Eneco gasspeicher

Underground gas storage in salt cavern

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Q.A.L.V Noordoven

Abstract

The Dutch national energy company Eneco is in the process of implementing a large project involving the storage of gas in salt caverns in Epe, Germany. For short-term gas trading and flexibility in the gas market Eneco intend to lease two caverns till 2030 with an option to lease till 2060. The caverns are leached by Salzgewinnungs Geselschaft Westfalen (SGW). This company has produced brine from this area since the 1972. The two caverns will have a geometrical volume of 500 000 m3 and 400 000 m3, and will be operated between 40 and 210 bar, resulting in a working gas volume of 170 million m3.

Eneco expects the project to contribute to an increased security of supply and liquidity of the north-West European gas market. To complete this project, Eneco Gasspeicher team asked me to give a complete overview of he project. And to give all parameters involved in this project.

This paper will describe the project in some more detail.

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Introduction

Since July 2004, market liberalization for gas as well for electricity is effective for all groups of customers, including residential customers. Distribution companies, like Eneco, and other shippers nowadays import gas for their own portfolios, whereas in the pre-liberalization era the distribution companies purchased their gas requirements from the formerly integrated Gasunie. (Hoelen, Q., van Pijkeren, G., Teuben, B.,Steenbergen, B., Breuning, P.) The energy companies can use storage facilities like salt cavern for their own flexibility. Eneco plans to use natural gas storage for commercial reasons;
- to offer more trading opportunities
- increase profits by short-term gas trading
- Reduce costs related with peak load demands

The natural gas storage is facilitated in a salt cavern leached out by solution mining. In this report are listed the various methods for solution mining, the storage parameters, the lithology and the rock mechanics. Also are listed the Eneco Gasspeicher plan for underground gas storage and some recommendations.

1. Solution mining

1.1 Introduction:

Mining is the process of extracting ore or minerals from the ground. Solution mining is a process of recovering minerals; it is primary used for salt minerals. Salt solution mining is the mining of various salt minerals by dissolving them with water and pumping the resulting brine to the surface. Water or undersaturated brine is injected through a well drilled into a salt bed layer to etch out a cavern or void. The brine is extracted for processing. It usually targets salts at depths greater than 400 meters and up to 2800 meters in the Baradeel consession in the Netherlands. (Breunese, J., van Eijs, R., de Meer, S., Kroon, I.) At depths greater than 2000 meter ongoing salt creep tend to reduce cavern size.

In China brine wells are used for more than 2000 years, especially in the Scechuan and Yunnan provinces. Marco Polo reported annual production in a single province of more than 30000 tons. With bamboo poles they leached shallow salt formations. In Lorraine, France, the first simple wells were sunk by hand as early as in the year 858. And by 1830 in the USA there were more than 60 brine wells in operation in the Ohio region.

The advantage of solution mining over conventional mining or surface evaporation is that product quality and the extracting operation is not dependent of climate or rock strength and is not dangerous for personnel and equipment. Solution mining can exploit folded and disturbed beds or deep lying strata, conventional techniques are not commonly used in these situations.

1.2   Mining process:

The design of a salt solution well consists of two or more columns of steel pipes (figure 1). Fresh water needed for the solution process is pumped into the well to create a cavity in the targeted salt by leaching, the following leaching fluids can be used:

- Surface water from rivers
- Well water
- Sea water
- Water from sewage / purification plants
- Undersaturated brine from other caverns
- Condensate from salt production plants.

The resulting brine is then returned to the surface for the processing and recovery.

The first step in solution mining salt is to drill a borehole, large enough for the required pipes and casings. Solution wells are wider than oil, gas or water wells. Near the surface the borehole is the widest. The surface casing is cemented in place to prevent any leakage and contamination of groundwater, also to prevent a blow out. The final casing string is set at some depth below the top of the target salt, so that during dissolution a set thickness of salt remains in place. In some wells there is another string that controls the thickness of the fluid blanket. A fluid blanket is usually pumped into a solution cavern to prevent rapid upward leaching and a possible collapse of the cavern roof. Blanket fluid is inert so it does not dissolve the target salt.
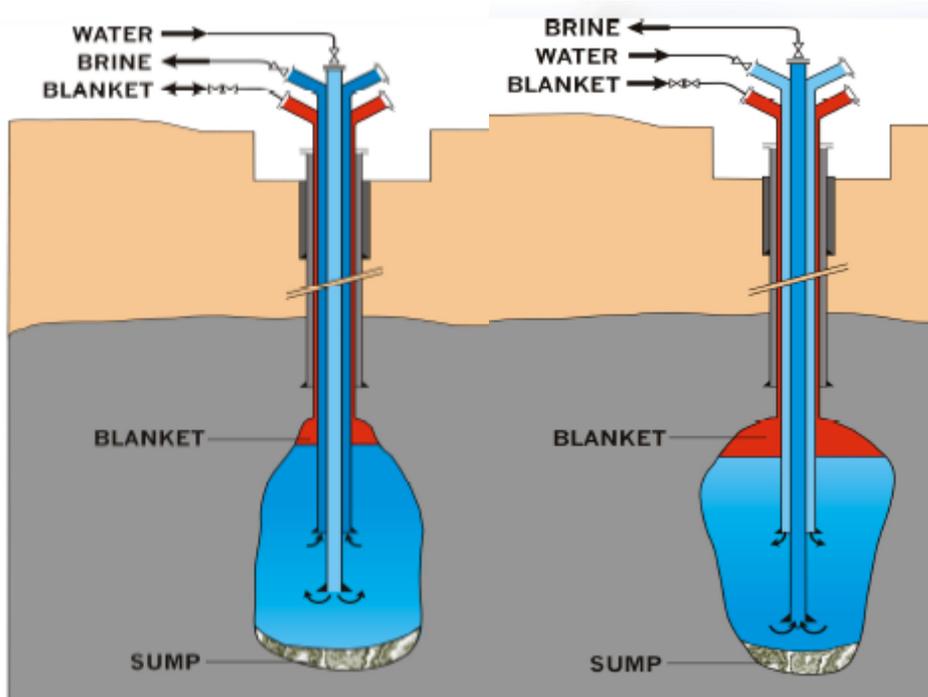

Figure 1a: Method of direct circulation.   Figure 1b: Method of indirect circulation

There are two methods for developing and shaping caverns as seen in figure 1.

In the direct circulation method, feed solvent is injected through the tubing string and dissolves the salt at the bottom of the formation. The brine is then drawn out through the annular space between the tubing string and the final casing.

In the indirect circulation method fresh water is injected between the tubing and the casing. This system is called the "top injection method". By the top injection method the water enters the salt deposit at the top of the formation and starts to dissolve the salt near the roof. The salt brine flows downward to the bottom of the tubing where a sump effect has been produced by the pump drawing on the tubing. The sump is a leftover of the brine production of the inhomogeneous rock salt. The brine is pumped from the well and then it is ready to be processed.
Under the design scenario, strings can be rotated and raised as the cavern grows and the bottom fills with debris.
When a single hole solution mining well is first drilled, the flow rate through the cavity and up the pipe is ussually kept very low to maintain higher brine concentration. After some years the surface area and the cavity volume increase, the extracted brine flow can be raised.

Leaching rates and thus construction times vary with the amount and degree of salinity of the water injected. It is common to find that for every seven cubic meters of fresh water injected, a volume of one m^3 is leached (Leith, 2001). Leaching rates are normally expressed as the amount of water or brine circulated and can reach rates of 1600 m^3 per day. In the U.S., leaching rates of 320,000 m^3 to 400,000 m^3 per year are common (Leith, 2001). Construction rates for the two 150,000 m^3 solution-mined caverns at Huntorf in Germany were an average of about 360 m^3 of salt per day, at a maximum circulation of 600 m^3 per hour. Each cavern was completed in about 14 months and it took a further five months to remove the brine from each of the caverns (Leith, 2001).
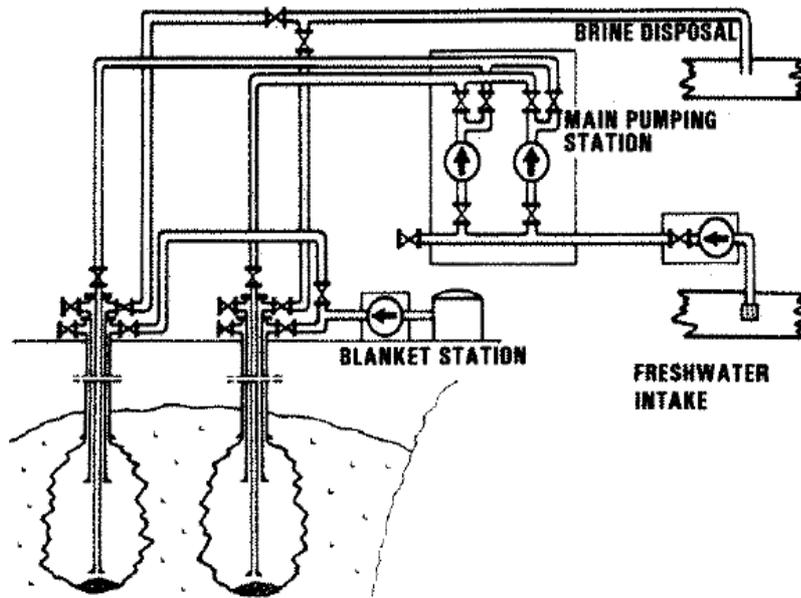

Figure 2: Construction for salt leaching.

There are two methods of salt production.

The single- well method of solution mining involves the drilling of a single large diameter drill hole into a salt formation. A casing is used in the hole to stop the walls from caving. A second tubing af smaller size is then placed in the cased drill hole. The single well method is mostly applied for deeper salt formations.

The two well method of solution mining is based on drilling two identical wells into a salt body at a distance from tenths to several hundreds of meters. One well is assigned as production well and the other for injection. Several well methods starts in the same way as single-well method solution, forming two caverns. After completion, high pressure water is applied at the injection well in order to cause hydraulic fracturing. The brine is then drawn from the production well. The volume of water will only rise so the production will decrease also. The main concern in the stability of the large caverns is roof control. For this type of mining is the depth of salt solution limited to 300-500 meters. That is why in Epe this method is not used.

2. Hydrocarbon storage

Crude oil, Liquefied Petroleum Gas (LPG) and light hydrocarbons can be safely stored in the underground storage facilities. The earliest oil storage in caverns was in Canada during World War II. In 1949 LPG was stored in caverns in Texas, USA. In the past decades natural gas is stored in (salt) caverns, underground mines, aquifers, oil- and gas fields in increasing volumes. The first storage of natural gas in a salt cavern was at Unity Saskatchewan, in the USA, in 1959. Nowadays there are many salt caverns used for oil and gas storage

worldwide. In total over 600 underground gas storage facilities are used. Figure 3. presents a summary of the installed working gas volume (10^6 m^3) by nations.

Salt deposits are extensively used for underground storage of hydrocarbons and other products as well as for waste disposal. The storage caverns in salt deposits are constructed by the solution process described in the previous chapter solution mining. Today's brine producers are also aware of the potential storage opportunities. One reason to make the cavern is their brine feed, but on the other hand they produce tight cavern suitable for storage. The rent they receive from energy companies are of great amounts. The storage caverns have to meet the criteria necessary to assure stable and tight high pressure, sub surface storage vessels.
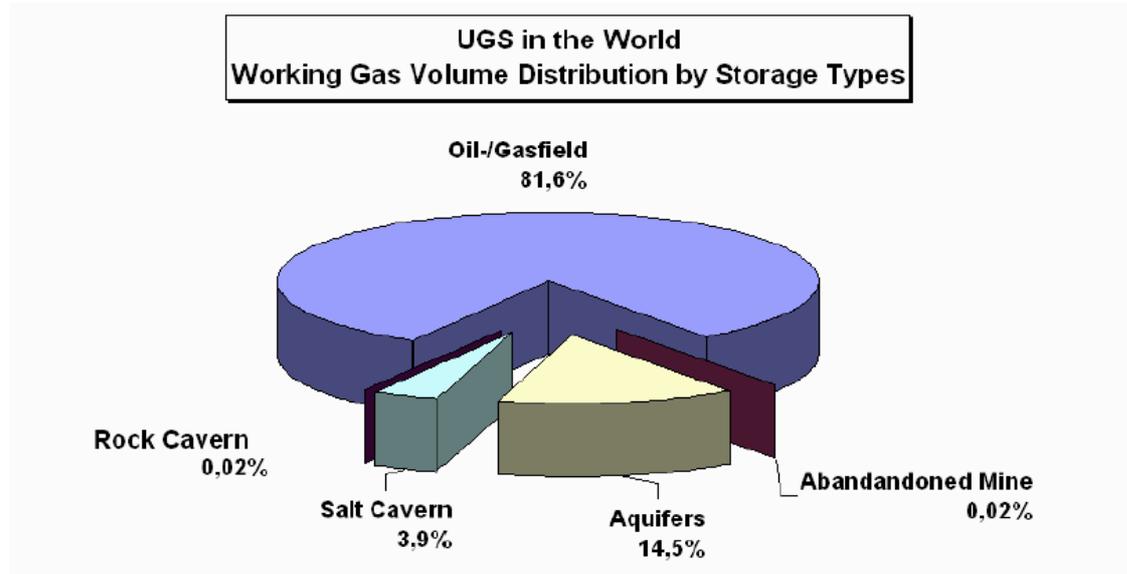

Figure 3 : Underground storage facilities in the world

Natural gas has become a prime source of energy worldwide, especially in residential heating and gas-fired power plants. Traditionally the demand for natural gas is usually higher during winter, partly because it is used for heating in residential and commercial settings. Stored natural gas plays a vital role in ensuring that any excess supply delivered during the summer months is available to meet the increased demand of the winter months. However, with the recent trend towards natural gas fired electric generation, demand for natural gas during the summer months is now increasing, because of the need of more electricity in summer months, for air conditioning for example. Natural gas in storage also serves as insurance against any unforeseen accidents, natural disasters, or other occurrences that may affect the production or delivery of natural gas. Natural gas storage plays a vital role in maintaining the reliability of supply needed to meet the demands of consumers.
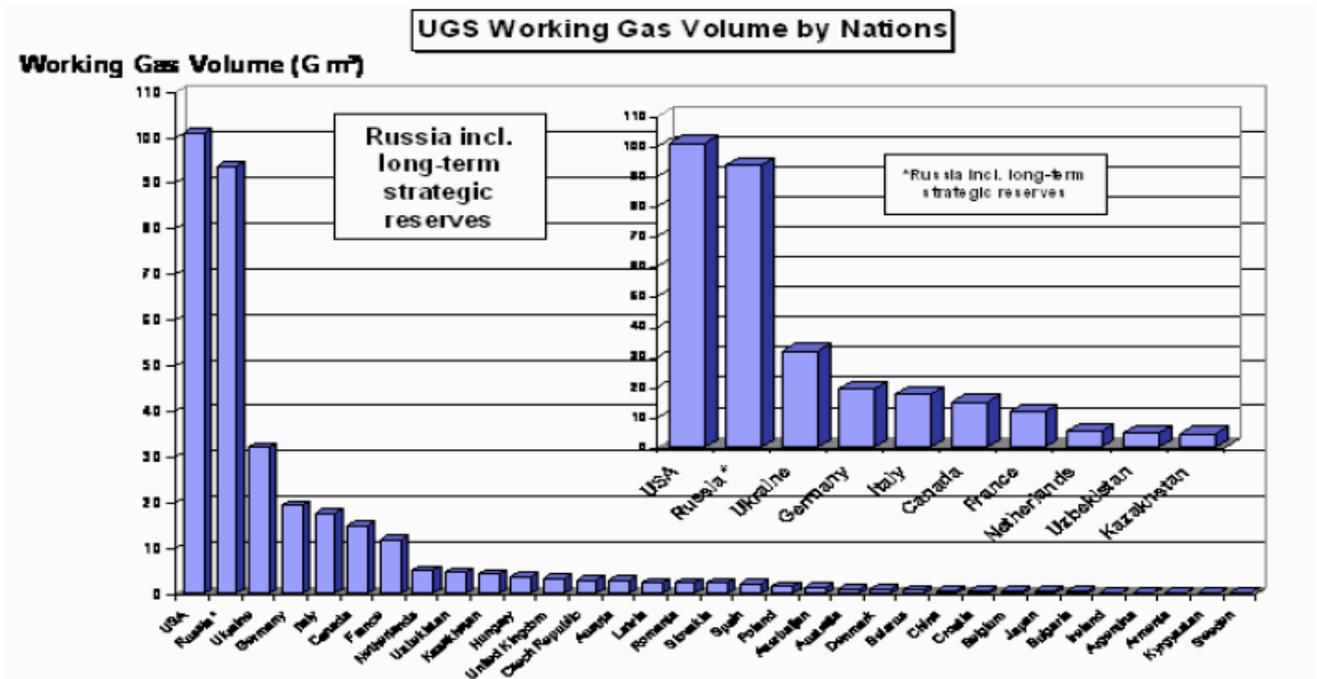
Figure 4: working gas volume by nations

Germany is in the last decades the leading storage country of Western Europe. According to CEDIGAZ, Germany has an estimated 713 Bcf of working natural gas storage capacity, the largest amount in the EU and the fourth-largest in the world. The capacity is spread among 43 facilities. In 1976 the first German gas storage facility was created in a salt cavern. Figure 5 gives the development and planning of new gas storage facilities. In the recent years it is a trend to use salt cavern for gas storage.

Figure 5: Gas storage in Germany

3. Eneco Gasspeicher

3.1 introduction

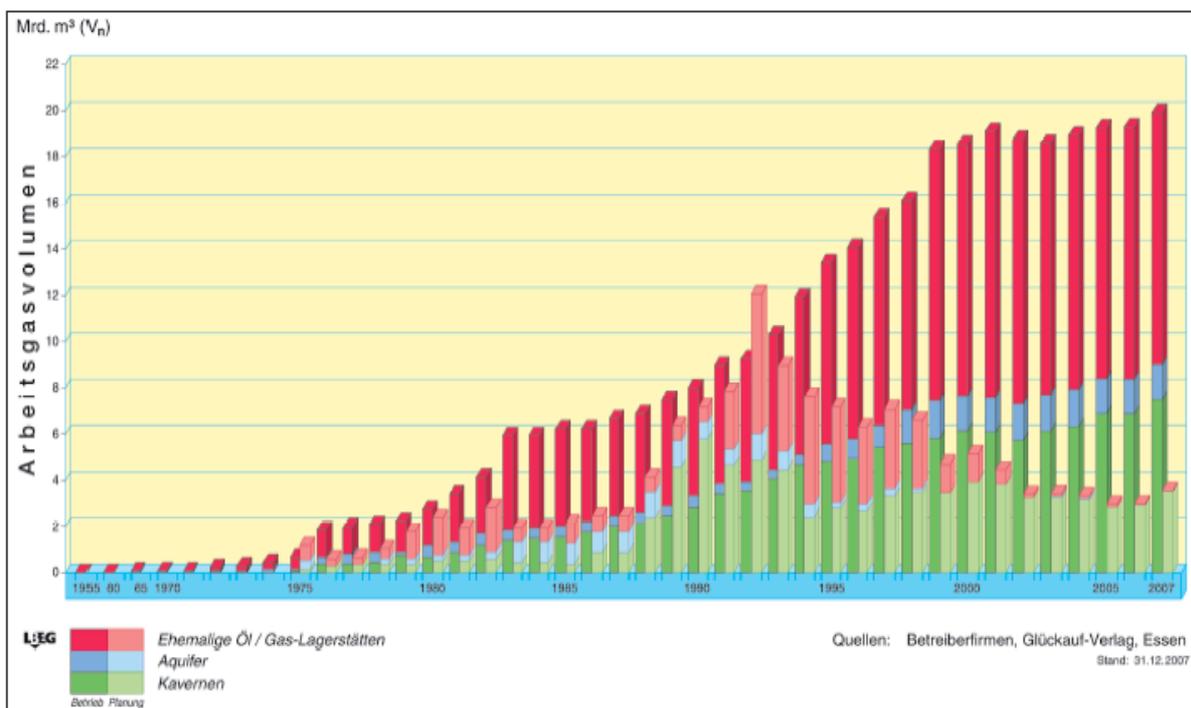For short-term gas trading and flexibility in the gas market Eneco intend to lease two caverns till 2030 with an option to lease till 2060. The caverns, named Epe S81 and Epe S82, are leached by Salzgewinnungs Geselschaft Westfalen (SGW). The caverns are near the village Epe, in North-Rhine Westfalen in Germany. It is located near the border with the Netherlands and is part of the town Gronau. For years the Epe area is the centre of salt solution mining, because of the thick salt formation underground. The SGW has in the Epe area over 90 caverns. They were first used for brine production only. Later the SGW used the caverns for storage of various chemicals and gases.

The caverns are located in the Zechstein salt formation. The drilling process for well S81 started February 2002, S82 started January 2003. The volume of S81 cavern measured in April 2006, was 129029 m^3. The leaching process was not finished yet in that period. In July 2006 the volume of S82 was 133801 m^3. The caverns are connected with gas storage facilities. From Hengelo in the Netherlands an approximately 21 kilometer long natural gas pipeline is connected to this natural gas storage facility. The gas will be transported from Hengelo to the gas storage facility in Epe, there the gas is injected into the caverns with the help of two compressors that can operate at a maximum capacity of 100,000 m^3/h each. The gas is then withdrawn from the storage facility back to the Dutch supply network. Before the gas can be used again its pressure is reduced in the gas treatment plant. Furthermore, the humidity is extracted from the gas.

The planned cavern layout:

Cavern	Width (m)	Height (m)	Depth (m)	Volume (m^3)	Time to leach
Epe S81	60	243	1357	519.000	2003-2012
Epe S82	66	171	1283	395.000	2003-2010

Table 1, planned layout.
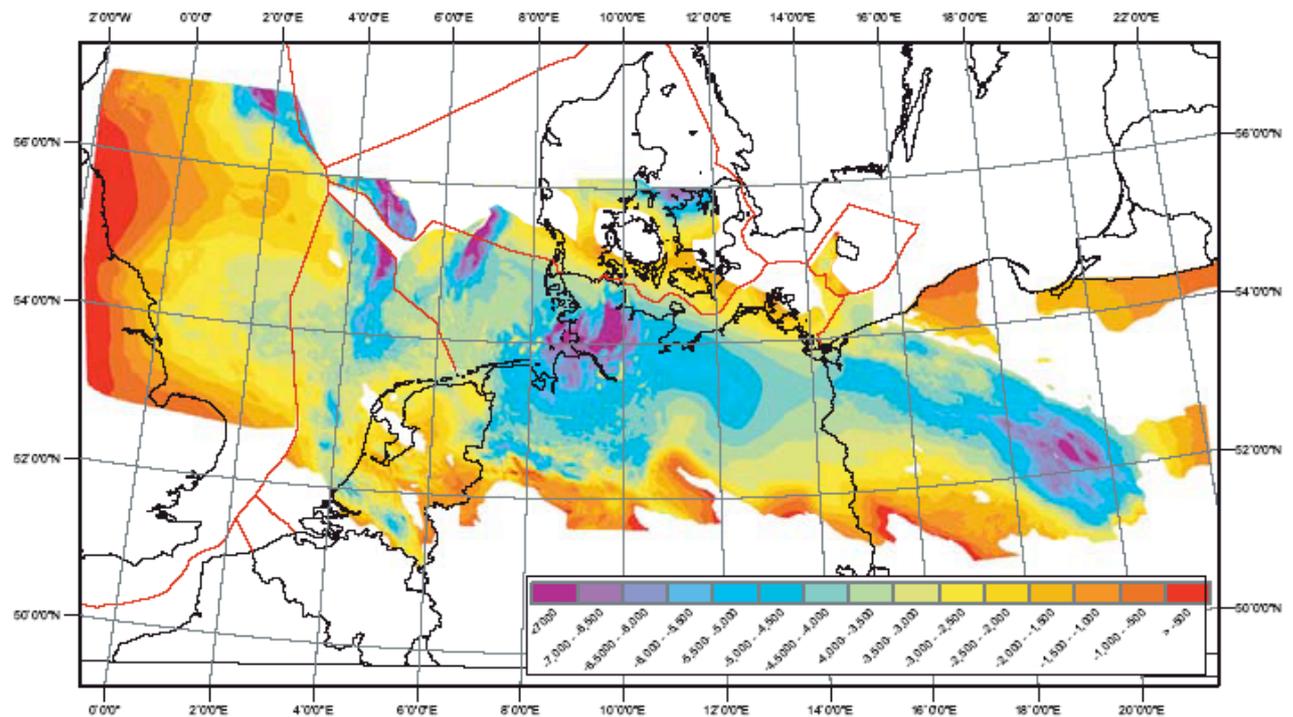
3.2 Stratigraphy

Figure 6: Preliminary depth map of the Base Zechstein Group (resulting from the SPBA pilot mapping project)

The common goal of stratigraphy studies is the subdivision of layered rocks. It can tell us much about the processes affecting the deposition of sediments.

The evaporate rocks of the Zechstein formation were laid down by the Zechstein Sea, an epicontinental or epeiric sea that existed in the Guadalupian and Lopingian epochs of the Permian period. The Zechstein Sea occupied the region of what is now the North Sea, plus lowland areas of Britain and the north European plain of The Netherlands, Germany and Poland. In its own era the continent was located near the Earth's equator where high temperatures and arid conditions facilitated evaporation as seen in figure 7.
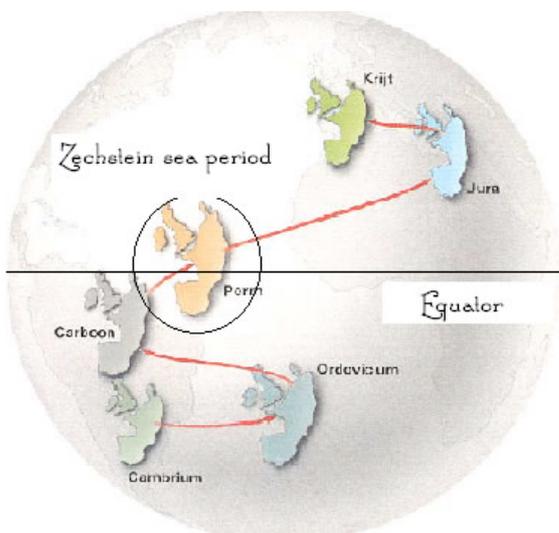

Figure 7: Location of the continent in the Perm era.

The Zechstein formation itself consists of at least five depositional cycles of evaporate rocks, which are called Z1 to Z5 respectively and is hardly tectonically deformed.

In the group, a twofold subdivision can be made based upon the depositional character into marine evaporate deposits in the lower part of the group (i.e., the Z1, Z2 and Z3 Formations) and playa-type deposits in the upper part (the Z4 and Z5 Formations) (Geluk et al., 1997). A playa is a dry or ephemeral lakebed, generally extending to the shore. Such flats consist of fine-grained sediments infused with alkali salts.
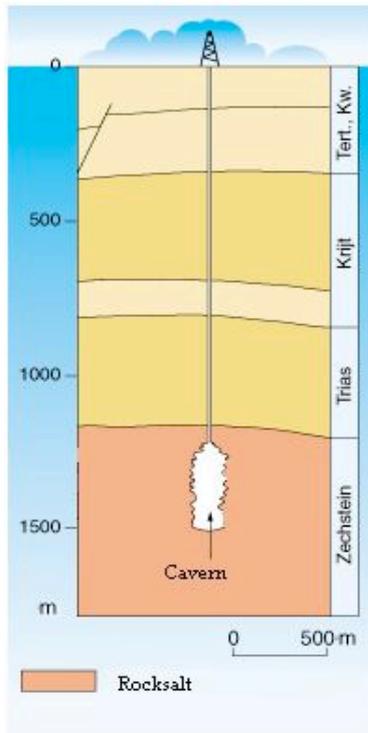
Figure 8: Lithology.

The Zechstein 1 salt in the Epe area is considered of good quality and relatively pure with 99% NaCl, it is the Werra Steinsalz, Na 1. And the formation is a bedded Zechstein salt formation with changes in thickness of rock salt mass and depth of the salt top. The thickness of the Zechstein 1 salt in well S81 is about 370 meters, the thickness of the werra- steinsalz in well S82 is about 300 meters. Furthermore, there are faults existing either at the basis of the salt layer or at its top. The faults at the salt basis are syngenetic regarding the genesis of the rock salt mass and have created a special geotectonic structure at the salt basis, called fault zone.
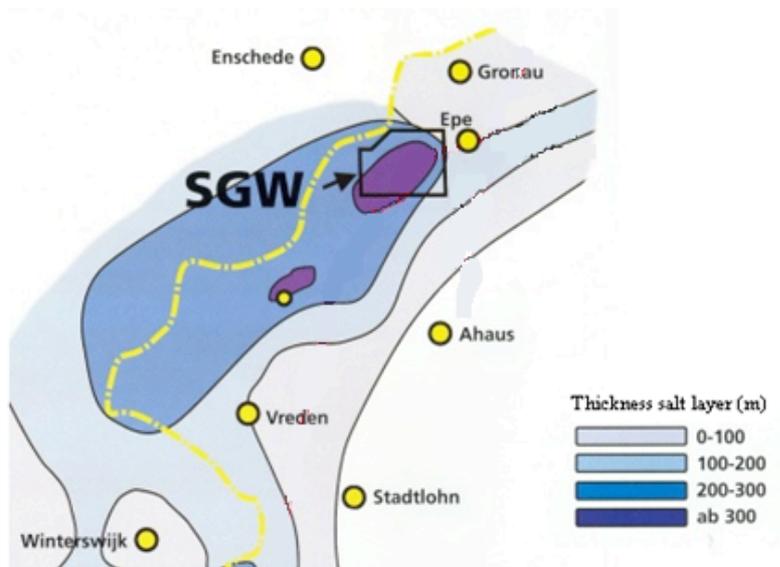
Figure 9: Thickness of the Zechstein saltformation

In the northern and western part of the deposit the rock mass at the salt basis is characterized by significant fault zones with a throw of hundred and more meters. The other caverns show that the fault systems at the basis and above the salt deposit are not the same. Therefore the salt rock mass itself seems to be not destrengthened by the fault systems.

The available bore logs (see appendix) show sandstone, shale and anhydrite.

Below the Werra-salt a thick anhydrite layer exists with a normal thickness of about 100 m and more. Below this anhydrite layer the carboniferous rock mass follows which consists of changing layers of sandstone, siltstone and claystone. (Lux, Wermeling, Bannach)

3.3   Wells

The Eneco wells (S81 and S82) are cluster wells. Cluster well pads allow multiple caverns to be created beneath a large pad and are cheaper alternative to single well pads. They have a lower infrastructure costs and land area requirements. However compared to the single well pads, they suffer from less flexibility in ongoing planning and maintenance. Casings are a critical feature in cluster pad wells, especially for hydrocarbon storage.

Figure 10: Cluster well pads, deviated well   *figure 11: Installation, well pad and well location.*
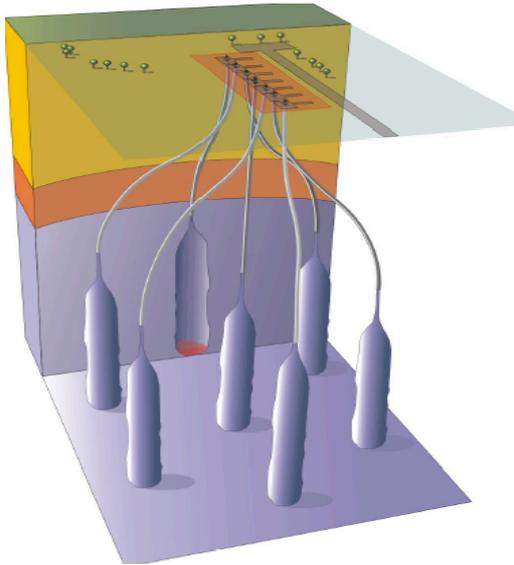
3.4   Installation

There are two methods by which gas is injected into underground storage and both methods will be used depending on the pressure of the gas in the pipeline compared to the gas in the cavern at the time of the required injection. If the pressure in the pipeline is higher than the pressure in the cavern, the gas will flow free from the pipeline into the cavern without any additional effort. This occurs when the gas inventory in the cavern is at a low level. If the pressure in the pipeline is lower than the pressure in the cavern, the gas pressure will be increased by using gas compressors.

These two methods are also used in the withdrawal process only in reverse. If the pressure in the cavern is higher than the pipeline, the gas will free flow out of the cavern into the pipeline. If the pressure in the cavern is less than the pipeline pressure, the gas will be compressed using the same compressors. In storage, gas absorbs water, which then has to be separated to prevent any corrosion or gas hydrate formation in the pipeline. The first step involves separating tiny free drops of water from the gas stream in the so-called free water knockout process. A preheater heat up the gas to prevent any gas hydrates formation in the processing facilities when pressure is reduced for the gas supply grid. The gas is now just as it was when it was originally delivered to the storage facility.

The usability of the injection and withdrawal capacities is affected by the filling level of the storage facility. Once a certain level of volume is injected, the pressure inside the storage facility is so high that the original injection capacity is no longer completely available. Accordingly, below a certain volume withdrawn, the pressure inside the storage facility is no longer sufficient to maintain the entire withdrawal capacity.

4.1   Storage parameters

There are several volumetric measures used to quantify the fundamental characteristics of an underground storage facility and the gas contained within it. For some of these measures, it is important to distinguish the characteristic of a facility such as its capacity, and the characteristic of the gas within the facility.

Total gas capacity:	The maximum volume of gas that can be stored in an underground storage facility.
Total gas in storage:	The volume of storage in the underground facility at a particular time.
cushion gas:	the volume of gas intended as permanent inventory in a storage reservoir to maintain adequate pressure and deliverability rates throughout the withdrawal season.
Working gas capacity:	The total gas storage capacity minus cushion gas.
Working gas:	The volume of gas in the reservoir above the level of base gas. Working gas is available to sell.
Withdrawal:	Most often expressed as a measure of the amount of gas that can be delivered (withdrawn) from a storage facility on a daily basis. The deliverability of a given storage facility is variable, and depends on factors such as the amount of gas in the reservoir at any particular time, the pressure within the reservoir, compression capability available to the reservoir, the configuration and capabilities of surface facilities associated with the reservoir, and other factors.
Injection capacity:	The complement of the deliverability or withdrawal rate. It is the amount of gas that can be injected into a storage facility on a daily basis. The injection capacity of a storage facility is also variable, and depends on factors comparable to those that determine deliverability. By contrast, the injection rate varies inversely with the total amount of gas in storage: it is at its lowest when the reservoir is most full and increases as working gas is withdrawn.

Cycling refers to the storage facility's ability to complete the injection and withdrawal of working gas. Traditionally reservoir storage is designed to complete one cycle in each year. Recent market trends have produced the need for storage facilities capable of completing multiple cycles per year.

None of these measures are fixed because the rates of injection and withdrawal change as the level of gas varies within the cavern. The facility's total volume can vary, temporarily or permanently, as its defining parameters vary. Storage facilities can withdraw cushion gas for supply to market during times of heavy demand, although this gas is not intended for that use.

boundary conditions given by Bergamt

- Minimum pressure in cavern Pmin is given around 40 bar.
- There cannot be a pressure drop (dPmax)of 10 bar in one day.
- Maximum pressure in gas cavern Pmax is around 210 bar.
- Geometric volume Vc is constant.

- <u>Maximum injection / production capacity</u>
- Maximum gas volume: Pmax * Vc
- Maximum workinggasvolume: (Pmax-Pmin) * Vc
- Maximum gasvolumechange per day: (dPmax/Pmax) * (Pmax * Vc) = dPmax * Vc
- Maximum avarage injection/productie per hour: dPmax * Vc/24
- Minimum cycletime with working gas volume: 2*((Pmax-Pmin) * Vc/dPmax * Vc)) = 2* (Pmax-Pmin)/dPmax

Example

Vc	1 mln m3
Pmax	210 bar
Pmin	40 bar
dPmax	10 bar

Maximum gas volume	210 mln m^3
Maximum WGV	170 mln m^3
Maximum gas volume change per day	10 mln m^3
Maximal injection/production	0,417 mln m^3/hour
Cycletime	34 days

4.2 Gas hydrates

If the brine in the sump or on the walls have a higher water vapor pressure than the partial pressure of the water vapor in the injected gas, water will move from these sources into the injected gas. Water vapor in gas cavern can cause two problems, the presence of water can cause gas hydrates and possible metal corrosion in the pipeline can occur. In the longer gas storage cycles the equilibrium of the gas and brine vapor can be reached.

Gas hydrates are crystalline water-based solids physically resembling ice, in which gasses are trapped inside "cages" of hydrogen bonded water molecules. Without the support of the trapped molecules, the structure of hydrate clathrates would collapse into conventional ice crystal structure or liquid water.

Hydrates have a strong tendency to agglomerate and to adhere to the pipe wall and thereby plug the pipeline. Once formed, they can be decomposed by increasing the temperature and/or decreasing the pressure.

In Europe the water content limitation is 70mg/m^3 at 70 bar. This concentration is capable of allowing hydrates to form if the temperatures become low enough. Hydrates take a significant time to grow to large sizes and they will decompose rapidly if exposed to low pressures and warm temperatures.
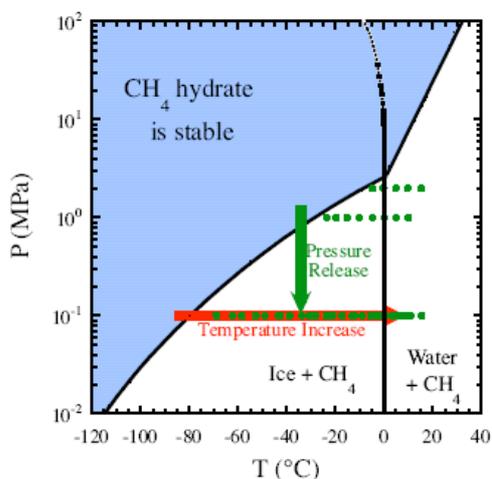

Figure 12: Methane Hydrate stability field

When operating within a set of parameters where hydrates could be formed, there are still ways to avoid their formation.

- adding chemicals can lower the hydrate formation temperature and/or delay their formation

- Replacing brine with organic liquids

- Sump coverage

- Cavern drying

These operations are considered enough to avoid formation.

Temperature

The temperature of rock increases with depth, a typical value being a temperature rate of 45°C per 1000 m, but caverns are leached out using soft water pumped from a river, lake or shallow aquifer whose temperature is cooler. Brine temperature at the end of leaching, is close to the soft water temperature and significantly smaller than rock temperature. During construction of natural gas storage caverns by solution mining, the temperature distribution in the surroundings of the cavern is extensively disturbed.

When the cavern remains inactive, after leaching is completed, the initial temperature difference slowly resorbs with time, due to heat conduction in the rock mass and heat convection in the cavern brine (Berest, Broaurd, Karimi-Jafari).

During gas withdrawal, the expansion of gas causes cooling in the cavern. The necessary energy for expansion work is supplied by the heat content of the gas itself. The higher the withdrawal rate, the less is the time available for heat transfer at the cavern wall. Therefore, the gas temperature decreases more rapidly. The extreme case is an adiabatic expansion without any heat transfer at the wall.

In this case, the previous cooling of the salt rock by the solution mining process has a negative effect. Because of a considerable decrease in temperature, the risk of developing gas hydrates increases. Gas hydrates develop in case of high pressure and low temperature, as well as in the presence of water. The gas withdrawal rate has to be reduced or withdrawal even interrupted in order to avoid pressure and temperature conditions when hydrates can develop. (Walden S.)

When the formation of hydrates is considered, the presence of water as a precondition for this is also related to the cooled rock, but now in a positive sense. While measuring the water content in natural gas storage caverns, it was noticed again and again that there was a rapid increase of water content of gas in the lower part of the cavern. Therefore, it can be concluded that this wet gas is immobile and thus not involved in the convection flow in the upper part of the cavern. Beside loss of heat due to evaporation at the brine surface in the cavern sump, considerable cooling of this section during solution mining can be assumed because of the long duration of influence of the cold water. Nevertheless, with regard to these questions, each cavern should be regarded individually, as considerable specific differences between caverns may exist. (Walden S.)

The temperature distribution in the surrounding salt body will affect the gas temperature in the cavern in the short and long term. Because of the heat reserves in the rock, the cooling effect of the solution mining process will decrease in the course of the operation time. But the initial temperature gradient can never be reached again, due to convection flow in the gas phase and disturbances caused by gas injection or withdrawal activities. (Walden S.)

4.3. Rock mechanics in salt

The behavior of caverns and mines can only be understood and predicted by taking into account the creep and other aspects of salt. But the mechanical behaviour of salt is of a very hard complexity, and several aspects of

it are still open to discussion. In all the articles I read you see a lot of different ways to describe salt mechanics. I will try to give some aspects of mechanical behavior of salt.

Under certain loading conditions salt may become permeable or fail in compression or fracture under tension. Fracturing can result in fluid or gas losses from a cavern or flooding of a cavern, when a connection to an aquifer has been accidentally established by fracturing.

4.3.1. Creep of rock salt

Rocksalt creep is usually in three stages: primary, secondary and tertiary. Primary creep components may be negligible for geological studies, because its time scale is very small. But researchers are in debate whether or not primary creep has to be taken into account in the case of mining and storage in salt. The shorter the period of loading and the lower the temperature, the more important the primary creep component becomes. Temperature is a very important parameter covering the creep of rock salt, since all mechanisms under consideration are thermally activated. (Breunese, J.N et al.)

Secondary creep represents an equilibrium state between strain hardening and recovery processes. Tertiary creep is usually attributed to expansion and is the phase of a full disintegration of the polycrystal structure.

Figure 13 schematically illustrates the form of creep curves as obtained with uniaxial creep tests, which are unconfined compression tests with a constant load (σ = const.), used to obtain time-dependent mechanical properties.

The stress σ leads to elastic deformations ε^{el}, which not depend on time, as well as to creep deformations ε^c depending on time. If the creep stress σ is smaller than a stress σ_F, the so-called uniaxial yield stress, the increase of the creep deformation with time, i. e. the creep rate $\dot{\varepsilon}^c$ is largest after applying the creep stress and then converges to a constant value. The creep deformation can, in this case, be subdivided into two components. One is the so called primary component of the creep deformation ε^p, which converges to a constant value and does practically not anymore increase after a certain time. Therefore, the primary creep is also called non-steady creep. The other component is known as secondary or steady state component of the creep deformation ε^s; it increases linearly with time in an uniaxial creep test ($\dot{\varepsilon}^s$ = const.).

If the creep stress is larger than the yield stress σ^F, the creep curve usually has a point of inflection. After a delayed creep at the beginning, an accelerated creep process starts as soon as the inflection point is passed, finally leading to a creep failure (see figure below). This behavior can be interpreted by a tertiary creep portion ε^t, increasing over proportionally with time and being superimposed to the elastic, primary and secondary deformation components.
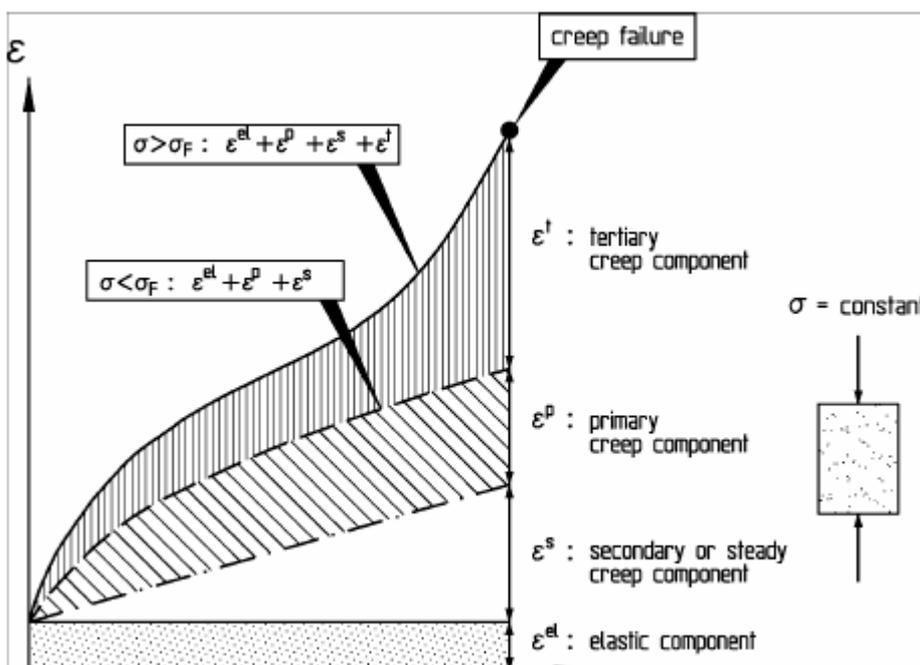

Figure 13: Primary, secondary and tertiary creep in an uniaxial creep test

4.3.2. Primary creep

Primary creep is dependent on temperature. The relation between stress and strain rate can be given by a power law function. This law is called the creep law of Menzel-Schreiner (1972).

This law with an extension of a temperature function (the Arrhenius function):

$$\dot{\varepsilon} = (\dot{\varepsilon_1 0})\, e^{\dagger}(((-Q)/RT))\, (\sigma/(\sigma_1 0\, \varepsilon^{\dagger}\beta\,)\,)^n$$

Where values β can be calculated to range between 0.33 and 0.44. Where n ranges between 9 to 15. Temperature T (K), gas constant R (8.314 J/K/mol) and activation energy Q (J/mol).

4.3.3. Secondary creep

At relatively elevated temperatures (500 – 1000 °K) and low strain rates, secondary creep starts to play an important role. Strain is caused by directed stress . The secondary creep law (Poirier 1972, Fransen 1993) is :

$$\dot{\varepsilon} = \dot{\varepsilon_0}\; e^{\left(\frac{-Q}{RT}\right)} \sigma^m$$

Poirier mentions a range of m from 4 to 7.

However, not every problem requires the determination of all parameters. As already mentioned, stresses smaller than the yield stress only lead to elastic as well as primary and secondary creep deformations. In such cases, the stress-strain behavior of the salt rock is completely described by the parameters E, v, Ep, ηp, m, a and n. In long-term studies, the secondary creep often prevails, because the stress alterations due to an opening's excavation and, thus, the primary creep deformations are limited with respect to time. In such cases, the primary creep deformations may be neglected so that only the parameters E, v, a and n are necessary to describe the stress-strain behavior.

Main features of steady-state creep are captured by the following simple model (Norton-Hoff power law):

$$\dot{\varepsilon} = A\, e^{\wedge}(((-Q)/RT)\,)\, (1/(n+1))\, (\partial/\partial\sigma)\, [(\sqrt{3}J_2)^{n+1}$$

Where $J2$ is the second invariant of the deviatoric stress tensor; A, n, Q/R are model parameters.
To slow down the creep effect it is important to keep the pressure close to lithostatic and the shear stresses close to zero. In the case of Eneco Gasspeicher it is not favourable to keep the pressure close to lithostatic pressure. To slow down the creep effect there has to be an healing period, where the gaspressure in the cavern is close to the lithostatic pressure.

However, these simple approximations are poorly suited for underground storage caverns , where cavern gas pressure varies significantly with time. These formulae does not capture the transient effects, which play a major role in this context. (Vouille et al. and Hugout)

4.4 Permeability

Salts behave in a manner somewhere in between a ductile material (like steel) and a brittle manner (like hard rock). Insufficient bonding strength and non uniform internal stresses lead to micro- cracks when loaded under the wrong conditions.

The elastic breakdown pressure is theoretically more than twice the lithostatic pressure for an isotropic stress field in elastic rock $\sigma_\theta(wall) = 2p_{lithostatic} - p_{borehole}$ However elastic breakdown is never reached at this level. According to a lot of theories, the stresses around the borehole drop as a result of creep, if the

borehole pressure is for a long time below the lithostatic pressure. When the borehole is pressured fast, the tangential stresses become tensile at a pressure that is below the elastic breakdown pressure. But a creep related stress drop will have some effect in the breakdown pressure.

By entering the crystal boundaries, fluids no longer support the salt, instead they decrease the crystalline stresses and the salt strength. Another important factor for the permeability is the hydraulic fracturing. It is a source of cavern leakage because of the fractures it generates in the salt mass. Salt permeability is strongly influenced by the state of stress. Especially stresses, like tensile or high deviatoric stresses, developed at the cavern wall. They occur when the intern cavern pressure is very high or very small. So a fast pressure build up will lead to a higher breakdown pressure, since micro crack and fluid intrusion take time.

So we can say that by fluid intrusion salt behaves as if it was a permeable matter. The maximum fluid excess pressure in an underground cavern, with respect to the minimum in situ stress is equal to the tensile strength.

The real problem is usually the "piping" or casing, the cemented well that connects the cavern to the ground surface. Correct and strong well designs prevent most leakages, testing is necessary to ensure that there is acceptable tightness.

4.5 Cavern spacing

For developing new caverns the stress distribution and concentration around and between caverns is important. For stress evaluation it is necessary to know the virgin stress of the salt deposit and the mechanical properties of the salt. Stress distribution around multiple caverns is very complicated. The domain of stress interaction between salt caverns is difficult matter, because plasticity solutions indicate that stresses beyond the yield zone surrounding a cavern are greater that would be predicted by an elastic solution. A safe formation of multiple wells is achieved by a trigonal layout of single wells. As seen in figre 14 the distance between the wells have to be 2* diameter of the cavern + 2* pillar zone + 2* radius of the cavern
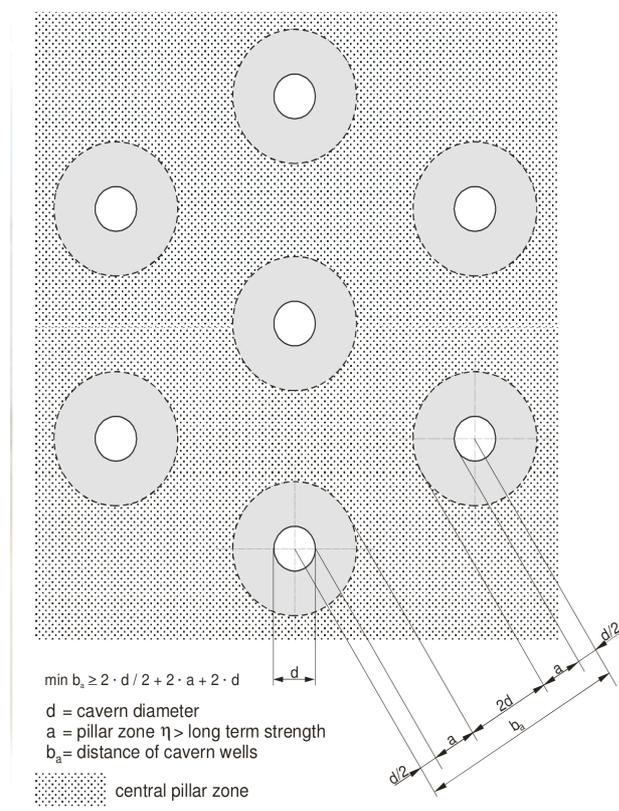

figure 14: Determination of cavernwell spacing

4.6 Subsidence

It is a well-known fact that natural solution of concealed salt beds by circulating groundwater leads to subsidence of the land surface. In addition, subsidence and impacts on hydrologeological regimes occur at many underground mining operations, causing changes to surface landforms, ground water and surface water flow. All solution-mined caverns converge as they very gradually shrink due to salt creep (Bérest & Brouard, 2003). The shape and depth of the subsidence bowl vary according to many parameters. Like cavern volumes, depth, spacing between caverns, rock properties and the production rate and scenario. Very rapid squeeze from a single cavern is believed to result in a narrow bowl because salt squeezes over a limited area. Slow squeeze from a single cavern result in a wide bowl because the squeeze is spread over a larger area.
To control subsidence, it is of great importance to design a proper thickness of salt pillar above the cavern. The best control of cavern subsidence is achieved by a trigonal layout of single wells. The collapse of a cavern leads to damage of the surface only in the case of shallow solution mining. At greater depth (like over 1000 meter) destruction of the ground surface is impossible.

Several mathematical models have been developed for the analysis of subsidence. All of them have some drawback because they do not held the discontinuous nature of rock salt in mind.

There has to be some features held in mind:

- Squeeze volumes are not the same as leaching volumes
- The dip of the salt layers
- The elastic properties of the overburden
- The occurrence of faults
- The salt mass is uniformly deformed.

Because the Epe area is a rural area it is very important that subsidence is monitored constantly. The vertical magnitude of the subsidence itself typically does not cause problems. Only for drainage it cause problems. More dangerous is the associated surface compressive and tensile strains, curvature, tilts and horizontal displacement. These factors cause the worst damage to the natural environment, buildings and infrastructure.

4.7 Storage pressure

Determination of the maximum storage pressure in the cavern is a function of several variables: design specifications, regional pressure and known temperature gradients. Calculations vary from company to company and site to site. The most important fact is the over pressuring of the casing shoe. High temperature effects are not that important, but the lithostatic pressure calculated from well logs is important.

Lithostatic pressure is a pressure, equal in all direction, caused by the weight of the overlying rocks. Lithostatic pressure indices a stress in rocks. When the elastic limit of the rock is reached, it will change shape in non-reversible fashion.The lithostatic pressure at depth z is given by the formula below. Where $\rho(z)$ is the density of the overlying rock and g is the acceleration due to gravity. And p_0 is the datum pressure, the pressure at the surface. In the attachment you find the calculation of the pressure in the two Eneco wells.

$$p(z) = p_0 + g \int_0^z \rho(z)dz$$

Temperature affects the minimum storage pressure because the higher the temperature, the more likely creep and closure will occur. Higher temperature also affects the maximum allowable diameter of the cavern. It is more difficult to calculate the minimum pressure for inhomogeneous salt.

Maximum safe operating pressures for a reservoir depend on four primary factors:

- The mechanical properties of the reservoir and overburden
- The in situ stresses and fracture pressure in the reservoir

- Stresses induced in the reservoir by gas cycling; and,
- Stresses induced in the caprock material by gas cycling

From SMRI research work on the determination of the maximum internal cavern pressure for gas storage caverns it is known further, that the shape of the cavern's roof has a major influence.

To have safe gas storage the maximum allowable operating pressure (MAOP) is a percentage of the calculated rock pressure.

For safe gas storage in salt cavern the rule of thumb are the following equations in bar.

For the rock pressure: $\qquad$ P rock = 0.22 * depth

For maximum gas pressure: $\qquad$ P max = 0.18 * depth

Minimum gas pressure: $\qquad$ P min = 0.3 * P max

In the Eneco case I took a percentage of 10 percent:

Cavern	Depth (m)	Rock pressure (bar)	Max gas pressure (bar)	Min gas pressure (bar)	Calculated rock pressure (bar)	Calculated max gas pressure (bar)
Epe S81	1357	298.5	244.3	73.3	278.3	250.5
Epe S82	1283	282.3	230.9	69.3	270.1	243.9
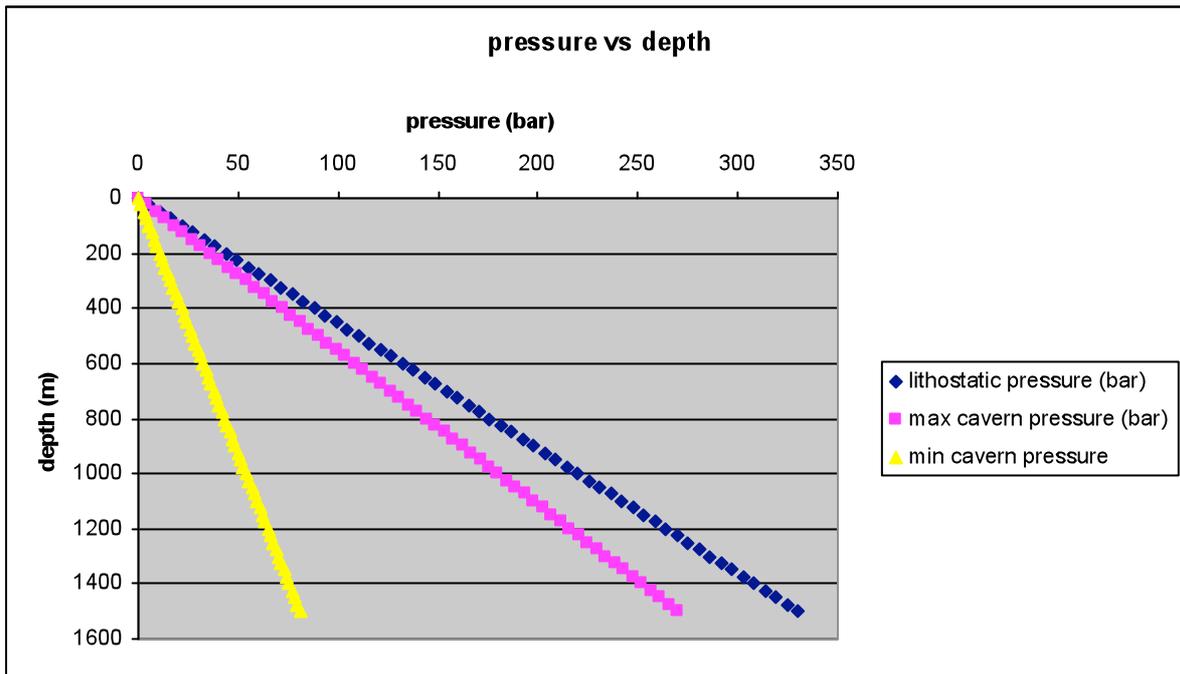
Figure 14: pressure vs depth

For natural-gas storage, little brine is left at the bottom of the cavern. Gas pressure builds up when gas is injected and drops when gas is withdrawn. The danger for the environment can only be caused by wellhead failure, the gas volume of the full cavern would be expelled but takes several weeks, depending upon the initial gas pressure and head losses through the well. The gas cloud would move upward rapidly and disperse in the higher atmosphere. In some cases, the cloud could kindle at an early stage, but, if it does not, the risk of explosion would be small (Berest et al.)

4.8 Caverns abandonment

When the caverns will not be used any more, the cavern will usually be filled with brine. This is maybe the case for the Eneco caverns in 2030. Cement will be poured in the well and casing. After the cavern is sealed, the brine pressure will build up. The final value of cavern brine pressure is the most important.

As salt creeps toward a cavern, the cavern brine is forced in a smaller room, and its pressure builds up in a sealed cavern. After some time, the process becomes slower as the cavern pressure becomes higher, ultimately stopping when the cavern pressure is equal to geostatic ($P_i = P_¥$), after several centuries (Wallner and Paar, 1997)

The authors Bérest and Brouard, fear that brine pressure eventually reach a figure larger than the geostatic or lithostatic pressure, leading to hydrofracturing. Which can lead to upward brine flow through fractures and polluting drinkable water. The main factors of brine pressure build up are cavern compressibility, salt mass creep, salt permeability, leaks and brine thermal expansion.

5 Conclusions and recommendations:

The geotechnical design of gas storage cavern in rock salt is a complex task. As there are no general accepted design criteria available, a lot of different design methods do exist all over the world. It is a general understanding that the demands of static stability and tightness as well as public safety at the surface must be guaranteed by the design and the operation of these geotechnical constructions.

Stress fields caused by the presence of a cavern result in creep at any shear stress and any in situ temperature. Cavern volume reduction with time accompanied by surface subsidence is an important consequence. By keeping the pressure close to lithostatic and the shear stresses close to zero, the effect of those are slowed down. Because it is not favorable there has to be a healing period every while.

In the course of solution mining operations for constructing a natural gas storage cavern, a considerable amount of thermal energy is withdrawn from the salt rock. The reason lies in the use of a cold leaching fluid and the consumption of energy in the dissolution of salt. During gas withdrawal, the gas cools down due to expansion. This cooling effect is partly compensated by heat supply from the rock. The more the rock is already cooled by the solution mining process, the less favourable are the conditions with regard to gas withdrawal. These conditions have to be held in mind with regard to formation of gas hydrates.

The problem of water evaporation from the cavern sump into the stored gas has so far not been solved. That is why the Eneco facility must be equipped with gas drying system. If the gas contains too much water there is a possibility for formation of gas hydrates.

Gas hydrates:
- Avoid operational conditions that might cause formation of hydrates such as pressure and temperature

- Temporarily change operating conditions in order to avoid hydrate formation;

- Prevent formation of hydrates by addition of chemicals or inhibitors

The position of the cavern is important for the stability of the cavern. There are many parameters that play important roles, including roof shape, distance to the top of the salt formation, spacing between two adjacent caverns, and distance from the dome flanks.

Abandonment of the caverns has to be studied more closely, especially the hydrofracturing feared by the authors Bérest and Brouard and Wallner and Paar.

Cycles and storage parameters can be easily calculated by software specially designed for underground gas storage facilities. Like Salt Cavern Gas Storage Toolbox by Gas Technology Institute, Pipeline Research Council International and Technical Toolboxes it contains a mathematical simulator to create alternative detailed design simulations calculating transient wellhead pressures and temperatures, feasibility calculations for meeting potential gas nominations, hydrate formation restrictions etc I recommend Eneco to purchase this software tool to understand and use it for their gas storage project.

For further questions or recommendations the author will be grateful.

6 Data

Main Attributes	Metric Units
Installed max/planned/undeveloped Working Gas Volume	10^6 m³(Vn))
Cushion Gas Volume incl. inj. + indig.	10^6 m³(Vn))
Peak Withdrawal Rate	10^6 m³(Vn)/h
Nominal Withdrawal Rate	10^6 m³(Vn)/h
Last Day Withdrawal Rate	10^6 m³(Vn)/h
Injection Rate	10^6 m³(Vn)/h
Installed Compressor Power	(MW)
Areal Extent Storage Reservoir	(km²)
Minimum Storage Pressure @ Datum Level	(bar)
Maximum Allowable Storage Pressure @ Datum Level	(bar)
Initial Reservoir Pressure @ Datum Level	(bar)
Pressure Datum Level below Surface	m
Depth Top Structure/Cavern Roof	m
Maximum Depth of Storage Structure	m
Net Thickness	m
Porosity (average)	%
permeability	mD
Reservoir Temperature	(°C)
Cavern Height average	m
Cavern Diameter average	m
Distance between Caverns average	m
Convergence Rate of Caverns	%/ year
Total Convergence of Caverns	%
Gasquality H_{sup}	(kWh/m³)

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system	years	group	foundation	meter	
			Stratigraphy S81		
quartiar				5	1950
Lower Cretaceous	112 - 145,5		basissandstone	203,2	2250
		middle buntsandstein		299	2230
			solling- hardegsen Folge	109,4	
			with Hardegsen sandstone	27,9	
			detfurth folge	81,7	
			With Clay	27	
			With sandstone	54,7	
			volpriehausen sandstone	107,9	
			With volpriehausen sandstone	30,3	
		unterer Bundsandstein		359,7	2230
			Bernburg Folge	136,3	
			Calvorde Folge	190,1	
			zechstein ubergangsfolge	33,3	
Late permian	252	Zechstein Z4		6,9	2240
			pegmatit Anhydrite	1,4	
			Red salt Clay	5,5	
	253	Zechstein Z3		52,2	2240
			Upper Leine Anhydrite	3,6	
			Leine Salt rock	0,8	
			main Anhydrite	1,5	
			Platty dolomite	43,7	
			Grey Salt clay	2,6	
	254,5	Zechstein Z2		48,7	2900
			Basal anhydrite	31,1	
			Dolostone	16,6	
	256	Zechstein Z1		397,5	2168
			Upper Werra- Anhydrite	13,5	
			Werra Rock salt	368,3	
			Lower Werra Anhydrite	15,7	
	258				
			lithostatic pressure	27831480 Pa	

Stratigraphy S82					
system	years	group	foundation	meter	density
quartiar				5	1950
Lower Cretaceous	112 - 145,5		basissandstone	215,8	2250
		middle buntsandstein		311,9	2230
			solling- hardegsen Folge	109,2	
			with Hardegsen sandstone	27,6	
			detfurth folge	83,6	
			With Clay	27,1	
			With sandstone	56,5	
			volpriehausen sandstone	119,1	
			With volpriehausen sandstone	24,6	
		lower Bundsandstein		384,5	2230
			Bernburg Folge	153,7	
			Calvorde Folge	201,6	
			zechstein ubergangsfolge	29,2	
	252	Zechstein Z4		5,9	2900
			pegmatit Anhydrite	1,6	
			Red salt Clay	4,3	
	253	Zechstein Z3		41,1	2240
			Upper Leine Anhydrite	3,9	
			Leine Salt rock	1,2	2185
			main Anhydrite	0,8	2168
			Platty dolomite	33,5	
			Grey Salt clay	1,7	
Late permian	254,5	Zechstein Z2		49,4	2240
			anhydrite	24,6	2900
			stassfurt salt	3,8	2240
			Basal anhydrite	24,6	
			Dolostone	11,3	
	256	Zechstein Z1		324,4	2168
			Upper Werra- Anhydrite	14,9	
			Werra Rock salt	296,3	2168
			Lower Werra Anhydrite	13,2	
	258				
Breunese J.N et al.			lithostatic pressure	27013161 Pa	

Location wells