Groundwater management during the construction of underground hydrocarbon storage in rock caverns

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ABSTRACT

During the construction of underground rock caverns, the hydrogeological environment is thoroughly monitored through an adequate network using adopted procedures and criteria. Methodology and description of this groundwater management is proposed for the various construction stages of hydrocarbon storage in rock caverns.

Water management procedures are presented. One concerns a Liquid Petroleum Gas (LPG) storage in unlined rock cavern and another Liquefied Natural Gas (LNG) storage in lined rock cavern.

For LPG storage in unlined rock caverns, it is absolutely necessary to avoid a de-saturation of the rock-mass in the vicinity of storage galleries whereas in LNG storage, a containment system to insure both product containment and rock-mass protection against thermal shock is combined with a drainage system for removing water from around the cavern galleries and preventing hydrostatic pressure acting against the containment drainage system.

INTRODUCTION

Groundwater behaviour and more precisely hydraulic potential distribution is of paramount importance and needs to be closely monitored and managed during all the different stages of the completion of hydrocarbon storage in rock caverns. From exploration stage to cavern operation phase, groundwater data are collected in order to have a good knowledge of the water flows in the storage area.

Indeed, the groundwater flows have a crucial role in underground storage conception since the containment principle of hydrocarbon storage in rock caverns is based on groundwater characteristics.

Containment concepts are quite different depending on the type of product to store, Liquid Petroleum Gas (LPG) being stored in unlined rock cavern and Liquefied Natural Gas (LNG) being stored in lined rock cavern.

The gas-tightness principle for underground LPG storage in mined rock caverns is based on hydrodynamic containment criteria: a permanent flow of water from the surrounding rock is caused to be directed inwards, into the storage galleries, in order to oppose any outward migration of the stored product. The storage facility must, therefore, be located at sufficient depth below the groundwater table and in the vicinity of a permanent source of groundwater recharge so that the natural hydrostatic head cannot be depleted by drainage into the cavern. Despite the vicinity of water bearing zones, the variable hydraulic continuity in fractured rock often requires the implementation close to the storage caverns of a so called water curtain system. This device prevents rockmass desaturation during construction and ensures a stable, homogeneous potential distribution around the storage caverns under operation conditions. The main purpose of the water curtains is to provide an artificial water recharge in the rock mass in order to enhance flow patterns and to maintain a high hydraulic potential in the storage cavern vicinity.

The principle of the containment criteria is illustrated in the simplified following sketch (Figure 1), which shows a permanent flow of water from the rockmass and the water curtain directed into the storage galleries in order to oppose any outward migration of stored product.

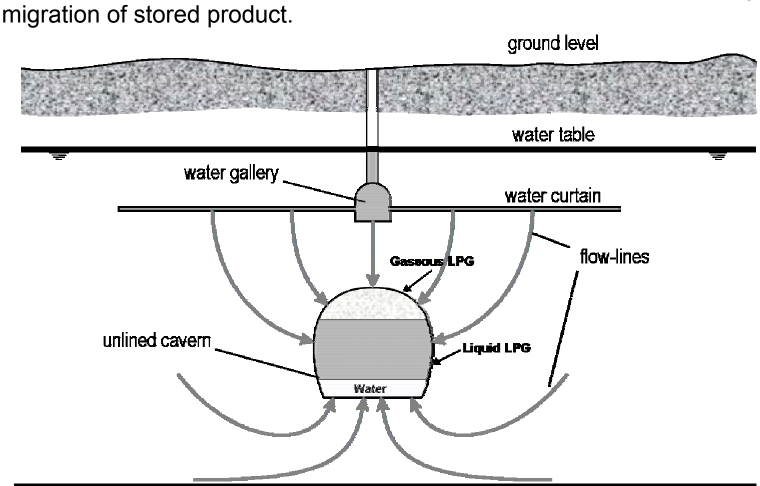

Figure 1: Schematic principle of containment criteria for LPG storage cavern

The construction phases consist of the access works (tunnel and/or shaft), the ancillary works (water curtain) and the underground storage caverns themselves. The next figure (Figure 2) displays a 3D view of an underground facility with the various parts of the works.

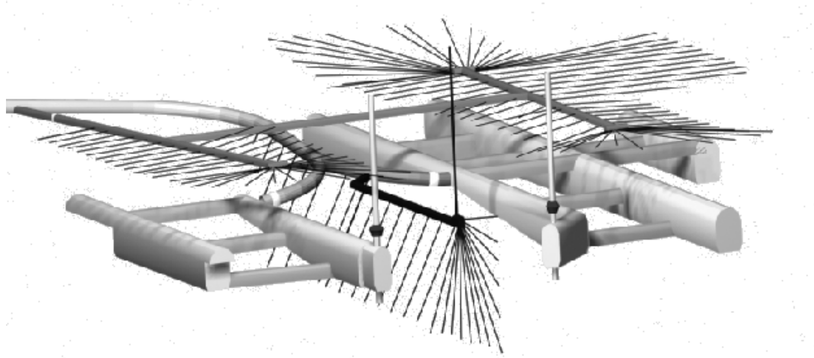

Figure 2: 3D view of an underground LPG storage facility

The concept of LNG storage in lined rock cavern is based on the combination of:

- a containment system to insure both LNG containment and rockmass protection against thermal shock,
- a drainage system to be used during the first months of the storage operation to drain water around the cavern and prevent hydrostatic pressure acting against the containment system. Once sufficient thickness of rockmass has been chilled, drainage system is then stopped to allow water to seep back into the cold rockmass and form, in a controlled manner, an impervious ring of ice, forming a double barrier concept.

The two following cross sections (Figure 3) illustrate the containment principle and especially the gas tight liner and ice fringe.

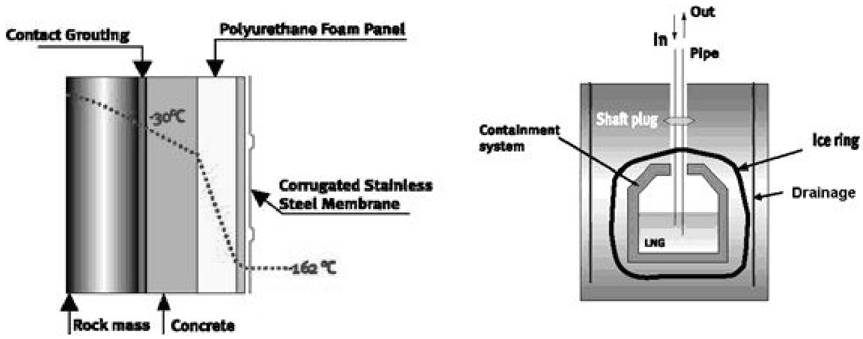

Figure 3: Schematic principle of containment for LNG storage cavern

The dedicated water drainage system installed around the cavern allows controlling the ice formation in the rock mass during the cooling down process. This system is made of a series of pumping holes drilled around the cryogenic caverns, in a box-type configuration, with boreholes drilled from surface and underground specific galleries (water curtain systems) such as shown on the following figure (Figure 4).

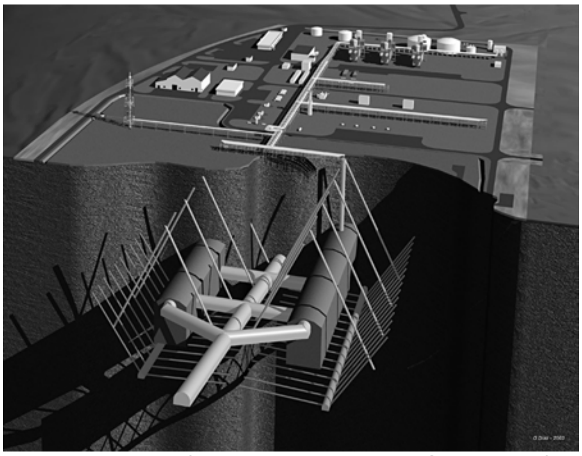

Figure 4: 3D view of an underground LNG storage facility

This drainage hole pattern is designed in order to:

- check the pore pressure and water saturation in the surrounding fissured rock mass,
- reduce water intrusions in the cavern during installation of the containment system and,

- control the ice lenses formation in the fissured rock mass during the cooling phase.

For both storage concepts, the overall hydrogeological environment is monitored thoroughly during each of the construction stages. The hydrogeological monitoring is based on similar water management procedures but with totally different objectives depending on the type of storage.
It is also outlined that the experience gained over the implementation of many projects in different hydrogeological environments is crucial for properly managing this core-activity and it is a fundamental aspect for the success of such projects.
Methodology and description of this groundwater management is proposed for the various construction stages of hydrocarbon storage in rock caverns and more particularly hydrogeological specifications and guidelines, in-situ monitoring and adjustments/evolutions based on observations collected during construction.

METHOLOGY OF GROUNDWATER MANAGEMENT

Monitoring network :
Before and during construction, the water table has to be closely monitored. Before the commencement of the works, the water table is observed in order to determine its initial characteristics. During the works, the water table changes are monitored in order to make comparisons with the initial stage and control the impact of the groundwater management.
The hydrogeological monitoring focuses on parameters collected both from surface and in the underground openings: piezometers, pressure gauge holes, etc… Therefore, to follow the hydrogeological behaviour, the monitoring network consists of:
- existing boreholes drilled from surface during investigation phases and converted into piezometers,
- new boreholes specifically drilled from surface for piezometric purpose at the commencement of underground construction phase or during construction,
- underground holes drilled from the access tunnel, the water curtain gallery or the main galleries.

The following items are given particular attention during construction:
- water levels measured in the surface piezometers and serving for investigation of external influences (rainfall, water flows into galleries, interference…)
- tides, barometric pressure and rainfall data be collected as natural hydrogeological parameters influencing the piezometric variations,
- pore pressure changes measured by a system of undergound holes fitted with pressure gauges

Periodical water sampling in piezometers is also performed in order to detect any change of the groundwater quality compared to the initial conditions. Changes in water chemistry (physico-chemical and bacteriological analyses) are closely followed in order e.g. to follow possible development of salt intrusion.
Control of water ingress during construction :
During mined rock caverns excavation, water ingress in cavern must be controlled in order to maintain acceptable and safe conditions and manage the underground water flows in the cavern vicinity. The objectives of this groundwater management are totally different depending on the storage concept.
In the case of LPG storage, the objective is to maintain the integrity of the existing water table, which is essential to avoid the risk of rock desaturation and to maintain the cavern gas tightness. When excavating access tunnel, shafts and galleries, the water table and pore pressure above the works must be maintained at a minimum hydraulic head above the water curtain level for LPG storage cavern (guideline value).
On the contrary, in the case of LNG storage, the objective is to drain the rock mass from the commencement of construction with the drilling of surface boreholes. These boreholes are opened to drainage: the rock mass desaturation is started partially in order to reduce water seepage in cavern during excavation.
Therefore, in order to fit all these requirements grouting operations can be used and cover at least with the following situations:
- improvement of working conditions by reducing the water ingress or seepage and also preventing deterioration of the stability conditions due to water,
- management of the water table for LPG storage cavern by reducing rock mass permeability in order to avoid water desaturation,
- preparation of the grouting works in cavern (cement membrane)

During excavation works, probe holes are drilled in order to detect water bearing structures and/or weak rock, ahead of the excavation face. Probe holes shall be drilled at each round, from each working face; locations may be occasionally adapted to geological and hydrogeological observations and/or interpretations. When drilling is finished (or when a significant water ingress is detected), the water inflow and pressure shall be measured.
Grouting may be required if water ingress is encountered during or after the drilling of probe holes. Grouting consists of the introduction of cement-based and/or chemical grout (or slurry), under pressure, into the rock mass, using drill holes (probe holes or dedicated grout holes).
From the surface monitoring network, if disturbance to the water table is discovered, effort shall be done to locate the water ingress source and follow the procedures set by the grouting specification to stop the water leakage.
Water curtain – Efficiency test
Water curtains consist of sets of boreholes located in the cavern vicinity and aimed at sustaining continuous water flow to the LPG storage cavern or at draining water for LNG storage cavern.
Concerning LNG storage cavern, it is decided to complete the drainage boreholes drilling before or after the cavern excavation works depending on the site hydrogeological characteristics. Indeed, in case of high water

seepage during cavern excavation, the whole system could be completed and the drainage started to minimize water ingress in cavern.
On the contrary, during LPG cavern construction, the primary function of the water curtain is to avoid the risk of rock desaturation around the caverns (between cavern and water curtain). Pressure in water curtain boreholes must be kept as close as possible to the static pressure before construction. Water curtain boreholes are supplied with water before commencing excavation of the storage galleries, and maintained so throughout the duration of the tunnelling. Water recharge system must be under operation at a certain distance ahead of any working face
In case of difficulties during bolting or grouting works, pressure might be lowered to a guideline value.
For both storage concepts, possible particularly unfavourable hydrogeological characteristics are detected by the so called efficiency test. According to the test results, it will be decided if the water curtain efficiency is to be enhanced by the drilling of additional water curtain boreholes.
For LPG storage cavern, a single efficiency test is performed when, at cavern level, the top heading excavation is completed whereas for LNG storage cavern, two tests are generally performed: a first one at the end of cavern excavation (galleries still unlined) and a second one after the grouting of galleries.
During the efficiency tests, the hydrogeological parameters to be monitored are:

- the water levels on the various surface monitoring holes,
- the pore pressures in the underground holes: in close proximity to cavern walls and water curtain boreholes
- the pressure and flow rate on each drainage borehole
- the infiltration flow rate in galleries
- the natural water supply

For LPG storage cavern, the observed hydraulic potential distribution is compared to theoretical values and some local inefficient or less efficient areas can be detected then remedial actions can be implemented such as additional drilling.
For LNG storage cavern, the hydrogeological monitoring is focused on:

- the follow-up of the pore pressures in the host rock mass, which indicates the low saturation zone range,
- the overall hydrogeological water balance for quantification of the system performance: the water balance is made between water ingress in cavern, water injection through the boreholes and natural water supply.

Water curtain - Full scale test (only for LPG cavern):
For LPG storage caverns, in addition to the water curtain efficiency test, it is necessary to perform a full size hydraulic test. Indeed, the efficiency test aims at testing the performance of the system at sustaining water pressure in the boreholes vicinity whereas the full size hydraulic test aims at evaluating the global hydraulic impact of the water curtain system, i.e. all water curtain boreholes and water galleries.
If required:

- the test shall be performed prior to the closure of the storage caverns, such as to allow access to equipment in order to perform for example additional grouting works in the storage cavern, therefore cavern plug construction and/or manhole closure are to be delayed,
- the construction of a concrete plug at the entrance of each water curtain gallery is needed.

Preliminary Operation Processes
Several preliminary operation processes are to be carried out to ensure definitively the tightness of the hydrocarbon storage in rock caverns.
For LPG cavern, before commissioning the storage facility, the gas-tightness of the storage galleries has to be air-tested at a pressure determined by relevant hydrogeological conditions.
After the closure of the storage caverns, all the access begin to be filled with water until a certain level (guideline value) above the cavern crown. When this level is reached, the air compression of the cavern can start under a certain daily pressure increase. Access tunnel and/or shafts water filling and cavern compression are simultaneous and continuous until the test pressure defined according each site and stored product.
The hydrogeological behaviour is closely monitored (water levels in surface monitoring network, pore pressure distribution around the storage caverns, water seepage into the galleries…). In the event of abnormal change on the hydrogeological situation, the compression rate may be reduced.
For LNG storage, once the construction of the storage facility is completed and before the storage caverns are filled with product, all the boreholes are opened to drainage, and the water is temporary removed from the rock immediately surrounding the cavern. This preliminary desaturation of the host rock mass aims at preventing unacceptable hydrostatic pore pressure and ice formation behind the cavern lining.
The drainage stage is controlled by monitoring:

- water table levels changes,
- flow rates and pressures in the drainage boreholes.

The host rock low saturation degree is maintained during:

- the membrane erection works,
- the storage caverns filling and the propagation of the cold front in the rock mass.

When the cold front has advanced far enough, drainage can be stopped progressively to allow water to re-invade the rock and quickly form a thick ring of ice around the cavern so withstanding the outside water pressure. The

thickness of the frozen rock ring required to sustain the outer pore pressure is about 1 to 2 metres, depending on the strength of the rock mass.
In parallel, a close monitoring of the flow rate and pressure in the boreholes and the piezometric levels is done, in order to adjust the drainage stop procedure for the rock mass imbibition control. The objective is to increase progressively the rock mass saturation, and to prevent membrane damage, possibly caused by propagation of ice up to the lining.

CONCLUSION
Based on Geostock's large experience of monitoring LPG underground storage in unlined rock cavern, a similar approach for the groundwater management has been considered and applied for LNG underground storage in lined rock caverns. Monitoring is part of the whole Quality Control/Quality assurance process.
Indeed during operation, the hydrogeological monitoring and groundwater management will be carried out during all the life of the facility. It has to be verified that the containment principles are always maintained and no adverse changes occur.
Therefore possession of a complete uninterrupted record of hydrogeological data from the very start of operations is of crucial importance. Understanding of the hydrogeological situation during cavern operation and establishing datum levels is largely governed by the continuity of the earlier collected data, especially during construction.

REFERENCES
Amantini, E. *et al.* 2005. The LNG storage in lined rock cavern, Pilot cavern project in Daejon (South Korea). *Gastech 2005*, Bilbao. 17 p. under press.

Claude, J. & Londe, L. 1994. A New Concept for LNG Storage in Lined Rock Caverns. *Gastech 1994*, Kuala Lumpur 434-443.

Grappe, J. & Londe, L. 1995. Underground storage in mined caverns. Experience of LPG storage and application to natural gas storage. *International conference on underground storage of natural gas*, Moscow, 1-10.

van Hasselt, B. *et al*. 2003. Hydrogeological monitoring construction and operation of underground LPG storage facilities in mined caverns. *International congress Groundwater in fractured rocks*, Prague, 389-390.