DEVELOPMENT OF THE PERFORMANCE OF THE LOENHOUT UGS (ANTWERP - BELGIUM) DRILLING THROUGH A HIGHLY KARSTIFIED AND FISSURED LIMESTONE RESERVOIR UNDER GAS STORAGE OPERATION

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Keywords: 1. Underground gas storage; 2. Aquifer gas storage; 3. Karstified limestone gas reservoir; 4. Live well snubbing; 5. Snubbing drilling of gas wells.

1 Loenhout UGS Background

a. Development History

The Fluxys Loenhout Underground Gas Storage (UGS) facility, located in the Campine region (Province of Antwerp, North of Belgium), was developed in an aquifer system. Gas is stored in the top Dinantian karstic limestones (Visean age) of the Heibaart structure. The Loenhout UGS is one of the two gas storages connected to the Fluxys gas transport grid (see Figure 1).

First gas injection in the aquifer system started in 1985 after 5 years dedicated to design studies and construction.

There are three types of well architecture at the Loenhout site:

- Production wells used for the injection and production of gas: these wells are drilled into the Dinantian and are located according to the reservoir's production requirements.
- Peripheral and interface control wells: these wells are also drilled into the reservoir and allow monitoring and sampling of reservoir water, measuring the gas-water contact and provide an adapted monitoring to prevent the risk of lateral gas outlet.
- Upper aquifers monitoring wells, which enable the supervision of the caprock gas-tightness, are located above the caprock and perforated in order to monitor the required aquifer levels.

If necessary, the wells are deviated so as to benefit from the surface installation while reaching their pre-defined target.

The produced sour gas must be processed in order to be sent to the gas grid. 4 production platforms and a main central station are operated to remove the sulphur, to dry the gas and to control its pressure. A total of 12 production wells are operated to inject or withdraw the gas. Another 36 wells monitor the reservoir parameters and are located on isolated platforms spread out around the main facilities.

At the start, the gas storage comprised 8 injection/production wells distributed on 3 operations platforms installed along the crest of the aquifer structure. In addition, 6 control wells have been drilled prior to storage operation start-up for monitoring the gas progression in the aquifer. In 2000, 2 additional injection/production wells were added to the storage facility. Just recently, 2 new production wells were drilled from a fourth new operation platform, bringing the number of production gas wells up to 12.

From 1985 to 2008, the total stored volume of the Loenhout aquifer gas storage was progressively increased from 1 billion Nm^3 (i.e. 35 MMSCF) up to 1.25 billion Nm^3 (i.e. 45 MMSCF) by carrying out additional seismic surveys and drilling wells on new production platforms (see Figures 2-a & 2-b)

Presently, steps are taken to extend storage capacity to about 1.4 billion Nm^3 (i.e. 50 MMSCF). In 2007, Fluxys began work to expand the underground storage capacity by 15% over a four-year period, moving from a working volume of 600 million Nm^3 (i.e. 20 MMSCF) up to 700 million Nm^3 (i.e. 25 MMSCF). At the same time, use of the facility will be made more flexible, increasing both the sendout and injection capacities from respectively 500,000 to 625,000 Nm^3/h (i.e. 425 MSCF/D to 530 MSCF/D) and from 250,000 to 325,000 Nm^3/h (i.e. 210 MSCF/D to 275 MSCF/D).

Such continuous improvement process of the storage capacity and gas wells deliverability, is necessarily based on reasoned scheduling and design of new drilling works into the reservoir structure, without interfering with the gas storage operating activities.

Fig 1 Belgium Gas Transport and Storage network

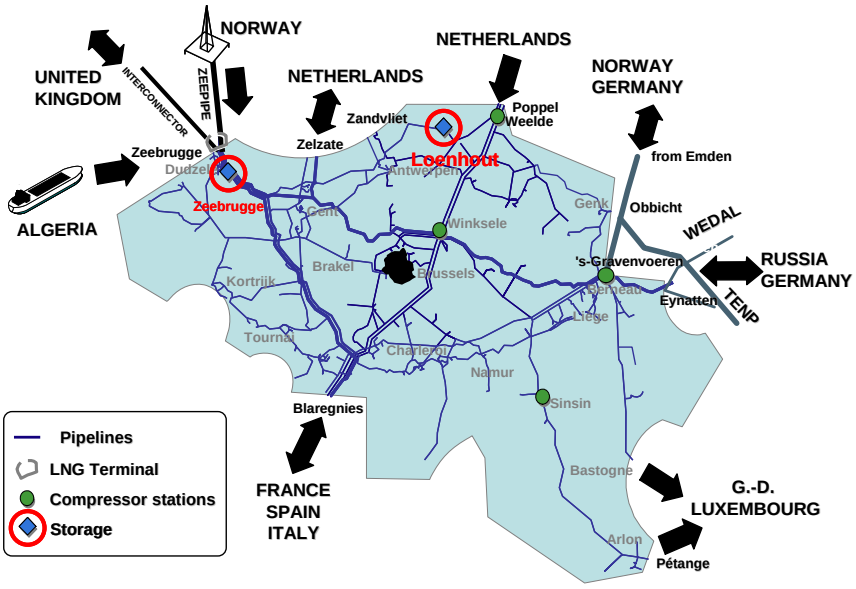


Table 1 - Development of Loenhout UGS - Brief History

1960-62	Oil exploration took place in 1960 by Petrofina looking for hydrocarbons. Drilling of first exploration wells
1973-77	The site was chosen for the development of an underground storage facility. Seismic survey and geological studies. Drilling of an investigation well for pre-feasibility study.
1979-80	Workover on Petrofina exploration wells. Plugging and completion works. Drilling of 5 wells indicating feasibility of the project.
1981-82	Engineering study and Construction. Drilling and completion of 8 injection/production gas wells 3 control wells and 3 monitoring wells.
1985	Loenhout I - First gas filling.
1990-92	Loenhout II - Storage capacity extension. Complementary seismic survey and drilling of 4 control wells and 2 monitoring wells.
1994-97	Loenhout III - Storage capacity extension. Complementary seismic survey and drilling of 4 control wells and 9 monitoring wells.
1999-2000	Storage capacity and deliverability extensions. Drilling of 2 injection/production wells, 1 control well and 3 monitoring wells.
2008	Storage capacity and deliverability extensions. Drilling of 2 injection/production wells and one monitoring well.

Fig 2-a – Loenhout UGS Development history – Schematic Profile

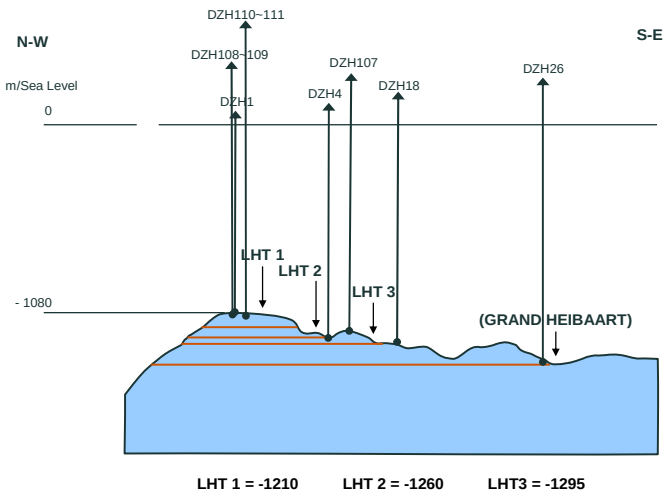
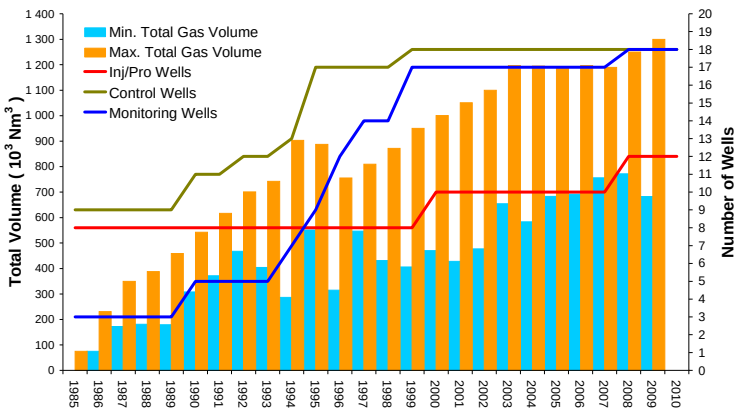


Fig 2-b – Loenhout UGS Development history – Storage Capacity Enhancement



b. Geological Background

The Loenhout reservoir consists of fissured and karstified rockmass developed into a tight and compact carbonated rocks matrix. The original carbonated massif has been subjected to erosion and dissolved by rainwater during its emersion between the Dinantian and the Namurian. The result is an aquifer reservoir consisting of a complex network of dissolved volumes, partially filled with both uraniferous calcitic and shaly materials. Locally the karstified reservoir exhibits extremely high permeability.

The top of the structure is 1080 meters below sea level. The antiform structure (see fig 3) is covered with an impermeable layer composed of a hundred meters thick cover of Namurian shales.

Due to the absence of Permian, Triassic and Jurassic formations, an unconformity separates the marly and chalky Cretaceous formations and the Lower Carboniferous reservoir and its caprock.

The 300 meters thick Cretaceous layers are overlaid by an alternation of 650 meters of clay and sand layers of Tertiary and Quaternary ages.

One of the characteristics of the reservoir is that the available workable volume comes from complex interconnected caves network created by the dissolved carbonates (karst), which is very unusual for an Underground Gas Storage. The secondary permeability due to the karstic network is therefore excellent and has to be compared with the very low primary permeability of the tight matrix.

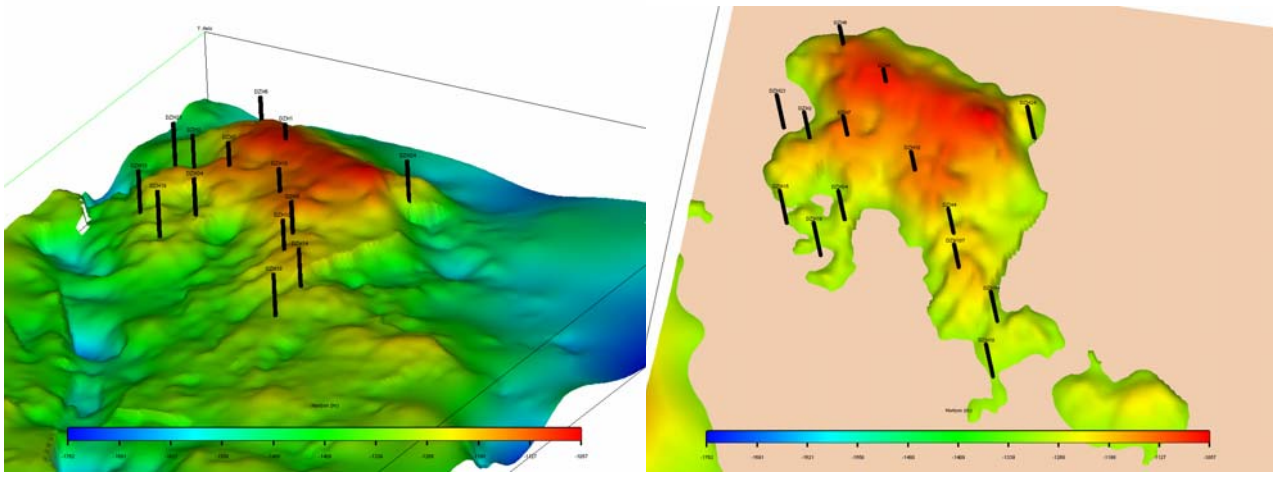
Up to now, no seismic investigation method has allowed the evaluation of karsts distribution in the reservoir, and attempts of geological modelling of the karst system have been vain. The identification of the karst system is essentially obtained during the drilling and logging of the boreholes.

As far as porosity and permeability aspects are concerned, two karsts configurations can be observed:

- Opened karsts exhibiting very high local permeability values, which are revealed during drilling phases by total or partial losses of drilling mud or even by free falls of drilling tool by some meters. The caliper logging showing local increases of borehole diameter combined with borehole imagery tools, allow correlations with opened karsts location.

- Karsts filled with sediments rich in uranium, composed of detritic material (breccia) and carbonated fluid deposits coming from upper Namurian cap rock formation (hot shales), of which the presence along drillings can be detected by Spectral Gamma-Ray logs.

Fig 3 – Dinantian Reservoir Structure North-West view & Slice @ Loenhout III



2 Selection of an Adapted Drilling Methodology

As presented here above, the development of the Loenhout UGS did not make exception to the general rule which consists in adopting a step by step approach to develop an underground storage of gas in aquifer structures. Such development process is based on progressive monitoring of the behavior of the host reservoir, the hydrogeological environment and the operation wells while operating the storage facility.

The inevitable pursuit of the knowledge of the underground gas storage behavior makes necessary to adapt the initial monitoring and operation wells networks in accordance with the accumulated observations. To meet these requirements, complementary seismic investigations and additional drilling works are carried out without any interruption of the gas storage operation.

The wells drilled during the construction phase of the gas storage, into the reservoir zone, have been realized while the gas was not in place. During the operation period, the aquiferous reservoir is drained, at least partially by gas showing bottom-hole pressure ranging from 110 to 145 bars.

Drilling work experience at Loenhout site has shown that there is a real risk of losing mud circulation through the highly permeable karstic reservoir. Even more, the chance to recover circulation is very low. The problem of drilling in such reservoir conditions is thus the following:

> How to manage in fully safe conditions, the drilling and then the setting of a final completion in a karstic zone where the well is likely to intersect vacuums and highly permeable fissures, constantly supplied in pressurized gas?

Several solutions were considered at the time of the design studies and early years of the storage operation.

The basic principle envisaged in the early 80's consisted in drilling the last phase, i.e. the entry in the Dinantien reservoir, with a Bottom hole Assembly (BHA) comprising a liner and a packer to anchor in the preceding cemented production casing in case of the occurrence of gas. This early solution had the disadvantage of using new drilling equipment, which had not yet proved their worth in the context where they should be employed.

The continuous development in the drilling technologies and in equipments of production until Loenhout UGS start-up date, led us to dismiss the initial solution envisaged in favor of equipments which, realizing simple and tested adaptations would make possible the drilling in gas zones, under safe conditions. Since early 90's, the use of a snubbing unit appeared as the most favorable to answer to Loenhout site imposed criteria.

A Snubbing System is basically a well servicing system used for running and retrieving jointed pipe under live well conditions. Nowadays, Snubbing Units are commonly used to undertake operations previously regarded as only within the scope of a drilling rig, and the "Snubdrill" is generally the preferred technology used for under-balanced drilling. Hydraulic Workover unit (HWO) can solve problems where it is hard to strip, or eliminate risks of blowing-out when you move drill bits or liner nearly to the wellhead. Front snubbing unit can be applied to strip and snub the drill pipe under high pressure from the well. Compared with killing well, HWO greatly improves efficiency and economic benefits *(ref. 1 -Hodgson, R. and al. Sept. 1994)*

3 Drilling and Completing live gas wells in the Loenhout Dinantian Reservoir

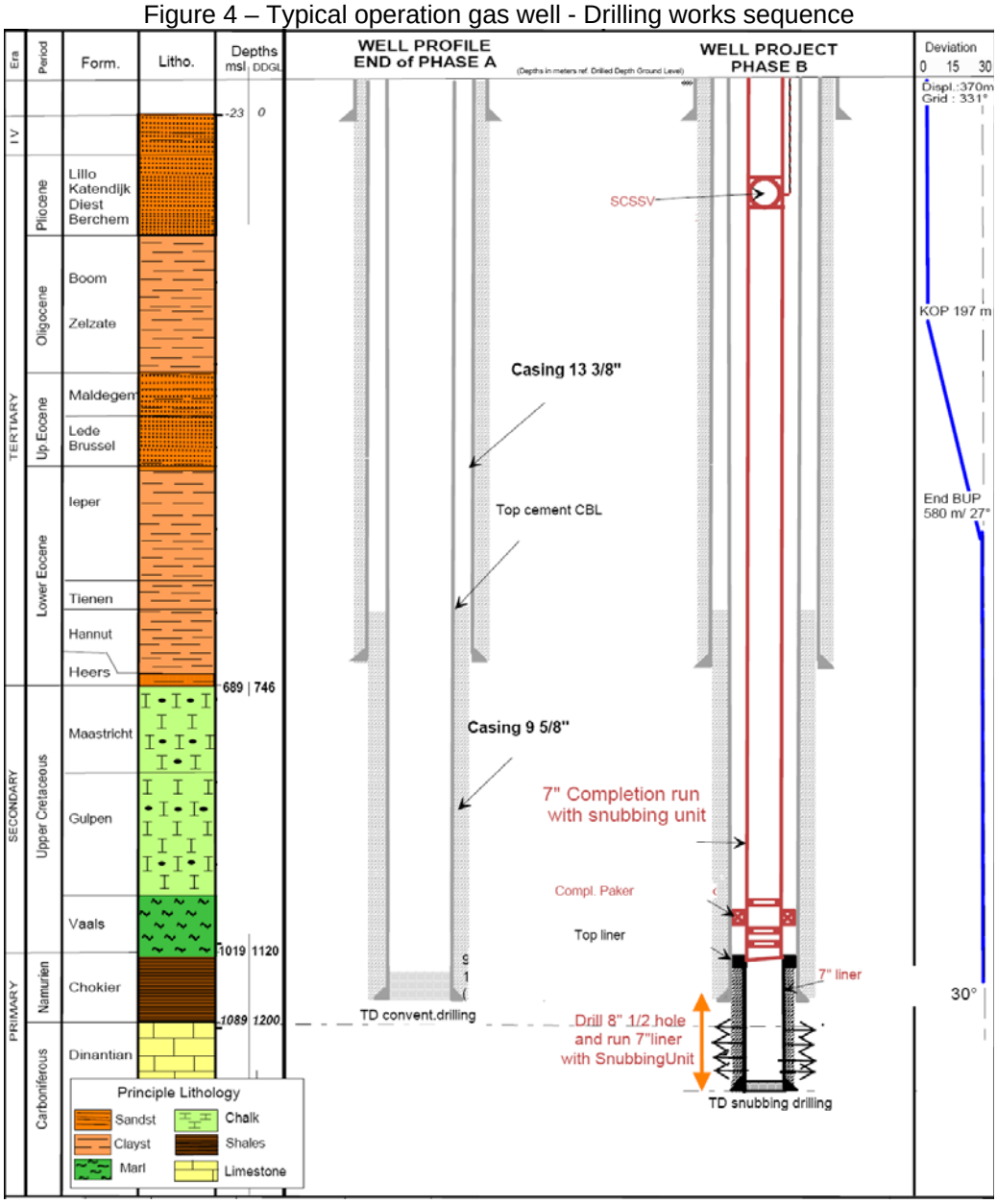
The drilling of any well in the gas zone of the Dinantian reservoir of the Loenhout underground gas storage is systematically broken down into two main phases (see figure 4):

- The first phase (noted phase A) consists of drilling through all the upper aquiferous formations down to the Namurian caprock, casing the holes and cementing the 9 5/8" production casing into the Namurian shales. Since there is no gas involved in this phase the well is drilled with a conventional drilling rig equipped with a standard Blowout Preventer. The well equipment is designed according to API standards (casing, well head).

- The second phase (noted phase B) consists of drilling through the caprock and through the karstic reservoir formation under gas pressure. This phase is drilled with a snubbing unit to

allow complete control of the drilling operations (snubbing mode, total losses) without any mud return with gas pressure at the wellhead. After drilling the reservoir, the well is fully under gas and 7" liner equipment has to be snubbed in and tightly set in the 9 5/8" production casing, in order to control the well and go on with the completion operations.

Figure 4 – Typical operation gas well - Drilling works sequence



a. Risks Assessment during Phase B

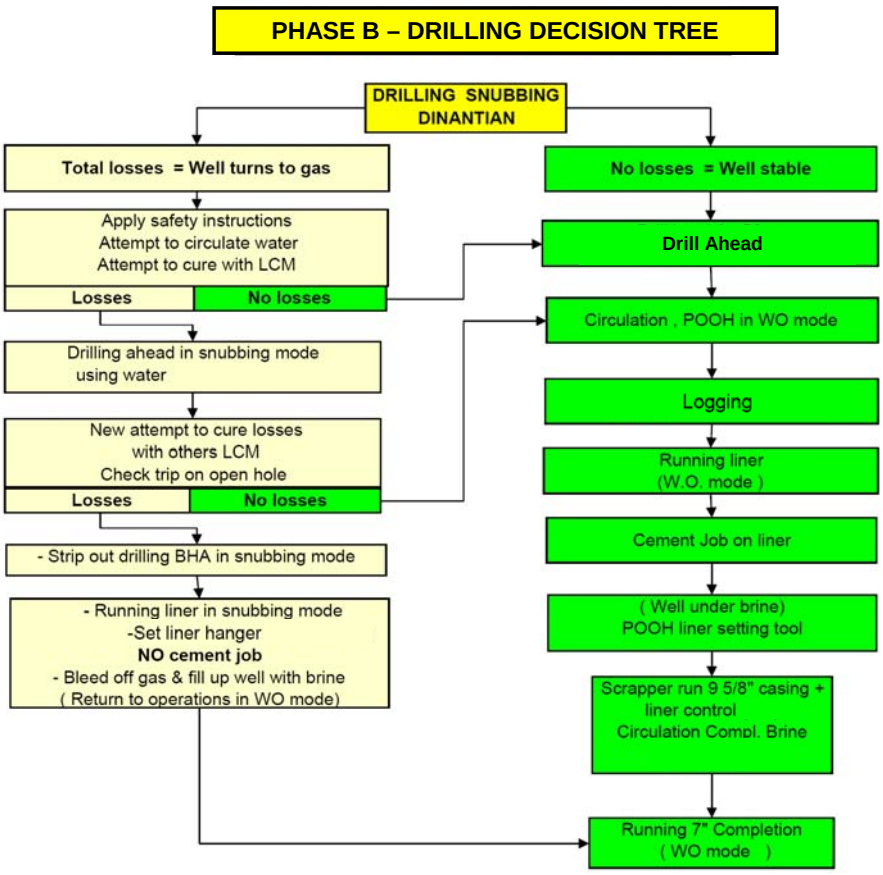
A HSE study is systematically performed as a preliminary step to the elaboration of basic drilling program and of works specification. The more severe risks occurred during the second drilling phase (phase B) of a gas live well are, per risks domains, the following:

- <u>Particular conditions when drilling with a HWO</u>: The teams and the material of snubbing are dedicated especially to operations of workover under gas. Drilling with this type of equipment is rather exceptional and new for the personnel. The presence of a professional driller (e.g. Directional driller) in the snubbing team is necessary during all the drilling period. All particular work phases: handling of BHA and stems, addition of stems, put in circulation, put in safety of the well in the event of arrival of gas, etc will have to be the subject of pre-job meeting and repetitions.

- Working under gas reservoir pressure at wellhead: The risk-taking appears when the drilling enters in Dinantian gas reservoir, with risk random of partial or total loss of circulation which can quickly put the well under gas at the pressure of the tank. Using the snubbing unit and an adapted BHA, it is possible to continue drilling with total losses (without mud return at surface) by closing the rotary annular BOP, and reach an adapted final depth in the reservoir consistent with the deliverability objectives of the operation gas well. However and in order to avoid working under gas conditions at wellhead (especially pulling out drillpipe and BHA and running the liner) and to perform an efficient cementing job, tries of reduction of drilling fluid losses are carried out by pumping appropriate Loss Circulation Material (e.g. LCM compatible with BHA characteristics and acid soluble), in order to try to restore an acceptable hydrostatic equilibrium..

The diagram here below (see fig 5) presents the snubbing drilling strategy adopted, in order to mitigate the risks and reach the gas well objectives.

Figure 5 – "Snubdrill" strategy



b. Liner running and setting in gas conditions

A particular attention has to be taken when designing the liner equipment specifications. The liner equipment are likely to be run in snubbing mode. This work phase necessitates the elaboration of specific work procedure, which has to be discussed and elaborated in collaboration with the selected contractor.

Main Design Requirements for the liner equipments (i.e. shoe, float sub, liner hanger, liner packer …) are:

- Liner elements have to be strippable; i.e. length and diameter of assemblies have to be compatible with HWO characteristics,
- The liner shoe has to be equipped with a double check valves system in order to be run in hole for any possible wellhead pressure condition,
- The liner packer has to be tightly set in the cemented production casing, in order to be able to install the gas well completion in workover mode, under hydrostatic conditions,
- The liner can be cemented if reservoir permeability conditions allows to.

4 Last history case - 2008 Drilling Work at Loenhout Site

The first drilling in the Loenhout Dinantian reservoir, using a HWO, was carried out in 1995 at the periphery of the gas zone. Later on, in 2000, two production/injection gas wells were drilled at the top part of the reservoir, from the main operating platform of the storage facility, applying similar drilling methodology. During this works, snubbing mode was not necessary. Indeed, the local permeability of the Dinantian limestone was sufficiently low to keep the well in stable conditions until final depth.

In 2008, two additional operation gas wells (named DZH110 & DZH111) were drilled at crest of the Dinantian reservoir structure, on a new operation platform. Both wells reached karstic vacuums, exhibiting a very high hydraulic conductivity, which led to non recoverable drilling fluid losses.

Phase A of the two new wells was carried out by COFOR using a conventional drilling rig (MR7000). During these works a particular attention was taken when adjusting the final drilling depth to actual geological conditions.

As per design, the 9 5/8" production casing has to be located in the gas tight cap rock of the reservoir at a sufficient distance from the gas reservoir. This cemented casing forms the first tightness barrier of gas wells, as the second barrier is brought by the packer of the 7'' tubing of the final completion.

Phase B of both wells was performed by HALLIBURTON using an adapted HWO unit (see Figure 6) and the drilling was carried out running a specific BHA (about 10 meters high, ended by a 8 1/2" Tricone drilling bit).

Partial to total drilling fluid loss occurred on both wells approaching the available flow rate capacity during drilling (e.g. about 75 m^3/h), and the pressure at wellhead, in the production casing, increased up to reservoir pressure (e.g. ranging from 110 to 115 bar g) during observation periods. As a consequence, the 7'' Liner, equipped with a specific expandable liner hanger system, was run and set successfully under full reservoir pressure at wellhead *(ref. 2 - Wim Bossewinkel and al. – Halliburton SPE 121741 – April 2009)*

Taking into account the conditions of permeability observed and of the pointlessness to carry on with intensive LCM works, it was decided for each well not to cement the liner 7 ".

Phase B on each wells was carried out one month after completion of phase A, allowing sufficient curing time for the production casing cementation.

After moving of the HWO rig, third and final completion works phase (Phase C) was carried out, which consisted in perforating the liner using Wire Line equipment.

Water injection tests were performed just after perforating the liner and permitted to assess, as a preliminary evaluation, the hydraulic injectivity ratio of each completed well. Strong water injectivity ratios in the range of 30 to 600 m3/h/bar, were observed at that time, which are the highest values observed on site since the beginning of the development of the Loenhout UGS. These values led to the decision to cancel stimulation jobs and let envisage very strong gas wells deliverability.

The cumulative duration of the HWO work phase was of 7 weeks, including 2 weeks for mobilisation and moving of equipment. The Figure 7 presents the actual overall work schedule for the drilling of these two last operation wells.

Figure 6 – Halliburton HWO – Stack-up

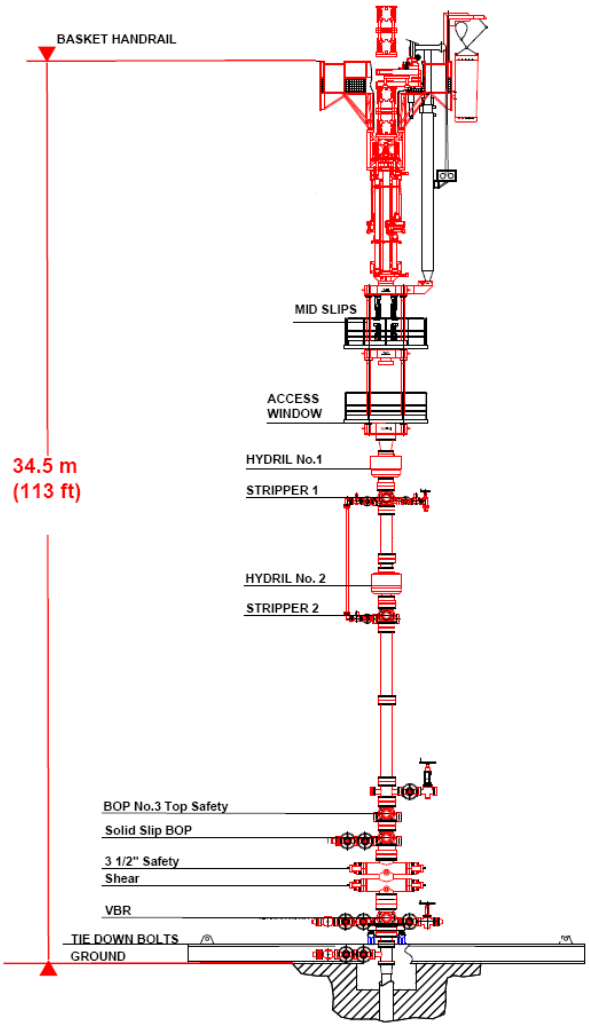
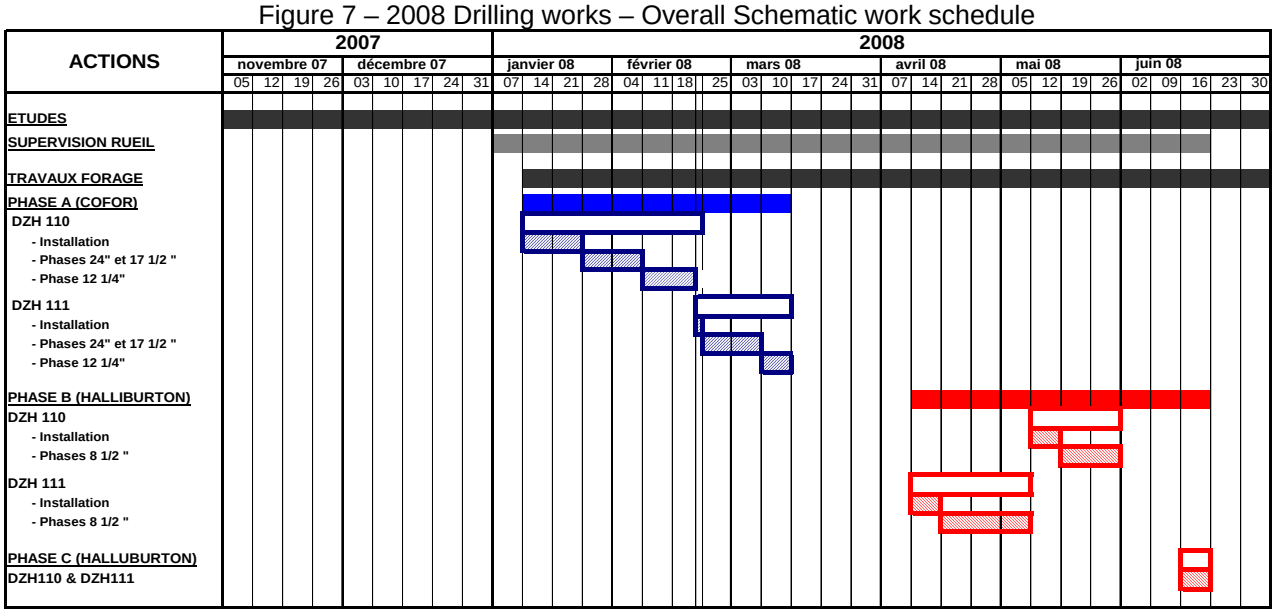


Figure 7 – 2008 Drilling works – Overall Schematic work schedule



5 Summary - Conclusions

The underground natural gas storage of Loenhout (Antwerp - Belgium) was put in operation by FLUXYS (formerly known as DISTRIGAZ) in 1985, with an initial wells network composed of 6 injection/production wells and 8 monitoring wells drilled in the reservoir structure. Since then, FLUXYS implemented progressive extension works, aimed at increasing the storage capacity and the performances of the underground gas storage, with the objective of reaching by 2010 a total gas inventory of 1 400 Million Nm3 (i.e. 50 MMSCF) and injectivity and deliverability of respectively 8.5 Million Nm3/D (i.e. 275 MSCFD) and 15 Million Nm3/D (i.e. 530 MSCFD). In order to achieve this performance, 4 new 7'' diameter operation wells were added to the original storage wells array, of which 2 wells were successfully drilled in 2008. These new wells were drilled and completed under gas conditions, without any interruption of the storage operation activities, which constituted a particularly delicate operation and required calling on innovative technical solutions, due to the characteristics of the storage reservoir.

The storage reservoir consists namely of fissured and highly karstified aquiferous limestones which develop locally extremely high permeability. In the course of a drilling operation, the probability of intersecting a several meters high karstic gas zone, resulting in total circulation loss, is quite high, and generally, the cased wells perforated at the level of the limestone aquifer exhibit water injectivities varying from 30 to several hundreds of m^3/h/bar. Such gas reservoir characteristics which are very favorable for the performances of an underground gas storage facility are constraining for the realization of new gas wells. Indeed, the dimensions of the karstic vacuums are such that the control of massive gas arrivals during drilling by the drilling fluids can turn out totally impossible.

Thus FLUXYS and its consultant GEOSTOCK had to develop a methodology adapted to the particular characteristics of the Loenhout gas storage, allowing drilling under gas conditions with total circulation loss of the drilling fluid. Running and cementing casings, liners and the gas completion needed also to be addressed by a specific program.

The methodology implemented is based on a combination of conventional drilling down to the storage caprock where a production casing is cemented, followed by the use of a snubbing unit in drilling mode, for drilling through the reservoir, running a liner and setting the gas completion.

During the last 2008 drilling campaign, comprising two new production/injection wells, this methodology was successfully implemented by companies COFOR and HALLIBURTON under supervision of GEOSTOCK. Both wells intersected large karstic voids in the reservoir, resulting in total circulation loss. Drilling operation was continued under full reservoir gas pressure at wellhead; and the liner was run and set in place under the same condition.

The methodology and strategy designed and developed for the drilling of live wells in the karstic gas reservoir of Loenhout, has demonstrated its full effectiveness during the drilling campaign of 2008, and validated the technical options selected at design stage.

It has been demonstrated that an optimal combination of a conventional drilling rig with an adapted snubbing unit allows to successfully satisfy the safety requirements, while maintaining the control of the work schedule.

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