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Tightness Testing of Unlined Rock Storage Caverns

G. Kannan, A. Nanda*

Engineers India Ltd., New Delhi, India

**Email: gopi.kannan@eil.co.in*

ABSTRACT

Underground rock storage caverns are being increasingly used for the strategic as well as commercial storage of hydrocarbons. These are stored directly in unlined rock caverns unlike conventional storage containers with steel or concrete lining. These rock caverns are excavated in hard rock where joints and other small geological features are common. Therefore, it is of utmost importance to contain the stored crude oil along with its vapor pressure entirely within the rock mass where cavern is excavated. Hydraulic containment of the hydrocarbons within the rock mass using water curtains above storage caverns is a proven technology, however, tightness of the stored crude oil within the storage cavern and its vapour within the rock mass in the vicinity of the caverns is very crucial to such projects. The success and failure of the project is based on the evaluation of cavern for its tightness of the stored product so that the cavern is accepted for further crude commissioning. This paper describes the tightness test of excavated caverns, called cavern Acceptance test (CAT), performed in one of the crude oil storage projects in India where it was successful. The paper gives briefly how the test is carried out along with the results and evaluation of its tightness using compressed air before the actual crude storage.

Keywords: Rock cavern; Hydrocarbon; Containment; Concrete plugs; Tightness test

1. INTRODUCTION

Storage of hydrocarbon in unlined rock caverns is one of the most economical solutions for storage of large volumes. It also serves the strategic purpose of crude storage with very limited foot print on surface and comes handy during the time of crisis of war in the country. The facility is designed to handle the product stored and to control the entire process for receipt and evacuation of the product from the cavern while ensuring secure inventory of the product.

The basic principle of storage in unlined rock caverns is the hydraulic containment. Thus the rock caverns are planned at a depth such that there is sufficient hydrostatic pressure to counter the vapour pressure or liquid pressure of the stored product on the walls of the cavern (Aberg, 1977). These caverns are created where permanent ground water table is high. In order to further secure the water flow from the rock mass towards the cavern, a water curtain system is provided consisting of galleries located above the crown of the cavern. A saturated rock mass and ground water flowing into caverns, ensures proper sealing of the stored product from leakage.

The layout, cross-section and elevation of the caverns are designed considering the product to be stored and operational requirements as well as the geotechnical conditions and geological setting at site. The overall layout and the cross-section of the cavern is selected so as to achieve a favourable induced stress condition vis-à-vis the in-situ stress regime of the site which also take into account any major geological structures. The caverns are oriented in a direction so as to come across minimum geological problems such as joints, shear zones and principal planes of horizontal stresses in the rock while excavating the caverns. The caverns, in general have a D shaped cross section. For ensuring stability of the caverns, a support system of shotcreting and rock bolting is commonly used (Nanda, 2012).

Depending on the site conditions, while the size and shape of the caverns could vary, the crown level of the caverns is designed adequately below the ground water level so as to ensure the hydro static pressure required for containment of the product. The storage caverns are designed for particular design operating pressure especially the vapour pressure of the stored product. Once the construction of storage caverns is completed, before crude-in operation, the caverns are evaluated for their tightness before it is accepted for the storage purpose. This cavern tightness evaluation test is called cavern Acceptance Test (CAT). The test is to ensure that stored products are contained within the caverns without any leakage. This paper explains the cavern acceptance test using compressed air before actual storage and operation of the storage. The storage caverns are located in East Coast of India with 1.33 MT crude storage capacity and under operation for over a year.

2. CAVERN LAYOUT

The storage caverns located in East Coast of India, consist of two sets of storage units with each unit having different input and output system so that they can be operated independently. Refer to Fig. 1 below for the layout. The storage caverns are typically ‘D’ shaped in cross-section about 30m height and 20m width. The length of the smaller unit consisting of two caverns in ‘U’ shaped is 320m each and of the longer unit with three caverns in ‘W’ shaped is 840m each. The total storage capacity of the facility is about 1.33 MT of crude oil. The caverns are parallel with separation of about 30m within unit and 60m from each unit (Fig. 1).

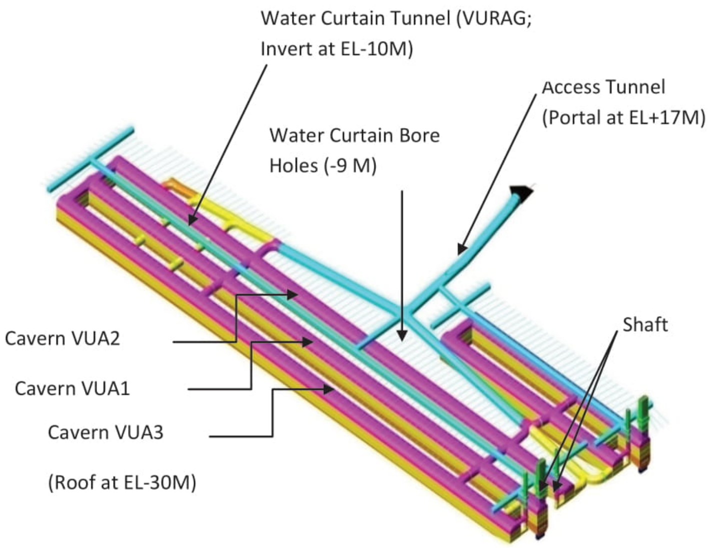

Fig. 1: Cavern layout for storage of crude oil

Each cavern unit is designed to have a shaft with pump installations and pump pit, located at the end of one leg of the cavern, while the inlet shaft is located at the end of the other leg. The cavern roof is horizontal along the full length of the cavern. To facilitate the flow of crude as well as de-waxing / de-sludging during operation, flushing and cleaning of the floor, the cavern bottom is given a longitudinal & transverse slope and covered by floor concrete laid in slope. The section of the water curtain tunnels has been designed with a dimension of 6.5m x 6.5m (w x h).

3. GEOLOGY OF THE PROJECT

The water curtain system consisting of water curtain boreholes are drilled from the water curtain tunnel with an initial typical spacing of 10 m, with an extension of 20 meters outside the storage caverns. The submersible pumps in the caverns are designed to deliver the crude oil to the nearest refineries through new pipelines connected to the existing pipelines. The cavern project is located within the geological setting of Eastern Ghat mobile belt, which is characterized by Khondalites as the predominant litho unit. The topography of the area exhibits an undulatory hilly terrain flanked by two valleys one to the north and oriented east-west and one to the east oriented north-south. The ground elevation varies from +10m to +125m. Khondalite in the area is covered with soil and laterite as capping (thickness varying from 1 m to 6 m). Weathered Khondalite layer persists up to a depth of approximately 30 m below ground level. Pegmatitic veins and quartzite were found at very few places in the bed rock.

The underground cavern is oriented at N70°E considering geological and underground stress aspects. Three major joint sets encountered in the cavern project are tabulated in Table 1 and few other random joints were also encountered.

Table 1: Major joint sets encountered

No.	Feature	Dip Direction	Dip
1.	Foliation/Bedding joints (J1)	N165°	65° to 75°
2.	Joint (J2)	N70° & 255°	65° to 80°
3.	Joint (J3) (sub-horizontal)	10°	20°

One major shear plane was later encountered in cavern VUA1 during excavation and it was found intersecting all the caverns oriented sub-parallel to the caverns and dipping 65-75° towards south (Fig. 2).

Barton's Q classification was used to classify the rock masses and the tunnel support design was further checked and modified with the help of numerical analysis and implemented.

4. HYDROGEOLOGY OF THE PROJECT

The cavern is seated in the bedrock of Khondalite. Soil and Laterite capping exists on the hill tops above cavern for a thickness of 0.2 m to 6 m. This laterite grades into weathered Khondalite. Weathered rock exists up to a depth of as much as 30m at some places. Thus a conceptual three-layer model, layer-A (top soil), layer-B (weathered bed rock) and layer-C (fresh jointed bed rock), showing separate hydraulic properties can be found clearly in the storage cavern area. The hydraulic conductivity of soil/laterite is high and of the weathered bedrock here is found to be of the order of 5×10^{-6} m/sec. The storage cavern area falls within the hill side, and the average groundwater level here is in the range of +60 m MSL. However, at the eastern part of the cavern area, close to the valleys, the bedrock cover is about 50 m. Ground water level in this area is 10 m below the ground surface which is about EL +10 m.

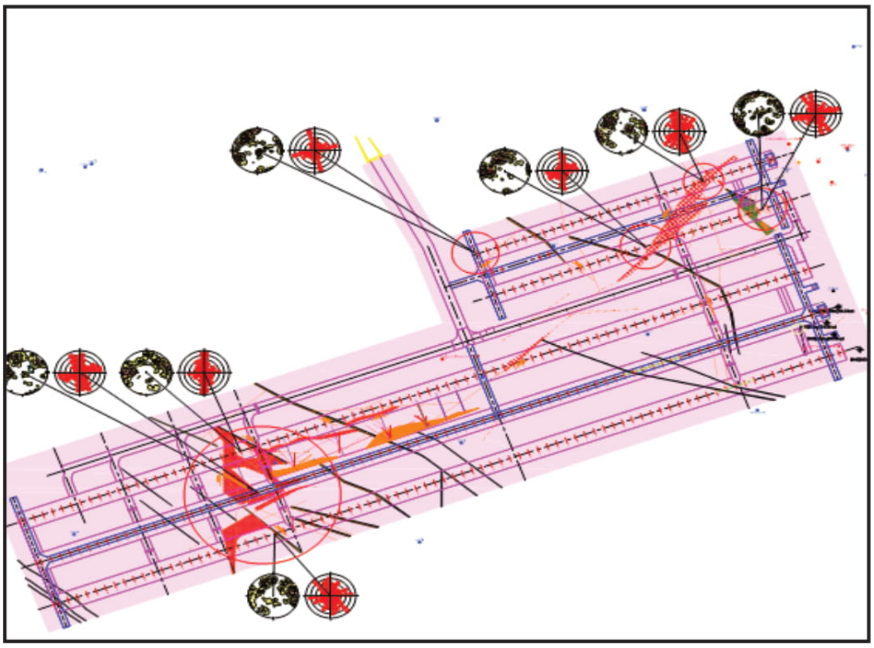

Fig. 2: Geological map of the storage caverns at end of construction

The water pressure test results from the surface investigation boreholes in bedrock represent the average hydraulic conductivity of 5.1×10^{-8} m/sec. During construction of the underground water curtain boreholes, water pressure tests were conducted in the water curtain boreholes (apprx. 50-75 m length each) indicating hydraulic conductivity of 7.6×10^{-9} m/s. Based on the test results, an average hydraulic conductivity of 3×10^{-8} m/s has been used for the hydrogeological model studies.

About 1000mm of average annual rainfall is generally recorded in this site. The ground water level generally follows the rainfall pattern, varying for about 2-3 m between monsoon and non-monsoon season.

4.1 Water Curtain System

The water curtain system in this project is emplaced through water curtain gallery at EL-10m which in turn is connected to the access tunnel open to the surface at portal level (EL +17m). Water pressure in the water curtain system is maintained by maintaining the water level in access tunnel/water curtain level at EL+10m as per the project hydrogeological design. Ground water level above the water curtain system and surrounding the cavern storage facilities (cavern roof at EL-30m) are monitored through monitoring wells drilled for the purpose as per the hydrogeological management plan of the project. This water curtain requirement to be respected at all times in and around storage facility during operation to maintain the hydraulic confinement of crude oil in the cavern.

There are two water curtain tunnels in the project as shown in the layout one four Unit-A and one for Unit-B. In addition to the above, access tunnel, filled with water upto portal also forms part of the water curtain system in this project. Before excavation of the gallery of storage caverns, and during the entire excavation period, the boreholes in the water curtain tunnel above were pressurized with water to a minimum distance of 50 m ahead of the cavern excavation face. The boreholes were supplied with water to the operation level (EL +10m), or above.

As outlined in the geology of the storage cavern, joints in the rock mass of storage caverns are clay filled at some places and clay coated at most of the places. This prevent water from water curtain system to reach the storage caverns, however, it aids in the tightness of caverns too. Hence the seepage in caverns is found lower than those estimated. In order to prevent the interference between the units, such as transfer of hydrocarbons, water curtain system consisting of water filled access tunnel has been designed between unit-A and unit-B. However, as outlined in the geology chapter, a shear body runs across all the caverns, cutting across Unit-A and B. Hydro geologically both the units are interconnected through this shear body. To hydro geologically separate unit A and unit-B, water curtain boreholes were added in the water filled access tunnel, every 10m horizontally, on both side walls of the access tunnel where these shear body encountered. About 16 boreholes have been drilled each about 15m length. Along with water charged access tunnel, these water curtain boreholes act as a vertical water curtain system between the two units in the shear body.

4.2 Groundwater Monitoring

A Groundwater Monitoring Program was set up before the excavation started. If the ground water level falls below the acceptable level, appropriate actions, such as grouting and infiltration, are taken to restore an acceptable ground water level. During the operation phase the ground water level monitoring shall continue in selected boreholes. The groundwater levels in the main part of the site area shows in general a similar pattern, water levels respond to precipitation events, followed by dry periods with gradual declining water levels. Generally in the hilly side, where the main cavern is, the groundwater level was about 40-50 m below the ground before the excavation and it remains same after the cavern excavation also. In valley area near shaft, in general, the ground water level is less than10m below the ground throughout. The groundwater level monitoring indicated, in general, no impact from the excavation.

4.3 Seepage

The seepage to the caverns was estimated about 10-15 m^3/h and the water intake to water curtain is 5-10 m^3/h. During construction, seepage was not an issue and hence this project can be safely called as “no grout” project. The reason for this is being clay filled/clay coated joints in the rock mass. Also in the seepage expected valley area, the weathered rock mass extend downwards to water curtain tunnel level but not below in the storage cavern level.

5. CONCRETE PLUGS

Concrete plugs in crude storage facilities are a critical component used to contain the crude oil inside the rock cavern. These plugs are designed as gas tight to prevent any escape of oil and gas and to withstand differential pressure occurring on account of different fluid pressures stored across the plugs. There are generally two types of plugs required in underground storage; tunnel plugs and shaft plugs.

In case of tunnel plug, it is vertically located at a point to isolate crude oil, forming a separation between oil and water. On the contrary, shaft plug is horizontal in the section and is covered by a long column of water or concrete while oil and vapour is retained below it. Plugs construction involves substantial volume of concrete, which results in the development of large heat of hydration. Therefore the probability of cracks occurring due to heat of hydration of the cement needs to be avoided. Provision is made in the design stage as well as during the construction process to prevent the development of large temperature gradients caused by hydration of cement using concrete cooling arrangements.

In order to ensure air tightness of the plug for prevention of any gas leakage, contact grouting of the plug is carried out at concrete and rock interface until a proper seal is established.

The plugs are constructed in specially excavated plug key-in designed for the purpose. Primarily in order to construct stable plugs, plug key-in locations are chosen in rock mass which is massive and less jointed with high rock quality (RQD) and Q values. Selected location should have nil or minimum seepage. It should also be not very close to any tunnel/cavern junction areas.

Tunnel plugs are dimensioned as per the size of cross tunnel which is typically 8 x 8 m (D Shaped cross section) in this present study. Tunnel plugs are 3 m thick and extend into rock surface with a key depth of 1-2 m as shown in Fig. 3.

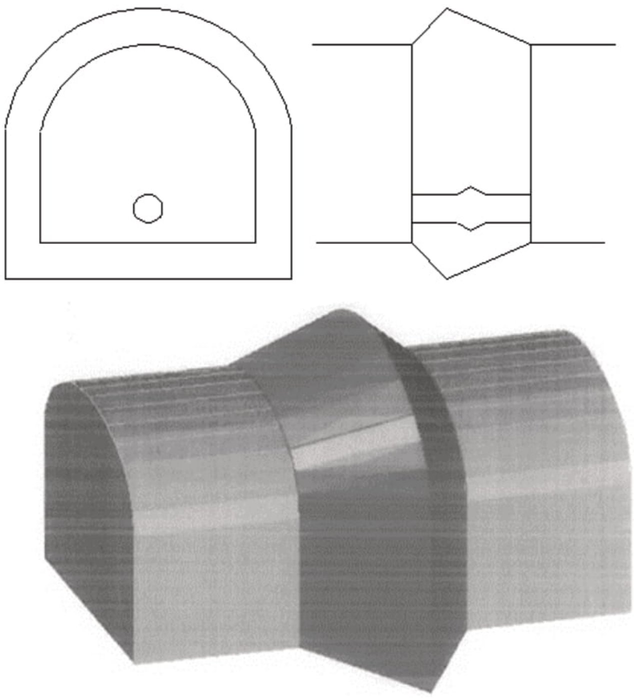

Fig. 3: Concrete plug in cross tunnel

In storage projects, tunnel plugs are mainly designed to resist raw crude oil pressure, which also includes pressure of the gas above the oil surface which is typically around 1.5 bars. These plugs are also designed to resist hydraulic pressure at bottom of the plug due to water head (on other side of plug) used to maintain hydraulic confinement around the caverns. In case of Shafts, Main pump shaft (12 x 6 m) & Inlet shaft (4 x 4 m), plugs are located at an interface where crude oil is located in the lower zone below the plug and the upper zone is filled either by concrete (Usmani, 2016).

6. WATER CURTAIN FLOODING

After the excavation of storage caverns are completed and tunnel plugs and shaft plugs are put in place, flooding of water curtain and access tunnel is carried out up to the design level (EL +10 m), fulfilling the hydraulic containment criteria. Full flooding of water has to be carried out within 15 days in order to reduce the risk of desaturation. This starts with dismantling of water curtain boreholes in a least possible of time of about 2 days. The water used for filling is to be of acceptable quality so that no chemical or biological clogging of water curtain boreholes takes place during the storage period of the cavern project. After water filling, a stabilization period of at least one week, with respect to the stable water curtain system, groundwater pressure levels and the stable hydraulic gradients in the rock around the caverns is required.

7. CAVERN ACCEPTANCE TEST (CAT)

Cavern acceptance test is carried out for each storage unit, to investigate the tightness of the unit. The storage units are tested independently. Before CAT, the tightness and function of each critical technical system – i.e. process piping, concrete barriers and the water curtain system – has been tested as explained above. The cavern tightness test includes applying an air over-pressure inside the caverns, followed by a holding period, during which, pressure, temperature and water seepage into the caverns are recorded. In addition, groundwater monitoring is made before, during and after the test period.

The evaluation is focused on the pressure drop in a storage unit during the holding period, the monitored air over-pressure in the start and the end of this period being corrected using temperature and seepage data. In addition, technical data of the instruments are used to evaluate the uncertainty of the test results. Groundwater monitoring is evaluated with respect to any impact from the CAT on the groundwater levels.

The cavern acceptance test (CAT) includes the following elements:

Cavern Compression - - Compressed air was injected through the vapour manhole pipe of the inlet shaft during a period of 10-20 days. At the end of this period, the pressure was 1.30 bar (g).
Cavern Stabilization. - When the overpressure was reached, the injection of compressed air was shut off, and a stabilization period of at least 24 hours took place, for stabilization of temperature etc.
Cavern Pressure Test. - A holding period of 96 hours took place, during monitoring of specified parameters, see below.
Cavern Depressurization. - When the holding period was finalized, cavern depressurization took place by venting, until atmospheric pressure was reached.

7.1 Monitoring System during CAT

The following parameters as given in Table 2 were monitored during cavern acceptance test. It should be noted that "water level in caverns" in the table is converted into "seepage water volume "in a storage using "strapping table", which is established for each storage unit.

7.2 Monitoring Instruments and Data Plot

The instruments used for monitoring during the caverns acceptance tests (CAT) were identical for all four storage units. The technical data is presented in Table 3.

CAT monitoring data of the project is presented below in Figs. 4 & 5 for both the storage units which includes cavern air pressure, air temperature and seepage volume.

8. CAT EVALUATION

8.1 Pressure Data

The monitored air pressure data, presented as time series, shows (small) cyclic variations with a period of approximately 12 hours in both storage units. In general, the pressure variation range within each cycle is maximum 0.005 bar (g). In order to minimize the influence from this kind of pressure variations on the evaluation, pressure figures are calculated as 12 hours mean values, at the start and at the end of the holding period. The pressure data are given in bar (g) referring to the atmospheric pressure. To obtain the total pressure in the cavern, the atmospheric pressure is added to the monitored cavern pressure.

Table 2: The monitoring parameters and its frequency during CAT

Parameter	Instrument Location	Monitoring Frequency
Cavern pressure	Above ground on shaft top	hourly/continues
Atmospheric pressure	-	hourly/continues
Cavern temperature	Monitored at shaft in 16 points between EL-72m and -32m in both storage units	hourly/continues
Water level in caverns	At EL-72 m in Unit A & at -72.5 m in Unit B	Twice daily
Groundwater level in piezometers	All piezometers	Twice daily
Piezometer inspection (in case of blow out)	All piezometers	hourly/continues

Table 3: Measuring range and accuracy of monitoring parameters

	Cavern Temperature	Cavern Pressure	Atmospheric Pressure
Measuring Range	-25 to +125 °C	0-2 kg/cm^2	
Accuracy	$\pm$0.2 °C	$\pm$0.075%	0.0015 bar

Note: 1MPa = 10kg/cm^2

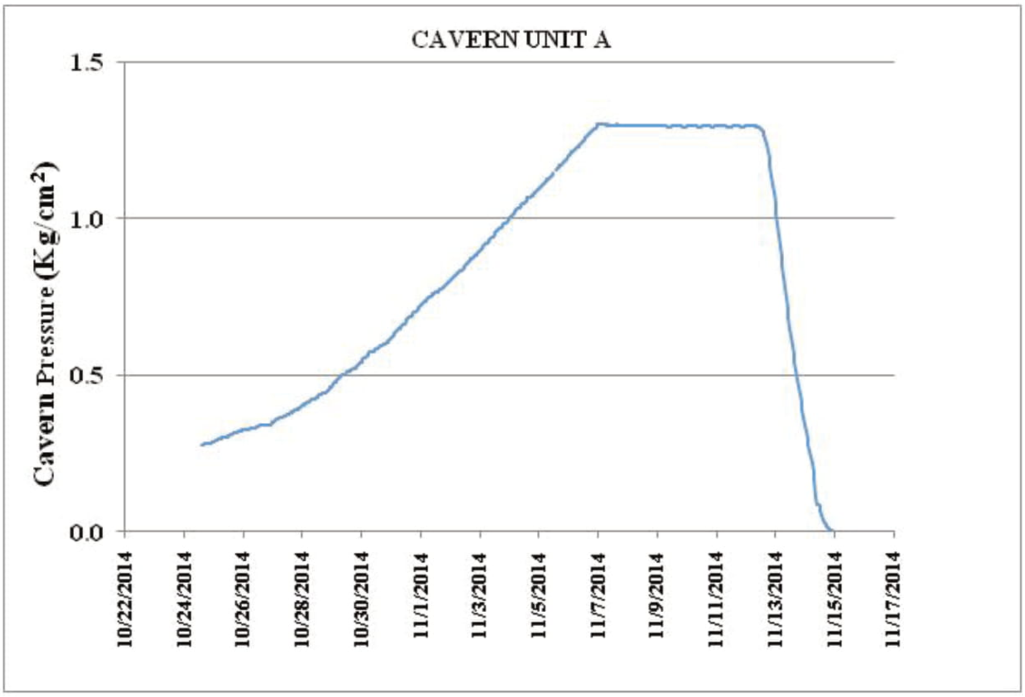

Fig. 4: Storage Unit A: Cavern air pressure during CAT

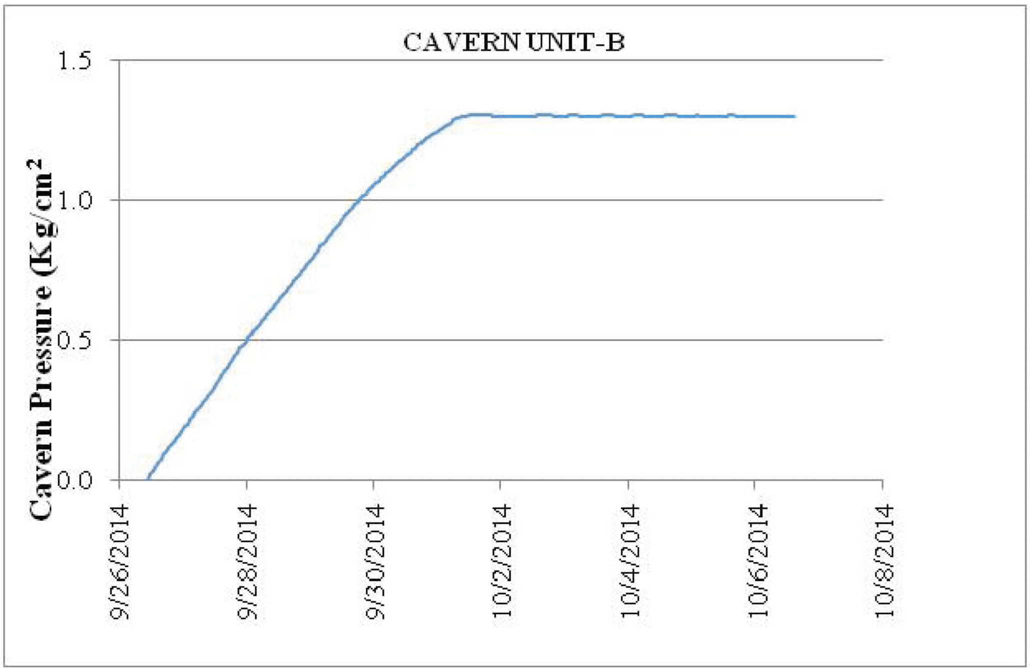

Fig. 5: Storage Unit-B: Cavern air pressure, during CAT

8.2 Temperature Data

In the calculations, the monitored cavern air temperature is used in combination with pressure data, hence the temperature calculated as a 12 h mean value, in the same manner as the monitored cavern pressures are handled. Temperature variation observed during the tightness test varies between 29.22°C to 29.33°C in Cavern A and between 28.99°C to 28.96°C in Cavern B.

8.3 Seepage Data

The seepage during the holding period is calculated based on single water level readings at the start and end of the holding period. Seepage figures have been calculated from recorded water levels by a “strapping table”.

8.4 Correction of Monitored Cavern Pressure at the End of Holding Period

At the end of the evaluated holding period of 96 hours, some factors will influence the final monitored pressure, which have to be corrected. The factors considered are:

- Seepage volume change during the holding period
- Solubility of air (oxygen and nitrogen) in the seepage volume (seepage entering the caverns during the holding period)
- Temperature change during the holding period

Correction for the final pressure is made for increase in pressure due to seepage, and decrease in pressure due to solubility of oxygen and nitrogen in seepage during the holding period. Furthermore corrections are made for temperature changes during the holding period.

From the monitored start pressure of the holding period and the corrected end pressure, the change (in general a decrease) in cavern air pressure during the period is calculated. To exemplify the meaning of the calculated pressure change during the holding period, the pressure change is converted into a corresponding gas volume change, using the ideal gas law and the free (available)volume in the caverns at the end of the holding period (cavern volume minus the seepage water volume).

8.5 Uncertainties of the Monitoring Instruments

The uncertainty of the monitored initial pressure (at the start of the holding period) is limited to the uncertainty of the cavern pressure instruments. The uncertainty of the final pressure (at the end of the holding period) is a combination of the uncertainties of the cavern pressure instrument, the temperature meters and the monitored seepage water volume in the cavern. These uncertainties are combined using the method of “root sum of the squares” to estimate the instrument uncertainty in the pressure measurements (Table 4).

Table 4: Pressure reduction (bar) between start and end of the holding period

	Monitored pressure reduction (bar)	Seepage during CAT (m^3)	Corrected pressure reduction (bar)	Instrument uncertainty considered (bars)	
				Minimum pressure reduction	Maximum pressure reduction
Unit-A	0.0025	110	0.0029	0.0005	0.0064
Unit-B	0.0019	36	0.0019	-0.0015	0.0053

9. RESULTS AND DISCUSSION

The difference between monitored start and end air pressures during the holding period for the two separate storage units are 0.0025 bar (Unit-A) and 0.0019 bar (Unit-B), see Table 4. Monitored pressure differences during the holding period are affected by seepage and, in some cases, temperature.

Corrected pressure differences are 0.0029 bar (Unit-A) and 0.0019 bar (Unit-B). For Unit B the pressure reduction is the same after correction, as both the monitored seepage and the temperature change are small.

When instrument uncertainties are considered, the possible pressure reduction may vary between minimum and maximum values according to Table 4. It can be noted that the negative figure of Unit B (Minimum pressure reduction) is unlikely; it would demand inflow of gas (air) to the storage unit during the holding period.

It should here be stressed that the cavern acceptance test uses compressed air at the maximum allowable pressure level in caverns that are almost empty (only some seepage water in the lower parts of the cavern floor area). During operation the caverns will normally be more or less filled with crude oil and the gas will be in contact only with the cavern roof and some upper part of the walls. It is also expected that the normal gas pressure inside the caverns will be lower than the test pressure during operation. This will considerably further reduce any potential for gas escape.

9.1 Groundwater Monitoring during CAT

All the monitoring wells drilled during construction, were monitored during Cavern Acceptance Test twice every day (morning and evening). During CAT, all of the piezometers close to Unit A and B, present stable groundwater levels. There were no indications of any influence from the pressure test on the groundwater levels. Also no air leakage was observed in any of the monitoring wells indicating hydraulic containment.

10. CONCLUSIONS

The conclusion from the CAT is that the observed loss of air during the tests is well within the limit and detection level of the test set-up and that the storage units are fit for the purpose of storage and commissioning.

Accordingly, the storage caverns were filled with oil and successfully commissioned in May 2015. The product is successfully contained in the storage caverns now without any leakage.

Acknowledgement

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