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IMPORTANCE OF SONAR SURVEYING IN THE MONITORING AND OPERATION OF NATURAL GAS CAVERNS

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Abstract: It is becoming increasingly important to carry out thermodynamic calculations starting from the very first stage of storage planning and continuing right on up to the actual storage operation in gas caverns. The reason for this is that on the one hand the availability of gas quantities and the efficiency of the storage facilities need to be determined and on the other hand these have to be predicted as reliably and as quickly as possible. History match methods and particularly the predictions (on a daily or hourly basis) of pressures, temperatures and operating gas amounts in relation to the existing storage situation are therefore important tools for the storage operator to enable him to react to short and medium-term market needs. SOCON Sonar Control Kavernenvermessung GmbH recognized the need for and so developed a software package that, based on the SOCON sonar survey in caverns under gas with the accompanying logs, answers the remaining thermodynamic and rock mechanics questions. This provides the cavern operator with the opportunity to increase operational safety and at the same time allows the capacities and performance profiles during injection and extraction to be assessed (history match) and predicted.

Key words: natural gas caverns, sonar survey, thermodynamics of natural gas storage

INTRODUCTION

The structure of storage caverns makes them ideally suitable for handling short-term peaks in gas consumption as the large volume of gas stored allows high rates of extraction owing to the gas expansion. The prevailing pressure and temperature conditions in the cavern, the gas composition, the size and design of the casing and tubing, the pressure and temperature losses in the surface facilities as well as in the field pipelines all together determine the overall performance of the cavern storage system.

As a result of the changeover from the traditional, annual-storage-cycle way of operating a gas cavern to short-term, multi-cycle storage operations, various thermodynamic and rock mechanic calculations are becoming increasingly significant. As the most important input parameters for these calculations, such as the initial pressure and temperature conditions, gas humidity and current cavern volume, are measured directly in cavern surveying it is not surprising that sonar cavern surveying, too, is becoming more important in this connection.

THE BASICS OF SONAR CAVERN SURVEYING

Cavern geometries are measured using sonar tools on the basis on traveltime measurements (Fig. 1). What is actually measured is the time an acoustic pulse takes to travel from the survey tool to the cavern wall and back. The required distance *d* to the cavern wall is determined from the measured traveltime *T* and the acoustic velocity v_p in the medium.

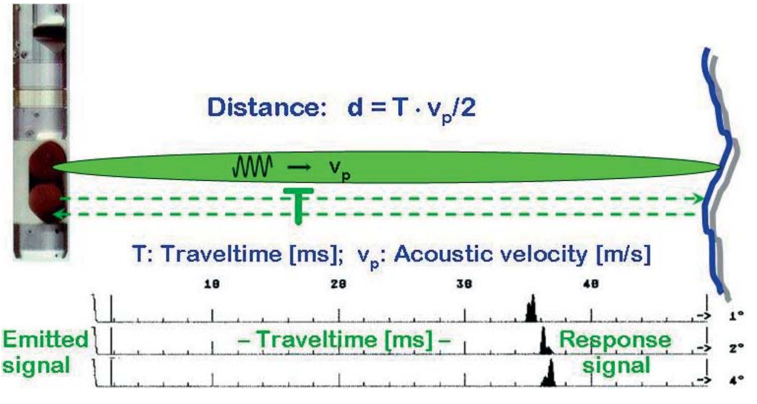

Fig. 1. Distance determination by measuring the traveltime

In order to accurately determine the distance it is necessary to have not only the traveltime, but also, and this is highly important, the precise knowledge of the acoustic velocity in the cavern medium. This velocity is subject to a complex interrelationship of physical parameters, but in the first place it depends on the medium as well as on the temperature and pressure conditions inside the cavern. Table 1 shows the range of expected acoustic velocities of different media in caverns.

Table 1

Acoustic velocity in different media

Medium	Acoustic velocity [m/s]
Air	300–375
Natural gas	400–500
Oil products	1200–1500
Brine	1750–1900

Before carrying out the actual sonic survey the physical conditions prevailing in the cavern must first be measured. This is done by running logs along the survey axis to record the vertical variation in acoustic velocity, pressure, temperature and dewpoint. When measuring these data it is of utmost importance for controlling the surveying procedure and for the subsequent interpretation that the data are measured continuously over the entire depth range of the cavern. Data measured at individual points cannot supply sufficient detail of the true physical conditions (Reitze & von Tryller 2004).

Once the required physical parameters have been measured the sonar survey of the cavern geometry is carried out by measuring numerous horizontal sections over the entire depth range of the cavern. Measurements with the tool head tilted enable the floor and the roof of the cavern to be sampled and possibly any hidden leached zones that may exist (Fig. 2). Not only the vertical intervals between the individual horizontal sections but also the angular intervals between the tilted measurements are optimised to suit the cavern geometry.

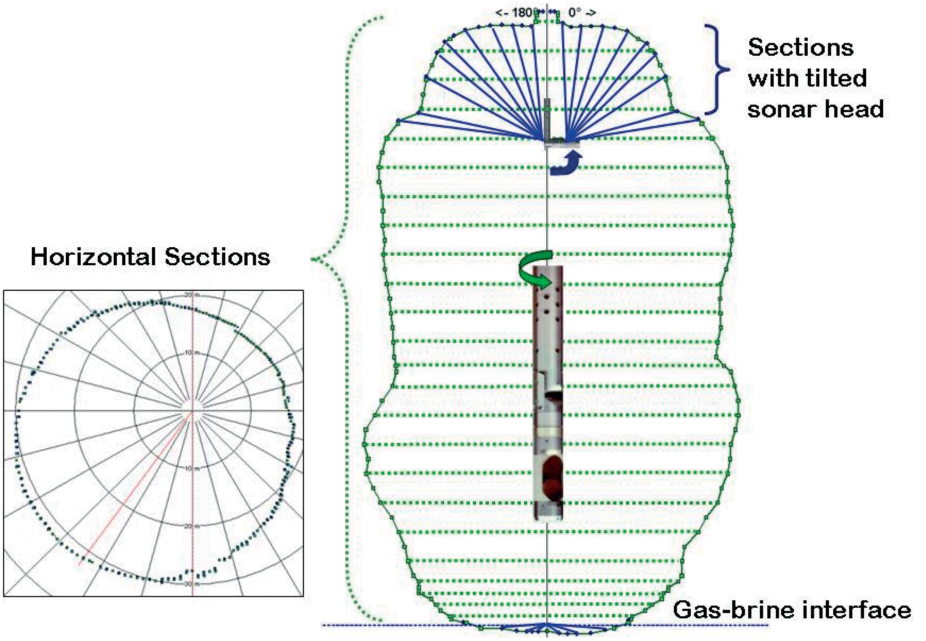

Fig. 2. Measuring the cavern geometry

The SOCON measuring principle is based on a point-to-point, azimuthal sampling of the cavern wall. In the first place the survey head holding the sonic transducers is positioned in the required direction and at the appropriate inclination. It remains fixed there until a point on the cavern wall is determined with certainty and all the necessary correlations and plausibility checks have been carried out. This procedure is possible only because the SOCON sonar tools are equipped with a patented gyro stabilisation which prevents rotational vibrations of the tool.

Sophisticated sonar tools created in SOCON's own research and development department are used for executing the surveys. With these sonar tools it is possible to carry out surveys in any of the relevant media, such as brine, crude oil and natural gas. The latest BSF II generation of tools are based on the well-established modular concept and their technical specifications and functionality correspond to the BSE and BSF tool generations. Each of the integrated functional units, such as the transmitter-receiver unit, compass, rotation-tilt controls, acoustic velocity measurement and MCCL (Multiple-Casing-Collar-Log), is equipped with its own processor and is controlled by the central computer at the surface via a digital bus. A module for determining the dewpoint is available especially for measuring in gas-filled caverns.

The new BSF II tools have additionally an integrated natural-gamma sensor, an optimised stabiliser unit for fixing the tool while measuring as well as three magnetic field sensors. The physical parameters that need to be known for optimally controlling the survey procedure as well as for interpreting the cavern survey results can be recorded continuously as a log by the sonar tools during a single survey run. CCL or MCCL sensors are used to obtain the correct depth reference.

SONAR SURVEYS OF GAS-FILLED CAVERNS AS THE BASIS OF ROCK MECHANICS AND THERMODYNAMIC SURVEILLANCE

Sonar surveys are regularly carried out in gas-filled caverns to comply with the requirements of the mining authorities and the needs of operational surveillance. The deep drilling regulations (BVOT) in fact require that such surveys are carried out, whereby the intervals between individual surveys are defined more precisely based on the cavern operating schedules. In particular the surveys can be used to determine the cavern geometry and so provide evidence of any possible changes that have occurred in the cavern, such as convergence and wall collapse. Considering the accuracies that can be achieved as well as the operational needs the appropriate time interval between full surveys has been established as 6 to 10 years. At shorter intervals of up to three years, partial cavern surveys are executed targeting solely the roof and floor regions. If the measurement of those areas does not reveal any significant alterations then it is assumed that also in the unsurveyed part of the cavern no large changes in shape have occurred. As it is not possible to determine the cavern volume when carrying out partial surveys, the volume at the time a partial survey is carried out is estimated from previous full surveys.

The results of the cavern surveys must be documented in the working drawings of the cavern in compliance with Section 63 of the Federal Mining Act (BBergG) and the drawings subsequently updated, which according to surveying and mining regulations are prepared as cross-sections and plans. The surveys supply information particularly about the volume convergence as well as about any possible changes in the contours that have occurred and so form – in addition to elevation observations at the surface – the basis of rock mechanics monitoring (Reitze *et al*. 2007). Sonar cavern surveys are of immense operational importance to the cavern operator because in addition they provide a range of *in-situ* parameters, namely the pressure, temperature and dewpoint, as well as the volume. This information is the absolute basis for the thermodynamic calculations that need to be made to optimise operations.

THERMODYNAMIC CALCULATIONS IN GAS-FILLED CAVERNS

The traditional way of having an annual storage cycle when operating a gas cavern (Fig. 3) has already changed during recent years for some gas cavern operators, and as a result of the continuing liberalisation of the gas market it will carry on changing drastically in the future. It is not possible to give at present an accurate prediction of this development but even now there appears to be a clear trend towards multi-cycle storage operations interspersed with short-term injection and extraction periods (market-based storage).

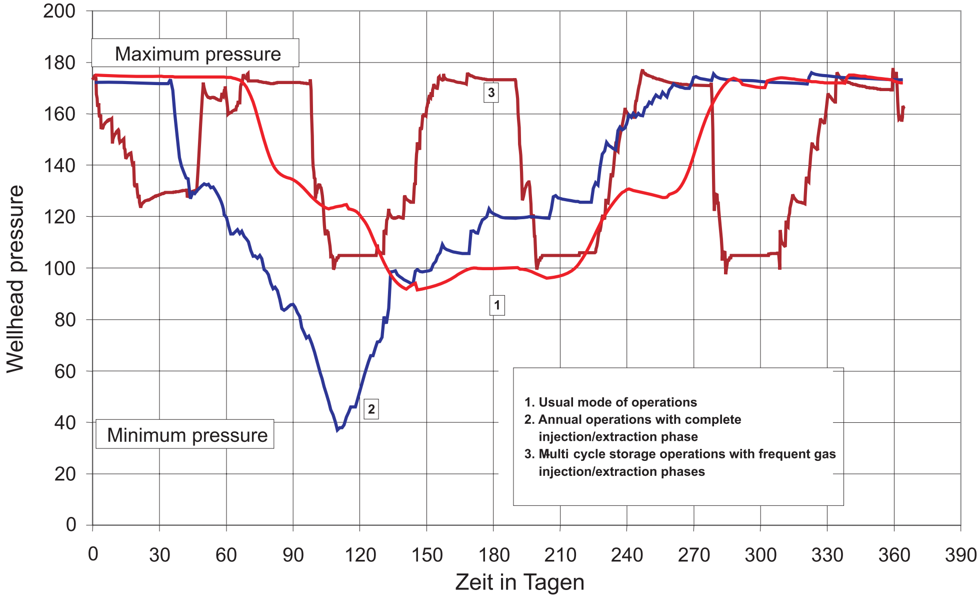

Fig. 3. Examples of modes of cavern storage operations (head pressure curves)

Thermodynamic calculations (Fig. 4) are becoming increasingly important from the time a storage system is first planned and right through to the actual storage operation in gas caverns. The reason for this is that on the one hand the availability of gas quantities and the efficiency of the storage facilities need to be determined and on the other hand these have to be predicted as reliably and as quickly as possible. "History Match" methods and in particular calculations (on a daily/hourly basis) of predicted pressures, temperatures and operating gas quantities in relation to the existing storage situation are therefore important tools for the storage operator to enable him to react to short and medium term market needs (Krieter 1998).

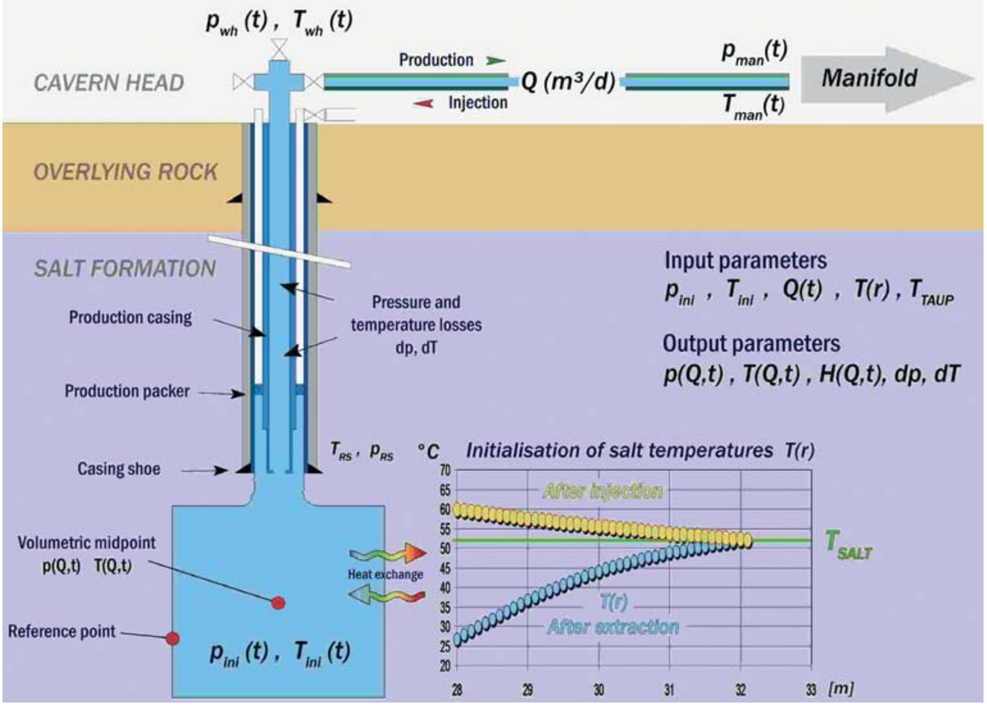

Fig. 4. Sketch of the principle of thermodynamic cavern calculations

The most important parameters to be monitored during operation are:

- pressure at the casing shoe (p_{RS}),
- cavern pressure at the reference point (p_{Ref}),
- pressure rates at the cavern reference point,
- service life at the lower pressure range,
- convergence/distortion,
- hydrate formation parameters.

To satisfy these needs SOCON Sonar Control Kavernenvermessung GmbH has developed a software package (CavBase Gas Storage) that resolves the thermodynamic as well as the rock mechanics problems, offers the cavern operator a safer way of operating, and at the same time considers (History Match) and can predict (Prediction Mode) the capacities and performance profiles during injection and extraction.

The most important dynamic parameters to be input into CavBase Gas Storage are the initial pressure pini and temperature conditions T_{ini} in the volumetric centre of the cavern at the start of the program, the temperature distribution $T(r)$, starting at the cavern wall and going into the salt body, the volume rate $Q(t)$ during gas production, the volume of the cavity V_o, and the total gas quantity GIP in the cavern. All those parameters (Fig. 5) are measured during a SOCON cavern survey in gas or are appropriately derived (cf. Fig. 2).

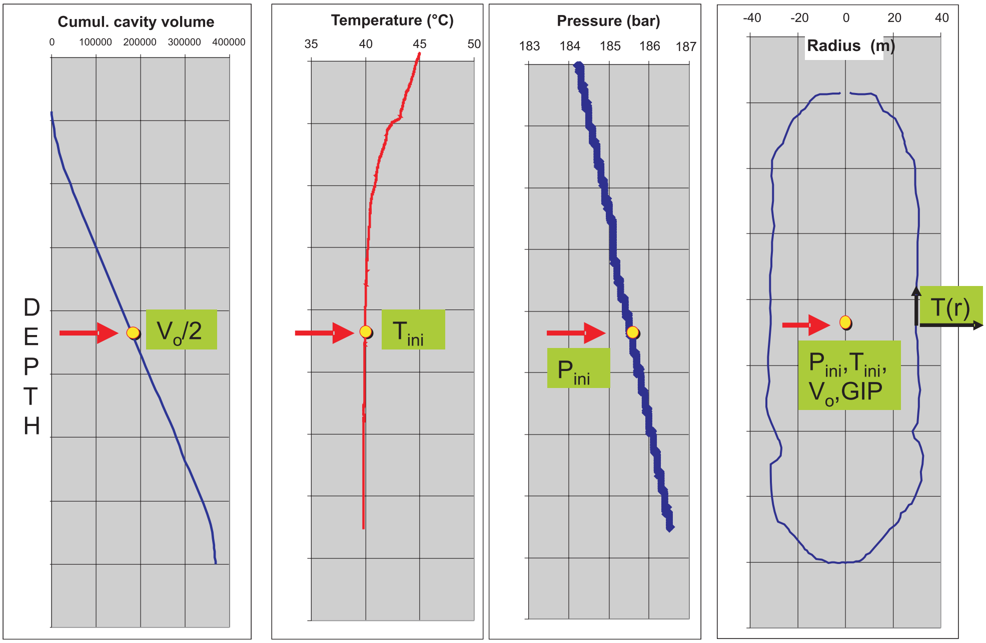

Fig. 5. Determination of the thermodynamic calculation parameters from SOCON logs

ACCOMPANYING ROCK MECHANICS CALCULATIONS DURING CAVERN OPERATIONS

Rock mechanics criteria for dimensioning have changed considerably over the past 10 years also as a result of the changeover from traditional Continuum Mechanics (CD) to Continuum Damage Mechanics (CDM) (Lux *et al*. 2002a; 2002b).

This relates for instance to:

– reduction of the minimum pressure,
– increase of the injection and extraction rates,
– consideration of service life and mending effects,
– measurement and calculation of the volume dilatancy,
– detection of the time-dependent fracture and creep fracture behaviour.

Thermodynamics and rock mechanics mutually affect each other with the result that a combination of rock mechanics and thermodynamics calculations are performed in the (daily) operational monitoring of limits. This in turn leads to guaranteed safe storage operations as a result of the rock mechanics restrictions being observed. Another aspect is to consider a mode of operation that minimizes convergence/deformation while allowing maximum storage changeover rates in caverns and avoiding thermally induced fissuring.

In cooperation with E.ON Ruhrgas AG an operations model (CavBase Gas Storage) has been developed that connects by means of calculation the components of cavern, borehole and pipelines up to the manifold (Krieter & Brüß 2008). Extension of the pressure allowance and the extraction rates accompanied a similar extension of the monitoring philosophy regarding the rock mechanics threshold parameters.

It was needed to provide at short notice details of the behaviour of rock mechanics and fracture mechanics of several caverns depending on the way they were operated. Owing to the long computing times needed, FE calculations were from the very beginning out of the question for an auxiliary software solution. The basic idea was therefore to divide up the individual caverns of a field into groups (Fig. 6) and to make a common numerical FE model for each cavern group (Krieter & Benke 2005).

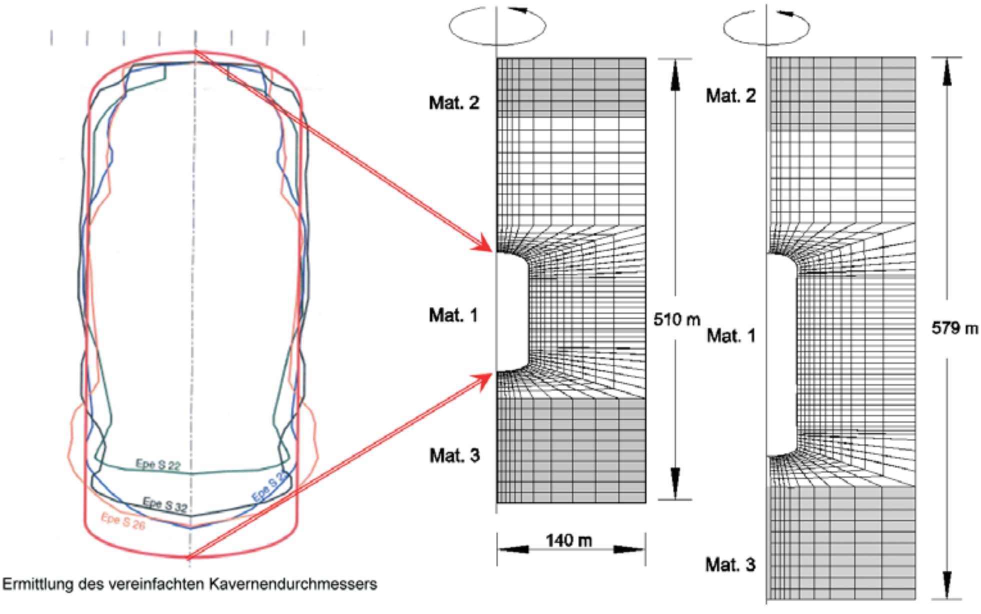

Fig. 6. Generation of FE cavern models and division into different classes

Subsequently different modes of operation were calculated on a grid basis with the FE models. The results of these calculations provided the convergence and deformation of the caverns in relation to the mode of operation, and these were combined subsequently in reference fields.

A fundamental goal of the processing was to be able to calculate for any given mode of operation not only the convergence but also the deformation of the salt body surrounding the cavern. By way of example only the convergence is considered in the following.

The convergence is determined through various reference fields:

- reference field for extraction ($dp/dt < 0$),
- reference field for standstill after extraction ($dp/dt = 0$),
- reference field for injection ($dp/dt > 0$),
- reference field for standstill after injection ($dp/dt = 0$).

This type of division was chosen as the convergence in each case depends on the current condition in the cavern and the history leading up to that condition. The numerical calculations of the convergence are made using the reference fields. Only after the survey data have been merged with the thermodynamics and rock mechanics (Fig. 7) is it possible to calculate the cavern pressure and the convergence/deformation resulting from it.

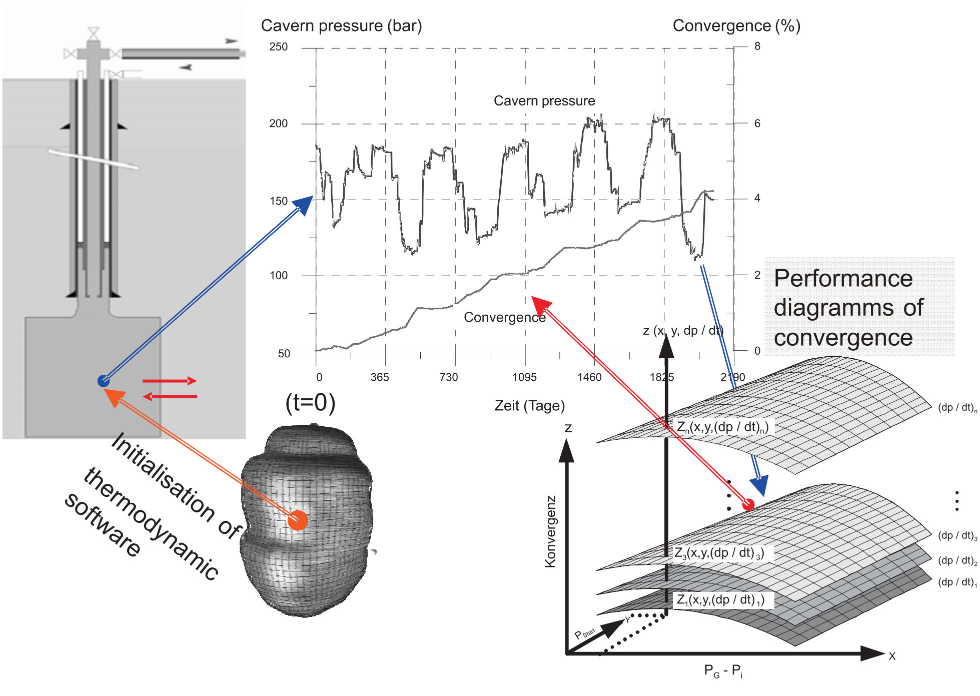

Fig. 7. Merging thermodynamics with rock mechanics

The FE calculations are calibrated using two consecutive SOCON cavern surveys in gas (Fig. 8).

For monitoring the above mentioned rock mechanics parameters, a report function was integrated in the CavBase Gas Storage package. The program calculates, in relation to the original conditions and the current volume rates, the pressure and temperature in the cavern, at the casing shoe depth and from the borehole head up to the manifold.

So as to reconstruct the original conditions in the cavern and in the salt body as precisely as possible the last sonar cavern survey in gas is used as the starting point for the thermodynamic calculations. As not only the cavern volume is measured in the survey but also the pressure and the temperature, all the relevant parameters are available for fixing the starting values.

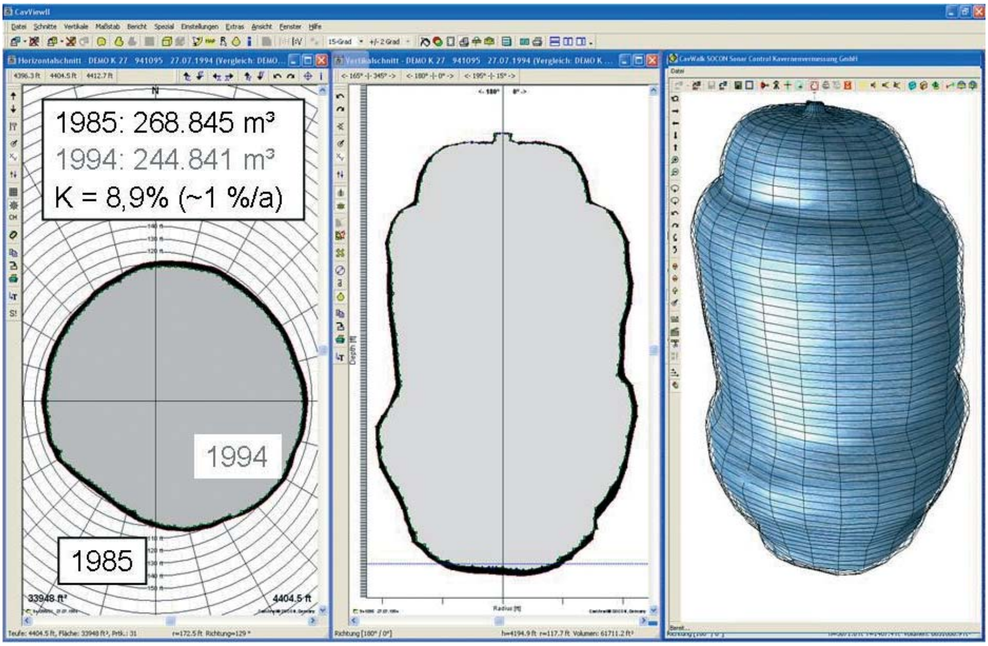

Fig. 8. Determination of the cavern convergence from two cavern surveys in gas (the outer (grid) contour represents the first survey, and the inner contour the second survey)

INHIBITION OF HYDRATES

The tool technology used by SOCON for sonar cavern surveys enables a dewpoint log to be recorded additionally, which provides important data for dealing with different operational difficulty. To estimate the inhibition quantities for combating hydrates it is not sufficient to permanently measure pressures and temperatures at the head, as is the case at the majority of gas cavern storage systems. The amount of water calculated from these two parameters is estimated to be a great deal too much if neither the hydrate temperatures nor the dewpoint temperatures are known. There are several programs on the market for calculating the hydrate formation temperatures, however, in some respects they vary considerably from one another. SOCON has tested diverse hydrate formation programs on survey values, compared the findings and integrated the most stable tool for achieving results in a program for combating hydrates. A similar procedure was chosen for calculating the dewpoint temperatures and the water content in gas (Althaus 1999).

Procedure for hydrate inhibition:

1. Measurement of head pressure and temperature.
2. Calculation of hydrate formation conditions.
3. Comparison of head and hydrate formation temperature for a point in time during extraction with an appropriate head pressure.
4. Calculation of water content.

5. Comparison of calculated water content with measured water content (SOCON survey technique) in the cavern (Fig. 9).
6. Calculation of dewpoint from measured water content and pressures.
7. Comparison of dewpoint and hydrate formation temperature.
8. Calculation of temperature depression.
9. Calculation of inhibition quantities.

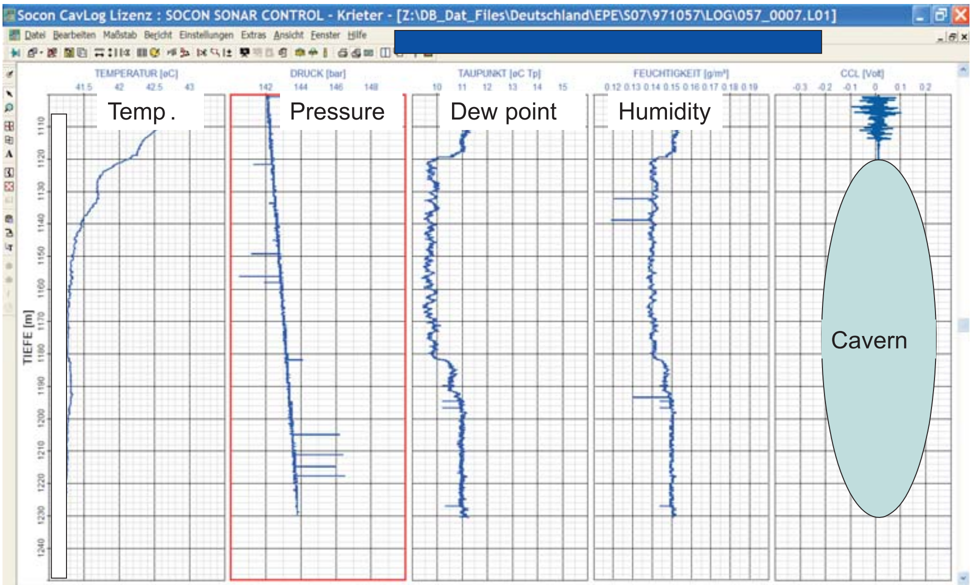

Fig. 9. Log for determining temperature, pressure, dewpoint and humidity in a cavern

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