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Abstract

The Nord-West Kavernengesellschaft mbH (NWKG) operates 39 caverns at the Rüstringen site for the storage of various types of crude oil. As the demand for oil storage will decrease in course of the planned energy transition, thus freeing up storage space, it is planned to store green hydrogen in the future.

In preparation for this change, a concept for conversion of the Rüstringen site to a green hydrogen storage facility has been developed, which builds upon interdisciplinary cooperation spanning the fields of drilling, geomechanics, solution mining and geology. The concept is based on the current cavern field layout and the current storage medium. Accordingly, an initial determination has been made regarding which caverns should be abandoned due to their incompatibility for hydrogen storage. Secondly, a set of caverns that are suitable for conversion to store hydrogen have been identified. In the final step, potential locations for the construction of new caverns have been identified.

In order to provide insights into the practical implementation of this transition, a pilot project to convert the K410 oil storage cavern into a hydrogen storage cavern is introduced. For this project a comprehensive evaluation of the brine-filled cavern well has been conducted firstly, followed by the formulation of a systematic re-leaching plan as well as a geological assessment of the cavern. Subsequent to this, planning for the re-completion of the well is initiated. This planning encompasses the upgrading of the well in accordance with the prevailing state-of-the-art and the design of the resulting well completion for safe hydrogen storage.

Key words: rock salt, gas storage, salt caverns, hydrogen, conversion

1. Introduction

Nord-West Kavernengesellschaft mbH (NWKG) operates 39 caverns at the Wilhelmshaven-Rüstringen site for the storage of various types of crude oil. The Rüstringen cavern storage facility, located west of Wilhelmshaven, is the largest of NWKG's four storage facilities with a net storage volume of approx. 11 million m³ (see Figure 1).

Figure 1: Site plan of the NWKG cavern storage facility Rüstringen

Due to the focus on oil storage, the NWKG is currently storing exclusively liquid hydrocarbons. Due to a changing energy landscape it is expected that less oil will be stored throughout the upcoming years. In preparation for this transition, NWKG is evaluating possibilities to further use the existing caverns. In cooperation with DEEP.KBB GmbH (DEEP.KBB), a concept to convert the Rüstringen site into a hybrid storage site has been developed, storing both crude oil as well as gaseous media. Hydrogen has hereby been identified as the major gaseous storage medium, due to the local proximity of the cavern site to the port of Wilhelmshaven as well as a close connection to the planned European hydrogen backbone network. Based on these considerations, a sequence for the abandonment or conversion of existing caverns as well as the construction of new caverns for hydrogen storage has been devised, taking into account the legal requirement to store oil as well as the geological and geomechanical framework conditions of the site.

As a first step of this transition, NWKG set up a pilot project to convert the K410 oil storage cavern into a hydrogen storage cavern. The "K410 Kaskade" project was created to plan and execute this conversion. The project encompasses planning for the re-leaching of the cavern, including geomechanical, geological and integrity assessments of the brine-filled cavern well. This is followed by the detailed planning of the re-completion of the cavern. Planning includes the establishment of a second barrier through the installation of a new casing according to the state-of-the-art and the design of the well completion for safe hydrogen storage.

2. Transforming an Oil Cavern Field for Hydrogen Storage

NWKG evaluates the Rüstringen cavern site for potential hydrogen storage. Therefore, a three-staged approach including the abandonment or the conversion of existing caverns and the construction of new caverns is developed. The outcome of this approach is a field layout that allows the storage of crude oil along with hydrogen.

2.1 Background

From the four sites of the NWKG the Rüstingen cavern site was selected for conversion, due to several favorable characteristics. These include among others:

- Close proximity to an overseas port, offshore wind farms and planned electrolyzers (Figure 2)
- Connection to the "European Hydrogen Backbone"
- Existing discharge permit for the produced brine
- Site being a brownfield with existing cavern storage facilities as well as infrastructure
- Salt dome itself is well-known

Figure 2: Regional setting of Wilhelmshaven with the Rüstringen cavern site as well as areas of hydrogen production and hydrogen demand (Modified, Source: Deutsche Energie-Agentur GmbH; Fraunhofer-Institut für Schicht- und Oberflächentechnik IST, 2022)

Beside these advantages several other parameters on the surface and in the subsurface have to be considered. There are geological features such as the depth of the salt dome and the geological risk horizons. At the surface limiting parameters are the proximity to the city of Wilhelmshaven and therefore to civil infrastructure.

The following chapters describe the planning process and visualize the results using maps created in GIS.

2.2. Planning Process

The planning was carried out in four phases:

1) Depiction of all caverns with their geomechanical safety pillars
2) Identification of caverns with characteristics not suitable for further storage operations
3) Identification of caverns suitable for conversion to hydrogen storage based on:
    - geomechanical relations to the surrounding caverns
    - diameter increase during the re-leaching and cleaning process
    - possible enlargement, based on geological information (Figure 3)
4) Identification of areas for the construction of new caverns for hydrogen storage (Neocaverns) based on:
    - geomechanical relations to the surrounding caverns
    - geological features
    - target volume between 450,000 and 800,000 m^3

For every phase the potential field layout is presented in a map. The total cavity volume as well as possible volumes of stored gas and oil are estimated.

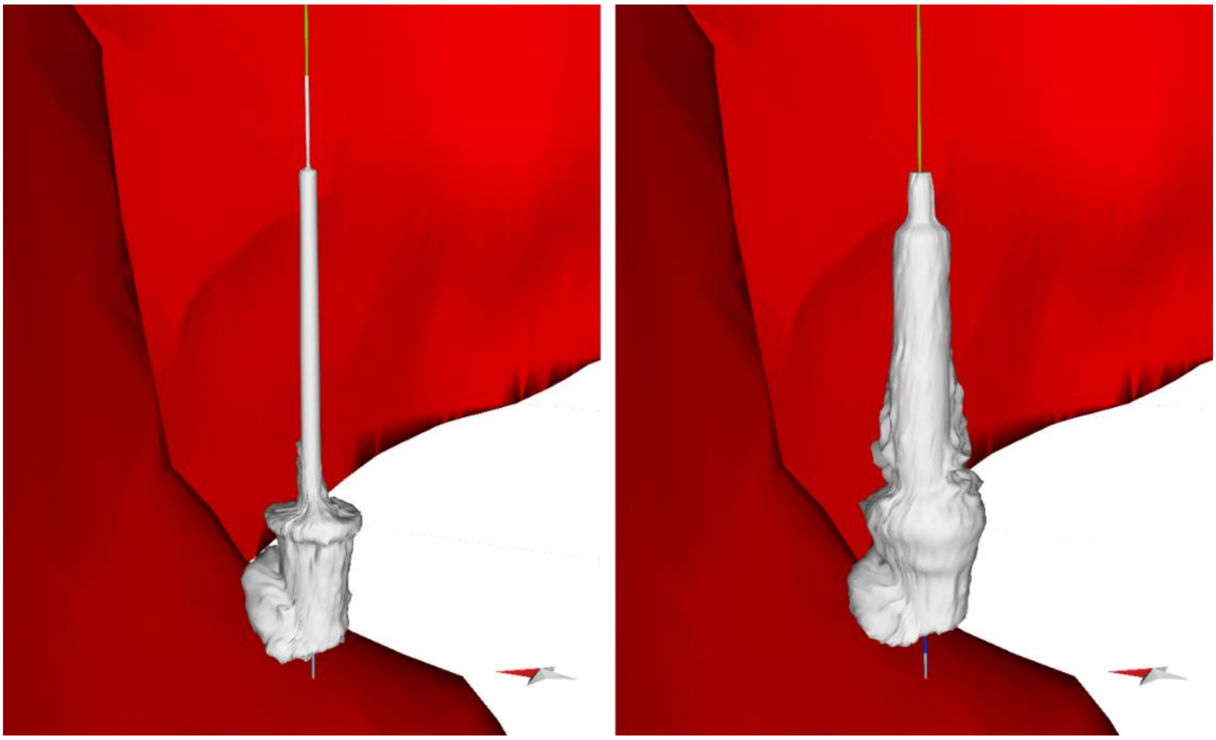

Figure 3: Depth specific enlargement in the upper part of the cavern K410 avoiding the solution of the geological risk horizon "Staßfurt potash seam" (red)

2.3 Parameters

As stated above several parameters need to be considered for the detailed planning. Among others these include geological, geomechanical, infrastructural and legal parameters, relevant for the planning stages conversion and construction:

- **Geological**: Different salt lithologies have to be considered in Rüstringen and evaluated for their suitability for the construction of caverns. The boundary between the suitable (Zechstein 2) and unsuitable (Zechstein 3 – Zechstein 4) salt is defined by the Staßfurt potash seam. The spatial extend of this horizon was constructed in a geological 3D model.
- **Geomechanical:** Neighboring caverns must maintain a certain distance according to the geomechanical safety pillar. These safety pillars vary with depth and different storage media whereby the cavern diameter resulting from the re-leaching process is decisive.
- **Infrastructural:** The proximity to civilian buildings in the city of Wilhelmshaven. In Germany, a safety distance must be maintained between buildings and hydrogen cavern heads.

- **Legal:** The obligation of the NWKG to hold a stock of crude oil to ensure the national supply in times of an emergency. The planning has been done assuming a decreasing need to store crude oil, thereby freeing up cavern volume for hydrogen storage. However, it is ensured that the legal requirements for storing hydrocarbons are met at any time.

For the construction of new caverns additional parameters have to be considered:

- **Geological**: The depth of the salt dome is ranging between -950 m and -2.300 m. The focus of the study was the construction of caverns with a maximum LCCS depth of -1.700 m. Areas with salt too deep for cavern construction were excluded from the planning (Figure 4).
- **Infrastructural**: The construction of caverns below buildings is not an option for the NWKG. Such areas have therefore been excluded (Figure 4).

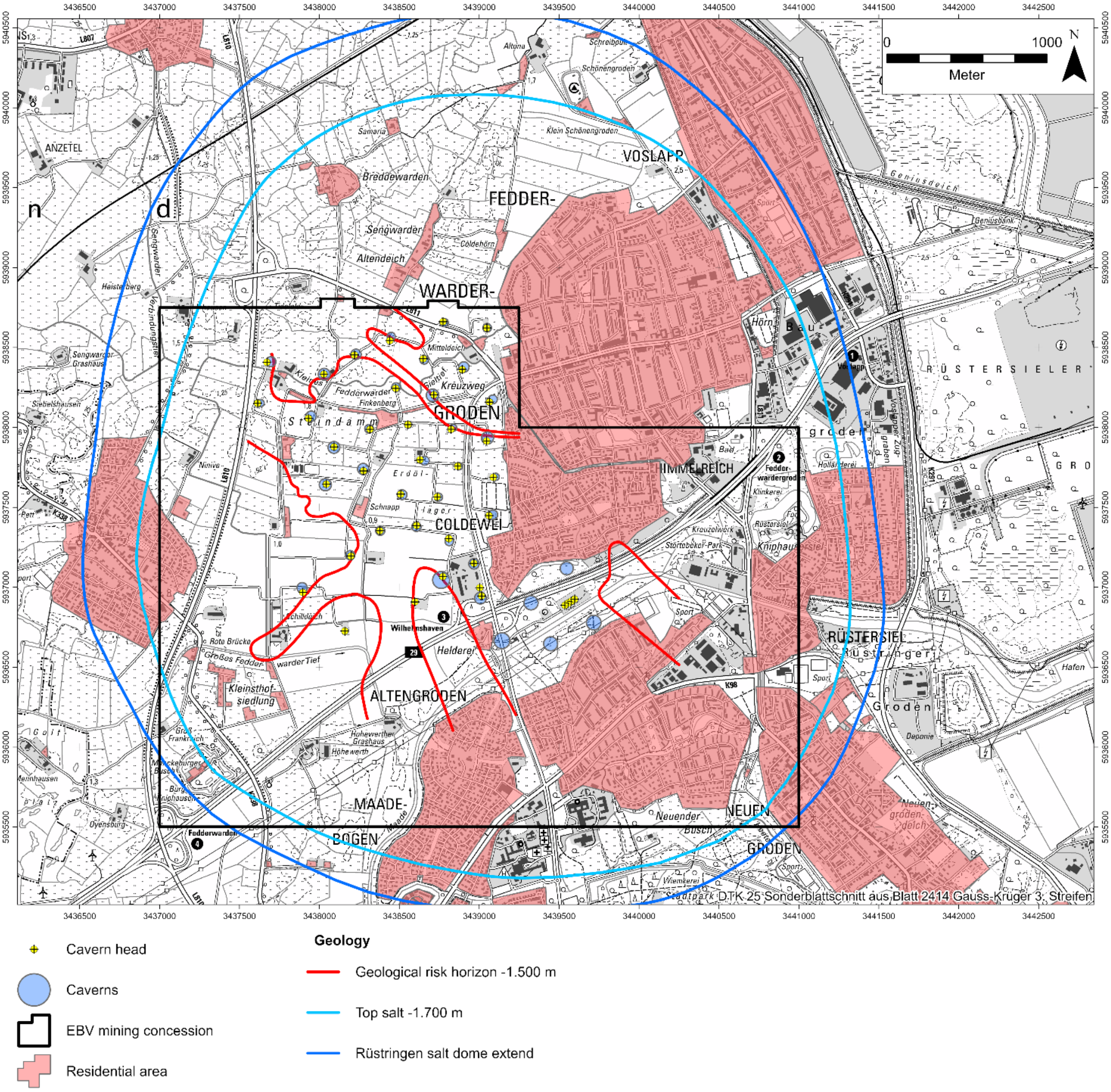

Figure 4: Salt dome Rüstringen, EBV (Erdölbevorratungsverband) mining concession, residential areas and cavern localities

2.4 Incorporation of the Parameters into the Planning

In the following chapter it is described how the parameters are incorporated into the planning phases. Infrastructural parameters are considered as excluded areas in the map. Legal parameters have been considered in planning, but are based on internal information from the NWKG. These parameters are therefore not further explained.

Geomechanical Safety Pillars

Generally, the given geomechanical envelope and the corresponding safety pillar from expert opinions is used for planning purposes.

In some cases, it can be beneficial for optimization purposes within an existing cavern field to identify possible expansion potential by evaluating the current cavern situation and its dependent safety pillar. This applies for instance to caverns that are planned to be abandoned.

Therefore, the most recent sonar surveys were used to represent the current geometries of the caverns. These surveys were used to generate maxplots, a depth-independent representation of the widest extent of the cavern in each direction (Figure 5). The perimeter around this maxplot defines the geomechanical envelope, from which the geomechanical safety pillars can be calculated. These safety pillars are used to plan the positioning of new caverns and to determine the maximum diameter of surrounding caverns in the re-leaching process.

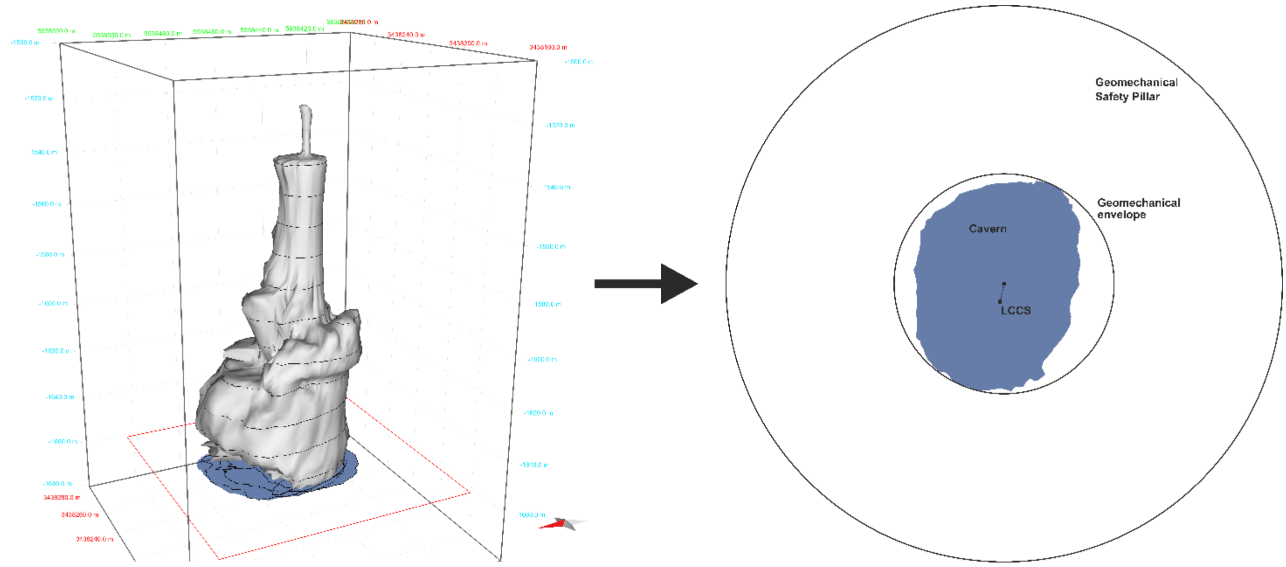

Figure 5: Determination of the geomechanical safety pillar, based on the geomechanical envelope and the maxplot (blue area)

Geological 3D Model

In order to ensure an efficient use of the available salt suitable for cavern construction, a geological 3D model has been set up. This model is based on the interpretation of the geophysical logs, drilling results, as well as cores from the cavern wells. Additional spatial information from structural data, georadar and cavern shapes was used. This geological 3D model incorporates the spatial extent of the risk horizon “Staßfurt potash seam” inside the salt dome (Figure 6), separating suitable and unsuitable salt formations. Using this model, the maximum diameter of conversion caverns and target locations for Neocaverns were determined.

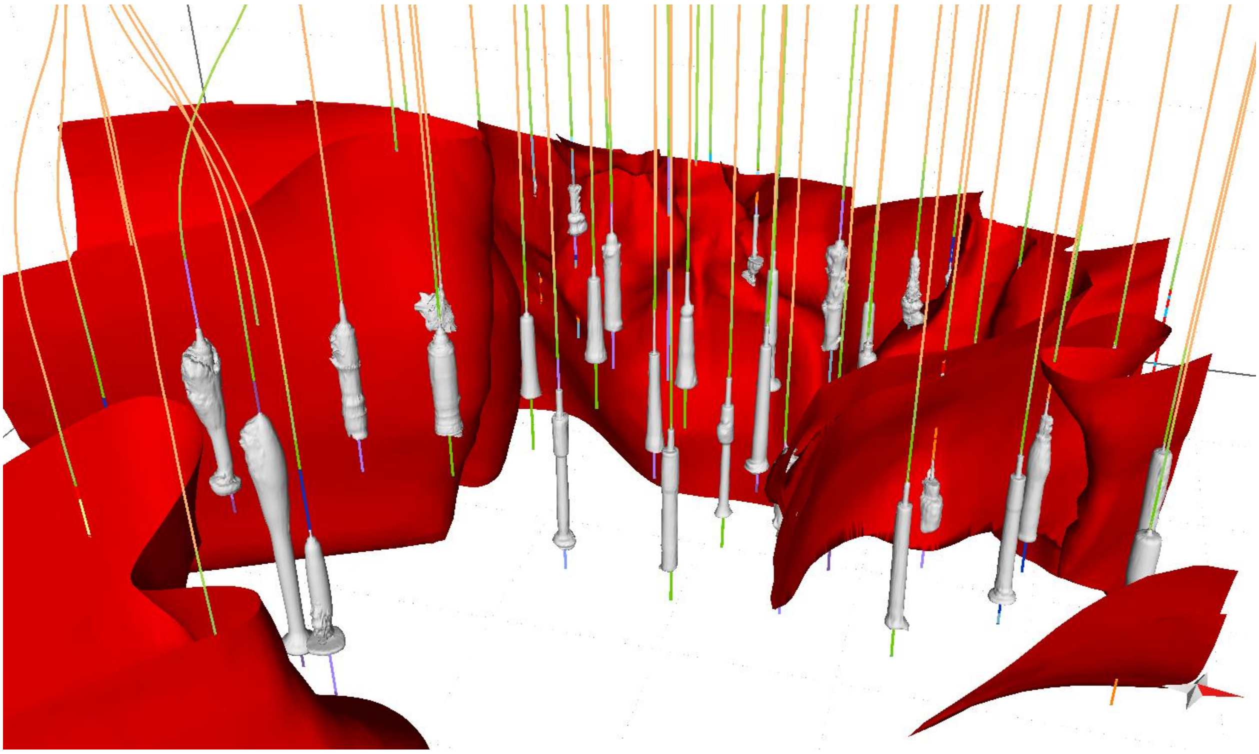

Figure 6: Geological 3D model of Rüstringen with the Staßfurt potash seam as a geological risk horizon (red), wells and caverns

2.5 Results

The current field layout (phase one) is shown in the map in *Figure 7*. At this point in time there are 39 caverns in operation and 2 abandoned caverns, which are filled with the following media, listed with their quantities:

- Oil: 32
- Brine: 7
- Abandoned caverns: 2

Currently, the site has the following storage capacities:

- Geometrical cavern volume in general: 11.5 mio. m³
- Volume of stored oil: 10.9 mio. m³
- Free volume currently filled with brine: 600,000 m³

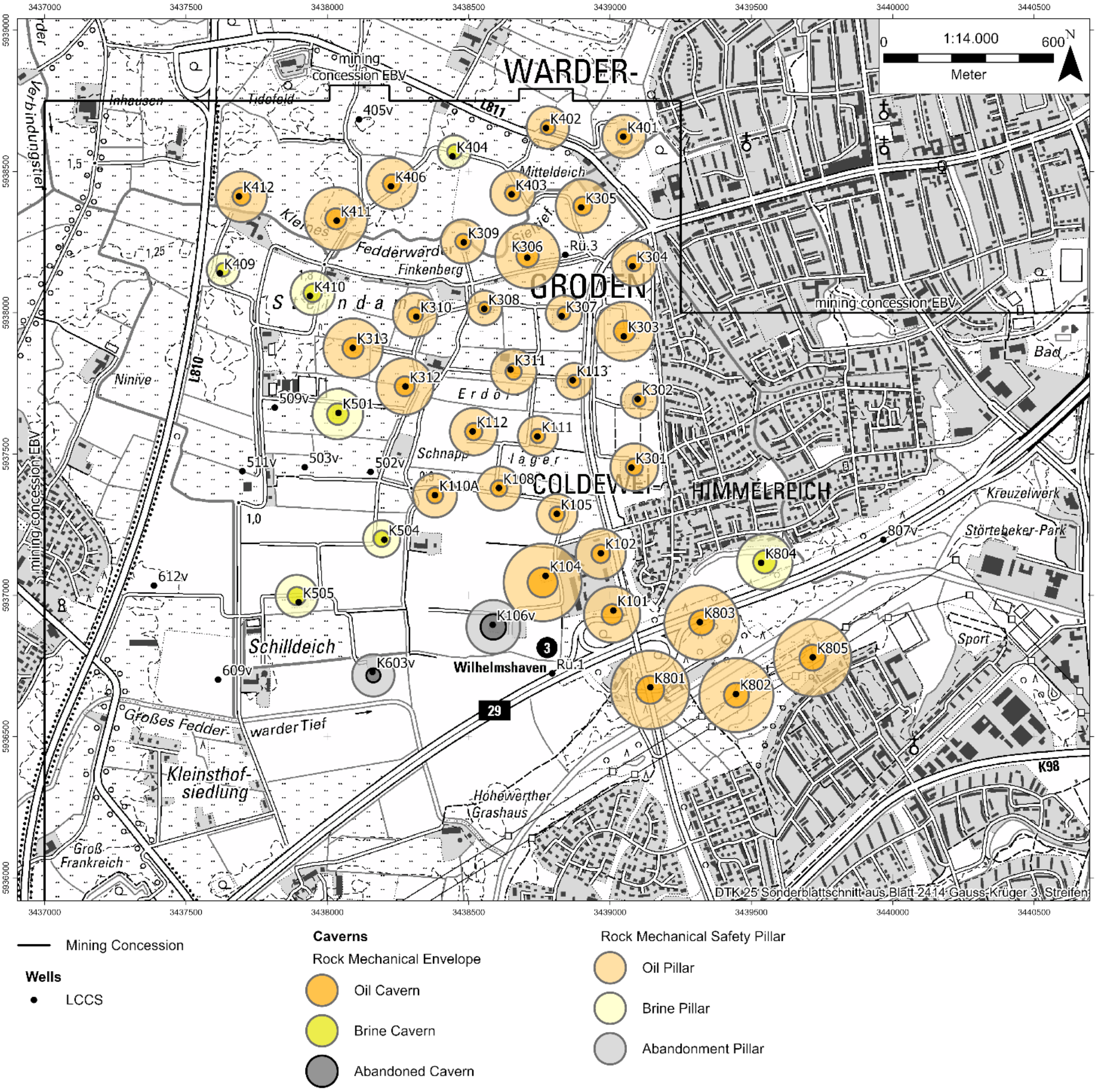

Figure 7: Map of the current state of the Rüstringen site

In the second phase six caverns for the abandonment have been selected. In the third phase 14 caverns suitable for conversion and optional re-leaching were proposed. In the last phase (phase four) suitable areas for 13 Neocaverns have been identified.

The resulting field layout (phase four) is displayed in the map in *Figure 8*, showing the great potential of the site. At this point in time there will be 47 caverns in operation and 7 abandoned caverns, which are filled with the following media, listed with their quantities:

- Hydrogen: 27
- Oil: 21
- Abandoned caverns: 6

As a result, the site has the following storage capacities:

- Geometrical cavern volume in general: 23.5 mio. m³
- Volume of stored oil: 10.5 mio. m³
- Geometrical volume used for gas storage: 13.0 mio. m³
- Volume of stored hydrogen: 2.2 bil. m³

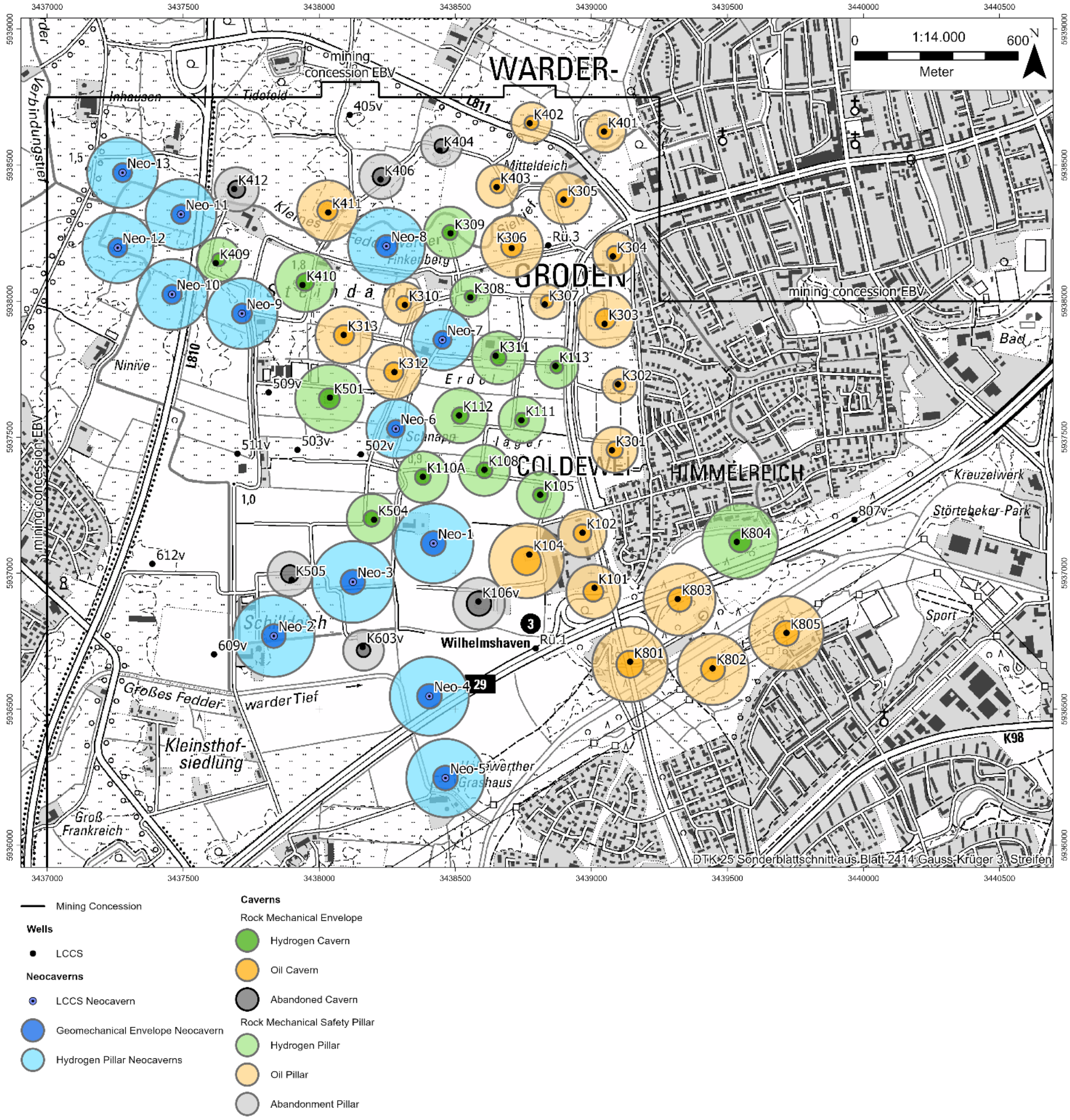

Figure 8: Rüstringen site with converted and new hydrogen storage caverns, abandoned caverns and oil storage caverns

3. Insights from the Rüstringen K410 Conversion

In order to test the storage of hydrogen at the Rüstringen site, a pilot project to convert the K410 oil storage cavern into a hydrogen storage cavern has been set up. For this project a comprehensive evaluation of the brine-filled cavern well has been conducted firstly, followed by the formulation of a systematic re-leaching plan based on a geological assessment of the cavern. Subsequent to this, planning for the re-completion of the well was initiated. This planning encompasses the upgrading of the well in accordance with the prevailing state-of-the-art and the design of the resulting well completion for safe hydrogen storage.

3.1 Re-leaching and Cleaning

In order to store a significant amount of hydrogen for the pilot, it was determined that the cavern K410 would need to be re-leached to a volume of approximately 450,000 m³. For this purpose, geomechanical and geological evaluations of the cavern were carried out.

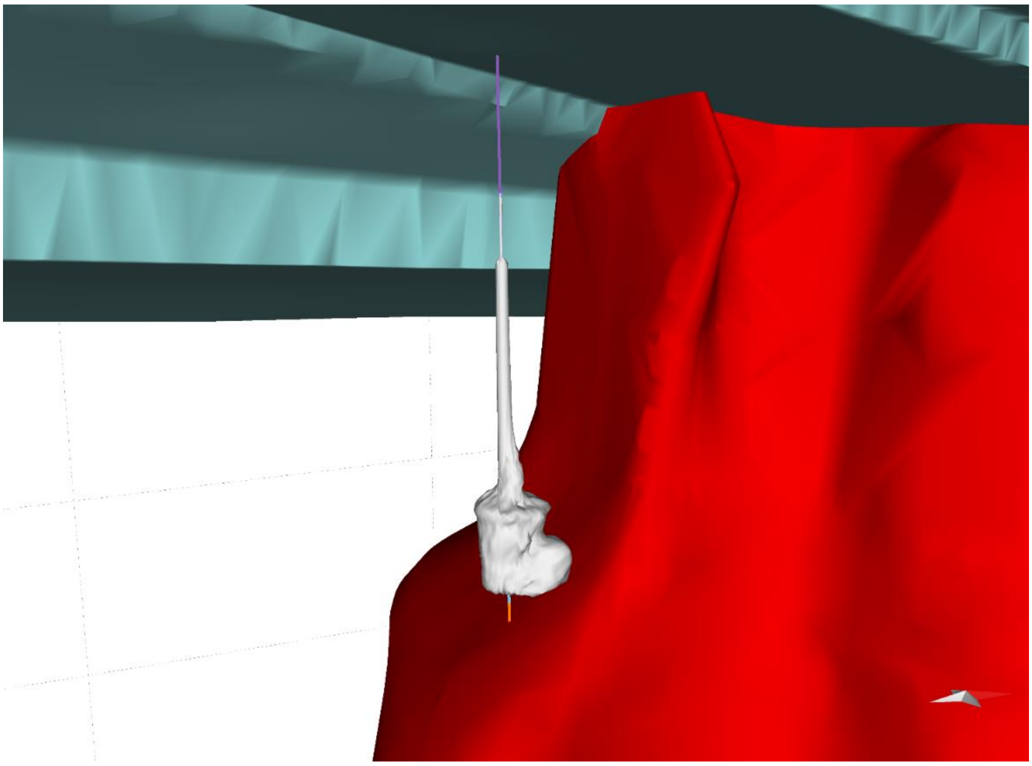

Figure 9: Geological surroundings K410

In order to assess the need to clean the cavern of oil residues, possible cavities that could be filled with oil were evaluated. These cavities are located below approx. 1,630 m TVD (see Figure 10), i.e. in the cavern sump. It was decided not to access these cavities due to the undesirable risk of leaching of the potash seam. This means that small amounts of oil will remain in the cavern even after the ongoing re-leaching process.

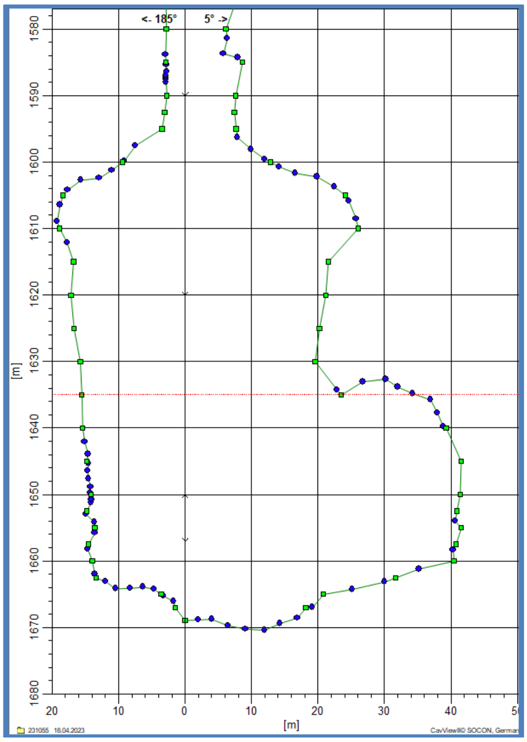

Figure 10: Sonar Survey before Start of Re-leaching K410

Re-leaching of the cavern began in April 2023. During re-leaching, daily samples of the extracted brine are analyzed to determine the concentration of ions and hydrocarbons. The measured hydrocarbon concentrations show a decreasing trend as the leaching process progresses. After approx. one year, the detection threshold of the analyzer was reached at a cavern expansion of a few meters. This analysis will be performed on additional caverns being converted to verify the results.

3.2 Detailed Planning of the Conversion

3.2.1 Well Configuration

The K410 well has a 13 ⅜" last cemented casing (LCC). A 10 ¾" and 7" leaching completion and a 2 $^{7}/_{8}$" brine dilution string are currently installed and will be removed for conversion. The current configuration is shown in Figure 11 (without the brine dilution string):

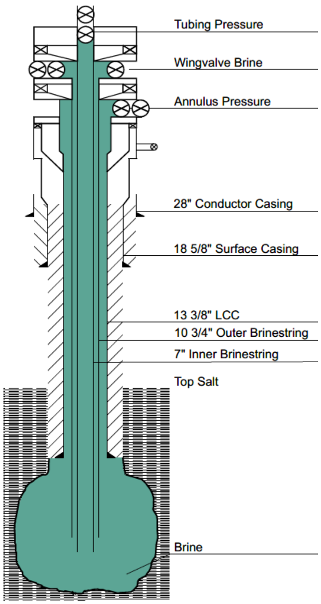

Figure 11: Current Well Configuration K410

3.2.2 Integrity Assessment for Hydrogen Storage

As the K410 was initially operated as an oil storage cavern, a gas completion has not yet been installed. Therefore, there are currently no primary and secondary barriers for use as a gas storage cavern installed. However, this is necessary for an underground gas storage due to open-flow potential. Since the new cavern completion will be designed for hydrogen storage and will serve as the primary barrier of the well, it was initially examined whether the 13 ⅜" LCC could serve as a secondary barrier for hydrogen storage.

The evaluation has shown that the 13 ⅜" LCC does not allow for state-of-the-art gas storage. Due to its original storage purpose the casing was installed with connectors not designed to prevent gas flow. In order to achieve a sufficient state-of-the-art double barrier system it was therefore decided to install a new technical casing in the existing LCC, designed for gas storage.

The cementation of the 13 ⅜" LCC cannot be finally evaluated, as there is no information available at this time on the suitability of the cement (PozMix 80) for hydrogen storage. However, there are no known reports or tests that indicate that the cement is not suitable for hydrogen. In the course of the project, the suitability of the cement for hydrogen storage will be evaluated. First, logging will be executed to verify that the acceptance criteria according to Bundesverband Erdgas, Erdöl und Geoenergie (BVEG) is met. Afterwards the integrity will be verified by two separate gas tightness tests.

The cavern head and bottom flange are not considered in the integrity assessment as a new cavern head and a bottom flange according to the required pressure ratings and gas storage requirements are to be installed as part of the conversion.

3.2.3 First Gas Tightness Test

The first gas tightness test is carried out after re-leaching of the cavern and after removal of the leaching strings. The general test concept and execution are based on the standard procedure for a gas tightness test using the SoMIT (**So**nar **M**echanical **I**ntegrity **T**esting) method. To prevent possible hydrogen "contamination" behind the LCC due to "poor" cementation, the first tightness test is performed with nitrogen as the test medium.

Since the 13 ⅜" LCC is installed with connectors that are not designed for gas storage, it is covered with a test packer on a test string. The test setup is illustrated in Figure 12.

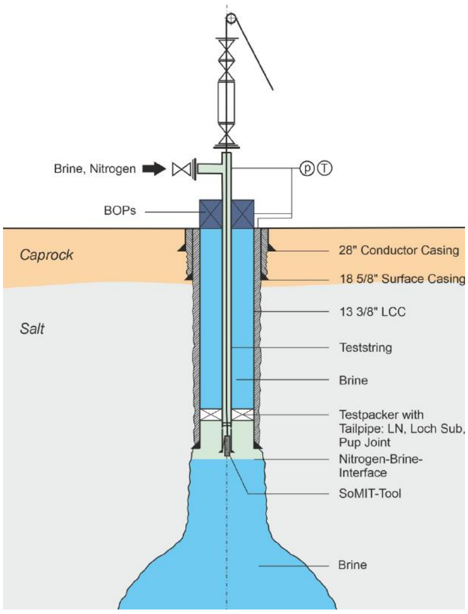

Figure 12: Concept of the first Gas Tightness Test K410

First the annular space between the test string and the 13 ⅜" LCC is pressure tested to confirm its integrity. The next step is to pre-pressurize the cavern with saturated brine close to the test pressure at LCCS. Afterwards, nitrogen is injected below the 13 ⅜" LCCS, and the nitrogen-brine interface is detected via wireline measurement. After a waiting period for temperature stabilization, the test is conducted over the scheduled test period with continuous level monitoring.
The evaluation of the first gas tightness test is based on calculated apparent leakage rates over the observation phase.

3.2.4 Installation New, Partially Cemented Technical Casing

As the LCC is not suitable for gas storage due to connectors not designed for gas storage, it was decided to install a new technical casing inside the existing LCC. For safety reasons and to provide the best possible setting conditions for the gas completion it was decided to cement the new casing inside the LCC at the salinar section and approximately 50 m above.

Several options have been discussed for restoring integrity in the event that the LCC shows integrity issues during the initial gas tightness test or wellbore measurements show poor cement bond behind the casing. One of these options is milling, which could be used to achieve a new cement bond with the formation when cementing the new casing, thereby restoring the wellbores tightness. Based on the results of the initial gas tightness test, the final procedure will be determined.

Due to the existing 13 ⅜" LCC, various dimensions were discussed for the new technical casing. It was decided to install a 9 ⅝" version as this is a standard size for the subsequent installation of a gas completion. In addition, the 9 ⅝" casing provides slightly more space for installation and cementation within the 13 ⅜" LCC compared to a 10 ¾" casing. The top 50 meters of the new technical casing will be widened to 10 ¾" to provide sufficient space for the installation of the subsurface safety valve integrated into the gas production casing. The new casing will be designed for hydrogen storage and equipped with premium gas tight connectors. The casing shoe of the 13 ⅜" pipe will be set inside the 13 ⅜" LCC next to its casing shoe, using a liner hanger (Figure 13).

After cementing, the workover rig will be demobilized due to the cement setting time of at least 4 weeks.

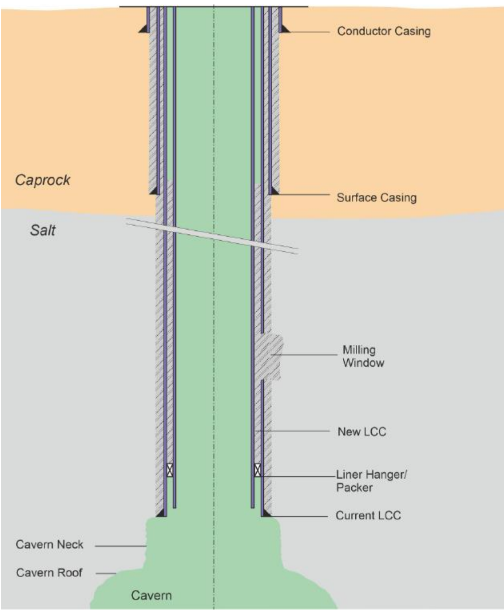

Figure 13: Concept for the Installation of a New, Partially Cemented Technical Casing

3.2.5 Second Gas Tightness Test

The second gas tightness test is performed after the installation and cementation of the new 9 ⅝" x 10 ¾" casing. This test is designed to verify the integrity of the 9 ⅝" x 10 ¾" casing using the test procedure of a coMIT (**co**mbined **M**echanical **I**ntegrity **T**est), i. e. the will be performed in two steps. In the first step of the coMIT nitrogen will be used as test medium and hydrogen in the second step. The test setup is visualized in Figure 14.

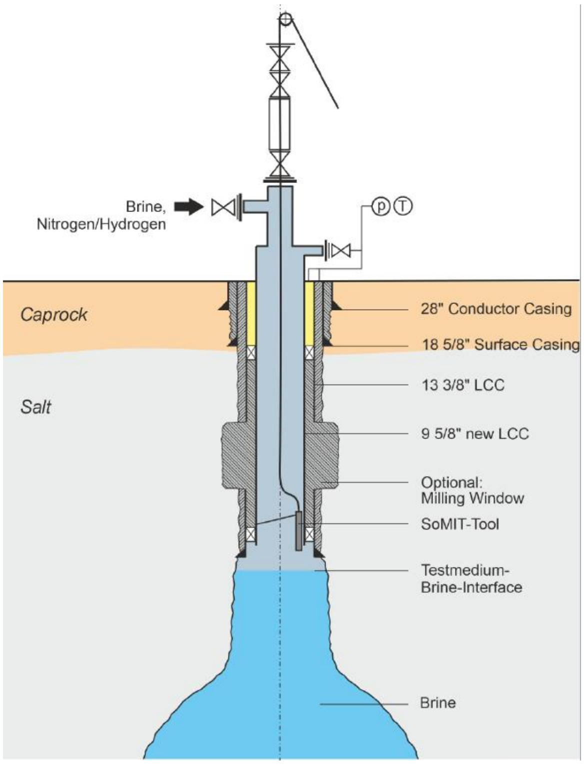

Figure 14: Concept of the second Gas Tightness Test K410

The general test concept and execution are based on the standard procedure for gas tightness tests using the SoMIT method on the LCCS. The cavern is not equipped with a workover rig for the second gas tightness test. Since the 9 ⅝" x 10 ¾" casing is designed for hydrogen storage, no test string or test packer is required. The test is performed on the entire new technical casing and the casing shoe of the 13 ⅜" LCC, in the first step with nitrogen and, if no leakage is shown, in the second step with hydrogen.

For test execution, the cavern is pre-pressurized with saturated brine close to the intended test pressure. Afterwards, the test medium is then injected below the 9 ⅝" x 10 ¾" and 13 ⅜" casing shoe into the cavern neck area. The gas-brine interface is measured by wireline during injection. Continuous SoMIT measurements of the second gas tightness test are carried out. after a waiting time for temperature stabilization

The evaluation of the second gas tightness test is again based on the calculated apparent leakage rates during the observation phase.

3.2.6 Installation of the Gas Completion and Functionality Test

Several possible designs for the completion of the cavern were discussed. A two-packer solution was agreed upon as the preferred option. Hereby, the lower packer acts as a "protective permanent packer", enabling the cavern to be shut off from the well during the installation of the gas completion and any future workovers.
The upper packer functions as a production packer and will have a removable design (cut-to-release).

After the second gas tightness test, the workover rig is set up and the completion operations are performed. Firstly, the protective permanent packer is placed in the well. Next, the production packer is installed above the first pipe of the gas production casing, its tailpipe inserted into the protective packer. Based on the 9 ⅝" x 10 ¾" new technical casing, a 7" gas-production string was specified. A threaded string was selected as hydrogen-compatible connectors are already available on the market and potential problems with the embrittlement of weld seams due to hydrogen can be eliminated.

To reduce the use of elastomers during subsequent hydrogen storage operations, a "tubing mounted" subsurface safety valve was selected. This valve is installed during the installation of the gas production casing. The planned completion design is shown in Figure 15.

Since a relatively small amount of hydrogen is expected for the gas first fill, a 4" de-brining string will be provided. The de-brining string will also be installed with premium connectors.

The cavern head and the bottom flange will be replaced and will be designed with pressure range API 5,000 and "H_2-ready" designs.

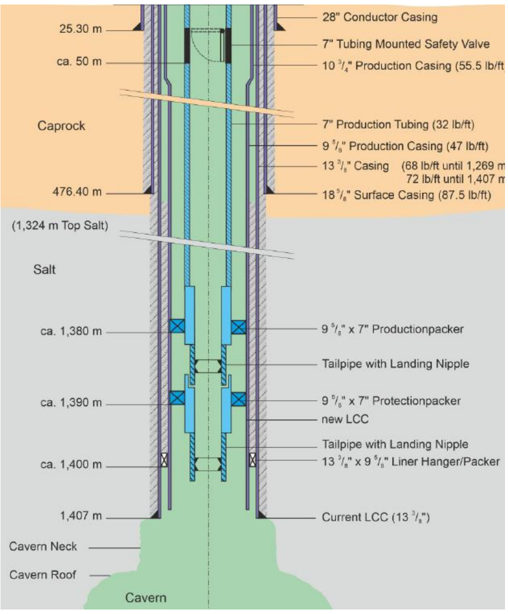

Figure 15: Concept for Completion K410

The third gas tightness test is performed using hydrogen as a test medium as part of gas first fill. The purpose of this test is to verify the integrity of the installed completion by monitoring the annulus between the 7" gas production casing and the new 9 ⅝" x 10 ¾" technical casing as well as in the cemented annuli 9 ⅝" x 13 ⅜" and 13 ⅜" x 18 ⅝" for pressure changes. A wireline level check is performed to ensure that the hydrogen level is still below the LCCS in the cavern neck. The functionality test concept is shown in Figure 16.

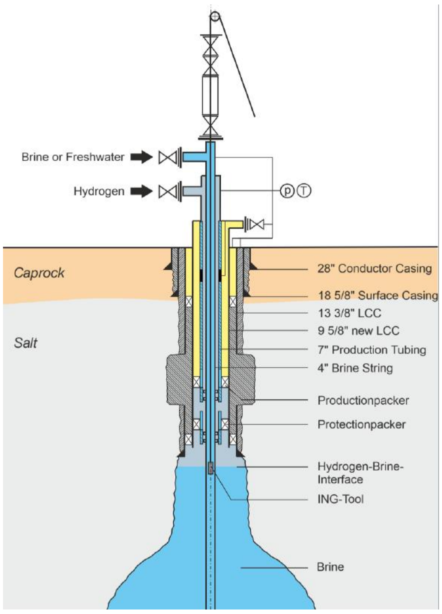

Figure 16: Concept of the Functionality Test K410

4. Summary and Lookahead

The conversion of the Rüstringen site from a crude oil to a hybrid storage facility is based on interdisciplinary cooperation. It involves issues from the fields of drilling, geomechanics, solution mining and geology. The planning is based on the current state of the cavern field and the current storage medium. Based on this, 14 caverns were identified that are suitable for a conversion to a gas storage (hydrogen) due to their technical characteristics and sufficient distances to surrounding caverns. Taking into account the geomechanical and geological conditions, expansion was considered for all caverns. Based on this planning,and considering the geomechanical restrictions as well as the geological conditions of the Rüstringen salt dome, landing points and depth of the LCCS of 13 new caverns were defined. The combination of crude oil and hydrogen storage caverns would allow the Rüstringen field to be transformed into a hybrid storage site with an estimated gas volume of 2.2 billion m³ and 10 million m³ of crude oil.

Based on the conversion considerations, the K410 cavern in Wilhelmshaven is intended as a pilot cavern for hydrogen storage. In the course of the detailed planning, a concept for the conversion of the cavern was developed in collaboration between NWKG and DEEP.KBB. This includes expanding the K410 to a volume of approx. 450,000 m³ and removing remaining oil residues as much as possible.
After re-leaching and the subsequent waiting period, a first gas tightness test is performed on the LCCS using nitrogen as the test medium. If this test is positive, a new technical casing will be installed to cover the existing 13 ⅜" LCC and its connections, which are not designed for gas storage. This casing will be cemented in the section of the salinar and approx. 50 m above. For the case of a negative first gas tightness test, several options to restore an integer connection between the salinar, cement and casing have been discussed. The decision for an option will be made based on the results of the first gas tightness test.

After cementing the new casing and a corresponding waiting time for cement hardening, a second gas tightness test is performed, this time as a combined test. According to the state-of-the-art, the entire casing and casing shoe of the LCC and the newly installed technical casing are tested with nitrogen using the SoMIT method. If this test is positive, the test is repeated with hydrogen as a test medium.
After the second gas tightness test, the gas completion is installed by placing two packers in the lowest pipe of the new technical casing. The lower packer serves as a protective permanent packer and can be closed in the tailpipe if measures need to be taken inside the well. The top packer serves as the production packer and accommodates the 7" gas production string. All casings are designed and installed “H_2-ready” with premium gas tight connectors.

The execution of the re-completion is scheduled to start in Q2 2026. The gas first fill is expected to start on January 1st, 2027.

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