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**TNO report**

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# Abandonment of solution mined salt caverns in the Netherlands

## Part 1: Review
## Part 2: Best Practises and methods

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# Contents

**Appendices**

**Part 2: Best practises and methods**

# List of tables and figures

## Tables

## Figures

# 1 Introduction

Salts have been mined in different parts of the world since ancient times for human consumption and industrial purposes. Besides a traditional dry mining method, solution mining has been commonly employed in the Netherlands and elsewhere in the last five to six decades. Large brine-filled underground voids, i.e. caverns, are constructed by exploiting the easy dissolution of salt. As a consequence of the withdrawal of salt, the rock mass in the subsurface deforms and subsidence bowls and –in a worst case situation- sinkholes occur at the ground surface. This is potentially damaging to engineering structures at the ground surface and to the environment in general. Predicting the in situ mechanical and deformational behaviour of salt and other rock masses nearby and above caverns is therefore of interest not only for production and operational purposes, but also for environmental and safety reasons.

At the end of salt production, leached out caverns can be either sealed-off and abandoned or used for storage or disposal purposes (cf. Thoms and Gehle, 2000). Storage concerns mainly hydrocarbons or compressed air and possibly food, hydrogen gas or anhydrous ammonia. Disposal generally concerns non-toxic by-products of oil, gas or brine processing, but may include toxic and radio-active materials. In the Netherlands no caverns are currently used for storage or disposal purposes, with the exception of the disposal of a small amount of gypsum (Nedmag, 2001) and sludge (Van Sambeek, 1998).

In particular in the last two decades experience has been gained worldwide with the consequences of cavern abandonment. Nevertheless, the problem of long-term abandonment and monitoring of salt caverns has not received proper attention by the mining industry in the past. To our knowledge, a generally accepted concept or approach to the abandonment of salt caverns does not exist. This problem deserves our attention due to:

Specific time-dependent mechanical behaviour of the salt (e.g. creep), which requires careful planning and monitoring of the engineering operations in the abandonment- and post-abandonment phase.

Recorded evidence of problems related to the long-term use and/or abandonment of caverns.

Liability of mining companies for damage claims caused by mining activities during and after the lifetime of a mine. In the new Dutch Mining Law, this liability extends 30 years after the abandonment of a mine. Damage may still occur when this time period is exceeded.

Increasing trend to use abandoned salt caverns as storage and disposal caverns, due to nearly perfect isolation capacity of salt.

Recent studies on cavern abandonment (cf. Bérest et al., 2001; 1999b; Rokahr et al, 2002; Ratigan, 2003) focus mainly on solution mining in salt domes. Salt domes are common in the subsurface of for example France and Germany. Caverns are typically situated at depths of 1-2 km below the surface and in rather pure halite. However, in the Netherlands (Figure 1) caverns are also found in thin or bedded salt layers, in potassium salts, and at depths significantly larger or smaller than the aforementioned depth interval (Table 1).

*Table 1 Characteristics of active salt exploitation areas in the Netherlands.*

| exploitation area | depth (m) | mineral | type |
|---|---|---|---|
| Twenthe-Rijn | ~400 | NaCl | thin, horizontal salt layer |
| (Uitbreiding) Adolf van Nassau | ~1000 | NaCl | salt diapir |
| Veendam | ~1700 | KMgCl | salt pillow |
| Barradeel | ~2800 | NaCl | thick package of stratified salts |

The aim of this report is to provide the scientific background for a (draft) protocol documenting a general concept for cavern abandonment in the Netherlands, based on best practises and methods with a focus on human and environmental safety as well as damage control. For this purpose a review is presented of the current knowledge on salt behaviour (section 2), salt exploitation in the Netherlands (section 3) and existing experience with cavern abandonment (section 4). In this way the available technology, current best practises and methods related to the long-term abandonment and monitoring of salt caverns are summarised. On this basis a risk assessment is performed (section 5), taking into account the regulations on the liability expressed by the Dutch Mining Law. The exertion results in a discussion of the best practices and methods for cavern abandonment (section 6).

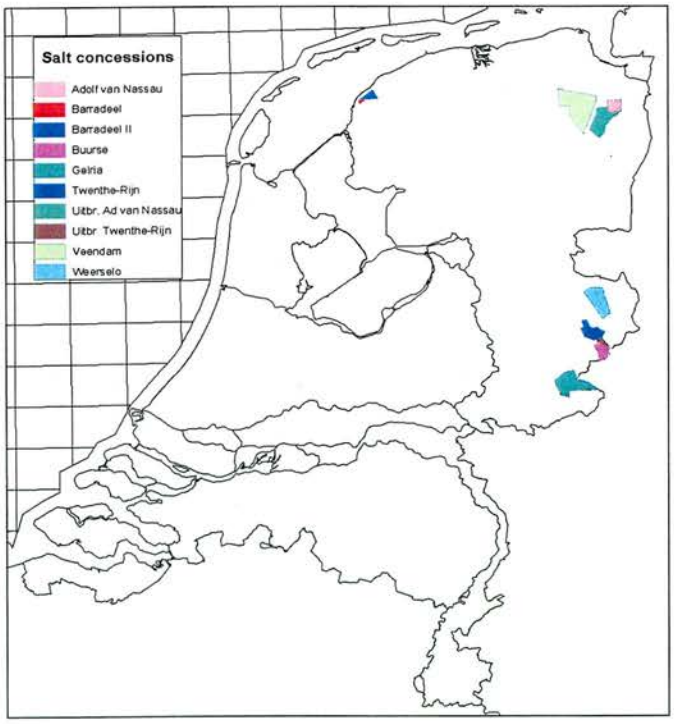


*Figure 1 Overview of salt exploitation in the Netherlands*

# 2 Salt behaviour

## 2.1 Elasticity

The most important evaporite minerals are listed in Table 2. Different elastic parameters have been proposed for halite and other evaporites (Table 3a, b and e; Bérest et al., 1999a). Values for Poisson's ratio range from 0.25 to 0.35. Young's modulus values are more variable, but generally range between 2 and 40 GPa. Anhydrite is more rigid, whereas bischoffite and other potassium salts are less rigid than halite (Liezenberg et al., 1987; Van Montfrans, 1991; Jeremic, 1994). This is supported by in situ observations where carnallite pillars are significantly less rigid than halite pillars (Jeremic, 1994).

At cavern scale the elastic properties of the salt surrounding the cavern determine the cavern compressibility, which also depends on brine compressibility and cavern shape (Bérest et al., 1999a). Caverns with a spherical shape are less compressible than caverns that have a flat, oblate shape. Cavern compressibility is significantly larger when a gas pocket is present in the cavern, even if the gas pocket volume is small (Bérest et al., 1999a).

*Table 2 List of the evaporite minerals.*

| **mineral** | **constituent** |
|---|---|
| halite | $NaCl$ |
| carnallite | $KClMgCl_2+6H_2O$ |
| kieserite | $MgSO_4+H_2O$ |
| bischoffite | $MgCl_2+6H_2O$ |
| sylvite | $KCl$ |
| anhydrite | $CaSO_4$ |
| gypsum | $CaSO_42H_2O$ |
| polyhalite | $K_2SO_42CaSO_42H_2O$ |
| kainite | $MgSO_4KCl_3H_2O$ |
| langbeinite | $K_2So_42MgSO_4$ |

## 2.2 Creep

Salt creep depends on temperature, pressure and site specific salt minerals (Table 3) as well as grain size, impurities, age, deformation and load history, stratification and layering (Appendix A; Hunsche and Schulze, 1994). Creep can be subdivided in primary, secondary and tertiary creep. Primary creep occurs during short term deformation (hours-days up to weeks-months) after a change in stress, humidity or temperature (Hunsche and Hampel, 1999). It results in net strain hardening or softening. Tertiary creep is related to micro-crack development due to dilatation and material damage. Secondary creep is a steady state mechanism and it is thus important for long term predictions of salt behaviour (years or more). Both primary and steady state creep represent the macroscopic effect of the movement of dislocations in salt crystals (i.e. dislocation creep) (cf. Hunsche and Hampel, 1999). For low differential stress conditions (Figure 2) a diffusion creep mechanism may be important (Spiers et al., 1990).

Halite creeps up to a factor 50 faster in the presence of water/brine in comparison to dry conditions (water content < 0.1 wt%) (Hunsche and Schulze, 1994). Wet salt behaviour is best reproduced in the laboratory by experiments using confining pressure to prevent the escape of water/moisture from the sample during deformation rather than by standard uni-axial experiments (see Appendix A). Natural salt usually behaves "wet". The effect is enhanced by the presence of crystal water or trapped water. The former is common in carnallite. The de-hydration of gypsum to anhydrite can introduce pockets of trapped water into a salt body. Trapped water is often in equilibrium with minute amounts of gas, resulting in a risk of gas outburst after disturbance. These pockets can be quite large (for example the Klodawa salt dome, Poland; Jeremic, 1994) and are natural analogues for brine filled caverns (Langer en Rőthemeyer, 1996).

## 2.3 Diffusion creep

Diffusion or pressure solution creep in halite, and possibly also in other evaporitic minerals, depends on the water content and is strongly grain size sensitive (Spiers et al., 1990). Grain size distribution is a function of deposition and deformation. Samples from the Gorleben salt dome indicate that increasing deformation results in a decrease of crystal size (Wildenborg et al., 1993). Dynamic re-crystallisation can be important at confining pressures below 10 MPa (Peach et al., 2001). Re-crystallisation can cause only a limited weakening, because grain sizes evolve towards a balance near the boundary between dislocation and diffusion creep (De Bresser et al., 2001; Ter Heege, 2002). Dry gypsum deforms primarily by dislocation creep, but in the presence of saturated brine intergranular pressure solution is probably the dominant mechanism for flow and compaction. A reliable constitutive equation for this type of creep in gypsum does not exist yet (De Meer et al., 2000).

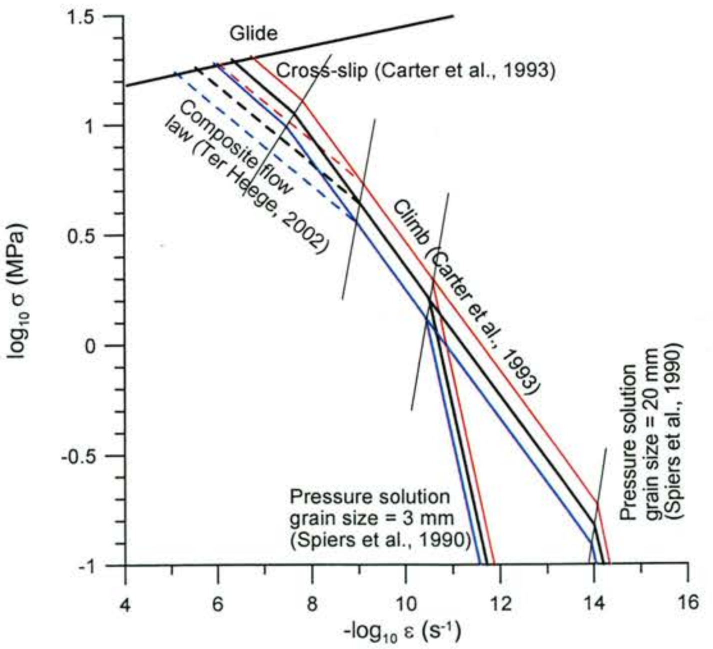


*Figure 2 Dominant deformation mechanism diagram for halite in the Barradeel concession. Thick blue lines represent a temperature of 105 °C, blue lines 125 °C and red lines 85 °C (De Meer, 2003).*

## 2.4 Dislocation creep

An overview of published equations for dislocation creep based on halite samples from different locations is given in Appendix A. Different equations result in a variation of over one (at 100°C) or two (at 22°C) orders of magnitude, depending on halite type as well as on the temperature and stress interval. Creep parameters for Zechstein 2 en 3 halite samples (> 95% halite) from the Gorleben salt dome show a variation of a factor 10 to 100 (Figure 3; Table 3). Similar variation in creep rates (up to one order of magnitude difference) was found in limited testing of West Hacberry salts (Wawersik and Zeuch, 1984 in Ehgartner and Sobolik, 2002). A more detailed study of creep parameters in 10 successive stratigraphic layers within the Zechstein 2 Stassfurt-series showed a systematic change in creep rate (Figure 4). Both the large variation (Figure 3) and the systematic change (Figure 4) are mainly attributed to changes in the distribution of microscopic small impurities in the salt (Langer en Röthemeyer, 1996; Hunsche and Schulze, 1994; Hunsche and Hampel, 1999). There are also indications that creep rates are slightly higher (by a factor 1.7) in extension than in compression (Hunsche and Schulze, 1994).

Other minerals, like carnallite, sylvite, anhydrite or gypsum, show different creep behaviour. Carnallite has a creep rate, which is almost 10 times faster than halite (Hunsche and Schulze, 1994). Bischoffite flows still faster than carnallite by a factor 100 (Jeremic, 1994). Anhydrite on the other hand flows less easy in comparison to halite, but still easier than most other rock minerals (Carter and Tsenn, 1987; Jeremic, 1994). The properties of gypsum are closer to those of halite than to those of anhydrite (Table 3c and d, Nűesch and Baumann, 1989). Natural salt layers are usually composite rather than consisting of pure minerals. Unfortunately, the influence of this on creep behaviour is not well know (Jeremic, 1994).

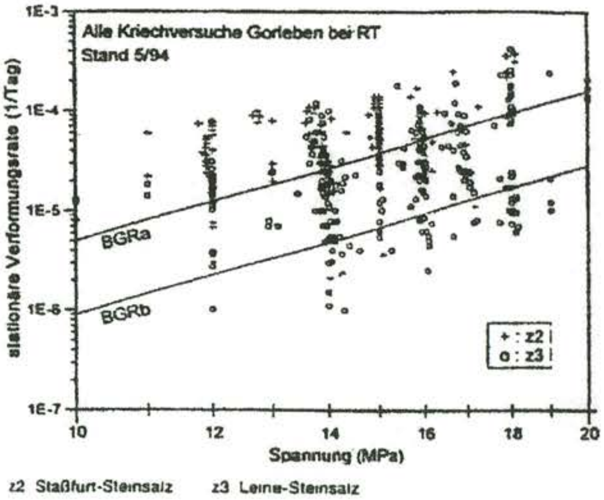


*Figure 3 Laboratory results for secondary creep at room temperature in halite from the Gorleben salt dome (Langer en Röthemeyer, 1996). Note the single logarithmic scale.*

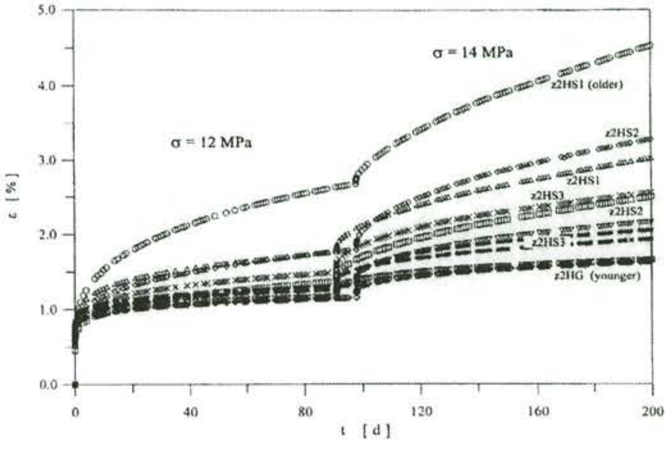


*Figure 4 Laboratory results for secondary creep using uniaxial tests at 22°C in 10 halite specimen from successive stratigraphic layers in the Stassfurt-series of the Gorleben salt dome (Hunsche and Hampel, 1999).*

*Table 3 Material parameters.*

a) Elastic and secondary salt creep parameters (Brouard et al., 2002).

| **salt source** | **A** **($MPa^{-n}.year^{-n}$)** | **n** **(-)** | **Q/R** **(K)** | **E** **(GPa)** | **$\upsilon$** **(-)** | **$\rho$** **($kg.m^{-3}$)** |
|---|---|---|---|---|---|---|
| Avery Island* | $6.4*10^{1}$ | 3.14 | 6495 | - | - | - |
| Etrez | $6.4*10^{1}$ | 3.10 | 4100 | - | - | - |
| Bayou Chocklaw | $6.4*10^{1}$ | 4.06 | 5956 | - | - | - |
| Salina | $2.78*10^{5}$ | 4.10 | 8715 | - | - | - |
| West Hacberry (WH1) | $4.52*10^{2}$ | 4.73 | 6606 | - | - | - |
| West Hacberry (WH2) | $9.4*10^{-1}$ | 4.99 | 10766 | 2.48 | 0.25 | 2300 |
| West Hacberry caprock** | - | - | - | 7.0 | 0.29 | 2500 |
| Bryan Mound (BM3C) | $1.32*10^{3}$ | 4.54 | 7623 | - | - | - |
| Bryan Mound (BM4C) | $1.04*10^{5}$ | 5.18 | 8977 | - | - | - |
| Waste Isolation Pilot Plot | $1.04*10^{0}$ | 5.00 | 5035 | - | - | - |
| Salado* | $3.67*10^{4}$ | 5.09 | 8333 | - | - | - |
| Palo Duro (Unit 4) | $1.81*10^{5}$ | 5.60 | 9760 | - | - | - |
| Asse (Speise-series)* | $2.51*10^{4}$ | 6.25 | 9969 | - | - | - |

*Carter et al. (1993) **Ehgartner and Sobolik (2002)

b) Elastic and secondary creep parameters (Eickemeier et al., 2002).

| **Salt** | **A** **($d^{-1}$)** | **n** **(-)** | **Q** **($kJ.mol^{-1}$)** | **R** **($J.mol^{-1}.K^{-1}$)** | **E** **(GPa)** | **$\upsilon$** **(-)** | **$\rho$** **($kg.m^{-3}$)** |
|---|---|---|---|---|---|---|---|
| Halite (BGRa05) | 0.18 | 5 | 54.0 | 8.3143 | 25 | 0.27 | 2200 |
| Halite (BGRa07) | 0.72 | 5 | 54.0 | 8.3143 | 25 | 0.27 | 2200 |
| Halite (ECN)* | 22.9 | 5.5 | 68.6 | 8.3143 | 0.76** | 0.30 | 2200 |
| Brine | - | - | - | - | - | - | 1200 |
| Carnallite*** | 2.0 | 4 | 75 | 8.3143 | 5 | 0.25 | - |

*Broerse (1993) and Beemsterboer and Preij (1993) in Eickemeier et al. (2002)

** low value accounts for primary creep, plasticity and microcracks

***Urai (1983)

c) Secondary creep parameters (Carter and Tsenn, 1987).

| salt | A<br>($Pa^{-n}s^{-1}$) | n<br>(-) | Q<br>($J.mol^{-1}$) |
|---|---|---|---|
| polycristalline anhydrite | $31.6*10^{-12}$ | 2 | $1.51*10^{5}$ |

d) Secondary creep parameters (Von Nűesch and Baumann, 1989).

| **salt** | **A**<br>**($s^{-1}$)** | **n**<br>**(-)** | **Q**<br>**($J.mol^{-1}$)** | **$\sigma_0$**<br>**(MPa)** |
|---|---|---|---|---|
| gypsum | 4.5 | 4.5 | $1.32*10^{5}$ | - |
| halite | $2.6*10^{-6}$ | 5.5 | $0.96*10^{5}$ | - |
| anhydrite* | 6030 | 1.5 | $1.14*10^{5}$ | 170 |

*$\sinh(\sigma/\sigma_0)^n$ (see Appendix A)

e) Elastic, primary and secondary creep parameters (Fokker, 1995).

| **salt** | **E**<br>**(GPa)** | **υ**<br>**(-)** | **$n_1$**<br>**(-)** | **$Q_1/R$**<br>**(K)** | **β**<br>**(-)** | **$\sigma_0$**<br>**(MPa)** | **$d\varepsilon_0/dt_0$**<br>**($s^{-1}$)** | **$n_2$**<br>**(-)** | **$Q_2/R$**<br>**(K)** | **ρ**<br>**($t/m^3$)** |
|---|---|---|---|---|---|---|---|---|---|---|
| halite* | 30 | 0.35 | 4.5 | $8.0*10^{3}$ | - | - | - | 1 | 3240 | 2.2 |
| halite | - | - | 10 | $13.8*10^{3}$ | 0.2 | 3 | 1 | - | - | - |
| carnallite** | 5.5 | 0.35 | 5 | - | - | - | - | - | - | 1.6 |
| bischoffite** | 1.8 | 0.35 | 3.5 | - | - | - | - | 1.5 | - | 1.6 |
| brine | 0.5 | 0.35 | 1 | - | - | - | - | - | - | 1.3 |
| polycristalline halite*** | 36.7 | 0.26 | - | - | - | - | - | - | - | - |

*Spiers et al. (1987); Carter en Hansen (1983) in Fokker (1995)

**Urai (1983)

***Hunsche and Schulze (1994)

f) Primary and secondary creep parameters (Hunsche and Hampel, 1999).

| **salt** | **$v_0$**<br>**($ms^{-1}$)** | **$d_p$**<br>**(m)** | **$\sigma_p$**<br>**(MPa)** | **$k_w$**<br>**(-)** | **$k_a$**<br>**(-)** | **$k_p$**<br>**(-)** | **n**<br>**(-)** | **$Q_1$**<br>**($kJ.mol^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| halite Zechstein 2 Speise-series (Asse) | $4*10^{6}$ | $1*10^{-9}$ | 0.4 | $30*10^{-3}$ | $3*10^{-3}$ | $2*10^{-3}$ | 7 | 180/R |

## 2.5 Primary creep

Primary creep depends non-reversible on deformation history and plays an important role in laboratory experiments on halite samples (Fokker, 1995; Yahya et al., 2000). One way to introduce primary creep into constitutive equations is to split primary and dislocation creep into separate terms (cf. Hunsche and Schulze, 1994 and references therein; Fokker, 1995). Different power laws or exponential laws are used to describe primary creep (Appendix A). The equations and parameter values vary considerably, even for identical temperature and pressure intervals. According to Hunsche and Schulze (1994) the main reasons for this large variation are halite type and the use of different protocols for the measurements. Instead of using two equations for primary and dislocation creep they can also be integrated into one composite equation. The equation proposed by Hunsche and Hampel (1999) considers only parameters which can be measured on rock samples. This equation can fit a large range of stress-strain relations in different halite samples by only varying the value for spacing of hindering impurities inside the subgrains (*$d_p$*). Their estimate of the power law component *n* (7) is higher than most other estimates reported (Table 3). However, it is within $n$ = 5-7 reported by Hunsche and Schulze (1994) for dislocation creep in halite for the stress interval 10-20 MPa. Another attempt is given by Yahya et al. (2000). In their set of equations evolutionary internal state variables determine which competing creep mechanism (hardening or softening) prevails. Temperature dependency is not taken into account.

Laboratory experiments on synthetic halite samples with different amounts of anhydrite (Price, 1982) show that the samples flow more easy for a higher halite content and/or confining pressure. Both strain hardening and softening are observed. Carnallite on the contrary has no strain-hardening (Hunsche and Schulze, 1994).

## 2.6 Tertiary creep

Tertiary creep is related to micro-crack development due to dilatation and material damage. The most generally used criterion for the onset of dilatation is the one proposed by Critescu and Hunsche (1998) (Figure 5). The corresponding constitutive equation for the dilatant regime is not explicitly dependent on temperature or humidity. Viscosity coefficients for (primary and/or dislocation) creep are included in the equation, as well as elasticity. The type of salt does not have a considerable influence on the onset of dilatancy (Critescu and Hunsche, 1998). Dilatant microcracks form at low confining pressure (< 3-3.5 MPa) (Figure 5). Due to the pressure distribution only the salt in the vicinity of a cavern will be affected by dilatancy. It is important to note that re-crystallisation does not occur in dilatant salts (Spiers et al., 1987; Peach et al,, 2001).

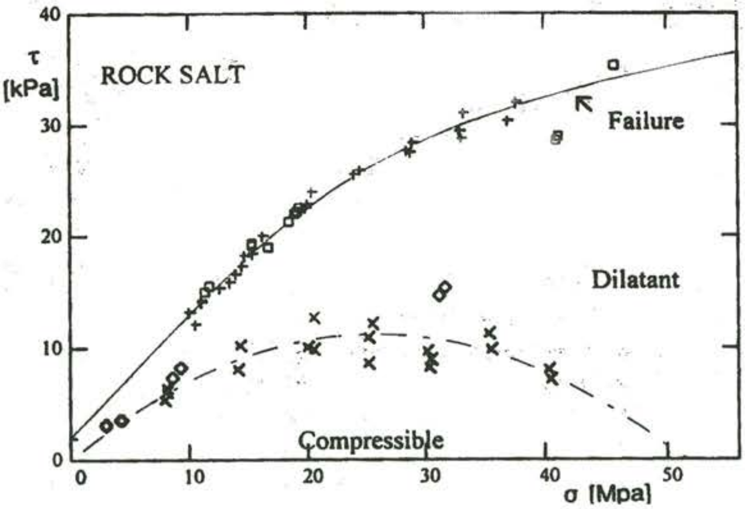


*Figure 5 Data for Gorleben (closed symbols) and Avery Island (open symbols) types of halite compared with the criterion for the onset of dilatation and failure after Critescu and Hunsche (1998).*

## 2.7 Salt strength

Strength values for some evaporitic minerals are given in Table 4. Halite is stronger than the potassium salts, but weaker than anhydrite. Therefore, it is not surprising that a direct relationship is found between rock strength and anhydrite content in synthetic halite (Price, 1982). A particular large increase in strength is observed for an anhydrite content of more than 75%. According to Fokker (1995) halite can withstand a fluid pressure excess of 2 MPa before fracturing under laboratory conditions without confinement. Carnallite on the other hand fractures already at 0.1 MPa excess pressure. Indeed, large vertical tensional fractures are frequently observed in potash mines (Lajtai et al., 1994 in Stead et al., 2000). Caverns are not suitable for storage of liquid petroleum gas because of (observed) brittle failure of salt at low temperatures (Haddenhorst et al (1977) in Thoms en Gehle, 2000).

*Table 4 Laboratory strength values from uni-axial tests (Fokker, 1995).*

| **material** | **compressive strength (MPa) without brine** | **compressive strength (MPa) with brine** | **compressive strength (MPa)*** | **tensile strength (MPa)*** |
|---|---|---|---|---|
| halite | 27-33 | 27-33 | 28.0 | 2.4 |
| carnallite | 8.5 | < 8.5 | 22.5** | 1.5** |
| bischoffite | 6.5 | near zero | 21.0*** | 1.0** |
| gypsum | - | - | 12.5 | 1.0** |
| anhydrite | - | - | 75.0 | - |

*Liezenberg et al. (1987)
**best guess
***Stead et al. (2000)

## 2.8 Mechanical salt behaviour

In Table 5 an overview is presented of the main factors that influence creep rate variations in salts. In order to obtain salt creep parameters that are adequate, it is particularly important to be able to discriminate between linear diffusion creep and non-linear types of dislocation creep.

The type of mineral is important. Halite is usually the main rock component, but where layers of bischoffite or other potassium salts are present, creep rates are strongly enhanced for the same pressure and temperature conditions. Furthermore, natural salt rocks are usually composite. The presence of secondary minerals such as anhydrite in rock salt can alter the overall mechanical behaviour. Microscopic impurities in halite also have a significant effect on creep rates (Table 5). In addition diffusion creep can occur in "wet" salt with small grain sizes (less than 3-5 mm) (Figure 2).

For a reliable macroscopic description of the mechanical properties of a salt body site-specific data on salt minerals, impurities, water content and grain size is required, preferably at the scale of individual stratigraphic layers. As these properties will not always fully coincide with the stratigraphic layers due to post-deposition processes, the internal structure and deformation history should also be considered. In many cases this information will not be readily available. In that case a wide range of creep parameters and/or creep equations (at least a factor 10-100, but possibly up to a factor 1000) should be considered.

*Table 5 Creep rate variations in salt*

| factor | dominant creep process | order of magnitude |
|---|---|---|
| mineral type | dislocation | 10-1000 |
| impurities in pure halite | dislocation | 10-100 |
| temperature and pressure | dislocation | 10(-100) |
| water content | diffusion | 50 |
| grain size | diffusion | 1000 |

## 2.9 Permeability

Primary (intrinsic) salt permeability is small. Values from laboratory experiments on halite are somewhat variable: $1*10^{-22}$ m$^2$ (Sitz en Koch, 2000), $1*10^{-21}$ m$^2$ (Peach et al., 1991 in Carter et al., 1993) and $< 1*10^{-20}$ m$^2$ (Spiers et al., 1987). In situ observations of the primary permeability of halites are scarce and variable. Examples are $2*10^{-19}$ m$^2$ (Bérest et al., 1999b), $1*10^{-21}$ m$^2$ (WIPP, Howarth et al., 1991 in Brouard et al., 2002), $6*10^{-20}$ m$^2$ (Durup, 1994 in Brouard et al., 2002). The presence of natural brine and gas inclusions in salt layers support the notion that salt at large depth and elevated temperature can be impermeable for long periods of time (Kenter et al., 1990). The intrinsic permeability of anhydrite is $< 1*10^{-19}$ m$^2$. Gypsum rocks also have a low permeability (De Meer et al., 2000).

While the intrinsic permeability of evaporitic minerals is small, permeability may increase significantly due to secondary effects like dilatancy or effective pressure differences (Peach, 1991; Fokker, 1995; Minkley en Menzel, 1995; Wallner et al., 2000; Ratigan, 2003). The secondary increase in permeability is recoverable due to salt creep/crack healing. Peach (1991) showed that the permeability of halite may increase up to $1*10^{-16}$ m$^2$ under very small volumetric amounts of dilatancy (~ 2%). According to Schulze et al. (2001) permeability can increase four orders of magnitude at low confining pressure (< 5 MPa), whereas porosity increases only slightly. At a confining pressure of 30 MPa the increase of permeability is insignificant, whereas crack density and hence porosity is still increasing. The relation between permeability and porosity in halite is thus non-linear. It depends on the state of stress and the accumulation of strain during loading. In situ observations perpendicular to the side of a well show permeability values decreasing from $1*10^{-18}$ to $1*10^{-22}$ m$^2$ within 40 cm (Sitz en Koch, 2000). In the gallery wall of the Asse mine at 800 meter depth salt permeability decreases from $1*10^{-18}$ to near $1*10^{-21}$ m$^2$ within 3 meter (Peach, 1991). Cracks in walls are expected to be anisotropic. Hence, permeability is also likely to be anisotropic (Schulze et al., 2001).

A secondary increase in permeability is found not only in halite, but also in potassium salts. However, the permeability of anhydrite does not depend on the state of pressure (Minkley en Menzel, 1995). Halite containing more than 10-15% anhydrite clasts may become permeable due to dilatancy within the anhydrite clasts for conditions where pure halite is non-dilatant (Peach, 1991). This is not directly applicable to banded halite-anhydrite, where the permeability is likely to show a strong anisotropy. Dilated anhydrite is permeable for saturated brine but not for unsaturated water, due to cementation by gypsum (Spiers et al., 1987). According to Wallner et al. (2000) solution/precipitation of salts does not play an important role in the brine permeation process.

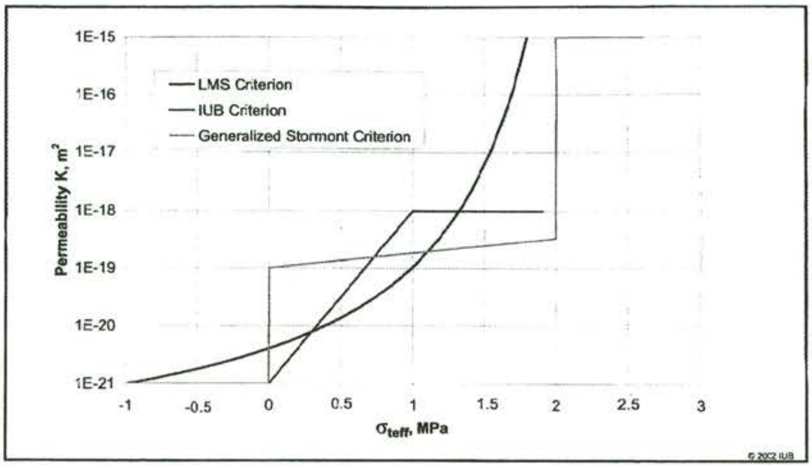


*Figure 6 Best fits of three different criteria for stress related permeability development in halite experiments (Rokahr et al., 2002).*

Currently three different criteria (LMS, IUB, Stormont) are used for the transition to secondary permeability (Figure 6; Rokahr et al., 2002 and references therein). The UIB criterion simply assumes a linear increase in permeability within a specified stress trajectory. The LMS criterion assumes a non-linear increase in permeability towards infinity. The Stormont criterion relies on the combined effect of pore-scale damage (including porosity) and a limited tensile strength of crystal boundaries (Figure 6). All three criteria can describe the observed infiltration volumes in laboratory test samples equally well using one (non-unique) set of parameter values for all experiments. There are no substantial differences for different types of salt (i.e. fine grained and homogeneous versus coarse grained with clay impurities). Intrinsic permeability is the most sensitive parameter in the criteria (Rokahr et al., 2002) and a cut-off value is always applied for the maximum secondary permeability.

## 2.10 Solubility

Many salt formations show a clear stratification of different salt minerals, because the minerals precipitate according to their solubility (Table 6). In general, calcium carbonates and iron oxides are the first minerals to precipitate. For normal conditions gypsum precipitation starts at a water density of 1.129 g.cm$^{-3}$ and is joined by the precipitation of halite at a density of 1.218 g.cm$^{-3}$. Further concentration may lead to precipitation of polyhalite, kieserite and anhydrite and eventually to precipitation of easily soluble minerals like carnallite, sylvite, bischoffite and kieserite. These minerals are the first to dissolve again. This occurred for example along fault zones in the Gorleben salt dome (Wildenborg et al., 1993). Similarly, the shape of solution mined caverns in salt bodies where different minerals are present is strongly affected by their configuration (e.g. Veendam; Buyze, 1985).

The solubility depends also on brine composition, temperature, pressure and dissolution rate. Gypsum precipitation is reduced in the presence of magnesium, phosphates or organic matter (Hellberg et al., 2000). The solubility of anhydrite rapidly decreases for temperatures below 70°C. Gypsum has a high crystallisation rate and is stable till 60-70°C (Hellberg et al., 2000).

Cooling of the brine during transport through the well may cause problematic gypsum precipitation in the casing. The concentration of elements originating from minerals like anhydrite, polyhalite and kieserite increases significantly when no fresh water is introduced into the cavern, due to ongoing leaching until the brine is completely saturated (Herbert, 1989; Hellberg et al., 2000). This is the case during the abandonment phase. A stable density stratification may then develop in the brine (Sander en Herbert, 1985).
The dissolution rate is more sensitive for temperature than the solubility (cf. Fokker et al., 2002). Ehgartner and Sobolik (2002; and references therein) find their model to be insensitive to this, whereas Eickemeier et al. (2002) recommend that the thermal effect should be taken into account. It should be noted that the thermal expansion coefficient of halite is around 10 times larger than that of most other rocks.

*Table 6 Salt mineral solubility in water at 55 °C (Jeremic, 1994).*

| material | salt concentration in brine (%wt) | density saturated brine ($t.m^{-3}$) | volume ratio $m^3$water/$m^3$salt |
|---|---|---|---|
| halite | 27 | 1.18 | 5.8 |
| carnallite | 34 | 1.28 | 1.6 |
| bischoffite | 37 | 1.34 | 0.4 |
| kieserite | 34 | 1.36 | 3.8 |

# *3* Salt exploitation in the Netherlands

There are several salt concession areas in the Netherlands (Figure 1). The active concession areas are situated at various depths and geological settings (Table 1). Accordingly, current cavern field characteristics are also quite variable between the different areas (Table 7). The various settings and production histories are presented below. The latest concession is the Barradeel II concession, where salt production has not began yet. In addition to these active concessions there are three inactive concessions in the Netherlands. The Gelria concession (1930) is valid for halite (Rőt) and coal, but the halite is only allowed to be exploited using the room and pillar method (Harsveldt, 1980). The Weerselo concession (1967) applies to Zechstein salt, but the salt pillow is smaller than previously thought (Harsveldt, 1980; NITG, 1991). In the Buurse concession salt exploitation (Rőt) took place between 1919 and 1952 by N.V. Koninklijke Nederlandse Zoutindustrie (currently Akzo Nobel Chemicals BV). Since 1994 this concession is an extension for the Twenthe-Rijn concession.

*Table 7 Cavern characteristics of active salt exploitation areas in the Netherlands.*

| | **Onset production** | **No. cavern** | **Height (m)** | **Diameter or width/length (m)** | **Cavern convergence** | **Maximum subsidence (m)** |
|---|---|---|---|---|---|---|
| Twenthe-Rijn | 1933 | > 450 | 40 | 80/120 | Very slow | 4.5 |
| Adolf van Nassau | 1957 | 11 | 750 | max 125 | 0.5 ‰ $y^{-1}$ | 0.07 |
| Uitbreiding Adolf van Nassau | 1968 | 8 | 725 | max 125 | 0.04 % in 5 months | 0.07 |
| Veendam | 1982 | 11 | max 100 | max 200 | 30-40 % production rate | 0.12 |
| Barradeel | 1995 | 2 | 250-400 | max 60 | ≈ production rate | 0.26 |

## 3.1 Twenthe-Rijn

In this concession (for location see Figure 1) halite is produced from the Main Röt Evaporite (Trias, Late Scythian to Ladinian), which is located nearly horizontally at a depth of 350 to 400 meter below the surface. The average salt thickness is about 50 m, but the salt layer can be as thick as 100 m. The Röt salt consists mainly of halite, with thin layers of potassium salts locally (NITG, 1998) and are interlayered by clayey and anhydritic layers. On top lies a 20 meter thick layer of anhydrite. The salt is covered by at least 160 m of claystone (Middle and Upper Röt Claystone), partly interlayered by evaporites. The sequence is covered by the Muschelkalk (mainly marly to clayey little consolidated carbonates) or the Altena Formation (mainly claystone) or younger Formations. The area is covered near the surface by an approximately 100 meter thick layer of Tertiary and Quartenary clays. Some faults cut through the area (Harsveldt, 1980). Over 70 years of salt exploitation by Akzo Nobel Chemicals BV (Table 7) has resulted in the presence of more than 450 caverns in a relatively small area (Brand et al., 2002).

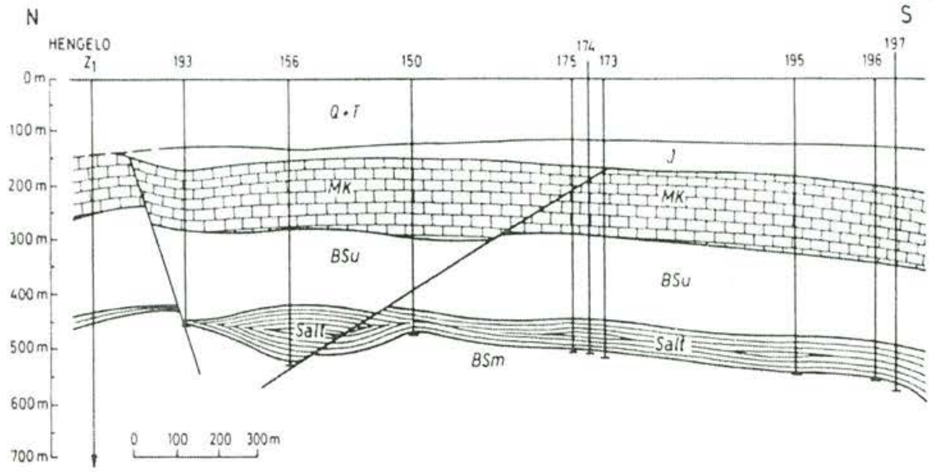


Figure 7. Hengelo Z1 profile. Twenthe-Rijn concession

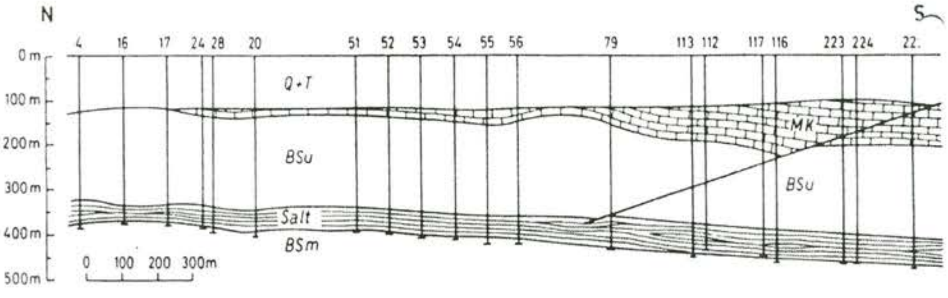


Figure 8. Profile along Holmersweg-Grote Veldweg. Twenthe-Rijn concession.

*Figure 7 Two sections across the Twenthe-Rijn concession (Harsveldt, 1980).*

## 3.2 Adolf van Nassau and Uitbreiding Adolf van Nassau

The Adolf van Nassau concession dates from 1954. Halite has been produced since 1957 by Akzo Nobel Chemicals BV. In 1967 the concession was extended to the Zuidwending area (Table 7; Figure 1). The Late Permian Zechstein 2 halite is rather pure and coarse with halite crystals up to 15 cm in size (Harsveldt, 1980; NITG,1995). No continuous clay, anhydrite or dolomite layers are found within the salt, but the salt smells of suphuretted hydrogen (Harsveldt, 1980). A continuous Z2 anhydrite layer with a thickness of at most several meters is overlying the halite (NITG, 1995). In the Winschoten/Heiligerlee salt diapir, situated in the Adolf van Nassau concession, the salt has a total thickness of 2200 meter. The top of the diapir lies 400 meter below the surface and has 6-40 meter of caprock (Harsveldt, 1980; NITG, 1995). The Cretaceous Rijnland Group that consists largely of claystone is lying discordantly on the caprock. The Zuidwending diapir has 40-50 meter of caprock.. The top of the salt is situated shallower at 110 meter below surface. The Zechstein 2 salt layers have at present a steep position (70-90°) due to strong halokinesis (NITG, 2000). Here too the halite is coarse and very pure (Harsveldt, 1980). Dutch and German diapirs typically have a maximum internal uplift-velocity of 0,6 mm/y due to halokinesis in Quaternary times. Maximum subrosion rate is 1.3 mm/y at depths of less than 50 meter (Prij et al., 1993 in Wildenborg, 1996; Wildenborg et al., 1993).

Until recently the caverns were leached by groundwater, but currently surface water is used (Eickemeier et al., 2002). Average volume convergence rate during production is 0.5 ‰ per year in Winschoten (Eickemeier et al., 2002). The measured cumulative surface subsidence above the Winschoten diapir due to salt exploitation amounts to ~7 cm (Brand et al., 2002). Maximum subsidence rate during production is 3.5 mm/y (Eickemeier et al., 2002). The rock salt in the Zuidwending diapir creeps slower than was predicted on the basis of core investigation. The in situ creep rate was determined from the observed convergence rate of 0.04% in one of the wells during a 5 month production stop (Wassmann, 1993) (Table 7).

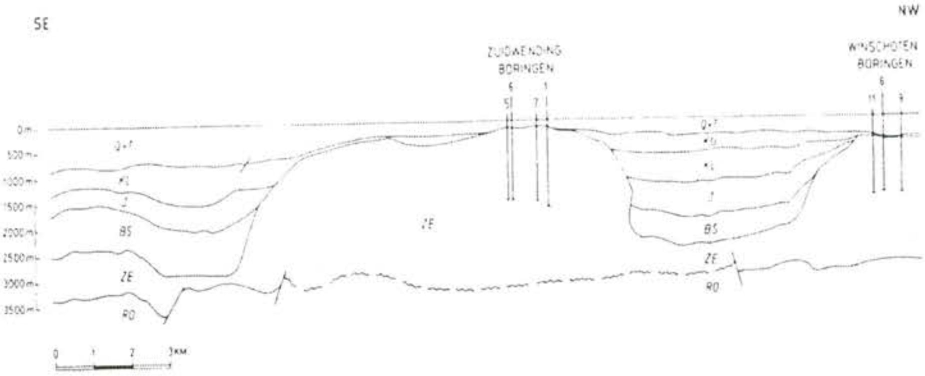


*Figure 8 Section across the Zuidwending and Winschoten salt diapirs (Harsveldt, 1980).*

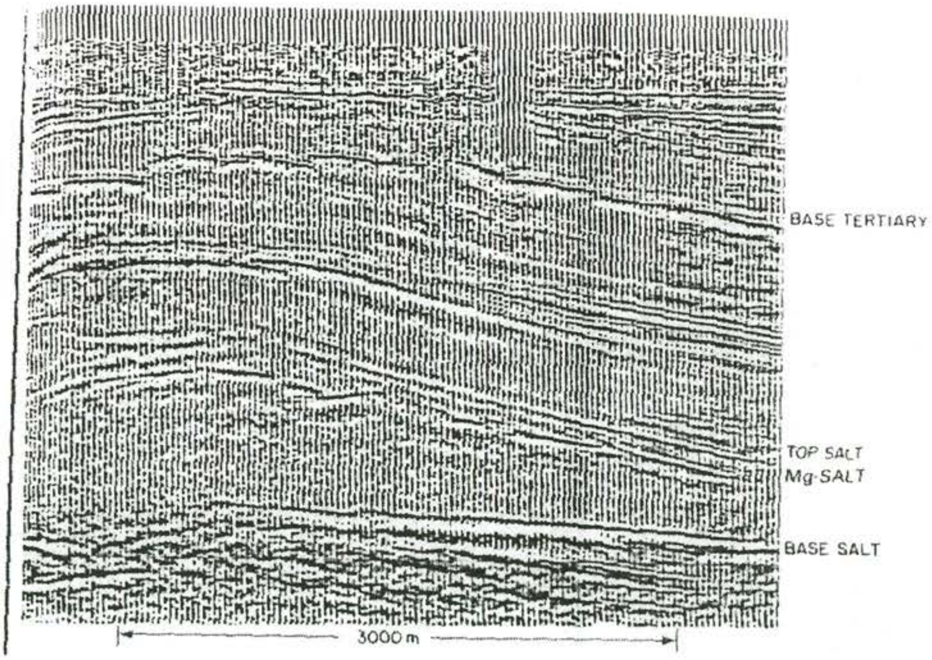


*Figure 9 Migrated acoustic impedance time section of the Veendam structure. Vertical scale to base salt approximately 3000 m. After Coelewij et al. (1978).*

## 3.3 Veendam

In this locality (Figure 1) a salt pillow is present with a top at approximately 1200 meter depth (Figure 9; NITG, 2000). The third cycle of the Zechstein Group that consists of 5 or 6 evaporite cycles is the most complete cycle and includes potassium salts. The Zechstein 3 Formation can be subdivided into two parts. The lower part consists mainly of halite. The upper part has two potassium salt layers inter-layered by clays and separated by halite (NITG, 1995). Carnallite (40 %) and kieserite are the most abundant potassium salts, but rare minerals like bischoffite (in layers up to 10 m thickness), sylvite and langbenite are also present. The potassium layers in this concession are thickened by up to a factor 3 and uplifted by around 1000 meter (Coelewij et al., 1978). They have a dip up to a maximum of 20° (Fokker, 1995).

Potassium salts are being mined in the Veendam locality since 1972 by Nedmag Industries Mining & Manufacturing BV (formerly Noordelijke Zoutwinning BV and Billiton Refractories). The caverns are situated in two clusters (Borgercompagnie and Tripscompagnie) between 1500 and 1800 m with a spacing of 350 meter (Buyze and Lorenzen, 1986 in Jeremic, 1994). Currently, bischoffite is exploited in 5 out of 12 caverns (Tr-2, 6-8, Ve-4). Three other caverns (Tr-3-4, Ve-3) produce carnallite brine that is re-injected into the cavern field to efficiently produce bischoffite brine (Nagelhout et al., 2000; Nedmag, 2001). The four remaining caverns are currently out of use. Due to the preferential solution of potassium salts (cf. Buyze, 1985; Nedmag, 2001) the caverns have an irregular shape and are in some cases interconnected. The maximum allowable diameter of the caverns is 200 m since 1994 for section 1b of the Zechstein 3 (Nedmag, 2001). Their height is limited by the thickness of the magnesium salt layers (about 100 m) (Kenter et al., 1990). The total cavern volume is nearly stabilised at approximately $4*10^6$ $m^3$ (Fokker, 1995; Nedmag, 2001). The caverns are situated between 100 and 250 meter below the top salt (Nedmag, 2001) and have a temperature of 70 °C (Fokker, 1995). Precipitation of newly formed salts in the caverns is part of the production process. Sylvite and carnallite are the main precipitants. Convergence rates can amount to 30-40% of the production rates (Fokker et al., 2000). Within 4 years of production the casing became corroded due to the contact with saturated brine (Nagelhout et al., 2000).

## 3.4 Barradeel

The concession to Frima Zout Industrie BV dates from 1995. Current exploitation is done by Frisia Zout BV. The Zechstein Formation near Harlingen (Figure 1) is hardly deformed and consists of four evaporite cycles (Zechstein 1 to 4). The Zechstein 2 Salt cycle is complete. Near the top a thick layer of potassium salts is present (40 meter, elsewhere 8 meter) (NITG, 1991). The Zechstein 2 rock salt below this potassium rich layer is very pure (low contents of K and Br). Attempts were made during the early seventies to take the Zechstein 2 potassium salts into production (cf. Du Mée, 1971). However, their creep properties (i.e. carnallite, kieserite) and large depth made exploration not economical (NITG, 1991). Today, the pure halites of the Zechstein 2 Salt (Stassfurt Formation, locally 515 meter thick) are exploited in what is currently the deepest salt solution mine in the world (Van Eijs et al., 2000; Engelhardt et al., 2000; Fokker et al., 2002).

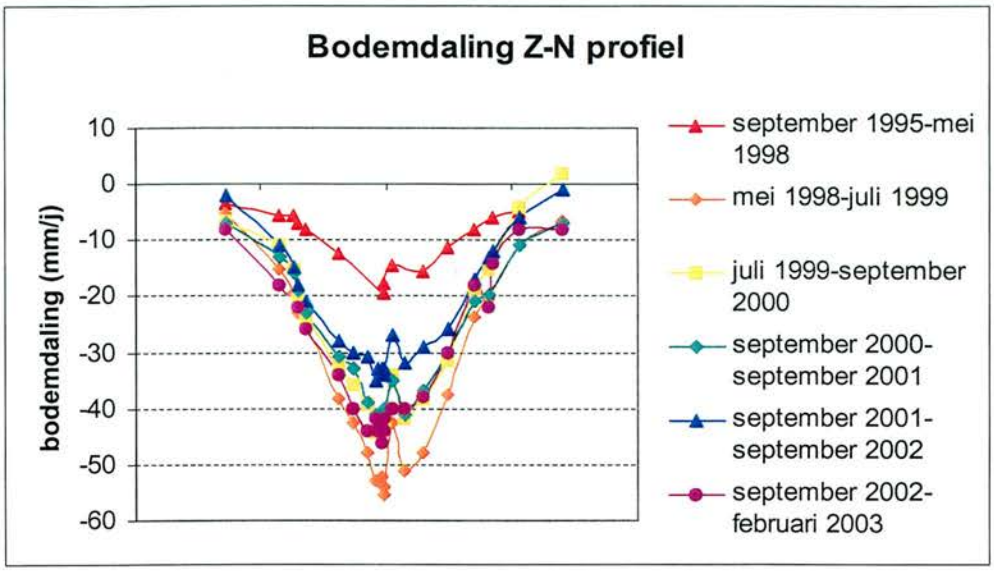


*Figure 10 Surface subsidence in the Barradeel concession during salt production.*

Problematic gypsum precipitation occurred in the casing during the first leaching phase, which was performed with sea water at low injection rate. The gypsum was derived from anhydrite particles distributed within the rock salt formation (Hellberg et al., 2000). A significant amount of insoluble residue (most probably anhydrite given the temperature conditions in the brine) is accumulating on the cavern floor (up to 100 meter) (see also Charnavel and Lubin, 2002). The floor of the cavern is rising by 10-20 m/y, which could be a combination of the residue fall and faster convergence due to the larger depth (cf. Cristescu and Hunsche, 1998).

There are two caverns at a depth between 2570 and 3050 meter at a distance of approximately 500 meter from each other (Table 7). Brine temperature is 60-70 °C, whereas the geostatic temperature at this depth is 104 °C. After approximately one year of production the total volume of the two caverns remained nearly stabile, as cavern leaching and convergence balance each other during exploitation. Observed cavern convergence is 13-18 times higher than was expected on the basis of laboratory values for creep on local core samples (Van Eijs et al., 2000). A mass balance relationship exists between the amount of extracted salt/production rate, cavern convergence rate, cavern volume and the volume of the subsidence bowl at the surface (Van Eijs et al., 2000). Maximum surface subsidence is currently 26.2 cm (February 2003) (Figure 10), whereas the lifetime of production is limited by a maximum surface subsidence of 35 cm. Thus, the two caverns are approaching their abandonment. Currently, a third well is being drilled to continue production in another part of the concession. There is an ongoing discussion about the prognosis of surface subsidence in relation to salt production in Barradeel (cf. Van Eijs et al., 1999; Breunese et al., in prep.).

# 4 Cavern abandonment in the Netherlands

## 4.1 Twenthe-Rijn

Some of the caverns in this concession area have been abandoned for several decades. The caverns are currently monitored by levelling and sonar (Van Sambeek and Ratigan, 2002). Most abandoned caverns have been stable, i.e. subsidence rates are low. However, since 1963 five subsidence bowls with a diameter of 150-300 meter and a depth of 1-3.5 meter were created by gradual surface subsidence above abandoned caverns. And in 1991 one sinkhole of 4.5 meter in depth and a diameter of 30 meter formed overnight (Figure 11). Mechanical instability of the cavern roof and subsequent upward void migration is the main process leading to sinkhole formation (Van Eijs and Voncken, 1997; Bekendam and Paar, 2002). For normal conditions stresses within the roof remain low enough to prevent yielding, explaining why most caverns are stable. The critical conditions which may result in roof collapse and subsequent upward void migration are mentioned by Bekendam and Paar (2002). They include caverns that are not completely filled with brine and/or where the roof does not contain a supporting layer. It is known that some of the early caverns have been "overmined", i.e. there is no or not enough halite and/or anhydrite left in the cavern roof (see also section 3.1).

*Figure 11 Sinkhole above cavern 70 in the Twenthe-Rijn concession (De Mulder et al., 2003).*

There are typically three stages of subsidence (Figure 12), reflecting the different properties of the layers that become unstable (Bekendam, 1996; Bekendam and Paar, 2002). In the first stage surface subsidence is negligible. During the second stage relatively slow subsidence occurs. In the third stage subsidence accelerates rapidly as the void has reached the Tertiary clays subsidence and then slows down again until it is mainly due to compaction of the collapsed material. An upward velocity of 5-15 cm/y is estimated for void migration in the Twenthe-Rijn area (Bekendam and Paar, 2002). The fastest velocity (10-14 cm/y) applies to the Tertiary clays, where the process may be enhanced by contact between brine and clays. A "chimney" of compacted material may be 200 m high (Bekendam et al., 2000). It will only result in a subsidence bowl at the surface, if cavern height is large enough to prevent the void being completely filled by collapsed material before it reaches the surface. Van Eijs and Voncken (1997) showed that the presence of an existing fault plane is able to significantly enhance surface subsidence, perhaps explaining the 1991 sinkhole.

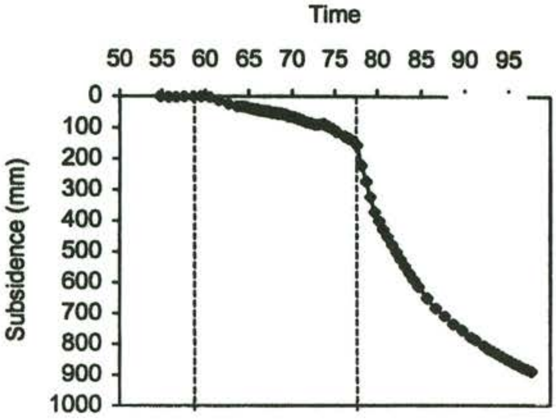


*Figure 12 The three stages of subsidence due to void migration, after Bekendam et al. (2000).*

The subsidence stages (Figure 12) have been used to classify the risk on accelerated surface subsidence (Bekendam et al., 2000; Van Sambeek and Ratigan, 2002). Unfortunately, it is difficult to distinguish between caverns in the first stage and stable caverns in this way, even if combined with numerical modelling studies (cf. Van Eijs and Vonken, 1997; Bekendam, 2000; Van Sambeek en Ratigan, 2002). Fortunately, Dortland (2003) showed that the upward migration of the cavity results in a significant change in the gravity field, even before the cavity has reached the critical depth, i.e. the base of Tertiary and Quaternary sediments. Using a 3D forward gravity modelling method the migration of the cavity from the top of the rock salt up to the base of Tertiary results in a change in the gravity response of at least 1690 μGal above the cavity for a brine filled cavity with an initial height and diameter of 40 and 80 meters respectively. This change in gravity response is detectable with time-lapse gravity measurements. The change in gravity response is based on a model in which a minimal bulking factor of 1.07 for the rock debris in the cavity was used. Higher bulking factors – up to 1.14 for the Twenthe-Rijn concession area, according to Mensen and Paar (2002) – result in an even more pronounced change in gravity response of 2440 μGal (Dortland, 2003).

Once it is determined that a cavern is vulnerable for void migration measures can be taken. Clearly, dry caverns and caverns with a roof containing insufficient halite and anhydrite should be avoided. Akzo Nobel Chemical BV currently maintains a minimum thickness of 5 m halite (which seems a rather subjective choice) in the cavern roof during leaching in order to prevent caverns from future collapsing (BGR, 1998; Wallner and Paar, 2000). Similarly, an anhydrite thickness of at least 10 m over the entire cavern should be maintained (Bekendam and Paar, 2002). It is not clear whether any measures can be taken to avoid abandoned caverns from draining. Brine leakage itself is not a major risk in this site, because the natural groundwater system surrounding the Main Röt Evaporite is salt-saturated. In existing caverns backfill by sludge is applied –though on a very small scale- in order to reduce the risk on surface subsidence (Van Sambeek, 1998). This measure does increases the risk on groundwater pollution, as oil is one of the contents of sludge. Restrictions on land use are a way to mitigate potential damage (cf. Fawcett, 1998).

## 4.2 Adolf van Nassau and Uitbreiding Adolf van Nassau

The production of salt was initially limited by a maximum value of 100 m for the cavern diameter. However, Akzo Nobel Chemicals BV gained permission from Staatstoezicht op de Mijnen to enlarge the cavern to a diameter of 125 m (Eickemeier et al., 2002). This decision prolongs the production life of the cavern fields substantially, as 5 out of 9 caverns were about to reach the maximum diameter. Eickemeier et al. (2002) presented a preliminary study (Eickemeier et al., 2002) about future abandonment of caverns in the Winschoten salt diapir. Their numerical calculations of cavern abandonment by hard shut in indicate that thermal expansion of the brine plays a large role in the brine pressure increase. Unsurprisingly, convergence and subsidence rates are predicted to decrease by two to three orders of magnitude after shut in. Cavern spacing is a relevant factor for the Winschoten cavern field, as most caverns are more or less positioned in (double and single) row configuration. Convergence and subsidence rates are higher when caverns are closely spaced. For a spacing of more than about 750 m caverns behave like single caverns (Eickemeier et al., 2002). The moment where brine pressure reaches lithostatic pressure is also a function of cavern field spacing (Figure 13). For single caverns lithostatic pressure is reached 10-13 years after shut in, whereas this is postponed by several years for caverns in rows. The risk on fracturing is thus larger for single caverns (e.g. cavern I).

During an in situ test in an analogous cavern in the Etrez salt diapir at 950 meter depth (Bérest et al., 2001) it was impossible to artificially increase the brine pressure above a certain level. Brine pressure remained below lithostatic due to permeation of brine into the surrounding rock salt (see also Ratigan, 2003). However, in the Ez53 cavern thermal expansion of the brine can be disregarded due to the long period (13 years) since the end of leaching. Therefore, the risk on fracturing can not be neglected in the Adolf van Nassau case.

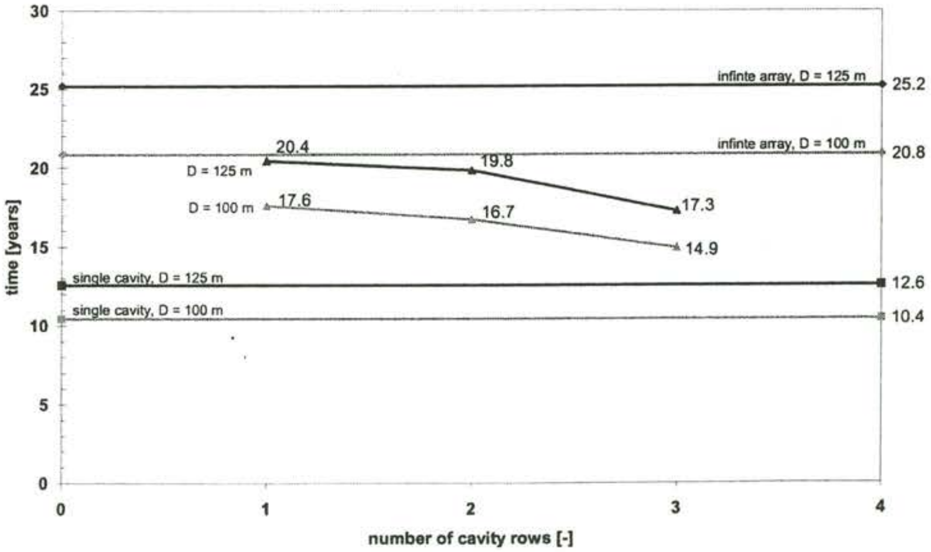


*Figure 13 The time lithostatic pressure is reached at the top of the cavern after closure as a function of the number of cavern rows. After Eickemeijer et al. (2002).*

Storage of gas in caverns is common practise (cf. Thoms and Gehle, 2000 and references therein). It may be a future option for Dutch caverns and particularly those within Zechstein salt diapirs, like Zuidwending, Winschoten, Anloo, Onstwedde, Gasselte-Drouwen, Hooghalen and Boertange (NITG, 2000). The use of caverns for storage purposes is outside the scope of this study (see section 1), but experience with gas storage provides some information on cavern behaviour that may be relevant for cavern abandonment.

Gas storage leads to a decrease in subsidence and convergence rates (Minkley and Menzel, 1995). Several decades of experience with gas storage as well as with artificial explosions (e.g. the Tatum salt dome, U.S.A.) confirms that the sealing capacity of salt is high (Thoms and Gehle, 2000). Most problems are related to loss of well integrity (e.g. corrosion of the casing), or well control (during repair or use). For example, in 1992 a gas explosion occurred in the Brenham salt dome (Texas) due to uncontrolled outflow of LPG through the well onto the surface. Three people were killed during the explosion that was a 4+ event on a Richter scale in Houston. The cavern, however, later "passed" a mechanical integrity test (Thoms and Gehle, 2000). Gas explosions can be particularly unpredictable when the gas moves through the heterogeneous cap rock, as happened in 1980 in Barbers' Hill dome (Texas).

Caverns are vulnerable for substantial volume losses, in particular deep caverns. The Eminence dome (U.S.A.) at a depth of 1737-2042 meter and Tersanne (France) at a depth of 1400-1500 meter have been used for gas storage since 1970. They experienced volume losses of respectively 40 and 30 %. The problem of volume loss can be controlled by maintaining a minimum operating pressure (Thoms and Gehle, 2000). Casing strings are sometimes damaged by salt fall (Munson et al., 1998). Another problem worth mentioning is contaminating of the stored product by natural gas-emission from the surrounding salt (cf. Ehgartner et al., 1998).

## 4.3 Veendam

Already in the late eighties a study to the consequences of cavern abandonment in the Veendam concession was prompted (Kenter et al., 1990). This study concluded that the convergence of the Veendam caverns (0.015 $m^3$/bar, year, $m^2$) is high enough to induce overpressure (~3 bar) within the first year of hard shut in and to sustain this overpressure for a longer period of time. They predict for the long term brine leakage through the halite roof of the caverns at a rate of 1000 $m^3$/y, resulting in a surface subsidence of 0.2 mm/y for a cluster of 6 Veendam cavities of 70 m radius and 100 meter height (Nedmag, 2001). Predicted brine leakage in combination with the efficiency of magnesium salt exploitation, quality of the brine, reduced drilling costs and clear regulation of surface subsidence costs made Nedmag and Staatstoezicht op de mijnen decide in 1995 that cavern volume should be diminished as much as possible during the operational period of the caverns. Hence, Nedmag changed the production method to squeezing (Nedmag, 2001). The decision was supported by 1) numerical calculations and 2) a field test, both demonstrating that queezing can be performed at the Veendam locality without compromising cavern and overburden integrity (Fokker, 1995; Nedmag, 2001). Technical problems with well control are expected for hydrostatic cavern pressure conditions due to the risk of gypsum precipitation in the well resulting from an increase in anhydrite concentration in the brine (BECi, 2000; Nedmag, 2001). For this reason the current squeezing method uses a minimum well head pressure of 4 MPa (up to 9 MPa).

The squeezing method implies that surface subsidence takes place during and shortly after exploitation. It has up to now resulted in a 6 km wide ellipse-shaped subsidence bowl of at most 12 cm in depth at the surface (Brand et al., 2002). Between 1993 and January 2000 maximum subsidence was 10.5 cm (Nedmag, 2001). The current exploitation has a maximum subsidence rate of 1.5-2 cm/y, corresponding to a yearly production of $0.2\text{-}0.25*10^6$ $m^3$ brine. Permitted maximum subsidence is 50 cm (Brand et al., 2002). In addition to squeeze, cavern volume (and hence subsidence) is diminished by injecting gypsum, which is a by-product of processing of the saturated brine, into the cavern field (Nedmag, 2001).

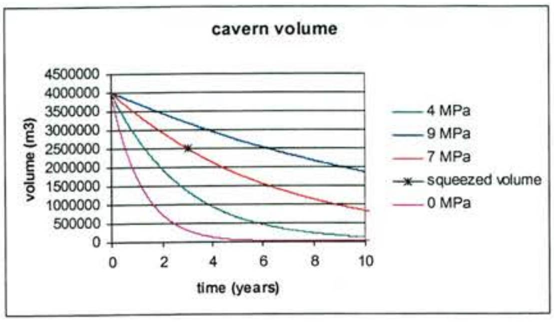
*Table 8 Model parameters in the Veendam abandonment scenario's. Creep parameters for Veendam are estimated from fitting the squeeze potential.*

| parameter | Value |
|---|---|
| Initial cavern volume | $4*10^6$ $m^3$ |
| Cavern height | 100 m |
| Cavern average diameter | 225 m |
| Casing-shoe depth | 1600 m |
| Cavern average depth | 1700 m |
| Average geothermic temperature | 70 °C |
| Initial brine temperature | 45 °C |
| A | 75 $MPa^{-n}year^{-n}$ |
| Q/R | 4100 K |
| n | 3.1 |
| E | 11000 MPa |
| v | 0.25 |
| Initial permeability | $1*10^{-20}$ $m^2$ |

Several years of experience with squeezing (Nedmag, 2001) indicate that the current total cavern volume ($4*10^6$ $m^3$) has a squeeze potential of about $1.5*10^6$ $m^3$ for a 3 year production period (star in Figure 14). Fitting this one data point with the LOSAC© software (Appendix C; Brouard et al., 2002) enables a first, non-unique estimate of in situ (bulk) creep parameters for the Veendam locality (Figure 14). The obtained creep parameters and other model parameters are presented in Table 8. It is difficult to compare the values for potassium salts including bischoffite with those of halite (section 2). Nevertheless, the values are close to the creep parameters of Carter et al. (1993) for climb controlled dislocation creep in wet polycristalline halite (Figure 2). They are also quite similar to the creep parameters of halite from the Etrez salt dome. In Etrez the creep parameters determined in the laboratory matched with those obtained in situ for a halite layer at approximately 920-970 m depth, containing ~10% of anhydrite and thin intergranular clay impurities (Bérest et al, 2001). In addition, the values in Table 8 are also quite similar to those obtained by Breunese et al. (in prep.) for Barradeel (section 4.4) for a combination of dislocation and diffusion creep.

It is obvious that Veendam creep parameters of Table 8 are not yet well constraint. More data are needed for that. Within this limitation the model predictions show complete loss of volume for the Veendam caverns after 6 years of squeezing at hydrostatic pressure (Figure 14). For continuation of the current cavern squeezing scheme at 7 MPa overpressure estimated brine production slows down only after more than 10 years, whereas it takes about 30 years for the caverns to squeeze completely (Figure 15).

*Figure 14 Squeeze scenario's for various well head pressures*



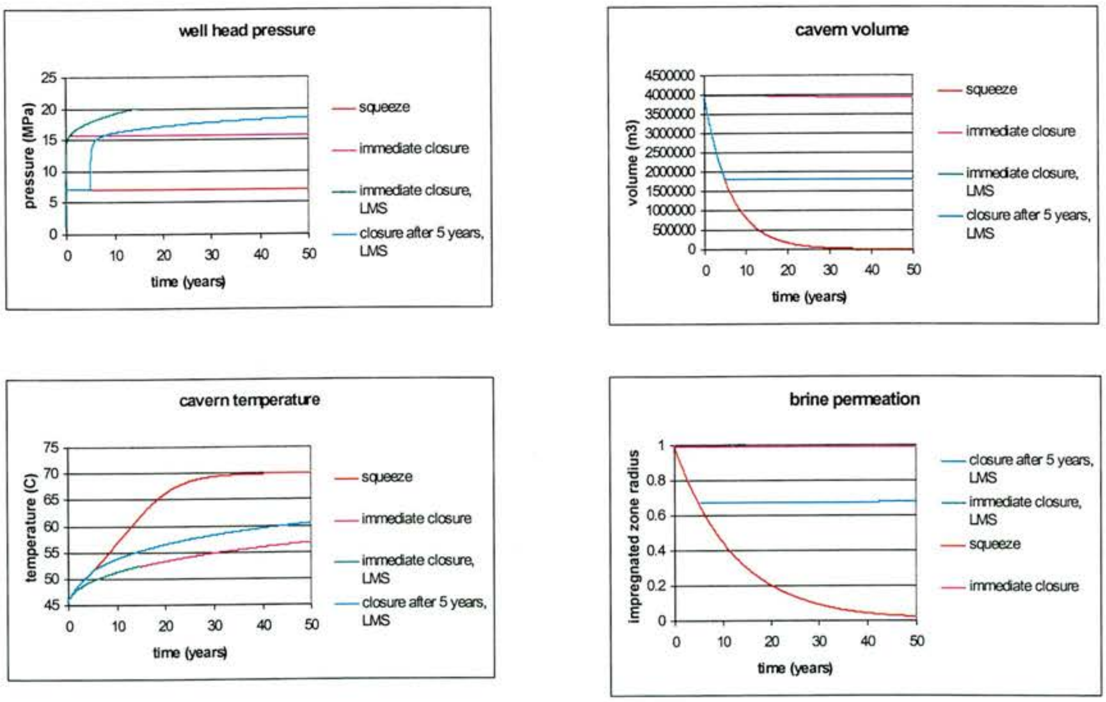


*Figure 15 Abandonment scenario's for the Veendam caverns.*

Immediate closure of the caverns results in a potential fracture after less than 1 year or in 15 years, depending on whether permeability is assumed constant or not (Figure 15). Introducing a 5 year period of squeezing before closure prevents fracturing during the first 50 years due to the secondary permeability increase (Figure 15). In line with the results of Kenter et al. (1990) brine leakage is predicted after closure of the caverns when secondary permeability is taken into account.

However, the impregnated zone ratio (Figure 15) does not exceed 1 in any of the scenario's.
This means that brine only permeates into salt that flows into the space formerly occupied by the caverns. Thus, the model results indicate that fracturing is the main problem related to closure (hard shut in) scenario's for the Veendam caverns.
The clustering of the caverns nor their irregular shape have been taken into account. In practise complete squeezing is not possible, as irregularities in cavern shape probably will result in the formation of local brine inclusions. At the late stage of squeezing periodic dilution of the saturated brine with fresh water (10%) may be required during workover to maintain well control (BECi, 2000). Due to the presence of various salt minerals a density stratification is likely to develop in the brine after hard shut in, where Mg-brine is located near the cavern bottom with Na-brine above (cf. Sander and Herbert, 1985). Halite tends to precipitate at the boundary between Mg- and Na-brine. This suppresses fluid circulation and slightly diminishes the stress difference with the surrounding rocks. Surface subsidence, cavern shape, squeezed brine volumes and well head pressure need to be monitored both during and after production. Given the problems with corrosion of the plug during production, this requires a check on a regular basis after abandonment.

## 4.4 Barradeel

In literature different options have been considered for cavern abandonment of the Barradeel 1 and 2 caverns (cf. Van Eijs et al., 1999, BECi, 2000; Fokker et al., 2002; Breunese et al., in prep.). One option concerns hard shut in and sealing of the caverns, possibly in several stages. Contrary to earlier predictions of very slow subsidence rates (Brand et al., 2002; Fokker et al., 2002), Breunese et al. (in prep.) predict a substantial rebound at the surface after abandonment due to the influence of pressure solution creep (Figure 16). Hard shut in of the Barradeel caverns could possibly compromise the mechanical integrity of the salt structure by fracturing, due to the large temperature difference between salt rocks (104 °C) and brine (65 °C) (Van Eijs et al., 2000; Fokker et al., 2002). In order to closer approach thermal equilibrium a waiting time is necessary. However, due to the high rate of cavern convergence at this depth (Van Eijs et al., 1999) the caverns are probably squeezed before thermal equilibrium is reached, unless some overpressure is maintained.

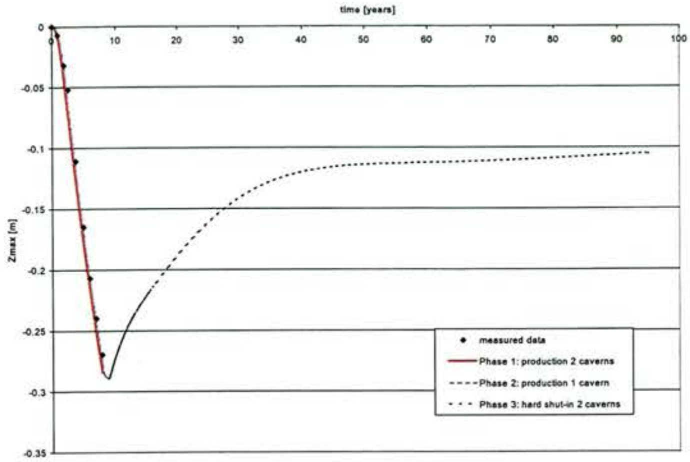


*Figure 16 History match and an example of a prediction of the maximum subsidence following a phased scenario of shutting-in the Barradeel caverns. After Breunese et al. (2003).*

Cavern squeezing may enhance the tendency of the caverns to migrate upwards, especially after removal of the oil blanket. This has the disadvantage of lessening the distance between cavern roof and potassium salts that are currently situated approximately 40 m above cavern roof. If a connection would be established between the cavern and the carnallite, the brine would dissolve carnallite even though it is saturated with halite and possibly anhydrite (cf. Pruiksma and Kruse, 2002). Carnallite dissolution as well as its high creep rate (see section 2) could then significantly influence the system.

# 5 Risk assessment for cavern abandonment

Abandonment is the phase directed at the final closure of a cavern. The aim of this risk assessment is to identify potential risk scenario's for cavern abandonment in the Netherlands (Table 1). The chosen time frame is approximately 250 years, which is sufficiently long to include those effects that are likely to occur well after the 30 year period regulated by the Dutch Mining Law. The risks depend on the adopted abandonment scenario (Figure 1 in Part 2). In the risk assessment only the two most extreme abandonment scenario's are considered, i.e. hard shut in and squeezing. Preventive and/or damage mitigating measurements can be formulated on the basis of these risk scenario's. This knowledge will be integrated into a best practise and methods document on cavern abandonment.

## 5.1 Methodology

The Features, Events and Processes (FEP) risk assessment methodology (Prij et al, 1993; Wildenborg et al, 1993) aims to generate a comprehensive set of risk scenario's in a systematic and transparent way on the basis of expert judgement. In practise only a limited selection of risk scenario's can be dealt with. This urges classification, ranking and grouping according to site specific conditions and necessitates early expert judgement on the risk potential. Quantification of the risks may be achieved by modelling of risk scenario's. The FEP methodology explicitly aims at comprehensiveness as a condition for acceptance of potential risks by the general public. The focus of the current risk assessment is more on the technical aspects of dealing with risks (towards preventive and/or damage mitigating measurements).

## 5.2 Qualitative risk assessment

Expert judgement was provided by dr. B. Scheffers, dr. B. Orlic, dr. J. Breunese, drs. R. van Eijs and dr. I. Kroon. An overview of the identified FEP's is given in Appendix B. The 23 FEP's are divided into 1) natural phenomena related to the system response, and 2) external phenomena that may have an additional impact on the system. The main relationships between the different FEP's are presented in Figure 17, 18 and 19. In these Figures the FEP's are shown in boxes and the interrelations are represented by arrows. FEP's that are closely linked are grouped together to form a risk scenario. These risk scenario's are outlined and numbered alphabetically.
In Figure 17 an increase in brine pressure induced by creep and thermal expansion during cavern shut in (cf. Ratigan, 2003) is linked to loss of seal integrity (cf. Brouard et al., 2002) and hence pose a risk on groundwater pollution (scenario A in Table 9). Several processes may cause the cavern roof, pillars and/or overburden to collapse (Figure 17, 18 and 19). Once started this can become a self-stimulating process potentially resulting in severe surface subsidence (cf. Bekendam and Paar, 2002) (scenario B). If present in the seal in sufficient amount, natural gas may accumulate in the cavern, where it could lead to an explosion (Elewaut et al., 1998 and references therein) (scenario C) or lessen the cavern volume by exchange between compressible gas and nearly incompressible brine (Ehgartner and Tidwell, 2000).

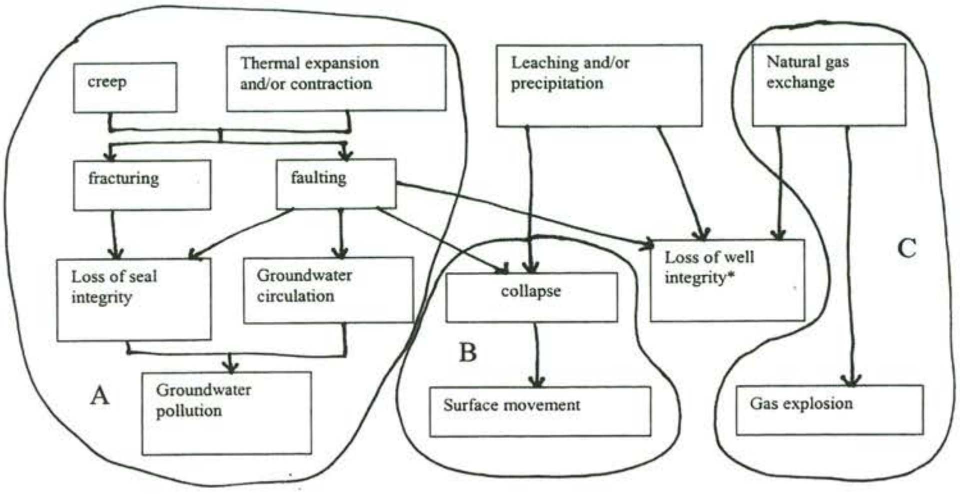


*Figure 17 Relational diagram showing FEP's and risk scenario's A, B and C for hard shut in.*

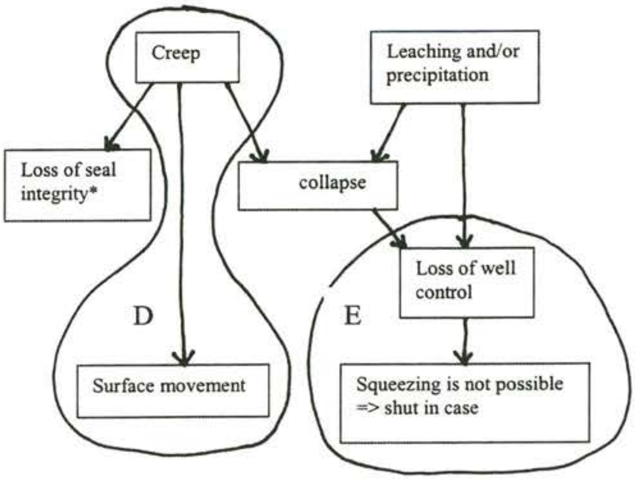


*Figure 18 Relational diagram showing FEP's and risk scenario's D and E for squeezing.*

During squeezing of a cavern (Figure 19) the main negative effect is surface movement (e.g. Veendam) (scenario D). During squeezing (permanent) loss of well control needs to be avoided, because it will effectively result in an uncontrolled shut in situation (scenario E). Loss of well integrity (Figure 20) may cause groundwater pollution (scenario F), the severity of which is highly dependent on the location, amount of leakage and contact with natural aquifers. Theoretically, a contact between a fresh water aquifer and the seal/cavern may be established, resulting in uncontrolled subrosion at potentially substantially higher rates than natural subrosion (scenario G).

A risk is a function of probability times damage. Hence, the risk scenario's may be ranked according to these two variables (Table 9). The four risk scenario's that rank high in Table 9 certainly require attention in case of cavern abandonment, because the underlying processes are common. The additional risk of loss of well control (E) is largely covered by the scenario's A and B. The remaining two scenario's of Table 9 (G and C) are mainly of interest when the specific local conditions are particularly favourable for the underlying processes.

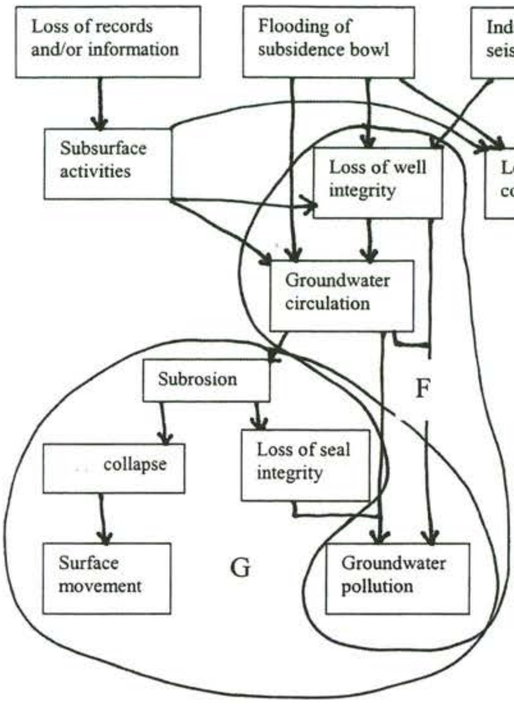


*Figure 19 Relational diagram showing FEP's and risk scenario's F and G for human induced phenomena*

*Table 9 Ranked risk scenario's.*

| **Rank** | **Scenario** | **scenario description** | **probability** | **damage description** | **damage** |
|---|---|---|---|---|---|
| 1 | B | roof collapse | low to high | surface movement | severe |
| 2 | D | cavern convergence | high | surface movement | moderate to severe |
| 3 | A | loss of seal integrity | moderate to high | groundwater pollution | low to severe |
| 4 | F | loss of well integrity | moderate to high | groundwater pollution | low to severe |
| 5 | E | loss of well control | moderate to high | uncontrolled shut in | low to moderate |
| 6 | G | induced subrosion | low | loss of seal integrity, roof collapse, surface movement | moderate to severe |
| 7 | C | natural gas exchange | very low | gas explosion | severe |

The risk assessment recognises three main processes that could cause damage: surface movement, groundwater pollution and gas explosion (Appendix B). Surface movement is the most common type of damage during and after cavern exploitation (section 4). It may severely affect buildings and infrastructure, but it could also have a strong influence on groundwater circulation and on flood risk (e.g. lowered dikes). For these reasons the maximum amount of subsidence is normally regulated. A more extreme variant of surface movement above caverns is sinkhole formation (section 4.1). This

abrupt movement is potentially dangerous for humans and may cause substantial damage on buildings, infrastructure etc. The presence of neighbouring caverns within the sphere of influence increases the risk on mechanical instability of the system (i.e. pillar collapse) and enhances the rate and amount of surface movement (cf. Eickemeijer et al. (2002). In general any change in surface movement may invoke alterations in ecosystems as well as in land use (Appendix B).
Leakage may result in pollution of groundwater, soil and subsurface by brine or oil (Appendix B). Apart from its effect on land use and ecosystems this may endanger drinkwater supply. Even when it is saline -often the case in natural groundwater at large depths- oil input still causes pollution and brine input will result in loss of information on the original composition of the groundwater. Furthermore, any major change in the hydrological system (scenario F and G) is also expected to affect ecosystems and land use. An explosion or blow-out due to compressed gas in brine filled caverns (Appendix B) is extremely rare, because of the lack of oxygen (see however Thoms and Gehle, 2000; Bérest et al., 2003). It is potentially dangerous for humans and could cause substantial damage on buildings, surface and subsurface infrastructure etc. and could furthermore result in leakage due to damaged casings.

## 5.3 Suitability of software packages for quantitative risk assessment

The risk assessment identified several risk scenario's that could be relevant for salt cavern abandonment (Table 9). For a quantification of the risks a proper simulation of the underlying processes in combination with site specific data is essential. Analytical descriptions are helpful, but in most cases the processes are non-linear and interdependent. Hence, a numerical approach is required. Therefore an overview of the suitability of various software packages with respect to the above mentioned risk scenario's is presented in Table 10. In Appendix C and D the main features of the software packages are shown. Ideally, each (combination of) process(es) should be modelled within a single package. However, there are cases where the different functionality of the software is needed to adequately model (part of) the problem.
Sinkhole formation and subsidence in the Hengelo area is attributed to roof collapse, based on the conceptual three phase model of Bekendam (1996) (Figure 12). Phase II is characterised by collapse of the roof above the cavern and upward migration of the cavern void through the 'hard' Mesozoic rock until it reaches the contact with the 'soft' unconsolidated Tertiary deposits. Brittle failure in jointed rock masses and this process of caving can adequately be modelled by assuming that the rock mass is represented as a discontinuous medium and consists of assemblages of discrete blocks. This approach is followed by UDEC, but is not available in other packages here reviewed. *Comment: Itasca, the manufacturer of UDEC & FLAC, lists on their web-site Akzo Salt USA as a selected client of their services (http://www.itascacg.com/mining.html).* FLAC, DIANA, ANSALT and ADINA are deemed to be suitable for modelling phase I and III of subsidence, in which the rock mass affected by subsidence can well be modelled as continuous media. Van Eijs and Voncken (1997) use DIANA for modelling phase III. The FLAC model is used in Bekendam (2000), whereas Van Sambeek and Ratigan (2002) use the SPECTROM-32 model that is not considered here. Gradual surface movement above salt caverns is mainly governed by creep mechanisms and rock elasticity. Hence processes affecting pressure, temperature and material characteristics/rheology are important. A thermo-mechanical approach is appropriate and the following packages are generally suitable (Appendix C): FLAC, UDEC, DIANA, ANSALT, ADINA and Aesubs.

Brine nor oil normally enters the groundwater system. One of the processes that is affecting seal integrity and could result in brine or oil escape is permeation under high pressure conditions. This process can be modelled in LOSAC. Some of the aforementioned packages (FLAC, DIANA, and ADINA) have modules dealing with fluid flow through a porous medium. These packages are thus able to couple both the mechanical and fluid flow part of the problem and are useful for modelling of brine migration through the subsurface. The combined migration of oil and brine through the subsurface (two phase flow) is a more difficult problem. It may be addressed by software packages like FLAC, MARTHE+SCS or MODFLOW. In addition MARTHE+SCS is also able to deal with the flow of gas through a porous medium.
METROPOL has been previously used to model salt solution in caprock (Sauter et al., 1993). Most likely MODFLOW and MARTHE+SCS are also able to deal with salt solution and precipitation. Cavern leaching may be simulated using DIANA, UDEC or ADINA, but the procedure is most not very convenient.

*Table 10 Suitability of software packages for processes related to cavern abandonment.*

| | Roof collapse and void migration | Surface movement | Mine design and stability | Pressure in and around caverns | Fluid flow and brine/oil migration | Salt solution and/or precipitation |
|---|---|---|---|---|---|---|
| FLAC2D, FLAC3D | Limited | Good | Good | Rock pressure and hydraulic gradient | Good, two phase flow through porous medium | ? |
| DIANA | Limited | Good | Good | Rock pressure and hydraulic gradient | Good | Limited: non-automated removal of elements |
| ANSALT I & II | Limited | Good | Good | Rock pressure | ? | ? |
| UDEC & 3DEC | Good | Likely good | Likely good | Rock pressure | Not possible | Probably good: null blocks are available |
| ADINA | Limited | Likely good | Likely good | Rock pressure and hydraulic gradient | Good | Limited |
| Aesubs | Not possible | Good, also suitable for inversion of subsidence data | Not possible | Rock pressure | Not possible | Not possible |
| LOSAC | Not possible | Limited | Very limited | Well head pressure | Only brine permeation is included | Not possible |
| MODFLOW | Not possible | Not possible | Not possible | Hydraulic gradient | Good | Probably good |
| METROPOL | Not possible | Not possible | Not possible | Hydraulic gradient | Good, single phase flow through porous medium | Only in caprock |
| MARTHE+ SCS | Not possible | Not possible | Not possible | Hydraulic gradient | Good, two phase flow and gas flow through porous medium | Probably good |

# 6 Discussion

Salt solution mining in the Netherlands is in a stage where caverns are abandoned or approaching the last part of their productive life in three out of five active Dutch salt concessions (Twenthe-Rijn, Veendam and Barradeel). There have been substantial differences in the approach to cavern abandonment between the different concessions and in time (section 3 and 4). These differences reflect the geological and technical particulars of the various concession areas, but are also partly the result of different and/or changing views on the approach to cavern abandonment and the various abandonment scenario's.

## 6.1 Risk assessment

In the risk assessment (section 5) only the two most extreme abandonment scenario's (hard shut in and squeeze) are considered. For the risk assessment this is sufficient. However, for practical purposes intermediate scenario's like limited brine outflow and temporary shut in with bleed off (see Figure 1 in Part 2) are worth considering. A systematic comparison of the different abandonment scenario's is required, because the risks and consequences depend on (the combination of) the scenario's. This is clearly illustrated by the differences between Figure 17 and 18.

The risk assessment highlights potential problems and damage related to cavern abandonment. The risk scenario's (Figure 17, 18 and 19) are a good starting point for discussing the problems as well as some preventive or damage mitigating measures. Collapse (scenario B) is, once triggered, difficult to control. For this reason it is important to rely on preventive measurements, as far as possible. Especially in thin and shallow salt layers this requires maintenance of a suitable (small and flat) cavern geometry. In particular the presence of a cavern roof and pillars sufficiently thick to withstand the stresses after the end of the solution mining phase is important. Mitigating measures are at present restricted to backfill. Backfill can help to obtain a more suitable cavern geometry and/or to diminish surface movement in case roof collapse (cf. Schmidt et al., 2000). Unfortunately, it is time-consuming to backfill a cavern and it requires a large volume of suitable material that is often not available at low costs at the site. While gypsum is a suitable material that is often naturally found in salt layers, sludge for instance contains oil remnants that could cause groundwater pollution. Both the risk on and damage by collapse is worsened if caverns are closely spaced and/or interconnected. This situation is in many respects analogous to flood risk in dry salt mines. If the risk is high, controlled flooding of the dry salt mines is sometimes used as a mitigating measure (cf. Ahmedinovic et al., 2002). Thus, controlled triggering of collapse may be an alternative to backfill in case of a high risk on collapse. The development of additional tools to monitor the stage of roof collapse (cf. Dortland, 2003) may substantially reduce the hazard by allowing to take measures before the damage occurs.

Within the time limit of 250 years surface movement (scenario D) may be lessened by cavern backfill, or reduced to a slow rate by hard shut in of the cavern. A serious drawback of hard shut in is the higher risk for groundwater pollution, especially if thermal equilibrium is not reached (Figure 17). Temporary shut in with bleed off or a limited brine outflow could help to establish a thermal equilibrium, while the corresponding surface movement is limited. For these scenario's the quality of the well casing is important, as it has to withstand periodical high pressures. The severity of groundwater pollution may be also substantially diminished by effective removal of the oil blanket at abandonment. Leakage can be detected by monitoring the groundwater composition.

The risk on groundwater pollution (scenario A) may be reduced by applying cavern squeezing during a certain period of time - at the cost of continuing surface movement. Gradual surface movement may be considered acceptable, provided that good agreement has been reached on maximum limits and liability. Careful monitoring of surface movements is a necessary procedure. Squeezing will ultimately lead to damaging the casing and other parts of the equipment in the cavern, threatening well control (Figure 18). This may pose technical limitations to its applicability. In the final stage of squeezing local brine inclusions will be created due to cavern shape irregularities. These brine inclusions could pose the problems analogous to those encountered during hard shut in, but on a much smaller scale, as the brine volumes involved are much smaller.

Loss of well integrity (scenario F) is likely to result in groundwater pollution. However, pollution will generally be minor and relatively easy to detect. However, in case a connection becomes established between the location of leakage and an aquifer the consequences can be dramatic. It is thus necessary to use high quality material for the seal and to check well integrity at the time of abandonment. Regular checks of seal and well integrity during the abandonment phase are required, if technically possible. Leakage can also be detected in an early stage by monitoring changes in groundwater composition surrounding the well.

Finally, some technical concerns related to long term cavern abandonment are worth mentioning. The equipment and the plug are vulnerable for corrosion, in particular when in contact with brine. Their long term integrity is being studied (cf. Herbert and Meyer, 2000), but the results are not yet conclusive. For instance, it is not clear why the plug is leaking at low pressure in laboratory test (Pfeifle et al., 2000). Still, the behaviour of vertical plugs is relatively well known and attention is shifting towards horizontal plugs (Sitz en Koch, 2000). In the Netherlands wells drilled for solution mining purposes used to be vertical, but the presence of new, highly deviated wells (Barradeel) may pose some difficulties in the future.

The accumulation of natural gas in the cavern may occur (scenario C). The accumulation rate is highly variable and may fluctuate largely even between caverns situated in the same salt body. Gas bubbles in the cavern can be detected easily and at low cost at the moment of abandonment or during the production phase by measuring oscillations in the system after a change in pressure (Bérest et al., 1999).

## 6.2 Influence of cavern abandonment on existing and future activities

Subsurface activities may have an impact on cavern abandonment (Figure 19). Similarly, within its sphere of influence the abandoned cavern may affect existing or future (sub-)surface activities, especially at the long term. Cavern abandonment in the Netherlands could potentially interfere with the exploitation of subsurface resources like hydrocarbons and groundwater or with geothermal, storage and disposal purposes (Remmelts, 1997; Van Leeuwen et al., 2003). In spite of its importance this aspect is not usually considered at present. Naturally, cavern abandonment should pose as few constraints on existing and future activities within the sphere of influence of a specific cavern as possible. Any constraints on the use of the (sub-)surface by cavern abandonment should be made explicit and well documented, as it is necessary to consider them for future applications (Van Leeuwen et al., 2003). Indeed, the choice between various abandonment scenario's should also take these considerations into account.

## 6.3 Forecasting of cavern behaviour during abandonment

For a meaningful forecast of how a cavern will behave after abandonment in any abandonment scenario the behaviour of the cavern during the production phase must be well understood. This information also forms the basis for a quantitative treatment of the risks involved. Unfortunately, the past has shown that it can be quite difficult to understand and predict cavern behaviour during production. For example in the Barradeel concession salt creep rates were initially underestimated by a factor 18 (Van Eijs et al., 2000), whereas in the Winschoten salt diapir creep rates were overestimated (section 3). The prognosis for surface subsidence in the Veendam concession needs constant updating (Kruse and Van den Berg, 2001), thus hampering adequate long term predictions. This is mainly due to the complexity of processes governing the salt creep (section 2). Clearly, more effort should be made in order to improve our understanding of cavern and salt behaviour.

Dominant creep mechanism diagrams for a specific temperature and pressure range (Figure 2) should be more commonly used, as they make (the lack of) information on the relevant creep mechanisms explicit. This is particularly important in rapidly converging caverns at large depth (e.g. Barradeel) or in potassium salt layers (e.g. Veendam). The relative importance of various dislocation creep mechanisms as well as the importance of fluid controlled diffusion creep has to be known in order to predict the long term behaviour of caverns after abandonment. New results (Pruiksma and Kruse, 2002; BECi, 2002; Breunese et al., in prep.) indicate that surface rebound could be significantly accelerated by diffusion creep.

Another main issue are the missing creep parameters for the aforementioned different creep mechanisms in potassium salts (mainly carnallite and bischoffite), anhydrite and gypsum. These rocks are quite common in bedded salt formations and in salt pillows. Even where caverns are positioned within rather pure halite rocks interference with potassium salt layers can not always be excluded on the long term (section 4). Due to their fast creep rates (Table 3 and 5) potassium salts are likely to have a significant influence on the deformation pattern. A related item concerns the behaviour of salt composites instead of pure minerals. The presence of anhydrite particles in halite is known to have a profound influence on macroscopic creep rates (section 2) and analogous effects are expected for other mixtures. The effect of crystal impurities, secondary permeability and mechanical integrity has only been widely studied in halite and not in other salt minerals. Another important process is de-hydration of gypsum to anhydrite or vice versa, as gypsum and anhydrite have widely variable mechanical properties.

# 7 Conclusion

Salt solution mining in the Netherlands is in a stage where cavern abandonment has become of current interest as caverns are within the last part of their productive life in three out of five active Dutch salt concessions (Twenthe-Rijn, Barradeel and Veendam).

The main risks for cavern abandonment in the Netherlands are surface movement, groundwater pollution and gas explosion. Seven risk scenario's are identified: collapse, cavern convergence, loss of seal integrity, loss of well integrity, loss of well control, induced subrosion and gas accumulation.

Cavern abandonment may be achieved by hard shut in, temporary shut in with bleeding off, limited brine outflow, squeezing or a combination of these. The risks depend on the chosen scenario.

It is necessary to quantify the risks associated with the risk scenario's by numerical or analogue modelling. The models have to be validated by data from the production history of the cavern under consideration. Case-specific geological and technical aspects need to be taken into account separately.

The Features, Elements and Processes (FEP) methodology has been successfully applied to perform the risk assessment for cavern abandonment.

Several aspects of cavern abandonment need more attention:
1. Interference with the hydrological system
2. Creep and failure characteristics of various evaporitic minerals
3. Interference with and restrictions on existing or future subsurface and surface activities
4. Systematic documentation of production data, problems, incidents and technical limitations as a support for the risk assessment and the best practices and methods

A draft document for the best practises and methods for the abandonment of solution mined salt caverns in the Netherlands is presented in Part 2.

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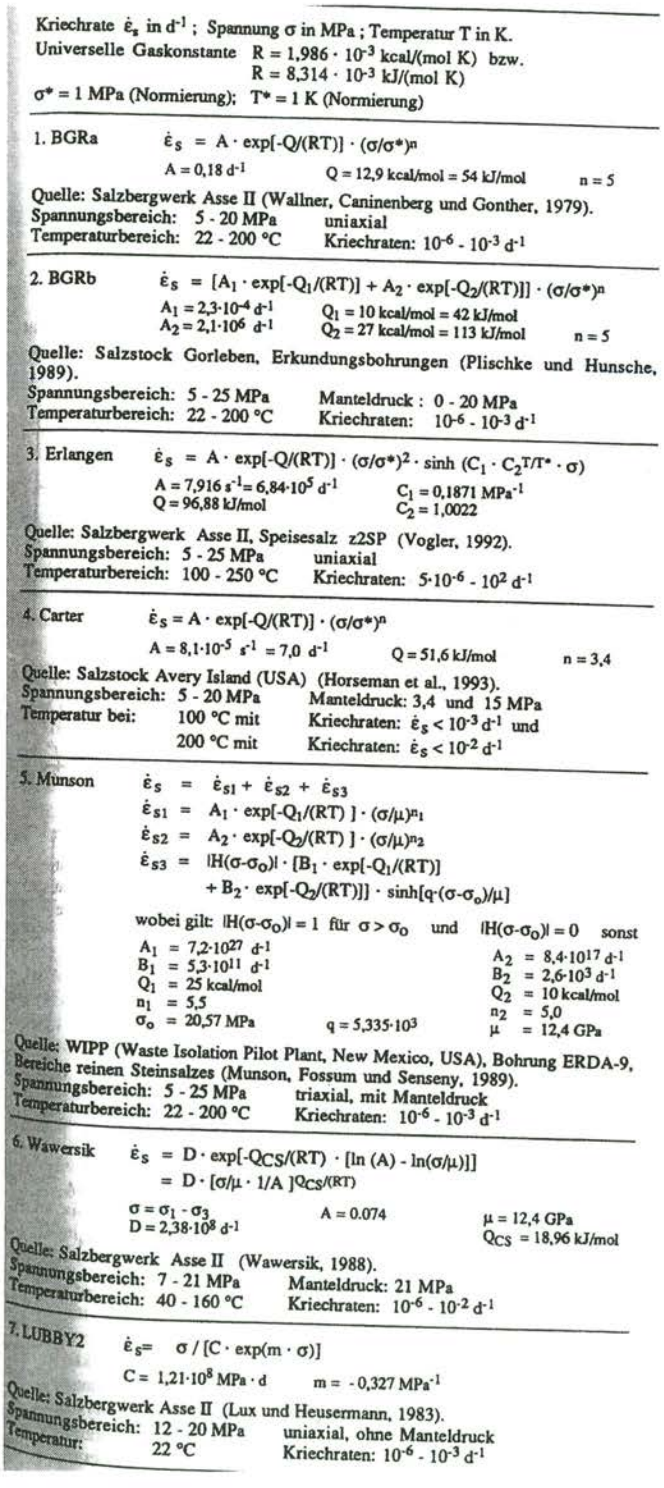
# A Constitutive equations for primary and secondary creep in halite.

*Table A Steady state creep equations after Hunsche and Schulze (1994).*



Kriechrate $\dot{\varepsilon}_s$ in $d^{-1}$ ; Spannung $\sigma$ in MPa ; Temperatur T in K.
Universelle Gaskonstante $R = 1{,}986 \cdot 10^{-3}$ kcal/(mol K) bzw.
$R = 8{,}314 \cdot 10^{-3}$ kJ/(mol K)
$\sigma^* = 1$ MPa (Normierung); $T^* = 1$ K (Normierung)

**1. BGRa**

$$\dot{\varepsilon}_S = A \cdot \exp[-Q/(RT)] \cdot (\sigma/\sigma^*)^n$$

$A = 0{,}18\ d^{-1}$ $Q = 12{,}9$ kcal/mol $= 54$ kJ/mol $n = 5$

Quelle: Salzbergwerk Asse II (Wallner, Caninenberg und Gonther, 1979).
Spannungsbereich: 5 - 20 MPa uniaxial
Temperaturbereich: 22 - 200 °C Kriechraten: $10^{-6} - 10^{-3}\ d^{-1}$

**2. BGRb**

$$\dot{\varepsilon}_S = [A_1 \cdot \exp[-Q_1/(RT)] + A_2 \cdot \exp[-Q_2/(RT)]] \cdot (\sigma/\sigma^*)^n$$

$A_1 = 2{,}3 \cdot 10^{-4}\ d^{-1}$ $Q_1 = 10$ kcal/mol $= 42$ kJ/mol
$A_2 = 2{,}1 \cdot 10^{6}\ d^{-1}$ $Q_2 = 27$ kcal/mol $= 113$ kJ/mol $n = 5$

Quelle: Salzstock Gorleben, Erkundungsbohrungen (Plischke und Hunsche, 1989).
Spannungsbereich: 5 - 25 MPa Manteldruck : 0 - 20 MPa
Temperaturbereich: 22 - 200 °C Kriechraten: $10^{-6} - 10^{-3}\ d^{-1}$

**3. Erlangen**

$$\dot{\varepsilon}_S = A \cdot \exp[-Q/(RT)] \cdot (\sigma/\sigma^*)^2 \cdot \sinh(C_1 \cdot C_2^{T/T^*} \cdot \sigma)$$

$A = 7{,}916\ s^{-1} = 6{,}84 \cdot 10^{5}\ d^{-1}$ $C_1 = 0{,}1871\ \text{MPa}^{-1}$
$Q = 96{,}88$ kJ/mol $C_2 = 1{,}0022$

Quelle: Salzbergwerk Asse II, Speisesalz z2SP (Vogler, 1992).
Spannungsbereich: 5 - 25 MPa uniaxial
Temperaturbereich: 100 - 250 °C Kriechraten: $5 \cdot 10^{-6} - 10^{2}\ d^{-1}$

**4. Carter**

$$\dot{\varepsilon}_S = A \cdot \exp[-Q/(RT)] \cdot (\sigma/\sigma^*)^n$$

$A = 8{,}1 \cdot 10^{-5}\ s^{-1} = 7{,}0\ d^{-1}$ $Q = 51{,}6$ kJ/mol $n = 3{,}4$

Quelle: Salzstock Avery Island (USA) (Horseman et al., 1993).
Spannungsbereich: 5 - 20 MPa Manteldruck: 3,4 und 15 MPa
Temperatur bei: 100 °C mit Kriechraten: $\dot{\varepsilon}_S < 10^{-3}\ d^{-1}$ und
200 °C mit Kriechraten: $\dot{\varepsilon}_S < 10^{-2}\ d^{-1}$

**5. Munson**

$$\begin{aligned}
\dot{\varepsilon}_S &= \dot{\varepsilon}_{S1} + \dot{\varepsilon}_{S2} + \dot{\varepsilon}_{S3} \\
\dot{\varepsilon}_{S1} &= A_1 \cdot \exp[-Q_1/(RT)] \cdot (\sigma/\mu)^{n_1} \\
\dot{\varepsilon}_{S2} &= A_2 \cdot \exp[-Q_2/(RT)] \cdot (\sigma/\mu)^{n_2} \\
\dot{\varepsilon}_{S3} &= |H(\sigma-\sigma_o)| \cdot [B_1 \cdot \exp[-Q_1/(RT)] \\
&\quad + B_2 \cdot \exp[-Q_2/(RT)]] \cdot \sinh[q \cdot (\sigma-\sigma_o)/\mu]
\end{aligned}$$

wobei gilt: $|H(\sigma-\sigma_o)| = 1$ für $\sigma > \sigma_o$ und $|H(\sigma-\sigma_o)| = 0$ sonst

$A_1 = 7{,}2 \cdot 10^{27}\ d^{-1}$
$B_1 = 5{,}3 \cdot 10^{11}\ d^{-1}$
$Q_1 = 25$ kcal/mol
$n_1 = 5{,}5$
$\sigma_o = 20{,}57$ MPa
$q = 5{,}335 \cdot 10^{3}$
$A_2 = 8{,}4 \cdot 10^{17}\ d^{-1}$
$B_2 = 2{,}6 \cdot 10^{3}\ d^{-1}$
$Q_2 = 10$ kcal/mol
$n_2 = 5{,}0$
$\mu = 12{,}4$ GPa

Quelle: WIPP (Waste Isolation Pilot Plant, New Mexico, USA), Bohrung ERDA-9, Bereiche reinen Steinsalzes (Munson, Fossum und Senseny, 1989).
Spannungsbereich: 5 - 25 MPa triaxial, mit Manteldruck
Temperaturbereich: 22 - 200 °C Kriechraten: $10^{-6} - 10^{-3}\ d^{-1}$

**6. Wawersik**

$$\begin{aligned}
\dot{\varepsilon}_S &= D \cdot \exp[-Q_{CS}/(RT) \cdot [\ln(A) - \ln(\sigma/\mu)]] \\
&= D \cdot [\sigma/\mu \cdot 1/A]^{Q_{CS}/(RT)}
\end{aligned}$$

$\sigma = \sigma_1 - \sigma_3$ $A = 0.074$ $\mu = 12{,}4$ GPa
$D = 2{,}38 \cdot 10^{8}\ d^{-1}$ $Q_{CS} = 18{,}96$ kJ/mol

Quelle: Salzbergwerk Asse II (Wawersik, 1988).
Spannungsbereich: 7 - 21 MPa Manteldruck: 21 MPa
Temperaturbereich: 40 - 160 °C Kriechraten: $10^{-6} - 10^{-2}\ d^{-1}$

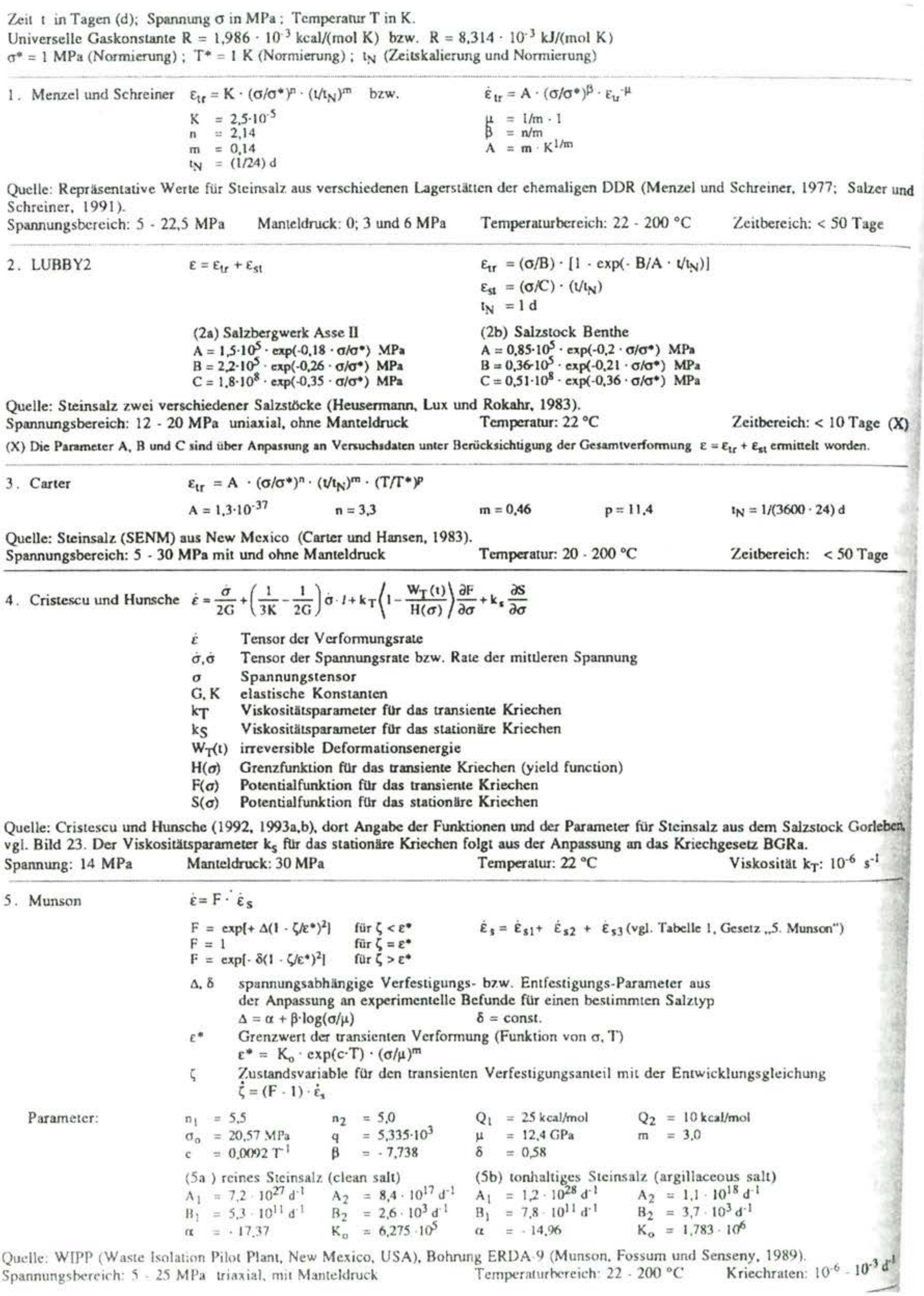
**7. LUBBY2**

$$\dot{\varepsilon}_S = \sigma / [C \cdot \exp(m \cdot \sigma)]$$

$C = 1{,}21 \cdot 10^{8}\ \text{MPa} \cdot d$ $m = -0{,}327\ \text{MPa}^{-1}$

Quelle: Salzbergwerk Asse II (Lux und Heusermann, 1983).
Spannungsbereich: 12 - 20 MPa uniaxial, ohne Manteldruck
Temperatur: 22 °C Kriechraten: $10^{-6} - 10^{-3}\ d^{-1}$

## *Table B Primary creep equations after Hunsche and Schulze (1994).*



Zeit t in Tagen (d); Spannung $\sigma$ in MPa; Temperatur T in K.
Universelle Gaskonstante $R = 1{,}986 \cdot 10^{-3}$ kcal/(mol K) bzw. $R = 8{,}314 \cdot 10^{-3}$ kJ/(mol K)
$\sigma^* = 1$ MPa (Normierung); $T^* = 1$ K (Normierung); $t_N$ (Zeitskalierung und Normierung)

---

1. Menzel und Schreiner $\varepsilon_{tr} = K \cdot (\sigma/\sigma^*)^n \cdot (t/t_N)^m$ bzw. $\dot{\varepsilon}_{tr} = A \cdot (\sigma/\sigma^*)^\beta \cdot \varepsilon_{tr}^{-\mu}$

$K = 2{,}5 \cdot 10^{-5}$
$n = 2{,}14$
$m = 0{,}14$
$t_N = (1/24)$ d

$\mu = 1/m - 1$
$\beta = n/m$
$A = m \cdot K^{1/m}$

Quelle: Repräsentative Werte für Steinsalz aus verschiedenen Lagerstätten der ehemaligen DDR (Menzel und Schreiner, 1977; Salzer und Schreiner, 1991).
Spannungsbereich: 5 - 22,5 MPa Manteldruck: 0; 3 und 6 MPa Temperaturbereich: 22 - 200 °C Zeitbereich: < 50 Tage

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2. LUBBY2 $\varepsilon = \varepsilon_{tr} + \varepsilon_{st}$

$\varepsilon_{tr} = (\sigma/B) \cdot [1 - \exp(- B/A \cdot t/t_N)]$
$\varepsilon_{st} = (\sigma/C) \cdot (t/t_N)$
$t_N = 1$ d

(2a) Salzbergwerk Asse II
$A = 1{,}5 \cdot 10^5 \cdot \exp(-0{,}18 \cdot \sigma/\sigma^*)$ MPa
$B = 2{,}2 \cdot 10^5 \cdot \exp(-0{,}26 \cdot \sigma/\sigma^*)$ MPa
$C = 1{,}8 \cdot 10^8 \cdot \exp(-0{,}35 \cdot \sigma/\sigma^*)$ MPa

(2b) Salzstock Benthe
$A = 0{,}85 \cdot 10^5 \cdot \exp(-0{,}2 \cdot \sigma/\sigma^*)$ MPa
$B = 0{,}36 \cdot 10^5 \cdot \exp(-0{,}21 \cdot \sigma/\sigma^*)$ MPa
$C = 0{,}51 \cdot 10^8 \cdot \exp(-0{,}36 \cdot \sigma/\sigma^*)$ MPa

Quelle: Steinsalz zwei verschiedener Salzstöcke (Heusermann, Lux und Rokahr, 1983).
Spannungsbereich: 12 - 20 MPa uniaxial, ohne Manteldruck Temperatur: 22 °C Zeitbereich: < 10 Tage (X)

(X) Die Parameter A, B und C sind über Anpassung an Versuchsdaten unter Berücksichtigung der Gesamtverformung $\varepsilon = \varepsilon_{tr} + \varepsilon_{st}$ ermittelt worden.

---

3. Carter $\varepsilon_{tr} = A \cdot (\sigma/\sigma^*)^n \cdot (t/t_N)^m \cdot (T/T^*)^p$

$A = 1{,}3 \cdot 10^{-37}$ $n = 3{,}3$ $m = 0{,}46$ $p = 11{,}4$ $t_N = 1/(3600 \cdot 24)$ d

Quelle: Steinsalz (SENM) aus New Mexico (Carter und Hansen, 1983).
Spannungsbereich: 5 - 30 MPa mit und ohne Manteldruck Temperatur: 20 - 200 °C Zeitbereich: < 50 Tage

---

4. Cristescu und Hunsche $\dot{\varepsilon} = \frac{\dot{\sigma}}{2G} + \left(\frac{1}{3K} - \frac{1}{2G}\right)\dot{\sigma} \cdot I + k_T \left\langle 1 - \frac{W_T(t)}{H(\sigma)} \right\rangle \frac{\partial F}{\partial \sigma} + k_s \frac{\partial S}{\partial \sigma}$

$\dot{\varepsilon}$ Tensor der Verformungsrate
$\dot{\sigma}, \dot{\sigma}$ Tensor der Spannungsrate bzw. Rate der mittleren Spannung
$\sigma$ Spannungstensor
G, K elastische Konstanten
$k_T$ Viskositätsparameter für das transiente Kriechen
$k_S$ Viskositätsparameter für das stationäre Kriechen
$W_T(t)$ irreversible Deformationsenergie
$H(\sigma)$ Grenzfunktion für das transiente Kriechen (yield function)
$F(\sigma)$ Potentialfunktion für das transiente Kriechen
$S(\sigma)$ Potentialfunktion für das stationäre Kriechen

Quelle: Cristescu und Hunsche (1992, 1993a,b), dort Angabe der Funktionen und der Parameter für Steinsalz aus dem Salzstock Gorleben, vgl. Bild 23. Der Viskositätsparameter $k_s$ für das stationäre Kriechen folgt aus der Anpassung an das Kriechgesetz BGRa.
Spannung: 14 MPa Manteldruck: 30 MPa Temperatur: 22 °C Viskosität $k_T$: $10^{-6}$ $s^{-1}$

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5. Munson $\dot{\varepsilon} = F \cdot \dot{\varepsilon}_s$

$F = \exp[+ \Delta(1 - \zeta/\varepsilon^*)^2]$ für $\zeta < \varepsilon^*$
$F = 1$ für $\zeta = \varepsilon^*$
$F = \exp[- \delta(1 - \zeta/\varepsilon^*)^2]$ für $\zeta > \varepsilon^*$

$\dot{\varepsilon}_s = \dot{\varepsilon}_{s1} + \dot{\varepsilon}_{s2} + \dot{\varepsilon}_{s3}$ (vgl. Tabelle 1, Gesetz „5. Munson")

$\Delta, \delta$ spannungsabhängige Verfestigungs- bzw. Entfestigungs-Parameter aus der Anpassung an experimentelle Befunde für einen bestimmten Salztyp
$\Delta = \alpha + \beta \cdot \log(\sigma/\mu)$ $\delta = \text{const.}$
$\varepsilon^*$ Grenzwert der transienten Verformung (Funktion von $\sigma$, T)
$\varepsilon^* = K_o \cdot \exp(c \cdot T) \cdot (\sigma/\mu)^m$
$\zeta$ Zustandsvariable für den transienten Verfestigungsanteil mit der Entwicklungsgleichung
$\dot{\zeta} = (F - 1) \cdot \dot{\varepsilon}_s$

Parameter:

$n_1 = 5{,}5$ $n_2 = 5{,}0$ $Q_1 = 25$ kcal/mol $Q_2 = 10$ kcal/mol
$\sigma_o = 20{,}57$ MPa $q = 5{,}335 \cdot 10^3$ $\mu = 12{,}4$ GPa $m = 3{,}0$
$c = 0{,}0092\ T^{-1}$ $\beta = -7{,}738$ $\delta = 0{,}58$

(5a) reines Steinsalz (clean salt)
$A_1 = 7{,}2 \cdot 10^{27}\ d^{-1}$ $A_2 = 8{,}4 \cdot 10^{17}\ d^{-1}$
$B_1 = 5{,}3 \cdot 10^{11}\ d^{-1}$ $B_2 = 2{,}6 \cdot 10^3\ d^{-1}$
$\alpha = -17{,}37$ $K_o = 6{,}275 \cdot 10^5$

(5b) tonhaltiges Steinsalz (argillaceous salt)
$A_1 = 1{,}2 \cdot 10^{28}\ d^{-1}$ $A_2 = 1{,}1 \cdot 10^{18}\ d^{-1}$
$B_1 = 7{,}8 \cdot 10^{11}\ d^{-1}$ $B_2 = 3{,}7 \cdot 10^3\ d^{-1}$
$\alpha = -14{,}96$ $K_o = 1{,}783 \cdot 10^6$

Quelle: WIPP (Waste Isolation Pilot Plant, New Mexico, USA), Bohrung ERDA-9 (Munson, Fossum und Senseny, 1989).
Spannungsbereich: 5 - 25 MPa triaxial, mit Manteldruck Temperaturbereich: 22 - 200 °C Kriechraten: $10^{-6}$ - $10^{-3}\ d^{-1}$

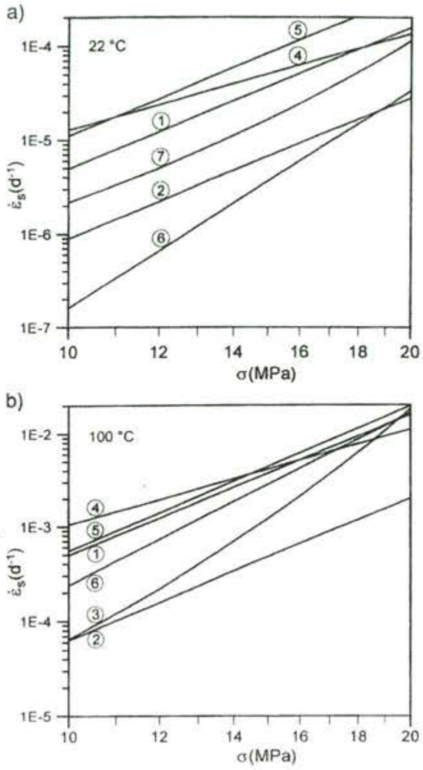

*Figure A Comparison of the steady state creep equations from Table A.*

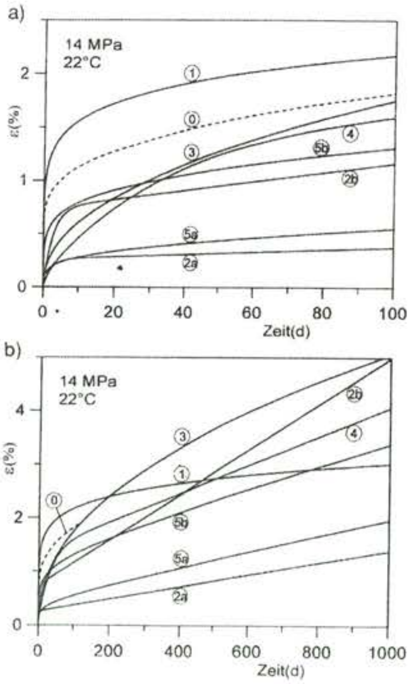

*Figure B Comparison of the primary creep equations from Table B*

# B Features, Events and Processes for cavern abandonment

| **Features, Events and Processes** | **Effect** |
|---|---|
| *Natural phenomena* | |
| Leaching/precipitation<br>(salt solution within the cavern, brine saturation, insoluble residue) | -collapse<br>-loss of well control<br>-loss of seal integrity<br>-pressure distribution => fracturing/faulting |
| Creep<br>(salt creep, cavern convergence) | -in combination with thermal expansion => cavern pressure => fracturing/faulting<br>-surface movement<br>-upward migration of cavern => collapse<br>-upward migration of cavern => loss of seal integrity |
| Thermal expansion/contraction<br>(of brine within the cavern) | -in combination with hard shut in => cavern pressure => fracturing/faulting |
| Fracturing | -loss of seal integrity |
| Loss of seal integrity<br>(brine and oil permeation, migration through e.g. anhydrite layers, leakage etc.) | -in combination with groundwater circulation => groundwater pollution |
| Groundwater circulation<br>(groundwater flow system) | -in combination with brine and oil leakage (see loss of seal integrity) => groundwater pollution<br>-subrosion<br>-compaction |
| Subrosion<br>(salt solution by contact with unsaturated groundwater) | -loss of seal integrity<br>- collapse<br>-surface movement |
| Faulting<br>(plastic/brittle deformation) | -loss of seal integrity<br>-loss of well control<br>-loss of well integrity<br>-collapse<br>-groundwater circulation |
| Collapse<br>(roof, pillar and/or overburden collapse due to geometrical /mechanical/chemical instability, sometimes causing upward migration of cavern) | -surface movement<br>-loss of well control<br>-compaction |
| Compaction | -surface movement |
| Natural gas exchange<br>(between seal and cavern) | -gas explosion |
| Surface movement<br>(sinkhole formation, subsidence bowl formation, rebound) | -human health<br>-damage on surface and/or subsurface man made constructions<br>-enhanced risk on flooding<br>-groundwater circulation<br>-land use<br>-ecosystems |

| **Features, Events and Processes** | **Effect** |
|---|---|
| Groundwater pollution<br>(by brine or oil) | -ecosystems<br>-land use<br>-drinkwater quality |
| Gas explosion | -human health<br>-damage on surface and/or subsurface man made constructions<br>-loss of well control<br>-loss of well integrity |
| Undetected features | not specified |
| *External phenomena* | |
| Loss of seal integrity<br>(brine and oil permeation, migration, leakage) | -in combination with groundwater circulation => groundwater pollution |
| Groundwater circulation<br>(groundwater flow system) | -in combination with brine and oil leakage (see loss of seal integrity) => groundwater pollution<br>-subrosion<br>-compaction |
| Loss of well control | -cavern pressure => fracturing/faulting<br>-cavern squeezing is not possible => shut in scenario (NB well integrity) |
| Loss of well integrity | -groundwater pollution, in particular in combination with groundwater circulation<br>-groundwater circulation |
| Flooding of subsidence bowl | -loss of well control<br>-loss of well integrity<br>-groundwater circulation |
| Induced seismicity | -loss of well integrity<br>-loss of well control<br>-faulting/fracturing |
| Subsurface activities | -loss of well integrity<br>-loss of well control<br>-groundwater circulation<br>geothermal effects:<br>-faulting/fracturing<br>-creep |
| Loss of records/information | -subsurface activities |

# C Features of software packages developed for rock deformation and subsidence.

| Features *** | FLAC2D, FLAC3D (Fast Lagrangian Analysis of Continua) | DIANA (Displacement ANAlyser) | ANSALT I & II (Analysis of Nonlinear Thermo-mechanical Response of Rocksalt)* | UDEC & 3DEC (Universal Distinct Element Code) | ADINA (Automatic Dynamic Incremental Nonlinear Analysis) | Aesubs (Analytic Elements Method for subsidence prediction) ** | LOSAC (Semi-analytical Code) |
|---|---|---|---|---|---|---|---|
| Description | Widely used 2 and 3D package for thermo-mechanical problems | In house program widely used for thermo-mechanical problems | Widely used package for specific salt related problems | Advanced package aiming at faulted and fractured hard rock solutions | Widely used package for thermo-mechanical and salt problems | In house combined analytical and numerical code applicable to horizontally layered model of subsurface | Specific cavern abandonment program |
| Commercial package | yes | yes | no | yes | yes | no | yes |
| Used within NITG-TNO | ? | yes | ? | no | no | yes | yes |
| Continuity of soil&rock medium | Continuous medium | Continuous medium | Continuous medium | Discontinuous medium | Continuous medium | Continuous medium | Not relevant |
| Numerical method | Finite difference | Finite element | Finite element | Distinct element | Finite element | Finite element | Not relevant |
| Calculation scheme | Explicit | Implicit | ? | explicit | Implicit/ explicit | Nucleus of strain | Not relevant |
| Numerical vs. physical stability | Gives a stable numerical solution to unstable physical processes | Numerical and physical instabilities occur at the same time | ? | Gives a stable numerical solution to unstable physical processes | ? | Numerical and physical instabilities occur at the same time | Not relevant |
| Small strain prediction | good | good | good | good | good | good | Not relevant |

| Features *** | FLAC2D, FLAC3D | DIANA | ANSALT I & II | UDEC & 3DEC | ADINA | Aesubs | LOSAC |
|---|---|---|---|---|---|---|---|
| Large strain prediction | Good: displacements are added during each calculation cycle | Poor: the mesh is fixed | Good | Good | Good: automatic remeshing procedure | Poor: the mesh is fixed | Not relevant |
| Creep materials for salt | Burger creep viscoplastic, crushed-salt consolidation, two-component power law, WIPP-creep viscoplastic model, classical viscosity, WIPP reference creep model. | Power Law, Maxwell chain, Kelvin chain. Creep models primary and secondary creep by P. Fokker as hidden feature. Dorn model and Lubby 2 model implemented but not tested. | Power law, Lux | available | available | Linear visco-elasticity: uniform properties for each layer, with linear elastic overburden and linear (visco-)elastic reservoir rock. | Power law |
| User definded material models | possible | possible | ? | ? | ? | Not available | Not available |
| Cavern geometry | good | good | ? | good | good | Not possible | Limited/ fair |
| Fault modelling | possible | possible | ? | possible | possible | Not possible | only onset fracturing |
| Temperature | Spatial& temporal variation | Static | ? | Spatial& temporal variation | Spatial& temporal variation | Static | Static |

* Information on the ANSALT package was obtained from S. Heusermann (BGR, Ingenieurgeologie/Geotechnik; personal communication).

** Fokker (2000; 2002); Orlic et al. (2001)

***

| | |
|---|---|
| FLAC | Itasca, http://www.itascacg.com/flac.html |
| DIANA | http://www.diana.nl/ |
| ANSALT | http://www.bgr.de/ |
| UDEC | Itasca, http://www.itascacg.com/udec.html |
| ADINA | http://www.adina.com/l |
| Aesubs | Fokker, 2000; 2002 |
| LOSAC | http://www.Brouard-Consulting.com/ |

# D Features of software packages developed for fluid flow and geochemical reactions.

| Features<br>** | MODFLOW | METROPOL<br>(Method for Transport of Pollutants)* | MARTHE+SCS |
|---|---|---|---|
| Description | Widely used package for 3D groundwater flow modelling, particle tracking, contaminant and reactive transport. | 3D groundwater flow modelling, transport of solutes and transport of heat. | MARTHE, for 3D groundwater flow modelling, coupled with SCS, i.e. Specific Chemical Simulator, for geochemical modelling |
| Commercial package | yes | no | Pegase (BRGM, Alterra and other institutes) |
| Used within NITG-TNO | yes | yes | ? |
| Continuity of soil&rock medium | Continuous medium | Continuous medium | Continuous medium |
| Numerical method | Finite difference | Finite element | Finite difference |
| Calculation scheme | Implicit | Implicit/<br>explicit | Implicit |
| Numerical vs. physical stability | Numerical and physical instabilities occur at the same time | Gives a stable numerical solution to unstable physical processes | Numerical and physical instabilities occur at the same time |
| Mesh properties | Mesh is fixed, grid density and pixel shape are variable | Mesh is fixed | Irregular rectangles and nested grids |
| Cavern geometry | Limited | Limited | Limited |
| Fault modelling | Through a permeability contrast | Through a permeability contrast | Through a permeability contrast |
| Temperature | ? | Spatial&<br>temporal variation | ? |

* Information on the METROPOL package was obtained from T. Leijnse (GM, TNO-NITG; personal communication).

| ** | | |
|---|---|---|
| | MODFLOW | http://www.modflow.com/ |
| | METROPOL | Sauter et al., 1993 |
| | MARTHE | http://www.brgm.fr/pegase/model/marthe.html/ |

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**TNO report**

**NITG 03-172-B**

# Abandonment of solution mined salt caverns in the Netherlands

## Part 2: Best practises and methods

| | |
|---|---|
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# Contents

# List of tables and figures

## Tables

## Figures

# 1 Introduction

The life time of solution mined caverns is limited by regulations posed on cavern size, maximum subsidence, the time period in which a concession is valid etc., as well as by technical and geological limitations. Salt solution mining in the Netherlands is at a stage where cavern abandonment has become of current interest as caverns are approaching or finishing the last part of their productive life in all four Dutch concessions (Part 1). In this document a general concept is proposed for dealing with cavern abandonment issues in the Netherlands. There are several advantages of using one concept for dealing with cavern abandonment in the Netherlands:

1. It offers a transparent, explicit and reproducible way for dealing with cavern abandonment problems.
2. It enables potential risks and damages to be identified and quantified in a systematic way, thereby providing the information upon which decisions on preventive or mitigating measurements and/or between various abandonment scenario's can be made.
3. It can be easily updated when new developments render this necessary.
4. Standardised documentation of current knowledge and practise offers a good starting point for future evaluation.

From a geological point of view this concept concerns caverns situated in quite variable settings, from salt diapirs to thin, horizontally bedded salt layers and from quite shallow (~ 350 m) to very deep (~ 3 km) (Table 1 of Part 1). For this reason the concept allows for implementation of case-specific conditions.

The concept is based on best practises and methods with a focus on human and environmental safety as well as damage control. These aspects are explicitly addressed through an internal risk assessment following the FEP methodology (Part 1). The risk assessment takes into account the:

1. Current practises and methods related to the long-term abandonment.
2. World-wide experience with problems related to the abandonment of caverns.
3. State of the art knowledge of salt behaviour.
4. Specific layout and problems of the four active salt concessions in the Netherlands.
5. Dutch Mining Law.

Use of abandoned salt caverns as storage and disposal caverns requires an additional analysis that is out of the scope of the current document.

It should be noted that this is a draft document and as such requires further specification. At the current state it intends to present the outline of a systematic and best practises approach for dealing with cavern abandonment.

# 2 General

The general requirements that abandoned caverns should comply to are given here. More specific requirements are given in section 4. In the following text, focus is in principle on the sphere of influence of the single cavern that is to be abandoned. For this purpose the entire system that is or may be influenced in any way by the presence of this cavern is taken into account. The system (Figure 1) consists of the cavern itself, its walls, pillars, floor and roof, the salt layer(s), the overburden, the groundwater system, the well and plant area, and the land surface (i.e. the subsidence bowl and margin). The system may overlap with neighbouring caverns and/or other subsurface and surface activities.

## 2.1 Long-term abandonment of salt caverns

Caverns must be abandoned in a way ensuring that all the relevant short and long term effects remain under control, protect human health safety, conserve the environment and obey legal regulations. Preferably, abandonment should also be cost efficient and without threat for public acceptance.

This presupposes:
1. adequate knowledge of the geological setting.
2. full use of all relevant information on cavern behaviour during the production history for predicting cavern behaviour after abandonment.
3. case-specific abandonment scenario's and measurements.
4. demonstration that the abandoned cavern including the technical material is capable of maintaining long term hydraulic and mechanical integrity.
5. no interfering activities shall be developed within the sphere of influence of the cavern.

## 2.2 Safety and environmental conservation

The abandoned cavern must be designed, operated, maintained or squeezed so as to present no inadmissible risk to the safety of the staff and public and to prevent any inadmissible impact on the environment, either at the surface or underground.

This presupposes:
1. Additional measures to the usual safety rules and recommendations applicable to all comparable industrial installations in order to reduce the risk and consequences of blow-out, leakage and surface movement.
2. Adequate protection of the environment.

## 2.3 Monitoring

In order to verify that the recommendations above are met, monitoring systems and procedures shall be implemented.

# 3 Abandonment strategy

## 3.1 Abandonment principles

Proven technology (best practises and methods) should be used for cavern abandonment measures, as well as for the necessary analyses, calculations and measurements.

All relevant data concerning abandonment (production history, problems and incidents, equipment specification, operating procedures, quality assurance plan, forecast, methods and alternatives) should be documented and made available to the owner and the operator of the facility.

All relevant information on cavern behaviour during production should be used for: identifying and quantifying risks to the point where the responsible parties (government and companies) have enough information by forecasting cavern behaviour during abandonment to decide between different (combinations of) abandonment scenario's and to take (case-specific) measures to control the risks.

Abandonment measures must be documented (in written form) and performed by competent personnel and companies.

Surface and subsurface installations shall be adapted or designed to control the process of cavern abandonment at any combination of pressure and temperature that may occur within a (pre-) determined range of conditions. They shall be conform the existing standards for individual parts of the system.

Emergency procedures should be developed.

Adherence to the safety and environmental requirements shall be monitored.

## 3.2 Geological concerns

Surface movement, groundwater pollution and gas explosion are the main processes that may potentially result in damage after cavern abandonment according to the risk assessment (Part 1). The risk scenario's that could lead to such damage are described in Part 1. It must be ensured that any damage remains within acceptable limits. This requires long term predictions of relevant geological processes (Table 2 in Part 1) for caverns that are to be abandoned. Consequently, geological studies need to be undertaken.

Sufficient (qualitative and quantitative) information on the case-specific risks must be available to decide between (combinations of) the abandonment scenario's (Part 1). This information shall be derived from case-specific geological data, cavern behaviour during production and model studies. The different abandonment scenario's must be documented and specified for the local conditions at the onset of abandonment. Furthermore, a sensitivity study must be performed to demonstrate the possible deviations from the predicted behaviour due to parameter uncertainties.

The final cavern configuration must be determined and tested on its mechanical stability.

The cavern field configuration and interference between active and/or abandoned caverns must be documented and explicitly taken into account.

Information about the local geological setting must include at least geometry, stratification, thickness, salt type, composition, grain size distribution and amount of insolubles of the entire Formation in which the cavern is situated.

In situ salt creep must be determined, preferably from the production history, otherwise from in situ samples and literature values (Part 1).

Idem for elastic and plastic parameters of the local materials.

Intrinsic salt permeability must be determined by a permeability test. Factors likely to influence salt permeability (e.g. anhydrite layers) must be documented.

Permeability and other hydraulic parameters must be determined for the local materials, aquifers and containment layers.

The temperature gradient must be determined or estimated.

Brine temperature in the cavern must be determined.

The primary stress state around the cavern must be determined (Rokahr et al., 2002), for instance by an in situ pneumatic fracturing test, an in situ hydraulic fracturing test, borehole break outs, or an interpretation of the geology in combination with the gravity signal (Staudtmeister and Schmidt, 2000).

Faults in the vicinity of caverns must be mapped and documented (Bekendam and Paar, 2002).

An estimate must be made on the amount and spacing of additional salt leaching after abandonment.

Especially for caverns situated in thin salt layers it must be demonstrated that:
1. the seal, consisting of salt and other relevant layers surrounding the cavern, is sufficiently thick to preserve seal integrity and is able to prevent any infiltrated brine to reach other materials than salt
2. the geometry of the cavern is and remains suitable to prevent pillar and roof collapse.

Special attention must be paid to demonstration of cavern, seal and overburden integrity for caverns with a large height and/or rapid upward migration.

Idem for caverns where no thermal equilibrium is reached.

It must be demonstrated that if the plant is flooded no connection can be established between the surface and/or aquifers and the salt body and/or cavern.

## 3.3 Technical concerns

In order to avoid the risk on damage during cavern abandonment, technical requirements for the facility must be determined to ensure that well integrity and –if relevant- well control are maintained.

Sufficient (qualitative and quantitative) information on the case-specific risks must be available to determine the technical limitations of the abandonment scenario's (Part 1). This information shall be derived from case-specific technical data, production history and model studies. The different abandonment scenario's must be documented and specified for the local conditions at the onset of abandonment. Furthermore, a sensitivity study must be performed to demonstrate the possible deviations from the predicted behaviour due to parameter uncertainties.

The maximum pressure the equipment can withstand must be determined and documented. The minimum pressure to prevent stoppage must be determined and documented. Seal quality must be determined.

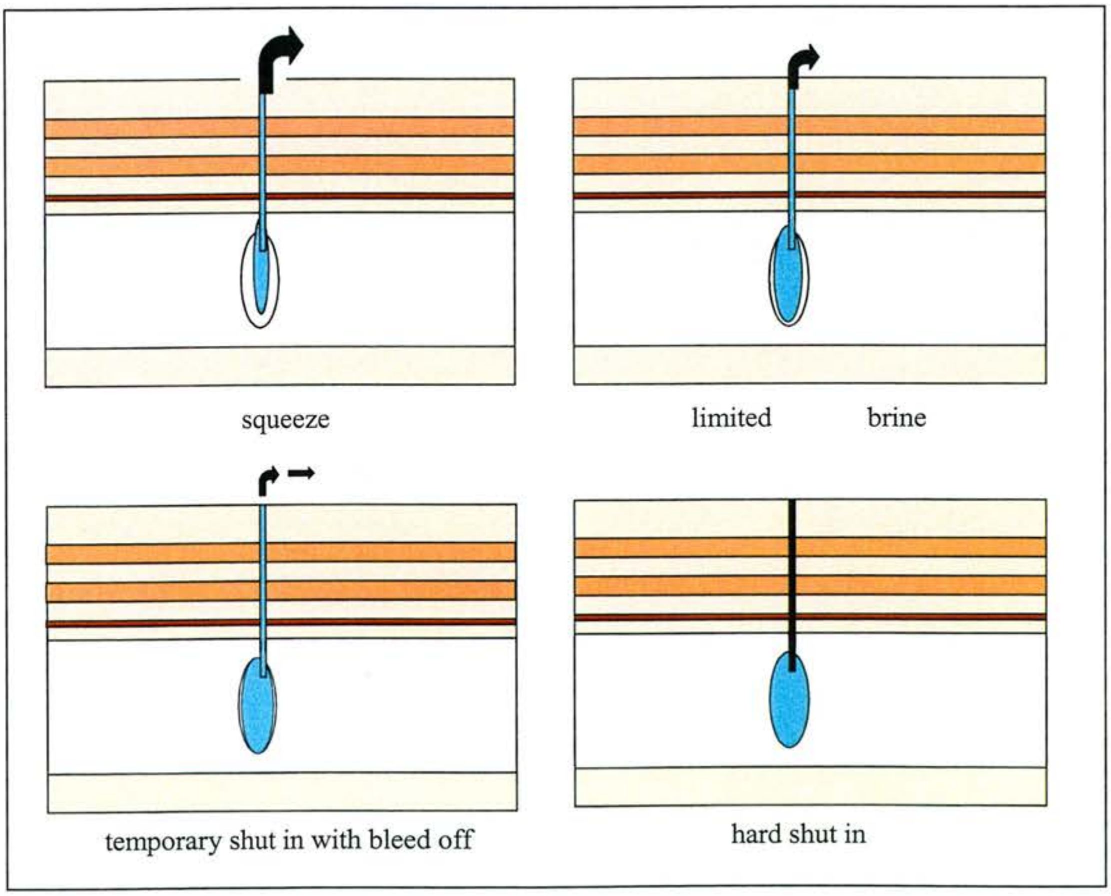

*Figure 1: Different scenario's for cavern abandonment.*

## 3.4 Abandonment scenario's

The different abandonment scenario's, i.e. squeeze, limited brine outflow, temporary shut in with bleeding off and hard shut, are visualised in Figure 1. Their advantages and disadvantages are presented in Table 1.

*Table 1: Overview of the (dis)advantages of the different scenario's.*

| | |
|---|---|
| **Squeeze** | |
| goal: maximal reduction of cavern volume and brine content | |
| application: only feasible for caverns with a high creep rate | |
| **advantages** | **disadvantages** |
| establishing thermal equilibrium in cavern | surface movement takes place at high rate |
| no leakage | due to ongoing brine production total subsidence is larger |
| brine production is continued | casing may be damaged |
| no risk on gas accumulation within the cavern | no permanent solution |
| equipment does not have to withstand high pressures | technical equipment must be maintained |
| **Limited brine outflow** | |
| goal: maintaining a maximum brine pressure and limited reduction of cavern volume and brine content | |
| application: feasible for all caverns | |
| **advantages** | **disadvantages** |
| establishing thermal equilibrium in cavern | surface movement |
| low risk on leakage at maximum brine pressure | large brine volume remains |
| known brine production | no permanent solution |
| no risk on gas accumulation within the cavern | technical equipment must be maintained |
| **Temporary shut in with bleed off** | |
| goal: maintaining a maximum brine pressure | |
| application: feasible for all caverns | |
| **advantages** | **disadvantages** |
| establishing thermal equilibrium in cavern | irregular brine production |
| low risk on leakage at maximum brine pressure | irregular surface movement |
| low risk on gas accumulation within the cavern | damage related to surface movement is postponed |
| slow surface movement | large brine volume remains |
| control over the maximum pressure that the equipment has to withstand | no permanent solution |
| | technical equipment must be maintained |

| **Hard shut in** | |
|---|---|
| goal: permanent abandonment | |
| application: not feasible for caverns with a high creep rate and no thermal equilibrium or for caverns in a gas-rich salt formation | |
| **advantages** | **disadvantages** |
| extremely slow subsidence and sometimes even rebound | high risk on leakage at lithostatic brine pressure |
| permanent solution | risk on gas accumulation within the cavern |
| technical equipment can be largely disabled | damage related to surface movement may occur in the far future |
| | large brine volume remains in the subsurface |
| | equipment has to withstand continual high pressure |

# 4 Best practises and methods

## 4.1 Measures

Different (combinations of) abandonment scenario's require specific measures.

Measures and requirements apply to the time the abandonment scenario is performed with a maximum time period of 250 years, unless explicitly stated differently.

### *4.1.1 Squeeze*

It must be demonstrated that creep rate (and hence cavern convergence) is high enough to enable squeezing.

As the cavern is still producing salt, all regulations for salt production apply.

It must be demonstrated that cavern, seal and overburden integrity is not compromised with special attention for the roof stability.

It must be demonstrated that the pressure in the cavern does not drop below hydrostatic pressure (e.g. by brine leakage), as this threatens the roof stability (Bekendam and Paar, 2002).

Maximum surface subsidence must be regulated.

The consequences (cost and liability) of surface subsidence must be regulated (e.g restrictions on land use).

A schedule must be made including the conditions at which squeezing shall be finished and a follow up scenario.

In order to avoid stoppage by gypsum precipitation and/or insolubles in the well, overpressure must have a minimum threshold.

It must be demonstrated that the (weakest part of the) well seal is capable to withstand at least the expected maximum brine pressure in the cavern.

The maximum pressure that the casing and other relevant parts of the equipment can withstand must be determined and documented.

The casing and other relevant parts of the equipment must be regularly checked on corrosion and/or other weaknesses. The result must be documented. If they are in bad condition they must be repaired.

Use permanent backfill of suitable non-toxic and non-polluting materials (no storage or disposal) to diminish the cavern volume as far as possible.

If fresh water dilution is necessary to maintain well control, the amount of additional salt leaching and the effect on cavern integrity must be checked and documented.

A procedure must be developed in case brine production exceeds demands.

A procedure must be developed in case loss of well control occurs.

### *4.1.2 Limited brine outflow*

As the cavern is still producing salt, all regulations for salt production apply.

It must be demonstrated that cavern, seal and overburden integrity is not compromised with special attention for the roof stability.

It must be demonstrated that the pressure in the cavern does not drop below hydrostatic pressure (e.g. by brine leakage), as this threatens the roof stability (Bekendam and Paar, 2002).

Maximum surface subsidence must be regulated.

The consequences (cost and liability) of surface subsidence must be regulated.

A schedule must be made including the conditions at which the brine outflow shall be stopped and a follow up scenario.

It must be demonstrated that the (weakest part of the) well seal is capable to withstand at least the expected maximum brine pressure in the cavern.

The maximum pressure that the casing and other relevant parts of the equipment can withstand must be determined and documented. A casing shoe integrity test must be passed (Ratigan, 2003).

The casing and other relevant parts of the equipment must be regularly checked on corrosion and/or other weaknesses. The result must be documented. If they are in bad condition they must be repaired.

The rate of brine outflow must be sufficient to keep brine pressure below a fixed maximum.

The casing and other relevant parts of the equipment must be regularly checked on corrosion and/or other weaknesses. The result must be documented. If they are in bad condition they must be repaired.

Use permanent backfill of suitable non-toxic and non-polluting materials (no storage or disposal) to diminish the cavern volume as far as possible.

A procedure must be developed in case brine production exceeds demands.

A procedure must be developed in case loss of well control occurs.

### 4.1.3 *Temporary shut in with bleed off*

As the cavern is still occasionally producing salt, all regulations for salt production apply.

It must be demonstrated that cavern, seal and overburden integrity is not compromised with special attention for the roof stability.

It must be demonstrated that the pressure in the cavern does not drop below hydrostatic pressure (e.g. by brine leakage), as this threatens the roof stability (Bekendam and Paar, 2002).

The consequences (cost and liability) of future surface subsidence (after the 30 year period determined in the Mining Law) must be regulated.

A schedule must be made including the conditions at which the temporary shut in shall be stopped and a follow up scenario.

It must be demonstrated that the (weakest part of the) well seal is capable to withstand at least the expected maximum brine pressure in the cavern.

The maximum pressure that the casing and other relevant parts of the equipment can withstand must be determined and documented. A casing shoe integrity test must be passed (Ratigan, 2003).

The casing and other relevant parts of the equipment must be regularly checked on corrosion and/or other weaknesses. The result must be documented. If they are in bad condition they must be repaired.

The rate of brine outflow must be sufficient to keep brine pressure below a fixed maximum.

The oil blanket must be removed, unless it can be demonstrated that (oil) leakage will not take place and/or that upward migration of the cavern is likely and undesirable.

Use permanent backfill of suitable non-toxic and non-polluting materials (no storage or disposal) to diminish the cavern volume as far as possible.

A procedure must be developed for exploitation and/or disposal of the brine.

A procedure must be developed in case loss of well control occurs.

### 4.1.4 *Hard shut in*

It must be demonstrated that cavern, seal and overburden integrity is not compromised with special attention for the roof stability.

It must be demonstrated that the pressure in the cavern does not drop below hydrostatic pressure (e.g. by brine leakage), as this threatens the roof stability (Bekendam and Paar, 2002).

Check if the brine within the cavern has reached thermal equilibrium. If not, hard shut in must be postponed until thermal equilibrium is reached, unless it has been demonstrated that brine pressure will remain below the maximum acceptable level (Ratigan, 2003).

It must be demonstrated that the (weakest part of the) well seal is capable to withstand at least the expected maximum brine pressure in the cavern. Tests have shown that pressure may exceed lithostatic pressure by 10% without seal failure (Pfeifle et al., 2000). However, this maximum should be avoided by all means, particularly because other parts of the equipment are more vulnerable.

The maximum pressure that the casing and other relevant parts of the equipment can withstand must be determined and documented. A casing shoe integrity test must be passed (Ratigan, 2003).

The casing and other relevant parts of the equipment must be checked on corrosion and/or other weaknesses and the result must be documented. If they are in bad condition they must be repaired.

It must be demonstrated that the seal integrity will be maintained and no substantial leakage will occur out of the cavern. If not, hard shut in must be cancelled, or additional measures must be made that reduce leakage to acceptable levels.

Record pressure oscillations induced by the withdrawal stop, as this gives an independent estimate of the cavern volume and can detect (natural) gas pockets trapped in the cavern (Bérest et al., 1999).

If there are gas pockets in the cavern and/or other indications for the presence of gas during the life time of the cavern or within the salt formation, hard shut in should be cancelled, or additional measures should be made in order to avoid gas build up in the cavern.

The consequences (cost and liability) of future surface subsidence (after the 30 year period determined in the Mining Law) must be regulated.

The oil blanket must be removed.

Use permanent backfill of suitable non-toxic and non-polluting materials (no storage or disposal) to diminish the cavern volume as far as possible.

Injection of a small amount of additional brine into the cavern before final sealing in order to slightly exceed the predicted equilibrium pressure. After one month a tightness test (fuel oil test, nitrogen leak test) should show a negative pressure built up in the cavern (Bérest et al, 2001).

Injection of a small amount of **inert** gas into the cavern before sealing in order to increase the cavern compressibility significantly (Bérest et al., 2001).

The time necessary to seal the well must be minimised in order to increase the strength of the seal (Ratigan, 2003).

The quality of the well seal must be tested before final sealing (Ratigan, 2003).

The state of the plugs (plug integrity) should be checked on a regular basis after abandonment (Herbert and Meyer, 2000; Pfeifle et al., 2000; Ratigan, 2003).

## 4.2 Interference with subsurface and surface activities

Current use of the subsurface within the sphere of influence of the cavern to be abandonment must be documented.

Current use of the surface within the sphere of influence of the cavern to be abandonment must be documented.

It must be demonstrated that cavern abandonment and the current use of the subsurface and surface can be combined. If not, additional measures must be taken and/or abandonment measures must be adjusted.

Constraints on future use of the subsurface within the sphere of influence of the cavern to be abandonment must be documented and made available to all parties involved.

Constraints on future use of the surface within the sphere of influence of the cavern to be abandonment must be documented and made available to all parties involved.

## 4.3 Monitoring

The purpose of monitoring is to provide information on the conditions and behaviour of caverns at the onset of and during the abandonment phase.

Several monitoring systems and procedures are available to measure and document relevant parameters of the surface and subsurface during the abandonment phase. Which parameters are relevant should be determined from a quantitative risk analysis including a sensitivity analysis to detect the key variables. For each specific abandonment scenario a subset of relevant parameters to be monitored must be chosen.

The observations/measurements must be interpreted and compared with forecasts. Significant discrepancy between forecasted and observed cavern behaviour must result in a solid (re-)evaluation, an update of the forecast and -if necessary- in an altered scenario and adjusted measures.

### *4.3.1 Monitoring at the surface*

**brine production**
It is common practise to measure the volume of produced brine at well head.

This can be useful to check the forecasted squeezed brine volume.

**brine temperature at well head**
It is common practise to measure brine temperature at well head using temperature monitoring equipment.

This can be useful to determine whether thermal equilibrium is reached in the cavern or not.

**brine composition**
It is common practise to measure brine composition at well head.

This can be useful as a warning system for casing stoppage due to gypsum cementation.

**well head pressure**
It is common practise to measure brine pressure at well head using pressure monitoring equipment.

This can be useful as a warning system for fracturing.

**cavern compressibility**
A small, nearly instantaneous change in cavern shape cause flow and/or pressure changes at well head. These can be measured by using pressure and/or flow monitoring equipment.

This can be useful to predict pressure build-up rate in a closed cavern.

**pressure oscillations**
Acoustic pressure oscillations that are induced by small pressure changes cause flow and/or pressure changes at well head. These can be measured by using pressure and/or flow monitoring equipment.

This can be useful as a warning system for gas and to check the results of a static test (see cavern compressibility).

**surface movement**
It is common practise to measure surface movement using optical levelling, GPS, InSAR or tilt meters. Optical levelling is at present the most common and reliable method (Kenselaar, 2002). The geographical positioning system (GPS) is as precise as optical levelling only for elevation differences over very long distances. Typical accuracy of a GPS geodetic network lies in the order of 40 mm (Wildenborg et al., 2002). Interferometric synthetic aperture radar (InSAR) remote sensing is still under development. Accuracy's in the order of 10 mm can be obtained for a grid spacing in the order of 50 m. Tilt meters can be permanently installed and are proven technology.

Regulations about density and layout of a grid, frequency of measurements and interpretation of the results can be found in the Mining Law (see Duquesnoy, 2002 for an introduction).

**void migration**
Cavern void migration may be monitored indirectly by dynamic variations in the gravity field, especially for relatively shallow caverns (Dortland, 2003). Up to date no applications of gravity monitoring for void migration are known to the author.

This can be extremely useful as a warning system for sinkhole formation.

**plug integrity**
It is common practise to monitor plug integrity on a yearly basis.

This can be useful as a warning system for leakage.

### 4.3.2 *Monitoring in the subsurface*

**cavern configuration**
It is common practise during the production phase to measure cavern configuration using monitoring equipment like sonar, gamma/ccl, ground penetrating radar (Gundelach et al., 2002) or metered oil inventory (Munson and Myers, 2000). A comparative study of errors in the different methods to measure cavern volume in the Strategic Petroleum Reserve (SPR) caverns (Munson and Myers, 2000) suggests that there is a random uncertainty in the sonar survey of ± 2%, whereas it is ± 3% in the production data. Furthermore, a bias of a few percent exists, seemingly depending on the specific survey company.

This can be useful as model input.

**brine temperature at depth**
Temperature monitoring sensors are commercially available and have an expected life span in the order of 5 to 10 years.

They can be useful in the cavern to check if thermal equilibrium is reached and as a warning system for brine leakage.

**micro-seismicity**
Micro-earthquakes caused by sudden rock failures due to local stress accumulation can be measured within a few tens of meters away from the epicentre by three component geophones. The technique is considered mature.

This can be useful as an early warning system for subsidence or gas breaching the caprock.

**groundwater salinity**
Chlorine saturation in groundwater can be measured by conventional wireline resistivity or conductivity logging or by thermal decay time logging (TDT). TDT is considered mature technology. The response is relatively unaffected by the usual borehole and casing sizes (cf. Wildenborg et al., 2002). Another technique is fluid sampling, which can only be done through wire line operation with direct access to a well.

This can be useful in aquifers above the cavern as a warning system for leakage.

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