Demonstration of the LRC Gas Storage Concept in Sweden

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SUMMARY: The Lined Rock Cavern (LRC) concept is a new technology for underground storage of natural gas. The main principle is to store gas at high pressures in lined rock caverns at relatively shallow depths. The rock absorbs the pressure load and the lining ensures gas tightness. Included in the concept is a system for circulation heating or cooling of the gas to improve the working gas amount and lower the specific storage cost.

The aim of the LRC Demo Project (joint-venture between Gaz de France and E.ON Gas Sweden) was to prove the technology by constructing a demonstration storage plant situated in south-western Sweden. After the construction of the LRC Demo plant (1999-2002) was finished, an extensive testing and demonstration programme started. The programme included loading of the cavern with up to 220 bar internal pressure and multiple load cycles, all performed with water as the pressure media. This was followed by three full pressure cycles with natural gas. During the entire test and demonstration period the deformation behaviour of the rock mass and the cavern lining was monitored by a comprehensive measurement system in addition to the pressure and temperature measurements inside the cavern.

The following main conclusions can be drawn based on the performed tests and demonstrations at the LRC Demo Plant:

• The rock mass and the cavern wall have responded according to the design expectations and the deformation level is generally lower than expected. This means that the design assumptions have been confirmed within a comfortable margin. The temperature variation in the cavern during gas operation has, as expected, a large influence on the deformation pattern.
• The steel lining of the cavern is absolutely gas tight. Gas leak tests proved that the leak monitoring system is capable of detecting a small gas leak from the cavern in a very short time.
• The demonstration operation with gas proved that the high demands on deliverability and turnover rates have been met, which is of great importance to the commercial potential of the LRC concept.
• It has been shown that the gas cooling/heating circulation system can control the temperature in the cavern, thereby increasing the storage deliverability and the possible number of annual turnovers.

The LRC concept is now a proven commercial technology and is ready to challenge other existing storage alternatives on the market. The main advantages of the LRC technology are: great freedom of localisation with respect to geology, high deliverability and turnover rates, no gas treatment, low impact on landscape and environment and a possibility to expand a storage plant in steps by adding storage cavern modules.
1. INTRODUCTION

The world’s first natural gas storage based on the LRC (Lined Rock Cavern) technology has been successfully completed and is now in commercial operation as part of the Swedish gas grid, providing peak shaving and seasonal storage services. The construction of the LRC Demo Plant was the final step of a long development process that started 20 years ago. The LRC Demo Project is a joint venture between Gaz de France and E.ON Gas Sweden.

The aim of the LRC Demo project was to demonstrate the feasibility of the LRC technology. In order to verify the economical and technical feasibility at a full commercial scale, it was judged necessary to design, construct and operate a demonstration plant. One major objective of the demonstration plant was to turn this concept into a proven storage technology. In addition, the construction of the demo plant should bring enough information for designing, dimensioning and pricing an LRC storage complex at another site. Furthermore, the technical risks related to a first time construction of the cavern wall, i.e. the liner construction and function, needed to be demonstrated in order to be approved and accepted. Some of the major technical issues were to prove the tightness of the storage cavern, to achieve the estimated working gas volume and to prove the deliverability.

The LRC concept combines modern technology, safety and environmental thinking. The main principle is to store gas at high pressures, in lined rock caverns, at relatively shallow depths (100-200m). The pressure load is absorbed by the surrounding rock mass. The lining is only there to make the cavern absolutely gas tight and carries only a negligible part of the gas pressure. The LRC storage system is also a completely closed system; the gas is at all times enclosed (in the lined cavern, in the gas pipes etc.) and is never in contact with the surrounding rock mass. The construction of the LRC Demo Plant started 1999 and was finished during 2002. After that, an extensive scientific testing programme started, including loading of the cavern up to 220 bar and multiple load cycles. The behaviour of the rock and the lining was monitored by a comprehensive measurement system. The storage is now in commercial operation as part of the Swedish gas grid, providing peak shaving and seasonal storage services.

2. THE LRC DEMONSTRATION PLANT IN SWEDEN

The LRC Demo Plant is situated south-western Sweden near the main gas pipeline along the west coast of Sweden. The main parts of the plant are the above ground facility, the underground storage cavern and the connecting pipeline to the gas grid. Access to the cavern during excavation and construction is provided by a system of transport tunnels, see Figure 2.1.

Figure 2.1. Layout of storage cavern and access tunnels at the LRC Demo Plant.
The storage cavern is shaped like a vertical cylinder with a spherical top and rounded bottom, see Figure 2.2. The internal diameter is 35 m and the height is 51 m. The top of the cavern is at a depth of 115 m below the ground surface. The geometrical volume is 40 000 m³, which means that 10 MNm³ of natural gas can be stored at the maximum pressure of 200 bar.

The entire cavern is enclosed by a drainage system, see Figure 2.3. The system consists of a rhombic network of perforated plastic pipes mounted on the rock surface prior to the casting.
of the concrete wall. The system has a lower exit connected to a pump in the lower tunnel and an upper exit via the vertical shaft to the surface.

The layout of the Above Ground Facility is fairly conventional. There are two building inside a fenced area; the process building and the control building. The control building contains the local control room. The process building mainly hosts the compressor, the boilers and the utilities. The LRC Demo Plant can be operated from the control room in the above ground facility. The storage plant is however normally remotely operated from the central gas grid control room.

3. DEMONSTRATION PROGRAMME

3.1 Demonstration and test programme

The total scope of the demonstration programme for both the Above and the Below Ground Facilities can be summarized as:

- Extended commissioning
  - Commissioning. This test was scrutinised by Authorities as part of the approval procedure for gas filling.
    - Mechanical integrity test of the cavern at 220 bar
  - Demonstration tests
    - Mechanical behaviour test under cyclic loads (25 cycles 30-200 bar)
    - Constant pressure test after cyclic test (at 200 bar)
    - Gas leakage test

- Preparation for gas operation
  - Dewatering procedure (replacing water with gas)
  - Gas drying procedure
  - Gas quality check

- Demonstration of gas operation
  - All six operational cases
  - Capacities for injection and withdrawal
  - Total storage capacity

The mechanical tests under cyclic loads were performed in order to validate the long-term mechanical behaviour of the cavern wall and the rock mass. The goals were:
- to confirm the design model during the increase of pressure: the predicted average radial displacement in the rock, the tangential deformation, and the range of strain in the steel
- to test the mechanical stability of the cavern and the cavern wall (not too much additional deformations) under pressure cycles,
- to give data for estimation of the long-term mechanical behaviour of the cavern.

The demonstration of the gas operation was a demonstration of the main gas storage function. The objective of this phase was to demonstrate that LRC storages are able to furnish peak services to potential customers. That means to be able to operate the demonstration plant in such a way that:
- the working gas amount can be withdrawn in 10 days, and injected in 20 days.
- the working gas amount can be cycled several times depending on commercial conditions.
- the temperature in the cavern can be controlled with the circulation system.
3.2 Measurement system

The storage cavern is equipped with an extensive measurement system to monitor the deformation and the temperature in relevant parts (on the steel lining, in the concrete lining and in the rock mass) as a complement to the pressure and temperature measurements inside the cavern.

There are extensometers with a total of 54 measuring points in the rock mass, 123 points in the concrete lining and 36 points on the steel lining. The movements of the concrete barriers are monitored by 5 extensometers and the temperature is measured in 64 points. The main extensometer system for monitoring of cavern deformations is illustrated in Figure 3.1.

![Figure 3.1 Main measurement system for monitoring cavern deformations](image-url)
3.3 Expectation model

An expectation model was established for the behaviour of the LRC Demo cavern before start of tests and demonstrations. The expected behaviour was based on the assumptions and calculations made in the design. Alarm limits were also established to avoid damaging the cavern during the tests. The alarm limit should represent a magnitude of deformation (or stress/strain etc.) that is getting to be of importance considering the maximum capacity of the cavern. The safety margin against damage must on the other hand be reassuring.

Expectations concerning the behaviour of the LRC Demo cavern were established for the following systems/functions:

- Rock mass properties and behaviour (rock types, zones) for single and multiple cycles
- Cavern wall behaviour for single and multiple cycles
- Barriers
- Drainage system (gas leak detection, collection and evacuation)

The LRC gas storage uses a steel lining to provide absolute gas tightness. The limiting failure mechanism for the lining is expected to be fatigue, and the important factors in that respect are the total number of cycles and the strain range $\Delta \varepsilon$.

The assessment of the rock mass parameters (primarily the rock modulus) aimed at finding properties giving a good assessment of the final maximum deformation after many cycles, as this is of primary interest to the design. This means that the deformation growth during cyclic loading is “included” in the assessment of the rock mass parameters. A consequence of this is however that a calculated expected behaviour based on such rock mass parameters does not directly describe the “real” behaviour.

Figure 3.2 Difference between “expected” behaviour and “real” behaviour.

![Image of a graph showing deformation vs. pressure with labels for First Demo load, Last Demo load, and Deformation growth during cycling. The graph compares “Real” and “Expected” behaviour with markers and lines indicating the growth during cycling.]
The principles are described in Figure 3.2 where both the “real” and the “expected” behaviour are illustrated. The diagram can be seen as an example representing the radial rock deformation during the hydraulic tests.

There is a difference in slope of the expected and the real (last cycle) graphs, which represents a difference in modulus definition. The expected deformation is based on a rock modulus that is reduced to compensate for plastic deformations. The actual modulus of the rock mass, as can be derived from the graph of the last cycle, is higher (note however that the real deformation curve at this stage does not start from zero).

Concerning the distribution of the deformation in the rock mass, the expectation is that 50% of the deformation occurs within the first 10 m of the rock mass. 65% has occurred within a distance of one cavern radius and 85% within one cavern diameter. Less than 10% of the deformation remains at a distance of three cavern radiiuses. The vertical rock deformation above and below the cavern is expected to diminish slightly quicker with the distance from the cavern due to the three-dimensional load distribution.

4. TESTING OF THE BELOW GROUND FACILITY

4.1 Performed pressure test of the cavern with water and with gas

The cavern was already filled with water during the construction phase to support the steel lining during concreting. Prior to the start of the hydraulic pressure tests, water was filled all the way to the ground surface above the cavern. The hydraulic tests started in June 2002, see Figure 4.1. The pressure was increased in steps up to the maximum test pressure 220 bar. All valves were closed and the cavern let resting for almost 11 days and then the pressure was reduced again.

![Pressure variation in the cavern during the hydraulic test period (cavern pressure is referring to top of cavern).](image)
The cycling loading started in with one pressure cycle to 200 bar and down to 30 bar. The following cycles were performed between 30 bar and 200 bar. The typical time for one cycle was 12 h. The maximum pressure of 200 bar for the 25th cycle was kept constant for 3 days. Finally, the pressure was reduced again as the hydraulic tests were completed.

After the pressure tests with water were completed, there was a long period of low pressure in the cavern (approximately 30 bar). During this period the water in the cavern was replaced with gas. The gas also had to be dried to lower the water content to an acceptable level. Adjustments and tests were also performed on the process control system. So far (autumn of 2005), more than three full pressure cycles with gas have been performed, see Figure 4.2.

![Figure 4.2](image.png)

**Figure 4.2** Performed pressure tests with gas (until autumn 2005).

Gas cycle 1 was started in the middle of May 2003. The pressure was increased in steps up to approx. 100 bar. Then there was a standstill over the summer due to the need for further adjustments on the process control system. After the summer, Cycle 1 was continued up to the maximum pressure of 200 bar. After some test runs of the circulation cooling, resulting in decreased temperature and pressure, the cavern was filled up again. A maximum cavern pressure for Cycle 1 of 203 bar was reached. During October, the pressure was rapidly (in 15 days) reduced from 200 bar down to approx. 60 bar and Cycle 1 was finished. The maximum and minimum temperatures in the cavern during Cycle 1 were 43°C and -19°C respectively (measured in the upper part of the cavern).

Gas cycle 2 started in November 2003 with a rapid (14 days) continuous pressure increase from 60 bar to 200 bar, resulting in a maximum cavern temperature of 52°C. Then followed a sequence of circulation cooling and topping up the cavern to 200 bar again. During December, the cavern pressure was reduced more or less continuously and gas cycle 2 was finished at 30 bar and the cavern temperature was -3°C.
Gas cycle 3 started in May 2004 with a rapid injection up to 200 bar and a temperature of almost 60°C. After a long standstill, the pressure was reduced by a long withdrawal in the beginning of 2005. Cycles 3 completed the demonstration operation. Cycle 4 starting in the beginning of the summer 2005 was the first cycle during commercial operation.

The main difference when pressurizing the cavern with gas compared to the water tests is the temperature. The unaffected temperature in the rock mass surrounding the cavern is approx. 10°C. During the water tests the temperature in the cavern was almost constant at 14°C, whereas the temperature during the gas tests shows a great variation, see Figure 4.2. The temperature variation has a great effect on the tangential strain in the cavern wall but a minor effect on the radial displacement.

During gas injection, the cavern temperature increases and vice versa. During periods of stand-still, the cavern temperature is slowly levelling out with the rock mass temperature due to the heat exchange. For example, during the long stand-still in the summer of 2003 (see Figure 4.2), the cavern temperature decreased from 43°C to 15°C. After the withdrawal in cycle 2, the cavern was left resting for about one month and the cavern temperature slowly increased towards 12 °C.

4.2 Observed rock mass behaviour

The measured behaviour of the rock mass during pressurization with water and gas is illustrated in Figure 4.3 and Figure 4.4. The diagrams show the total measured deformation versus pressure for extensometers E11 and E12, placed horizontal radially outwards from the mid cavern height level and in two perpendicular directions, see Figure 3.1.

![Figure 4.3](image-url)  Measured deformation in the 40 m long horizontal radial extensometer E11 at mid cavern height during pressure cycling with water and first three gas cycles.
Both extensometers show similar deformation behaviour during both water and gas pressure tests. The maximum deformation at 200 bar gas pressure is 5.6 mm for E11 and 4.8 mm for E12 (at 220 bar during the hydrotest it was 5.3 mm for E11 and 4.3 mm for E12).

The deformation curve is more or less a straight line during the initial stepwise pressure increase with water up to 220 bar. The small steps in the curve at 100, 150 and 200 bar are caused by “creep” deformation during the resting times at these pressures. The same phenomena can also be observed at the long resting time at 220 bar where the deformation increases at the same time as the pressure is slightly reduced. When the pressure is reduced after the resting time at 220 bar, the deformation remains unaffected for a while before it starts to decrease.

When the pressure is reduced down to the start pressure, the deformations do not go down to zero, i.e. there is a clear amount of permanent (or plastic) deformation. During the cyclic loading the deformation curve forms a stable loop with very little increase between the cycles.

During the initial phase of the gas pressurization, the deformation curves follow the same track as had been recorded during the hydrotests. But at higher pressure levels the deformation deviates slightly and ends up being approx. 10% larger at 200 bar compared to the deformation during the hydrotest. During the rest of the gas cycles the deformations form a loop with the same shape, but slightly “lifted” in deformation level, as was found during the hydrotests.

Figure 4.4 Measured deformation in the 40 m long horizontal radial extensometer E12 at mid cavern height during pressure cycling with water and the four gas cycles.
The explanation to the increased deformation level can be sought in two different phenomena. Firstly, the pressurization with gas is much slower and has had a much longer duration than the hydrotest, which could lead to a slight increase of the deformation level. Secondly, it is probable that the temperature increase in the cavern has had an effect of the recorded radial deformation (the extensometer readings are not corrected for temperature, so an increased rock temperature causes a “false” increase of the recorded deformation due to the thermal expansion of the extensometer rod).

The results from the pressurization with water and gas indicate that the modulus is higher than expected, much higher than the modulus used in the design, and that the rock mass strength is, as expected, higher than the maximum cavern pressure obtained.

4.3 Observed cavern wall behaviour

The measurements of the tangential strain have confirmed the general function of the cavern wall, which is to mitigate the local effect of rock joint opening and movements in the rock surface. The strain level is substantially reduced in the steel lining compared to the rock surface.

The most important parameter for the steel lining (and indeed for the technical function of the LRC concept), is the strain range for a pressure variation between 30 bar and 200 bar (the minimum and the maximum operating pressure). The strain range in the steel lining determines the service life of the cavern.

One high strain area identified in the design is the horizontal strain at the cavern mid height section. There are no horizontal extensometers placed on the steel lining in this area but a good estimation of the strain level can be evaluated from the measurements in the complete ring of extensometers placed in the concrete lining at that level, see Figure 3.1.

The deformation in the extensometer ring corresponds to an average strain of just below 0,6 ‰ and a strain range of approx. 0,23 ‰. The strain level in the steel lining will be approx. 0,1-0,2 ‰ higher due to the compression of the sliding layer and the concrete lining. An estimation for the steel lining strain range at the mid cavern height is thus 0,4 ‰. This should be compared to the strain range value of 0,89 ‰ used in the design. The strain range is thus well below the design value (Note: the design strain range resulted in allowable number of cycles much above what is necessary for the Demo plant, so the margin is even larger than indicated by the values above).

As mentioned earlier, it is the tangential deformations in the cavern wall that are most affected by the temperature variations in the cavern. In fact, Figure 4.5 clearly shows that the registered behaviour in the ring of extensometers placed in the concrete lining at mid cavern height is totally different during the gas cycles compared to the hydrotests.

Figure 4.6 illustrates the principles for the effect of the temperature variations on the tangential deformation in the cavern wall. During constant temperature conditions (e.g. the hydrotests), the deformation is proportional to the pressure (in principle). If the temperature variation is great (as for gas operation without use of the circulation cooling and heating system), the thermal expansion of the cavern wall is a very important factor. If the deformation due to the pressure load is moderate and the temperature variation great, it might
well happen that the deformation is smaller at maximum pressure than at minimum pressure. If the circulation cooling/heating system is used to moderate the temperature variation, the result will be a deformation curve that is closer to the one at constant temperature.

Figure 4.5  Average tangential (horizontal) strain in the concrete lining at the cavern mid height section measured in extensometers M1-M36 during pressure tests with water and gas.

Figure 4.6  The principles for the thermal effect on the tangential deformation.
5. TEST OF THE DRAINAGE SYSTEM FUNCTION

The leak detection and collection ability is important for the overall safety of a LRC Plant, but also to prove the absolute gas tightness of the steel lining. Different tests of the gas leak detection and collection capacity of the drainage system were therefore included in the Demo test programme. The drainage system is illustrated in Figure 2.3.

The test equipment was placed in the lower tunnel outside the concrete barrier, see Figure 5.1. Nitrogen gas from a gas bottle package was injected via a small diameter steel pipe leading to simulated leakpoints previously installed in the concrete wall close to the steel lining.

![Figure 5.1 Sketch of the test equipment](image)

Leak detection and flow measurement was done with several instruments:
- Flow meter at top of drainage system venting pipe
- Oxygen content meter at top of the drainage system venting pipe (temporary instrument used to simulate a gas detector)
- Water pressure gauge at the bottom of drainage system venting pipe
- Water pressure gauges at the bottom of the drainage system/pump pit
- Pressure gauges on leak gas injection pipe (temporary instrument)
- Flow meter on leak gas injection pipe (temporary instrument)

Leak test have been performed on several occasions and under different conditions; high and low leak rates, high and low pressure in the cavern, different water levels in the drainage system etc. The main results were:
- It was possible to clearly detect the simulated leaks with different types of measurements during all conditions.
- The detection time was roughly 1-2 min. for the quickest instruments and the detection was very clear.
- The collection capacity is generally good (90-100%).

The overall conclusion of the drainage system tests is that the Demo plant is equipped with a very efficient leak monitoring system that is able to detect even small leaks in a short time. One important consequence of this is that the absolute tightness of the storage cavern could be proved later during the two gas cycles. No indication of gas leak from the cavern has been recorded.
6. TESTING OF THE ABOVE GROUND FACILITY AND DEMONSTRATION OF THE STORAGE FUNCTION

6.1 Test of storage capacity and injection/withdrawal rates

The design values for the main parameters regarding the performance of the storage are presented in Table 6.1. An important part of the tests of the Above Ground Facility was to demonstrate that these demands could be met.

Table 6.1 Design values for the Demonstration Plant regarding storage performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum cavern pressure</td>
<td>30 bar</td>
</tr>
<tr>
<td>Maximum cavern pressure</td>
<td>200 bar</td>
</tr>
<tr>
<td>Maximum storage capacity</td>
<td>10 MNm$^3$ (at 200 bar and 10 °C)</td>
</tr>
<tr>
<td>Injection rate</td>
<td>15 000 Nm$^3$/h</td>
</tr>
<tr>
<td>Injection time</td>
<td>Fill-up of the cavern in 20 days (from 30 to 200 bar)</td>
</tr>
<tr>
<td>Re-circulation period</td>
<td>Re-circulation in 10 days</td>
</tr>
<tr>
<td>Withdrawal rate</td>
<td>40 000 Nm$^3$/h</td>
</tr>
<tr>
<td>Withdrawal time</td>
<td>Withdrawal of the cavern in 10 days (from 200 to 30 bar)</td>
</tr>
</tbody>
</table>

The largest quantity of gas in the cavern so far was achieved on the 23rd of September 2003 with 8,7 MNm$^3$ of natural gas (during the first gas cycle). The temperature inside the cavern was 38,3 °C and the pressure at the wellhead was 199,8 bar.

The design demand of 10 MNm$^3$ storage capacity was demonstrated in the end of 2005.

The design demand is that the cavern can be filled up from 30 bar to 200 bar in less than 20 days. At the beginning of the first gas cycle, the cavern pressure was approx. 30 bar. The pressure in the network was around 58 bar at this period. The first step of the injection was to bring the pressure in the cavern from 30 bar up to the network pressure. During the Injection with Reduction operational case, a total gas volume of 1,28 MNm$^3$ was injected in less than 48 hours. The average injection rate was 27 750 Nm$^3$/h and the highest flow rate measured was 31 775 Nm$^3$/h.

Once the pressure in the cavern equals the pressure in the network, the gas has to be compressed to be injected. During the Injection with Compression phase of the second gas cycle a total gas volume of 4,95 MNm$^3$ was injected in 14,3 days. The average injection rate was 14 450 Nm$^3$/h and the highest injection rate measured was 23 560 Nm$^3$/h.

As described above, the “Injection with Reduction” and “Injection with Compression” operational cases demonstrated that the LRC Demo storage can be filled up from 30 bar to 200 bar in less than 17 days, which is less than the design demand of 20 days.

During the withdrawal phase of the first gas cycle in October 2003 a total gas volume of 5,83 MNm$^3$ was withdrawn in 10 days (effective withdrawal time). The average withdrawal rate was 24 300 Nm$^3$/h and the maximum rate was 35 000 Nm$^3$/h.
The design demand of maximal withdrawal rate of 40 000 m³/h was demonstrated when the network situation allowed withdrawal at maximum capacity.

6.2 Demonstration of the six operation cases

All six operational cases were tested during the first gas cycle. Each operational case met the design specification in terms of flow, maximum pressure, maximum and minimum pressure and temperature. Figure 6.1 illustrates when the different operational cases were run during the first two gas cycles.

IR  Injection with Reduction
IC  Injection with Compression
W   Withdrawal
WC  Withdrawal with Compression
CC  Circulation with Cooling
WHC Withdrawal with Heating Circulation

Figure 6.1 Illustration on how and when the six operational cases were used during the first two gas cycles.

6.3 Thermodynamic behaviour

Although the complete analysis of all temperature behaviour of the cavern is not over yet, some obvious and general comments can be made based on the recorded pressure and temperature curves (cf. Figure 4.2). As expected, the temperature reached 50°C after fast injection of gas to 200 bar (cycle 2) and dropped to negative temperature (down to -19°C) at low pressure after quick withdrawal (cycle 1).
The natural rock temperature (10°C) tends to temper these temperature variations; this can be clearly seen during resting periods. This natural tempering effect is completed by the circulation heating/cooling system allowing fast injection/withdrawal gas movements without reaching too extreme temperatures. As an example, during the second gas cycle, the withdrawal with heating circulation mode allowed to reach minimum pressure in the cavity while keeping reasonable temperature.

### 6.4 Gas cooling and heating circulation system

The Circulation with Cooling case was tested successfully in November 2003 during the 2nd gas cycle, when temperature inside the cavern decreased by 10,3°C in 47 hours of circulation. The temperature decrease caused a pressure drop of 23 bar (from 198 bar to 175 bar) which allowed an extra quantity of 0,5 MNm$^3$ to be injected as the cavern pressure was raised to 200 bar.

Without the circulation cooling it would take more time to observe such an important temperature drop (caused by thermal exchanges between the gas and the rock around the cavity). This operational case allows the 10 MNm$^3$ full capacity of the storage to be reached in a reasonable time. This can also be a tool to benefit from favourable gas prices, giving the storage an extra capacity at a very low investment cost.

The Withdrawal with Heating Circulation case was successfully tested at the end of the first gas cycle. Gas was withdrawn at a flow rate of 10 000 Nm$^3$/h at the same time as the recirculation flow rate was approximately 30 000 Nm$^3$/h. The gas was heated by 1,5°C in 11 hours.

The Withdrawal with Heating Circulation was further demonstrated during the second gas cycle. Gas was withdrawn at a flow rate of 7 000 Nm$^3$/h at the same time as the recirculation flow rate was approximately 20 000 Nm$^3$/h. The gas was heated by 2,5°C in 31 hours.

### 6.5 Gas quality test

The gas quality tests have been performed with two purposes. The first was to check that the water content was below the acceptable limit, the second was to check that the gas composition had not changed during the storage time in the cavern (e.g. changed heating value or contamination)

**Water content:** The cavern was filled with water already during the construction phase. When the cavity finally was emptied of water and filled up with natural gas, the initial load of gas mixed with the remaining water in the cavern.

The gas was recycled and dried using temporary dewatering equipment in order to decrease the water content. After this operation the water content of the gas inside the cavern was 38 mg/m$^3$(n) (the measured dew point was -20°C at 40 bar), which was below the acceptable limit put up by the network owner.

**Check of gas heating value:** The purpose was to check that the heating value of the gas was not affected by the storage process. The results of tests made on gas before and after it had been stored in the cavern have shown that there is no significant difference in heating value.
Therefore it can be assumed that only a very small amount (or nothing) of the heavy hydrocarbons remains in the storage when the gas is withdrawn.

Check of gas contamination: This check was demanded by the network owner in order to allow withdrawal of gas. The first test on the withdrawn gas indicated that the oil content was higher than it was in the gas from the grid. Later it was shown that the reason for this high value was oil from the gas compressor; the measuring point was too close to the compressor. After changing the measuring point the gas composition was approved by the network owner.

7. CONCLUSIONS FROM DEMONSTRATION AND TESTS

The following main conclusions can be drawn based on the performed tests and demonstrations at the LRC Demonstration Plant:

- The rock mass has responded according to the expectations and the deformation level is generally lower than expected. This means of course also that the design assumptions have been confirmed with a margin.
- The behaviour of the cavern wall is as expected and the strain level is generally well below the design values. The temperature variation in the cavern during gas operation has, as expected, a large influence on the deformation pattern.
- The steel lining of the cavern is absolutely gas tight. Gas leak tests have proved that the leak monitoring system is capable of detecting a small gas leak from the cavern in a very short time.
- The three demonstration gas cycles demonstrated that the Demo Plant can fulfill the requirements regarding storage capacity and deliverability.
- It has been shown that the gas cooling/heating circulation system can control the temperature in the cavern, thereby increasing the storage deliverability and the possible number of annual turnovers.
- The environment of the project put many constraints on the performance of the gas tests. Restrictions put up by the network owner priorities prevented demonstration of the full capacity of the plant except for shorter time periods.