General Concept for the Abandonment of the Gas Storage Caverns of Gasunie at Zuidwending, The Netherlands

for:

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1 Introduction

Within the scope of the "Aardgasbuffer Zuidwending" project several caverns were constructed for the purpose of underground gas storage. For the post operation phase a cavern abandonment concept is required in order to demonstrate the technical feasibility to the authorities and to provide the costs and time, which are necessary for performing the required abandonment measures.

Cavern abandonment concepts shall comprise the following aspects:

- requirements of the Dutch State Supervision of Mines (SSM),
- general description of the technical concept for cavern abandonment, necessary measures to be taken and the possible impacts on the environment,
- site specific proof of the selected technical concept,
- site specific estimate of costs,
- application for permission,
- preparation for abandonment including on-site preparation and testing, and
- plugging and abandonment of the cavern and the well.

Besides the present study about the general abandonment concept of its Zuidwending gas storage caverns, Gasunie asked for the prediction of surface subsidence in the post operation phase of these caverns. This is presented in a separate study.

DEEP. Underground Engineering (DEEP.), Bad Zwischenahn, Germany, was appointed by Gasunie Zuidwending B.V (Gasunie), The Netherlands, to prepare a conceptual study for a general abandonment procedure for the Gasunie owned caverns at Zuidwending. This study covers the first two items of the above stated list. The purpose of this conceptual study is to provide Gasunie with a road map for cavern abandonment that can be used internally (e.g. for liability provisions) and externally (e.g. for information of the authorities). The proof of the long-term safety of the Gasunie Zuidwending caverns after plugging has to be investigated in proceeding detailed studies as well as the compilation of required activities (e.g. in-situ tests as proof of concept) and a detailed cost estimate for the whole program.

The Scope of Work of this study is presented in the following Chapter 2. The study was organized by DEEP. The 'Institut für Gebirgsmechanik' (IfG), Leipzig, Germany, contributed to the technical / rock mechanical part of the study, KBB Underground Technologies GmbH (KBB UT), Hannover, Germany, provided the technical concept study.

2 Scope of Work

The general background and the necessity for planning of the abandonment of salt caverns are given in Chapter 3.

Then the study continues with the description of different concepts for cavern abandonment, which are presented in Chapter 4, where the key points of the legal requirements for cavern abandonment in The Netherlands are briefly reviewed also. Thereafter, different geotechnical abandonment concepts are presented. At the end a recommendation is given for a suitable abandonment concept of the Zuidwending gas storage caverns.

The recommended abandonment concept is described in greater detail in Chapter 5, while considering the following special items

- principal description of the concept,
- rock mechanical concept,
- required technical measures,
- requirements prior to plugging and abandonment, and
- costs and time.

The study ends with a summary of results and the conclusions given in Chapter 6.

3 General Background

Currently, there are several thousand caverns that were created by solution mining as salt storage facilities (THOMS AND GEHLE [2000]) worldwide. These caverns were created for the storage of gaseous and liquid hydrocarbons as well as for brine production. They show geometrical volumes, which range from a few thousand to several millions of cubic meters, while their depth location vary between a few hundred up to 3,000 meters.

Literature is available on all aspects of solution mining, storage operation and safety issues above and below the surface. Particularly, from the Solution Mining Research Institute (SMRI), known since its foundation in 1958, a number of publications consider the technical, geomechanical and safety issues associated with salt caverns. In the past the number of caverns that are used in an industrial scale for gas storage and brine production grew, while the cavern size was increased and they were located at greater depth. But, the lifetime of caverns is limited, and in consequence attention was drawn to abandonment concepts for salt caverns.

After finishing operations of gas storage caverns in rock salt they cannot left in the status as they are. Similar to conventional salt mines they have to be abandoned according to a concept that ensures long-term stability of the surrounding rock mass as well as long-term safety of the environment.

If at the end of storage operations the gas would be withdrawn completely and the caverns would be left under atmospheric pressure, this would lead to a time dependent progressive failure of the rock salt mass. This process would start at the cavern walls until the whole cavity would be filled with salt rubble. However, this cannot be permitted because of stability and safety reasons, if the main elements of the load bearing system are affected. Even if this self-filling method could be tolerated, the stabilizing support of this bulked deposit of salt material in the former cavern has to undergo compaction over a relative long period, before a substantial support (backpressure) can be provided.

As a conclusion, stabilizing measures have to be applied in order to guarantee a long term support to the cavern walls by an adequate internal backpressure. Further, this supporting pressure has to be in place within a relative short period of time after the end of storage operations in order to prevent the cavity from high convergence rates and thus high subsidence rates. Thus, backfilling comes into account. In principle solids, liquids or pressurized gas may be suitable back-filling materials. Their pros and cons are discussed in greater detail in Chapter 4. However, the essential questions to be answered with regard to the selected backfill material and procedure shall be discussed shortly in this chapter.

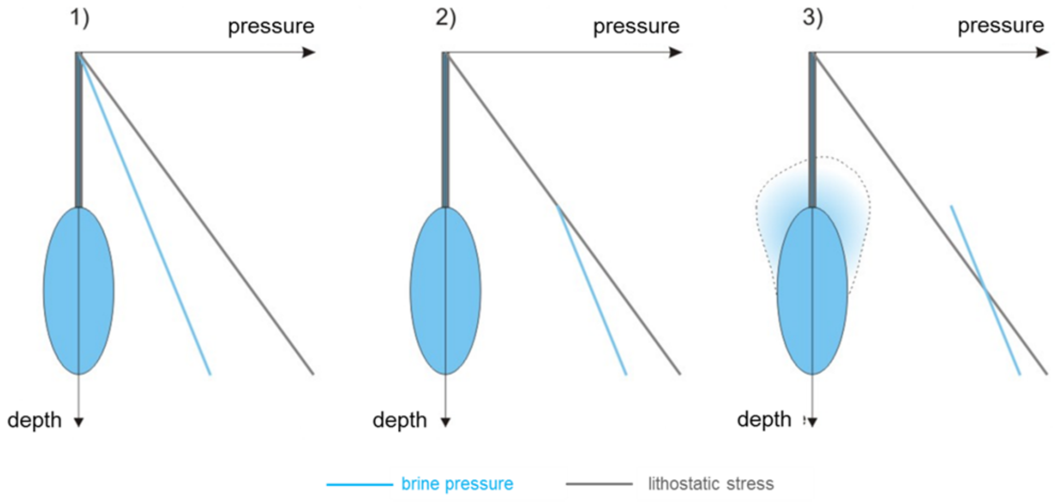
Using gas as supporting medium for the cavern walls will have to be restricted to air or nitrogen. Compressed air will be the cheapest medium. If the cavern will be plugged at high internal pressures, cavern convergence rate can be kept low after plugging, but the cavern pressure always has to be kept below a certain maximum pressure to avoid macro-fracturing.

In the public often backfill with solid materials like gravel or sand is recommended, because incompressible solids would prevent from total convergence of the cavern and will lead to less subsidence. Practical experience with backfill in salt mines however, shows that a compaction phase is necessary before a noteworthy backpressure can be achieved. The main drawback however, why solids can realistically not be considered as backfill material, is that for many caverns, because of their big volumes of up to more than 1 million cubic metres, it will be practically an unsolvable problem with the supply, the transportation and the injection through a small diameter but extremely long well, which has further to be managed within a relative short time period.

This leaves the alternative of back-filling with liquids – brine or freshwater, which represents a method that has been applied for abandoned salt mines worldwide since many years and still is applied. However, special aspects have to be considered for a plugged brine filled cavern as it is illustrated by *Figure 3.1* and described in the following.

Initially after filling the cavern with brine and plugging the well the internal pressure will be equal to the pressure of the brine column to surface (see sketch (1) of *Figure 3.1*). Since the brine pressure in the cavern is lower than the lithostatic pressure of the surrounding salt rock mass, the salt will creep and because of the plugged well the brine pressure will be increased. As shown in the below sketch the brine pressure (blue line) will move to the lithostatic pressure (black line) and may after some time even exceed the lithostatic pressure in the top part of the cavern, see situation at the right hand side.

Figure 3.1 *Pressure build-up in a plugged brine filled cavern*



In the early years of cavern construction there it was feared that this situation might lead to macro-fracturing into the surrounding rock salt mass with subsequent uncontrolled leakage of brine. Comprehensive research that was performed by the industry in the Netherlands, France, and in Germany, by the Solution Mining Institute and by rock mechanical institutes worldwide however, have demonstrated meanwhile that no fracturing and no uncontrolled leakage will occur, if the abandonment measures will be designed in a suitable way. In this regard in-situ tests with caverns in Etzel (see STAUDTMEISTER ET AL. (1994)), Etrez (see BÉREST ET AL. (1999)), Staßfurt (see BANNACH ET AL. (2009)), Carresse (see BROUARD ET AL. (2006)), Bernburg (see BRÜCKNER ET AL. (2003)) have to mentioned as well as laboratory tests, e.g. salt permeability testing under abandonment conditions (see BÉREST ET AL. (2001)).

This is the reason why the cavern abandonment concept recommended in this study for the Zuidwending gas storage caverns is based on brine-filling and plugging.

In Chapter 4 the alternatives for cavern abandonment will be discussed in greater detail and in the context of the so far performed research work. These introducing remarks were intended for giving a general overview.

4 Concepts for Cavern Abandonment

The recommended abandonment concept has to be in line with the Dutch legislation with regard to mining (Mining Act) and the protection of the environment (Environmental Management Act). With regard to these laws the technical feasibility of the cavern abandonment concept has to be generally demonstrated. After a short review of main clauses of the legal framework different technical alternatives for cavern abandonment will be discussed. At the end of the chapter a recommendation for a suitable overall concept for cavern abandonment of the Zuidwending caverns is given.

4.1 Short overview of legal requirements in The Netherlands

The requirements for cavern abandonment have to be in compliance with the Dutch law. Within the scope of this study it is not intended to discuss this from the legal aspect but, to highlight some particular aspects of the Mining Act, the Mining Decree and the Mining Regulations of the Netherlands that directly influence possible abandonment procedures.

In the Mining Act article 44 demands for the removal of the mining installation that is no longer of use. However, the Minister may limit this to a certain depth under the soil of surface water. This would mean that cemented casings will not have to be removed at full length.

More precise directives are given in the Mining Decree of the Netherlands. Article 39 demands for a closure plan, which has to be delivered by the operator to the ministry within one year after totally or partially finishing mining works. In Article 40 the requirements on the closure plan are specified in greater detail. It has to address a concept or description of

- the way the material belonging to the mining works will be removed,
- the waste substances present at the mining works and their intended purpose,
- the measures to prevent damage,
- the measures to be taken the site into its original state as much as possible.

If the original state cannot be restored a description of the status, in which the mining work is left behind has to be given. A time table has to be given, addressing start of closure activities and duration.

Further rules for the closing plan may be set by ministerial regulation.

The Mining Regulations address the decommissioning of wellbores. Article 8.2.4.1 specifies the contents of the work programme for decommissioning. Among others special items are mentioned as the reason for decommissioning, the expected maximum pressure in the closed well, the description of safety of the closed well and a precise documentation. Detailed rules are given further in Part 8.5, where the well shall be filled with fluid, a durable plug set and tested, and casings have to be removed up to at least 3 m below ground level. Within the remaining cemented casings a cement plug of at least 100 m or a combination of a mechanical plug plus 50 m cement plug shall be installed.

A comparison with laws and regulations in Germany shows a similar procedure. An abandonment plan has to be provided by the operator. The geotechnical concept for sealing the well(s) has to comply with the applicable mining laws Although the currently valid directives for Lower Saxony in §35 of the BVOT do not specify any details for abandonment of wells but a safe sealing and protection against interference by unauthorized persons as well as a monitoring programme for wells still under pressure, more detailed information can be drawn from the directive ‘Richtlinie über das Verfüllen auflässiger Bohrungen’, dated 29.07.1998. This directive demands for a cement plug of at least 100 m extending into the salt (if explored) and 50 m into the surrounding rock. The geomechanical concept has to show the long-term stability and safety of the environment. Actually, such a geomechanical concept is based on the state of the caverns, considering:

- a tight borehole sealing,
- an integrity test at the main sealing element, and
- the requirements for special sealing sections, called “besondere Verfüllstrecken” in the regulations for plugging and abandonment of deep well.

In both countries a comprehensive concept is demanded to show and test the technical tightness of the plugged well and geological tightness of the cavern in order to achieve the goals of long-term safety and protection of the environment.

4.2 Review of cavern abandonment concepts

Concepts for cavern abandonment have been discussed for many years, although only a few caverns were plugged and abandoned until now. Different concepts for cavern abandonment were proposed as a result of theoretical studies and in-situ tests.

General differences of the concepts originate from the kind of fill medium and the plugging concept for the well. Principally, solids and fluids can be considered as appropriate filling media for cavern abandonment. Alternatives are shown by *Figure 4.1* to *Figure 4.2* for air-filled and brine-filled caverns (with or without additional solids). Cavern convergence in the post operating phase is an important issue.

As shown in *Figure 4.3*, cavern convergence in the post filling phase is faster for an air filled cavern (curve I) compared to a brine filled cavern (curve II). A substantial reduction in the convergence rate can only be achieved, when the well is plugged (curve IV). Then the creep deformations of the salt rock mass surrounding the cavern will rapidly slow down because of the pressure built-up in the cavern. This means, plugging a brine-filled cavern reduces the convergence rate to very small values.

Figure 4.1 *Cavern abandonment with air fill at atmospheric pressure (Crotogino et.al. [2006])*

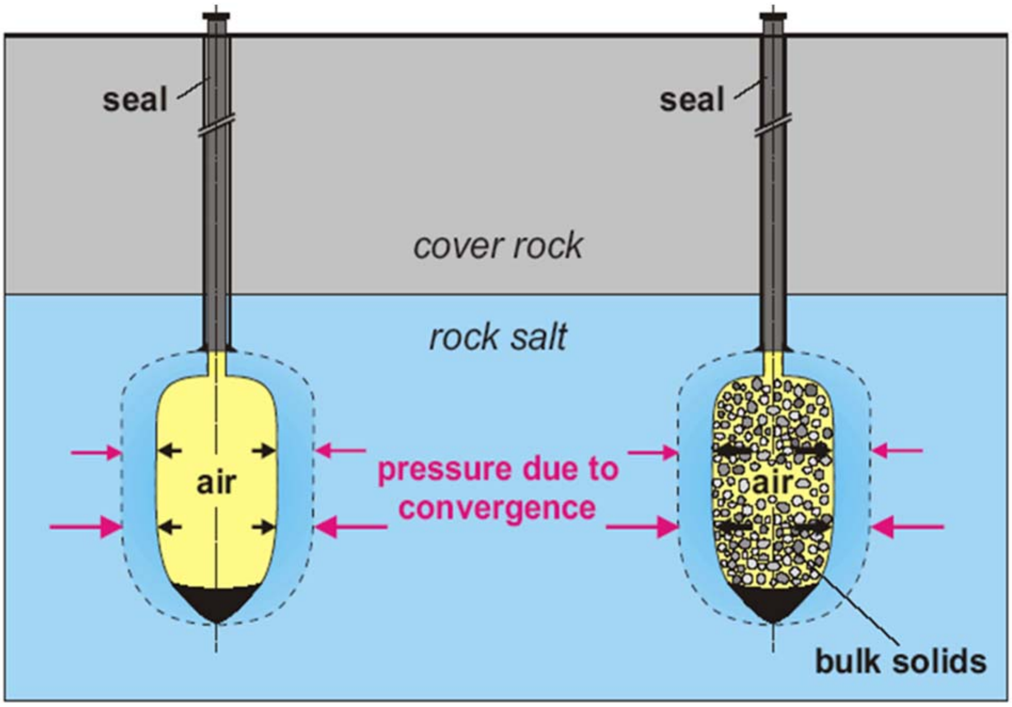


Figure 4.2 *Cavern abandonment with brine fill at brine pressure less than maximum pressure (Crotogino et.al. [2006])*

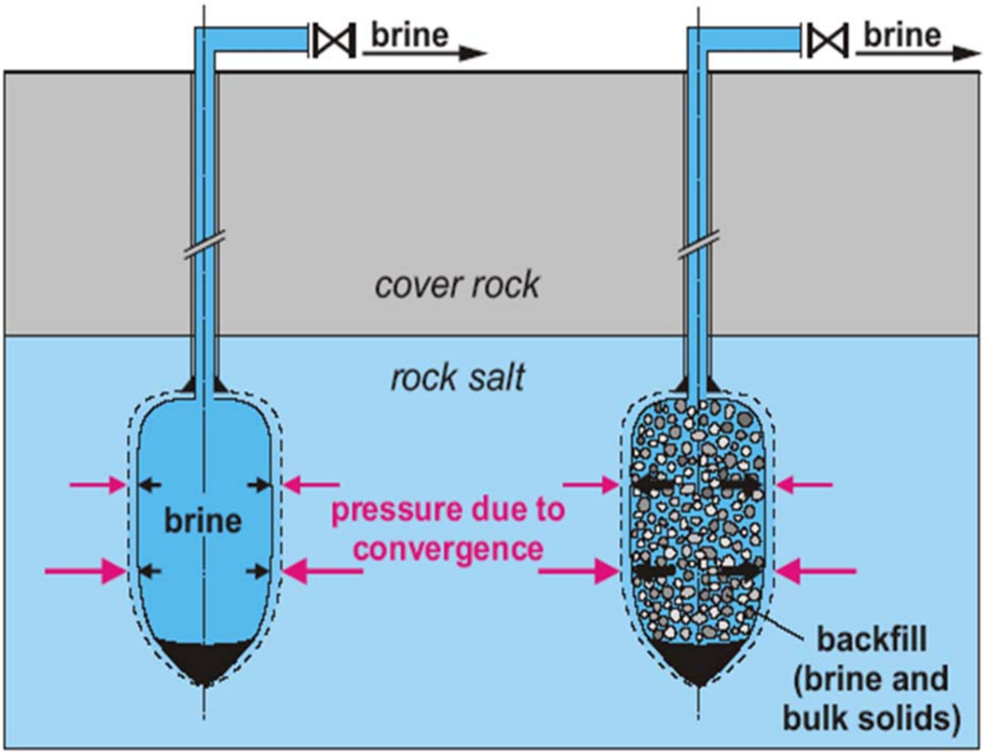
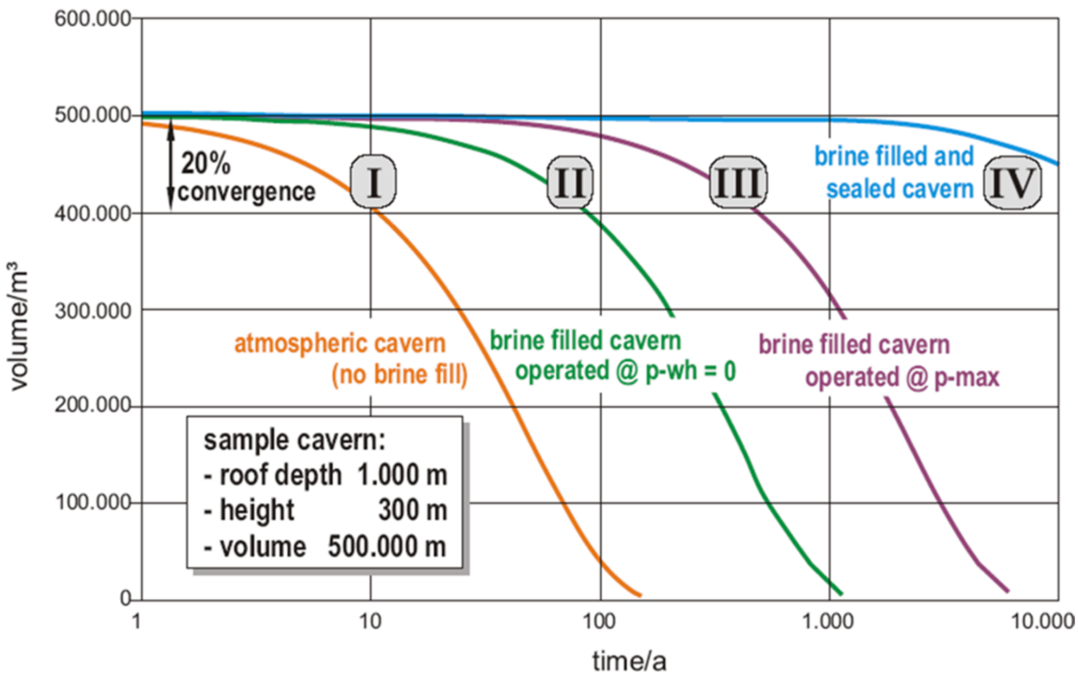


Figure 4.3 *Cavern volume losses after plugging (Crotogino et.al. [2006])*



Practically solid fills can be disregarded for most caverns. Because of the relative big volumes of the caverns the necessary amount of filling material will not be available within the relative short period of time that is available for building up an adequate back-pressure in the cavern. Furthermore, if waste materials are considered, additional legal and environmental requirements have to be complied with. For the abandonment of salt mines flooding is known as an appropriate concept for filling and stabilizing in time. This concept has been investigated in great detail in the recent past for the abandonment of salt caverns and could be shown as a safe and suitable concept.

If a salt cavern is filled with brine and plugged, the pressure built-up process after plugging has to be considered especially for cylindrical cavern shapes. As mentioned in several studies and technical papers there will be an on-going process of creep closure in the deeper part of a cylindrical cavern, whereas in the roof part of the cavern the brine pressure has already reached the lithostatic stress. This leads to the question, which brine pressure level can be permitted (tolerated) in the upper most part of the cavern without losing tightness of the surrounding rock mass, i.e. the initiation of macro-fracs has to be excluded.

In this regard the cavern industry performed various in-situ tests. The Etzel K102 test in the mid of 1990s revealed that the internal cavern pressure could not be increased above a certain level. It was concluded that above a certain pressure level brine infiltrates on a micro-scale basis into the salt rock mass. This observation was made also in other in-situ tests (see BÉREST ET AL.[1998], BROUARD ET AL.[2006], BANNACH ET AL.[2009], BRÜCKNER ET AL. [2003]).

Beside the pressure built-up in a plugged cavern, temperature induced pressure increases have to be taken into account, if the temperature of the brine-fill is not in equilibrium with the rock mass temperature. This means, a waiting time for brine warming-up has to be considered.

In the late 1990s the Solution Mining Research Institute (SMRI) started a comprehensive research project in order to develop a concept for the abandonment of salt caverns. This research project was called ‘Cavern Sealing and Abandonment’ (CS&A) programme. Within the scope of this project abandonment of brine-filled and plugged cavern was studied in greater detail. Beside laboratory tests for the tightness of the casing shoe of the last cemented casing and the general technical concepts for plugging the well, the pressure built-up in the cavern was investigated in by coupled process with micro-scale brine infiltration into the surrounding rock mass as well as brine warming. It was concluded that for an evaluation of the abandonment concept for a brine filled cavern five different mechanisms have to be considered according as listed in *Table 4.1*.

Table 4.1 Processes influencing the fluid pressure in a sealed cavern in salt acc. to RATIGAN [2003]

Mechanism	Influence on Fluid Pressure	Time Scale
Salt creep	Monotonically ***increases*** cavern fluid pressure at a decreasing rate	The majority of pressure increase occurs within tens of years after cavern sealing.
Heat transfer between cavern fluid and surrounding salt rock mass	Heating of the cavern fluid causes cavern fluid expansion and ***increases*** cavern fluid pressure at decreasing rate	The majority of pressure increase occurs within tens of years to many tens of years after cavern sealing.
Dissolution of salt in the cavern fluid	Increases cavern volume and decreases fluid temperature which in turn causes a ***decrease*** in fluid pressure	The majority of pressure decrease occurs within months after cavern sealing.
Cavern fluid transport into the formation	Results in cavern fluid pressure ***decrease***	May continue indefinitely.
Cavern fluid transport through sealing elements (plugs) and/or casing cement	Results in a cavern fluid pressure ***decrease***	May continue indefinitely.

The impact of post-filling dissolution of salt in brine can be reduced, if nearly saturated brine is used for filling. Prior to plugging leaks have to be excluded by tightness testing (e.g. of the cementation of the last cemented casing). Furthermore, the implementing of an appropriate design for the decisive plug has to ensure for the long-term tightness. Three options for this design of a decisive plug element were suggested by CROTOGINO ET AL. [2006] with regard to its location:

(1) decisive plug in the cased hole,

(2) decisive plug in the cavern neck, and

(3) decisive plug above the casing shoe of the last cemented casing in a milled and under-reamed window section.

If leaks can be excluded by the above measures, then the processes that require consideration within the evaluation of a cavern abandonment concept are salt creep, heat transfer and fluid infiltration.

Main conclusions from the research project were summarized as follows by RATIGAN [2003]:

- In the absence of brine thermal expansion, the vast majority of solution-mined salt caverns can be sealed and abandoned without concern for salt fracture generation or significant brine migration from the cavern.
- Prior to cavern sealing, all caverns should be kept open as long as possible and practical to ensure a minimization of the temperature difference between the salt and the internal cavern brine.
- Casing shoe integrity tests should be performed prior to sealing to ensure this potential pathway has maintained integrity comparable to that required during the cavern operational history.
- Tall caverns and/or caverns that must be sealed before thermal equilibrium is approached require a case-by-case evaluation of sealing strategy.
- Salt permeability at brine pressures approaching the confining salt stresses is an extremely strong function of the difference between the salt total stress and the brine pore pressure. As this difference becomes small or slightly tensile, salt permeability increases significantly (i.e., many orders of magnitude).

Related to this major research project three main items were investigated:

- proof of concept by in-situ tests,
- measures for reducing of the waiting period for brine warming, and
- evaluation of the long-term infiltration/pressure build-up process.

In-situ tests in Etrez (see BÉREST ET AL. [1998]), Bernburg (see BRÜCKNER ET AL. [2003]), Carresse (see BROUARD ET AL. [2006]) and Stassfurt (see BANNACH ET AL. [2009]) gave a proof of the general SMRI concept. And the whole concept was principally reviewed by Duquesnoy [2011].

As possible solutions in order to overcome the initial waiting period small gas injections before plugging or brine warming before filling were suggested as practical methods (see BROUARD ET AL. [2007]).

In the meantime the pressure build-up/brine infiltration process was studied in greater detail as well as in the laboratory and by numerical simulation techniques in order to answer the question, if this process is on-going or will come to a halt. This was done especially at IfG and the Technical University of Clausthal (TUC), Prof. Lux, Germany.

In laboratory tests it was observed that low permeability is induced in the salt when the fluid pressure comes close to the confining pressure. In *Figure 4.4* the results of such a permeation experiment by IfG is represented, which clearly shows the onset of permeation, if the fluid pressure exceeds the matrix pressure. At the same time it was observed that pathways start to open at this point of the experiment at a micro scale (see right part of *Figure 4.4*). Similar observations were made at TUC (see *Figure 4.5*), were the fine dispersed infiltration pathways were made visible after a permeation experiment with high fluid pressures. Although the induced low permeability can be increased by orders of magnitude with higher fluid pressures the absolute value remains relatively small (not comparable with porous rocks). However, pathways are created or opened up at microscale, along which the brine fluid migrates into the salt. In the original SMRI concept a Darcy flow was assumed because of at that time missing experiments in the laboratory or in-situ. In the meantime research progressed, especially by the investigations of IfG and at TUC.

Figure 4.4 *Generation of salt permeability driven by fluid pressure (lab-testing results of IfG)*

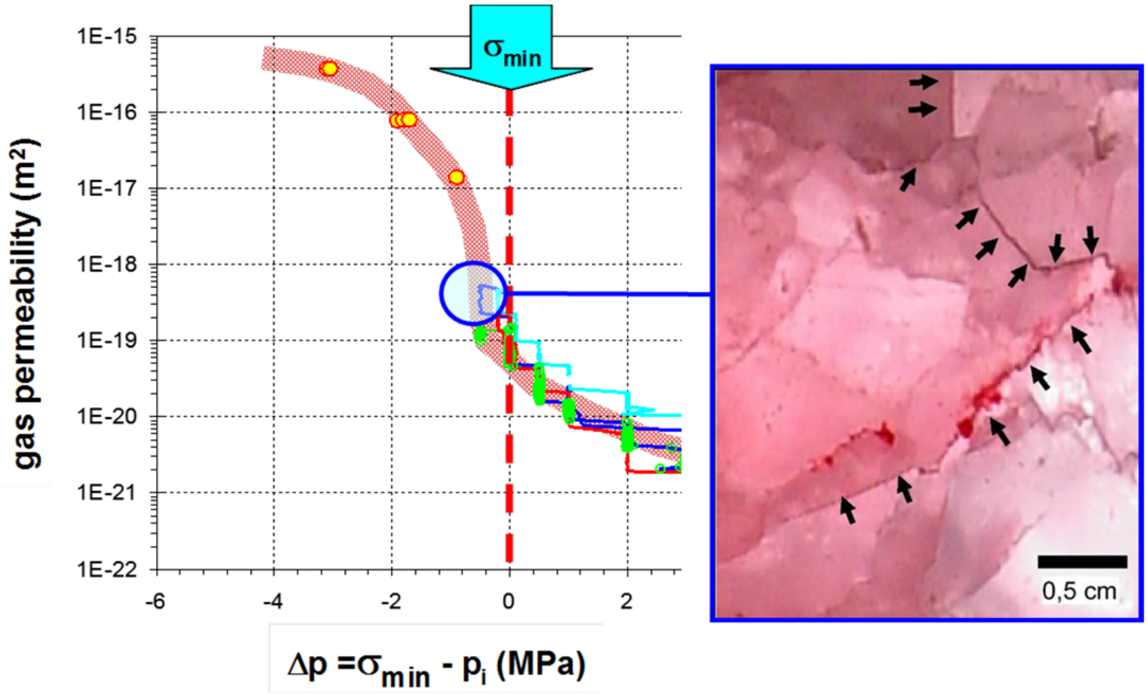
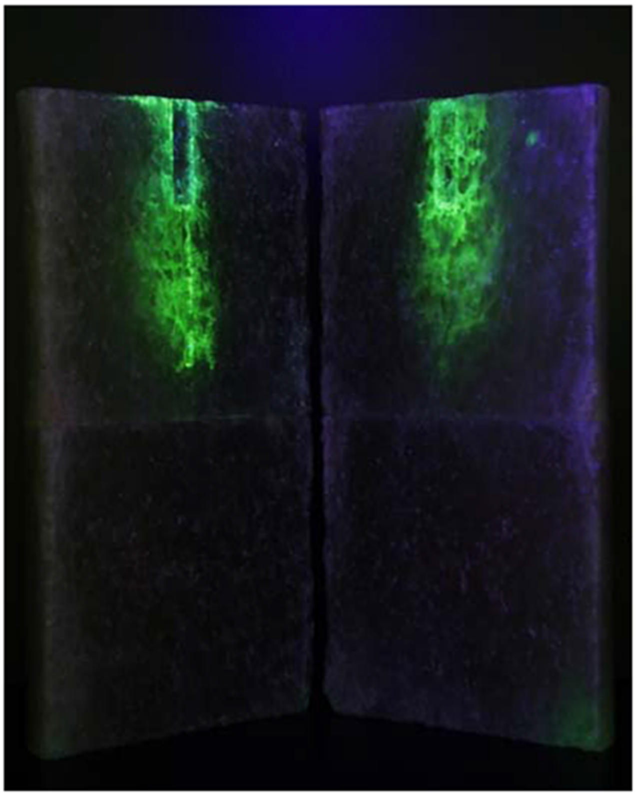


Figure 4.5 *Fluid infiltration test with a salt core with high fluid pressures (test experiment performed at TUC, Prof. Lux)*



By incorporating these new results from laboratory experiments both research groups could show, by the help of numerical simulations, for the long-term infiltration process of brine that this is a very slow process transporting very small fluid volumes. In the long-term the preferred propagation of this process will be vertically (upwards) irrespective of the assumed transportation mechanism either based on induced percolation or micro-permeability. Currently it is not clarified, if for tall cylindrical caverns this infiltration process will come to a halt. In case brine might reach the top of salt, this will be not before many tens of 10,000 years, while the volume rate will be very small (see WOLTERS ET AL. [2012] and MINKLEY ET AL. [2013]). However, further research and in-situ tests may show that due to frictional effects at micro-scale the infiltration process will come to halt.

4.3 Conclusion and recommendation

When comparing the abandonment concepts for caverns, which are based on brine-fill or solid-fill, the necessary backpressure for stabilisation can be provided in a brine-filled cavern within shorter period of time, because brine or water will be available by an appropriate amount and within the limited time scale. Further, there will be no waiting time for compaction with brine-fill. However, there are two drawbacks of the brine-filled abandonment concept:

(1) It has to be waited for the warming-up of the brine until nearly formation temperature is reached, before the decisive plug can be set. This has to be waited for in order to prevent from temperature induced pressure increases in the plugged cavern that cannot be compensated.

(2) It has to be demonstrated, especially for cylindrical caverns, that the pressure increase in the upper part of the cavern can be compensated by a brine infiltration process into the rock mass and that this infiltration will be in compliance with the requirements for the environmental safety.

In recent research works as well as in-situ tests and laboratory experiments it could be shown that the pressure increase due to creep can be balanced by a decrease of pressure due to infiltration of brine into the salt rock mass. Both processes are extremely slow, i.e. in case brine will ever infiltrate the salt as far as to the top of salt, this will last several ten thousands of years or more and the volumes transported are very small.

The temperature balancing problem can be mitigated by just waiting or e.g. pre-heating of the brine before filling the cavern.

Based on these recent improvements the abandonment concept of filling with brine and then plugging the cavern can be regarded as a concept that meets the requirements on long-term stability and safety. However, this has to be demonstrated in a detailed geotechnical study considering the individual characteristics of the cavern to be abandoned and shown for a reasonable period of time.

5 Description of the Selected Abandonment Concept

The recommended abandonment concept with a brine filled cavern is presented in greater detail by describing the general procedure, the rock mechanical concept, and the required technical measures for plugging. An outline of necessary measures that have to be taken prior to (e.g. sonar surveying, testing programme, etc.) and after plugging (e.g. surface levelling), will be presented in combination with a prediction of the necessary time period.

Required financial provisions will not be given quantitatively. However, a list of the main items that have to be taken into account will be compiled.

5.1 General description of the concept

Main phases of the cavern abandonment process are described by CROTOGINO AND KEPPLINGER [2006]. According to them the following phases have to be performed at the end of cavern operation:

- Preparations for abandonment
- Replacement of the product by injection of brine or water (w/o pre-heating)
- Performing measurements and in-situ tests
- Waiting for temperature balancing between fluid fill and rock mass
- Abandonment by plugging the well
- Post abandonment observations

5.1.1 Preparations for abandonment

The abandonment plan, which is mandatory for the permitting process, describes the planed procedures.

The planned design for plugging and sealing of the well(s) has to be presented as well as the results of the geotechnical/rock mechanics study on long-term tightness and stability of the sealed cavern. Occasionally a hydrogeological study may be necessary in order to check possible influences of the abandonment on the long-term water management. Necessary measurements prior, during and after abandonment, if necessary, have to be addressed. Basic data about the cavern(s), which are intended to be abandoned, such as volume, depth location, characteristics of the well completion have to be compiled. The time table for the abandonment process has to be shown.

Finally a risk assessment has to be carried out, in order to find out, if the goals for long-term stability and safety of the environment can be reached.

5.1.2 Replacement of the product by brine or water

Before replacing the product(s) in the cavern, a sonar survey should be performed. As replacement fluid brine or freshwater can be used. The procurement of a sufficiently high amount of fluid has to be ensured. If freshwater will be used, a leaching analysis should be made. After finishing the replacement procedure a final sonar survey is recommended.

The gas removal should start with decreasing the gas pressure to the minimum allowed pressure. In case of tubing mounted subsurface safety valve this will be deactivated before the brine injection string can be snubbed in. Brine filling then can start until all gas is squeezed out of the cavern. As practically the gas cannot be squeezed out totally, the last remains of gas are released by burning it in a flare, which has to be installed on site before the filling process starts. By injecting nitrogen in the very last phase of gas displacement, it can be controlled that the natural gas is practically removed from the cavern. The cavern is then under brine pressure and the brine injection string can be pulled out before the gas completion can be removed. Removal of gas completion may be carried out later depending on the possibly necessary tests in the following phases.

A casing inspection and cement bond log should be run in order to check and document the status of the last cemented casing. If the cemented casing will be part of the long-term tightness concept of the decisive plug (as discussed in Chapter 5.4 as option (1) for plugging) a tightness test must be performed.

5.1.3 Performing measurements and in-situ tests

As in the beginning the temperature of the brine will be lower than the rock mass temperature, the waiting period for brine warming-up can be used for in-situ testing of the cavern, if required. The results will give a proof of the geotechnical abandonment concept.

In minimum a final sonar survey is recommended in order to have secured information about the final cavern volume. Temperature measurements will be helpful for the decision when to plug the cavern.

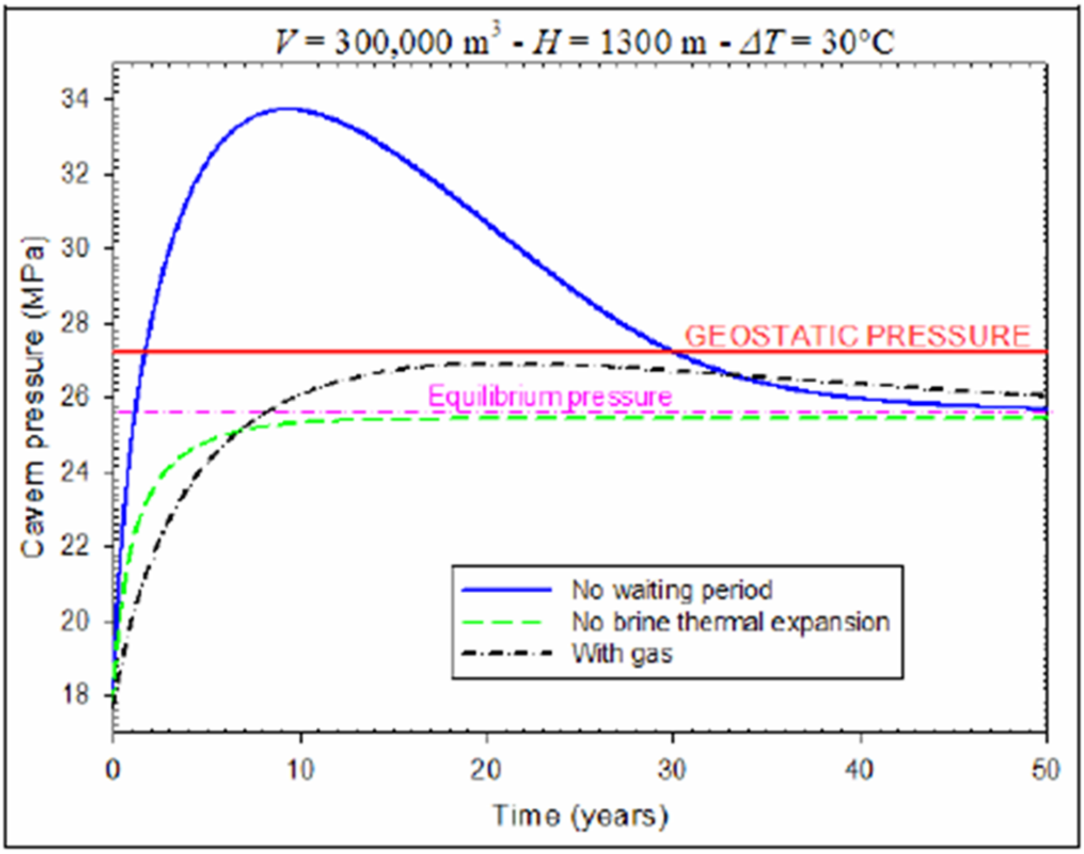
For the first cavern to be abandoned in a salt deposit, a preliminary abandonment test could be performed in order to confirm the validity of the abandonment concept and to gain additional specific data from the location such as cavern compressibility, pressure increase rate etc.

5.1.4 Waiting for temperature balancing

An adequate balance of brine and rock mass temperatures is necessary in order to avoid thermally induced increases of the cavern pressure that are too high for guaranteeing the geological tightness. As a rule of thumb the increase of the brine temperature by 1 Kelvin leads to a pressure increase of 1 MPa in a plugged cavern. The acceptable brine temperature at point in time of plugging will be determined by the geotechnical study. Until this temperature is not reached, the cavern cannot be plugged. In this intermediate time between end of operation and abandonment the wellhead pressure has to be monitored and kept not higher than the allowed maximum cavern pressure. However, this waiting period can be used for testing and measurements as mentioned above. The results of these tests may improve the prognosis for the required waiting time.

There are options to reduce the waiting time for brine warming-up. One of these is to fill the cavern with pre-heated brine, which is an energy consuming and therefore expensive alternative. Another option has been proposed by BÉREST ET. AL. [2007]. By injecting a small volume of gas in the roof of the cavern before plugging, the high compressibility of the gas can be made advantage of in order to consume the expected pressure increases induced by brine warming-up. As shown in *Figure 5.1* for a cavern with a volume of 300,000 m³ (location at depth about 1,300 m, initial brine temperature 30 Kelvin below rock mass temperature) the increase of the cavern pressure due to brine warming-up could be reduced substantially, if a certain gas is additionally introduced in the cavern (comparison of blue line (only brine and no waiting time) with dash-dotted black line (brine-fill with additional small gas volume)). This option has not been tested for a longer period so far. Which option to select will be a case by case decision.

Figure 5.1 *Comparison of alternatives with respect to waiting time for plugging according to BÉREST ET. AL. [2007]*



5.1.5 Abandonment by plugging the well

The final step for abandonment can be made when all preceding steps were successfully carried out and the results of the in-situ tests confirmed the planned procedure. If still in place, the gas completion has now to be removed from the well.

A proper preparation of the well through cleaning is recommended before the decisive plug can be set – according to the selected plugging design – in the deepest part of the well, in the cavern neck or in a previously milled and under-reamed section above the last cemented casing shoe. The decisive plug seals the cavern from the well. Additional sealing element(s) will then be installed step by step. (see Chapter 5.4)

When all sealing elements are installed, the cavern pad area has to be re-cultivated. In principle this includes dismantling of the wellhead and other installations on the wellpad, cutting the casings adequately below surface and setting a concrete slab above and re-cultivation of the surface.

5.1.6 Post abandonment observations

Principally the abandonment concept intends to install a maintenance free technique. Therefore, post abandonment monitoring is not part of the concept. However, a surface levelling campaign should be carried out for purpose of documenting the actual situation after abandonment (conservation of evidence).

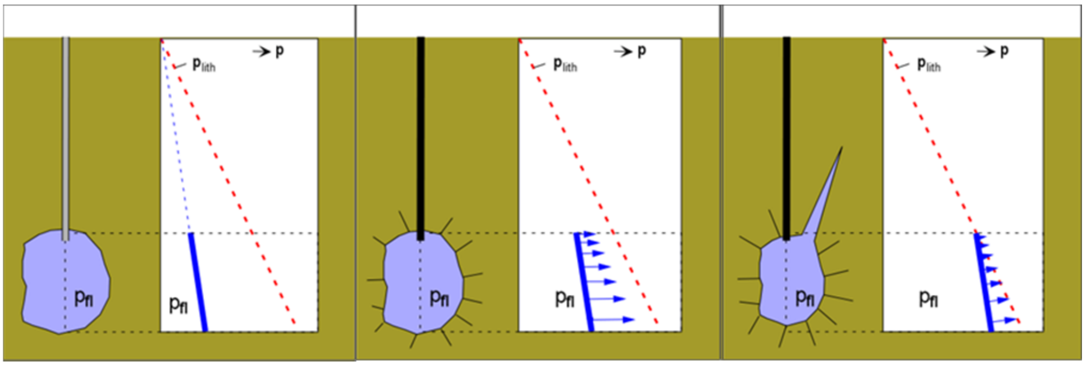
5.2 Rock mechanical concept

5.2.1 Background

The research activities conducted by SMRI in recent years on cavern sealing and abandonment (CS&A) revealed that it is basically feasible to permanently seal a brine-filled cavern in homogeneous salt structures like salt domes and thick bedded salt formations, where stability and integrity are ensured almost exclusively by the rock salt. In these cases and when complying with location-specific conditions no uncontrolled brine expulsion is expected to take place into the cover rock, into drinking water aquifers or at the surface.

As risk scenario related to the CS&A concept it is considered that a hydraulic pressure build-up in the sealed cavern by creep induced convergence and/or thermal expansion of the brine could lead to a fracturing in the rock mass of the hanging wall or in the bonded interface system of rock mass, cementation and casing above cavern. In this worst case rapid crack propagation into the overburden accompanied by rapid brine squeezing on newly created pathways in the hanging wall and the overburden is assumed, associated with a pressure drop in in the cavern.

Figure 5.2 *Fluid pressure in a brine filled cavern (left picture) and the pressure development after sealing (middle and right picture)*



According to *Figure 5.2* the fluid pressure in the cavern before plugging is determined by the brine column height. Gradually, the fluid becomes pressurized, because the confined fluid tries to expand as the temperature rises to equilibrate with the temperature of the surrounding salt rock mass. Meanwhile the volume of the cavern decreases due to the creep deformation of the salt, thereby compressing the confined fluid additionally. A pressure driven hydraulic fracturing may be induced due to the fact that the fluid pressure eventually approaches or even exceeds the lithostatic stress in the vicinity of the cavern.

In recent years studies have shown that although the fluid pressure approaches or even exceeds the minimum principle rock stress component, a macro fracturing of the rock salt and the associated creation of a pathway to the biosphere does not necessarily occur, providing that the pressure rise is not too fast. In this case, a locally limited zone of secondary permeability is formed close to the cavern contour, which limits and balances the fluid pressure build-up by a pressure-induced squeezing.

As stated above according to RATIGAN [2004] the pressure build-up in a plugged cavern results from the combination of five processes:

- salt creep,
- thermal expansion of the brine,
- transport of the brine into the formation,
- well leaks, and
- additional dissolution

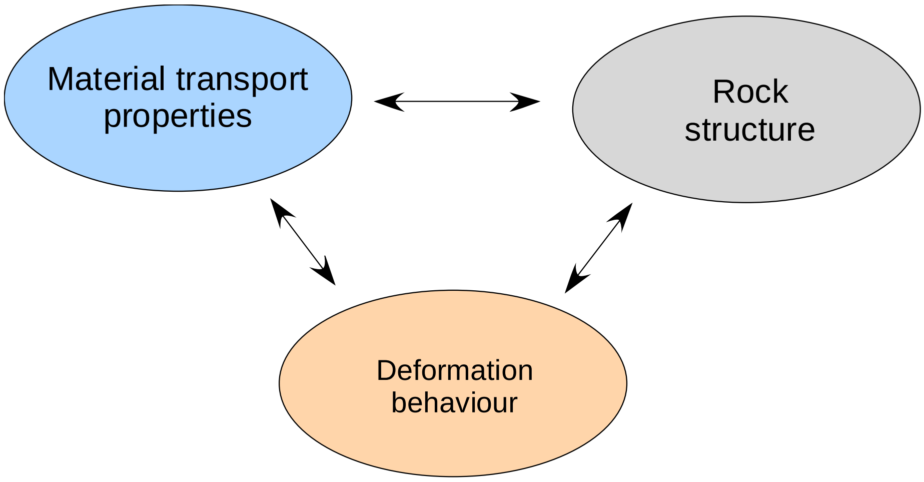
From the volumetrically point of view the five processes can be divided into two classes (see also ***Table 4.1***) those creating volume and those reducing volume. The most important problem relating to cavern abandonment is how to establish a maximum cavern pressure, while maintaining the structural integrity of the cavern sealing system, which is represented by the salt surrounding the cavern and the cement seals and plugs in the former cavern well.

Therefore, the functional interaction of the main processes with regard to cavern volume changes or cavern pressure evolution is described in greater detail in the following.

5.2.2 Pressure built up

A variety of petro-physical parameters have to be regarded, if the state variables for the system of an abandoned cavern (rock mass and fluids) have to be evaluated and assessed. As shown and summarized in *Figure 5.3* they are interconnected in a complex and interacting system comprising the rock mass structure, the deformation behaviour of the participating materials and the transport system.

Figure 5.3 *Relevant variables for a hydro-mechanical coupling of rock mass structure, deformation behaviour and material transport properties.*



Material transport	**Deformation**	**Structure**
permeability / porosity fluid pressure saturation by fluids percolation transport mechanism dissolution / precipitation	dilatancy compaction creep / failure effective stresses pore pressure bearing capacity	porosity pore geometry fissures / healing homogeneity saturation chemical reactions

For a sealed cavern, the conversion of volume changes into pressure changes is governed mainly by cavern compressibility. The main question is, whether an equilibrium state can be achieved, when minor rock salt permeability is taken into account.

This minor permeability has to be considered as a secondary induced permeability, which is created, when an increased fluid pressure leads to the onset of brine percolation. Percolation in the salt is representing a micro-scale transport process at the crystal boundaries, which before where tightly connected. The percolation process can be presumed in the rock salt, which covers a sealed and abandoned cavern especially at the top of the cavern and the hanging wall. Due to this process and due to an increased moisture penetration the strength of the affected rock salt may decrease, while the creep ability increases. Both effects together then lead to a reduction of the bearing capacity. This process again may cause an increased porosity by dilatant deformation.

Only the penetration of brine into the salt formation due to the percolation of rock salt counteracts the pressure build-up. With reference to a variety of in-situ and laboratory tests, rock salt permeability is very small and ranges significantly below 10^{-20} m^2. However, in case of small differences between overburden stress and fluid pressure percolation is sufficiently high to limit the pressure build-up and prevent the rock salt from self-fracturing.

In addition to specific studies on the permeability behaviour of rock salt and mechanic-hydraulic integrity of the casing-cement-rock salt bond in the laboratory, also extensive in-situ tests were carried out on sealed, brine-filled boreholes and caverns.

From the results of in-situ tests in borehole Etrez Ez58 and with caverns Etrez Ez53, Etzel K102, S102 Staßfurt and ‘Testkaverne’ Bernburg, the following findings can be summarized with special reference to the work of RATIGAN [2003] DUQUESNOY [2011], LUX [2005] und IFG [2005]

1. The various in-situ tests have consistently shown that, when pressure increase in the cavern takes place with low rates (Etzel K102: $\dot{p} \approx 0.02$ MPa/d; ‘Testkaverne’ Bernburg: $\dot{p} \approx 0.14$ MPa/d $\rightarrow$ 1.4 MPa/d) brine percolation into the rock mass is possible. This percolation of brine, however, is not based on a sudden macro cracking (hydraulic fracturing), but on an opening of grain boundaries.
2. The pressure level at which the brine percolation starts (change of the mechanic-hydraulic system at grain boundary scale –ultimate limiting mechanic-hydraulic state for the onset of percolation) is depending on the internal damage of the rock mass at the contour (extent of dilatancy zone) and the distribution of the minimum stress in the surrounding rock mass. In the case of contour damage or significant reduction of the minimum stress the percolation process starts at internal pressures that can be well below the lithostatic pressure at depth (cavern Etrez Ez53, ‘Testkaverne’ Bernburg). Only if the contour damage is negligible and the decline of the minimum stress due to a favourable cavity configuration is less pronounced, an internal pressure is reached approximately equal to the level of the lithostatic pressure or even higher (borehole Etrez Ez58, cavern Etzel K102 and Staßfurt S102).
3. The pressure increase in a tightly sealed cavern takes place, at least with sufficiently low rates, if the brine and the surrounding rock mass are almost thermally balanced. Thus a macro fracturing can be excluded. The onset of brine percolation is also slowly and proceeds gradually into the surrounding rock salt. The estimated

volume rates of brine at point in time 100 years after plugging of the cavern are only a few cubic meters per year.

4. In the sealed cavern, a support pressure builds up leading to a gradual decay of rock deformation, i.e. convergence rates are declining and therefore surface subsidence rates.

5. Natural analogues (gas and brine inclusions in salt) justify the assumption that after a long period (t >> 200 years) a stationary state will be established in brine-filled, sealed caverns. Converging rock deformation in the lower and diverging rock deformation in the upper cavern region will then be in equilibrium, i.e. the integral convergence rate is close to zero. The internal cavern pressure then corresponds to the gradient of the brine specific gravity and the overburden pressure in the centre of the cavern. Consequently, in the lower part of the cavern, brine pressure is below the overburden pressure, while in the upper region of the cavern roof brine pressure is greater than the overburden pressure.

5.2.2.1 Cavern Compressibility

Both the cavity and the cavity filling brine are compressible bodies acting as a system on any kind of induced convergence.

The system compressibility β of a brine-filled cavern arises from the superposition of the compressibility of the brine and of the surrounding rock salt mass (see Equation 5.2.1).

$$\beta = \beta_C + \beta_B \tag{5.2.1}$$

with

β_C	cavern compressibility resulting from $\beta_C = \frac{1}{K_{salt}}$
K_{salt}	bulk modulus of salt K_{salt}= 10 GPa)
β_B	brine compressibility resulting from $\beta_B = \frac{1}{K_{brine}}$
K_{brine}	bulk modulus of the brine K_{brine} = 3.9 GPa)

The volume change rate $\dot{V}$ caused by a pressure change rate ($\dot{p}$), for a defined cavern volume V is expressed by Equation 5.2.2)

$$\dot{V} = -\beta \cdot V \cdot \dot{p} \tag{5.2.2}$$

Typically a value of $3.704*10^{-4}$ 1/MPa for the compressibility β of a brine filled cavern can be assumed, which represents a bulk modulus of $\frac{1}{\beta} = 2.7\ GPa$ for the total system. For the comparison of different cavern systems concerning shape, size and depth this value for the compressibility β can always serve as the first orientation. However, the compressibility factor can increase significantly, when the cavern contains gas pockets. A comprehensive discussion of this can be found in BÉREST ET AL. [1999] and BRÜCKNER ET AL. [2003]. In this context, a number of results are presented in the literature for the pressure build-up in brine filled and sealed caverns or boreholes as compiled in Table 5.1.

Table 5.1 Values for the modulus of compression as measured in-situ

kind of cavity	location	depth [m]	volume	compressions modulus [GPa]
borehole	Zielitz	1,110	0.026 m^3	1.8 –2.7
borehole	Bernburg	490	0.022 m^3	1.5 – 1.7
Test cavern	Bernburg	500	22 m^3	2.5 – 2.8
cavern	Bernburg 07	500	225 Tm^3	1.5
cavern	Bernburg 103	500	490 Tm^3	2.52
cavern	Etrez EZ53	950	8 Tm^3	2.7
cavern	Stade T5	690	1,540 Tm^3	2.4
cavern	Stade T1	445	1,350 Tm^3	2.7
cavern	Hollenbeck 1	1,300	220 Tm^3	1.6
cavern	Etzel K102	830	233 Tm^3	2.5

From the slope of the characteristic curves in the Δp-V diagrams of pump- and pressure release tests, the bulk moduli of the caverns can be determined. It is of particular interest to what extent these slopes are influenced by the cavern size or whether it is a parameter of only characterizing the system of brine-fill/rock salt mass.

5.2.2.2 Salt Creep

When a rock salt is subjected to a stress difference (a stress difference exists when the three principal stresses are not equal), the salt deforms continuously. This time dependent visco-elasto-plastic deformation is termed as ‘salt creep’. The magnitude of the creep rate (creep velocity) of rock salt depends on:

- the physical properties of the rock salt,

- the magnitude of the stress differences acting in the rock salt, and
- the temperature in the rock salt.

When a cavern is created in a salt formation, stress differences develop, because the cavern pressure is not equal to the lithostatic stress, and thus the salt surrounding the cavern begins to creep into the opening as long as the pressure in the cavern will not as high as the far field rock mass stress (lithostatic stress).

When the salt surrounding the cavern flows toward the cavern and the cavern is sealed, then the fluid in the cavern is compressed and causes the cavern pressure to *increase*. Since the rate, at which the salt flows or creeps into the cavern, depends on the difference between the cavern fluid pressure and the stress level in the surround rock salt, the rate of cavern creep slows as the cavern fluid pressure increases.

In the case of brine filled caverns the volumetric deformation is determined by the creep properties of the surrounding salt. The creep rate results from the mechanical stress due to the difference (γH - p_i), where γ is the average unit weight of the overlying rocks, *H* the average depth of the cavity, which is subject to the internal pressure p_i. Related to salt deposits in the Netherlands and Germany the average unit weight of the overlying rocks can be estimated in the range of 0.021 MPa/m $\leq \gamma \leq$ 0.025 MPa/m.

From the results of creep tests on cylindrical rock salt specimens in the laboratory it is well known to illustrate the salt creep behaviour in a nonlinear relationship depending on stress and temperature. Within the visco-elasto-plastic material model that is used by IFG for modelling the rock salt, the stress dependency of the creep rate is defined by an exponential dependency for the MAXWELL viscosity η^M on the deviatoric stress σ_V including a structural parameter *m* (see Equation 5.2.3).

$$\eta^M = \eta_0^M \cdot e^{-m \cdot \sigma_V} \tag{5.2.3}$$

Including the Arrhenius-function as shown in Equation 5.2.4 the MAXWELL viscosity becomes a function of temperature. At subsurface the temperature rises with increasing depth.

$$\eta_0^M = \eta_{T0}^M \cdot \exp\left(\frac{Q}{R \cdot T}\right) \tag{5.2.4}$$

with

η_0^M	temperature dependent MAXWELL viscosity
Q	activation energy 54,000 J/mol
R	general gas constant 8.314 J/(mol*K)
T	absolute temperature [K]

Another way to illustrate the stress dependence of rock salt creep is of the power approach by NORTON, which describes the nonlinear relationship between creep, stress and temperature according to Equation 5.2.5.

$$\dot{\varepsilon}_{cr} = A \cdot e^{\frac{-Q}{R \cdot T}} \cdot \sigma^n \qquad (5.2.5)$$

with

A	structural parameter,
σ	acting stress difference,
n	stress exponent (defining non-linearity of creep with regard to stress)
Q, R, T	defined as per Equation 5.2.4

For a general three-dimensional formulation of the creep rate as formulated per Equation 5.2.5 for uniaxial load cases, abstractions with respect to the geometry are necessary. In the case of cylindrical symmetry, they lead to the relationship of Equation 5.2.6 for the convergence of a cavern under internal pressure.

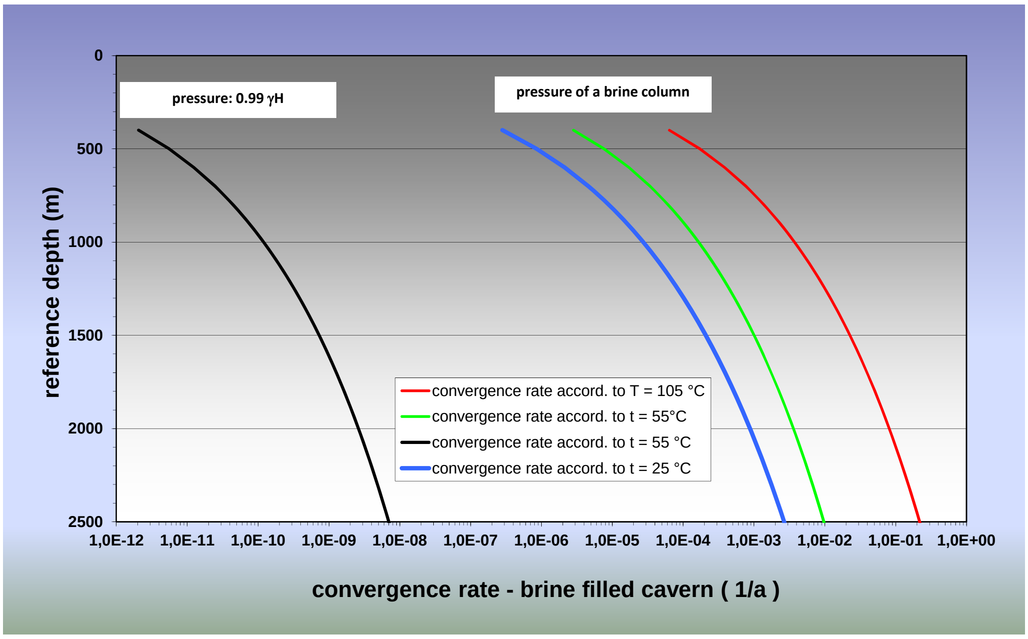
$$\frac{\dot{V}_{cyl}}{V_{cyl}} = -\sqrt{3} \cdot \left[\frac{\sqrt{3}}{n} \cdot (\gamma \cdot H - p_i) \right]^n \cdot A \cdot \exp\left(\frac{-Q}{R \cdot T} \right) \qquad (5.2.6)$$

with

$\dot{V}_{cyl}$	volume change rate of the cylindrical cavern,
V_{cyl}	volume of the cylindrical cavern,
γ	average unit weight of the overlying rocks
H	average depth of the cavity,
p_i	internal cavern pressure
n	as defined as per Equation 5.2.5
Q, R, T	as defined as per Equation 5.2.4

If common values for rock salt are assumed, i.e. $n = 5$, $A = 0.18\ d^{-1}$ and $Q/R = 6500$ K, a cylindrical cavern under brine pressure (without a plug) is characterised by a convergence rate according to the green line shown in *Figure 5.4*. While for a plugged cavern, where the pressure has increased for example up to the level of 99% of the lithostatic stress ($\gamma{*}H$), the convergence rate is much smaller (see black line). Furthermore, the temperature effect is shown, if an open brine filled cavern is assumed. Lower temperatures of the salt rock lead smaller convergence rates (compare green line with blue line); higher temperatures have the opposite effect (compare green line with red line).

Figure 5.4 *Convergence rate of cylindrical brine filled caverns related to the acting temperature and pressure.*



5.2.2.3 Thermal expansion of the brine

The temperature of rock salt increases with depth; caverns are leached using water pumped from the surface whose temperatures are significantly colder than the rock temperature at cavern depth. The difference between the cavern brine temperature and the temperature of the surrounding rock mass will gradually absorbed; absorption is governed by heat conduction through the rock mass to the cavern and by heat convection in the cavern.

The heat conduction phenomenon is transient and disappears over time, which equals a characteristic time t_C, which based on Equation 5.2.7 is depending on the cavern volume *V* and the thermal diffusivity *k* of the rock mass. According to Bérest [2000] the exact temperature evolution can easily be predicted through numerical calculation.

$$t_C = \frac{\sqrt[3]{V^2}}{4 \cdot k} \qquad (5.2.7)$$

When *k* can be assumed according to experiences in the order of 100 m^2 per year and the cavern volume *V* is 650,000 m^3, and then the characteristic time t_c, which is necessary to absorb 75% of the initial temperature gap, can be estimated to appox.19 years.

The average temperature change rate ranges from some 10 K per year in small caverns to less than 1 K in very large caverns. If an opened cavern is assumed, a temperature increase leads to thermal expansion producing an outflow of brine at the wellhead according to Equation 5.2.8.

$$\dot{Q} = \alpha \cdot V \cdot \dot{T} \qquad (5.2.8)$$

with

$\dot{Q}$ volume rate of brine outflow

α coefficient of thermal expansion for brine

$\dot{V}$ cavern volume,

$\dot{T}$ temperature change with respect to time

In a closed cavern, the increase of temperature leads to pressure build-up. Considering the coefficient α for brine thermal expansion and the compressibility of the brine and the cavern (system compressibility) the pressure increase can be calculated by Equation 5.2.9, where the ratio of α versus β describes the potential for pressure change per Kelvin of temperature change.

$$\dot{p} = \dot{T} \cdot \frac{\alpha}{\beta} \tag{5.2.9}$$

Considering typical values for α and β this leads to a pressure build-up of 1 MPa per temperature increase of 1 K in the brine. In other words, when an initial temperature difference of 25 K is resorbed, the related pressure build-up will be 25 MPa. This value is far exceeding the initial difference between overburden and brine column pressure and will most probably lead to a macro fracture in the salt.

In contrast to cavern convergence the thermal expansion rate is not influenced by the brine pressure.

It has to be emphasized, that according to the consequence of brine warming in a plugged cavern a long lasting period of time is necessary to equalize brine and rock temperature and to prevent a rapid over pressurization of the cavern. Related to the size and depth of the caverns this period will last up to 10 years or more depending of the original brine temperature when flooding the cavern.

5.2.2.4 Transport of the brine into the formation

Originally the rock salt mass surrounding a cavern provides a perfectly technical tightness. Due to the visco-plastic properties of salt rocks, the undisturbed state in-situ is characterized by nearly isotropic loading conditions. In accordance with Mohr's equations this means that the shear stresses at the grain boundaries of the polycrystalline salt rocks are nearly zero and the normal stresses are equivalent to the minimum principal stress σ_{MIN}.

However, flow paths may be opened on a micro-scale at the grain boundaries, if fluid (brine) pressures and rock mass stresses are at specific conditions.

Two processes are responsible for a possible transition of saliniferous barriers from the state of absolute tightness to a status where fluid percolation is possible:

- Fluid-pressure-driven generation of hydraulic flow paths along discontinuities on a micro- and macroscopic scale (e.g. grain boundaries, bedding planes) at fluid pressures higher than the normal stress (minimum stress criterion).
- Mechanical damage under deviatoric stress after exceeding the dilatancy boundary. This process is basically only relevant in the near contour area of an excava-

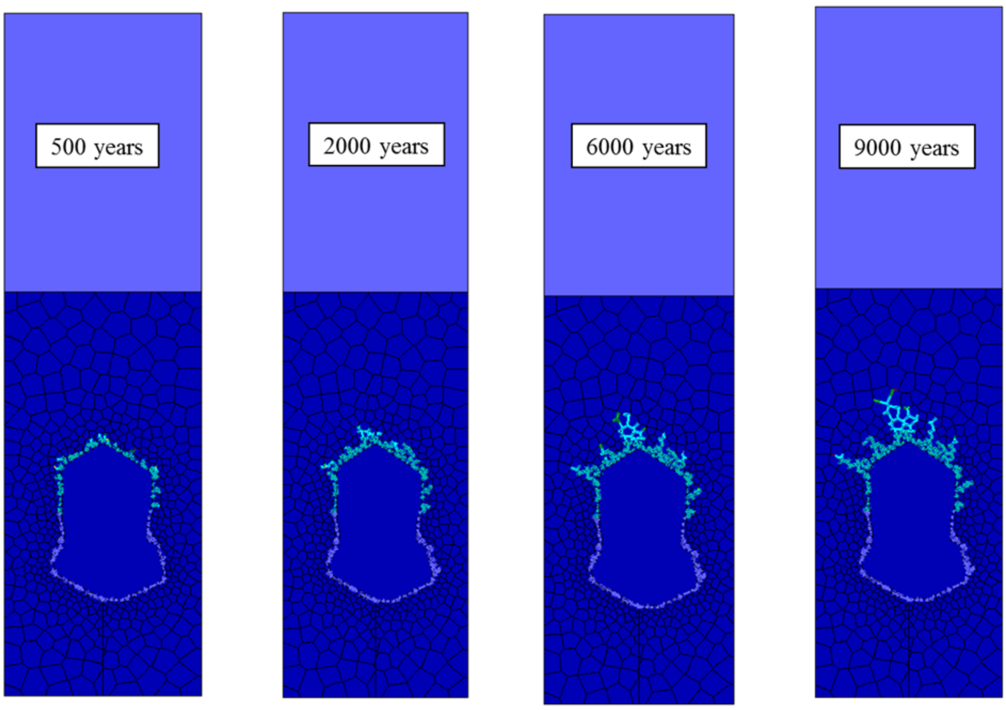
tion, because its extent into the surrounding rock is very limited (dilatancy criterion).

The impermeability of a saliniferous barrier in the hanging wall of a cavern for example will already be lost if one of these criteria is violated.

Generally, only after overcoming a percolation threshold the pressure-driven opening and interconnection of flow paths along grain boundaries is initiated in the salt rock and induces a directional percolation in the direction of the maximum principal stress.

Constitutive models like those developed at IfG, such as the visco-elasto-plastic model for the salt grains and an adhesive frictional shear model for the interaction between them, can be used to describe the mechanical behaviour, while the hydraulic description of fluid percolation is realized using the cubic law for laminar flow. An example for simulating the percolation process in the rock mass surrounding a plugged and brine-filled cavern is presented in *Figure 5.5*.

Figure 5.5 *Time dependent percolation of brine into the hanging wall of a cavern as calculated by IfG's constitutive law in a discontinuum mechanical approach*



Percolation occurs in the vicinity of a sealed cavern as a gradually and time dependent process, which progresses to regions, where differences between brine and overburden pressure are lower. Even though discrete pathways are shown, it has to be considered that the flow paths are at micro-scale. Currently, a simulation model applying the above described approach at micro-scale represents a capacity problem. However, special conclusions can be drawn with attention to the presented time steps. Many thousands of years are necessary for the percolation zone to cover an area of about one cavern radius behind the original cavern wall. This points out how slow or long-lasting this process is. Similar simulation results are reported by WOLTERS ET AL. [2012]. While applying a different approach for brine infiltration at micro-scale based on lab test results at TUC, the infiltration front slowly migrates into the hanging wall of the salt rock mass. After about 100,000 years the infiltration zone spreads over a zone that is extended about cavern diameter into the rock mass, while the cavern shape slowly changes from a cylinder to a sphere, which will possibly lead to a halt of the infiltration process.

Figure 5.6 *Simulation of the infiltration process by WOLTERS ET AL. [2012]*

For the brine penetrated areas it is necessary to prove that they are able to receptive brine in a sufficient extent and to prevent the contact of brine with the biosphere within a reasonable period of time.

5.2.2.5 Theoretical understanding of the process of abandonment

The aim of CS&A is to divide the cavern horizon and the biosphere without any risk for the environment, the surface and the deposit itself. Furthermore, the former operator wants to be released from government supervision by the mining authorities. To achieve acceptance for his abandonment concept, it has to be proven that abandoned caverns will fulfil the criteria for long-term stability and safety in the post operation period:

From the rock mechanical point of view the abandonment process has a special aspect concerning the environment safety, especially to guarantee the mechanical integrity of the sealed cavern without the risk to collapse. After the cavern has been sealed, a long lasting process with a very slowly ongoing cavern convergence is induced. Over periods of thousands of years the process is also characterized by brine percolation in the surrounding rock mass, but generally, CS&A is a procedure with a safe inclusion of cavity stabilizing brine. Related to the surface CS&A is a process without detectable subsidence compared to geomorphological processes.

5.3 Requirements prior to plugging

Actually, the common practice of CS&A is to leave the caverns in a brine-filled state and to seal the well under consideration of the current regulations for deep wells. When a separation between the cavity and the borehole is realized it leads to borehole abandonment according to the rules of the mining authorities (in the Netherlands: the Mining Decree and the Mining regulations; in Germany: the regional Tiefbohrverordnung, BVOT).

The geomechanical abandonment concept bases on an investigation of the actual state of the caverns, a proof for the post operation long-term behaviour of the brine-filled caverns, a proposal for the tight sealing of the borehole as well as for an indication concerning the material intended to be used, the service effort and the costs of the whole project.

The prerequisite to prove the long-term stability and the geomechanical integrity of the cavern abandonment is the numerical modelling and simulation. It has to be demonstrated by this approach that the suggested CS&A procedure has the ability to withstand the various geomechanical processes, described as fundamental basis for the geotechnical CS&A concept.

These models could be validated by in-situ tests, e.g. pressure tests with brine injection as well as brine withdrawal. The investigation methods may rely on both static as well as dynamic methods. In the case of the static method a pressure build-up as well as overflow measurement at surface in order to test a sealed, brine filled cavern is essential. Dynamic methods involve the active pumping of fluids at a constant volume rate potentially in cyclic modes in order to determine the compressibility of a brine-filled cavern. Furthermore, other input data from:

- the newest geological surveys,
- the cavern operation history,
- subsidence measurements,
- pressure measurements,
- temperature measurements,

are required to create a reliable data base for the final numerical proof.

For the first cavern to be abandoned in a salt deposit, temporarily abandonment test should be performed with an appropriately long observation period during that different initial brine pressures are set and then monitored over time. Pressure and temperature should be observed during this testing phase.

5.4 Technical options for plugging

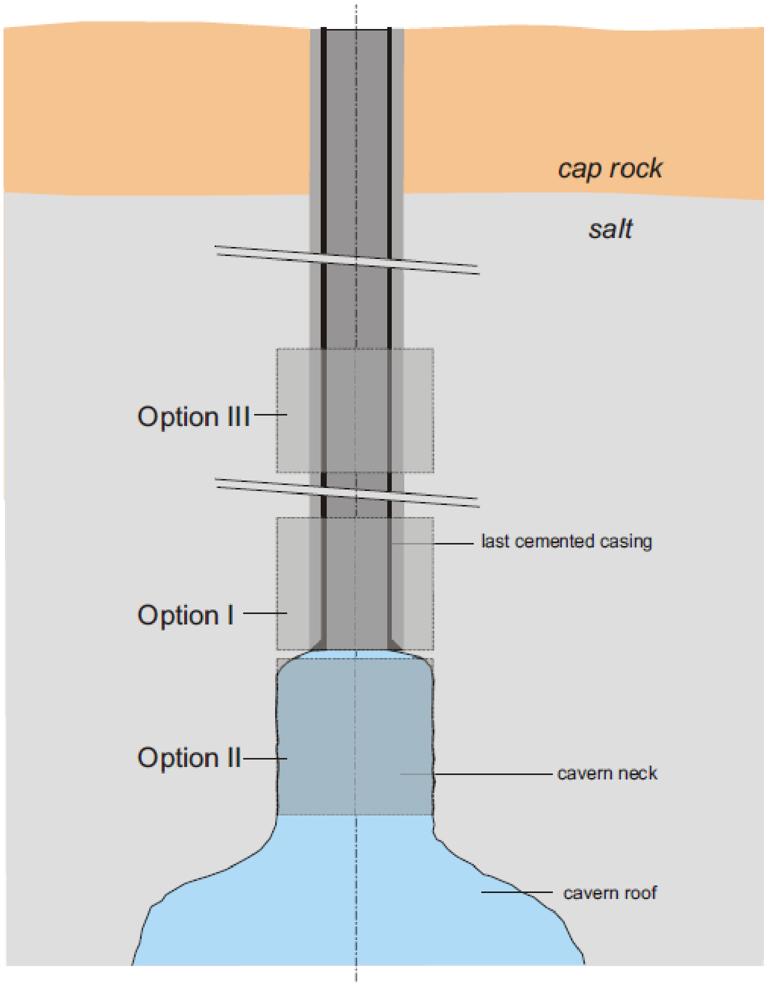
In the design of the abandonment of a well two requirements have to be considered. The plugging and sealing elements have to provide long-term tightness of the well/cavern against the environment and have to provide also long-term stability. A detailed list of requirements on plugs is given by CROTOGINO ET AL. [2006]. Beside others the following requirements for plugged wells are mentioned:

- Tightness against liquids and gas and for protection of the groundwater
- Plugs should seal off exploitable oil gas and salt deposits from exploitable storage an water horizons, and from high pressure horizons with inflows as well as to seal off liners, pipe joints, annuluses, the casing shoe of the deepest casing string, and the section immediately below the surface.
- Within thick salt deposits special plugs should be in place extending at least 100 m into the salt and 50 m into the surrounding rock
- A special plug should be installed in the borehole from surface to a depth of at least 100 m and possibly relocated according to freshwater horizons that have to be protected.

- Despite the above items a complete cementation of the borehole is recommended, although due to mining regulations it is possible to plug the well with alternating sections of cementation and mud or solid material.

In an SMRI research work of Crotogino et al. [2006] three different options for setting the decisive plug for tightness of a brine filled cavern are proposed as listed below. A principle sketch with regard to the location of the decisive plugging element is shown in *Figure 5.7*.

Figure 5.7 *Options for cavern well plugs according to Crotogino et al. [2006]*



The different options can be characterized as follows:

I Setting the plug in the last cemented casing

II Setting the plug in the cavern neck (open hole cementation) below the casing shoe, or

III Setting the plug in window that is milled in lower section of the last cemented casing near the casing shoe.

Pros and cons of all three options are discussed by CROTOGINO ET AL. [2006], but it is emphasized that the best solution has always to be selected by considering the specific situation of each cavern. However, from a first glance option III seems to offer the best conditions for long-term safety.

I For the feasibility of this method the long-term tightness of the bond between salt, cementation and last cemented casing has to be proven as permanently tight. This option is evaluated as critical by the authors.

II The geometry of the cavern neck may be unsuitable for the placement of a plug that should provide sealing and load-bearing abilities, e.g. elliptical cross sections, excessive diameters and/or insufficient available length for plugging. This means a smooth shape of the cavern neck is more or less a pre-requisite for the success of this option.

III Setting the plug in a milled and under-reamed window section close to the last cemented casing shoe provides good conditions for a permanent sealing, because of the direct bond between the salt and the cementation of the plug.

The three different options for a decisive plug as represented according to CROTOGINO ET AL. [2006] by *Figure 5.8* to *Figure 5.10*.

After setting and testing the decisive plugging element it is recommended to cement the remaining part of the well up to surface as mentioned above.

Figure 5.8 *Option I: Decisive well plug within cemented casing according to* C*ROTOGINO ET AL. [2006]*

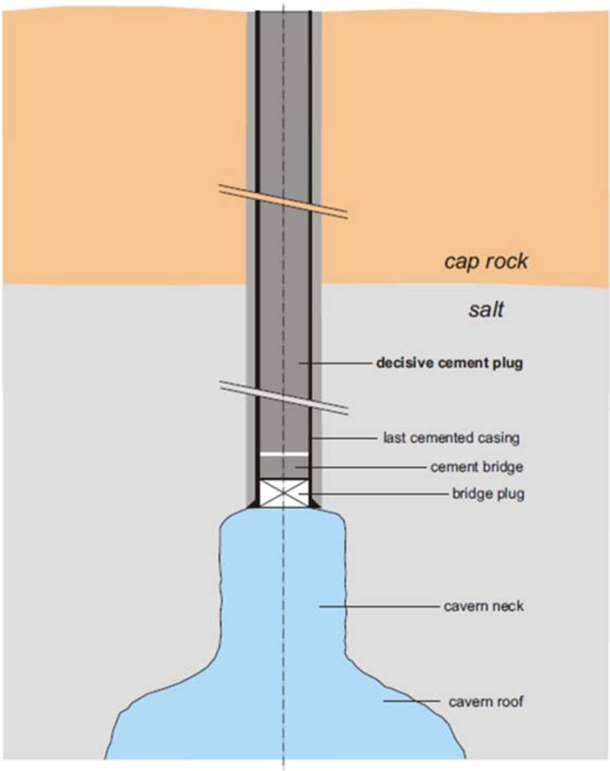


Figure 5.9 *Option II: Decisive well plug within cavern neck (open hole) below cemented casing according to* C*ROTOGINO ET AL. [2006]*

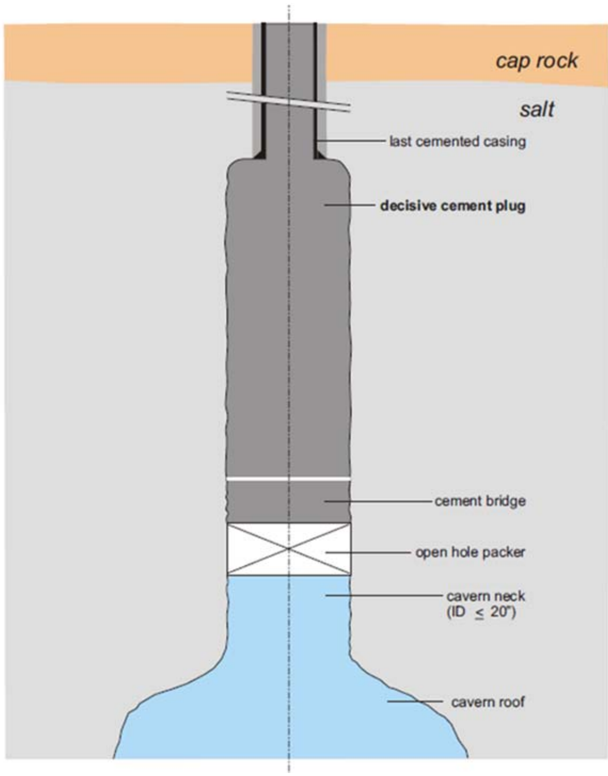
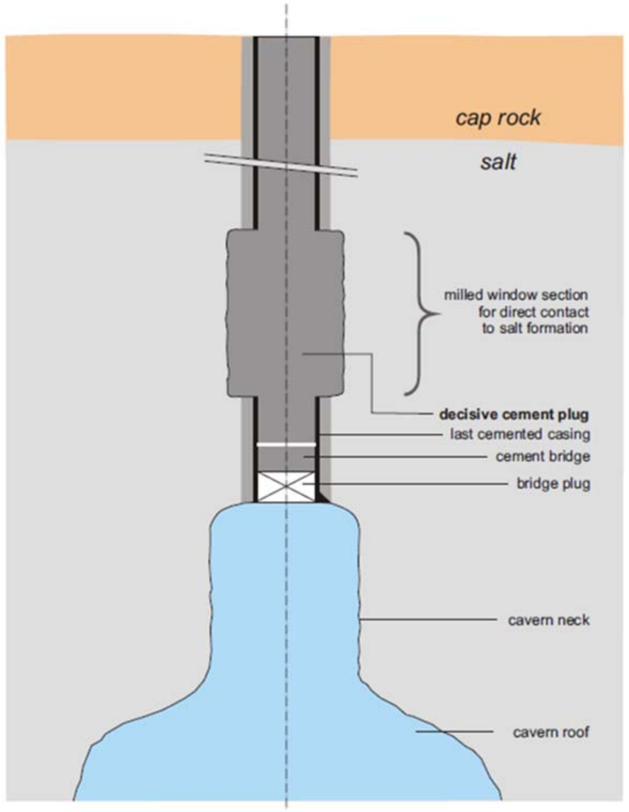


Figure 5.10 *Option III: Decisive well plug within milled casing section according to* CROTOGINO ET AL. *[2006]*



5.5 Financial items and estimate on time required

As proposed in the scope of work for the present study no specific or individual abandonment plans are presented because of its general character and therefore no estimates on costs. But, a list of principal items or activities that will afford financial expenses is given. These cost items have to be filled with estimated values in a detailed abandonment study, which has to be based on individual cavern data. According to the general abandonment concept as presented in Chapter 4.1 costs originate from the following principal categories of activities:

- Planning and first preparations, application for permits
- Flooding of the cavern
- Measurement and testing
- Waiting for temperature balancing
- Plugging and cementing the well
- Re-cultivation of the wellpad
- Post abandonment monitoring

5.5.1 Cost items for planning and preparation

Costs are generated by all activities necessary for the general planning of the abandonment concept, first tests and measurements and the preparations for flooding:

- Development of an abandonment plan
- Rock mechanical study for proving the individual concept
- Rock mechanical study on required tests before plugging
- Simulation of the re-leaching effect, if flooded with unsaturated brine or freshwater
- Detail planning for snubbing in of the flooding string
- Detail planning for flooding
- Detail planning for plugging and sealing the well
- Detail planning for deconstruction of the well pad
- Sonar survey at the end of gas operations
- Retrieving of the sub surface safety valve
- Snubbing in of the flooding string with a snubbing unit
- Supervision on side

5.5.2 Flooding

If the detail planning was done in the planning phase the flooding process produces costs for

- Procurement of water or brine
- Potentially provision of pumping capacity
- Energy costs for flooding
- Measure brine/gas interface measurements for monitoring the process
- Additional installations on the well pad (flare etc.)
- Nitrogen supply for final flushing
- Workover rig for pulling out the brine injection string
- Sonar survey at the end of flooding
- Casing inspection logs
- Temperature log
- Tightness test at the end of flooding depending on the selected plugging option
- Supervision and personnel

5.5.3 Measurement and testing period

The costs for in-situ testing and additional measurements may differ, if several caverns will be abandoned at the same location. Or the first cavern of the field a more comprehensive and therefore more time consuming in-situ test might be recommended as proof of concept. The following costs items may arise

- Compressibility test
- Proof of concept by an in-situ test
- Evaluation of the tests

5.5.4 Waiting period for temperature balancing

As described above the waiting time for brine warming up can be decreased. If no extras measures were taken then the temperature balancing period may last several years. During this period costs are generated by

- monitoring the saturation process of the brine
- measurements of cavern temperature and pressure
- keeping the cavern pressure below maximum (monitoring, brine release and disposal)
- personnel on site

At the end of the waiting period a

- final sonar survey

should be conducted.

5.5.5 Plugging and cementing the well

The process starts with dismantling of the production string and ends up with cementing the well to surface. The following principle cost items can be identified:

- Mobilization and de-mobilization of the workover rig
- Dismantling of the gas completion
- Cleaning the casing, casing inspection log, cement bond log
- Preparation for setting the decisive plug, e.g. milling and underreaming option (3)
- Plugging
- Back cementing to surface
- Supervision and personnel on site

Required activities and therefor costs depend on the selected plug design, costs for cementing the well on the setting depth of the casing shoe.

5.5.6 Re-cultivation of the well pad

Costs are generated by the following activities

- Final works regarding the sealing of the well
- Dismantling of pipelines
- Filling the place with topsoil and re-cultivation

Apart from dismantling all technical equipment at the well pad, the dismantling of pipelines and other infrastructure may be necessary. This is especially the case if more than one cavern is abandoned in a field of caverns. The dismantling of the gas plant has to be considered in an overall abandonment concept of the complete storage.

5.5.7 Post Abandonment activities

According to the permission for abandonment possibly some post abandonment monitoring is required. This depends on national and local regulations.

5.5.8 Rough estimate on required time

A rough time estimate for the whole abandonment procedure is given in **Table 5.2** according to the main phases of the abandonment procedure as described above.

Table 5.2 General and rough estimate on time for abandonment

Phase / Period	Estimate Time Required
Planning and first preparations	18 months
Flooding of the cavern	10 to 15 months depending on the cavern volume
Measurement and testing	24 months (first cavern) 3 months further caverns
Waiting for temperature balancing	120 to 240 months depending on initial filling temperature of the brine or water and the individual cavern can be reduced by special measures
Plugging and cementing the well	2 months
Re-cultivation of the wellpad	2 months
Post abandonment monitoring	depending on legal obligations

6 Summary and Conclusions

There is a variety of options for the abandonment of gas storage caverns in salt. However, in the past years concepts focussed on the abandonment of brine filled caverns.

Standard practice is to replace product with brine or water, to allow waiting time for achieving temperature equilibrium between the cold fluid in the cavern and warm rock mass surrounding the cavern, and then to plug the well with cement. After plugging the cavern pressure will increase, because of the higher creep deformations in the lower part, but this will not lead to macro-fracturing of the rock mass because of a limited brine infiltration, which will not endanger the stability and safety. This concept is based on comprehensive research activities by the SMRI.

As the salt creeps as long as the internal pressure is not equal to the lithostatic stress at every horizon in the cavern, especially for tall cylindrical caverns there will be no equilibrium of cavern pressure and rock mass stress across total cavern height. Because of higher differences between cavern pressure and lithostatic pressure in the bottom part of a tall cavern the creep deformation from the lower part will raise pressures in the roof of the cavern to values above the lithostatic pressure at this depth. However, a first pressure build-up test in Etzel in the early 1990s revealed that this pressure level could not be reached, because infiltration of brine started at a pressure levels close to lithostatic stress.

Research work progressed with the SMRI research project focussing on Cavern Sealing and Abandonment, which was started in the late 1990s and resulted in a general concept for abandonment of brine filled caverns that could be confirmed in general by in-situ tests. This concept addresses five different processes that have to be considered in an abandonment concept, which is mandatory in order to demonstrate compliance with the general requirements for long-term stability of the subsurface and safety of the environment. These mechanisms are

- creep of the salt,
- temperature increase of the filled-in brine or freshwater,
- saturation of the filled-in brine,
- infiltration of brine into the rock mass, and
- leaks.

An important point with regard to long-term safety in this concept is that brine infiltration balances the pressure increase due to salt creep, if leaks can be excluded (e.g. by tests of the design of the decisive plug), the temperature between fluid-fill in the cavern and the rock mass is balanced before plugging, and re-leaching effects have stopped. This leaves the question, if the infiltration process will transport brine up to the top of the salt deposit. The results of recently made investigations especially by IfG – Leipzig and at Technical University Clausthal (Prof. Lux) indicate that for caverns with a well dimensioned salt roof this will be an extremely slow process. If at all, the top of salt will be reached by the infiltration front only after many ten thousands of years. During this period the surface subsidence rate will slow down to values that practically cannot be measured.

The main ideas of the technical and scientific concept of IfG for cavern abandonment of brine filled caverns were explained in greater detail in Chapter 5. Currently, a few caverns were abandoned according to this concept, which represents an extension of the SMRI concept. Therefore, the abandonment of the Zuidwending gas caverns can be recommended according to this concept.

For the design of decisive plugs three different options were discussed. Which one will actually be selected depends on the condition of the last cemented casing and the geometry of the cavern neck. Generally, decisive plug designs should be preferred that rely on a direct bond between cement and salt.

There are options to shorten the waiting time for brine warming-up that has to be taken care of, in order to avoid temporarily cavern pressures that will be too high if the plug is set too early. Here the relative long waiting time of possibly more than 15 years for very big cavern is in contrast to higher costs for pre-heating of the brine or a possibly higher risk for long-term tightness, when introducing a small gas volume in the cavern roof right before plugging.

It is not reasonable to make cost estimates when the study is of principle character. Therefore, only the main cost items were addressed, which are related to the phases the abandonment process has to cover. The same accounts for the estimate on required time. The given rough estimates refer to the phases and not to specific tasks.

In order to provide more precise figures and estimates a detailed study which takes into account the individual cavern data has to be performed. This already indicates the first continuation step of the road map to abandonment. Principally it can be concluded that the abandonment of the Zuidwending gas storage cavern by filling with brine and plugging the wells is feasible and can therefore be recommended.

List of References

[1] **Bannach, A. and Klafki, M. 2009**. *Staßfurt Shallow Cavern Abandonment Field Test*, Solution Mining Research Report, RR2009-01, 2009.

[2] **Bérest P., Bergues J., Brouard B. 1999.** *Review of static and dynamic compressibility issues relating to deep underground salt caverns*,Int. J Rock Mech Min Sci 36:1031-1049, 1999.

[3] **P. Bérest, B. Brouard, J.G. Durup, 2000.** *SHUT-IN PRESSURE TESTS - Case Studies*, Palaiseau; Paris 2000.

[4] **Bérest P., de Greef, V., and Brouard, B., 2001.** *Salt Permeability Testing The Influence of Permeability and Stress on Spherical Hollow Salt Samples*, Research Project Report No. 2001-8-SMRI, SMRI, 2001.

[5] **Bérest, R., Karimi-Jafari, M., Brouard, B., and Durup, G. 2007,** *Brine Warming in a Sealed Cavern: What can be done?*, Solution Mining Research Meeting Paper, SMRI, 2007

[6] **Brouard, B., Bérest, R., Rokahr,R., Staudtmeister, K., Zander-Schiebenhöfer, D., Fourmaintraux, D., de Lageguerie, P. and You, T. 2006,** *Salt Cavern Abandonmant Field Test in Carresse,* Solution Mining Research Report, RR2006-01, 2006.

[7] **Brückner, D., Lindert, A., Wiedemann, M. 2003,** *The Bernburg Test Cavern . A Model Study of Cavern Abandonment*, Meeting Paper, SMRI, 2003.

[8] **Brückner, D., Wekenborg, H. 2003,** *Abandonment of Caverns at the Brine Field Stade-Süd, Germany, Geomechanical Concept, Geotechnical Procedures and the Proof of Long-term Safety by Numerical Modeling*, Meeting Paper, SMRI, 2006.

[9] **Crotogino, F. und Kepplinger, J. 2006.** *Cavern Well Abandonment Techniques Guidelines Manual. Hannover* **:** KBB Underground Technologies / SMRI, 2006.

[10] **de Laguérie, Patrick, et al. 2004.** *Decommissioning and abandonment procedure of LPG caverns at Carresse (France). s.l. :* SMRI, 2004. Technical Conference Paper.

[11] **Duequesnoy, A. 2011,** *Synthesis of SMRI Sponsored Shallow Cavern Abandonment tests*, Reearch Report RR2011-02, SMRI, 2011.

[12] **IfG, (2005),** *Rechentechnischer Nachweis der Stand- und Langzeitsicherheit der stillgelegten, soleerfüllt belassenen und durch Verschluss und Verfüllung der Kavernenbohrung zu verwahrenden Aussolkavernen des Solfeldes Stade – Süd durch gebirgsmechanische Modellierung*, Report, Institut für Gebirgsmechanik Leipzig, 03.05.2002

[13] **Lux, K.-H. (2005),** *Zum langfristigen Tragverhalten von Verschlossenen solegefüllten Salzkavernen – ein neuer Ansatz zu physikalischer Modellierung und numerischer Simulation – Theoretische und laborative Grundlagen*, ERDÖL ERDGAS KOHLE, 121. Jg., 2005, Heft 11

[14] **Minkley, W., Knauth, M. and Brückner, D. 2013.** *Discontinuum-mechanical behaviour of salt rocks and the practical relevance for the integrity of salinar barriers. ARMA 13-388:*, paper presented at the 47th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 23-26 June 2013

[15] **Ratigan J., 2000,** *"A status report on the SMRI cavern sealing and abandonment program"*, SMRI Report, 2000.

[16] **Ratigan, J. L. 2003,** *The Solution Mining Research Institute - Cavern Sealing and Abandonment Program 1996 Through 2002. Houston TX, USA* : Meeting Paper, SMRI, 2003.

[17] **Staudtmeister, K., and Rokahr, R. B., 1994,** *TPressure Build-Up Test in the Etzel K 102 Cavern*, Research Project Report No. 98-5-SMRI, SMRI, 1998.

[18] **Thoms, R. L., and Gehle, R. M., 2000,** *A brief history of salt cavern use*, keynote paper, Proc. 8th World Salt Symposium., R.M. Geertman ed., Elsevier. Vol. I, 207-214,

[19] **Wolters, R., Lux, K.-H. and Düsterloh, U., 2012,** *Evaluation of Rock Salt Barriers with Respect to Tightness: Influence of Thermomechanical Damage, Fluid Infiltration and Sealing/Healing*, 7th Confrence on the Mechnical Behaviour odf Salt, Paris, 2012.

[20] **Bergverordnung für Tiefbohrungen, Untergrundspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen im Land Niederachsen (Tiefbohrverordnung – BVOT -), 2006.**

[21] **Bergverordnung für Tiefbohrungen, Tiefspeicher und für die Gewinnung von Bodenschätzen durch Bohrungen - (Tiefbohrverordnung - BVOT) vom 29. July 1998 -** *§ 35 Verfüllen auflässiger Bohrungen***.**

[22] **Mining Act of the Netherlands,** unofficial translation prepared for NAM/NOGEPA by J.L. den Dulk**, 2009**.

[23] **Mining Decree of the Netherlands,** unofficial translation prepared for NAM/NOGEPA by J.L. den Dulk**, 2008**.

[24] **Mining Regulations** of the Netherlands, unofficial translation prepared for NAM/NOGEPA by J.L. den Dulk**, 2009**.