

SOLUTION MINING RESEARCH INSTITUTE

105 Apple Valley Circle
Clarks Summit, PA 18411, USA

Telephone: +1 570-585-8092

Fax: +1 570-585-8091

www.solutionmining.org

**Technical
Conference
Paper**



Some geomechanical aspects of compressed air energy
storage (CAES) in salt caverns

**U. Düsterloh & K.-H. Lux, Chair for Waste Disposal and Geomechanics, Clausthal
University of Technology, Clausthal-Zellerfeld, Germany**

SMRI Fall 2010 Technical Conference
3 – 6 October 2010
Leipzig, Germany

Abstract:

Because the availability of wind is time dependent whereas the need of electric power is continuous, an intermediate storage of wind power is required. The intermediate storage of wind power basically could be done by compressing air in times with more wind power than needed for the grid and decompressing air in times with less wind power than needed for the grid. The compressed air itself potentially could be stored in salt caverns. From the geomechanical point of view this simple idea causes some problems regarding to the cavern stability. In comparison to the well known geomechanical design of natural gas storage cavities four significant differences between gas and compressed air storage in salt caverns must be pointed out: (1) The cyclic turnover between fluid injection and withdrawal for compressed air energy storage is a multiple of that used by natural gas storage. (2) The maximum cavern inside pressure for compressed air energy storage is limited by the allowable turbine input pressure which is in a level between 30 and 80 bar. (3) Cyclic loading by compressed air energy storage requires to superimpose thermal induced and mechanical stresses. (4) Compressed air energy storage is defined by the need of an ordinary operation phase with atmospheric cavern inside pressure.

Key words: Compressed Air Energy Storage (CAES), Cavern Design, Computer Modeling, Rock Mechanics

1 INTRODUCTION

As titled the paper deals with some geomechanical aspects of CAES in salt caverns. One main aim of the paper is to analyse whether it is technical and economical feasible to store and restore wind power in salt caverns. Because the availability of wind is time dependent whereas the need of electric power is continuous, an intermediate storage of wind power is required. The intermediate storage of wind power basically could be done by compressing air in times with more wind power than needed for the grid and decompressing air in times with less wind power than needed for the grid. The compressed air itself potentially could be stored in salt caverns.

From the geomechanical point of view this simple idea causes some problems regarding to the cavern stability. To declare the reasons of the stability problems a comparison between successfully used salt caverns for natural gas storage with the demands for CAES is helpful.

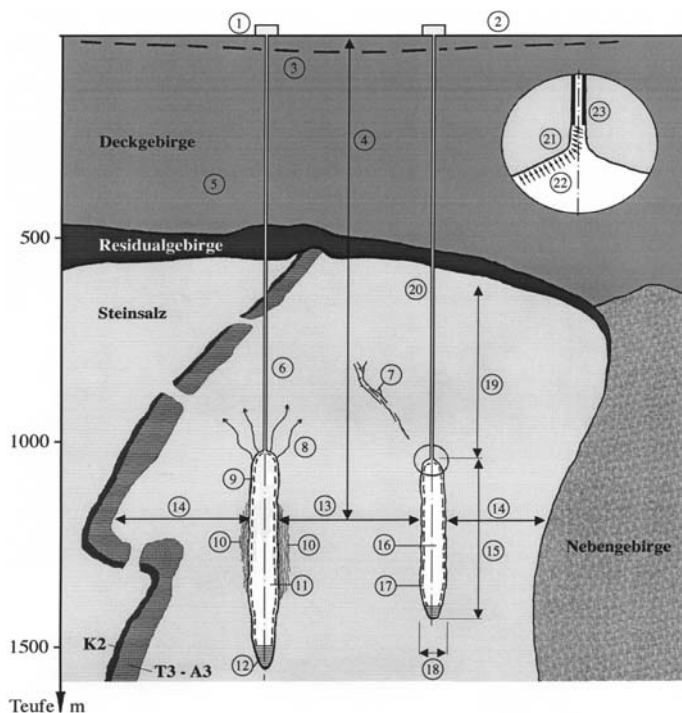
In Germany there are more than 250 salt caverns for natural gas and crude oil storage currently in operation. Because no accident is known, there must be a good understanding of the load bearing behaviour of such caverns. Or, the other way round, because of the good understanding of the load bearing behaviour of salt caverns no accident has occurred until now.

So the question is, what are the differences between salt caverns for natural gas and crude oil storage and salt caverns for compressed air energy storage? To answer the question some informations regarding the geomechanical design are needed.

2 MAIN DESIGN PARAMETERS AND GENERAL DEMANDS

Main design parameters and general demands of salt caverns are drafted in the Figure (1). Thereafter general demands could be summarized to stability, tightness, acceptable surface subsidence and later on an environmental safe abandonment. This general demands are heavily influenced by geomechanical design parameters such as

- cavern geometry and volume which are affected by cavern height and diameter as well as roof and floor construction,
- such as cavern depth, because the deeper the cavern the higher the overburden pressure and the rock mass temperature,
- such as minimum internal pressure, because the cavern inside pressure reacts like a static lining to the cavern contour,
- such as maximum internal pressure, because the maximum inside pressure must be fixed to avoid gas infiltration into the surrounding rock mass as well as cracking the surrounding rock mass,
- such as distance between individual caverns on the one hand and between caverns and adjoining rock, cap rock and geological interfaces within the salt deposit on the other hand,
- such as allowable convergence, because convergence generates surface subsidence,
- and last but not least the cavern operation pattern which is determined by the amount of injection and withdrawal cycles, the related cavern inside pressure and the related pressure rates.



General demands:

- static stability
- tightness
- acceptable surface subsidence

Design parameters:

- cavern geometry and volume
- cavern depth
- minimum inside pressure
- maximum inside pressure
- distance between individual caverns
- distance to adjoining rock, cap rock and geological interfaces
- convergence
- operation pattern

Figure 1: Main design parameters and general demands

Because all the mentioned design parameters have an impact to the static stability of salt caverns they must be taken into account by calculating the load bearing behaviour. Additionally to the design parameters a particular importance is given to the stress-strain and creep behaviour of the

rock salt. Rock salt is characterized by an extremely non linear, viscous, time dependent and rate sensitive material behaviour. Regarding to the design parameter “operation pattern” rock salt is known as a material which has memory properties concerning the creep behaviour as well as damage and healing behaviour.

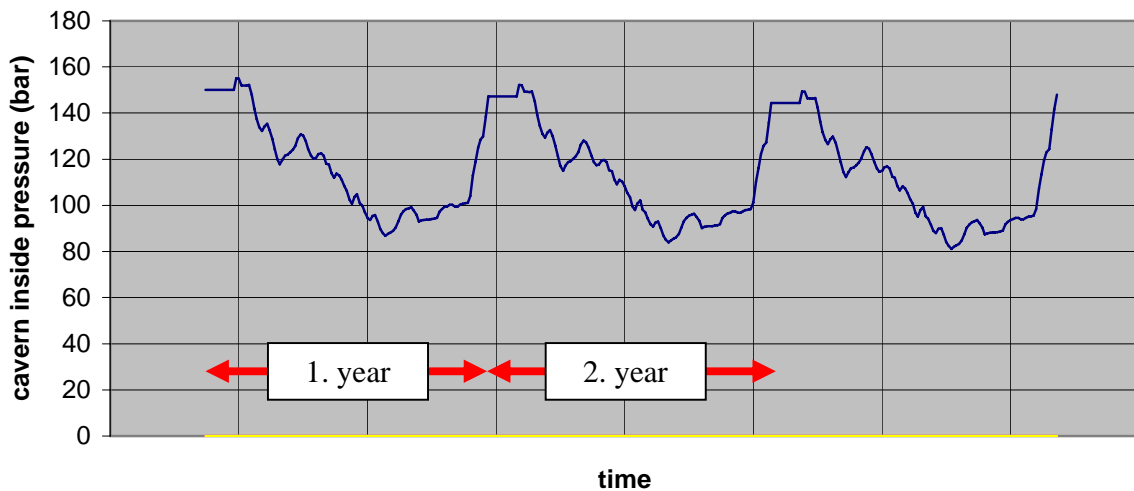
No matter if you are familiar with geomechanics or not it could be stated, that proof and estimation of static stability, tightness and surface subsidence of salt caverns is a more or less complex job because of the plurality of the influencing parameters.

3 DIFFERENCES BETWEEN NATURAL GAS AND COMPRESSED AIR STORAGE

After giving a short overview about boundary conditions and material and design parameters which have to be taken into account by analysing the load bearing behaviour of salt caverns the initial named question about the reasons of static stability problems by compressed air energy storage in salt caverns and the differences between natural gas and compressed air storage in salt caverns respectively must be answered.

In total four fundamental/significant differences between the storage of natural gas and compressed air in salt caverns must be pointed out:

(1) The cyclic turnover between fluid injection and withdrawal for compressed air energy storage is a multiple of that used by natural gas storage. As shown in the Figure (2) natural gas storage is normally done seasonal with only one or a few cycles per year. Injection of gas takes place in the summer months when usage of energy is low, withdrawal of gas takes place in the winter months, when usage of energy is high. In comparison to this seasonal storage the compressed air energy storage is characterized by a more or less daily alternation of injection and withdrawal of compressed air due to changeover of wind availability.



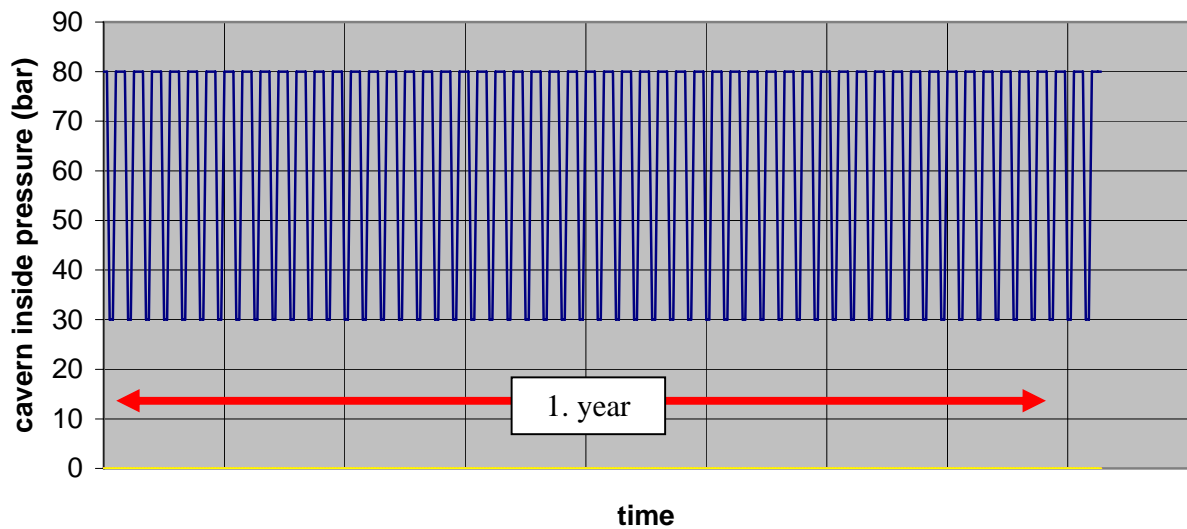


Figure 2: Comparison between operation pattern by natural gas and compressed air energy storage

Every decreasing of the cavern inside pressure, no matter if it has been carried out in a cavern for natural gas storage or in a cavern for compressed air energy storage, results in an increasing of the so called deviatoric stresses in the rock mass. From laboratory investigations it is well known that an increasing of the deviatoric stress leads to an increasing of the creep rate. Therefore the general answer of the surrounding rock salt to a single loading is equal for both types of salt caverns. But, as a consequence of the cyclic loading laboratory investigations regarding the creep behaviour of rock salt by cyclic loading are necessary. A first indication to the creep behaviour by cyclic loading in comparison to the creep behaviour observed by single loading is given in the next two Figures (3,4).

As shown in the little picture beside the diagram, creep tests are carried out by an uniaxial or triaxial constant loading of cylindrical samples. Observed by such tests directly after loading is a so called transient creep phase with a time dependent decreasing creep rate (measured creep strain is plotted to the vertical axes, testing time is plotted to the horizontal axes / creep rate is given by the inclination of the creep curve). Over a period of some weeks up to some months the transient creep phase passes over to a so called stationary creep phase with a constant creep rate. By computing the load bearing behaviour for a seasonal storage of natural gas it is assumed, that because of the long time between two cycles the rock salt lost the memory of the previous cycle. Following these boundary conditions every cycle of injection and withdrawal of gas causes a transient and a stationary creep phase in the rock salt.

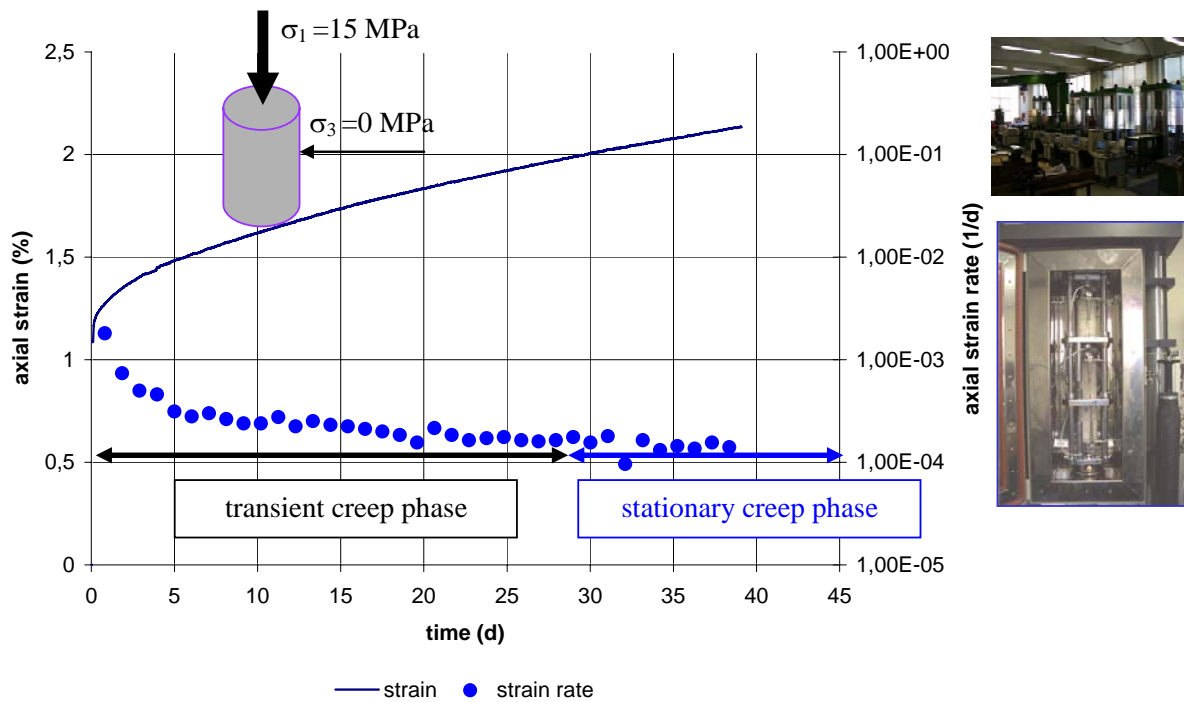


Figure 3: Transient and stationary creep behaviour by single loading

The next Figure (4) indicates the creep behaviour of rock salt by cyclic loading a cylindrical salt sample with levels of 14 MPa and 1 MPa one after the other. Each load level is performed over a time period of nearby 5 days. As shown in the diagram an overall decreasing of the creep rate could be observed. Therefore it could be stated, that the transient creep rate observed by single loading is not repeatable by cyclic loading. Further laboratory investigations are necessary to analyse what happens to the relation and quantity of transient and stationary creep phase depending to the cycle period, the number of cycles and the stress level.

Related to the load bearing behaviour of salt caverns the overall decreasing creep rate results in a reduced convergence (good for CAES because of the lower loss of cavern volume during operation) whereas the stresses in the rock mass will increase (bad for CAES because of the higher ratio between computed stresses and the fixed strength of the rock salt).

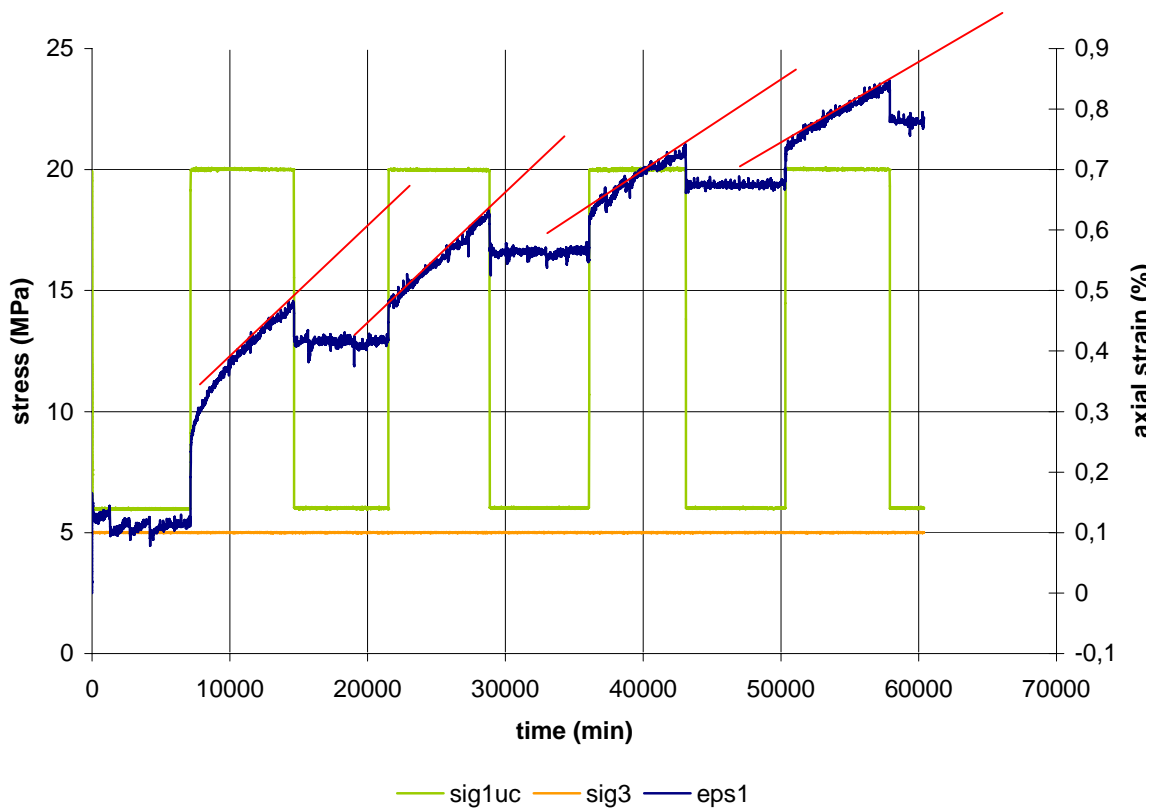


Figure 4: Transient and stationary creep behaviour by cyclic loading

(2) A second difference of importance between the storage of natural gas and compressed air in salt caverns is given by the possible maximum inside pressure. Generally the maximum cavern inside pressure for compressed air energy storage is limited by the allowable turbine input pressure. Common compressed air turbines are operating in a pressure level between 30 and 80 bar. To protect the turbine against demolition, the compressed air pressure at the input side of the turbine has to be limited to the technically given critical value. Generally this is an edge condition for both, natural gas storage as well as compressed air energy storage. But, in the case of natural gas storage decompression of the gas at the input side of the turbine is economically feasible whereas decompression of compressed air makes no sense. In the case of gas storage there is a big energy content in the fluid itself, so the loss of energy by decompressing the gas to a lower level is small in comparison to the energy content of the fluid. In opposite to that, in the case of compressed air the energy of the fluid is only given by the potential to expand, so decompressing the previously compressed air leads to a loss of energy. As a consequence the medium pressure level by compressed air energy storage is significantly lower than that usually used by natural gas storage.

Regarding the load bearing behaviour of a salt cavern for compressed air energy storage it has to be taken into account, that the expected convergence and in succession surface subsidence in comparable depths will be greater than by caverns used for natural gas storage. Maybe a solution is given by reducing the depth and the rock mass stress level of salt caverns respectively. But, beside the assumption to find convenient salt deposits in a lower depth, a third important

difference between natural gas and compressed air energy storage in salt caverns must be taken into account.

(3) Compression of a fluid – no matter if it is natural gas or compressed air – leads to an increasing of the fluid temperature, decompression of a fluid leads to a decreasing of the fluid temperature. Thermo dynamical calculations have been carried out to estimate the temperature of compressed air under alternating boundary conditions. As exemplarily shown in the Figure (5) several thermo dynamical calculations have been done by varying compressing and decompressing rates, cycle periods, pressure levels and cavern shapes. Evaluation of the examined load cases indicates, that in all cases the change of fluid temperature is given approximately by 1,3 degrees per bar pressure. That is, increasing the inside pressure about 10 bar results in an increasing of temperature by 13 degrees. The other way around, decreasing the inside pressure about 10 bar results in a decreasing of temperature by 13 degrees. Simultaneously to the heating and cooling of the fluid the rock salt surrounding the salt cavern is heated or cooled. Heating of rock salt creates thermal induced compressive stresses, cooling of rock salt creates thermal induced tensile stresses.

This process of creating thermal induced stresses in the rock salt is presented by both, natural gas and compressed air energy storage. However, because of the comparatively long period of an injection and withdrawal cycle by seasonal storage of natural gas, heat transmission between the rock salt and the gas reduces the thermal induced stresses in the near field of the cavern contour. Against this, cyclic loading by compressed air energy storage requires to superimpose thermal induced and mechanical stresses.

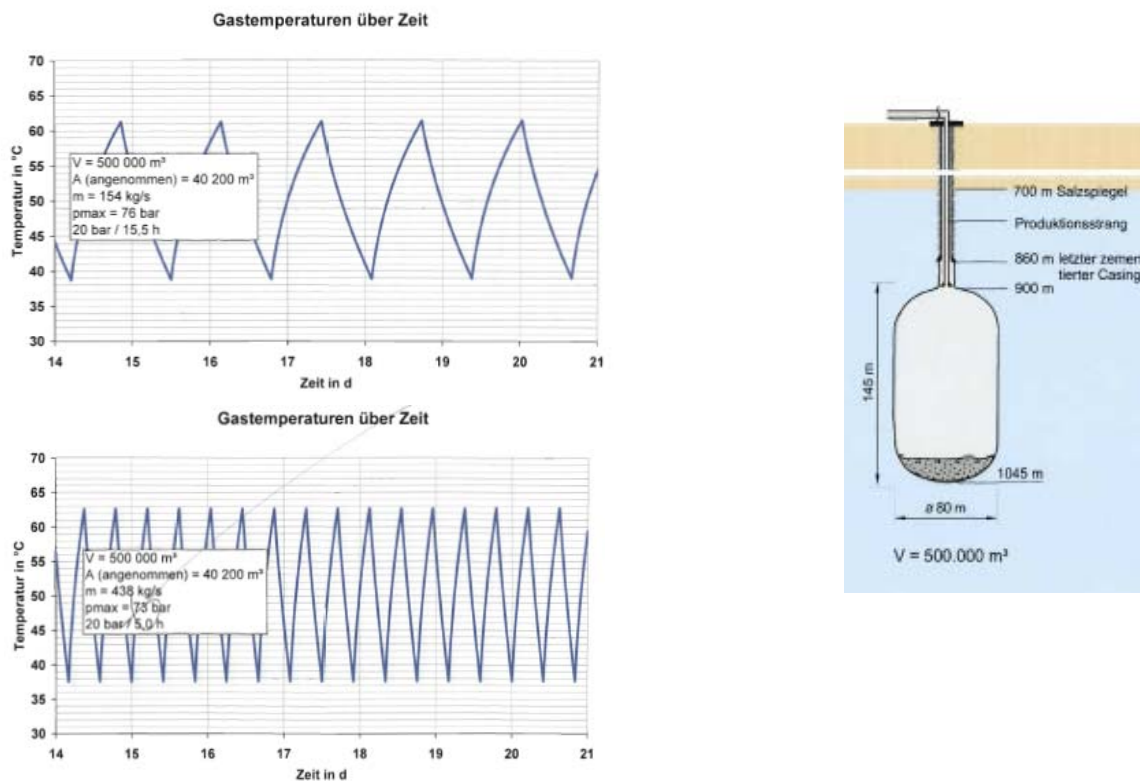


Figure 5: Thermo dynamical calculations for cyclic loading

Depending on the cavern depth and the stress level in the rock mass respectively the superposition of mechanical compressive stresses and thermal induced tensile stresses could lead in total tensile stresses in some parts of the rock mass. An example is given in the Figure (6). Therefore a thermal-mechanical coupled calculation for a daily pressure cycle between 8 and 4 MPa presents tensile stresses at the cavern contour in a depth of approximately 1000m. Because the tensile strength of rock salt is very small in quantity and comparatively great in scattering, fissuring and even spalling of the cavern contour could not be excluded. Knowing, that an increasing of cavern depth presents higher compressive stresses, the observed tensile stresses could be avoided for example by increasing the depth. However, regarding to the previous described boundary of limited cavern inside pressure increasing of cavern depth results in an increasing convergence and surface subsidence respectively as well as increasing of the ratio between the computed stresses and the strength of the surrounding rock salt. Therefore the two aims of lowering the cavern depth on the one hand and avoiding thermal induced tensile stresses on the other hand are in an opposite direction.

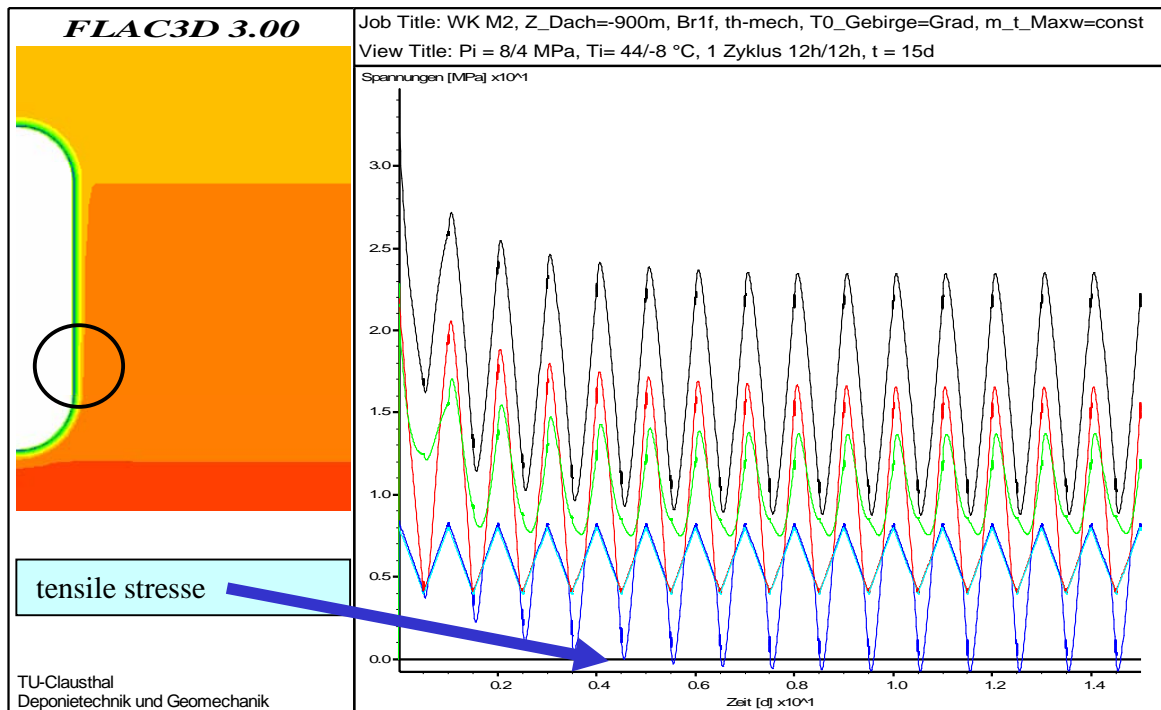


Figure 6: Thermal induced tensile stresses (thermo mechanical coupled calculation)

To analyse the interaction of thermo mechanical coupled loadings of rock salt on the one hand and to proof and validate the heat transfer between a fluid and rock salt, special laboratory investigations are in progress. One aim of these tests is to specify the so called heat transmission coefficient. The heat transmission coefficient on the one hand is responsible for the heat flow between the cavern fluid and the rock salt and between the rock salt and the cavern fluid respectively. On the other hand the heat transmission coefficient is not known very well because adequate measuring of rock salt and fluid temperature within the cavern is not possible. Therefore special laboratory tests with temperature measuring of both fluid temperature and rock

salt temperature are performed and be recalculated by a numerical back analysis. Fitting the measured temperatures to the calculated temperatures by varying the heat transmission coefficient gives an estimation of the heat transmission coefficient value. A photographic view of the testing facility used in our lab for rock salt hollow cylinders is shown in Figure (7). The test bench offers control and measuring of three pressure cycles. The axial and the confining pressure cycle are used for loading the sample accordingly to the vertical and horizontal stresses in the rock mass. A computer controlled heating of the hydraulic oil in the confining pressure cycle ensures a set up of the sample temperature equal to that of the rock mass. The third pressure cycle allows both a cyclic pressure and temperature alternating within the axial borehole of the hollow cylinder. Therefore the hydraulic pressure cycle within the axial borehole represents the fluid in the cavern.



Figure 7: Laboratory investigations of thermo mechanical coupled loadings

Typical test results are plotted in the next Figures (8, 9). As shown in Figure 8 stress boundary conditions of the test are given by a constant axial and radial pressure of 14,5 MPa and 14,0 MPa respectively, whereas the borehole inside pressure alternates between 8,0 MPa and 4,0 MPa. The temperature in the confining pressure cycle is set constant to +44 degrees, whereas the hydraulic oil within the borehole alternates parallel to the pressure between +44 degrees and -10 degrees. Measurement results of temperature within the salt sample are shown in Figure 9. It could be clearly observed from the diagram, by decreasing the fluid temperature within the axial borehole a temperature gradient with a lower temperature nearby the axial borehole and an increasing temperature with increasing distance to the borehole occurs in the salt sample.

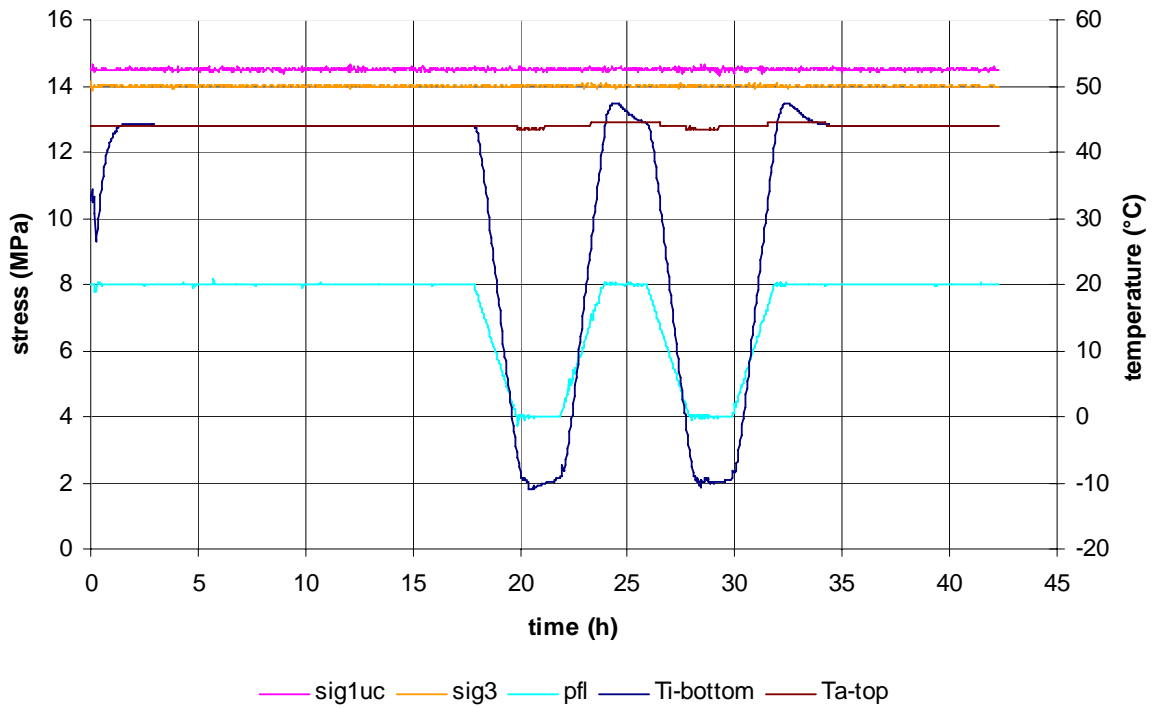


Figure 8: Pressure and temperature boundary conditions

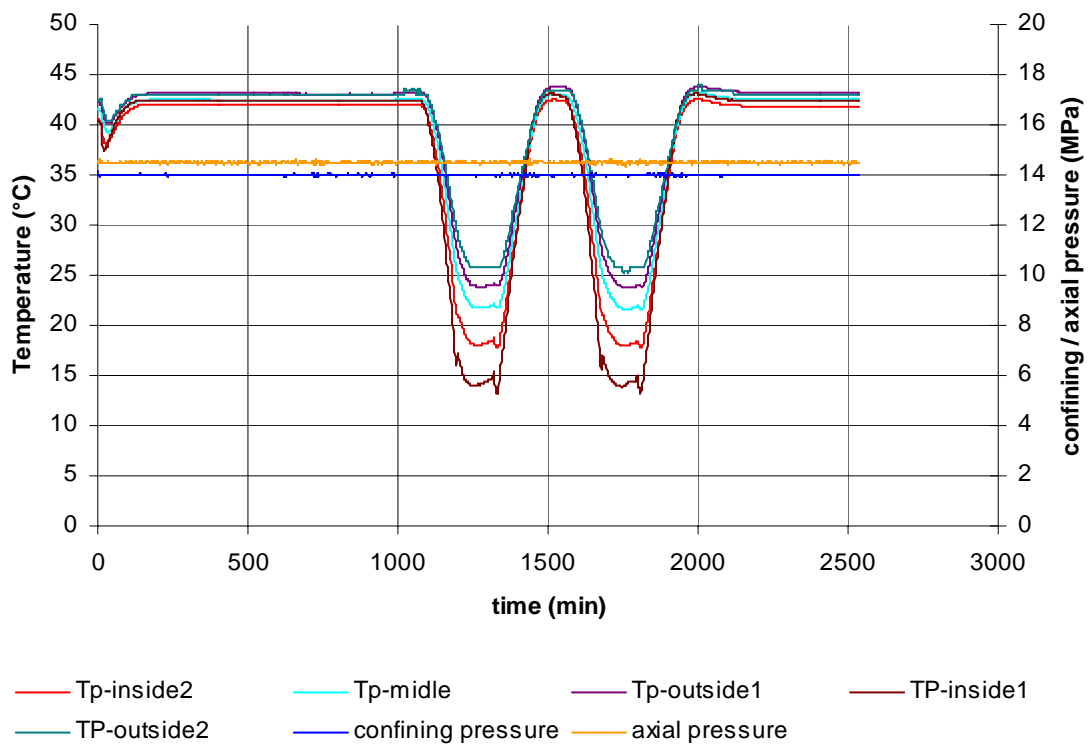


Figure 9: Temperature measurements hollow cylinder

To document the fitting between measured and computed temperatures by a back analysis an example is given in Figure (10). As shown in the diagram a good correlation between measured and computed temperatures could be found by varying the heat transmission coefficient.

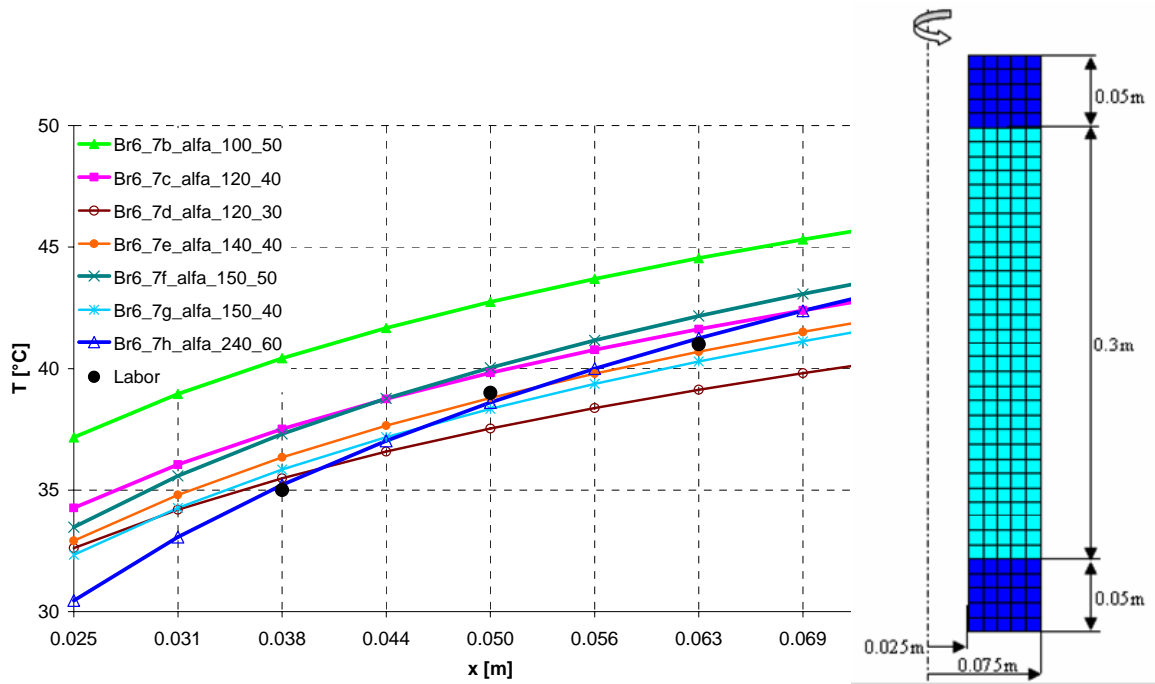


Figure 10: Back analysis of measured temperatures by varying the heat transmission coefficient

As a consequence of the temperature gradient tensile stresses could create cracks. A visualisation of such cracks could be done by a tracer as shown in the Figure (11). Therefore, tracing the samples after performing the tests enables investigations about the permissibility of selected load cases.

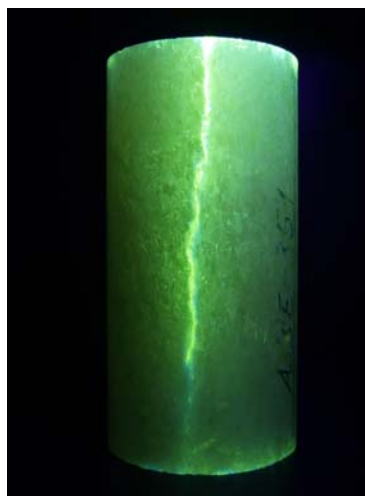


Figure 11: Visualisation of thermal induced cracks

Additionally to this specific tests regarding the thermo mechanical coupled load bearing behaviour of rock salt it must be emphasized, that neither the creep behaviour nor the strength of rock salt is investigated for temperatures below 20 degrees in an adequate amount until now. Therefore further laboratory investigations are needed for a better understanding of geomechanical processes which will take place by operating a compressed air energy storage cavern.

(4) The fourth main difference between the successfully operated gas caverns and the planned compressed air energy storage is defined by the need of an ordinary operation phase with atmospheric cavern inside pressure. Due to the significant higher volume flow rate by compressed air energy storage in comparison to the natural gas storage, corrosion of the production well is awaited. Therefore from time to time a replacement of the production well or other repair work demands a certain period of time under atmospheric cavern inside pressure. By operating a salt cavern under atmospheric pressure no support against the rock mass pressure is existing. Therefore this special load case needs high sophisticated calculations which take damage and spalling processes into account to avoid the cavern from progressive rupture.

4 CONCLUSIONS

Coming to the end, a short summary could be given by the following statement:

From the geomechanical point of view a raw estimation about the load bearing behaviour is available by using design concepts learned from natural gas storage in salt caverns. To transfer the idea of compressed air energy storage into a safe technical and economically optimized application, further investigations are needed to understand in detail the complex material behaviour of rock salt by cyclic mechanical and temperature loadings combined with multiple interactions to the operation pattern of CAES caverns