Determination of the Change in Shape and Volume of Salt Cavities During Storage Operation

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ABSTRACT

Storage caverns produced by solution mining can be filled with various liquid or gaseous mediums. Echometric surveys for determining changes in shape and volume of storage coverns in operation are only useful if specific rock mechanic effects, i.e., caving and sheeting, and especially actual convergence processes, can be detected.

A direct determination of convergence process is only possible by an areal comparison of correspondingly closely spaced and accurately measured horizontal cross-sections, i.e., by direct comparing of the mean value of radii for depth regions in an extensively homogeneous salt.

In order to attain the necessary survey accuracy the following technical improvements have been achieved:

1. *Development of new ultrasonic transducer and electric systems, whose ratio of range to power concentration can be adjusted to various mediums for example crude-oil or natural gas.*
2. *Introduction of true computer controlled measurements with computer assisted interpretation and results display so that with any survey point density can be efficiently surveyed.*

For the echometric survey of storage caverns which are filled with gaseous mediums an echo-sonde was developed additionally to work on the basis of travel times measurements of laser pulses which are reflected from the cavern wall. From 1982 it has consequently become possible to make complete laser surveys in compressed air storage caverns with survey distances of up to about 50 m. In storage caverns with natural gas under high pressure larger survey distances could still not be attained. Therefore, in the near future it will probably be possible also to jointly apply the two different physical survey methods, i.e., pulsed laser and ultrasonic, only to caverns up to a certain diameter.

In irregularly shaped gas or compressed air caverns there is the possibility of applying in addition to echo surveying the photographic technic of panoramic pictures especially in the roof area and the uncased cavern neck.

INTRODUCTION

Storage cavities, created by solution mining in rock salt, are subject to widely varying changes in shape and volume during use. Convergence effects are of particular significance; however, secondary solution, flow effects of the salt rock, sheeting of the salt rock, roof caving and ruptures in the cavity wall must also be mentioned.

The main task for geophysical surveillance of such cavities is to ascertain and observe such changes during the storage operation. Thus, on the basis of in situ surveys, predictions can be made concerning the future development in shape and volume of a storage cavity; also theoretical calculations can be checked resp. corrected. The most important survey method for the control of operating storage cavities is the echometric survey, as performed by PRAKLA-SEISMOS under the trade name ECHO-LOG.

The principal item of the ECHO-LOG method is an ECHO-SONDE, at the lower end of which the ECHO-SURVEY HEAD is located. This head consists of an ultrasonic transducer, or Pulse Laser transmitter/receiver system. The Echo-survey head can be rotated and tilted in any desired direction controlled by a magnetic compass device.

ECHOMETRIC SURVEY METHODS

A comprehensive view of the various echometric methods to apply for surveying storage cavities and the measuring frequencies or wavelengths used are shown in the table.

Echometric Survey of Brine-Filled Storage Cavities

The same survey equipment used during solution is usually also applicable for surveys in cavities containing brine or similar products. Some difficulties in sound propagation may occur, for example, in full saturated brine

TABLE

Echometric methods for surveying storage cavities

Cavity Contents	Survey Method	Frequency/Wavelength
Brine	ultrasonic	200 kHz 600 kHz 1000 kHz
Mineral oil	ultrasonic	100-300 kHz
Natural gas under pressure of more than 70 bar	ultrasonic	80-300 kHz
Natural gas under pressure of less than 70 bar	ultrasonic and Laser	80 kHz 820 nm
Air	Laser	820 nm

due to presence of slowly sinking crystallized solid particles, which requires, in general, the application of the lowest ultrasonic frequency of 200 kHz for echometric cavity surveys. In very extreme cases, interpretable echo signals will be obtained by using electronic signal-stacking.

Echometric Survey of Mineral Oil-Filled Cavities

To meet the necessary technical requirements for echometric surveying of oil storage cavities, PRAKLA-SEISMOS carried out a research and development program between 1975 and 1978, with financial backing from the German Federal Ministry for Research and Technology. A significant part of this work was the development of special ultrasonic transducers and high performance transmitter/receiver electronics which enable surveys in media such as high viscosity crude oil.

The first follow-up surveys, 5 years after the original survey of oil-filled cavities in Germany, have shown that it certainly is possible to prove convergence effects in the framework of in situ echo surveys. The method used applies the comparison of mean radii derived from the areal content of single horizontal cross-sections. The present relatively large error of ± 0.1 m per meter of average radial convergence depends to a great extent on irregular velocity distribution encountered in unsaturated brine during the final survey of the cavity. In comparison, the measured velocity at the survey axis can also be expected at the cavity wall, in the case of a homogenous medium such as oil; thus a second survey, carried out in the same medium, allows a comparison which should supply exact convergence values.

Up to now, for surveying in oil storage cavities in Germany, the following procedures had to be done:

- depressuring of the cavity
- extracting the 2⅜" freshwater injection pipe
- raising of the production string into the cemented casing.

The costs involved here are usually much greater than the costs of the echometric survey.

Some years ago the consideration of whether it would be better to limit echometric surveillance to the brine-filled part of the cavity below the production string was brought to discussion at PRAKLA-SEISMOS. Such surveys could be carried out without depressurization, in conjunction with temperature, pressure, gamma and gamma-gamma surveys to locate oil/brine interface at intervals of one year. For operations in Germany, availability of an echosonde with 42 mm diameter is a prerequisite. On the basis of our experience in developing and constructing echosondes with 65 mm diameter, the construction of such a sonde should be possible. Echo surveys at these depth regions can be carried out with great accuracy, since depth errors due to the proximity of the casing shoe, which is taken as depth reference, can be eliminated. The annual comparison of mean radii and the depth of the cavity floor can then supply a very good representation of convergence effects.

Echometric Surveying of Natural Gas Storage Cavities Using the Ultrasonic and Pulse Laser Methods

Cavities filled with natural gas, in which the tubing ends at the roof, can generally be surveyed using the ultrasonic method. With an increase in storage pressure, higher measuring frequencies can be applied. This results in a much narrower beam allowing higher resolution, which subsequently leads to greater survey accuracy. For this reason surveys should be carried out with the storage pressure as high as technically possible; in fact, pressures of 200 to 300 bar present no particular obstacle to surveying. In the recent past new types of ultrasonic transducers and electronic transmitter/receiver systems have been developed to allow the use of the ultrasonic survey method gas storage cavities.

To obtain comparable data concerning convergence in cavities, follow-up surveys should be carried out under the same pressure and temperature conditions and, as far as possible, with the same gas qualities and vapour content. Because the convergence movements are probably affected by regional zones of strain, it cannot be ignored that the casing in the roof is also subjected to horizontal displacement which shifts the casing shoe and thus, also, the measuring axis for subsequent surveys. The result is that, although distance comparisons in different directions in order to estimate the field of strain are possible, the mean effect of convergence can only be obtained by comparison of the mean radii.

Because, in addition to convergence effects, flow of non-NaCl salts cannot be neglected, convergence studies should be made only in pure NaCl areas. To verify all the data collected by echometric surveys using ultrasonics it is possible to apply a physically different survey method; tests have been made using a Pulse Laser, at the near infrared end of spectrum, to survey gas storage cavities. At present

it appears that survey distances of 30 m at a pressure of up to 70 bar can be attained at a wavelength of around 820 nm.

Echometric Surveys of Compressed Air Storage Cavities Using Pulse Laser

Echometric surveys of compressed air storage cavities using ultrasonics with various frequencies gave maximum measuring distances of 12 m only. A complete survey of such cavities could only be carried out successfully, on the basis of echo travel-time measurements, with an infrared Pulse Laser. Survey distances of up to 50 m were obtained.

IMPROVEMENT OF THE ACCURACY OF ECHOMETRIC SURVEYS

An improvement could only be attained by increasing the density of measuring points, particularly in the horizontal plane. For this reason computer controlled recordings of the survey data and computer aided reportings based on an HP 9845 computer were introduced for the ECHO-LOG by PRAKLA-SEISMOS at the beginning of 1981. It is now possible to record any number of independent plane elements of a cavity wall, with direction and distance from the echosonde, and to report the results during the survey. In the case of ultrasonic surveys horizontally, survey point intervals of 3° to 5° azimuth angle are possible, with the Pulse Laser from 1° to 2°.

As opposed to other so-called SONAR methods, for the ECHO-LOG surveys the peak value of the echo low frequency summation signal, composed from the original high frequency ultrasonic signal, is evaluated directly by computer. The digital value of the echo signal peak can be stored directly with a resolution and accuracy of 50 microseconds. For a constant sound velocity of 1200 m/s for oil this corresponds to a deviation of 3 cm maximum from the true value.

Multiple echos, produced by a rough, broken cavity wall or from cavity wall forming an acute angle to the ultrasonic beam up to 4 echo signals per measuring interval, each with different energy content, are recorded and stored by the computer. By means of the direct evaluation the echo signals can be processed with the high accuracy of the computer and subsequently displayed on the screen and represented as a print-out. For a convergence determination the horizontal density of survey points, based on an angular interval of 3°, should be complemented by a vertical series of further horizontal cross-sections at close intervals of 25 or 50 cm. Five such horizontal cross-sections supply the correct survey point density for accurate determination of convergence effects for the depth zone of the mean horizontal cross-section. The practical application of this method for convergence determination can be provided for surveying of gas storage cavities at depth zones with pure NaCl salt. The cavity msut have free access from the roof to the floor and retain the same pressure, temperature and, therefore, velocity distribution conditions for subsequent surveys. In oil storage cavities with constant head-pressure and completely installed tubing, this method should be carried out in the region of saturated brine between the end of the production string and the cavity floor.

In conclusion, PRAKLA-SEISMOS' ECHO-LOG is an up-to-date technical system allowing the investigation of storage cavities with sufficient accuracy with respect to convergence effects. Thus, an instrument has been created that can proof and even correct theoretical calculations carried out in the laboratory.

OTHER GEOPHYSICAL ENGINEERING BOREHOLE METHODS FOR THE SURVEILLANCE OF STORAGE CAVITIES

Based on approximately three years of experience in surveying storage cavities for oil, gas and compressed air, it has been proved that additional to the echometric surveys the following borehole measuring and investigation methods for cavity surveillance are necessary:

1. Inclination surveys with high resolution and accuracy in the salt region of the cemented casing. Such surveys can locate even minimal displacements of the casing which may have been caused by convergence.
2. Mechanical caliper surveys in cavity neck without casing using a measuring sonde with 4 independently recording caliper arms.
3. Photographic surveillance of the wall of gas or compressed air storage cavities, in particular in neck and roof zones. In special cases photographs of the cavity sump can also be of interest. A stereo photo-sonde with magnetic compass steering is available for such purposes. Either vertical or horizontal directed photographs can be taken.
4. Location of the interface between stored medium and brine using so-called interface logging.
5. Temperature measurements with high resolution and accuracy, particularly in brine-filled parts of storage cavities to locate possible secondary solution effects.
6. Extraction of fluid samples for quality control of stored oil products. With one of the sampling sondes developed by PRAKLA-SEISMOS several litres of fluids can be brought up to the surface from the immediate vicinity of the sonde axis or, with the help of a mobile extension arm, from the side space of the cavity.

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