FLOW TEST OF A PERFORATED DEEP DUAL CASED WELL

Jan-Erik Rosberg

Engineering Geology, Lund University
P.O. Box 118
Lund, S-22100, Sweden
e-mail: Jan-Erik.Rosberg@tg.lth.se

ABSTRACT

An example of well testing when there are limitations in available fluid storage capacity reducing the testing time. Flow tests were carried out in a deep geothermal well in the southernmost province of Sweden. The well is 3701.8 m deep with production zones located in a low temperature reservoir consisting of Cretaceous sandstone. The potential production zones were cased with dual casing, which was cemented into position. Perforation was used to reopen the production zones between 1425 m and 1950 m, followed by airlifting to clean out the debris. The production zones were flow tested separately as well as combined. The hydraulic parameters are evaluated applying groundwater well tests equations. One problem during the flow tests was the limited storage capacity at the drillsite, which affected the testing time. Because of this limitation no hydraulic boundaries were reached during the flow tests. Injection took place after running out of storage capacity and the water was injected back into the sandstone formation. To treat the geothermal water in the municipal wastewater plant was a too expensive option, because of the high salinity of the water. Direct disposal was prohibited due environmental restrictions.

Keywords: Well testing, perforation, dual casing, airlifting, storage capacity.

INTRODUCTION

The city of Lund, located in Scania the southernmost province of Sweden, has a long history when studying the use of geothermal energy in Sweden. Here is the only geothermal plant, which has been in operation since 1984. The plant is a result of the research efforts by the Department of Engineering Geology, Lund Institute of Technology, carried out in cooperation with the local energy company. The plant consists of 4 production wells and 5 injection wells, which are 500-700 m deep. The geothermal reservoir is a low temperature reservoir, which is located in the Campanian Sandstone from Late Cretaceous. The plant is extracting 500-600 l/s of approximately 20°C water and heat pumps are used to increase the temperature before it enters the district heating network. The temperature is around 4-5°C when it is injected back into the reservoir. The Lund geothermal heat pump plant stands for 30-35 % of the distributed energy in the district heating system.

In the beginning of 2000 the Department of Engineering Geology initiated a project to investigate the tectonised basement within the Tornquist deformation zone close to the city of Lund. The aim was to extract hot water from deep-seated fractures in the basement created by tectonic activities in the deformation zone. An estimation was done that temperatures around 110-125°C could be at hand at a depth around 3500 m. This was based one the results from years of studying of the temperature gradient in the region.

The local energy company, Lunds Energji AB, found the concept interesting with a possibility to cover more of the energy demand by using geothermal resources. The higher temperatures also make it possible to direct heat exchange the energy into the district heating system, without using heat pumps.

Reflection seismic was used to investigate the deformation zone and to select the best location of the exploration well. Towed array reflection seismic was used on the roads which made it possible to cover large areas in a time effective way compared to conventional seismic surveys. Some of the seismic survey lines were complemented with conventional reflection seismic to get a deeper penetration. In all cases a vibro energy source was used.

Comparing the result from the seismic surveys with data from other geophysical measurements like magnetometry and gravity and the distribution of the existing district heating system a drill site was located. The site for the exploration well is located in
Stora Råby south-east of the city of Lund. The name of the well is DGE#1, which stands for Deep Geothermal Energy and well number one.

The drilling operation started in October 2002 and became the second deepest drilling project in Sweden, with a depth of 3701.8 m. The aim with the drilling project was as mentioned above to investigate the possibility to extract hot water from deep seated fractures in the basement. Another task was to investigate different drilling methods and their applicability in basement rock drilling.

The fall-back of the project was the different types of sandstones that can be found in the sedimentary sequence, around 1950 m thick, resting on the basement.

Flow tests and injection tests were carried out both in the crystalline basement and in the sandstones in the sedimentary deposits. A decision to drill a second well was made after evaluating the results from the flow- and injection tests of the sedimentary deposits.

The second well, DGE#2, was drilled during the summer 2004 to a total depth of 1927 m. The well completion consists of around 138 m wire-wrapped screen located in the sandstone formation. This well was thought to be the production well and the first well DGE#1 should be the injection well.

DGE#2 was flow tested and stimulated during the autumn 2004. The flow rate was too low to fulfill the energy demands of the local energy company, why the project was abandoned. The flow test and the stimulation of DGE#2 will not be presented in this paper.

### DRILLING OF DGE#1

The drilling operation started in October 2002 and was finished in March 2003. The total depth of the hole is 3701.8 m and it is cased down to 3200 m. The drilling was performed in both sedimentary rock and in the basement. In this paper the drilling operation is just described briefly to give an understanding of the history of DGE#1. All the depth is measured from kelly bushing, which was located 7.1 m above the ground level.

Rotary drilling with clay based or polymer based mud was used from surface down to 2119 m. Thereafter air drilling with air or aerated water was used as drilling method down to total depth, except for two sections. The section between 2878 m and 2972 m was drilled as percussion drilling with a 12 ¼" percussion bit. Another section between 3666 m and 3675 m was shortly tested with a 8 ½" bit on a Wassara Mud Hammer.

The sizes and the installation depths of the casings in DGE#1 has been summarised in table 1.

<table>
<thead>
<tr>
<th>Casing size</th>
<th>Top of the casing</th>
<th>Depth of the casing shoe</th>
</tr>
</thead>
<tbody>
<tr>
<td>30&quot;</td>
<td>0 m</td>
<td>155 m</td>
</tr>
<tr>
<td>20&quot;</td>
<td>0 m</td>
<td>1005 m</td>
</tr>
<tr>
<td>13 ⅝&quot;</td>
<td>0 m</td>
<td>1975 m</td>
</tr>
<tr>
<td>9 ⅝&quot;</td>
<td>900 m</td>
<td>3198 m*</td>
</tr>
<tr>
<td>Open hole size</td>
<td>Starts</td>
<td>Ends</td>
</tr>
<tr>
<td>8 ½&quot;</td>
<td>3198 m</td>
<td>3701.8 m*</td>
</tr>
</tbody>
</table>

*The casing shoe is installed at 3310 m, but due to the whipstock installation the cased section ends at 3198 m.

The top of the 9 ⅝" casing was first installed at 1880 m, but due to collapse of the 13 ⅝" casing at 1030 m a 9 ⅛" tie-back casing was installed to 900 m. The casing collapse is the reason why the potential production zones in the sedimentary rock were cased with a dual casing.

At the depth of 3365 m the driller failed to clean the hole when the penetration rate got very high for a longer time. 38 m of the drilling assembly was left in the hole. An open-hole whipstock was first installed but due to a bad cementing job it started to move and was abandoned. Instead a casing whipstock was installed between 3191 m and 3198 m, which made it possible to reach the final depth.

### GEOLOGY

The investigated area is a part of the Tornquist zone (also called Tornquist-Teisseyre zone), which is one of the major geological structures in northern Europe. The Tornquist zone is a major tectonic deformation zone stretching from the North Sea into Poland continuing south-east to the Black Sea (Lindström et al., 1991). The Tornquist zone is also a part of the Fennoscandian border zone, which is the border zone between the Baltic shield and the Danish-Polish embayment.

This border zone is of great importance when studying the geology of Scania, the southernmost part of Sweden. The north-east part of the zone, the Baltic shield, consists of basement rocks and the south-west part of the zone, the Danish-Polish embayment, consists of sedimentary rocks resting on basement rocks. Along the zone there are a lot of block faults including the Scanian horst ridges, which stretch along this zone in a north-west to south-east trend.

The city of Lund is situated close to one of the Scanian horst ridges, the Romele horst ridge. The faulting along the Romele horst ridge is both normal...
and reverse faulting. The vertical displacement in this area can be as much as 1500-2000 m.

**Stratigraphy for well DGE#1**

DGE#1 is located within the fault zone running along the Romele horst ridge. The wellsite is in Stora Råby south-east of Lund. The total depth of the well is 3701.8 m and about 1900 m was drilled in sedimentary rocks and the last 1756 m in basement rocks. A simplified stratigraphy for DGE#1 is presented in Table 2 for more detail information see (Erlström and Sivhed, 2003).

<table>
<thead>
<tr>
<th>Depth (mKb)</th>
<th>Geological formation</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-47 m</td>
<td>Quaternary</td>
<td>Till, sand</td>
<td></td>
</tr>
<tr>
<td>47-211 m</td>
<td>Late Cretaceous</td>
<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td>211-223 m</td>
<td>Late Cretaceous</td>
<td>Mixed lithologies</td>
<td>Fault and fracture zone, unconformity</td>
</tr>
<tr>
<td>223-1058 m</td>
<td>Early Jurassic</td>
<td>Claystone, siltstone, mudstone</td>
<td></td>
</tr>
<tr>
<td>1058-1425 m</td>
<td>Late Triassic</td>
<td>Mudstone, claystone, sandstone</td>
<td></td>
</tr>
<tr>
<td>1425-1531 m</td>
<td>Late Cretaceous</td>
<td>Claystone, sandstone</td>
<td>Repeated stratigraphy</td>
</tr>
<tr>
<td>1531-1946 m</td>
<td>Early Cretaceous</td>
<td>Claystone, sandstone</td>
<td>Repeated stratigraphy</td>
</tr>
<tr>
<td>1946-1985 m</td>
<td>Precambrian</td>
<td>Gneiss</td>
<td></td>
</tr>
<tr>
<td>1985-2050 m</td>
<td>Precambrian Early Cretaceous</td>
<td>Claystone, sandstone, gneiss</td>
<td>Faulted zone, mixed sedimentary and basement rocks</td>
</tr>
<tr>
<td>2050-3154 m</td>
<td>Precambrian</td>
<td>Gneiss, dolerite, metabasite</td>
<td></td>
</tr>
<tr>
<td>3154-3520 m</td>
<td>Precambrian</td>
<td>Granite, metabasite</td>
<td></td>
</tr>
<tr>
<td>3520-3701.8 m</td>
<td>Precambrian</td>
<td>Gneiss granite, metabasite</td>
<td></td>
</tr>
</tbody>
</table>

Different potential production zones were located by comparing the lithology with results from different electrical logs. Two of the potential production zones in the sedimentary rock section are described more detailed with respect to the lithology (Erlström and Sivhed, 2003).

The lowermost is the section between 1827 and 1853 m, consists of well sorted fine- and medium grained sandstone, hard and dolomite and silica cemented. There is also hard to very hard and poorly cemented sandstone. The sandstones belong to Valanginian/Ryazanian, which are subdivisions within Early Cretaceous.

The upper is the section between 1427 and 1530 m, which can be divided into four subsections. The first one between 1427 and 1463 m consist of silty clay/claystone, sandy claystone and soft-hard, carbonate cemented sandstone/siltstone. The second one between 1463 and 1477 m consists of fine- and coarse-grained, poorly sorted, soft to hard and carbonate cemented sandstone. The section between 1477 and 1490 m is similar to the lithology between 1427 and 1463 m. 1490-1530 m consist of fine- to coarse-grained, poorly sorted, soft to hard and carbonate cemented sandstone. Except a section between 1501 and 1504 m, this section’s lithology is similar to the lithology between 1427 and 1463 m. The lithologies described above belong to Santonian or Turonian which are subdivisions within Late Cretaceous.

**TEST SET UP USED DURING THE TESTING OF DGE#1**

The well DGE#1 was flow tested during two different periods. The first was in March 2003 and the second was between September and December 2003. The first test was carried out to evaluate the hydraulic properties of the basement rock formation and the second was to evaluate the hydraulic properties in the basement rock and in the sedimentary rock formation. The test set up for those two attempts was in general the same.

The test set up for flow tests was designed for airlift operations. The test set up consisted of air compressors, a booster unit, a system to measure the flow rate and storage pits. The total storage capacity at the drill site was around 3000 m³.

The system to measure the flow rate included one muffler unit and two tanks of 86 m³ each. The muffler worked as a separator during the airlifting. The air went out through the top of the muffler and coarse particles settled in the muffler and the water flowed to the first tank. The first tank worked as a settling tank and was connected to the muffler. Two pipes were used to connect the settling tank with the second tank. The second tank, the weir tank, was the tank where the flow rate was measured. The weir tank consisted of a Thomson weir, a still well and baffles.

The still well was used to get undisturbed measurements of the head above the V-notch. The
aim with the installation of baffles was to get an almost laminar flow through the Thomson weir. A drawing of the test setup is presented in figure 1.

![Figure 1. The test setup used during the airlift operations.](image)

The flow rate through a triangular weir can be calculated by using Equation 1:

\[ Q = C_e \cdot \frac{8}{15} \cdot \sqrt{2} \cdot g \cdot \tan \left( \frac{\alpha}{2} \right) \cdot h^{5/2} \]  
(Eq.1)

where
- \( Q \): flow rate (m³/s)
- \( C_e \): weir coefficient (depending on the weir angle)
- \( g \): gravitational acceleration (m/s²)
- \( \alpha \): weir angle
- \( h \): head above the V-notch (m)

If the weir angle is 90° the weir is called a Thomson weir and then the weir coefficient \( C_e = 0.578 \). The head shall be measured upstream of the weir at a distance of at least 3-4 \( h_{\text{max}} \) (French, 1994).

High resolution downhole sensors were installed in the well to measure the pressure and the temperature during the flow tests. The sampling rate was every 15 second.

Different injections were made using mudpumps. The water was transferred from the pits to the mudpumps and from here through the mudline into the well. The water was injected directly through the well head or through a packer installed at a certain level in the well.

The injection rate was calculated from pump strokes and the injection pressure was measured at the wellhead.

**WELL TESTING PARAMETERS**

Equations developed for groundwater hydraulic have been applied to evaluate the well test data. The temperature of the pumped fluid is higher than ordinary groundwater, but as a geothermal fluid defined as a low temperature fluid. Earlier geothermal projects in Sweden have used the same type of application of groundwater equations for evaluation of well test data (Follin, 1984) and (Gustafson and Andersson, 1979).

Estimation of the transmissivity and the skin factor from the drawdown data has been done by using a modification of Cooper-Jacob solution (Cooper and Jacob, 1946) see equation 2.

\[ s = \frac{P}{\rho \cdot g} = 0.183 \cdot \frac{Q}{T} \cdot \left( \log \left( \frac{135 \cdot T \cdot t}{r_w^2 \cdot S} \right) + \frac{\xi}{1.15} \right) \]  
(Eq.2)

where
- \( s \): drawdown (m)
- \( P \): drawdown (Pa)
- \( \rho \): density (kg/m³)
- \( g \): acceleration of gravity (m/s²)
- \( Q \): flow rate (m³/s)
- \( T \): transmissivity (m²/s)
- \( t \): time (min)
- \( r_w \): radius of the well (m)
- \( S \): storage coefficient
- \( \xi \): skin factor

Estimation of the transmissivity from the recovery data has been done by using Theis recovery solution (Theis, 1935) see equation 3.

\[ s' = \frac{Q}{4 \cdot \pi \cdot T} \ln \left( \frac{t}{t'} \right) = 0.183 \cdot \frac{Q}{T} \log \left( \frac{t}{t'} \right) \]  
(Eq.3)

where
- \( s' \): residual drawdown (m)
- \( Q \): flow rate (m³/s)
- \( T \): transmissivity (m²/s)
- \( t \): time since pumping begun (s)
- \( t' \): time since pumping stopped (s)

The transmissivity is the product of the hydraulic conductivity (\( K \)) and the saturated thickness of the aquifer (\( z \)) see equation 4.

\[ T = \int K \cdot dz \]  
(Eq.4)

where
- \( K \): hydraulic conductivity (m/s)
- \( z \): saturated thickness (m)

The equations presented above for drawdown data and recovery data can be used for data acquired during injection tests. The drawdown is substituted with injection pressure and the flow rate with injection rate. When the injection stops the fall off of the injection pressure can be recorded and substituting the residual drawdown with the fall off of the injection pressure equation 3 can be used.

There are several equations and rule of thumbs to estimate the storage coefficient for a confined aquifer. In this paper Hall’s estimation (Hall, 1953), see equation 5, has been used to estimate the storage coefficient.

\[ S = \Phi \cdot \left( c_w + c_f \right) \cdot h \]  
(Eq.5)

where
S = storage coefficient  \( \Phi \) = porosity (-)
\( c_f \) = formation pore-volume compressibility (m\(^{-1}\))
\( c_w \) = fluid compressibility (m\(^{-1}\))
h = formation thickness (m)

**RESULTS FROM THE TESTING OF THE CRYSTALLINE BASEMENT**

The first flow test in the crystalline basement was made in March 2003, directly after the well was completed. The water in the well was unloaded by using air. The airlift operation was conducted from two different depths and lasted from 2003-03-09 to 2003-03-14. During this period 19 airlifts were done and the airflow rate varied between 19.8 and 31.1 m\(^3\)/min (700-1100 cfm).

The first part of the airlift operation was made from the depth of about 3690 m in the open hole section. From this depth 13 airlifts were made during the period from 2003-03-09 to 2003-03-12. The second part of the airlift operation was made during the period 2003-03-12 to 2003-03-14 from the depth of 3100 m in the cased section. 6 airlifts were made during this period. No consistent flow rate was reached during the different airlifts, instead slugs of aerated water were lifted out of the well.

The average flow rate was calculated as the produced volume of water during each airlift divided by the time between the actual airlift and the previous airlift. The most common time between two airlifts was around 5 hours and 30 minutes. The average flow rate was around 1.8 l/s. The density was around 1200 kg/m\(^3\).

One short injection test of the open hole basement section was made 2003-03-15, the test only lasted for 70 minutes. The average injection rate was around 2.2 l/s and the needed injection pressure was approximately 120 bar.

After completion of the test in March the well was shut in until October 2003. In the meantime the well had 6 months to recover. The first effort that was made in October was a bottom hole temperature measurement. A maximum temperature of 85.1°C was recorded.

To improve the inflow to the well the open hole was treated with acid (HCl) to remove potential precipitated carbonates in the rock mass fissures. The acid treatment didn’t improve the inflow to the well, which was verified by airlifting. No consistent flow was reached during the airlifting, only slugs of water were lifted out of the well.

Two injection and fall off tests were carried out during three days time. The recorded injection/fall off pressure and the injection rate can be seen in figure 2.

The perturbations in the injection rate and the corresponding pressure drops are due to that the mudpump went down. The average injection rate was 2.75 l/s with an increasing injection pressure. During the second injection test the injection pressure almost reached 200 bar before the test was shut down. The shut down was a forced action as the maximum pressure rating of the mudpump was 205 bar.

Due to the perturbations during the injection, only the data from the fall off have been used to get a rough estimation of the transmissivity of the basement. The fall off is evaluated with Theis recovery method and the pressure is converted to meters of water column. The estimation of the transmissivity from the first test is 4.7·10\(^{-7}\) m\(^2\)/s and 5.2·10\(^{-7}\) m\(^2\)/s from the second fall off test. The difference between the two values of the transmissivity is approximately 10%.

Using the average transmissivity of 5.0·10\(^{-7}\) m\(^2\)/s and a thickness of the open hole of 504 m the hydraulic conductivity can be estimated to 9.9·10\(^{-9}\) m/s. This is the minimum value of the hydraulic conductivity, because of the assumption that the whole thickness of the open hole is contributing to the flow. More likely is that only parts of the open hole are contributing, if that is the case the value of the hydraulic conductivity will be larger. The low values of the transmissivity and hydraulic conductivity can be compared with a deep well in Germany with similar conditions as DGE#1. The well is 4 km deep located in crystalline basement, with an open section of 150 m (Stober and Bucher, 2005). The transmissivity is 6.1·10\(^{-6}\) m\(^2\)/s and the hydraulic conductivity is 4.07·10\(^{-8}\) m/s. Showing for example a 12 times greater transmissivity than the one estimated from DGE#1.

An attempt to improve the inflow to the well was to perforate the cased section of the basement between 3125 m and 3135 m. Potential contribution to the inflow from this section was evaluated from a PLT (Production Logging Tool) log carried out in March 2003. The log shows peaks on the temperature curve over this section and some flow activity is also at hand. The section was perforated underbalanced,
with 180 charges. Airlifting was used to clean the perforations and to lift out the debris. There was no evident improvement in the flow rate and no consistent flow was reached.

Due to the result from the different airlift operations and from the different injection tests, the crystalline basement was abandoned as being a non-potential production or injection zone. The efforts were instead focussed on water production from the sandstones in the upper part of the well.

RESULTS FROM THE TESTING OF THE LATE AND EARLY CRETACEOUS SANDSTONE.

To establish contact with the potential production zones in the sedimentary section perforation of the casings was done. The charges were optimized to penetrate the cemented dual casing and to make flow pipes into the formation. The first perforation runs were done underbalanced, which force the fluid into the well. The last perforation runs were perforated balanced. Directly after each perforation run the debris were cleaned out using airlifting.

The different intervals that were perforated are presented in table 3.

Table 3. The perforated intervals and number of shoots per foot (SPF) used during the specific perforation run.

<table>
<thead>
<tr>
<th>Perforated intervals</th>
<th>SPF</th>
<th>Reperforation of</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895-1905 m</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1827-1840 m</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1472-1525 m</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1827-1853 m</td>
<td>6</td>
<td>1827-1840 m</td>
</tr>
<tr>
<td>1685-1717 m</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1427-1472 m</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1427-1530 m</td>
<td>6</td>
<td>1427-1525 m</td>
</tr>
</tbody>
</table>

The intervals are from top presented in chronological order in table 3 as they were perforated. The minimum order of number of shoots that were used was 6 SPF (shoot per foot). Two intervals 1827-1840 m and 1427-1525 m were perforated with 12 SPF, because these intervals were reperforated. The chose to reperforate these intervals was to reduce the flow resistance through the perforations.

Every interval that was perforated was flow tested separately, but the well was also flow tested with all the perforated intervals in cooperation.

The potential production zones were the interval between 1827 and 1853 m and between 1427 and 1530 m. The most productive section of the latter one was the lower part between 1472 and 1525 m. These intervals were interpreted by well testing and temperature logging carried out during production tests.

The well test was performed with airlifting followed by a recovery period. The transmissivity has been estimated both from drawdown data during production and from pressure build up data from the recovery.

Data from the flow test of the interval 1427-1530 m will be presented as an example of the methodology which is used to evaluate the flow tests when airlifting. A retrievable bridge plug (a type of packer) was set at 1610 m to make it possible to flow test only the Late Cretaceous sandstone between 1427 and 1530 m. The downhole pressure and temperature gauges were installed at 1356 m and the airsub was placed at 884 m. Three compressors and one booster were used. The flow test lasted for almost 5 hours and was followed by a 13 hours 30 minutes recovery period.

The transmissivity is estimated to $1.1 \times 10^{-4}$ m$^2$/s from the drawdown data from the flow test and an average flow rate of 55.7 l/s is used, see figure 3.

The transmissivity is estimated to $5.0 \times 10^{-5}$ m$^2$/s from the recovery data, see figure 4.
The transmissivity estimated from the flow test is 2.2 times greater than the one estimated from the recovery.

The transmissivity values for the potential production zones and from the flow test of all perforated intervals involved can be seen in table 4.

Table 4. The transmissivity values estimated from drawdown data and from recovery data.

<table>
<thead>
<tr>
<th>Section</th>
<th>Transmissivity (m²/s)</th>
<th>Transmissivity (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Airlifting</td>
<td>Recovery</td>
</tr>
<tr>
<td>1827-1840 m</td>
<td>1.6·10⁻⁴</td>
<td>9.5·10⁻⁸</td>
</tr>
<tr>
<td>1472-1525 m</td>
<td>9.6·10⁻⁵</td>
<td>3.4·10⁻⁵</td>
</tr>
<tr>
<td>1472-1525 m</td>
<td>1.4·10⁻⁴</td>
<td>5.3·10⁻⁵</td>
</tr>
<tr>
<td>1427-1530 m</td>
<td>1.1·10⁻⁴</td>
<td>5.0·10⁻⁵</td>
</tr>
<tr>
<td>1827-1853 m</td>
<td>2.5·10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>1427-1530 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1827-1853 m</td>
<td>2.2·10⁻⁴</td>
<td>1.0·10⁻⁶</td>
</tr>
</tbody>
</table>

Worth noting in table 4 is that the transmissivity estimated from the drawdown data is from 1.7 to 2.8 times greater than the transmissivity estimated from the recovery data. The transmissivity values should be almost the same (Kruseman and de Ridder, 2000).

The values of the hydraulic conductivities for each potential production zone and for all the zones combined can be seen in table 5.

Table 5. Hydraulic conductivity estimated from drawdown data and recovery data.

<table>
<thead>
<tr>
<th>Section</th>
<th>Hydraulic conductivity (m/s)</th>
<th>Hydraulic conductivity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Airlifting</td>
<td>Recovery</td>
</tr>
<tr>
<td>1827-1840 m</td>
<td>1.2·10⁻⁵</td>
<td>7.3·10⁻⁹</td>
</tr>
<tr>
<td>1472-1525 m</td>
<td>1.8·10⁻⁶</td>
<td>6.4·10⁻⁷</td>
</tr>
<tr>
<td>1472-1525 m</td>
<td>2.6·10⁻⁶</td>
<td>1.0·10⁻⁶</td>
</tr>
<tr>
<td>1427-1530 m</td>
<td>1.1·10⁻⁶</td>
<td>4.9·10⁻⁷</td>
</tr>
<tr>
<td>1827-1853 m</td>
<td>2.3·10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>1427-1530 m</td>
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<td></td>
</tr>
<tr>
<td>1827-1853 m</td>
<td>2.0·10⁻⁶</td>
<td>9.0·10⁻⁷</td>
</tr>
</tbody>
</table>

In table 4 and 5 it can be seen that the zone between 1827 and 1840 m has the highest transmissivity and hydraulic conductivity. The transmissivity values calculated using data from airlifting when testing the Late Cretaceous sandstone between 1472 and 1525 m are not equal. The difference is a factor of 1.46. This is probably due to that the first flow period was directly after the perforation and the perforations were cleaned during this flow test. The second flow test started when the well was almost free from the debris from the perforation and therefore gave a higher transmissivity value.

A representative transmissivity value for the whole well is around 2.4·10⁻⁴ m²/s and 2.2·10⁻⁷ m²/s being the average values of the transmissivity and the hydraulic conductivity. The skin factor was around 1. The storage coefficient estimated using Hall’s formula is 2.4·10⁻⁴. The density of the fluid is around 1140 kg/m³ with salinity around 14 %. The water temperature was around 31°C measured during the flow test. This is a disturbed measurement of the temperature because the fluid was a mix of cold injected water and formation water.

TEST LIMITATIONS DUE TO STORAGE CAPACITY AND ENVIRONMENTAL RESTRICTIONS

A major problem during the flow tests was the available storage capacity at the drillsite. The available storage volume directly controlled the length of testing. When the pits were full the pumping was terminated and to be able to carry out further flow tests the fluid had to be injected or transferred elsewhere. The fluid was injected back into the formation.

This means that the flow tests were only short term tests. The longest lasted for 12.5 hours, but the most common time was around 5 hours. To say something about the aquifer and about potential production is hard using these data. The duration of the tests was too short, which means that the long term effects such as boundary conditions could not be evaluated. The boundary effects must be known to say if the aquifer is suitable for production and injection. A major reason is for example spatial limitations of the aquifer.

Another problem with a limited storage capacity was to all the time keep space enough for the flow test. If such conditions were accomplished less flow time than required was at hand to clean the perforations before the next flow test began. This can be maybe the explanation why the transmissivity values for the interval 1472-1525 m, see table 4 differs with 46%.

It can also be discussed if mechanical cleaned and settled mud and formation water that has been oxidised or otherwise altered should be injected back into the formation. But during the circumstances the way it was done was the only solution at that time. The coarse particles in the produced formation water were of course allowed to settle before injection took place and top suction was always used when
transferring the water from the storage pits. However no decrease in the injectivity has been confirmed after those injections.

There was only one option to avoid injection of the fluid into the perforated zones in DGE#1. It was an old geothermal well in Flackarp located around 5 km from the drill site. Transferring of the water to this well was done with trucks, which was not an economical or environmental friendly way to solve the problem. A typical truck that was used could load 30 m$^3$ of water and a trip with unloading and loading took at least 1 hour. This is the same as 8.3 l/s of the produced fluid can be transferred with one truck instead of being stored in the pits.

Other existing wells in the area are wells used for drinking water. The produced water was saline, which means that it can’t be mixed with the groundwater used for drinking water or the surface water. To protect the drinking water the produced saline water had to be injected at great depths.

The water was also too saline to be transferred in the sewage system and to be treated at the wastewater treatment plant in the city. The wastewater-treatment plant isn’t designed for water with high salinity and the treated water’s outlet is a freshwater recipient.

The decision to drill a second well was dependent on the results from the short term flow tests carried out. This means to drill a second well before the flow tests were carried was never an option.

To make longer flow tests with the available storage capacity at the drill site is of course to use a lower pumping rate. However the Energy Company was only interested in which maximum consistent flow rate being available.

**THE CONTINUATION OF THE PROJECT**

The results from the flow test were enough for the energy company’s board to make a decision to drill a second well. This decision was only made from the result from the short term tests, without information about hydraulic boundaries. The second well DGE#2 was drilled during the summer 2004 and flow tested and stimulated during the autumn 2004. The flow rate was too low to fulfill the energy demands of the local energy company, why the project was abandoned.

**ACKNOWLEDGEMENT**

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**REFERENCES**


Theis, C.V. (1935), "The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage", *Transactions, American Geophysical Union*, Vol 16, 519-524.