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Sonar surveys under challenging conditions in gas at very low pressure and in crude oil

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Abstract

Sonar surveys have for decades been the established technique for the regular monitoring of gas and oil storage caverns. So as to have the best possible basic physical conditions gas caverns should be under the highest possible pressure at the time they are surveyed. This is all the more important the greater the distances to be measured. With regard to caverns located deeper than 1000 m pressures > 150 bar provide a good basis for achieving qualitatively reliable and focused measurements.

Surveying shallow caverns with a low maximum pressure < 100 bar or caverns that for operational reasons have to be under low pressure is considerably more challenging than a "standard survey" under high pressure. The lower the pressure the higher the attenuation of the acoustic waves.

Consequently to be able to interpret these reflections the measuring system must be in a position to amplify the significantly attenuated signal reflections by a suitable amplifier technology and by applying mathematical correlation techniques. Furthermore special transducer technology is necessary when working at such low pressures.

Surveys in caverns at pressures between 80 and 90 bar had been carried out successfully for years. Then the task of surveying gas caverns with a pressure of just 45 bars presented a new challenge. Indeed, to obtain qualitatively usable results under these demanding basic conditions it was essential to have sophisticated transducer technology as well as high performance transmitter and receiver equipment. By carrying out special developments and modifications in this area equipment has been designed which enables distances of more than 85 m to be measured even if the pressure is as low as 45 bar. This provides the customer with a means of monitoring all parts of those caverns which previously were internally regarded as "unsurveyable" without having to flood the cavern with brine.

The technical changes that have been made not only bring about advantages in terms of measuring greater distances at low pressure, but also provide extra performance. In caverns with an extremely long extension (e.g. elongated fingers due to leached potash zones, steeply inclined bedding and so on) it is now possible to measure considerably longer distances. In some cases it is even possible to measure distances of well over 100 m in gas or crude oil.

Key words: Sonar, cavern surveying, low pressure, gas cavern monitoring

Introduction

Sonar surveys have for decades been the established technique for the regular monitoring of gas or oil storage caverns.

Up until today sonar cavern surveys are the only method that can be properly used to measure caverns from the inside using borehole tools. Measurements using laser equipment do not work in liquid media because of the absorption of light, and do not work in gas because the wavelengths of the prevalent red or infrared laser coincide with the absorption maxima in methane, the main component of natural gas, and therefore the necessary distances cannot be achieved.

As a result of this absorption effect in natural gas there are nowadays in fact systems for locating leakage at the surface in which the wavelengths of the laser light has been selected so that it is absorbed by methane. The more methane that is present in the air, the more the light of the laser is absorbed, which can then be used to locate places of leakage from a distance.

Storage facilities are regularly surveyed using sonic tools at time intervals depending on the prevailing operational or national requirements that govern the monitoring of storage caverns. In particular for strategic oil storage facilities the regular monitoring intervals can be in the range of 10 to 15 years for full cavern surveys. In Europe, however, gas storage caverns are monitored at considerably shorter intervals.

Nevertheless a differentiation must be made here according to the goal: is the aim of the survey to monitor the changes in the cavern contours or is the prime interest to determine convergence losses. Changes in the cavern contours (e.g. any breaking off of protrusions, significant collapse in the roof section and so on) can be detected within a short period of time, in fact almost directly after they occur. Conversely, convergence effects can in general be definitely deduced in a standard survey only after a few years, unless extreme operations and long standstill times at minimum pressure have caused significant convergence in excess of that which would occur normally during moderate operations. If, however, a reliable assessment of the convergence is required after just a short time (e.g. after just one year) it is necessary to carry out a survey with a significantly higher sampling density with multiple measurements at every depth. If in connection with this you choose suitable sections of the cavern – suitable sections in this context means uniformly formed regions with no varying wall structure – then the accuracy of the survey can be increased on average by a factor of 10 so that effects that would otherwise be recognizable only after 10 years can be recognized after just one year.

A basic requirement for all gas cavern surveys which are to supply such high accuracy survey results is that the physical background conditions during the survey are selected or are arranged to be optimal so that any negative influences on the survey results are reduced to a minimum.

Ideally homogeneous conditions should prevail in the caverns to be surveyed (in particular with respect to the acoustic velocity distribution) and the attenuation of the emitted acoustic signals should be as low as possible. In practice this means the cavern should have had a long period of standstill (without any injections or withdrawals) prior to the survey and the cavern should be under as high a pressure as possible.

Obviously a compromise must be found between theory and practice. In the following it is shown how, even under unfavorable conditions, it is possible to obtain very usable results, for instance through new developments in surveying equipment and the associated greater efficiency of the tools now being used. It is also intended to show that the cavern operator should provide certain background conditions so that the quality he requires does in fact provide qualitatively reliable results also for the actual investigation target.

Sonar Surveying Caverns

Sonic measurements in caverns must be performed in widely differing media. The range of media extends from water and brine to liquid hydrocarbons and natural gas and even to air at atmospheric conditions. The physical conditions in a cavern depend in the first place on the actual medium, which itself is affected by any previous cavern operations as well as by the surrounding rock.

Basic measurement principle

Geometric surveying of caverns is based on travel time measurements (Fig. 1). The time taken by an acoustic pulse to travel from the measuring tool to the cavern wall and back is determined, i.e. the measured travel time corresponds to the two-fold distance. To convert the travel time into distance it is necessary to know the acoustic velocity in the medium. This means that the accuracy and reliability of the measured cavern geometry depends directly also on the quality of determining the acoustic velocity.

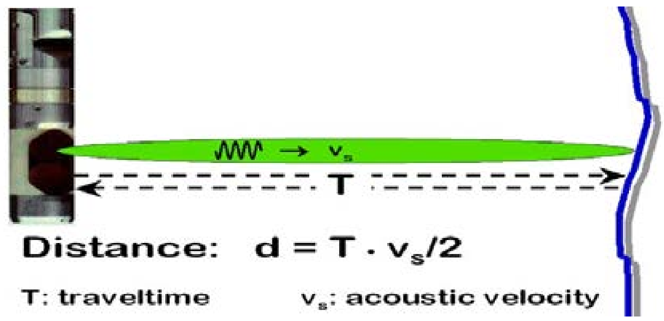

Fig. 1. Distance determination using travel time measurements

The acoustic velocity needed is subject to complex physical relationships. It depends essentially on the temperature and density of the medium but some of the distinct variations in a specific medium can not be explained solely by changes in these two parameters.

In the case of brine the acoustic velocity is strongly dependent on the salinity and the chemical composition. An occurrence of potassium and magnesium in the brine, for instance, tends to make the acoustic velocity higher. In liquid hydrocarbons the viscosity plays an important part. The acoustic velocity in gaseous hydrocarbons is affected not only by the pressure and temperature, but also by the moisture content and composition of the gas.

Conducting logging in the cavern can help identify certain situations that may exist inside the cavern. However, logging can supply values only along the borehole axis and it has to be assumed that the distribution of the measured parameter is homogeneous between axis and cavern wall, i.e. the acoustic velocity measured at a position on the axis is taken as a constant for the whole travel path of the sonar signal from the tool to the reflector and back again.

Fig. 2 shows the typical ranges of acoustic velocity that can be expected in different types of media.

As the sonic signals propagate they suffer from attenuation, the amount of which depends on the applied wavelengths resp. frequencies, the distance to the cavern wall and the medium in the cavern.

Fig. 2. Acoustic velocity in the different media

Medium	Acoustic velocity [m/s]
Saturated Brine	1790–1900
Water	1450–1550
Oil and products	1200–1500
Natural gas	390- 540
Air	330- 375

This process of dissipation or propagation attenuation increases with the distance from the acoustic emitter and is very much frequency dependent, i.e. high frequencies are more strongly attenuated than low frequencies. Furthermore the moisture content affects this attenuation; it is higher in humid gas and lower in dry gas.

The recorded signal response can in addition contain (apparent) echoes, which are caused by indirect reflections or particles floating in the medium.

Beam Opening

One of the special physical properties of sonic surveys is the propagation characteristic. When a sonic transducer emits an acoustic pulse this does not propagate as a beam but rather in the shape of a sonic lobe. The maximum sound pressure is along the longitudinal axis, whereas this pressure decreases at right angles to the direction of propagation and eventually drops to zero. The angle between the central axis of the sonic transducer and the line connecting the central point of the transducer to a point perpendicular to the direction of propagation at which the sound pressure has dropped to a specific value is called the angle of beam spread or the beam opening. For a specific decrease of the sound pressure (normally a decrease of 6 dB is used, equivalent to 50%) this angle depends solely on the size of the transmitter/receiver transducer and the frequency of the sonic signal used. Moreover around the primary sonic lobe, smaller secondary lobes are formed of lower intensity and extent (Fig. 3).

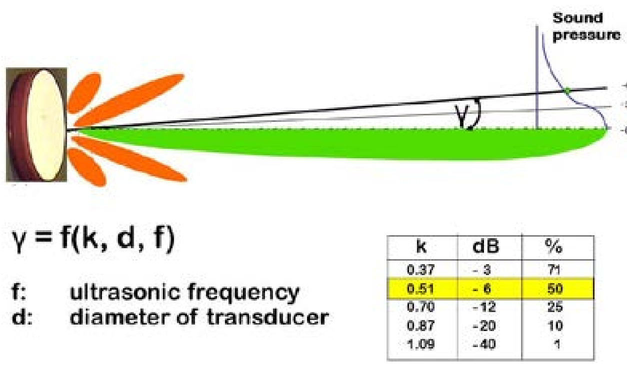

Fig. 3. Beam opening of a sonic lobe

The focus of the emitted signal is better the higher the frequency used and the larger the transducer used. As a result of the generally relatively small internal diameter of the casing, the external tool diameter is also comparatively small (SOCON's tools have an OD of 42 mm, 50 mm or 70 mm and consequently there is not much room to maneuver as regards the diameter of the sonic transducer used. The most effective way of focusing the emitted signal is therefore to use the highest frequency possible.

Survey procedure

In order to be able to perform optimal cavern surveying it is essential to find out the physical conditions in the cavern before the actual sonar survey is carried out. The variation of the individual parameters in the vertical survey axis should be measured by running a log in advance. It is extremely important that the data are measured continuously over the entire depth range of a cavern. Information obtained at isolated points cannot provide adequate clarification of the true physical conditions.

To convert the measured travel times into distances it is necessary to know the acoustic velocity over the entire vertical extension of the cavern. In addition, the temperature distribution should be recorded as it can be used for a plausibility check of the acoustic velocity distribution. Temperature recording must be made in particular with a view to cavern sections which have large temperature gradients or horizontal layering, because such zones must specifically be taken into account in order to achieve optimum results. If, for example, the temperature gradient is not recorded and the measurements with transducers are performed through a zone in which the temperature greatly varies, the ensuing refraction of the sonic beam would lead to an incorrect determination of the shape and volume of the cavern.

After the initial logging, the cavern shape is surveyed by a multitude of horizontal sections over the entire cavern depth as well as sections with titled sonar head to measure bottom, roof or any other irregularities of a cavern. During the survey procedure the measurement is based on point-by-point sampling of the cavern wall. First of all the survey head with its sonic transducer is positioned in the required direction with the appropriate tilt and is maintained in this position for as long as it takes to determine a point on the cavern wall with the required certainty (until all the necessary plausibility checks and correlations have been carried out).

In order to be able to apply this method properly SOCON's sonar tools are fitted with a gyro stabilization system, which prevents rotational movements of the tool while readings are taken. Without stabilization any movement of the survey head between the time of sending and receiving the signal will unavoidably lead to distorted results in the travel time measurement. Only when the tool is kept still is it possible to form an optimized sonic lobe, make multiple measurements of a single survey point and carry out subsequent correlation of the recorded response signals.

Finally, at the end of a survey, the depth reference point is checked again to verify that the depth has been correctly tied in. The following figure 4 gives an overview on the whole survey procedure.

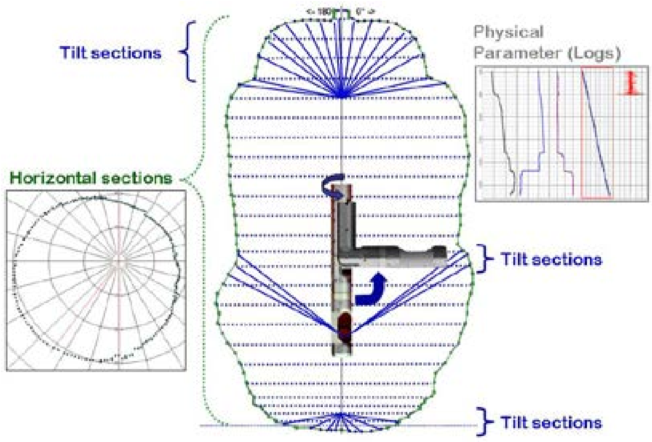

Fig. 4. Survey procedure

Practical examples of surveying

In the following a number of examples are shown to highlight how changes of individual physical parameters – as described in the previous section – can be recognized in the recorded data.

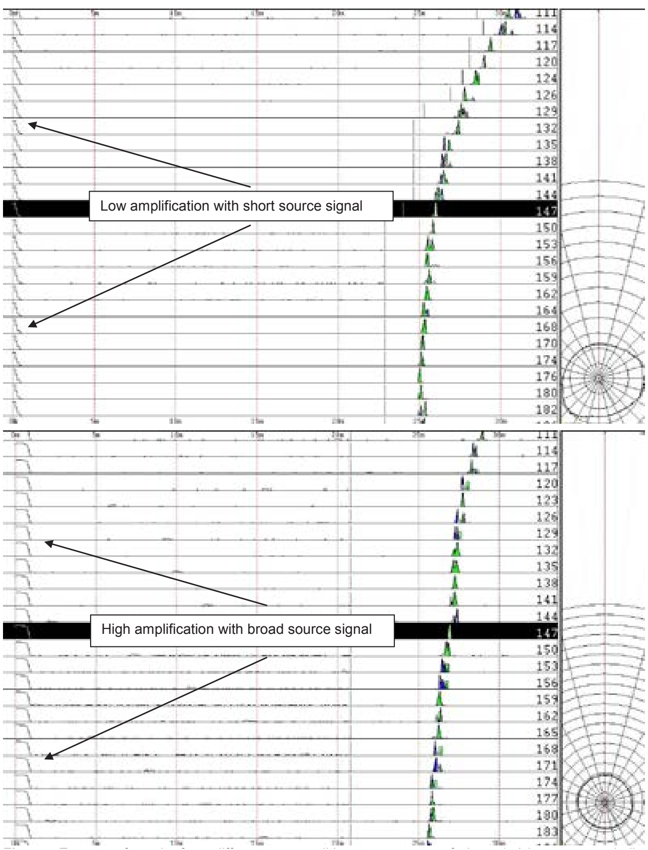

Fig. 4a. Extracts of results from different gas qualities at pressures of about 140 bar, ranges similar up to about 30 m, upper picture high caloric gas and lower picture low caloric gas

In Fig. 4a it is evident that the recording situation is generally worse for L-gas (low calorific) than for H-gas (high calorific) under similar pressure and temperature conditions. However, provided the distances to be measured are not too large surveying can be carried out satisfactorily using the standard gas surveying equipment.

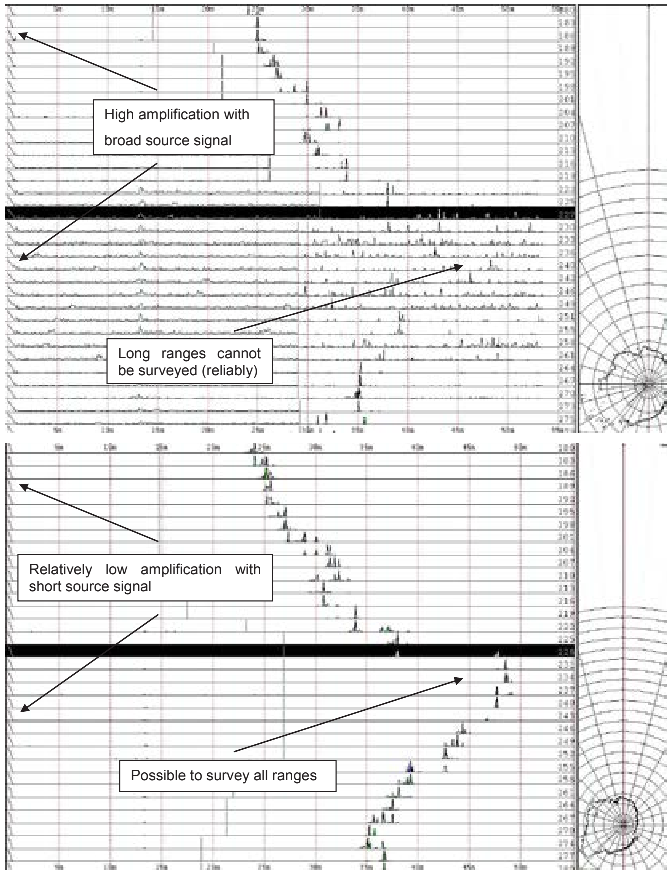

Fig. 5. Extracts of results for different pressures in low caloric gas, ranges similar up to 48 m, upper picture at 104 bar and lower picture at 194 bar

If the pressure during a survey is significantly lower and the distances to be measured are larger, then it is possible that sections of the cavern can no longer be measured or no longer reliably measured, as illustrated in Fig. 5. It must be noted here that it is no problem to survey an H-gas cavern at a pressure of approximately 100 bar and at corresponding distances of about 50 m.

Surveys in caverns at pressures between 80 and 90 bar had been carried out successfully for years. But then the task of surveying gas caverns with a pressure of just 45 bars presented a new challenge. The low pressure was just one aspect another was the relatively large distance that had to be surveyed (see Fig. 6 lateral distance up to almost 90 m).

Indeed, to obtain qualitatively usable results under these demanding basic conditions it was essential to have sophisticated transducer technology as well as high performance transmitter and receiver equipment.

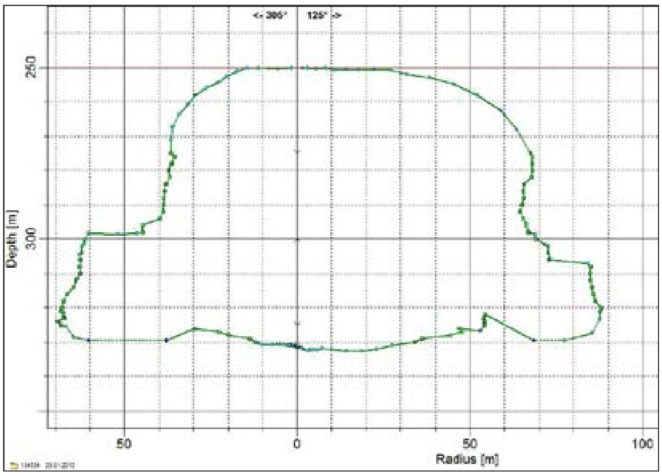

Fig. 6. Shallow gas filled cavern under maximum pressure of just 45 bar with max. horizontal extensions of more than 85 m

Fig. 7. Different sonar measuring heads with transducers for special survey tasks

By making special developments and modifications in this area, equipment has been designed which enables distances of more than 85 m to be measured even if the pressure is as low as 45 bar. This provides the customer with a means of monitoring all parts of those caverns which previously were internally regarded as "unsurveyable" without having to flood the cavern with brine.

The figure below shows part of the echograms (sonar recordings) at a single survey depth in brine (top) and in gas (bottom) recorded under this low pressure. It is quite evident that considerably more noise is recorded, which can, however, be attenuated by multiple correlation so that the actual outline of the cavern can be clearly recognized. The recordings in gas also contain interfering echoes, which can be seen for example at about 12 m. These are reflections from the floor. Such reflections are recorded because the emitted signal has to be amplified so much – because of the large distances and the high level attenuation – that also the secondary lobes of the sonic signal, which are usually suppressed (as can be seen in the brine recording), are also picked up.

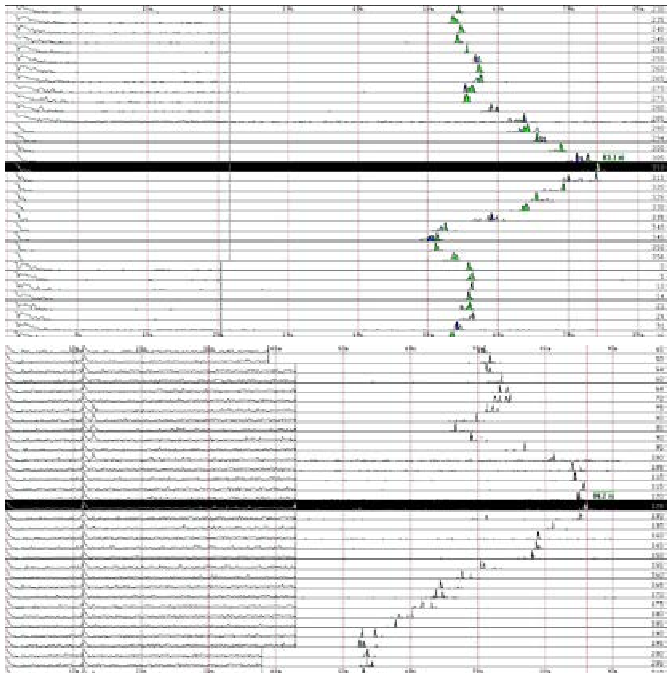

Fig. 8. Echograms for brine (top) and gas (bottom)

This clearly shows it is possible to measure under such difficult conditions. However, here it is necessary to use appropriate transmitter and receiver equipment with suitable transducers. Moreover it is evident that in every case when the signal/noise ratio is so unfavorable several measurements have to be made in every direction so as to significantly improve the signal quality by means of signal correlation. Correlation not only amplifies the wanted signal, but also at the same time suppresses the noise. It is the gyro stabilization fitted in the SOCON tools – which suppresses any rotational swinging of the tool while measuring each individual survey point several times – that provides the basis to obtain reliable echo signals by use of correlation. Without gyro stabilization the use of correlation would not be possible, or only to a very limited extent, so it would be impossible to perform sonar measurements under such difficult conditions.

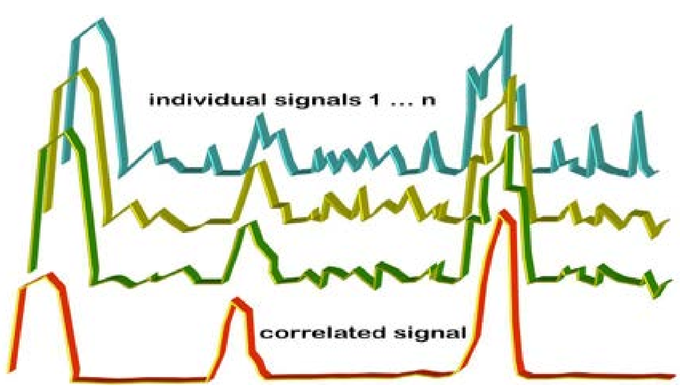

Fig. 9. Signal correlation

Furthermore suitable data recording (as shown in Fig. 8) is necessary that contains the entire signal train in every measured direction. Only then is it subsequently possible to recognize as such any interfering echoes which could not be removed by correlation and so disregard these non-echoes in the interpretation and exclude them from the display of the cavern outline.

The technical changes that have been made not only bring about advantages in terms of measuring greater distances at low pressure, but also provide extra performance. In caverns with an extremely long extension (e.g. elongated fingers due to leached potash zones, steeply inclined bedding and so on) it is now possible to measure considerably longer distances. In some cases it is even possible to measure distances of well over 100 m in gas or crude oil, as shown in Fig. 10.

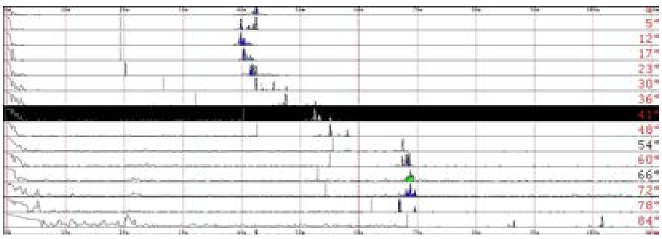

Fig. 10. Echogram in crude oil with max. ranges of > 100 m

Avoiding unfavorable physical background conditions

As a result of the high level of activity in constructing storage caverns in recent years we now have a considerably larger number of caverns than previously. As these are no longer operated just seasonally – as was the case some years ago – but instead as trading reservoirs with a considerably more rapid changeover between injection and extraction, the time windows that are granted by the gas dealers for leaving the cavern non-operational are often very short. The consequence of this is firstly that surveys cannot always be carried out under high pressure and secondly that less time is available for surveying. On its own this would not be a problem if the caverns had previously had a sufficiently long standstill time without any major injections or extractions. The following example shows what happens when these standstill times are not observed.

The results of all distances over 20 m show in part significant differences between the two surveys, even though these were carried out just one week apart. Distances >50 m reveal differences in some areas of more than 6 m, which is >10%. The probability of such changes in shape taking place within one week is almost zero, because in that case the cavern would have had to have shrunk abruptly.

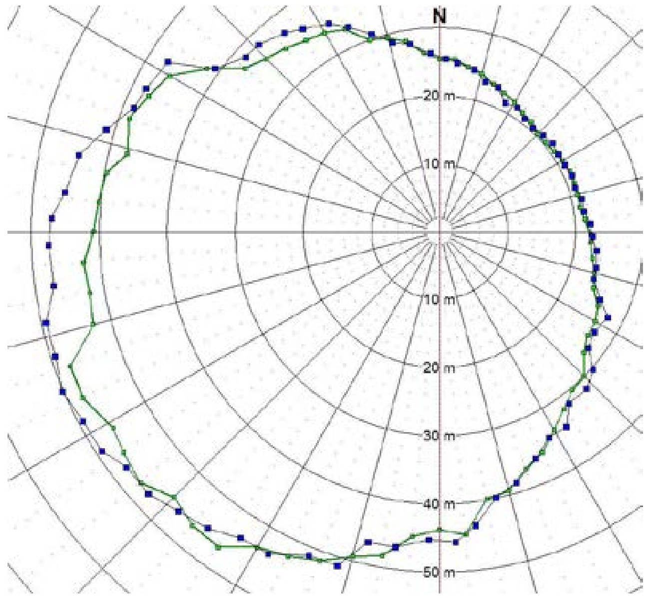

Fig. 11. Differences between survey results due to disturbed temperature and speed of sound distribution; green line shows survey results shortly after gas extraction, blue line shows survey results measured one week earlier shortly after gas injection

The differences shown are obviously not real, they are just apparent differences. In addition neither of the two surveys shows the true outline of the cavern.

The first survey, which was carried out shortly after gas had been injected, indicates distances that are too large. This is because the conversion of the measured traveltimes to distances was made using an acoustic velocity that was higher than under normal conditions owing to the temperature increase resulting from the gas injection. As a constant temperature from the measuring axis to the cavern wall had not been reached, there was no uniform acoustic velocity distribution. The emitted sonic signal had in fact travelled part of the way with a lower acoustic velocity. As it is not possible to measure this change in acoustic velocity along the measuring axis the conversion of the longer travel times results in apparently larger cavern dimensions.

Gas had been extracted until shortly before the second survey with the result that the temperature conditions had been disturbed the other way round. Lower temperatures existed along the measuring axis and consequently lower than normal acoustic velocities. The conversion of the measured travel times therefore results in distances that are apparently too short.

Neither of the two surveys can be used as a basis for making any qualified statements about the final cavern shape at this depth. It is therefore absolutely impossible to make any sort of investigation regarding convergence effects.

It is also very important to ensure there is a sufficient standstill and non-operational time in the cavern to prevent the survey results from being unusable. Preferably there should be a standstill time of at least 10 to 14 days prior to the survey (the longer the better) so as to allow the cavern conditions for surveying to become as uniform as possible.

This need for standstill time must of course take account of operational requirements. Therefore it may be better by way of a compromise to survey the cavern when the pressure is lower than the maximum (although then the focusing of the signal is worse and the attenuation higher), but when there has been a sufficiently long standstill time (which ensures that the distribution of the acoustic velocity is homogenous).

When in doubt the cavern operator should fix the most favorable survey date only after consulting the cavern survey company and not based solely on his operational schedule.

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