SOLUTION MINING
RESEARCH INSTITUTE
105 Apple Valley Circle
Clarks Summit, PA 18411
USA
Country Code: 1 ♦ Voice: 570-585-8092 ♦ Fax: 570-585-8091
E-mail: smri@solutionmining.org ♦ www.solutionmining.org

Research Project Report
No. 2006-3-SMRI

Cavern Well Abandonment Techniques Guidelines Manual

Fritz Crotogino

Jürgen Kepplinger

KBB Underground Technologies GmbH

Hannover, Germany

September 2006

Acknowledgment

We would like to express our thanks to the SMRI members listed below for their active participation. The contributions they provided are basically indispensable when writing a manual which seeks to meet the diverse needs of so many different countries.

- Pierre Bérest, LMS
- Benoit Brouard, Brouard Consulting
- Gerard Durup, Gaz de France
- Dr. Detlef Edler, UGS
- Paul Grönefeld, EWE AG
- Jeff McCartney, Texas Brine Company
- Joe Ratigan, PB ESS, SMRI Research Director
- Jay Russel, T&C Consulting
- Kurt Staudtmeister, IUB
- Helge Theylich, UGS, SMRI Sponsor
- Dirk Zander-Schiebenhöfer, IUB

Table of Contents

0 Summary

Introduction

The research activities conducted by SMRI in recent years on cavern sealing and abandonment (CSA) 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 a logical next step towards developing CSA procedures for specific caverns, SMRI engaged Kavernen Bau- und Betriebs GmbH (now KBB Underground Technologies GmbH) to elaborate a general manual for planning and implementing CSA measures in practice.

This manual is not conceived as a list of binding regulations, but rather as a basis upon which operators and engineering companies can develop their own CSA concepts for specific caverns as required.

Task

Based on the previous results of basic research performed on behalf of SMRI, the task was to elaborate a practice-oriented technical concept for CSA measures. This concept must fulfill the following requirements:

- Long-term protection from contamination of drinking water aquifers and the escape of brine and/or flammable and/or environmentally hazardous storage product residues at the surface
- Long-term stability of rock mass surrounding cavern
- Maintenance-free
- Application of tried-and-tested methods and materials as far as possible

- Affordability
- Acceptable by the authorities

The main sections in this manual are as follows:

- Assessment of well and cavern pre-sealing conditions
- Replacement of storage fluid with brine or water in the case of storage caverns
- Assessment of minimum waiting time before plugging
- Performance of waiting period for temperature equalization until plugging can commence
- Cavern plugging concepts for both storage and brine production caverns
- Monitoring after complete cavern sealing & abandonment
- Costs

Basic CSA concept

In the first phase of developing a concept, analysis was carried out of the practical experience and regulations existing for oil and gas wells, with the aim of integrating this experience where possible into the CSA concept for caverns. German and Texas regulations were looked at. The analysis concluded that this experience and the regulations are only of limited applicability to cavern boreholes. In addition regulations for monitoring abandoned caverns in the Netherlands and in Poland were considered.

An important aspect when designing a borehole plug is selecting the section of the borehole in which to install the decisive plug for guaranteeing long-term sealing. The options for suitable sections are:

Option I: Lower end of the last cemented casing string if the cementation is proven permanently tight

Option II: Cavern neck (open hole) if suitable bore hole section present below the casing shoe

Option III: Window milled in the lower section of the last cemented casing to provide an optimal bond between the cement and the rock, and not rely on existing cementation.

The CSA concepts for all options consist of the following main phases:

- Replacement of storage fluid with brine or water in the case of storage caverns
- Performance of tests and calculations to estimate site-specific rock mechanical, thermal and hydraulic characteristics
- Waiting until the necessary temperature equalization has taken place between the brine and the surrounding rock
- Cavern abandonment (work over activities for plugging cavern well)
- Surface monitoring

Assessment of location-specific conditions

SMRI has proven the basic feasibility of abandoning a sealed brine-filled cavern. However, this must be confirmed for an individual cavern or at least for a representative cavern in a cavern field. This particularly involves the estimation of the minimum necessary waiting period for temperature equalization and the long-term pressure build-up over time after plugging as a result of brine re-heating and convergence.

This usually requires numerical modeling which must be based on location-specific data (geology, well data, rock mechanics, salt permeability, and operational history).

Replacement of product or blanket

Brine or water can be used to displace liquid products from liquid storage or cushion gas from gas caverns. Brine is preferred because use of water will alter cavern conditions and may alter casing seat.

In the case of hydrocarbon products or blanket, an important aspect is cleaning the borehole to remove hydrocarbon residues to ensure that an optimal bond is created between the borehole wall and the cement plug.

Activities during waiting time

One of the main question marks is the waiting period required after flooding the cavern with cold brine or water; in special cases it may be reasonable to pre-heat the brine or water before injection for reducing waiting time. This involves analyzing the benefits of reducing the waiting time against the extra energy costs.

Cavern plugging concept

Independent of bore hole section selected for the location of the decisive plug, the section above the plug is to be completely cemented.

Either way, it is essential to ensure that an optimum bond is achieved which guarantees the long-term safe plugging of the compressed brine in the cavern.

In general all of the equipment in the borehole such as production strings and packer / tailpipe assembly in the case of gas caverns should be removed before installing the plug.

The borehole must also be properly cleaned because it is likely that HC blanket or product residues will accumulate in the roof of the cavern and in the borehole during the waiting period.

Then the installation of the actual plug can commence:

OPTION I: DECISIVE PLUG FOR SEALING WITHIN LAST CEMENTED CASING

A pre-condition for selecting Option I is confirmation of the tightness of the cementation around the last cemented casing. Setting the cement plug also assumes successful setting of a cement retainer or bridge plug and overlying cement bridge. The borehole can then be cemented to the surface.

OPTION II: DECISIVE PLUG FOR SEALING WITHIN CAVERN NECK (OPEN HOLE) BELOW LAST CEMENTED CASING

A pre-condition for selecting this option is a cavern neck of adequate length and suitable cross-section to enable an open hole packer to be set within the open hole, followed by the setting of a cement plug of adequate physical length to create a safe plug.

OPTION III: DECISIVE PLUG IN WINDOW MILLED IN CASING

This option does not depend on the cementation around the last cemented casing or the geometry of the cavern neck. In the first phase, a bridge plug is installed in the vicinity of the casing shoe. The window is then milled above the installed plug in the casing string through the cementation to the salt formation. The borehole can then be cemented to surface.

ADDITIONAL TASKS:

The following applies whichever of the options is selected: cutting the casing adequate below ground level, setting a concrete slab, dismantling the well head and other installations on the cavern pad, and renaturizing the cavern pad, paths and field lines.

In some instances[1], however, regulators require leaving the casing above ground and affixing a placard to the casing for identification and subsidence monitoring requirements

No ranking or recommendation of the best solution for locating the plug is possible when comparing the pros and cons of the different options. The optimum solution

[1] for example Kansas, USA

depends on the local conditions as well as the requirements laid down by the operator and the authorities.

A qualitative comparison of the costs involved in the different plugging measures for a model cavern reveals that the costs are largely independent of the option finally selected.

Costs

The costs for cavern abandonment divide up into the below stated tasks:

- Preparation including work over activities
- Flooding with brine or water
- Optional: Pre-heating the water/brine for flooding
- Waiting period for balancing out temperature differences
- Plug construction including workover
- Well head and pad deconstruction and renaturization
- Post abandonment monitoring
- Engineering

On request of SMRI no numbers for costs have been included, since the actual costs will depend on the specific situation (type of cavern, duration of waiting time, country, actual reason for compiling costs – building reserves or need for abandonment).

Another reason why to do without costs are the two tasks *optional preheating of brine or water* and *waiting period*. The actual costs for both tasks will depend to a large extent on the assumptions made, e.g. temperature difference during heating, energy costs, length of waiting time (years, decades). This does not allow to present reasonable numbers e.g. for a sample case.

1 Introduction

In recent years, the SMRI Cavern Sealing & Abandonment (CSA) Research Program has successfully established a scientific basis for practical cavern abandonment.

Based on this know-how, brine filled caverns in homogeneous salt structures like salt domes and thick bedded salt formations, where stability and integrity are ensured almost entirely by the rock salt, can be permanently sealed in a safe and environmentally compatible way without risk of uncontrolled brine displacement. Prerequisites are suitable rock mechanical and hydraulic (reservoir-mechanical) conditions as well as achievement of sufficient temperature equalization with the surrounding host rock before plugging. The SMRI research program indicated that in this case the subsequent pressure build-up is not expected to result in uncontrolled fracturing of the rock mass but in a gradual penetration of the brine into the surrounding salt rock.

The next logical step was for SMRI to consider drafting a general manual of guidelines of specific Cavern Sealing & Abandonment (CSA) techniques. Such a manual would be welcomed by cavern owners/operators as a basis for developing their own specific cavern sealing & abandonment concepts for specific caverns as need arises and by the authorities.

An important caveat is that all of the evaluations and analysis carried out to date, including this study, are based on homogeneous conditions existing salt domes and thick bedded salt formations, where stability and integrity are ensured almost entirely by the rock salt, see Figure 1-1.

After completion of this study it is intended to look at the more complicated conditions existing in thin bedded salt formations or salt breccia, where stability and integrity are partially ensured by massive non-salt layers or rafts within or close to the cavern.

2 Task

2.1 Primary goals

The primary goals during development of the concept/manual are as follows:

- Ensuring long-term permanent sealing

  The specific goals are:

  - Protecting freshwater bearing and other unrestricted aquifers from contamination from product residues or brine
  - Protecting the environment from the release of flammable and/or environmentally polluting gases and liquids
  - Protecting the surface from unlawful subsidence resulting from convergence or failure of the caverns

- Ensuring long-term stability of the surrounding rock mass
- Application of tried- and -trusted methods and materials as far as possible
- Minimization of time and cost factors to create practical application options for brine production and storage caverns

The measures described in this manual shall be primarily oriented to the conditions in homogeneous salt formations with adequate salt thicknesses above and below the cavern, no competent layers crossing the cavern area and no nearby faults, see Figure 1-1.

This manual shall provide cavern operators with general information and practical procedures on the planning of specific abandonment measures and provide authorities with the necessary background to assess future abandonment programs. Note that this manual should not be considered as a generally applicable set of rules.

2.2 Detailed tasks

(1) ASSESSMENT OF WELL AND CAVERN PRE-SEALING CONDITIONS

- Geological characteristics
- Well and cavern design and present status (tightness e.g.)
- Rock mechanical situation (creep behavior e.g.)
- Thermodynamics (history)
- Hydraulic properties[2] (primary and secondary salt permeability)

(2) REPLACEMENT OF STORAGE FLUID WITH BRINE OR WATER IN THE CASE OF STORAGE CAVERNS

- Comparison of brine and water as displacement media
- Requirements for total displacement in the case of storage media toxic to water
- Cleaning of well bore to ensure optimum bonding during plugging.
- Possibility of reducing the waiting time for temperature equalization by heating brine or water during injection
- Procedure for flooding the cavern

(3) WAITING PERIOD FOR TEMPERATURE EQUALIZATION

- Thermodynamics (estimation of temperature equalization development)
- Prognosis of pressure build up after plugging with the aim to reduce waiting time to a minimum
- Repeated verification of the cavern status

[2] *hydraulic properties* is synonymous with *reservoir-mechanical properties*; the flow in the salt rock is modelled according to Darcy's law.

(4) CAVERN SEALING CONCEPT FOR BOTH STORAGE AND BRINE PRODUCTION CAVERNS

- Basic considerations for tightness and long-term effectiveness
- Selection of borehole section for setting permanent plug (uncased cavern neck and/or cased well)
- Necessary pre-sealing workover of well bore
- Specific plugging concept

(5) MONITORING AFTER COMPLETING CAVERN SEALING & ABANDONMENT

- Development of monitoring procedure and schedule

(6) COSTS

3 Basic CSA concept

3.1 Results of previous SMRI R&D projects

In recent years, SMRI has conducted various basic R&D projects on crucial aspects of salt cavern abandonment which now form the basis for the development of this practice-oriented manual:

- Cavern Abandonment test at Etrez, France /BEREST ET AL.; 1998/.

  A Cavern Abandonment test was performed on a small brine filled cavern in Etrez under SMRI Contract. Results were presented during the 1999 Las Vegas SMRI Meeting /BÉREST ET AL.; 1999/.

  These in-situ tests confirmed previous lab investigations about brine impregnation.

- Controlled testing of the cavern-well cemented casing configuration under high internal fluid pressures
  Bench-scale experiments supplemented by numerical analysis were performed by RESPEC /PFEIFLE ET.AL. ; 2000/

  The study concluded that the pressure of the enclosed brine can exceed the lithostatic formation pressure at the casing shoe by up to 10% without fracturing the casing/cement/formation bond. This is an important piece of information in the context of whether to install the critical plugging element for long term tightness in the open hole or in the cased hole.

- Salt permeability under permeating fluid pressures near (and exceeding) rock salt confining stress
  Experiments at lab scale were performed by LMS, Ecole Polytechnique /BÉREST ET.AL.; 2001/

  When the *effective* stress in the salt (salt matrix stress less the pore pressure) reaches a specific level, micro-fracturing is initiated in the salt matrix and the salt permeability begins to increase. The rate of increase in permeability grows with increases in effective stress in the salt, until the salt permeability essentially increases by several orders of magnitude.

This effect enables a brine-filled cavern to be sealed for an unlimited period of time without leading to uncontrolled fracturing of the surrounding rock, because the brine rate displaced by cavern convergence can permeate into the salt rock and, thus, does not result in subsequent pressure increase in the cavern.

- Numerical rock mechanical and reservoir-mechanical modeling of a sealed cavern in homogeneous rock salt (domal or thick bedded salt) with a comprehensive consideration of the ranges in cavern parameters and salt behavior that might be encountered in caverns scheduled for plugging.

  The *High Pressure Cavern Analysis* was performed by IUB and KBB /ROKAHR, 2002/). Main conclusion: The pressure build up in sealed, brine-filled caverns will not lead to any significant long term rise above lithostatic pressure in the majority of solution mined salt caverns, and will therefore not give rise to any uncontrolled expulsion of the brine. Exceptions cannot be excluded e.g. in case of very tall and deep caverns.

  There is however one crucial restriction: the brine and the surrounding rock must be close to thermal equilibrium before plugging because a temperature increase in the brine as a result of reheating could give rise to a dangerous increase in pressure.

  Summary of the numerical sensitivity analysis:

  o Location-specific rock mechanical analysis including monitoring before plugging should be undertaken to estimate the pressure build-up over time to be expected in the cavern scheduled for plugging. This ensures that the brine penetration rate adequately compensates for the pressure build-up associated with the volume reduction rate (convergence). The analysis can be based on lab and/or in-situ creep tests.

- o The reheating of the brine needs to be looked at especially in young and/or large caverns, where brine warming is much slower, in deep caverns, where the initial temperature gap is likely to be large, in caverns where the brine temperature is still strongly influenced by the solution mining process, and storage caverns which were flooded with cold water as part of the abandonment procedure.

  The rise in temperature together with creep and brine permeation over time enables the pressure increase over time to be determined. This then needs to be rock mechanically assessed to rule out the uncontrolled expulsion of brine as a result of a impermissibly high pressure gradient.

A summary of all the previous CSA research activities carried out by SMRI to 2002, and which forms the basis for this manual is found in /RATIGAN, J.; 2003/

3.2 Basic existing considerations for oil and gas wells

The oil and gas industry has accumulated a great deal of experience over many years in the abandonment of boreholes drilled for the exploration and production of oil and gas. The special requirements for abandonment are laid down in various national regulations. It is therefore prudent to look in greater detail at the standard methods used by the oil and gas industry so that this experience can be used beneficially for the development of similar regulations for cavern abandonment. The review of oil and gas well abandonment practice was therefore conducted in the following by looking at the regulations existing in Germany and Texas as typical examples.

3.2.1 Germany

The design of the plugs in an abandoned well must be carried out in accordance with the German mining regulations for deep well drilling (BVOT). These regulations are issued by the Oberbergamt Clausthal-Zellerfeld (Bureau of Mining), which specify that plugging in accordance with Section 35 BVOT should be carried out as follows:

- A liquid-tight and gas-tight plug should be achieved and any detrimental impact on groundwater should be avoided.
- The borehole should be completely plugged (by cemented sections and intervening mud sections).
- Plugs should be specifically placed to seal off exploitable oil, gas and salt deposits from exploitable storage and 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.
- Special plugs should be placed in zones where difficulties were encountered during drilling or production.
- These special plugs should consist of suitable cement or other suitable solids in connection with mechanical seals where required. Suitable measures should also be undertaken to ensure that there is good bonding between the solids and the casing or borehole walls.
- Special plugs should be in place, covering the zone extending 250 m above and 250 m below the deposit.
- Within thick salt deposits, special plugs should be in place as a minimum in the top and bottom sections extending at least 100 m into the salt and 50 m into the surrounding rock.
- In uncased wells, a special plug at least 100 m long should be placed in the deepest casing string across the casing shoe, or that a mechanical plug be emplaced with a special plug extending for at least 50 m.
- A special plug should be emplaced in the borehole from the surface to a depth of at least 100 m. If freshwater horizons scheduled for use are located within this zone, then the special plug must be relocated accordingly.
- All casing strings within the borehole have to be removed so that nothing is left to jeopardize subsequent use of the ground at the surface; in the event that the remaining casing lies less than 2 m below the ground surface, the borehole should be additionally protected by a concrete slab.
- In general, all of the equipment installed in the borehole (e.g. packers, tailpipes, etc.) should be removed from the casing.

The design of the plugs should also ensure that the borehole is permanently stable and tight. The plug(s) in an abandoned well therefore have at least two functions: a static function and a plugging function.

The design of the overall plug is shown in Figure 3-1 in accordance with BVOT regulations.

3.2.2 Texas

Regarding the legislation applying in Texas, well plugging is covered by Rule 3.14 of the Oil and Gas Division of the Texas Railroad Commission.

General plugging requirements state that a well should be plugged to ensure that all formations bearing useable quality water, oil, gas, or geothermal resources are protected. Cement plugs shall be set to isolate each productive horizon and usable aquifers, and should have sufficient thickness to isolate sections of the well bore and withstand downhole conditions.

Cement plugs shall be placed by the circulation or squeeze method through tubing or drill pipe. All cement for plugging shall be an approved API oil-well cement without volume enhancers and shall be mixed in accordance with API standards.

The general requirement is that pipe and non-retrievable junk should not be cemented in the well without prior approval.

For onshore or inland wells, a 10-foot (3 m) cement plug shall be placed in the top of the well, and casing shall be cut off 3 feet (1 m) below the ground surface. The general requirement is that cement plugs, except the top plug, shall have sufficient slurry volume to fill 100 feet (30 m) of hole, plus 10% for each 1,000 feet (300 m) of depth from the ground surface to the bottom of the plug.

During plugging, mud-laden fluid of at least 9 ½ pounds per gallon with a minimum funnel viscosity of 40 seconds shall be placed in all portions of the well not filled with cement or other approved alternate material. The hole should be in a static condition at the time the cement plugs are emplaced.

In general, plugging a well bore without production casing or open-hole completion requires the isolation of any productive horizon, or any formation in which a pressure or formation water problem is known to exist, by cement plugs centered at the top and bottom of the formation. Each cement plug must generally comply with the same requirements as described in the previous paragraphs regarding the height of 100 ft (30 m) plus 10% per 1,000 ft (300 m) depth.

3.2.3 Summary

In short, both regulations reviewed above specify plugging with cement in the hydrocarbon-bearing zone, the last cemented casing shoe, and the top of the well directly beneath the surface. These regulations are primarily designed with the objective of:

- protecting humans and nature
- protecting useful water horizons from contamination
- isolating the former production horizons
- removing all of the technical equipment previously installed in the well
- sealing off any known problematic zones

In general, the plugging of caverns is also dealt with alongside the previously mentioned regulations for the plugging of oil and gas wells, however, the regulations do not contain any special plugging procedures specifically designed to cope with the special features of caverns. The aforementioned specifications for the abandonment of oil and gas wells in Germany and Texas provide initial ideas on their possible applications for plugging and abandoning brine-filled caverns.

3.3 Possible consequences for caverns

Salt cavern wells, designed for brine production or for storage, provide a number of unique features which influence the design of plugs, the material used for the plugs, and the time when plugging can be carried out after cavern operation has been shut down.

The regulations laid down for oil and gas wells are only of limited applicability because e.g. the term *deposit* is not directly applicable to caverns because in the case of caverns this would only apply to the actual cavity. The analysis below therefore ignores several of the specifications laid down for the oil and gas industry because the special conditions in caverns are not covered by these regulations.

Nevertheless, some of the national regulations on the abandonment of boreholes are useful because some of them can be directly applied, such as the special plugs within casing which cover the zone above the last casing shoe, top salt, valuable aquifers and shallow zones, see Figure 3-2. These aspects play a special role for the selection of materials for the plugs because the relatively shallow depths of most caverns compared to oil and gas wells means that continuous cementation to the surface has technical and cost advantages compared to alternating cement plugs and mud zones as recommended for oil and gas wells.

3.4 Basic considerations for tightness and long-term effectiveness

The plugging concept developed by SMRI is based on

- The long-term effective permanent containment of brine in the cavern with the exception of very minor losses over a very long period of time as a result of brine permeation into the surrounding salt.
- The long term stability of the surrounding rock-mass due to the demonstration of an equilibrium pressure close to the lithostatic pressure in the sealed cavern.

This concept requires that consideration is already given during design and subsequent installation to ensure that the *borehole plug* remains permanently tight. A major requirement for the specific abandonment concept is therefore to guarantee a *permanently* tight borehole plug.

Unlike similar requirements for the safe disposal of radioactive and toxic chemical waste, another factor in cavern abandonment is that the solution must be economically acceptable, e.g. also feasible for the operators of major brine production fields.

Another aspect is confirmation of the tightness of the plugging measures after installation, and the question of monitoring and maintenance. Unlike other areas of engineering, repairing already installed cavern seals would be extremely expensive if it became necessary, because the well would have to be re-opened down to the cavern neck. The aim of the abandonment concept proposed in this study is therefore to develop a maintenance-free concept which also requires no permanent in situ measurement to monitor the very slow processes taking place over very many years of up to decades.

Monitoring is thus limited to continuation of surface subsidence measurement for a limited period of time.

An international group commissioned by the French regulatory authorities was requested in 2002 to prepare a report on major trends in salt mining techniques and abandonment methods /BÉREST ET.AL., 2004/. In this paper, monitoring durations of 20 to 30 years are discussed for brine production caverns including those constructed in very inhomogeneous salt formations. Because the manual presented here only deals with caverns constructed in homogenous salt formations (salt domes or thick bedded salt formations), with confirmed long term stability, much shorter monitoring periods are acceptable.

3.5 Borehole section requiring plug

The plug crucial for the tightness of the abandonment measure can basically be installed in various parts of the borehole, see Figure 3-3.

(I) In the last cemented casing if the cementation is proven permanently tight

(II) In the cavern neck (open hole the cementation) below the casing shoe or

(III) In a window milled in the lower section of the last cemented casing to provide an optimal bond between the cement and the rock and not rely on existing cementation

These three options are discussed in the following because the selection of a plug location is closely linked with the associated consequences for technical implementation.

Option I: Decisive plug for sealing within last cemented casing

The simplest technical solution and therefore the most cost-effective option is to plug the borehole by cementing the inside of the last cemented casing, see Figure 3-4. For this method to be feasible, it is crucial to first confirm the mechanical integrity (tightness) of the existing cement between the casing and the formation, especially across the casing shoe e.g. by performing a mechanical integrity test.

The zone around the casing shoe of the last cemented casing string is particularly critical for the tightness of the well. The cement bond of the last cemented casing string can suffer from the many years of pressure and temperature fluctuations during storage or leaching operations, as well as the consequences of work-over activities. This is why it is so important to confirm the integrity of the casing when production operations have been terminated.

The basic aspects upon which the viability and applicability of Option I are based were discussed in the study funded and already quoted by SMRI /PFEIFLE ET. AL.; 2002/, cf. Chapter 3.1.

Option II: Decisive plug for sealing within cavern neck (open hole) below last cemented casing

If a mechanical integrity test of the last cemented casing does not prove sufficient tightness or if such a test cannot be performed by any reason, an alternative to Option I is to set a cement plug in the cavern neck below the casing shoe, see Figure 3-5, provided that an open hole of sufficient length and suitable cross section is available.

The open hole is generally a good place to achieve optimal bonding between the cement and the rock salt, and thus to create a plug which properly seals the borehole.

Option III: Decisive plug in window milled in casing

If the geometry of the cavern neck is unsuitable for the emplacement of a sealing and load-bearing plug because of e.g. an elliptical cross section, insufficient length, or excessive diameter, a third option would be to mill out part of the casing in the lower section of the last cemented casing string and to underream back into the salt formation to create a direct contact between the cement and the formation for optimal bonding of the cement in the plug, see Figure 3-6.

Having a plug in an uncased part of the borehole is definitely an advantage in the context of ensuring the obligatory long-term integrity of the plug because direct bonding is possible here between new cement and the formation in the absence of any extraneous material such as old cement from the casing cementation, and the casing itself.

In general, it is not possible here to establish a general rule for either the specific location of a sealing plug or the optimum length because this is directly dependent on the unique situation in each cavern and therefore always has to be considered on a case-by-case basis.

3.6 General Concept and Strategy

3.6.1 Basis SMRI

Before being able to abandon a cavern permanently without any need for future maintenance, the product (storage caverns) or the blanket (brine production caverns) first need to be removed and before the well is plugged.

The abandonment of caverns generally consists of the following phases:

Phase I: Replace product or blanket with brine or water

When **gas caverns** are involved, they first need to be flooded with brine or water to guarantee the long term stability of the caverns because there is no certainty that gas sealed in under high pressure will remain safely contained for very long periods of time after cavern abandonment.

When caverns containing hydrocarbon product or brine production caverns (hydrocarbon blankets) are involved, it is also necessary to replace the product with brine or water because there is otherwise no long term guarantee that the hydrosphere and atmosphere can be protected permanently from the risk of contamination from expelled product or hydrocarbon blanket.

Phase II: Waiting time until temperature equilibrium is reached between the brine and the surrounding rock

Replacing storage product with cold brine or water cools down the rock surrounding the cavern. The specific amount of cooling depends on whether only a small volume of blanket was replaced or whether the whole content of a gas cavern was replaced by water, in which case there is further cooling as dissolution heat is lost during saturation of the water with salt.

Because the warming up of the brine[3] in a closed cavern may result in an unacceptably high pressure gradient in the initial stages in particular, it is necessary to wait for a certain time to allow the temperature in the cavern/ rock system to sufficiently approach thermal equilibrium. Simulations have shown that the time involved until adequate temperature equilibrium has been reached can be several years or decades under unfavorable circumstances, like large initial temperature deviation and / or large cavern volume. Plugging before reaching the adequate equilibrium may result in uncontrolled expulsion of brine.

An important part of the planning for a cavern abandonment measure is therefore careful consideration of the temperature effect and/or the inclusion of measures right from the start which can restrict the level of temperature disequilibrium.

The following factors influence the rise in pressure in sealed caverns:

- **Re-heating of the brine** due to heat flow from the surrounding rock
- **Volume convergence**, which declines with increasing internal pressure;
- **Brine saturation**, a phenomenon that needs to be taken into consideration when flooding with water but rapidly comes to a stop;
- **Brine permeation** under consideration of primary and secondary permeability of rock salt.

[3] warming up of brine results in volume expansion in an open or pressure increase in a closed cavern.

- **Leak rate**: Even if a cavern well is considered technically tight, there is likely to be a small leak rate of a few cubic meters brine per year. Since this rate is extremely small, since it is impossible to determine the actual rate on the long-term and since any leak rate will *reduce* the pressure buildup in the sealed cavern, it is recommended to not consider this effect in the prognosis of the pressure build-up in the sealed cavern.

For each cavern candidate to be abandoned and applying the SMRI concept, a crucial part of the implementation consists in forecasting

- the cavern-specific impact of convergence, re-heating and brine permeation on pressure development, as well as the overall pressure build-up evolution after plugging;
- the duration of the necessary waiting time before definitive closure;
- the final equilibrium brine pressure demonstrating that fracturing pressure will not be reached on the long term.

Phase III: Cavern abandonment

After sufficient reheating of the brine, proven by numerical simulation, permanent sealing of the cavern can start.

When the plug is emplaced, the pressure in the cavern corresponds to the head pressure of the brine column i.e. atmospheric pressure. After plugging, the internal pressure at the roof of the cavern gradually builds up at a decreasing rate until it reaches the undisturbed formation pressure or a slightly higher value according to the results of the numerical analysis performed by IUB /Rokahr et.al., 2002/.[4]

At this point, and under these pressure or stress conditions, there is an increase in the permeability of the rock in the cavern roof. As a result, the continuing reduction in cavern volume in response to convergence no longer leads to a further increase

[4] In contrast to these theoretical results, in-situ tests performed at two sites in France in bedded salt formations resulted in internal pressures significantly lower than the formation pressure /BÉREST ET. AL.; 1998/.

in pressure but causes the brine displaced as a result of the convergence to penetrate the rock. Because of the minor difference between the internal and external formation pressure, the leaching rates involved are only around a few cubic meters per year or less for shallow caverns.

The design of the plug must comply with the regulations and be permanently stable and safely seal off the well. For the reasons mentioned earlier, every plug consists of at least one static load-bearing element and one plugging element. This means that when cementing a borehole with an open base, a mechanical plug is required to bear the weight of the cement column injected into the borehole.

Depending on their specific type of use, caverns can be divided into three major groups:

- brine production caverns
- liquid product storage caverns
- gas storage caverns

These different cavern types involve different completions, the risk of contamination by the medium in the caverns, and other specific problems which need to be taken into consideration in the cavern abandonment planning. The following discusses the procedures for each different type of cavern.

3.6.2 Brine production caverns

Brine production caverns are usually the simplest to prepare for plugging. Brine can be left as it is in the cavern. The first step of the abandonment program involves removing the blanket medium[5] and subsequently pulling out the leaching strings. Cleaning the relevant zones planned for positioning the plugs may be necessary especially if an oil blanket was used.

The cavern is then ready for abandonment when the brine is completely saturated and is in sufficient equilibrium with the formation temperature. The necessary

[5] Part of the brine production caverns do not use blanket. However most of those caverns are developed in thin bedded salt structures (non-homogeneous salt formations according to the terminology used in this manual). Caverns in such formations are not covered by this manual as mentioned before.

waiting period for temperature equalization in a brine cavern is probably much shorter than in the other cavern types because the brine has already been in the cavern for a long period of time and because the volume of the blanket, which was been replaced, is negligibly small compared to the volume of the whole cavern.

Generally, brine production caverns can be sealed using any of the three proposed sealing options:

I. plug in last cemented casing
II. plug in cavern neck
III. plug in a milled window in the last cemented casing

Selection of Option I requires prior confirmation of the integrity of the last cemented casing string.

3.6.3 Gas storage caverns

Plugging a gas storage cavern involves a complex preparation procedure: first, the gas has to be removed from the cavern and replaced by brine or water. This involves reducing the gas pressure in the cavern because lower pressure considerably reduces the risks attached to the subsequent work, and also simplifies injection of the brine or water. However, the pressure must still be high enough to guarantee the stability of the cavern for the whole filling period.

When the pressure has been reduced to the permissible minimum operating pressure, the subsurface safety valve is removed – if available - and replaced by a dummy. The brine injection string is then snubbed into the cavern under gas pressure.

This is followed by gas removal and brine / water injection into the cavern. When the cavern has been completely filled, the brine injection string and the gas completion can be removed. However, a short interruption in the flooding process may be recommended when the gas / brine interface reaches some meters below the last cemented casing shoe. At this point, a waiting period to allow the brine to approach saturation may reduce the risks of undesirable salt dissolution at casing shoe. For this, the brine/product interface and brine density have to be regularly monitored during the flooding process.

Because a gas cavern has to be completely filled with brine or water, there is a significant disturbance in thermal equilibrium between the fluid and the rock. The extent of this disturbance can be reduced by preheating the injected brine or water. In all cases, a longer waiting period is probably involved then in the case of comparable brine production or liquid product storage caverns.

During this waiting period, gas residues will probably collect in the roof of the cavern. This gas must be vented periodically. Once the pressure build up rate due to reheating has dropped to an acceptable value, cavern sealing proper can begin using one of the three alternatives already described.

3.6.4 Liquid product storage caverns

Preparations for the abandonment of a liquid product storage cavern involve replacing the product in the cavern with brine or water. The concentric casing acts as a kind of counter-current heat exchanger because the injected cold brine or water is heated up to a certain extent by the displaced product. This means that there may be less disruption to the temperature equilibrium than in gas caverns.

Once the product has been removed, it may then be necessary to also remove product residues remaining in the cavern neck if this zone is to be cemented. The residues in the last cemented casing string should also be removed. This can be done either mechanically or by cleaning with a suitable liquid – to ensure that there is a good cement bond.

Apart from these aspects, the remaining parts of the abandonment procedure are similar to those of a brine production cavern. The production strings can be removed once the cavern is completely filled with brine.

This phase is followed by a waiting period so that the brine reaches saturation, and especially to ensure that sufficient temperature equilibrium takes place, see chapter 5 *Assessment of well and cavern conditions…*. During this period the numerical predictions should be compared with in-situ data and adjusted if needed. The cavern borehole can then be plugged using one of the options described in Section 3.5.

4 Assessment of well and cavern pre-plugging conditions

4.1 Introduction

Before specific planning of any abandonment measure can be carried out, it is first necessary to have location-specific data on the cavern including geological and geotechnical information like creep parameters, initial rock temperatures. It is also important to compile data on the operational history of the cavern (construction and operation); this involves e.g. the injection and withdrawal schedule applied in the case of a gas cavern which are significant for assessing the temperature regime at a later date.

4.2 Geology

This manual is based on the option *Cavern solution-mined in homogeneous salt formations like salt domes and thick bedded salt*, see Figure 1-1. This is because the SMRI basic research carried out to date is all oriented to the relatively simple conditions in such formations where it can be assumed for the sake of simplification that:

- The stress redistribution only takes place in salt rock which is assumed to be homogenous.
- That the brine permeation takes place exclusively in homogenous salt surrounding the cavern.

The aim of the geological evaluation is firstly to assess and evaluate possible non-saline beds within the formation cut by the cavern or close to the cavern wall, which may represent points of weakness where there could be increased brine migration. This migration may however not be a problem as long as connection with any drinking water-bearing aquifers can be excluded.

Another aim of the geological assessment is to describe the geological conditions of importance for a subsequent rock mechanical analysis.

4.3 Cavern and well data

The following data are important for abandonment planning; most of them will be available, some may have to be provided by additional tests:

- leached gross cavern volume
- brine-filled net cavern volume in case of storage caverns
- recent sonar surveys conducted in the cavern
- compressibility of the brine filled cavern
- cavern location
- drilling and casing program, particularly the last cemented casing string
- well completion in case of storage caverns
- logs for evaluation of cement and potential corrosion of last cemented casing
- temperature logs.

4.4 Operational history

In Chapter 3 *Basic CSA Concept*, there was a discussion on the significance of brine temperature in relation to the undisturbed formation temperature field. It is important to have information on the operational history so that the development in brine temperature can be forecast and its impact assessed:

- In **brine production caverns**, the leaching data are important: leaching rate over time, shut in periods, where possible also in situ brine temperatures (which are often measured in connection with sonar surveys).
- In the case of **liquid-hydrocarbon caverns**, the operational history also plays a major role if the product in the case of strategic storages was displaced from the cavern with brine or water from a storage pond (temperature drop as a result of the injection of cold water and dissolution heat). The rates, durations and injection temperatures involved here may also be used for the evaluation and prediction of temperature equalization after cavern abandonment

- The injection and withdrawal operations (rates, duration) are important during the last period of operation of **natural gas storage caverns** because this information helps assess the temperature field in the rock. Standard computer programs like the GTI SALT CAVERN THERMAL SIMULATOR can be used here to simulate the thermodynamic behavior.

4.5 Rock mechanics

The sensitivity study conducted on behalf of SMRI /ROKAHR, 2002/ revealed that, brine filled caverns can be permanently sealed *under suitable conditions* in a safe and environmentally compatible way after achieving sufficient temperature equalization with the surrounding host rock

Despite these general findings, it is vital in each specific case that location-specific rock mechanical data on at least one representative cavern within the field is acquired so that an investigation can be carried out to confirm that the pressure build-up arising from convergence after plugging can be compensated for by the permeation of brine into the surrounding rock salt formation – if this cannot be confirmed, there is a risk that uncontrolled fracing will take place. This is of special importance in the case of very tall and/or large caverns.

If no data is available on the material properties of the salt or operational data on cavern convergence, this data has to be assumed on the basis of empirical data. A sensitivity analysis must be carried out to compensate for the uncertainties in estimating the data used in the evaluation.

5 Assessment of well and cavern condition during waiting period and after plugging

5.1 General

The aim of the assessment is to forecast the expected temperature development after flooding, the pressure build-up in the brine-filled cavern from the time the cavern was plugged until the conditions in the cavern become largely steady state. This is important because it is necessary to establish that there will be no uncontrolled expulsion of the brine through macro fracs in the salt rock.

The project-specific, time-dependent pressure build-up rate is a product of

- re-heating of the shut-in brine by the surrounding salt formation
- volume reduction of the cavern as a result of convergence
- re-leaching effects (in most cases expected to be negligible)
- brine permeation into the surrounding rock.
- leak rates (to be neglected in case of technically tight caverns, see sec. 3.6 on the same subject)

The basis for the cavern abandonment concept developed by SMRI is that the pressure build-up resulting from the first three factors only reaches a level slightly above the lithostatic formation pressure, after which brine permeates into the rock salt surrounding the cavern as a result of increased rock salt permeability, a process which compensates for the pressure build-up. This is the only process which prevents a further increase in pressure which would lead to uncontrolled fracturing of the rock and uncontrolled expulsion of brine.

It is therefore necessary to forecast the influence of the different factors and the resulting pressure increase over time for each specific case based on data compiled in Chapter 4 *Assessment of well and cavern pre-sealing condition*.

5.2 Thermodynamic situation

Once the fresh brine or water is in place in the cavern, it becomes re-heated by the warmer surrounding rock. This effect starts rapidly and then tails off as shown in Figure 5-1. In the early stage rapid re-warming can give rise to high pressure gradients in sealed caverns which can considerably exceed the pressure gradients associated with convergence, if the well was plugged too early. The forecast of the increase in brine temperature and the resulting rise in pressure can be based on two methods or a combination of the two:

- Running temperature logs in the brine-filled cavern at certain time intervals or permanently prior to installation of the plug and monitoring the temperature for a long period of time and then extrapolating the temperature development forward for a period beyond plugging.
- Numerical simulation of temperature development making allowance for the previous history (leaching process, storage process, flooding with brine or fresh water).

5.3 Rock mechanics

The expected pressure build-up in the plugged brine-filled cavern depends on various parameters such as cavern height, depth, creep behavior of the salt and the reservoir-mechanical properties of the salt before and after reaching the point where there is an increase in the permeability of the salt.

These complex relationships most likely require numerical simulation of at least a representative cavern within the field. This is the only way of confirming that pressure build-up as a result of convergence is compensated for in the long term by the permeation of brine into the surrounding rock.

6 Product replacement and waiting time

6.1 Water vs. Brine Injection

In general, it is possible to use either brine or water to displace the storage product or blanket. If available, saturated brine is the preferred medium because the injection of freshwater causes further dissolution of the salt and therefore additional cooling of the resulting brine; furthermore it will alter cavern conditions, possibly at the casing seat.

6.2 Preparation

6.2.1 Measures to achieve optimal removal of storage product or hydrocarbon blanket

Because different scenarios are involved when removing the storage product from each type of storage cavern or blanket in case of brine production caverns, it is worthwhile looking at the various aspects in detail.

Proper cleaning is a major factor in creating a successful plug because hydrocarbon residues can jeopardize formation of the desired bond between the plug and the formation and therefore jeopardize the long term integrity of the plug. After setting the plug, it is good practice to circulate the cased hole clean to remove any further hydrocarbon contaminates prior to cementing ensuring no cementing problems.

Product residues remaining in the cavern *after* displacing the product is however not problematic after successful installation of the plug.

6.2.2 Brine production caverns

Only minor volumes of blanket (hydrocarbon liquids, nitrogen or air) must normally be removed in the case of brine production caverns. The brine can be left unchanged in the caverns so that no expensive replacement operations are required.

6.2.3 Liquid product storage caverns

When a crude oil or hydrocarbon product storage cavern is flooded, brine or fresh water is injected into the existing production string so that the liquid hydrocarbons can be displaced from the cavern to the surface through the annulus between the production string and the last cemented casing string.

Problems can arise here associated with:

- persistent liquid hydrocarbon residues
- liquid hydrocarbon product trapped in pockets which is very difficult to remove – complete emptying is therefore difficult to achieve.

One of the methods for removing liquid hydrocarbon product is slow re-leaching to smooth out the contours of the cavern walls and to dissolve and break up any pockets that may be present. Another option is to inject a gaseous medium to displace the trapped product. The re-leaching option involves costs for the work-overs needed to properly position the leaching strings. Because of the high costs involved, this option only makes sense - if at all - if large volumes of trapped liquid hydrocarbons are expected.

In the gaseous displacement option using e.g. air or nitrogen, the aim is for the gas to displace the liquid hydrocarbon product by lowering the pressure in the cavern and push liquid hydrocarbon product out of the pockets. This option is also highly complex and is therefore basically only a theoretical possibility.

This raises the question of whether the expense involved in removing all of the product prior to abandonment is justified if the presence of these residues does not jeopardize the proper functioning of the plug in the borehole. Hydrocarbon residues in the cavern itself are not expected to be a hazard once the plug is in place.

6.2.4 Gas storage caverns

Before a flooding string is installed in a gas cavern, the pressure of the cavern should be reduced:

- to displace as much of the stored gas as possible into the grid
- to establish an internal pressure which is lower than the pressure due to the brine or water column in the later flooding string.

  In this way the water does not have to be pumped in against the gas pressure. The pressure however needs to be above the minimum allowable pressure defined for the period of time required for the flooding process.

A snubbing unit is required to run in the flooding string under gas pressure. This snubbing unit seals off the annulus (which is under gas pressure) from the atmosphere. When the snubbing unit is in place, the subsurface safety valve – if installed – is first removed with a wireline. The water flooding string is then run into the well through the snubbing unit into the cavern. In some cases a flooding string is permanently in place, thus there is no need for an extra string to be run in.

6.3 Option: Reduced waiting time for temperature equalization

6.3.1 Why reduce the waiting time?

In the case of gas or liquid product caverns, the storage product has to be replaced by fresh brine or water before abandonment can proceed. Injection of the fresh brine or water usually causes a considerable temporary temperature reduction in the cavern. If fresh water is used, this cooling effect is strengthened further by the leaching of the salt during saturation.

The cooling effect during brine or water injection is counteracted to a certain extent by the counter-current heat exchange effect in the borehole where the stored warm liquid or gas, flowing through the annulus, warms up the cold brine or water being injected through the flooding string. This effect is however negligible for gas caverns because of the low heat capacity of gas. In the case of liquid product caverns, the heat exchange effect is stronger but cannot fully compensate for the cooling effects.

Once the fresh brine or water is in place in the cavern, it becomes re-heated by the warmer surrounding rock. This effect starts rapidly and then tails off as shown in Figure 5-1.

Simulations conducted by IUB and KBB /ROKAHR; 2002/ on behalf of SMRI and earlier studies by Bérest and Brouard, /BÉREST ETAL, 1999/ revealed that after a cavern has been flooded with brine or water, there is often a very long waiting period until temperature equalization has reached an acceptable level. The required waiting period depends on various aspects including the temperature difference between the injected fluid, the temperature of the stored medium when the injection temperature is much lower than the undisturbed formation temperature (which is usually the case) and the cavern volume (larger volumes require longer temperature equalization time).

Examples for central Europe:

• average water temperature of a river	T =	8 46	deg C deg F
• initial formation temperature at 1200 m (4000 ft) depth	T =	35 95	deg C deg F
• temperature difference	ΔT =	27 81	K deg F

If a waiting period lasting many years is involved before temperature equalization has reached a satisfactory level, the operator basically has two options at its disposal:

(1) **Natural temperature equalization**: observing the temperature and periodically releasing brine when the maximum pressure has been reached – with associated expenses for a lengthy period for maintenance staff, maintenance and workover

(2) **Accelerated temperature equalization:** heating up the brine or water during flooding to lower the temperature difference between the brine in the cavern and the surrounding rock. Heating up the enormous volumes of brine or water during flooding will result in high expenses mainly for energy.

Option (2), heating up the water/brine before flooding is discussed in detail in the following sections.

6.3.2 Technical methods for reducing waiting time by heating brine or water

The cavern can be flooded with either saturated brine or fresh water. Brine / water should be heated up prior to flooding to a level close to the formation temperature. Given the average water temperature of approximately 8°C in central Europe, and an original formation temperature of around 35°C, the flooding water should to be heated up by 20 to 30 K depending on the depth of the cavern. The beneficial heat-exchange effect when displacing the storage fluid will reduce these temperature differences und has therefore also to be taken into consideration.

The additional heating required is generated using a heat generator and a heat exchanger positioned close to the cavern. This equipment can be leased for the period of the operation if required and is available in containers.

The fuel gas can be acquired directly from the cavern when a gas storage cavern is being flooded. In this case, the gas can be transported via a reducing station and a pressure regulator to the heating unit.

The heat needed for the pre-heater can be estimated as follows:

$$P = \frac{Q \cdot \rho \cdot c_w \cdot \Delta T}{\eta}$$

Where

P		W	power of heater
η	0.7		efficiency of pre-heater
Q		m³/s	flow rate
ρ	1 000	kg / m³	density of water
c_w	4 200	J / kg	specific heat of the water
ΔT		K	selected temperature difference in K

Sample for typical gas cavern size in domal salt:

V	500 000	m³	cavern volume to be flooded
Q	150	m³/h	flow rate
ΔT	15	K	selected temperature difference in K
Δt	139	d	flooding time
P	**2 625**	**kW**	**power of heater**
ΔW	**12 500 000**	**kWh**	**energy for heating**

6.4 Basic procedure

The **preparations** for replacing product or blanket primarily involve the work that needs to be carried out on the borehole and the cavern in order to inject brine or water, with pre-heating if applicable, and displace the product.

During the **product / blanket replacement phase**, the product or blanket is displaced from the cavern by brine or water. If it is planned to set the decisive plug in the last cemented casing, it is first necessary to prove the integrity of the bond between the cement and the formation, because the integrity of the plugged well will depend both on the existing and the new cement bond.

During the flooding phase, the only monitoring involves regular control of the product/ brine interface level. This can be done using three approaches.

(1) Frequent control of the interface-depth using a graph of “cumulative cavern volume versus depth“. The actual fluid level can be determined from the injected brine volume.

(2) Occasional direct measurement of the fluid level by Gamma-Gamma logging to control the results of (1) and for calibration.

(3) Evaluation of pressure difference at well head

When the product / brine interface reaches some meters below the last cemented casing shoe, a short interruption in the flooding process is recommended. This will allow the brine to approach saturation and thus reduce the risks of salt dissolution behind the casing shoe.

When the product has been replaced, the injection string is removed from the cavern.

During the **waiting time,** the brine and the surrounding rock are allowed to achieve the required level of temperature equilibrium. The required waiting period significantly depends on the type of cavern, the initial temperature differences and particularly the cavern volume.

During this phase, periodic or continuous measurement of cavern head pressure and in-situ brine temperature is required. It will also be necessary periodically to remove small quantities of brine to compensate for convergence effects. In the case of liquid hydrocarbon storages, product may appear from time to time at the well head if it is released from small traps and pockets in the cavern.

6.5 Summary of the basic work program for product or blanket replacement including waiting time:

(1) Preparations for replacing product or blanket

- Gas storage caverns only
    - Withdrawing gas down to minimum pressure to enable injection of the brine or water
    - Removing the subsurface safety valve where necessary and replacing it by a dummy
    - Snubbing in a flooding string down to the cavern sump

- Liquid and gas storage caverns:
  - Optional: installing a heat exchanger to heat up the flooding brine / water
  - Making brine or water available in the necessary quantities and flow rates
  - Installing a flare if necessary to burn off the residual gas in case of natural gas or liquid gas storages (LPG, ethylene etc.)

(2) Replacing product or blanket

- Injection of brine or water through the debrining / flooding string (brine or water pre-heated if planned)
- Displacement of storage product or blanket
- Flaring-off the displaced residual product or blanket if necessary
- Regular determination of the product / brine level by calculations and measurement.
- Removing the debrining / flooding string

(3) Waiting time

- Periodic release of brine if maximum pressure is reached
- Regular measurement of cavern head pressure and in situ brine temperature and or extrapolating temperature development vs. time.
- Prediction of brine temperature development based on history matching
- Estimation of earliest point of time to start cavern plugging

7 Cavern plugging concept

At the end of the waiting time when the necessary thermal equilibrium has been reached, such that the cavern pressure will increase after shut in only to a level always lower than the maximum allowed, work can begin on the actual plugging.

7.1 Plug material requirements

As already discussed, it is generally recommended that **cementation is continuou**s to the surface because cavern access wells are usually shallow compared to oil and gas wells, and the mixing of mud to fill in the gaps between individual cement plugs would involve extra expense and therefore not represent any real cost savings (cf. Chapter 3.3).

The cement mixture varies depending on whether it is positioned in open or cased hole.

Special properties for optimal adhesion are required when the plug is in direct contact with the surrounding salt. The cement used here needs to have high density and high strength when hardened, combined with low porosity and permeability. The cement slurries should be as dense as possible so that the hardened cement is as compact as possible. The slurries also need to be mixed with saturated brine to prevent any leaching of the borehole walls of the borehole in the salt.

The cement should also not suffer any shrinkage during hydration so that no micro-annulus is formed between the hard cement and the wall of the borehole or the casing. Blast furnace cement is recommended here because this only contains a very small percentage of Portland cement so that the amount of shrinkage is also lower than conventional cement.

7.2 Pre-plugging workover for gas caverns (European standards)

Gas caverns in Europe are normally completed with a production string which is hung in the well head and fixed at depth in a unit consisting of an anchor seal, and a permanent packer with tailpipe. More recent caverns are also fitted with a

Subsurface Safety Valve (SSSV). As much of this completion as possible should be removed before filling the casing with cement.

If a completion with an SSSV is involved, the SSSV must be pulled out of the hole, and the gas production string unlatched from the permanent packer and then removed. This step is not required if a tubingless completion was in place, where the production string is cemented in place.

If a tailpipe section is in place consisting of a permanent packer and a tailpipe, this also needs to be removed to ensure that nothing stands in the way of good cementation results in the underlying part of the casing shoe. It is recommended here that the packer is milled out and caught at the same time by a special tool. Depending on the procedure selected, the whole tailpipe section can then be removed or run out of the casing shoe in a controlled way and disposed of in the cavern.

If the tailpipe is simply cut off or shot off, there is a danger that it may become stuck in the casing shoe or in the cavern neck and hinder or complicate the subsequent plugging activity.

Another option is to leave the whole tailpipe section in the last cemented casing string. In Germany this would need to be approved by the authority because the general rule is for all installations to be removed from the borehole. This option will therefore only be approved if removal or lowering to the base of the cavern was not possible for technical reasons.

7.3 Additional cleaning activities

In crude oil caverns, the annulus between the last cemented casing and the tubing is filled with crude oil right up to the cavern head during the operations period. Crude oil flows through the annulus during injection and withdrawal. Because of the temperature gradient in the borehole and the possible precipitation of crude oil colloids, deposits form in the borehole consisting of solid paraffin mixed with crude oil colloids, sediment and rust particles.

If a tight cement plug is to be installed in the last cemented casing, it is very important that the old casing surface is basically oil-free.

The stored crude oil is largely displaced by brine or water during the preceding *flooding* stage of the abandonment procedure. Crude oil residues probably still remain on the cavern walls as well as in oil traps/pockets in the cavern. It is also likely that crude oil deposits remain on the last cemented casing. Such deposits can build up layers several centimeters thick on steel surfaces. To achieve an optimal bond during the subsequent cementation, it is very important that the cavern neck and the casing are successfully cleaned.

It is not recommended that the cavern neck be cleaned to remove oil residues by solution mining because this could raise the depth of the roof, increase the width of the neck, enlarge the volume of the roof and probably give rise to irregular leaching because of the absence of a blanket. This could have a negative effect on the plug if it is not possible to install a mechanical plug. Cleaning should be performed by washing with a solvent (hydrocarbons, aromatics plus dissolution improvers) or by mechanical means like a scraper and taper mill.

In general, however, complete cleaning of the cavern to remove oil residues is not always necessary for effective sealing. It is only important that the emplacement of the plugs in the cavern, and any rock packers and cementation which are emplaced are not negatively affected by any accumulations of residual oil in the zone immediately beneath the last cemented casing string.

7.4 Specific plugging concept

A discussion of the basic assumptions for placing plugs is contained in Chapter 3.5 *Borehole section requiring plug*. These discussions reveal that there are basically three possible options for plugging a cavern borehole:

- Option I: Decisive plug within *cemented casing* (Figure 3-4)
- Option II: Decisive plug within *cavern neck* (open hole) below cemented casing (Figure 3-5)
- Option III: Decisive plug within *milled casing section* (Figure 3-6).

According to the regulations for the plugging of boreholes described in Chapter 3.2, the plug needs to be designed to permanently stabilize and seal off the borehole. Every plug therefore needs to consist of two parts, a structural element and a plugging element.

This initially involves setting an inflatable packer at the required depth by pumping it up with cement (sealing tightly against the rock). A cement bridge several meters thick is then set on top of this packer. This bridge forms the abutment for the actual permanent cement plug, which includes filling the entire casing from the borehole plug to the surface in one or more stages

The plugging work is completed in all of the options discussed in the following by cutting off the casing strings below the surface and dismantling the remaining cavern head. A concrete slab is then poured to seal off the remaining casing which should be additionally closed by a cap which is welded on. The final step is dismantling the service facilities and starting renaturization[6].

7.4.1 Option I: Decisive plug in cased hole

If the tightness of the last cemented casing can be confirmed, and there are no problems with the potential long-term corrosion of the casing, the simplest and least expensive option is to set the decisive plug in the cased hole, i.e. inside the final casing.

The first step is conducting a standard mechanical integrity test (MIT) to confirm the tightness of cementation of the last cemented casing around the casing shoe. As part of the MIT the tightness of the casing itself is tested when applying pressure on the installed packer.

The MIT itself normally involves the injection of nitrogen or another fluid into the cavern neck at maximum allowable pressure[7]; the gas is then shut-in for a period of

---

[6] Renaturization means restoring surface and surrounding area to natural appearance

[7] Further discussion is required to answer the question raised by Benoit Brouard, whether *maximum pressure* should be the value true during regular cavern operation or a higher pressure expected after sealing, which might reach or even slightly exceed lithostatic pressure.

several hours to days. Analysis of the gas pressure, temperature and gas-liquid interface development enable the integrity of the cavern to be confirmed.

Abandonment by plugging in cased hole can only take place once this confirmation has been acquired.

The favorable conditions inside casing allow a packer to be set as the abutment for the cement plug: special cheap packers (cement retainer or bridge plugs) are also available which can withstand high differential pressures.

The borehole can be filled with cement once the abutment is in place.

The following procedures are required to install a permanent plug in a cased borehole:

- Gas caverns (completed with production string and other equipment):
    - Removal of the production string
    - If necessary, milling, catching and lowering of the packer / tailpipe section
- Liquid storage caverns: if necessary, cleaning of the cased borehole wall
- All cavern types:
    - Installation of an abutment (bridge plug, cement retainer) to cement the cased part of the borehole
    - Placement of a cement bridge on the abutment
    - Circulating hole clean of any product residues
    - Cementing the borehole to surface

7.4.2 Option II: Decisive plug in open hole

If the decisive plug needs to be installed outside of cased hole, another choice – if possible - is to seal off the open borehole just beneath the casing shoe.

The cavern neck needs to have the following properties for open hole plugging to be feasible:

- Limited diameter and regular caliper

  The diameter must not exceed a maximum beyond which installing an open hole packer below the last cemented casing string becomes impossible. The borehole must be properly formed in regard to roundness, diameter and length to ensure appropriate setting of the plug.

- Sufficient length:

  The cavern neck must be long enough to allow an abutment consisting of a packer and a cement bridge plus the actual plug to be installed. The actual length has to be defined for each project separately.

These two specifications are probably only rarely fulfilled in practice.

An inflatable open-hole packer is a possible means of anchoring a cement plug because using a gel plug would probably only be possible in an excessively long cavern neck. The overlying borehole can be filled with cement once the bridge has been successfully set and tested to ensure it has adequate load-bearing strength.

The following procedure is required to install a permanent plug in an open borehole:

- Gas caverns (completed with production string and other equipment):
  - Removing the production string
  - If necessary, milling, catching and lowering the packer / tailpipe section
- Liquid storage caverns: cleaning the borehole wall and the casing
- All cavern types:
  - Installing an inflatable packer as an abutment for the cementation of the borehole in open hole
  - Setting a cement bridge on the abutment
  - Circulating hole clean of any product residues
  - Cementing the remaining open hole and cased hole to surface

7.4.3 Option III: Decisive plug in window milled in casing

This option is to mill a window in the lowermost part of the final casing within the salt formation and set a plug.

Unlike Options I and II, Option III has the least number of restrictions as long as there is enough salt above the cavern roof.

Option III involves milling a window in the last cemented casing above the casing shoe so that the cement plug can bond directly with the salt formation. No confirmation of the integrity of the original cementation is required. Application of the method is also unaffected by the nature of the cavern neck. Furthermore the defined geometry of the window simplifies plug installation.

Specific procedure:

First, running a USIT log is recommended before milling starts to investigate possible corrosion, the thickness of the casing and the condition of the cementation. Then, a bridge plug is set below the base of the window to be milled in the casing. This has two objectives:

(1) It allows running in and out of the casing in the event that the lower part of the casing is damaged.

(2) The plug allows the progress of the milling to be controlled by monitoring the metal cuttings flushed out of the well.

The next step involves milling a window in a defined section in the last cemented casing. In addition to the casing, the cement mantle surrounding the casing up to the salt is also milled. Then the milled casing section should be underreamed back into the salt formation to expose good salt.

After setting the cement bridge, the decisive plug to seal off the cavern is then set.

A lightweight workover rig is required for the milling work. To ensure that enough room is available to place a tight plug, a casing section of sufficient length should be milled. The actual required length will be project dependent. This procedure is estimated to take around two to three weeks including assembling and dismantling the workover rig.

The following procedure is required to install a permanent plug in the milled section of the last cemented casing string:

- Gas caverns, if equipped with special completion:
  - Removal of the production string
  - If necessary, milling, catching and lowering of the tailpipe section
- Other caverns:
  - If necessary, cleaning the surface of the casing
  - USIT log
  - Bridge plug installation
  - Milling a window in the last cemented casing string through the cement mantle into the salt formation
  - Setting a cement bridge as an abutment
  - Circulating hole clean of any product residues
  - Cementing the borehole to surface

This method is the best means of complying with the current regulations in Germany (BVOT), and their modification to suit the conditions in caverns.

SPECIAL REMARKS FOR GAS CAVERNS EQUIPPED WITH A TAILPIPE SECTION: If it is not possible to remove the tailpipe section, an alternative would be to leave the permanent packer and the tailpipe in the last section of the last cemented casing string.

This involves setting a plug in the lowest landing nipple in the tailpipe to seal the borehole. A cement bridge is then set above the permanent packer plus tailpipe. The packer and the plug act as an abutment and the cement bridge as the static load-bearing element for the subsequent cementation of the last cemented casing to surface.

However, this is an exception and would need to be discussed in detail with the relevant mining authorities. Figure 7-1 contains an illustration of the plug construction.

7.5 Renaturizing of cavern pad

The following applies whichever of the options is selected:

- cutting the casing adequate below ground level,
- setting a concrete slab,
- dismantling the well head and other installations on the cavern pad,
- renaturizing the cavern pad, paths and field lines.

  In some instances[8], however, regulators require leaving the casing above ground and affixing a placard to the casing for identification and subsidence monitoring requirements

7.6 Comparison

Option I: Decisive plug in cased hole

Conditions required:

- The tightness of the last cemented casing string is to be confirmed in the casing shoe zone by a mechanical integrity test (MIT) or many years of positive operational data.

Advantages:

- The geometry of the casing is known and regular.
- The abutment can therefore be relatively easily emplaced in the lower part of the last cemented casing.
- The injection and selection of cement for the decisive plug is relatively simple because the whole section is cased.

[8] for example Kansas, USA

- This is the lowest-risk plug construction and also the most favorable both technically and in terms of time and expense.

Disadvantages:

- The decisive plugging function relies on the existing cementation of the last cemented casing.
- The tightness of the cementation must therefore be confirmed by a mechanical integrity test which can only be carried out if the cavern neck is suitable.
- There is no direct contact between the cement plug and the formation.
- The last cemented casing string is an essential part of the long-term plug: it is permanently in contact with the brine in the cavern. Confirmation is required that corrosion will not jeopardize the long-term tightness of the borehole.

Option II: Decisive plug in open hole

Conditions required:

- The geometry of the cavern neck (length, diameter, roundness) must be suitable for the installation of an inflatable packer out of the last cemented casing string.
- The cavern neck must be accessible
- The cavern neck must be free of all product residues to ensure that there a proper bond between the cement and the formation can be achieved.

Advantages:

- There is direct contact between the sealing cement and the rock and thus direct cement/salt bonding.
- The tightness relies on a newly sealed section in direct contact with the surrounding rock; it is not necessary for the last cemented casing string to be tight.

- The casing shoe of the last cemented casing string is also cemented in as part of the plug and is therefore additionally secured and sealed.

Disadvantages:

- Installing a plugging section in the cavern neck requires additional work to clean and/or smooth off the neck by underreaming.
- Installation may not be practical in many instances because the cavern necks in many cases will not be suitable.
- Installation requires a large amount of time, effort and money.

Option III: Decisive plug in window milled in casing

Conditions required:

- A cased section within the salt formation enabling the milling of a sufficiently long window within the casing.

Advantages:

- Tightness of the initial cementation of the last cemented casing string is not essential
- No work required in open hole
- Direct contact between the cement plug and the rock ensuring a direct bond between the cement and the salt.
- Establishing a new plugging section in direct contact with the surrounding rock.

Disadvantages:

- Time, expense and technical effort required in milling the window and emplacing the plug.
- There is a risk that the milling work will delay emplacement of the plug and give rise to a considerable increase in costs.

Summary

The specific type of plugging measure used in each case needs to be decided on a cavern-by-cavern basis. Each of the plugging options requires fulfillment of a different set of conditions. The procedure therefore needs to be selected for each cavern, adapted to the unique conditions existing in each cavern, and closely coordinated with the responsible authorities.

8 Monitoring in post-abandonment phase

As described in *Sec. 1.5 Basic considerations for tightness and long-term effectiveness*, the technical concepts developed in this manual are based on the decisive requirement to develop a maintenance-free concept which requires no (!) permanent in situ measurement to monitor the very slow processes taking place over many years up to several decades after plugging the well. This ambitious approach is justified by the extremely high repair costs that may otherwise become necessary if the well has to be re-opened down to the cavern neck.

With fulfillment of the conditions for relatively simple situations in mainly homogenous salt formations, combined with confirmation of long term stability (as assumed for the elaboration of this manual) satisfying the requirement for a maintenance-free concept appears realistic and affordable.

As a consequence, monitoring in the post-abandonment phase can be reduced to periodic measurement of surface movements. The previously quoted time period of 20 to 30 years for brine production caverns discussed in /BÉREST ET.AL., 2004/, and largely formulated for caverns in inhomogeneous salt formations, therefore appears to be very long given the much more favorable conditions assumed in this manual.

9 Costs

Cavern operators are interested in the estimation of abandonment costs for three different reasons:

- In some countries, operators of storage caverns have to build up reserves to cover final abandonment costs
- The operators of brine production caverns in particular are interested in abandonment when a cavern reaches its final volume so that they are released from their mining supervisory responsibilities and to avoid subsequent costs involved with long term maintenance.
- Technical problems with storage caverns or wells, which do not allow repair at reasonable costs.

The costs for complete abandonment in accordance with the concepts discussed in the preceding chapters reflect the following main aspects:

(1) Preparation

Preparation phase includes all of the necessary work required to flood the cavern scheduled for abandonment. The costs strongly depend on the nature of the cavern, i.e. whether it is a brine production, liquid storage or gas cavern.

In the case of gas caverns, subsequent flooding first requires **snubbing in of the flooding string**. Unlike installing a string in an oil-filled cavern, the snubbing procedure is extremely expensive. In addition to the snubbing itself, additional costs arise for the flooding string and additional well head components.

(2) Flooding

In the case of conventional flooding with fresh brine or water, the most important costs are associated with making available the brine or the water and the related connection and pipeline costs.

The main factors here are **personnel costs** and **workover rig** for removing the flooding string when flooding has been completed.

(3) Option: Pre-heating the water/brine for flooding

The costs for optional heating of the brine or water for flooding depend mainly on the assumed temperature increase in the heater, the resulting energy for heating the brine or water volume equivalent to the cavern volume and the assumed specific energy costs ($ or € / kWh).

Since the assumptions for the temperature difference and particularly for the specific energy costs vary to a large extent, it does not seem to be possible to come up with a cost estimate for a "typical" case.

(4) Waiting period for balancing out temperature differences

The waiting period is a very strongly project-specific cost factor because it depends on the initial temperature difference between the rock and the brine during flooding as well the cavern volume. Because natural re-heating only takes place very slowly, this period could be extremely lengthy under unfavorable circumstances (up to many years, decades or even longer).

The most unfavorable cases are: gas caverns flooded with cold water, and liquid storages which have been in existence for a long period but only experienced infrequent withdrawal and injection cycles (favorable).

The most important shares of the total costs for the waiting time are the assumed duration and the personnel needed for controlling the caverns; the manning will e.g. depend on whether the cavern is part of a cavern field still in operation or whether – in the extreme case – only one or two caverns are left for abandonment.

Particularly since the waiting time can vary by at least 2 orders of magnitude, again, it does not seem to be possible to come up with a cost estimate for a "typical" case.

(5) Plug construction

Major cost items are workover rig, logging, removing installations in case of gas caverns, bridge plug, cementation, etc. The cost for plugging itself will depend on the selected location for setting the plug.

(6) Well head and pad deconstruction and renaturization or alternative procedure

Major cost items are casing cutting, dismantling the well pad, etc.

(7) Monitoring after abandonment (Subsidence surveying)

(8) Engineering

In agreement with the SMRI sponsor, deliberately no costs are presented for the various items and the resulting total. In the draft of this study, the authors had at least presented the distribution of costs estimated for a model cavern.

After extensive discussions with other SMRI member colleagues the authors decided to completely to do without costs because of the two tasks *optional preheating of brine or water* and *waiting period*. The actual costs for both tasks will depend to a large extent on the assumptions made, e.g. temperature difference during heating, energy costs, length of waiting time (years, decades). This does not allow to present reasonable numbers e.g. for a sample case.

10 References

Behr, A., 2001:
Evaluation of Salt Permeability Tests,
SMRI Project No. 01-0003, prepared by Wilsnack & Partners (IbeWa), Freiberg, Germany

Bérest, P., Bergues, J., Brouard, B., Durup, J. G., Guerber, B., 1999:
A salt-cavern abandonment test
SMRI Spring Meeting, Las Vegas, USA,.1999

Bérest, P., Bergues, J., Brouard, B., DeGreef, V., Le Bras, Y., Durup, J. G., Guerber, B., 1998:
Long-Term Evolution of a Sealed Cavern,
SMRI Project No. 98-0004, prepared by Laboratoire de Mécanique des Solides, Ecole Polytechnique, Palaiseau, France; and Gaz de France, La Plaine Sant Denis, France

Bérest, P., Brouard, B., DeGreef, V.,, 2001:
Salt Permeability Testing – The Influence of Permeability and Stress on Spherical Hollow Salt Samples,
SMRI Project No. 01-0008, prepared by Laboratoire de Mécanique des Solides, Ecole Polytechnique, Palaiseau, France; and Brouard Consulting, Paris, France, for SMRI

Bérest, P., Diamond, B., Duquesnoy, A., Durup, G., Feuga, B., Lohff, L., 2004:
Salt and brine production methods in France: Main conclusions of the international group (IEG) commissioned by the French regulatory authorities
SMRI Fall Conference, Berlin, Germany 3.-6.10.2004

Crotogino, F., Behrendt, C., Hackney, J., 1997:
Bibliography for Cavern Abandonment,
SMRI Project No. 97-0002, prepared by KBB, Hannover, Germany; and PB-KBB Houston, TX, for the Solution Mining Research Institute, pp. 158.

Malinsky, L., 2001:
Evaluation of Salt Permeability Tests,
SMRI Project No. 01-0004, prepared by G3S, Ecole Polytechnique, Palaiseau, France, for the Solution Mining Research Institute.

Pfeifle, T. W., Mellegard, K. D. , Skaug, N. T. , Bruno, M. S., 2000:
An Investigation of the Integrity of Cemented Casing Seals With Application Salt Cavern Sealing and Abandonment,
SMRI Project No. 00-0002, prepared by RESPEC, Rapid City, SD; and Terralog Technologies USA Inc., Arcadia, CA, for Solution Mining Research Institute, Encinitas, CA, pp. 118.

Ratigan, J.L., 2003:
Summary Report – The Solution Mining Research Institute Cavern Sealing and Abandonment Program 1996 Through 2002
SMRI Project 2002-3

Rokahr, R. B., Hauck, R., Staudtmeister, K., Zander-Schiebenhöfer, D., Crotogino, F., Rolfs, O., 2002:
High Pressure Cavern Analysis,
SMRI Project No. 02-0002, prepared by Institut für Unterirdisches Bauen (IUB), Hannover University, Germany, and Kavernen Bau und Betriebs GmbH, Hannover, Germany

Rolfs, O., Schmidt, U., Crotogino, F., 1993:
Rock Mechanical Studies on the Post-operational Phase of a Disposal Caverns
– 3rd Conference on Mechanical Behavior of Salt, Paliseau, France

Staudmeister, K. ,R. B. Rokahr, Rolfs, O., 1998:
Pressure Build-Up Test in the Etzel K102 Cavern,
SMRI Project No. 98-0005, Institut für Unterirdisches Bauen, University of Hannover, Germany

Stormont, J. C., 2001:
Evaluation of Salt Permeability Tests,
SMRI Project No. 01-0002, prepared by Department of Civil Engineering, University of New Mexico, Albuquerque, NM, for the Solution Mining Research Institute.

Van Sambeek, L. L., 1990:
A Simple Method for Modeling the Pressure Buildup of Flow of an Abandoned Solution Well,
Spring Meeting of the Solution Mining Research Institute, Austin, TX, April, pp. 583-590.

11 ATTACHMENT: Alternative options for cavern abandonment

11.1 Introduction

The following section was added at SMRI's request following the first kick-off meeting in Berlin in fall 2004. The addition comprises a compilation and comparison of various alternative techniques for cavern abandonment in addition to the methods developed by SMRI, see manual.

A model cavern has been defined to allow comparisons based on figures:

- Volume: 500 000 m^3
- Depth of top of salt: 600 m
- Roof depth: 1 000 m
- Height: 300 m
- Rock salt with average creep

The assumed convergence rate versus pressure difference between initial formation pressure and internal pressure is shown in Figure 11-1.

11.2 Cavern abandonment of an empty cavern at atmospheric pressure

11.2.1 No backfill

To avoid problems associated with rising pressure in a sealed brine-filled cavern, one alternative option is to first empty the cavern of its contents. The problem here is that of long-term stability because brine production and storage caverns are generally not designed for operation at atmospheric pressure: i.e. a situation where there is no supporting pressure in the cavern to counteract the formation pressure, cf. Figure 11-2, left hand side. In the case of the model cavern (cavern top 1 000 m), this alternative is basically untenable because the cavern is likely to become unstable in the long-term if operated at atmospheric pressure.

In principle, this option can be expected to result in high rates of convergence together with high associated subsidence rates, and would first end when the entire subsurface space had almost completely squeezed up. Considering the model cavern, this scenario would have an initial convergence rate of 10 000 m^3 per year over a period of approx. 100 years before 100 per cent closure of the cavern (see Figure 11-3, curve I).

Taking stability considerations into account, this option would only be feasible, if at all, for small product storage caverns at shallow depths of between 400 and 800 m.

11.2.2 Dry cavern backfill

An option sometimes discussed to avoid the stability problems associated with empty storage caverns referred to above, and to reduce the absolute convergence and subsidence, is the possibility of backfilling a cavern with loose bulk solids (e.g. industrial waste), see Figure 11-2, right hand side. The related rock mechanical issues were investigated in a research project on repository caverns operated at atmospheric pressure and filled with waste briquettes. /ROLFS ET.AL.; 1993/.

During the backfilling and commencement of the first operational phase proper, the cavern's low internal pressure results in major deformation . The convergence rate in the initial phases is similar to that of an empty cavern (curve I, Figure A-3). During the resulting squeezing process, the backfilled bulk material is compacted. However, a noticeable supporting pressure within the cavern only builds up gradually over a long period of time until ultimately an equilibrium is reached in the cavern/rock system.

A typical characteristic of such loose bulk materials is that they require a considerable amount of compaction (15 - 20 %) before they provide any noticeable resistance to the rock deformation in the rock surrounding the converging cavern. Curve I, Figure 11-2, indicates that for an empty cavern, the point of 20 % convergence is reached after 10 years. Only after this time would the curve of a backfilled cavern start flattening out, and depending upon the original porosity of the bulk material, ultimately approach a final value of approximately 300,000 m³.

Conclusion: The great expense of backfilling only results in a limited supporting effect. Furthermore, despite backfilling, there will probably be significant volume convergence, with associated subsidence at an initially high rate, which continues until the compaction of the backfill bulk material is finally sufficient to provide effective resistance and support.

This technique is therefore only of any interest at depths where the stability of the cavern can be expected to last several years at least beyond the withdrawal and backfilling phase.

Notwithstanding the above, the main arguments against this option are the high costs of backfilling operations - unless suitable bulk waste materials are available to generate some form of revenue in return for their disposal in the cavern.

11.3 Brine-filled (flooded) caverns

11.3.1 Operation near maximum permitted pressure

This option (Figure 11-4, left hand side) is mostly practiced in the case of abandoned brine production caverns. To reduce subsidence, caverns are operated at a pressure near the maximum permitted operating pressure (approx. 15 – 20 % below lithostatic pressure). Before the pressure exceeds the permitted level, brine is released. As a result of the considerably lower rates of convergence (initially 0.045 %, i.e. 225 m³ per year in the case of the model cavern) this alternative requires all of the plant to be in operative order for an indefinite period (curve III, Figure 11-3). The statutory obligation to supervise the situation continues for an indefinite period.

11.3.2 Operation at a brine pressure equivalent to atmospheric wellhead pressure (open well)

Another option, which may also involve lower maintenance costs, is to simply leave the well open: i.e. the cavern internal pressure is equivalent to the pressure of the brine columnand the head pressure is equal to atmospheric pressure, see Figure 11-4, left hand side.

This option is only feasible if there is a permanent and intact run-off arrangement for the brine displaced by convergence. In the model cavern, the initial rate is 1 250 m^3 per annum. The time period for brine run-off is approx. 1.000 years, during which period a certain amount of maintenance would be required (curve II, Figure 11-3). This being the case, there would be a statutory obligation to supervise the situation for the foreseeable future.

11.3.3 Solid backfill alternative

It is also possible to set an upper limit on convergence by filling a brine filled cavern with solids. Because the solids would come into contact with the displaced brine in this case, the brine contamination risk means the number of suitable residuals is actually very limited.

As described previously, the bulk material in the cavern will only generate any noticeable supporting effect after approx. 15 - 20 % compaction. Consequently, the behavior of the cavern prior to reaching this degree of convergence is identical with that of the non-backfilled, brine-filled cavern. Curve II, Figure 11-3, shows that a period of approximately 100 years expires before there is any noticeable supporting effect generated by the backfill material, i.e. there would be a statutory obligation to supervise the situation for the foreseeable future.

The advantage in this case is, however, that the convergence is brought to a standstill after compaction is completed - as previously described for the *dry* backfilled cavern - and therefore the amount of content displaced from the cavern eventually reduces to a negligible amount. In particular, the maximum level of subsidence is also considerably reduced. The most significant aspect is that the cavern can be permanently plugged and abandoned after this point has been reached.

11.3.4 Brine disposal

In any case a solution needs be developed for the 3 options presented above for disposal of the displaced brine for the period until the cavern can be sealed.

11.3.5 Sealed well with perforated casing

In situations where the cover rock includes a saline aquifer, a further option which is often discussed is discharging the displaced brine into this aquifer.

For this purpose, the cemented casings are perforated in the aquifer zones, the well above this point is then permanently sealed with a cement plug (Figure 11-5). Convergence results in the brine being displaced upwards from the cavern into the aquifer. In contrast to all other options discussed above, this therefore represents a maintenance-free solution because no brine will appear at the surface; the inner pressure of the flooded cavern is determined by the aquifer, i.e. is equivalent to hydrostatic pressure, which cannot be exceeded.

The following must, however, be borne in mind when contemplating this method:

- The convergence rate (model cavern curve II, Figure 11-3) of 0.25 %, i.e. 1 250 m^3 per year is equivalent to that of an open brine-filled cavern; this means larger rates of convergence and larger subsidence compared to the standard SMRI method.
- Risk of blockage of casing as a result of salt crystallizing as the brine gradually rises upwards into cooler areas (geothermal temperature gradient!).

In principle, this abandonment alternative is similar to methods used when abandoning salt mines.

List of Figures

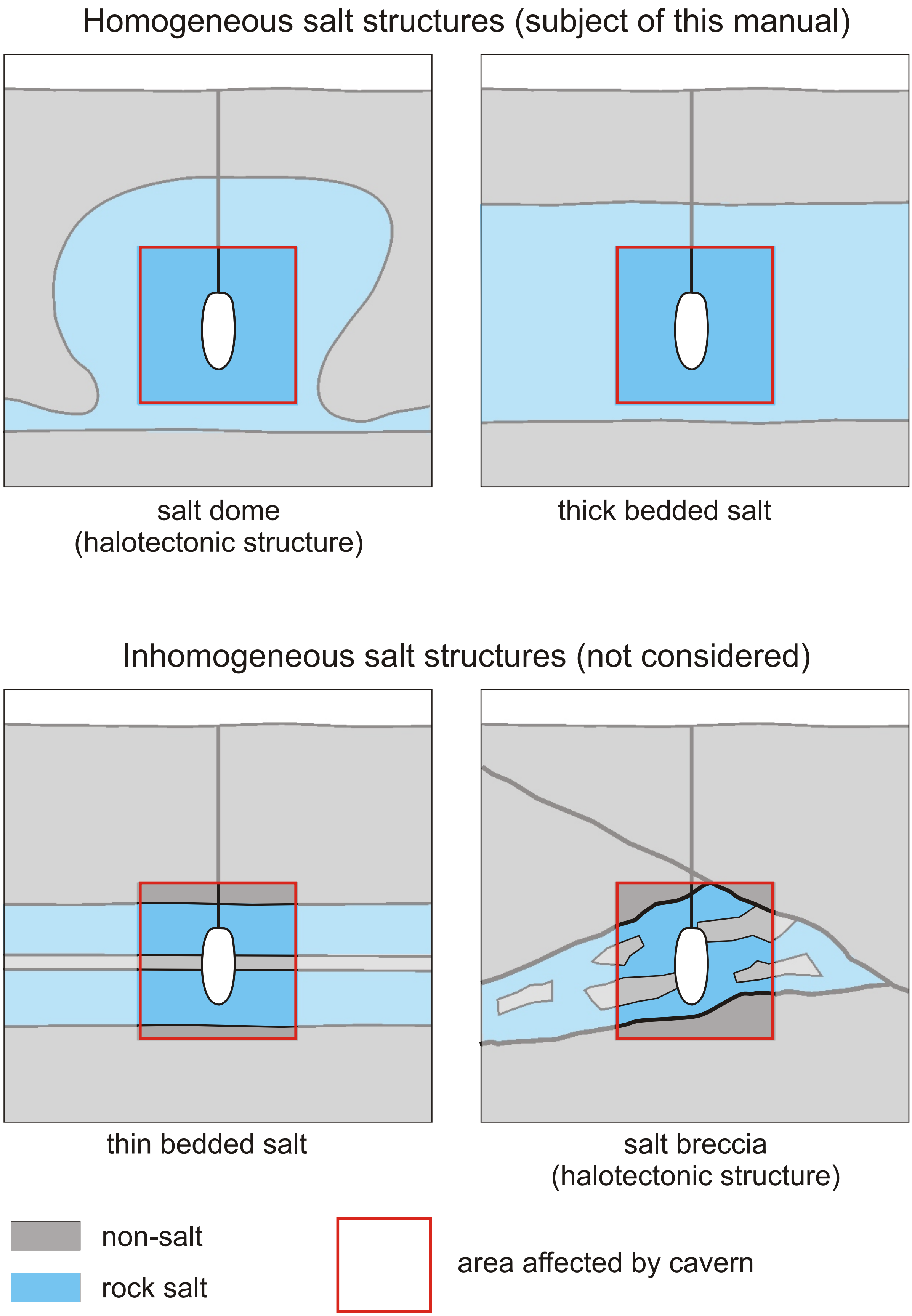

Figure 1-1
Definition for homogeneous salt structures
as applied in the manual

7006\Abb\2006\Sept\060913_Definion-homogeneous-salt_Fig1-1.cdr

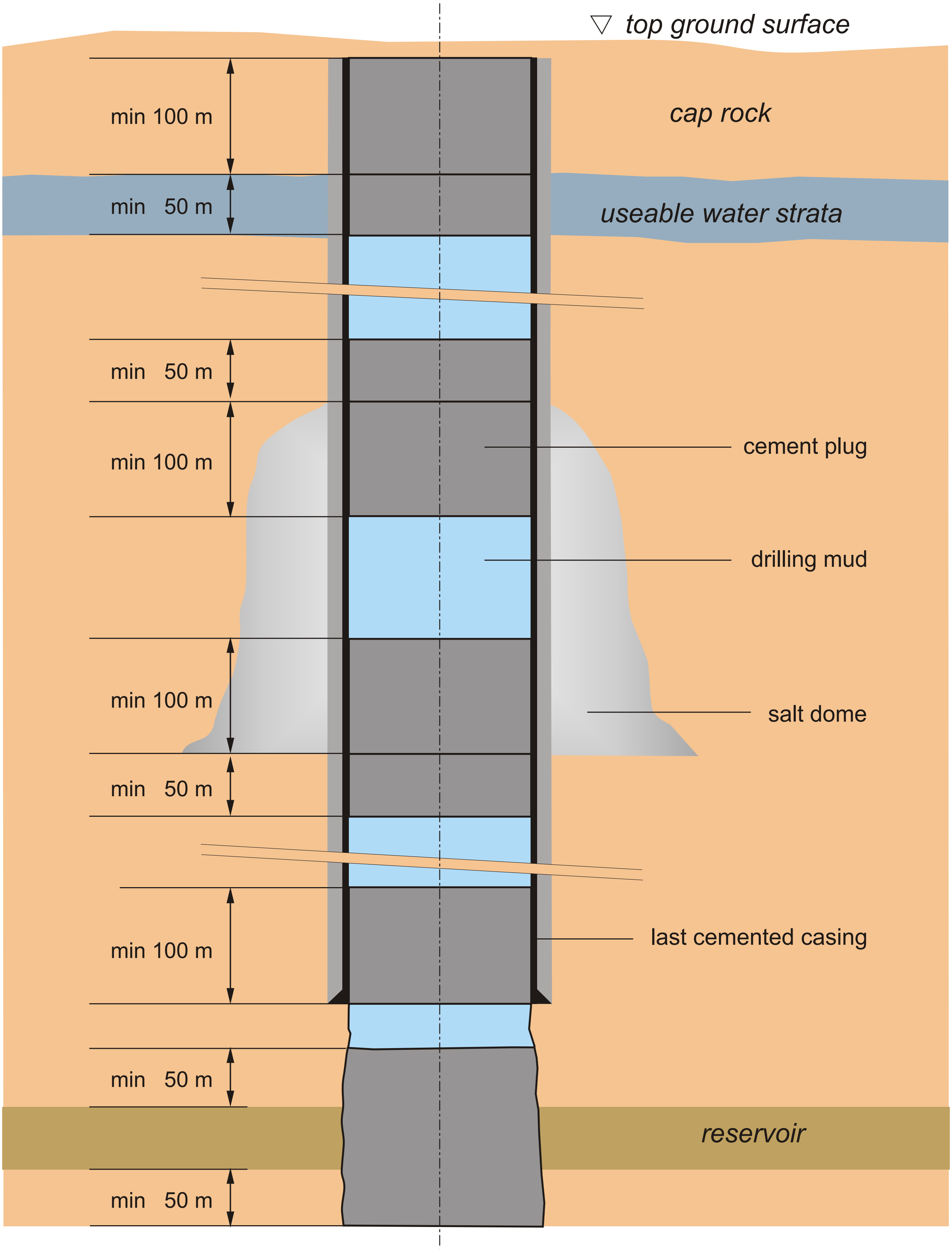

Figure 3-1
General plug & abandonment concept for oil & gas wells (according to German BVOT regulations)

7006\Abb\2006\Sept\060913_Figure_3-1.cdr

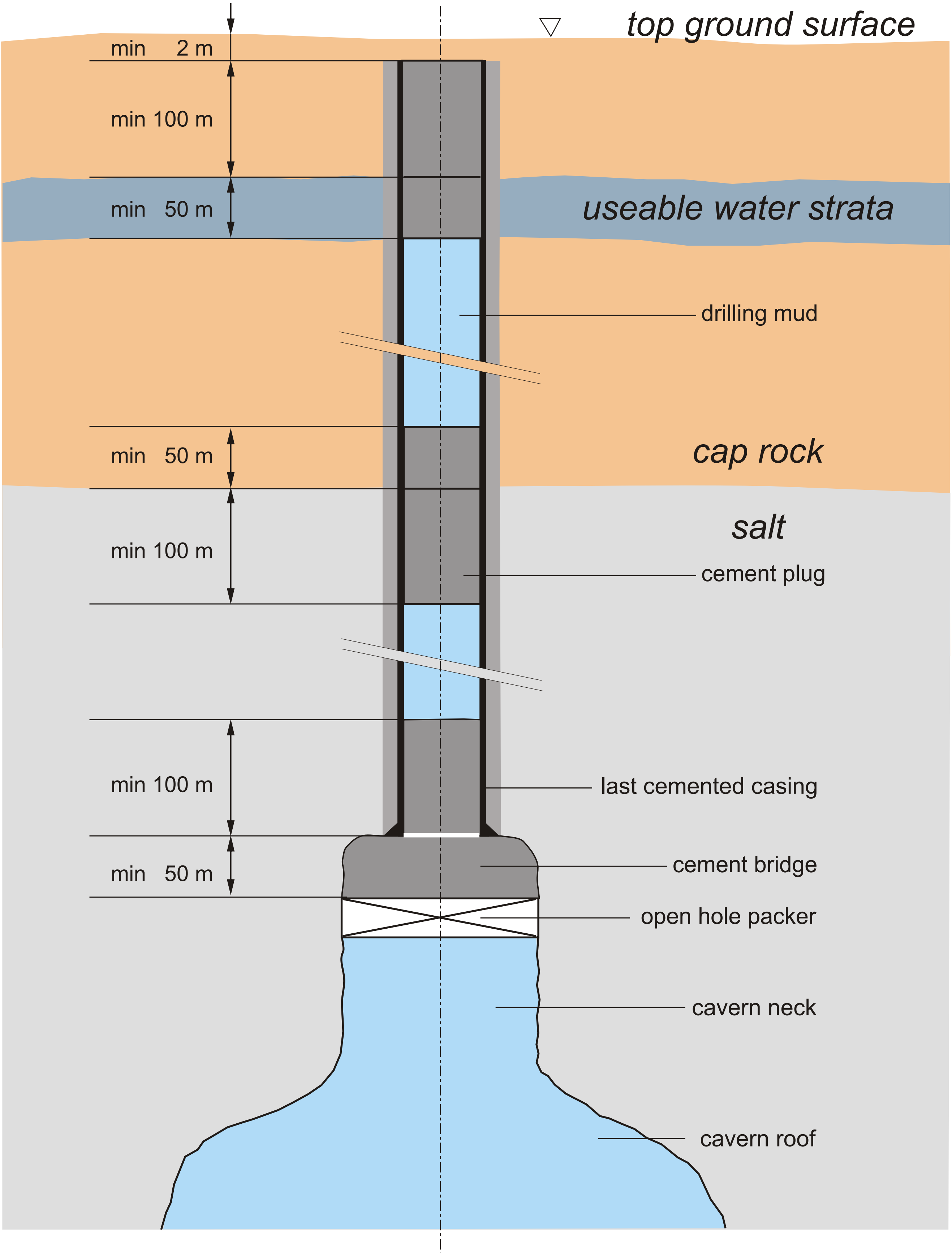

Figure 3-2
General plug & abandonment concept for oil & gas wells (applied to salt cavern wells)

7006\Abb\2006\Sept\060913_Figure_3-2.cdr

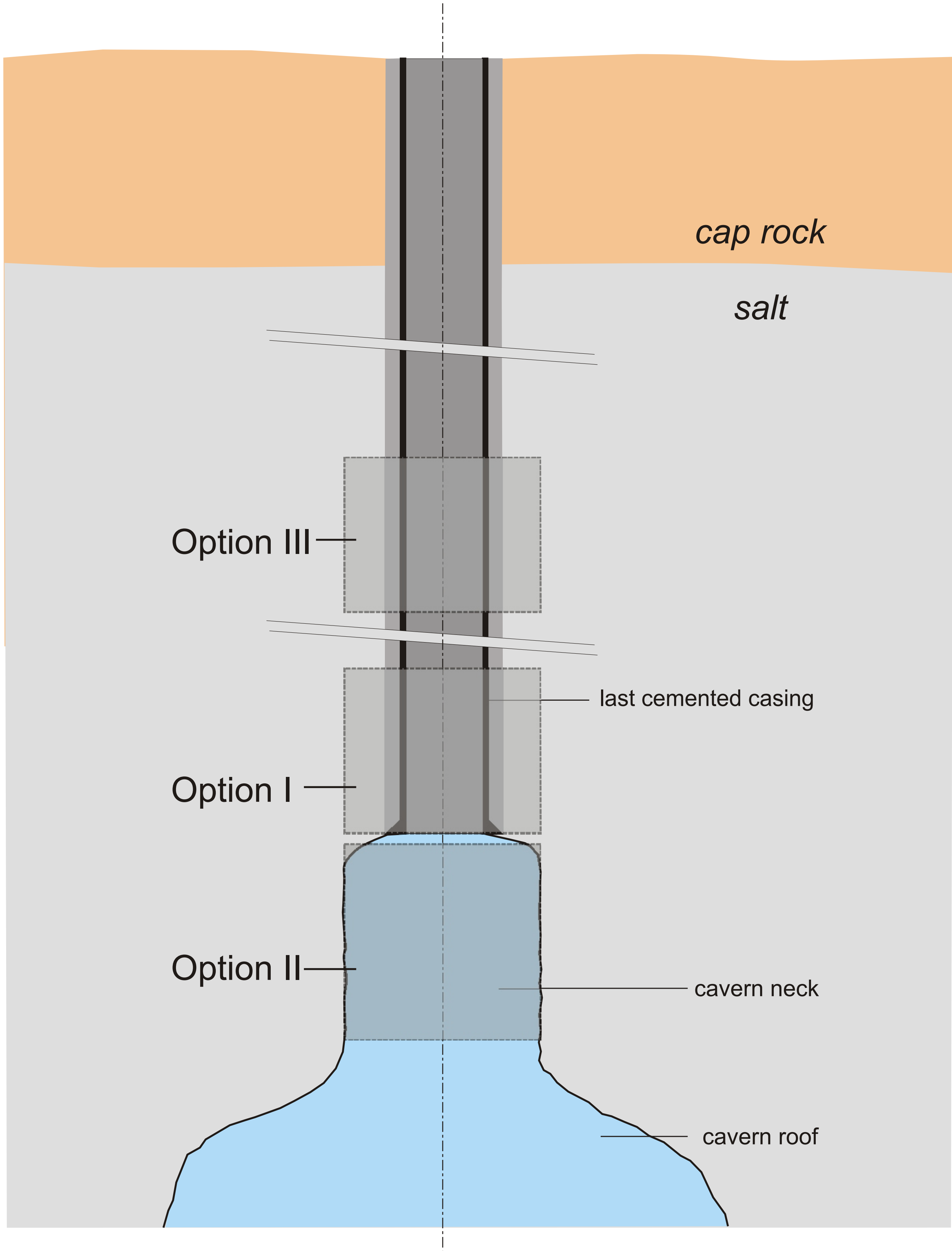

Figure 3-3
Options for cavern well plugs

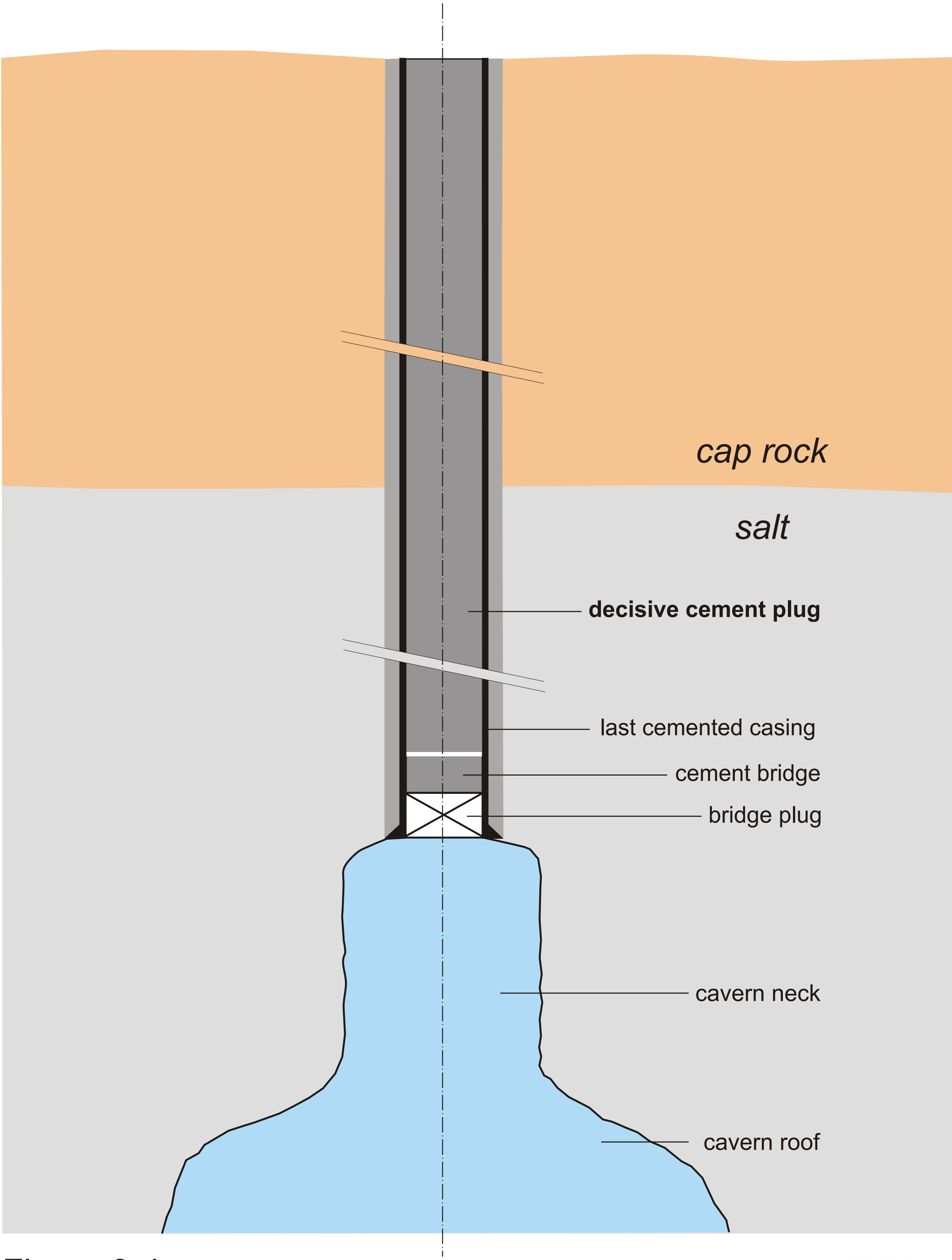

Figure 3-4
Option I:
Decisive well plug within cemented casing

7006\Abb\2006\Sept\060913_Figure_3-4.cdr

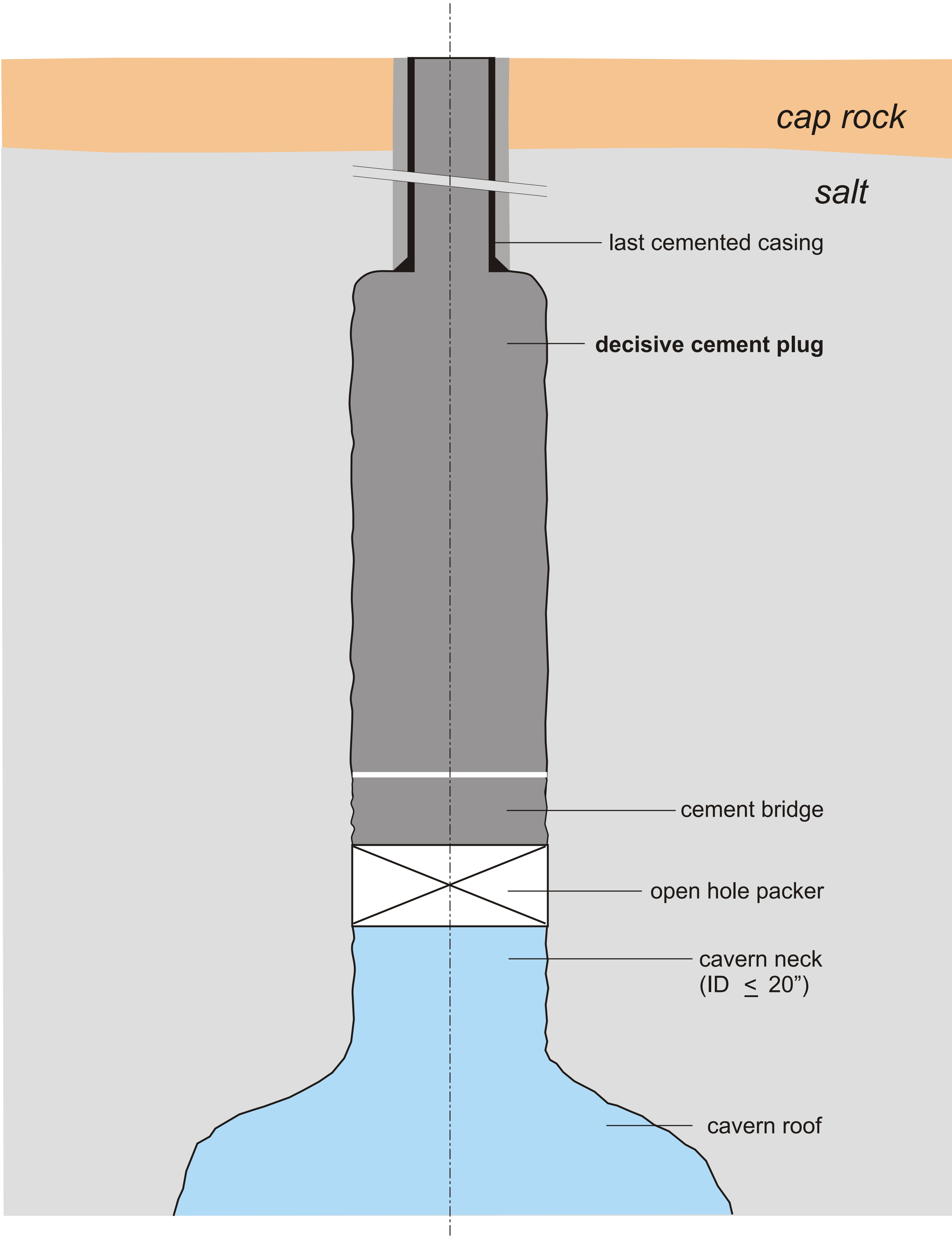

Figure 3-5
Option II: Decisive well plug within cavern neck (open hole) below cemented casing

7006\Abb\2006\Sept\060913_Figure_3-5.cdr

KBB UNDERGROUND TECHNOLOGIES

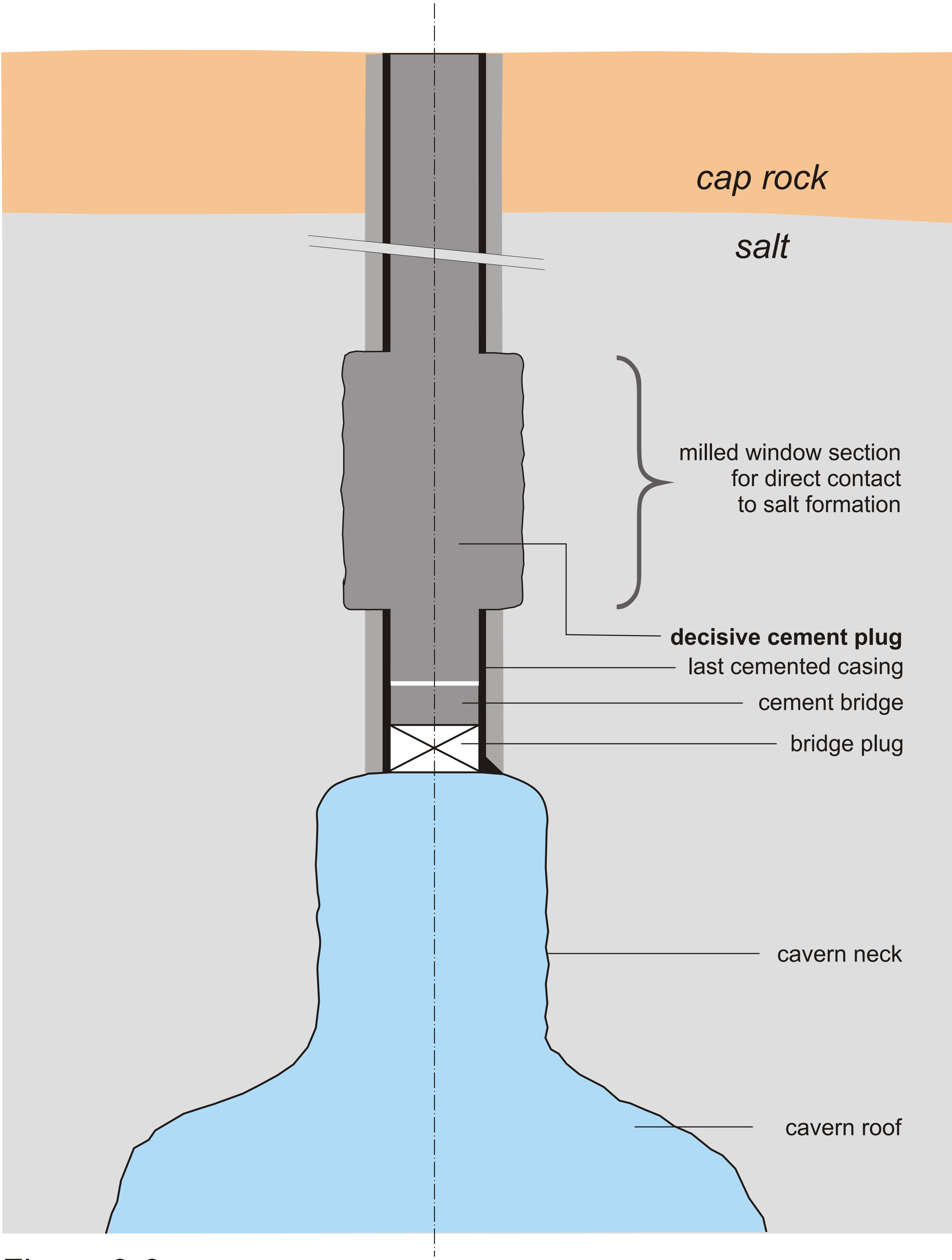

Figure 3-6
Option III:
Decisive well plug within milled casing section

7006\Abb\2006\Sept\060913_Figure_3-6.cdr

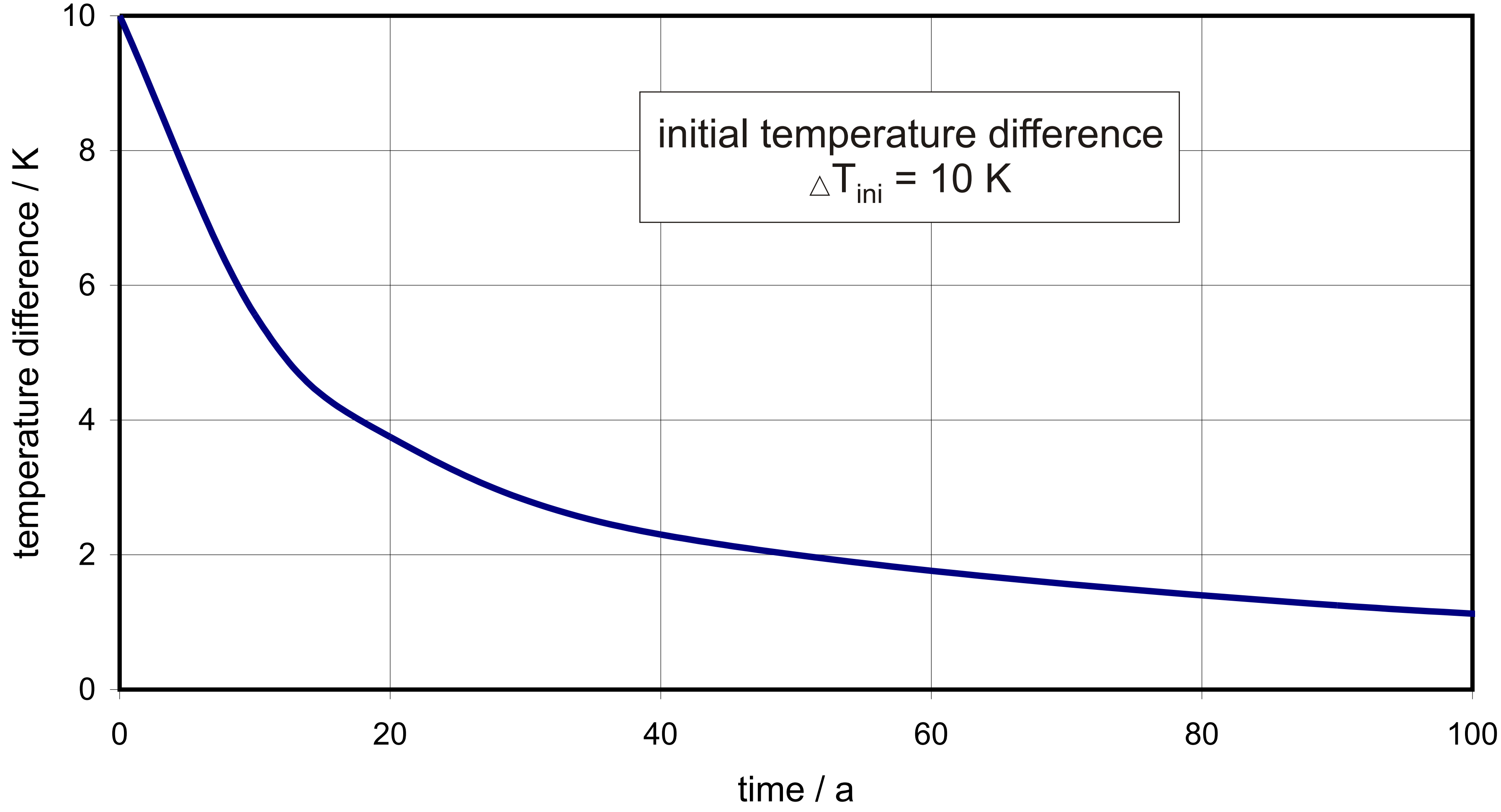

Figure 5-1
Sample for brine temperature decrease after flooding

7006\Abb\2006\Sept\060913_Figure_5-1.cdr

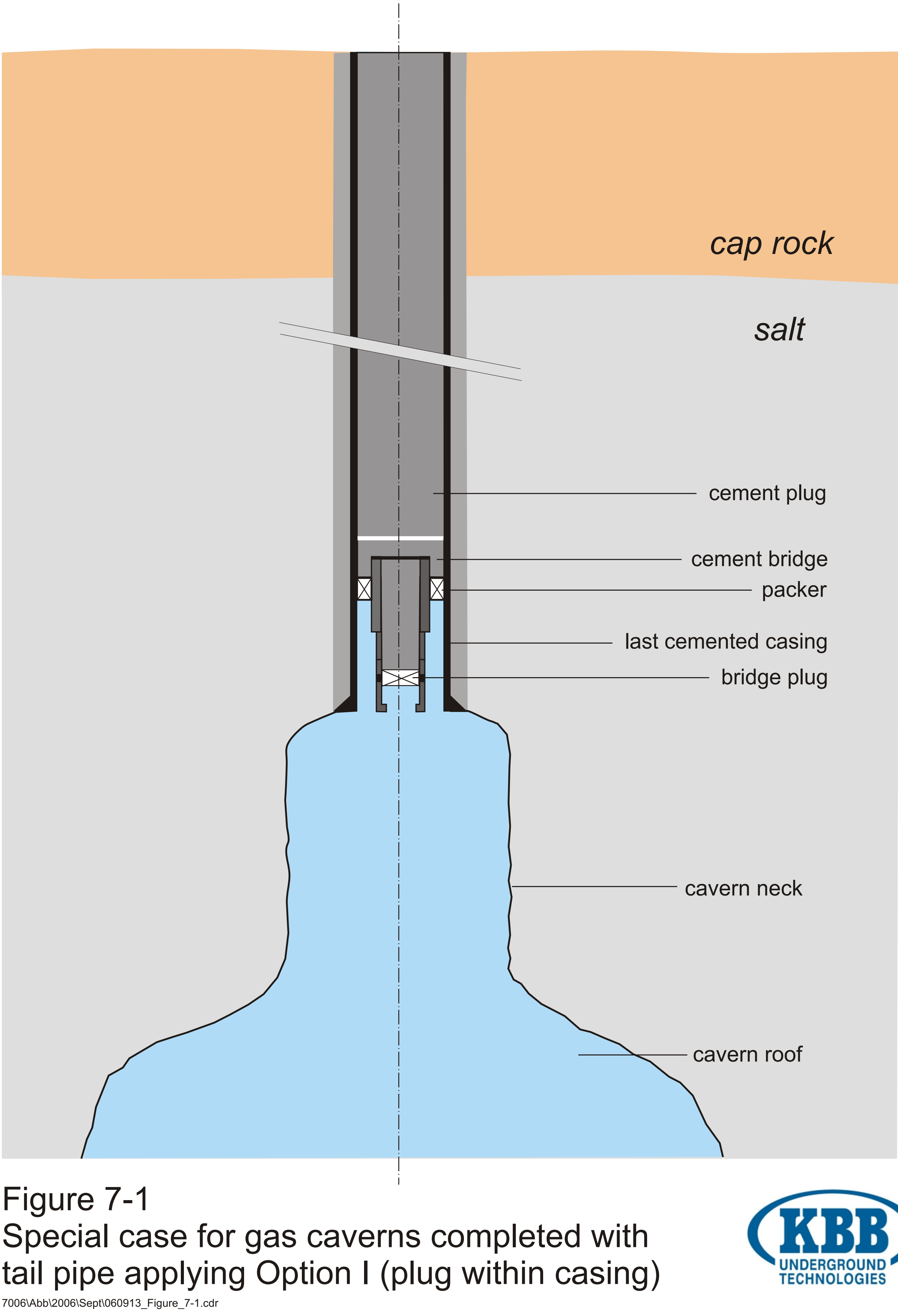

Figure 7-1
Special case for gas caverns completed with tail pipe applying Option I (plug within casing)

7006\Abb\2006\Sept\060913_Figure_7-1.cdr

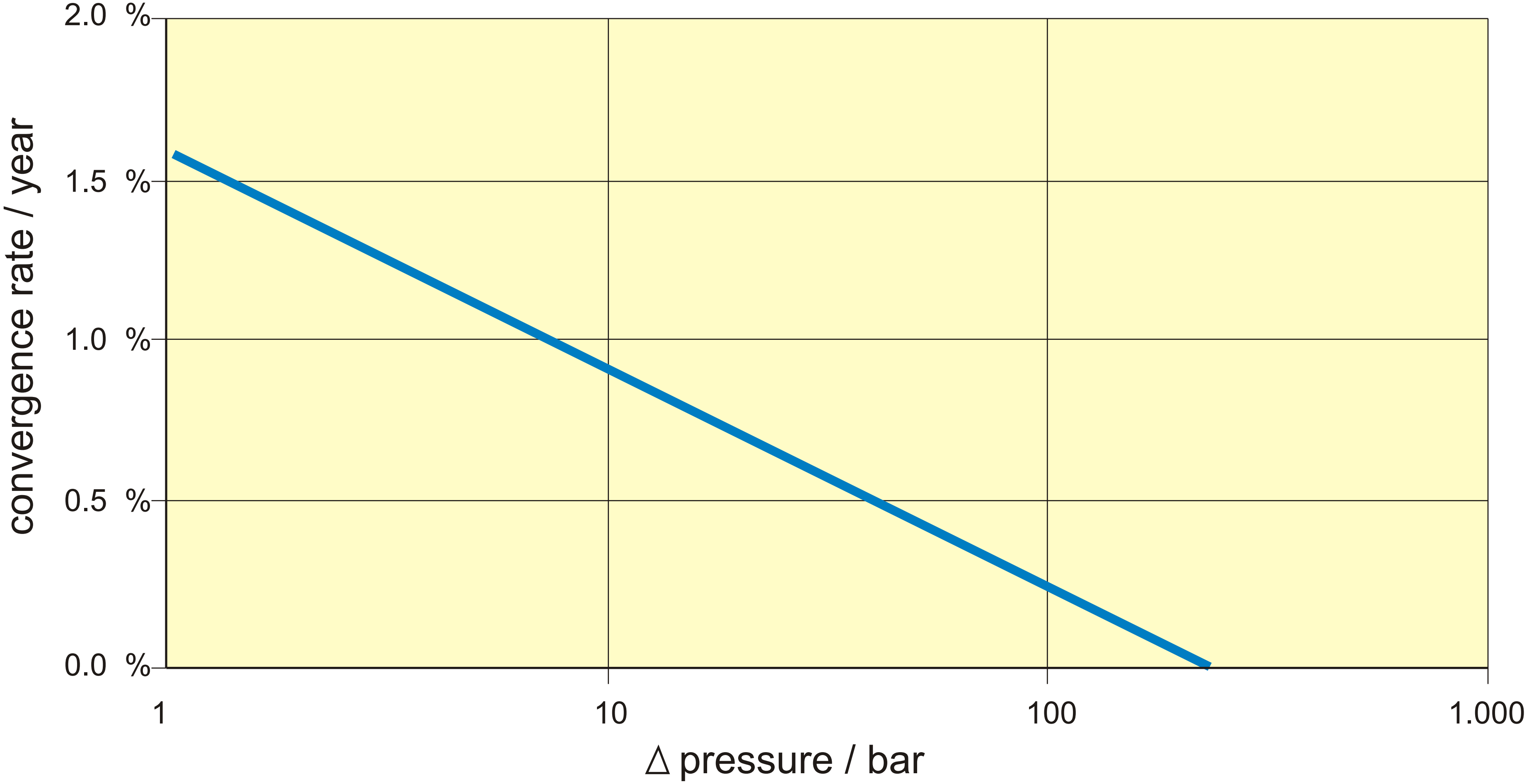

Figure 11-1
Convergence rate vs. pressure difference

7006\Abb\2006\Sept\060913_Figure_11-1.cdr

UNDERGROUND TECHNOLOGIES

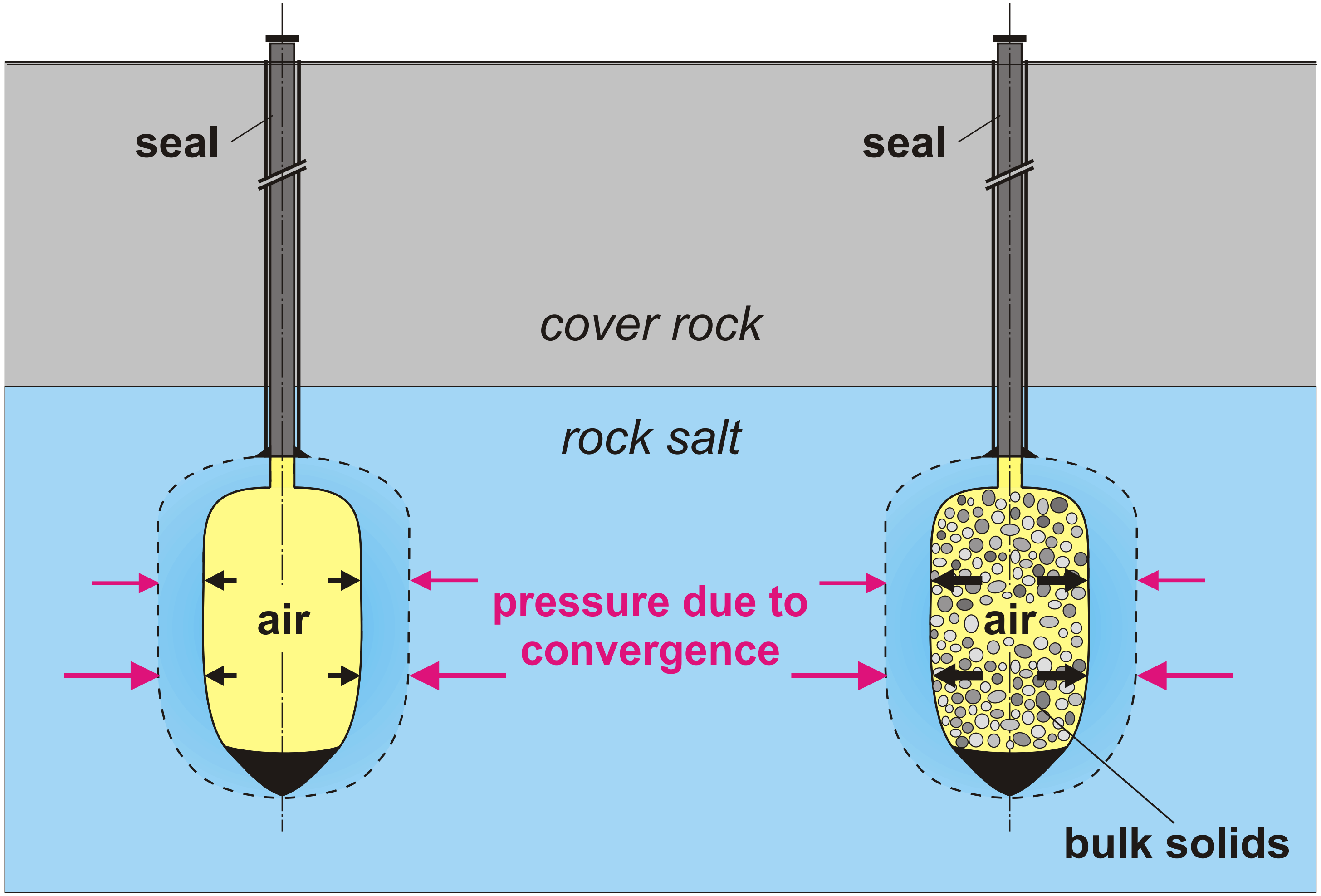

Figure 11-2
Cavern abandonment (air fill) at atmospheric pressure

7006\Abb\2006\Sept\060913_Figure_11-2.cdr

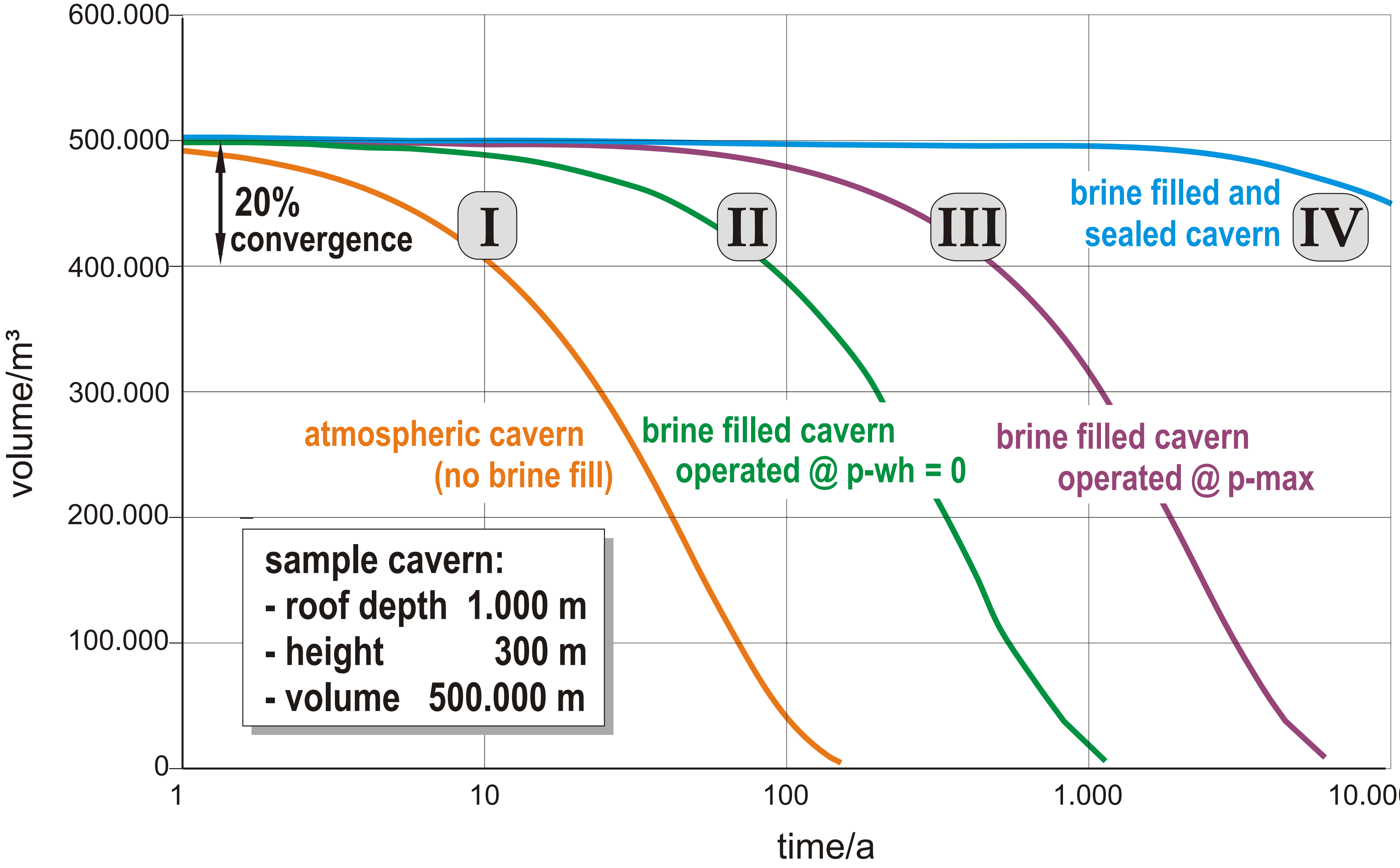

Figure 11-3
Cavern volume loss after plugging

7006\Abb\2006\Sept\060913_Figure_11-3.cdr

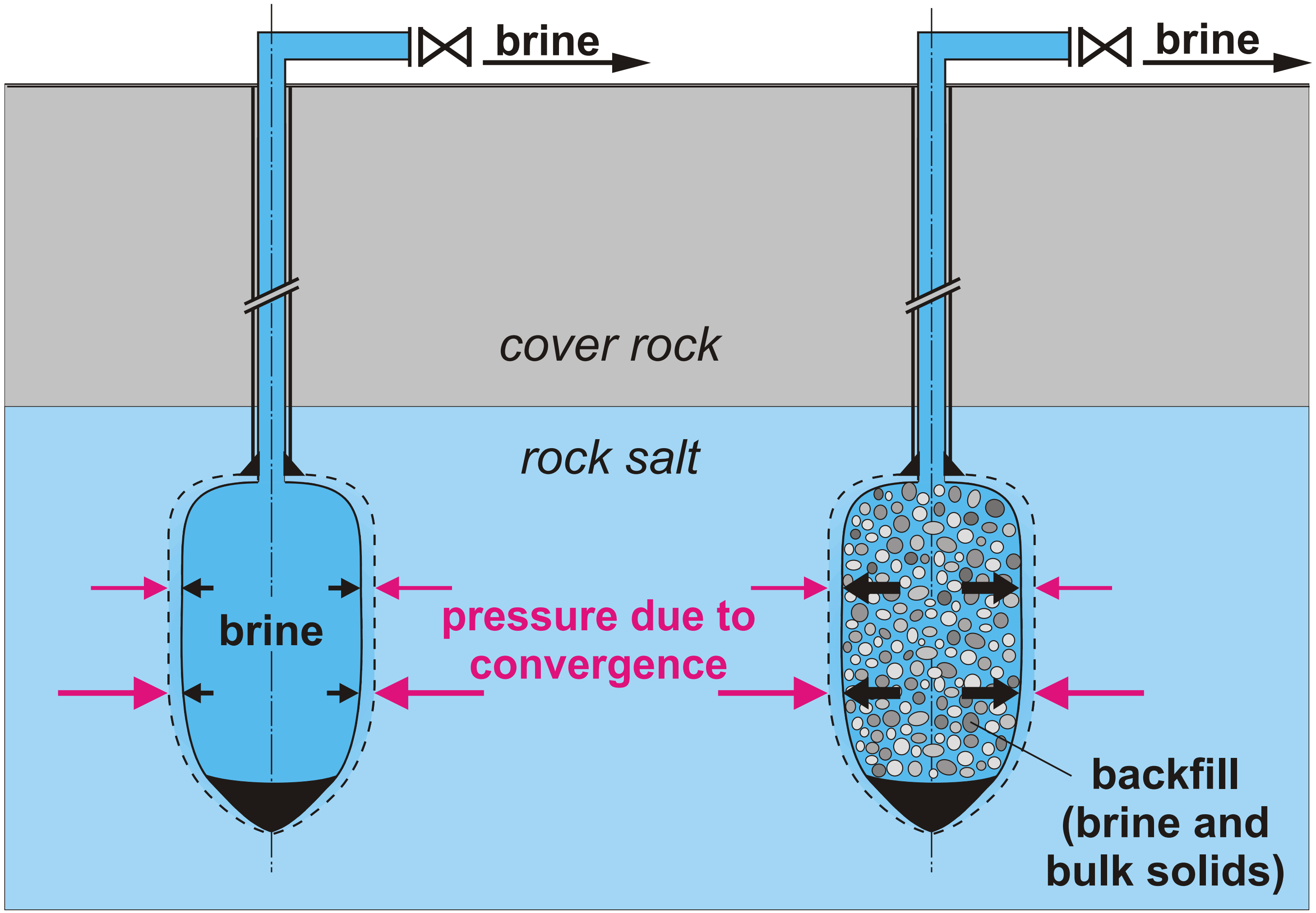

Figure 11-4
Cavern abandonment (brine fill) at p-brine < p-max /
brine disposal at surface

7006\Abb\2006\Sept\060913_Figure_11-4.cdr

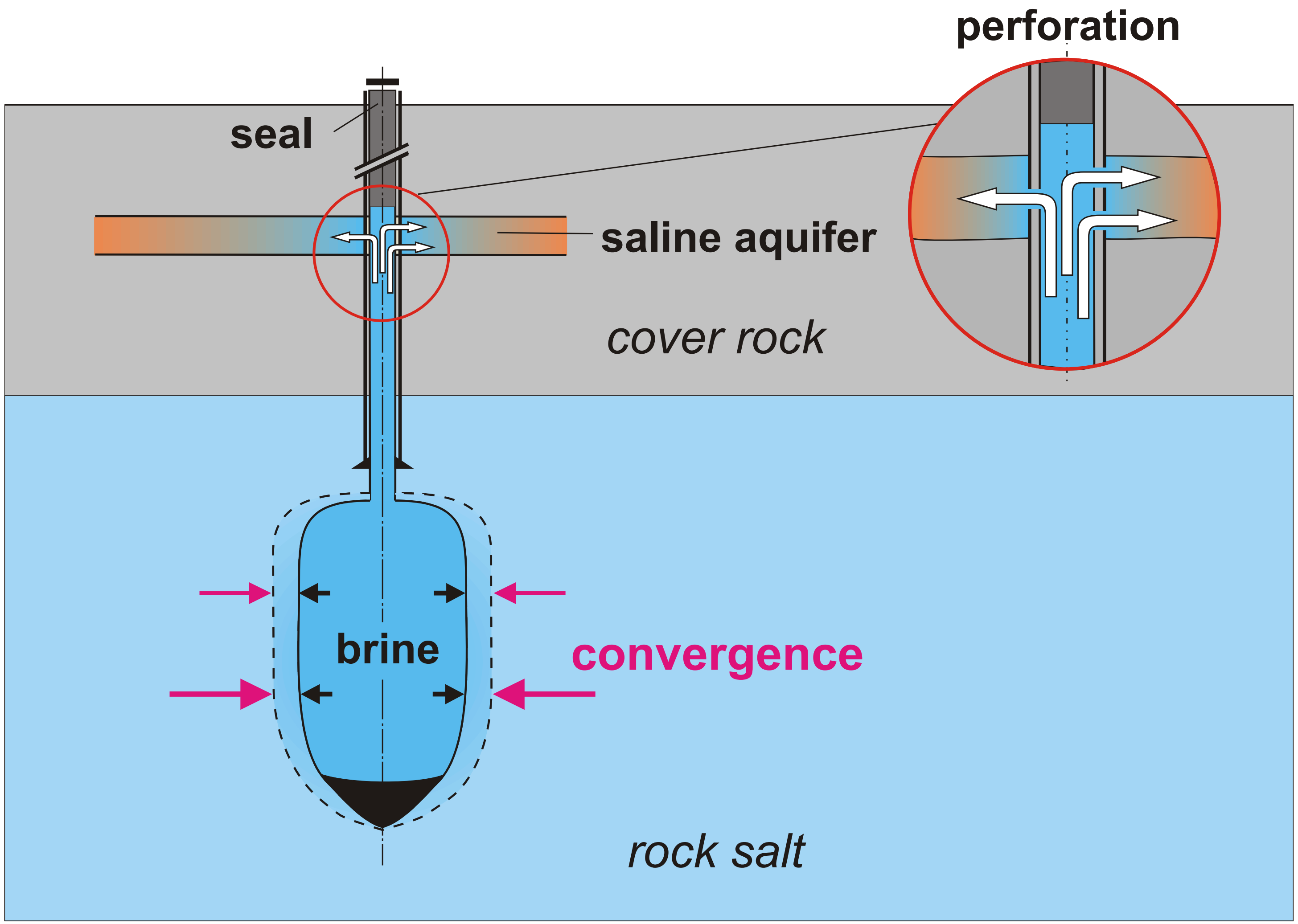

Figure 11-5
Cavern abandonment (brine fill) at p-brine < p-max /
brine disposal into saline aquifer

7006\Abb\2006\Sept\060913_Figure_11-5.cdr