KEM-28: *Risk assessment for Underground Hydrogen Storage (UHS) in Salt Caverns and Interaction with other Underground Storage Locations in The Netherlands*

KEM Quality review

Description of the scientific quality of the results (team, research method, research results, quality of the products, …), if needed external review result (project evaluation text website)

The overall objectives of this project were the development of guidelines and delineation of strategies for risk analysis, risk management and risk mitigation in relation to the underground storage of hydrogen (UHS) in a conglomerate of salt caverns onshore in the Netherlands. In particular, the research had to aim at quantifying and ranking the risks based on different failure scenarios, taking into account the likelihood of their occurrence and effects, and identifying measures to mitigate those risks.

The project was contracted to the H2 Cavern Conglomerate Consortium, composed of SmartTectonics GmbH, Germany; Brouard Consulting, France; MaP – Microstructures and Pores GmbH, Germany: Pondera Geo Energy, Netherlands; and GeoStructures Consultancy for Structural Geology and Geomechanics, Netherlands. MaP was in charge of the project management. The quality of the research team is, in general, assessed as high, with team members who have a broad expertise covering the areas of the project. The project started in May 2022 and the final reports were submitted in November 2023.

The work consisted of four main tasks:

i) A literature review on hazard and risks for UHS in conglomerates of salt caverns in the Northern and North-eastern Netherlands (focusing on the Zechstein salt layer), including a database of (near-)accidents occurred in the construction and operation of conglomerates of salt caverns for gas and/or oil storage, identifying the causes and consequences and an analysis of the likelihood of occurrence.

ii) A geomechanical study on the stability of the cavern field, seismicity and induced seismicity assuming that a conglomerate of salt caverns are used for storage of hydrogen and other underground storages (CAES, natural gas, CO2) or salt production.

iii) A generic risk analysis (semi-quantitative) in terms of health, safety and environment, related to UHS in conglomerates of salt caverns in the Zechstein salt of the Northern Netherlands. Also, insight on the onset of biotic and abiotic geochemical processes in salt caverns and recommendations for further research should be provided.

iv) A recommended strategy for a quantitative risk analysis, in terms of health, safety and environment, related to UHS in conglomerates of salt caverns in the Zechstein salt of the Northern Netherlands, as well as risk management and risk mitigation of conglomerates of UHS in salt caverns onshore, including criteria for spatial planning and locations of salt caverns.

The deliverables were presented in two final reports: a Phase 1 report of 259 pages on literature review, and a final report of 791 pages, that included the phase 1 report and reports on the other three tasks. The results of Task 1 is reported in Part 1 of the report, the results of Task 2 in Part 2 of the report and the results of Tasks 3 and 4 in a combined “Part 3&4” of the report.

Part 1: Literature review

The literature review, which was presented in the Phase I report, is quite extensive (in terms of references studied) and exhaustive (covering all relevant issues). It is a valuable compilation of the existing knowledge on the storage of liquids and gasses in (conglomerates of) salt caverns. It gives a thorough overview of the current experience with the more than 2000 salt caverns that are in operation worldwide. All relevant physical, chemical, and biological processes are described, potential problems that may occur are explained, and hazards and risks of storage in salt caverns are discussed. An important part of Phase 1 report was an extensive database of (near-)accidents. Whenever relevant, the significance of various aspects for the Dutch situation has been highlighted and discussed. Based on their report, they identify knowledge gap in relation to the design, operation, and risks associated with the storage of hydrogen in a conglomerate of salt caverns. Based on that, they formulate recommendations for further investigation and methods for selection of sites.

Part 2: Geomechanical study

Chapter 1 of Part 2 presents results related to task ii, aiming for **a geomechanical analysis of stability of the cavern field related to typical hydrogen-storage configurations**. The chapter describes six modelling studies which were performed: 1) modelling of well thermodynamics, 2) creation of 2D and 3D parameterized finite element models, 3) numerical calculations including sensitivity analysis, 4) blowout modelling, 5) workover of a reference case, and 6) analysis of the mechanical stability of a cluster of 9 caverns (task 6). All six studies are based on the use of software LOCAS. The chapter is structured in several sub-sections which are not structured in terms of the six studies. While the characterization of the relevant physics, including the discussion of constitutive laws, is qualitatively reasonable, the full set of governing equations, which is the basis for numerical modelling, is not presented in the chapter, and there is also no reference to the full set of governing equations. The discussion of relevant cavern configurations and related parameters, as well as operational parameters and subsurface characteristics seem relevant and reasonable, and a comprehensive overview is given based on relevant references. However, the Finite Element modelling seems to have problems as evident from the numerical results. As the rock parameters are homogeneous, monotone spatial results should be expected, but there are spatial spurious oscillations in the numerical results presented in plots of effective stress. Also, quantities derived from the numerical results such as computed dilation/dilatancy, and the related so called “dilation Factor of Safety” show similar spurious oscillations. While the details of the numerical approach are not presented or referenced in the report, the spurious oscillations appearing in the results indicate that there are problems with the numerical solution strategy. It is therefore not possible to have confidence in the quantitative analysis that is made based on these results. This includes the comprehensive sensitivity analysis of more than 50 different configurations, varying the depth of the cavern, its maximum diameter, the cycling frequency and the minimum pressure. In the sensitivity analysis, 14 indicators are defined to compare the mechanical stability and energy efficiency of the cases considered. While the overall concept and setup of the sensitivity analysis is reasonable, the quantitative results from the analysis cannot be considered as reliable due to the issues with the numerical results. However, the setup of the experiments are of interest for future work on numerical modelling of geomechanical effects. The more generic conclusions drawn from the study may also have interest as hypotheses for future studies. An additional shortcoming of Chapter 1 of Part 2 is that many of the figures are difficult to read as they are merely screen shots from results of the simulation software without any postprocessing and/or that the discussions of the results are limited.

In Chapter 2 of Part 2, **results of a large-scale 3D thermomechanical modelling and qualitative considerations on associated seismicity** are presented. In this study, the effects of a realistic, design-optimized, hydrogen-filled nine-cavern cluster on the host rock is investigated, focusing on the changes in the brittle deformation and the induced stress field under cyclic loading conditions. They study the impact of an optimized cavern field on the dynamics of a typical salt dome and the adjacent side and overburden rock mass under various conditions. The cavern cluster design and pressure cycle conditions were selected based on the geomechanical analysis (Chapter 1). A series of 3D high-resolution coupled modelling computations with and without cavern fields are carried out; the state of stress and the degree of brittle deformation were compared. The most important findings are as follows. (i) Location-wise, a cavern field in the centre of the dome has the least impact on the brittle deformation of host rock and overburden despite the stress being notably disturbed within a few hundred meters. (ii) The degree to which the stress field is perturbed depends on the creep rheology of the rock salt and the internal stratigraphy with distinct mechanical properties. (iii) If the cavern field is located near the salt-sediment interface and in close proximity to faults, induced brittle deformation can be observed in the pre-existing fault zones.

Chapter 3 reports on the study of **durability of salt rheology with respect to heterogeneities** like Kristallbrockensalz and anhydrite and the effect of second-phase rock salt impurities on the effective long-term creep properties of non-homogeneous rock salt. The study is based on a comprehensive analysis of numerical creep tests. A dataset of 420 synthetic models with varying intrinsic rock phases of rock salt (i.e., halite matrix, halite mega grains and anhydrite) were generated. The results show that only if the volume fraction of impurities (mega grains and anhydrite) is larger than 60 %, the effective creep behaviour of the rock salt conglomerate will be affected, because the impurities build a skeleton that dominates. In this case , the creep behaviour of the conglomerate will be less predictable and follows the individual and (uncertain) creep characteristics of the second-phase impurities.

Results of studies on **durability in salt with respect to biogeochemical processes** that may occur during hydrogen storage in salt caverns are presented in Chapter 4 of Part 2. These processes are associated with reactions involving H_2, CO_2, and H_2S with anhydrite and microbial activities. The study included laboratory investigation of microbial alteration of anhydrite and microstructural analysis of salt rock. The study's main findings include the influence of impurities and grain size on reaction kinetics, the impact of salt concentrations on sulfate-reducing bacteria and H_2S production, and the observation of dolomite formation due to microbial activity. Also it was found that anhydrite can allow the passage of aqueous solutions, causing increase of porosity, and affecting the mechanical and hydrogeological properties of salt rock. The study highlights the importance of site-specific investigations for understanding the biological and chemical impacts during hydrogen storage in various salt formations.

Part 3 and 4: Risk Analyses and Recommendations

Part 3 of the report is about generic risk analysis and a semi-quantitative risk assessment focussing on the operational phase of hydrogen storage. The results, however, are also useful for the risk assessment in other phases. A total of 31 stakeholders and 26 risks were assessed using the risk-based method. The results of the generic risk analysis represent a worst-case scenario. The analysis identifies 12 risks as potentially having a high impact. In particular, roof fall, tensile failure of cement debonding and other minerals due to alternating pressures and temperature, and leakage in vertical tubing/casing are found to have the highest impact. The report also suggests preventive measures to be taken related to the risk of surplus extraction of brine during construction.

Finally, in Part 4, recommendations for risk management and mitigation strategies are formulated. The main finding is that the hydrogen storage in a conglomerate of salt caverns in the Netherlands is technically feasible, but many preventive and corrective measures need to be implemented and additional research has to be performed to minimize risks. Also, the social acceptance remains an uncertain factor. The study identifies the following six research questions that have to be answered when designing a site-specific hydrogen storage project:
i) Characterization of the salt dome internal structure and mapping main heterogeneities and anomalous zones. This should be done using borehole logging and testing combined with site-specific integrated multi-scale modelling. I
ii) Research on creep properties and durability of the salt, damage and healing of salt, and determination of transport properties.
iii) Site-specific analysis of the mechanical stability of hydrogen storage caverns within an existing cluster of brine production or natural gas storage caverns using a site-specific model.
iv) Identifying conditions for the development of fractures when effective tensile stresses are developed in the cavern wall.
v) Generic research on prevention of micro fissures at the casing / cement / rock interfaces.
vi) Research on the interactions between various materials involved in the storage assembly with hydrogen and/or H_2S.

Summary on quality of research methodology and results: Except for the results reported in Part 2, Chapter 1 the quality of the work is high, relevant issues are addressed and deliverables were adequately met. Both quality and quantity of the work performed related to these parts of the report are very good considering the scope and resources in the project.

KEM Evaluation of the results

Evaluation whether the research questions are addressed adequately (questions answered, precision and uncertainties on outcomes, potential consequences on current practice addressed, ..) (project evaluation text website)

Specific research questions (R.Q.) of the study and corresponding main conclusions are given below:
R.Q. 1. What are the incremental effects of having conglomerates of salt caverns for UHS in the Northern and North-eastern Netherlands on the current levels of induced seismicity and subsidence, and how do they affect the stability of existing and new-to-construct salt cavern field(s)? The safe processing of produced brine in case that there will be no market for such large amounts of salt should be taken into account.

Conclusions: As commented in the previous section, numerical results show spurious oscillations (as), and thus the conclusions drawn from the sensitivity analysis cannot be accepted at face value. The stability measure depends on a dilation criterion, and a defined "factor of safety", both of which depend on the computed stresses. In the results, the "factor of safety" exhibits spurious oscillations in space, reflecting the problems in the numerical results as commented in the previous section of this evaluation report. Hence, the conclusions drawn in Part 2, Section 1.15, which are based on the results of 3D computations, are not reliable in a quantitative way. However, the following qualitative conclusions can be accepted:
- The stress field within a few hundred meters of a salt cavern will be significantly disturbed. The disturbance depends on the creep rheology of the rock salt and the dome internal stratigraphy.

- The best location for creating a cavern conglomerate is in the centre of the dome; this will have the least impact on the brittle deformation in the overburden.

- The cavern field should not be placed close to the salt-sediment interface and in the immediate vicinity of faults as it may result in induced brittle deformation in the pre-existing fault zones. This depends on the general dome dynamics.

R.Q. 2. What are the effects on the long-term durability (deformation and transport properties) of rocks surrounding the caverns and well materials in contact with hydrogen under an alternating pressure regime and what are the associated risks?

Conclusions:
- The development of a self-propagating damage zone in the salt rock of a hydrogen cavern is a real possibility. Such events may be caused by an interplay of stress changes due to cavern pressure, creation and destruction of porosity by microcracking, recrystallization, fracture healing, and salt deformation due to effective pressure changes and gas pressure gradients. The extent of these effects depends on the presence of heterogeneities (like anhydrite) and the nature of Kristallbrockensalz, and need to be determined by site-specific investigations and modelling.

- The presence of heterogeneities will not have a significant effect on the creep properties of the rock salt if their volume fraction is less than 20%.

- If the volume fraction of heterogeneities is 60 % or more, they will dominate the effective creep behaviour of the rock salt; a behaviour that is less predictable and follows the individual and (uncertain) creep properties of the mega grains and anhydrite impurities.

R.Q. 3. What are potential interactions between the stored hydrogen with the salt cavern itself and with the well infrastructure? Effects of possible permeation, changes in rheology, development of fractures, effects due to temperature and pressure differences in the cyclic operation of the storage location, and the long term effects on the installations had to be taken into account.

Conclusions: Due to the sudden passing away of a research team member (Janos Urai), numerical studies on the evolving rheology, transport properties, damage, and healing of salt could not be fully investigated and thus only limited conclusions could be reached., However, laboratory experiments were carried out, involving the visualisation of the onset of biological, chemical and structural changes in the sample material, down to the submicron pore scale, due to the presence of hydrogen. Dissolution of hydrogen gas in the brine leads to the formation of hydrogen sulphide which interacts with the surrounding rock salt and second phase lithologies, and thereby alters the composition of the stored gas. Also, changes in geometry and porosity may occur leading to the connectivity and permeability of the insoluble or low-soluble layers. The significance and consequences of these effects must be studied specifically for each storage site.

R.Q. 4. What are the possible interactions between a conglomerate with other nearby underground storage and/or production facilities? Interactions with gas production fields, gas fields used for CO_2 storage, and other salt caverns used for hydrogen storage or compressed air energy storage (CAES) had to be taken into account. Also, processes such as subsidence, casing deformation, salt deformation, mechanical feedback with the overburden and gas reservoirs below, and possible connection between caverns had to be considered.

The only relevant situation that is studied in relation to this question is the case of a brine production cavern in the corner of a cluster of hydrogen storage caverns. It was found that the corner cavern behaviour is practically unaffected by pressure cycling in other caverns. The reviewers could not find a sufficiently substantiated discussion of this research question in the report.

R.Q. 5. What are recommendations for risk management and mitigation? This had to include design criteria for dimensions, shape and depth of new caverns, distance between caverns, surface installation considerations, interaction with other possible underground storage techniques such as CAES and CO_2-storage, and brine processing.

Conclusions: In order to minimize risks, site-specific research must be carried out for each location. This includes: detailed geochemical studies and modelling, characterization of subsurface geologic conditions with sufficient spatial resolution to identify critical lithologies, and supplementary laboratory and in-situ testing. In particular, mineralogical, chemical, physical, and microbiological conditions of the site before injecting hydrogen into a cavern and during storage must be investigated and monitored. Risk measures should be evaluated and reported to all relevant stakeholders and the risk analyses should be updated during various stages of storage. Also, the following preventive and corrective measures must be considered:

Main preventive measures: selecting the best shape, depth, and location for caverns; using H_2- and H_2S-certified material; establishing minimum preconditions for H_2 storage caverns (regular cavern and well tests, sonar measurements, high-quality Mechanical Integrity Tests, cement bonding log, safety valve tests); open, pro-active communication with stakeholders (public, politics, and press) and other operators; implementing strict regulations (e.g., with respect to stacked mining) and strengthening the role of regulator.

Main corrective measures: developing and implementing a rapid response plan; adaptation of the storage properties (e.g., pressures (min/max), max. yield); treatment of micro-annuli and other parts with special materials (resins, silicates, etc.) and biological treatment); controlled production and/or flaring of H_2; open communication with stakeholders (public, politics and press) and other operators.

Overall, social acceptance of hydrogen storage is an important part of the success or failure of hydrogen storage and should receive attention from the government.

The KEM panel finds that most research questions have been addressed.

KEM interpretation of the outcome

The interpretation of the results (consequences on methods/data to be used in practice, con risk instrument modules, on inspection procedures and operator procedures, ..) (project evaluation text website)

This research has been about the feasibility of underground storage of hydrogen (UHS) in a conglomerate of salt caverns onshore in the Netherlands, analysing potential failure scenarios and quantifying and ranking the corresponding risks, and identifying measures to mitigate those risks. General guidelines and design factors for a conglomerate of nine identical salt caverns are determined and described. The results and conclusions of this study provide the basis for integrating the creep of a highly heterogeneous multi-phase rock salt into thermomechanical simulations, which ultimately supports the risk assessments of UHS in salt caverns. Based on this study, the following is established:

- Hydrogen storage in a conglomerate of salt caverns in the Netherlands is technically feasible. However, many preventive and corrective measures have to be implemented and additional site-specific research have to be performed to minimize risks.

- Use of old wells and caverns for storage should be avoided as they are not made of H_2- and H_2S-certified material. One should preferably start with new caverns.

- It is better to start with a relatively small design with low frequency operation. This should be accompanied with monitoring and performing additional research, and continuous evaluation.

It must be noted that this study has been a generic research and results cannot be applied directly to specific cases. Site-specific characterization and modelling is required for each individual UHS project. The main topics for **additional site-specific research** are:
- An improved characterization of the salt dome internal structure, including anomalous zones, using borehole logging and testing and site-specific integrated multi-scale modelling. This includes improving specific tools for the investigation of internal salt stratigraphy and heterogeneities.
- Creep research (e.g., effect of grainsize and impurities; calibration of a transient creep law for Dutch salt) and durability of the salt, including transport properties, damage and healing of salt.
- Analysis of the stability of a cluster of caverns that could be leached asynchronously, and analysis of possible development of fractures when effective tensile effective stresses appear on the cavern wall.
- Analysis of the surface effects of a blowout (jet fire, flash fire and unconfined vapor explosion), evolution of the hydrogen plume formed by a leak for several atmospheric conditions, calculation of the distance of effects for several scenarios.
- Research on prevention of micro annuli at the casing / cement / rock interfaces.
- Research on interaction of materials with hydrogen and/or H_2S.
- Development of high-quality mechanical integrity tests (MIT) including clear success criteria.

Results of this project and its recommendations are useful to the government and the regulators in formulating policies and informing the public, and companies that are involved in subsurface production or storage activities in the Netherlands. It is, however, important that more development and research is done to establish appropriate simulation models for quantitative predictions, risk assessment and uncertainty quantifications. In particular, the geometries of salt caverns, possibly in complex three-dimensional clusters, call for the application of numerical methods that are stable and do not suffer from locking phenomena. Specifically, the KEM panel recommends that numerical modelling of Part 2, Chapter 1, is revisited with appropriately verified simulation tools.

Closure text for the website

A summary in simple terms of the goal, the outcome and impact on mining policies or toolboxes of the research project (project evaluation text website)

The overall objectives of this project were the development of guidelines and delineation of strategies for risk analysis, risk management and risk mitigation in relation to the underground storage of hydrogen (UHS) in a conglomerate of salt caverns onshore in the Netherlands. In particular, the research had to aim at quantifying and ranking the risks based on different failure scenarios, taking into account the likelihood of their occurrence and effects, and identifying measures to mitigate those risks. The following conclusions and recommendations can be formulated:

- Hydrogen storage in a conglomerate of salt caverns in the Netherlands is technically feasible. However, many preventive and corrective measures have to be implemented and additional site-specific research have to be performed to minimize risks.

- Use of old wells and caverns for storage should be avoided as they are not made of H_2- and H_2S-certified material. One should preferably start with new caverns.

- It is better to start with a relatively small design with low frequency operation. This should be accompanied with monitoring and performing additional research, and continuous evaluation.

- The best location for creating a cavern conglomerate is in the centre of the dome; this will have the least impact on the brittle deformation in the overburden.

- The cavern field should not be placed close to the salt-sediment interface and in the immediate vicinity of faults as it may result in induced brittle deformation in the pre-existing fault zones. This depends on the general dome dynamics.

- The stress field within a few hundred meters of a salt cavern will be significantly disturbed. The disturbance depends on the creep rheology of the rock salt and the dome internal stratigraphy.

- The development of a self-propagating damage zone in the salt rock of a hydrogen cavern is a real possibility. Such events may be caused by an interplay of stress changes due to cavern pressure, creation and destruction of porosity by microcracking, recrystallization, fracture healing, and salt deformation due to effective pressure changes and gas pressure gradients. The extent of these effects depends on the presence of heterogeneities (like anhydrite) and the nature of Kristallbrockensalz, and need to be determined by site-specific investigations and modelling.

- The presence of heterogeneities will not have a significant effect on the creep properties of the rock salt if their volume fraction is less than 20%.

- If the volume fraction of heterogeneities is 60 % or more, they will dominate the effective creep behaviour of the rock salt; a behaviour that is less predictable and follows the individual and (uncertain) creep properties of the mega grains and anhydrite impurities.

- Dissolution of hydrogen gas in the brine leads to the formation of hydrogen sulphide which interacts with the surrounding rock salt and second phase lithologies, and thereby alters the composition of the stored gas. Also, changes in geometry and porosity may occur leading to the connectivity and permeability of the insoluble or low-soluble layers. The significance and consequences of these effects must be studied specifically for each storage site.

- Site-specific research must be carried out for each location for a thorough risk analysis. This includes: detailed geochemical studies and modelling, characterization of subsurface geologic conditions with sufficient spatial resolution to identify critical lithologies, and supplementary laboratory and in-situ testing. In particular, mineralogical, chemical, physical, and microbiological conditions of the site before injecting hydrogen into a cavern and during storage must be investigated and monitored. Analysis of the surface effects of a blowout (jet fire, flash fire and unconfined vapor explosion), evolution of the hydrogen plume formed by a leak for several atmospheric conditions, and calculation of the distance of effects for several scenarios.

- Risk measures should be evaluated and reported to all relevant stakeholders and the risk analyses should be updated during various stages of storage. Also, the following preventive and corrective measures must be considered:

Main preventive measures: selecting the best shape, depth, and location for caverns; determining methods of prevention of micro annuli at the casing / cement / rock interfaces, generic research on interaction of materials with hydrogen and/or H_2S and using H_2- and H_2S-certified material; establishing minimum preconditions for H_2 storage caverns (regular cavern and well tests, sonar measurements, high-quality Mechanical Integrity Tests including clear success criteria, cement bonding log, safety valve tests); open, pro-active communication with stakeholders (public, politics, and press) and other operators; implementing strict regulations (e.g., with respect to stacked mining) and strengthening the role of regulator.

Main corrective measures: developing and implementing a rapid response plan; adaptation of the storage properties (e.g., pressures (min/max), max. yield); treatment of micro-annuli and other parts with special materials (resins, silicates, etc.) and biological treatment); controlled production and/or flaring of H_2; open communication with stakeholders (public, politics and press) and other operators.

Overall, social acceptance of hydrogen storage is an important part of the success or failure of hydrogen storage and should receive attention from the government.