– Report –

Case studies for cyclic operated storage caverns 'Aardgasbuffer Zuidwending' NL

Institut
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GmbH

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Case studies for cyclic operated storage caverns

'Aardgasbuffer Zuidwending' NL

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1. Introduction

For realisation of the 'Aardgasbuffer Zuidwending' project, Nuon Storage B.V. and Gasunie Zuidwending B.V. are currently constructing salt caverns for underground storage of natural gas. The 'Aardgasbuffer Zuidwending' is the first gas cavern storage in The Netherlands.

The aim of the natural gas storage facility is to respond to seasonal as well as economical fluctuations on the gas market. From experience the development of the gas price is unpredictable and often very unsteady; high frequent and cyclic operation of the gas caverns is consequently envisaged by Nuon and Gasunie to encounter the demand of the grid balance.

Based on the results of a meeting on 7th July 2011 in Hannover between representatives of Gasunie, Nuon and rock-mechanical experts from DEEP, KBB UT, IfG and BGR, IfG was commissioned to define cavern operating envelope, by investigate (1) the allowable (maximum or minimum) gas pressure levels, (2) the pressure operation time at the respective pressure level and (3) at which permissible cycling rates a cavern can be operated without exceeding tolerable and permissible convergence rates for the Zuidwending cavern field.

Based on the principles of stability and long-term safety in cavern design, gained from long lasting rock-mechanical experiences in gas storage, IfG Institut für Gebirgsmechanick Leipzig GmbH has issued recommendations on the operating envelope (IfG 2011). These first finding have been confirmed in for lying report. Recommendations are given in the report dated 28th September 2011 based on the principles of stability and long-term safety in cavern design, gained from long lasting rock-mechanical experiences in gas storage.

The aim of the numerical modelling was to prove the estimated values for convergence rate related to the different cavern types at Zuidwending with respect to rock mechanical stability and tightness of the caverns surrounding host rock. For this purpose, a numerical modelling has been performed under consideration of the site-specific situation of the deposit and the respective properties of the relevant rock formations. As a prerequisite for numerical modelling due to the cyclic operation mode of gas storage also the thermo-dynamics was considered.

2. General situation and basic operating parameters of gas storage

The gas storage caverns are constructed by solution mining within the Permian (Zechstein) salt formation of the Zuidwending salt dome structure, southeast of Veendam. The Zuidwending salt dome is situated in the neighbourhood of the Groningen gas field, which lies beneath almost the whole province of Groningen, in the northeastern part of the Netherlands. The salt dome stretching SW-NE for about 8 km, with a maximum width of some 3 km in the SE-NW direction. Top of salt is located at about 150 - 200 m below sea level. The base of salt lies at 2,800 to 3,000 m below sea level.

In order to represent the individual caverns at Zuidwending four different type caverns were modelled (as agreed with the customer). They differ in volume and depth location. Figure 2.1 presents a groundmap of the caverns. The main characteristics of the planned caverns and basic operating parameters of the different types are given in Table 2.1. The geometrical volume of 650,000 to 1,000,000 m³ is a common size for gas storage caverns, and appears to be sufficient for the anticipated purposes.

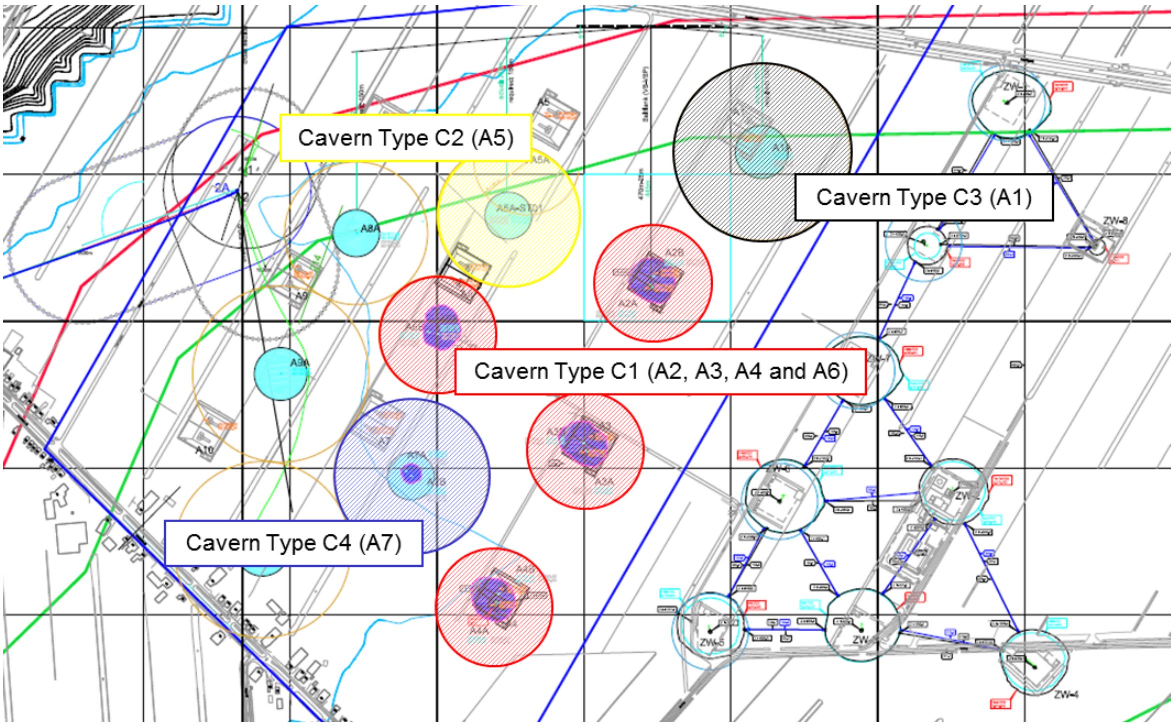

Fig.2.1: Groundmap of Zuidwending storage with investigated cavern types.

In this study the caverns currently in use for gas storage (A2, A3, A4 and A6) and the caverns currently under construction have been characterized based on their geometrical volume and depth position. Four type caverns have been characterized being: caverns A2, A3, A4 and A6 are type C1, cavern A5 type C2, cavern A1 type C3 and cavern A7 type C4 (compare Tab. 2.1 and Tab. 2.2).

Tab.2.1: Geometrical and operating parameters of the caverns modelled in this study

Type C1:	cavern roof	depth	1,030 m
	cavern bases	depth	1,230 m
	casing shoe	depth	1,000 m
	volume	V	650 Tm³
	operating parameters:	p_{MAX}	180 bar
		p_{MIN}	50 bar
		$p_{MIN(O)}$	80 bar
	*estimated convergence rate**	η	0.62 %/a
Type C2:	cavern roof	depth	1,130 m
	cavern bases	depth	1,410 m
	casing shoe	depth	1,100 m
	volume	V	1,000 Tm³
	operating parameters:	p_{MAX}	198 bar
		p_{MIN}	75 bar
		$p_{MIN(O)}$	110 bar
	*estimated convergence rate**	η	0.4 %/a
Type C3:	cavern roof	depth	1,080 m
	cavern bases	depth	1,360 m
	casing shoe	depth	1,050 m
	volume	V	1,000 Tm³
	operating parameters:	p_{MAX}	189 bar
		p_{MIN}	60 bar
		$p_{MIN(O)}$	90 bar
	*estimated convergence rate**	η	0.4 %/a
Type C4:	cavern roof	depth	1,080 m
	cavern bases	depth	1,500 m
	casing shoe	depth	1,050 m
	volume	V	1,000 Tm³
	operating parameters:	p_{MAX}	189 bar
		p_{MIN}	84 bar
		$p_{MIN(O)}$	84 bar
	*estimated convergence rate**	η	0.4 %/a

*values according to recommendations IfG 2011

Generally, the rock mechanical recommendations for the layout of the caverns include the parameters of the maximum (p_{MAX}) and two minimum cavern pressures. While $p_{MIN(o)}$, the upper minimum pressure represents the lower level of operations without any restrictions with respect to operation time, the pressure interval between p_{MIN} and $p_{MIN(0)}$ has to be checked against a limited life-time.

Tab.2.2: For comparison: Data of the caverns realised at Zuidwending gas storage

Caverne	**Depth LCCS [m TVD]**	**Deepest [m TVD]**	**Geometrics volume [10^6 m^3]**
A1A	1049.8	1431.8	1.0
A2A	980.0	1640.0	0.60
A3B	1005.1	1299.1	0.65
A4B	1027.2	1300.0	0.59
A5A	1106.0	1553.0	1.0
A6A	1004.0	1450.0	0.64
A7A	1038.4	1649.9	1.0

A maximum injection/withdrawal rate of 10 bar/d is allowed for all 4 types between p_{MAX} and $p_{MIN(O)}$. A rate of 3 bar/d is allowed in the range of lower pressure between $p_{MIN(O)}$ - p_{MIN}.

The estimated convergence rates are established in the report given by IfG (2011). These results are the limiting values for the following geomechanical calculation. They should not be exceeded in order to ensure that a limited surface subsidence will not be violated. Besides subsidence aspects geomechanical limitations have to be considered, (1) it must be excluded that tensile fractures occur due to exceedances of tensile strength in the cavern contour in consequence of withdrawal operation and (2) it has to be guaranteed that the long-term stability of support system surrounding the cavern (i.e. pillar, hanging and foot-wall) is given under all occurring load (operational) conditions. Therefore, the results of the numerical modelling were assessed applying rock mechanical safety criteria which will be described in detail later.

3. Basics of thermo-dynamic calculation

3.1 Characteristics of the used Salt Cavern Gas Storage Toolbox (SCGS)

The Salt Cavern Gas Storage Toolbox (SCGS Toolbox) is a suite of applications (software and electronic documents) used to meet the technical and economic needs of the gas industry, specifically in the field of Salt Cavern Gas Storage. The program suite is the collaborative effort between "Gas Technology Institute (GTI)", " Pipeline Research Council International, Inc. (PRCI)" and "Technical Toolboxes, Inc. (TTI)". The Salt Cavern Thermal Simulator (SCTS) is integrated within the SCGS-Toolbox. The SCTS software allows to evaluate complete thermal and thermo-dynamic histories of high compressed or fast depressurerized large volumes of natural gas in salt caverns.

The simulation of operating gas storage caverns demands thermo-dynamic calculations of heat transfer and heat convection in combination with injection/withdrawal cycles of water, brine and gas. The process of leaching is also integrated in the Toolbox.

To estimate the heat transfer between the cavern and the surrounding host rock, an implicitly integrated finite difference method is used. Thereby, the thermo-dynamic model is discretised in spherical arranged elements and an approach, as described by RESPEC (2004) is applied for calculation of temperature states.

Assuming a gas flow rate for injection or withdrawal, it is possible to calculate the cavern pressure and temperature in the process of leaching, dewatering, initial gas-filling and gas operation.

3.2 Used thermal parameters and results of the thermo-dynamic simulation

The assumed thermal parameters for Staßfurt rock salt are given below (BGR, 2000):

thermal conductivity	k = 5.22 W/m*K
specific heat capacity	c_P = 920 J/kg*K
coefficient of thermal expansion	$\alpha = 4 \cdot 10^{-5}$ 1/K
thermal gradient	K_T = 0.023 K/m
rock temperature	T = 290 K + 0,023 K/m · H

The values for the thermal gradient and the resulting rock temperature are specific to the location Zuidwending.

For the thermo-dynamic simulation the following steps were considered, significant results are shown in Table 3.1.

(1) Solution mining of the cavern / dewatering

The process of cavern leaching has been realized in 3 years.

For the solution mining process, fresh water was used with a mean temperature of 21°C, which lowers the host rock temperature around the cavern. According the principle of a counter-flow heat exchanger the average brine temperature decreases from between 24 and 26 °C in the initial leaching phase to temperatures below 23 °C at the end of the process. The average temperature of the brine is between 22 and 24 °C. Regarding the mean depth of the cavern the pressure of the cavern is relatively constant during the leaching simulation.

Subsequently, the process of dewatering followed. Thereby, it is aimed to maintain equilibrium between the pressure of brine and gas, whereby the overall pressure of the cavern remains nearly constant.

(2) Initial gas filling

The initial gas filling in the model was simulated using natural gas composed of 92% methane, 5% nitrogen and 3% other hydrocarbons.

The process of initial gas filling needs 86 days. The maximum pressure p_{MAX} was reached injecting different amounts of gas for each cavern type according to their individual size (see Table 3.1). At the maximum pressure of the cavern in all cases comparable temperatures of about 40°C were reached (after initial gas filling)

(3) First operational cycles

The first three withdrawal cycles from maximum pressure to a respective minimum pressure level were realized with an increased minimum storage pressure level to prevent a high cooling of the caverns and resulting thermo-dynamically induced damages in the rock mass at the cavern contour. The respective minimum pressure levels are 85 bar for Type C1 and 90 bar for Type C3. Afterwards the pressure was kept constant at the minimum pressure level for 10 days in all cases.

In the following simulation phase, the gas injection took place until p_{MAX} was reached. After the first 3 storage cycles the minimum storage pressure was lowered for the following cycles (Type C1 and C3). Because of the different boundary conditions this stage was not necessary for Type C2 and C4 calculations. According to the pressure regime and the maximum pressure rate applied in the models it was possible to realise 6 (C1 to C3) resp. 8 (C4) cycles per year in the models. The storage cycles and the resulting regimes of temperature for the different caverns are shown in enclosures 6 to 9.

Tab.3.1: Results of the thermo-dynamic simulation of the 4 cavern types Zuidwending.

	Type C1	Type C2	Type C3	Type C4
Mean depth of the cavern	1,130 m	1,270 m	1,220 m	1,220 m
Leaching temperature (start)	24.5 °C	25.4 °C	24.8 °C	24.0 °C
Leaching temperature (finish)	21.7 °C	22.6 °C	22.1 °C	22.9 °C
Average leaching temperature	22.2 °C	23.2°C	22.7 °C	22.7 °C
Time of initial gas filling	86 d	86 d	86 d	86 d
Initial gas inventory	120 mil m³	201 mil m³	194 mil m³	194 mil m³
Temperature after initial gas filling	41.8 °C	41.8 °C	40.6 °C	40.6 °C
Cycles per year	6.3	6.2	6.3	8.1
Increased minimum storage pressure (for first 3 cycles)	85 bar	----	90 bar	----
Minimum storage pressure	50 bar	75 bar	60 bar	84 bar

4. Basics of rock mechanical modelling

4.1 Characteristics of the calculation program FLAC^{3D}

Based on a numerical model, geomechanical investigations were carried out in order to proof the concept of long-term stability and hydraulic tightness, i.e. impermeability of the surrounding salt barrier for each cavern under all loading conditions. It has to be mentioned that the geomechanical model, as illustrated in the following, has the feature of a functional model, i.e. the actual deposit and mining situation is simplified in an acceptable manner and the rock mechanical behaviour occurring during the single phases of solution mining and storage operation is generalized.

The calculation program FLAC^{3D} (ITASCA, 2009) used for the numerical modelling has been developed particularly for solving geotechnical problems. This tool represents the current state of the art on an international level. A lot of practical experience exists with this code in the modelling of various rock mechanical problems. By the option of applying user defined modules, specific material laws can be implemented in the calculation procedure, thus the program developed by adapting to practical needs and considering latest research work. A specially developed visco-elasto-plastic constitutive law was applied for modelling the time-dependent stress, deformation, and softening behaviour as well as the associated dilatancy processes of salt rocks (MINKLEY, W., 2004). The law is described in Chapter 4.2 and has been implemented into the calculation program as "user defined model" (DLL-Modul).

The calculation code FLAC (Fast Lagrangian Analysis of Continua) utilizes the finite difference method. There, the structure under investigation (i.e. the deposit sector as a model body) is subdivided into a huge number of elements with respective node points.

Owing to its discretely pre-determined material behaviour each of these elements responses to the active forces and marginal conditions in a linear or non-linear and rheonomical manner. When the equilibrium conditions are distorted the system begins to oscillate and approaches an equilibrium state according to the given physical opportunities. For each element in correspondence with its adjacent elements this equilibrium state is calculated by solving the complete dynamic equations of motion by means of the explicit LAGRANGE algorithm. Within the used code the effects of large deformations (finite deformations) are appropriately considered. That specifically includes such deformations which play a decisive roll particularly in connection with the creep behaviour of rock salt. The individual elements are characterized by the fact that different properties and parameters such as depth-depending rock mass pressure or temperature-dependent creep rate are attributed to them in a manner that is independent from each other.

A specific programming language (FISH) is implemented in the code. By means of this language necessary modifications of the programmed material properties and program flows as well as specific geomechanical evaluations of the calculate values of the mechanical variables of state (state assessment) can be realized.

4.2 Visco-elasto-plastic constitutive model for salt rocks

A specially developed visco-elasto-plastic constitutive law was applied for modelling the time-dependent creep, stress, deformation, and softening behaviour as well as the associated dilatancy processes. The material model is available as a DLL-application for the codes FLAC und FLAC^{3D}. The theoretical background, as well as practical applications, for the solution of static and dynamic stability problems in potash mines is given by MINKLEY, 2004 or MINKLEY et al., 2007. This visco-elasto-plastic constitutive law is described in more detail in IfG (2009) also.

4.3 Used parameters

The parameters used for the numerical modelling represent the stress and strain behaviour of the rock salt from Zuidwending bases on site specific rock mechanical investigations which were performed by IfG in 2008. The material parameter that were used in this study had been determined on the basis of these rock mechanical laboratory tests.

The plastic behaviour with softening/hardening was determined by analysing triaxial compression tests with different confining pressures σ_3. According to the standard procedure of Deutsche Gesellschaft für Geotechnik e.V. (DGGT) the samples were loaded using a constant deformation rate between $1 \cdot 10^{-5}$ to $2.5 \cdot 10^{-5}$ s^{-1}. The resulting σ_{Diff}-ε_{Axial}- and ε_{Volume}-ε_{Axial}- diagrams are shown in detail in the laboratory report of IfG (2008).

The lower yield boundary of rock salt is described approximately by the stress where the progression of the observed ε_v-ε_1-curve is at its minimum. The transition between compaction and extension of the volume is called dilatancy boundary. At first hardening will occur when $\varepsilon^p > 0$ is reached. Load softening will start after the maximum load is exceeded. For the description of dilatant softening behaviour, the development of volume and strain under various confining pressure conditions was analyzed.

The used visco-elasto-plastic parameters are shown in Figure 4.1, 4.2 and Table 4.1, 4.2.

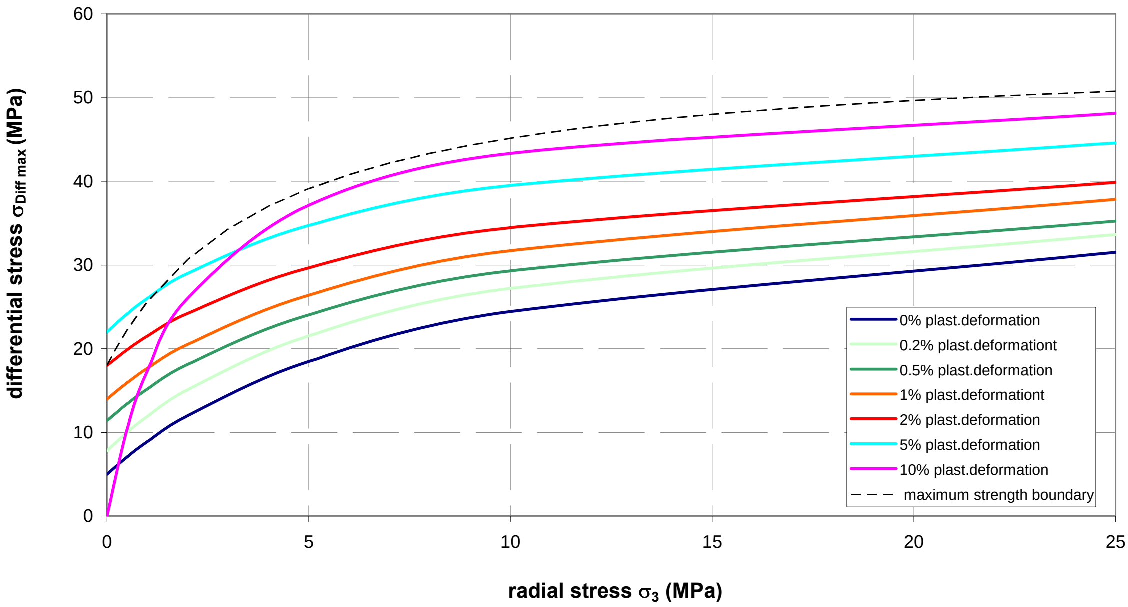

Fig. 4.1: Strength behaviour of Zuidwending rock salt depending on plastic deformation.

Tab. 4.1: Used strength parameters for the Zuidwending rock salt.

Plastic deformation ε_P [%]	**Uniaxial Strength σ_D [MPa]**	**Maximum effective strength σ_{MAX} [MPa]**	**Curvature parameter σ_ϕ [MPa]**
0.0	5.0	40.0	8.0
0.2	7.8	41.0	7.1
0.5	11.4	42.0	7.1
1.0	14.0	45.0	7.5
2.0	18.0	46.0	7.0
5.0	22.0	50.0	6.0
10.0	0.0	52.0	2.0

The analyzed curves of the triaxial compression tests describe the short-term strength of the salt. For the numerical modelling the listed parameters in Table 4.1 were reduced to the level of the dilatancy boundary (ε_P = 0). In consequence of the decreased parameters the long-term strength, which is described by the dilatancy boundary, was considered for numerical simulation. The velocity-dependent reduction of the short-term strength is described in detail by MINKLEY (2004) and MINKLEY et al. (2007). Therefore, the dilatancy boundary has also the feature of a long-term stability criterion, which was used for the stability assessment.

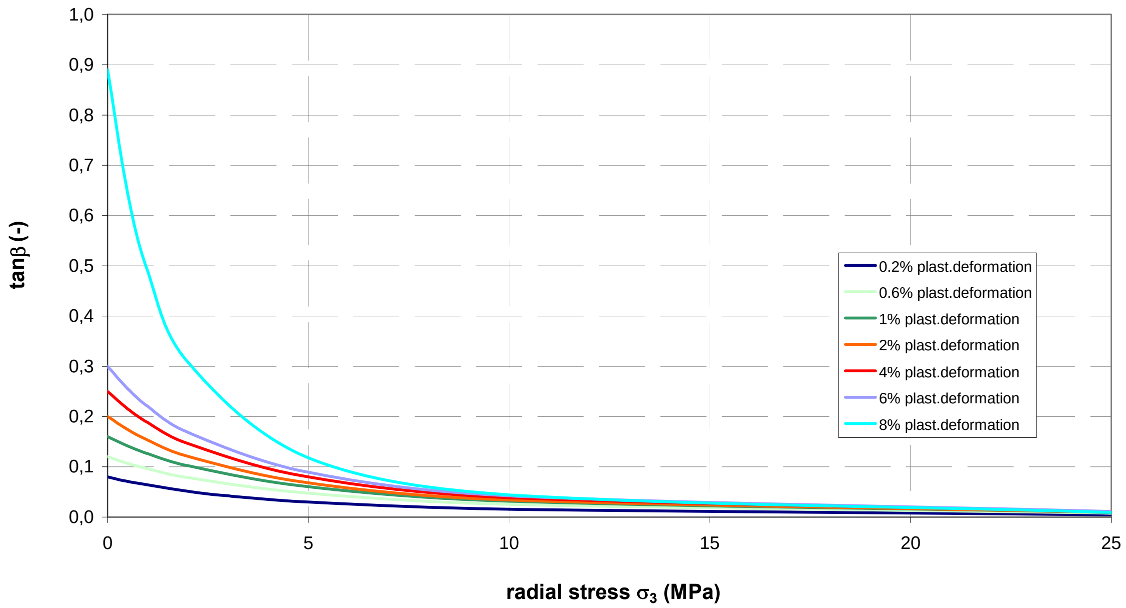

Fig. 4.2: tanß values as derived from triaxial compression tests on rock salt from Zuidwending site.

Tab.4.2: Used dilatancy parameters for the Zuidwending rock salt.

ε_P [%]	0.2	0.5	1.0	2.0	3.0	5.0	10.0
$\tan\beta^0$ [-]	0.08	0.12	0.16	0.20	0.25	0.30	0.89
σ_ψ [MPa]	8.0	8.5	8.0	7.0	6.5	6.0	2.86

The used elastic parameters are given as:

density ρ	2,179 [kg/m³]
Young's modulus E	30.0 [GPa]
Poisson's ratio ν	0.25 [-]

The viscous behaviour of rock salt is represented by the Burgers - model as described in IfG (2009, Chapter 2). The used creep parameters are shown in Table 4.3. These parameters are derived from long-term creep tests on core samples recovered from Zuidwending.

Tab. 4.3: Parameter for the viscose material behaviour of the constitutive approach by MINKLEY.

Material properties	**G^M [GPa]**	**η_0^M [MPa·d]**	**m [MPa^{-1}]**	**G^K [GPa]**	**η^K [MPa*d]**
rock salt	12	$1.08 \cdot 10^8$	0.34	63	$4.1 \cdot 10^5$

The temperature dependency of the MAWELL-viscosity η^M was considered as follows:

Parameter η_{TO}^M	$1.43 \cdot 10^{-1}$
Activation energy Q	54 KJ/mol
Universal gas constant R	$8.314 \cdot 10^{-3}$ KJ/mol·K
Rock temperature T	318 K

$$\eta_0^M = \eta_{T0}^M \cdot \exp\left(\frac{Q}{R \cdot T}\right) \tag{4.1}$$

The MAXWELL-viscosity is a function of the temperature according to equation 4.1. If the temperature acting on the rock is 318 K, the viscosity is correlates with the value of $\eta_0^M = 1.08 \cdot 10^8$ MPa·d.

For thermo-mechanically coupled calculations the thermal parameters as mentioned in Chapter 3.2 were used. The assumed temperature distribution in the models before the start of leaching operation is shown in enclosure 4.

The calculated temperatures in the caverns were applied to the caverns contour as boundary conditions. Furthermore, the temperature of the rock mass was assumed with regard to depth. Thereby, the thermal induced stresses and volumetric strains are considered in the numerical simulation. The value of the heat transfer coefficient was assumed very high. The heat transfer coefficient describes the degree of heat which is transferred across the interface between gas and the rock salt at the cavern wall. As a consequence of this assumption the calculated induced thermal stresses are higher than can be expected in-situ. Therefore the assessment of the temperature effect can be considered as is very conservative.

4.4 Assessment criterion

For the creation and subsequent long-term safe operation of storage caverns the observation of the following rock mechanical safety aspects is of essential importance (MINKLEY et al., 2005):

(1) Guaranteeing the stability of the cavern for long-term gas storage operation. This has to include:
- the comply of the load-bearing capacity of the rock salt strata over-spanning the caverns by considering the effective load of the overburden;
- the stability of the pillars between neighbouring caverns by considering the prevailing load exerted by the rock mass;
- the stability of the cavern contour under the effect of the loading as due to the storage pressure, particularly preventing such progressive rupture processes which might lead to collapse.

(2) Ensuring tightness of the caverns. This has to include:
- the geological tightness of the rock salt surrounding the cavern in a sufficient thickness under consideration of the necessary extent to which the rock salt is able to resist storage pressure in relation to the effective stress conditions;
- the tightness of the technical installations, i.e. the borehole system consisting of casing - cementation and rock salt under consideration of the loading conditions

acting in the cavern roof as well as of the impact of the vertical strain as caused by convergence.

(3) Prevention of inacceptable surface subsidence.

The evaluation of boundary situations regarding stability, consistency and geological tightness is performed by means of criteria, which have been elaborated on the basis of long-standing experience obtained in assessing the hydro-geologic risks and operational reliability of hydrologic protective layers in salt rock mining as well as in dimensioning of caverns for underground storage projects (MINKLEY et al. 2011).

Geological tightness

The geological tightness of a cavern is guaranteed, if the cavern under the maximum pressure p_{MAX} is enclosed by a zone with an extent of at least 25 m where the minimum principal stress is higher by 10 % than the maximum cavern pressure (see Equation 4.2)

$$1.1 \cdot p_{MAX} \leq \sigma_{MIN} \tag{4.2}$$

At the same time structural fracturing within the salt barrier which would imply an increase in permeability has to be excluded.

Technical tightness

The technical tightness of a cavern is guaranteed when a sufficient thickness of salt not less than 30 m in the roof above the last cemented casing shoe is existing, where the acting radial compressive stress σ_{xx} on the contact interfaces between salt ,cement and casing is in agreement with Equation 4.3:

$$\sigma_{xx} > \frac{p_{MAX}}{0.85} \tag{4.3}$$

Dilatancy Criterion

Due to the formation of micro-cracks and to crack accumulation, structural fracturing is associated with an increase in volume, i.e. dilatancy. The developed special visco-elastic-plastic constitutive law, which includes both, deformation-depending de-strengthening and dilatancy, allows to prove the occurrence of structural damage and, consequently, the infringement of the dilatancy criterion in a direct manner by the existence of regions where:

$$\varepsilon^{P}_{VOL} > 0 \qquad (4.4)$$

6. Geomechanical modelling of gas storage caverns in Zuidwending

6.1 Geomechanical calculation models

The purpose of geomechanical modelling is the validation of the recommendations (IfG, 2011) elaborated as preliminary for four different standard caverns which represent the individual caverns at Zuidwending. With regard to the limiting convergence rates per year as stated in Table 6.1 variations of different operation scenarios were investigated by using a 3D-model in order to consider boundary conditions of the caverns in more detail. A map of the location with a plane view of the different model situations is shown in enclosure 1.

For numerical modelling the rock mechanical properties of the host rock formation and the overlaying rock sequences are used as mentioned before (see Chapter 4) resp. given in the earlier IfG lab-report (IfG, 2008). The calculations are aiming at the proof of the barrier integrity and the compliance of the calculated convergence rates with the limitations fixed in advance. Results of the calculation which will be presented in the following after describing the geometrical boundary conditions of the respective cavern models.

Each 3D-model includes a cuboid-shaped segment of the cavern field (see enclosure 2). These modelled segments of the cavern field contain a quarter of a cavern representing the caverns as part of the real cavern-field. The shape of the cavern (2D-cross section) was generated using the code FLAC^{2D}. In the next step, the 3-dimensional shape was produced by the "Extrude" tool which is implemented in FLAC^{2D}. The extensions (cavity and pillar) of the models are between 105 m and 135 m in width and conform to the map issued by DEEP (2010rev). The models of Type C1 to C3 are 550 m high. Cavern Type C4 is 700 m high. The top of the models are located in a depth of 900 m below surface.

Vertical boundaries of the models are fixed with regard to horizontal deformations as well as the basis of the model to vertical deformations. Therefore, the rock pressure acting in formations far from the caverns can not be considered. Thus, at the top of the models, an initial load of 19 MPa corresponding to γ = 21.1 kPa/m is applied.

All models include more than 280,000 elements, whereby each cavern is completely situated in the rock salt-formation. The cavities itself are pre-defined by respective mesh elements which are step by step deleted during the calculation process in order to simulate the leaching process. In detail, the variations between the number and shape of the elements are a result of the different model extensions and cavern volumes. The cavities were modelled between 1,030 m and 1,500 m. In total the modelled cavern volume roughly represent the in-situ cavern volume. The developed geometries of the models are sufficiently conservative, because the real shape of the caverns can be placed within these envelopes. The dimensions of the numerical models are shown in Table 6.2.

Tab. 6.1: Pressure range assumptions according to the theoretical study (IfG 2011).

	Admissible minimum pressure p_{MIN}		Admissible upper limit of the minimum pressure $p_{MIN(O)}$	
	0.4 %/year	0.62 %/year	0.4 %/year	0.62 %/year
Type C1		50 bar**		80 bar
Type C2	75 bar		110 bar	
Type C3	60 bar		90 bar	
Type C4	84 bar		84 bar	

** Limiting value from the annually operated cavern

Tab. 6.2: Dimension of numerical models.

	Type C1	Type C2	Type C3	Type C4
Extension (pillar) [m]	105	125	135	135
Height of model [m]	550	550	550	700
Top of model [m]	900	900	900	900
Bottom of model [m]	1,450	1,450	1,450	1,600
Cavern roof [m]	1,030	1,130	1,080	1,080
Cavern base [m]	1,230	1,410	1,360	1,500
Assumed LCC [m]	1,000	1,100	1,050	1,050
Volume [m³]	650,000	1,000,000	1,000,000	1,000,000
Number of elements	282,367	287,569	301,167	485,073

6.2 Results from simulation

6.2.1 Primary stress state and leaching process

The primary load condition for the rock mass is calculated assuming the following pressure gradients for rock salt and overburden:

$$\gamma_{salt} = \rho \cdot g = 21.4\,\mathrm{kPa/m} \quad (6.1)$$

$$\gamma_{overburden} = \rho \cdot g = 20.1\,\mathrm{kPa/m}$$

resulting from	mean density of rock salt	ρ = 2,179 kg/cm³
	mean density of the overburden	ρ = 2,050 kg/cm³
	acceleration of gravity	g = 9.806 m/s²
	lateral pressure coefficient	λ = 1.0

and the respective thickness of the various geological horizons.

Under consideration of the viscous behaviour of salt rock it is usually permitted to assume an isotropic stress state on the basis of the parameters mentioned before. This is confirmed by the 3D-model calculations demonstrating stress equilibrium with nearly isotropic pressure conditions (see enclosure 3).

After initiation of the primary stress state the leaching of the cavity was simulated at first. In the 3D-models this process was carried out with 3 leaching steps within 3 years by deleting relevant mesh elements as already mentioned before (see enclosure 5). Simultaneously, hydraulic pressure conditions of a brine column (γ = 11.8 kPa/m) were applied to the contour of the caverns.
The termination of the leaching process represents the initially given stress and strain state which is the basis for further prognosis calculations.

6.2.2 Maximum pressure and tightness

After finishing the leaching process a high-frequency gas storage operation was simulated according to the procedure described in the enclosures 6 to 9. After dewatering and initial gas injection the pressure decreased from maximum pressure p_{MAX} to minimum pressure p_{MIN}. In the models the realised pressure decrease/increase rates are 10 bar/d between the maximum pressure p_{MAX} and the (temporary) upper limit of the minimum pressure $p_{MIN(o)}$ and 3 bar/d between upper limit of the minimum pressure $p_{MIN(o)}$ and the minimum pressure p_{MIN}.

The results were evaluated applying the criteria described in Chapter 5.4. For all cases the geological tightness is given when cavern pressures are at p_{MAX}. Based on the outcome, i.e. the calculated stress conditions during a long-term gas storage operation under maximum pressure, it can be stated:

- that all caverns are always surrounded by a zone with a sufficient extent, where the minimum stress σ_{MIN} is significantly higher (10 % or more) than the maximum gas pressure p_{MAX} in the cavern (see enclosure 10).

The accordance with the specification of the technical tightness criterion according to Chapter 5.4 is presented in enclosure 11 to 14 (left). The last cemented casing shoes are installed in a range between 1,000 and 1,100 m in depth. If the caverns are at maximum storage pressure of p_{MAX}, two conditions regarding a given safety factor with respect to the acting horizontal stresses above the cavern roof were considered:

- If a safety factor of 15% has to be considered (according to formula 4.3) a tight bond of the interfaces between salt/cement/casing contacts can not be guaranteed.
- If a safety factor of 10% is considered a tight bond is proven for all cases. The criterion with the decreased safety factor is fulfilled in a depth range of up to 30 m above the casing shoe. This range of 30 m above the last cemented casing shoe correlates with the value which has been proposed by the criterion.

Vertical strain will occur in the vicinity of the last cemented casing shoe as a consequence of cavern convergence. The maximum allowable strain at the last cemented casing shoe is requested to be less than 1% (10 mm/m). Calculation results show a maximum value below approx. 0.1% after 4 years of gas storage operation in all cases, i.e. there is no risk of tightness loss (enclosure 11 to 14; right).

In summary, it can be stated that:

- in total, the geological tightness of the modelled caverns is guaranteed in all cases if the gas storage regimes are limited to the given maximum pressures.
- the technical tightness of the technical installations, i.e. the tight bond between salt/cement/casing, could only be demonstrated if the safety factor is lowered. From the rock mechanical point of view, it is necessary to lower the maximum pressure to meet the technical tightness criterion.

6.2.3 Minimum pressure and contour stability

For ensuring the stability of the cavity system during gas storage operation the utilisation of long-term strength of the surrounding support elements (pillars, cavity contour, salt roof and bottom salt) is of decisive importance. The assessment was carried out with respect to the estimated volumetric, plastic deformations ε^{p}_{Vol} that summed up during the studied operation history. Structural salt damage is connected with an increase of volume (dilatancy as a result of micro-cracks and their accumulation) which may reduce the integrity of geological barrier within the contour zones close to the caverns. In order to assess the stability of the cavern contour the dilatancy criterion was applied as described in Chapter 5.4.

In all studied models and cases zones of softening and dilatancy occur only close to the cavern contour (see enclosure 15). A maximum extension of this zone is reached in model Type C1. The value of extension is 18 m after a calculation-time of 4 years. Therefore, it can be stated

- that dilatant processes affecting the contour stability only occur close to the cavern wall and will not affect the complete pillar zone. Pathways allowing fluid penetration into the pillar to neighbouring caverns can be excluded with respect to the modelling results.

If the tensile strength of rock salt is exceeded plastic deformations ε^{p}_{ten} would be initiated which may associated with tensile cracks occurring in-situ. In enclosures 16 to 19 (right) the principal stress components versus the time observed on a history point in reference depth are shown. In consequence of the gas withdrawal down to minimum pressure p_{MIN}, the temperatures at the cavern contour strongly decreases. In addition, also the minimum stress component σ_{MIN} is significantly decreased. However, the modelling results demonstrate that

- for each model configuration (especially under consideration of thermo-dynamical effects) tensile failure ($\varepsilon^{p}_{ten} > 0$) of contour elements is excluded with respect to the modelled storage regime and regarding the lifetime at minimum pressure p_{MIN} (see enclosure 16 to 17; left).

6.2.4 Volume convergence

Based on the calculated displacement rates the resulting subsidence of the cavern roof and the top of the model as well as the uplift of the cavern bottom can be predicted. Drawings of the displacements are shown in enclosure 20 to 23 (left). An average convergence rate (see enclosure 20 to 23; right) for each model is estimated by means of the numerical simulations. Using these results the decrease in cavern volume per time can be calculated and evaluated. The convergence rate and the volume decrease per time are shown in Table 6.3.

In detail, for Type C1 caverns the maximum convergence rate, estimated by IfG (2011), should be less equal 6.2 ‰/year. The numerical results show that under the applied conditions, i.e. when roughly constant temperature and pressure conditions have been established (> 100 d), the convergence rate is only 3.9 ‰/year according to the diagram in enclosure 20.

For Type C2 and C3 caverns the convergence rates, estimated by IfG (2011), were less equal 4.0 ‰/year. As proven by the numerical modelling, the calculated convergence rates for stable conditions (see above) are slightly higher, i.e. 4.4 ‰/year for Type C2 and 4.3 ‰/year for Type C3 caverns. However, it can be stated that under consideration of the limitations of numerical based predictions, the previously estimated convergence rates could be confirmed (compare enclosure 21 and 22).

The estimated convergence rate of the cavern Type C4 caverns is about 4.8 ‰/year. Based on the cavern bottom at 1,500 m the admissible upper limit of the minimum pressure $p_{MIN(O)}$ and the minimum pressure p_{MIN} were increased to prevent higher convergences. Due to the fact that the modelled cavern Type C4 is decreased in diameter and increased in cavern height, the predicted convergence rate is slightly higher than the maximum value postulated in the beginning.

Tab.6.3: Estimated decrease of the volume for the modelled cases for Zuidwending.

case	convergence rate [‰/yr]		decrease of volume [m³/10yrs]
	current simulation	recommendation	current simulation
Type C1	3.9	6.2	25,350
Type C2	4.4	4.0	44,000
Type C3	4.3	4.0	43,000
Type C4	4.8	---	48,000

7. Summary of the results and rock mechanical assessment

In general, the already existing estimates of the convergence behaviour for the different individual situations and operation modes of the Zuidwending gas storage caverns could be confirmed and clarified by the performed numerical modelling study.

The respective pressure regimes modelled for the individual situation of the four caverns were investigated with respect to limited convergence behaviour. The main focus was to find out and to define operation parameters that limit cavern convergence and only secondary, to assess the long-term integrity and stability of the caverns. As outcome it can be stated:

- The distance between caverns (pillar size) was proven and can be verified to be safe. The geological tightness as well as the contour stability of the modelled caverns is guaranteed in all cases.

- In addition, tensile failure at the cavern contour resulting from the combination of hydro-mechanical and thermo-dynamic loadings is excluded.

- The secondary stress field surrounding the cavern is influenced in such a manner that the technical tightness criteria for the last cemented casing shoe could not be proven within a sufficient safety margin as demanded for the confinement of the casing shoe. As demonstrated, the maximum cavern pressures represent 90 % of the lateral acting rock mass stress at casing shoe instead of 85 % postulated in the technical tightness criterion. The reason for this fact is caused by the high intensity of the storage operation – the cavern is operated too little time at maximum pressure to induce a secondary stress field with adequate safety margin. In detail, this is not a reduction of the safety or the tightness. However, the safety margin is reduced. To meet this fact with suspicion the maximum pressure should be reduced in an adequate manner if the cavern is intended to be operated with 6 or more full cycles per year.

According to the results of the computationally modelling some recommendations can be given to ensure limited cavern convergence, also with respect to high-frequent gas storage.

- If storage operations are limited to a maximum of 6 (type C1 to C3 caverns) resp. 8 (type C4 caverns) turnovers per year, a limited cavern convergence can be achieved by operating the caverns in the range between the permissible maximum storage pressures of p_{MAX} and the permissible minimum storage pressures of $p_{MIN(O)}$ and p_{MIN}.

- Between the maximum pressure p_{MAX} and the upper limit of minimum pressure $p_{MIN(O)}$ the rate of gas injection and withdrawal is limited to 10 bar/d while the rate is restricted to 3 bar/d between the upper minimum pressure $p_{MIN(O)}$ and the minimum pressure p_{MIN}. These values should be met for limiting unfavourable influences on the rock mass by thermo-dynamic effect.

- To ensure a long-term safe storage operations a limited maximum lifetime of 30 days/storage year at minimum pressure p_{MIN} and in total of 90 days/storage year between the upper minimum pressure $p_{MIN(O)}$ and the minimum pressure p_{MIN} is recommended.

The recommended pressure ranges are schematically illustrated below in figure 7.1.

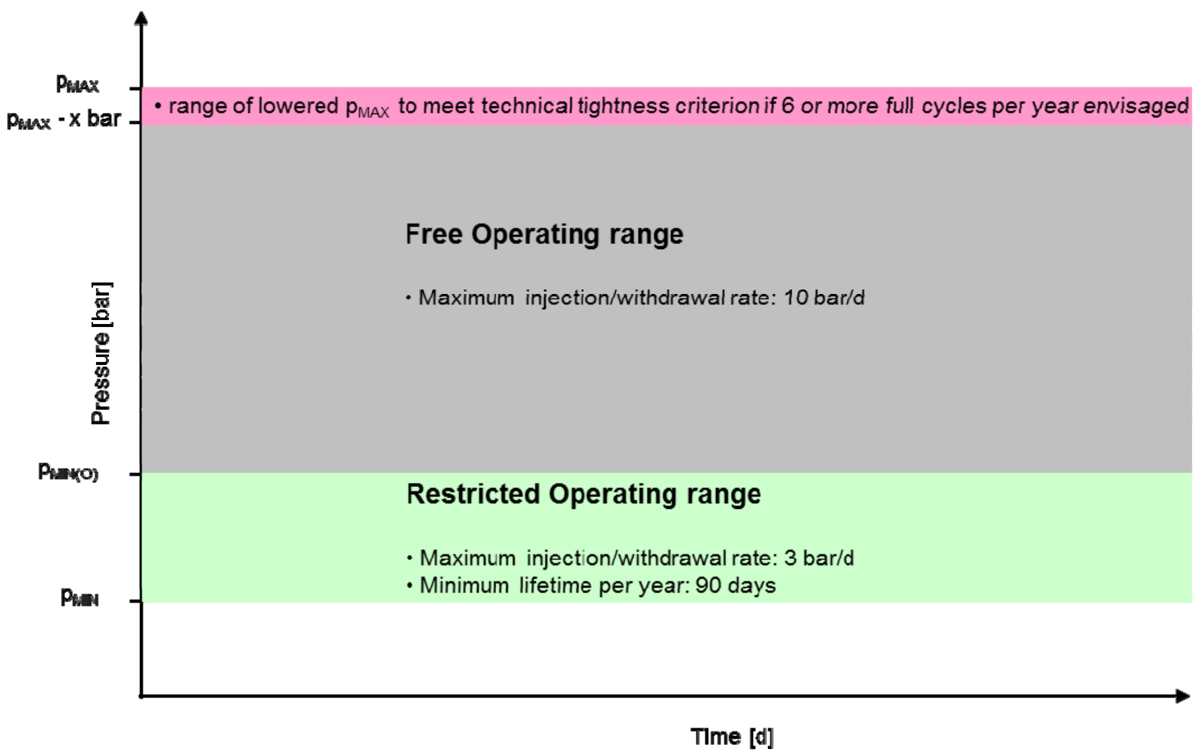

Fig. 7.1: Schematic overview of recommended pressure ranges.

- If it is intended to operate the cavern with 6 or more full cycles per year it is recommended to lower the maximum pressure to meet the technical tightness criterion. The lowered maximum pressure (p_{MAX} - x) are mentioned in the table 7.1.

Tab. 7.1: Lowered maximum pressure in case of 6 or more full cycles per year

	Type C1	Type C2	Type C3	Type C4
p_{MAX} - x [bar]	170 bar	187 bar	178.5 bar	178.5 bar

- Because of stronger influence by temperature effects it is recommended to increase the minimum pressure during the first year of cyclic storage operation at the values as given in brackets in Table 7.2 for caverns of Type C1 and Type C3.

Tab. 7.1: Pressure range for Zuidwending caverns.

	Admissible minimum pressure p_{MIN}	Admissible upper limit of the min. pressure $p_{MIN(O)}$	Admissible maximum pressure p_{MAX}
Type C1	50 bar (85 bar*)	80 bar	180 bar
Type C2	75 bar	110 bar	198 bar
Type C3	60 bar (90 bar*)	90 bar	189 bar
Type C4	84 bar	84 bar	189 bar

* limit of the minimum storage pressure for the first 3 cycles to prevent thermo-dynamically induced damage

- It is suggested to limit the minimum storage pressure for the first 3 cycles to prevent excessive cooling in the cavern and thermo-dynamically induced damage of the rock salt mass at the cavern contour. This recommendation should be applied to caverns of Type C1 and C3. Because of the different boundary conditions in the pressure regime, this recommendation is not necessary for Type C2 caverns.

- For Type C4 caverns, thermo-dynamically induced effects in the rock mass at the cavern wall should be minimized by a reduction of the withdrawal/injection rate to 3 bar/d between 125 and 85 bar during the first 3 cycles.

Average convergence rates were calculated regarding the lifetime and estimated:

- The calculated values are close to the values predicted in the “Recommendations for cyclic operated caverns” (IfG, 2011). The protection objective regarding the surface can be realised by adjusting the minimum storage pressure and the related lifetime. The convergence rates are derived from the results of the numerical calculations and listed un Table 7.3.

Tab. 7.3: Convergence rates with regard to cavern type.

	Type C1	Type C2	Type C3	Type C4
convergence rate [‰/year]	3.9	4.4	4.3	4.8

- It has to be considered that, if two neighbouring caverns in the cavern field are operated in a counter-rotating high-frequent storage mode the loading capacity of the pillar zone will be changed. For this case, it is suggested to perform 3D-calculation with two neighbouring caverns with counter-rotating high-frequent storage modes in order to prove the stability and integrity of the pillar zone.

Based on the results from the geomechanical modelling the admissibility of the cavern installation and of the long-term stability during storage operations could be proven and confirmed from geomechanical point of view in compliance with the above mentioned limitations. Summarising the case studies it can be stated that for a first operation phase up to the rerun the of sonar survey the recommended layout parameters for gas storage represent a reasonable approach for an operation producing convergence only within pre-postulated limits.

Naturally, the storage conditions have to be reviewed and adapted after comparing the predicted and measured data 3 to maximum 5 years (primarily survey period) after starting the operation.

References

BGR (2000): Erkundungsbergwerk Gorleben. Gebirgsmechanische Beurteilung der Integrität der Salzbarriere im Erkundungsbereich EB1 für das technische Endlagerkonzept 1. Ergebnisbericht Hannover, Sept. 2000

DEEP (2010rev): Cavern location planning Zuidwending. AGB ZW Phase II. 30.10.2007 revised version 04.08.2010

IfG (2008): Rock Mechanical Investigation on Rock Salt from the Zuidwending Gas Storage site. 30.05.2008

IfG (2009): Geomechanical numerical modelling for dimensioning, the possible operating regime and the prognosis of long-term gas storage operation of the natural gas storage caverns at Zuidwending. 30.09.2009

IfG (2011): Recommendations for cyclic operated caverns 'Aardgasbuffer Zuidwending' NL. 28.09.2011

Itasca (2009): Fast Lagrangian Analysis of Continua in 3 Dimensions, Version 4.00. ITASCA Consulting Group Inc. Minneapolis, Minnesota USA

MINKLEY, W. (2004): Gebirgsmechanische Beschreibung von Entfestigung und Sprödbrucherscheinungen im Carnallitit. Schriftenreihe des Institutes für Gebirgsmechanik - Band 1, Shaker Verlag

MINKLEY, W.; LINDERT, A.; SCHREINER, W. (2005): Zur Gebirgsmechanik von Gasspeicherkavernen, Freiberger Forschungshefte C505

MINKLEY, W.; MÜHLBAUER, J.; STORCH, G. (2007): Dynamic processes in salt rocks – a general approach for softening processes within the rock matrix and along bedding planes. 6th Conference on the Mechanical behaviour of Salt, SALTMECH6, Hannover, Juni 2007

MINKLEY, W.; LINDERT, A.; BRÜCKNER, D. (2011) The improved IfG Storage Cavern Design Concept. SMRI Fall 2011 Technical Conference. York, United Kingdom, 3-4 Oct. 2011

RESPEC (2004): Topical Report RSI-1760. Salt Cavern Thermal Simulator Version 2.0 User's Manual Respec an Integrated Consulting and Service Company, South Dakota USA

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