2/3} \times \exp \left[ -\frac{1}{2} \left( \frac{\ln(A/A_o)}{b} \right)^2 \right]
\]

\( a = 4.67, b = 1.97, \) and \( A_o = 0.91 \). \( A = \text{Height} / \text{Diameter} \)

Pressure build-up rates

Gellenoncourt
300 m

Stassfurt
600 m

Mont Belvieu
600 m

Etrez
1350 m

Hauterives
1500 m

Vauvert
2000 m
Why does pressure increase?

› Reason 2: Cavern creep closure
  - Salt is a viscous liquid
  - Cavern shrinks when brine pressure is smaller than stress in salt
  - Closure rate is highly non-linear dependent on pressure difference
Shallow cavern abandonment concept

- **P-decrease: Brine permeation**
  - Tests in small, shallow cavern show an equilibrium pressure.

- **Equilibrium pressure**
  - \( T_{\text{brine}} \approx T_{\text{salt}} \)
  - Rate creep closure = Rate permeation
  - Equilibrium pressure smaller than critical minimum principal stress
Shallow cavern abandonment concept

› P-decrease: Brine permeation
  - Tests in small, shallow cavern show an equilibrium pressure.

› Equilibrium pressure
  - $T_{\text{brine}} \approx T_{\text{salt}}$
  - Rate creep closure = Rate permeation
  - Equilibrium pressure smaller than critical minimum principal stress
Shallow cavern abandonment concept
Deep cavern abandonment

› More complex than shallow:
  - Higher temperatures cause higher creep and pressure build-up rates
  - Larger temperature gap to equilibrate
  - Tests more difficult, due to potential safety issues

› Complexity *high* caverns:
  - Large potential for over-pressure at cavern roof due to density difference
  - Socalled “Wallner’s margin”
High caverns – Wallner’s margin

[Diagram showing pressure and depth relationship with labels for Over-pressure and Under-pressure]
Cavern-scale - Summary

1. In shallow caverns a safe equilibrium pressure may be reached.
2. In deep caverns the pressure increase may be too rapid to accommodate by permeation.
3. In high caverns there is a large potential for overpressure.
4. SodM: The minimum principal stress may be lower than expected.
KEM-17 Dome-scale

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
Dome-scale

› Literature: What is known about the stress state in salt formations?

› Rheology: How to close the gap between micro-scale and macro-scale?

› What initial stress magnitudes can we expect?
Dome-scale

† Often the initial state of stress in a salt body is isotropic. How realistic is this?

† Numerical simulations were performed of relevant pillow and dome structures.

† Variations in salt rheology, glacial loading and anhydrite layers were simulated.

† Challenge: Realistically upscaling PS-DC creep behavior from lab to dome-scale.
Dome-scale

- Simulation were done on salt pillow, flat-bedded salt and salt wall.
Dome-scale

- Simulations are run for:
  - Base case
  - No glacial (un-)loading
  - Different dislocation creep laws
  - No KMg-salt layers
  - No heterogeneities
Dome-scale – Summary

Conclusions
1. Flat-lying salt layers have the only small differential stresses.
2. Differential stresses are larger near:
   1. Top of salt structure
   2. Close to lateral edge of salt body
   3. Dense anhydrite stringers or weak KMg-salts.

Recommendations
1. Models can be calibrated with sonar and microstructural observations
2. Consider a range of creep rheologies to map bandwidth of uncertainty.
3. Simulate models including salt structure, overburden and cavern construction, operation and abandonment.
KEM-17 implications

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
1. With the current knowledge it can not be predicted with certainty if a deep cavern will leak via slow permeation, a localized leakage path or hydraulic fracture.

2. Knowledge of micro-, cavern- and salt dome-scale is not integrated enough. Processes on all three levels influence the leakage mechanism.
## What options do we have?

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure shut-in</td>
<td>If safe, least amount of impact/work</td>
<td>Chance of hydraulic fracture and rapid and more subsidence.</td>
</tr>
<tr>
<td>Safe, high brine pressure</td>
<td>Safe option</td>
<td>Very long period of pressure management required.</td>
</tr>
<tr>
<td>Drain as much brine as possible</td>
<td>Minimum risk for the future</td>
<td>Maximum subsidence</td>
</tr>
<tr>
<td>Fill caverns</td>
<td>Minimum risk for the future</td>
<td>Large operation required. Impact at surface.</td>
</tr>
</tbody>
</table>
Nedmag - Implications

› New mining plan for 2022

1. Only small cavern pairs
2. Thick salt roof above caverns
3. No increase in pressure only decrease
4. Bleed off all brine after production
5. More environment-friendly blanket
Frisia - Implications

- Worst case: Hydraulic fracturing in multiple big caverns
- Onshore Barradeel
  - On land the total subsidence is what matters.
  - Subsidence has to be compensated by measures ‘peilbeheer’ of the Waterschap.

- Offshore: Havenmond
  - Production is moving offshore
  - In the Waddenzee the subsidence rate is most relevant.
  - Can the rate of sedimentation keep up with the rate of subsidence?
Storage caverns

› We may need storage caverns for the energy transition.

› Question regulator:
  – Are the caverns safe for the full life cycle, including abandonment?
  – What are the risks, uncertainties and control measures?

› Question ministry EZK:
  – Do the benefits outway the consequences?
  – Surface subsidence, impact surface facilities, etc...

TNO 2018 RR11372 – Ondergrondse opslag in Nederland – Technische verkenning
Final thoughts

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
6. Final thoughts
Three last thoughts about caverns

Safe abandonment is the future of salt caverns

Be honest about uncertainty and deal with it

Think about caverns as a cavern system

#full-life-cycle
#energy-transition

#all-realistic-scenarios
#salt-heterogeneity
#leakage-mechanisms
#anistropic-stress

#cavern-interaction
#jungle-in-the-undergrond
KEM-17 reports

1. Micro-scale report
2. Cavern-scale report
3. Dome-scale report
4. Conclusions and recommendations
5. Practical measures
6. Dutch summary

Reports can be found at KEM-website and SodM.nl > Search > KEM-17
Credits: KEM-17 Team

Micro-scale

Prof. Dr. Janos L. Urai
Dr. Joyce Schmatz
Dr. Job Klaver

Cavern-scale

Dr. Benoit Brouard
Prof. Dr Pierre Bérest

Salt dome-scale

Dr. Tobias Baumann
Prof. Dr. Boris Kaus
Dr. Anton Popov

Conclusions and Recommendations