Underground storage of Diesel fuel oil in Salt Caverns
Dirk-jan Mollema, 2011

Diesel fuel oil being added to a salt cavern
Introduction

About AkzoNobel

AkzoNobel is one of the biggest producers of chemical products worldwide. With the three divisions decorative paints, performance coatings and specialty chemicals the company has an annual revenue of 13.9 billion euro (2009).

The history of the company goes back to 1777, however the company as it is now was created as a fusion between AKZO (which was a fusion between the ‘Algemene Kunstzijde Unie’ and the ‘Koninklijke Zout Organon’) and the Swedish company Nobel in 1994.

Worldwide AkzoNobel has about 55.000 employees in 80 countries, with 50 locations and 5000 employees in The Netherlands. AkzoNobel is a Global Fortune 500 company.

AkzoNobel Hengelo

In Holland there are 2 different places where salt mining takes place by AkzoNobel. In the region Twente (Hengelo, OV) and in the region Delftziel (Groningen). The plant in Hengelo is part of the AkzoNobel Industrial Chemicals division (sub business unit of the ‘Specialty Chemicals’ division) and consists of 3 plants:

- Salt production plant (Salt bulk)
- Salt Specialties
- Salinco energy plant

The plant in Hengelo produces about 2.5 million tons of salt per year. This salt is used for many applications, for example as kitchen salt, industry salt, salt for de-icing, but also for other special products such as salt stones for animals.

Figure 1 - Production site hengelo
**Mining Technology Department**

The Mining Technology Department (MTD) is located in Hengelo and is responsible for the mining related decisions and research for the 2 plants in the Netherlands, as well as the plant in Mariager in Denmark. Due to new projects within AkzoNobel the department has grown in the past years to a team of about 12 persons. The team is a mix of both mining and geology specialists, with different backgrounds. Current projects include the storage of oil products in salt caverns, storage of waste materials to stabilize the older caverns and the development of a new area for future production.

Besides the research and working on new projects, the MTD is also responsible for the coordination of the production department, and makes decisions about which caverns should be opened or closed and where new caverns should be placed to keep the production level constant. Whenever problems arise in the field with caverns not producing as they are supposed to, the MTD provides solutions.

**History salt production Twente**

In 1886 the salt deposit in Twente was first discovered when locals constructed a well for drinking water, which produced salt water instead of fresh water. In 1909 some sample wells were drilled in Winterswijk, where the Zechstein Salt was found and in Boekelo, where the Rötsalt was discovered.

After the First World War, in 1918, the first salt production started in Boekelo by the Royal Dutch Salt Industry (Koninklijke Nederlandse Zoutindustrie, KNZ). They produced salt on a depth of 325 meter. In 1933 the winning area moved to Hengelo, a few years later the production plant followed also. The advantage of this location is the direct connection with the Twente channel. The current winning area north of the A35 motorway will likely be abandoned within a few years. Currently there are new caverns being created south of the motorway, on the future industrial area ‘Usseler-Es’. Also AkzoNobel is in the progress of moving their activities further south towards Haaksbergen.

In the years the winning method of salt changed. For a long time the salt caverns existed of series of 3 wells. Since 2006 a different winning method is used, only consisting of 1 well for both injection and production, the so-called Single Cavern Completion well (SCC). The principles of both types of wells will be explained later.
Geology of the area

The geology in Eastern Twente consists of the following layers: Solling Formation, Röt formation, the Muschelkalk formation, the Altena Group, the Niedersachsen Group and the North Sea Supergroup.

The salt is present in the Röt formation, where we distinguish layer A to D. Salt A is the thickest and the purest, in layers B, C and D there are also layers with rocks present. Only salt A and B are extracted completely, and a small part of salt C. This is to guarantee the stability of the cavern. There are no significant fault zones in the area, making it easier to create stable caverns.

In the northern part of The Netherlands salt is produced from salt domes. These are large structures, a few hundred meters in height but a relatively small diameter (20-30m). The Röt formation however is a flat layer, varying in thickness between 20 and 100 meter. This means that the caverns constructed are relatively flat compared to dome structures, especially if we take the safety thickness in account to prevent contact with the layers above. Caverns are only about 20 meters high (depending on the geographical location and the thickness of the salt layer there), but can have a diameter of about 130 meters.
Salt production – solution mining

Solution mining is the most common method used to extract salt. This method is also used in The Netherlands for salt production. The method consists of a simple process. Water is pumped down through a well. The rock salt dissolves in the water and becomes brine. The brine is pumped up and transported back to the production plant. The wells used by Akzo-Nobel are all vertical wells. For the transport of water and brine, a large network of pipes was built in the production area. The water comes partly from the ‘Twentekanaal’ channel and partly back from the production cycle. The brine is stored in tanks at the production plant, after which it is processed further to salt via a process of cleaning and drying.

Solution mining is also applied for various other materials. Common mined materials are potash, common salt and sulphur. Usually one uses a system of one or more injection wells and one production well. For ores not soluble in water chemical agents need to be added. It is also possible to heat the water to make the minerals more soluble. (Hartman, Introductory Mining Engineering, 2002; Hartman, SME Mining Handbook, 1992)

Cavern types

Series type wells

When the production of salt first started in the region, there was a system in use of 3 wells per cavern. In the beginning those functioned the same as a SCC well (see next point). After the cavern was large enough and the wells were connected, one well would be used to supply water (injection well), and another well for the production of brine (production well). These series of wells are not in use anymore nowadays, which is why this method won’t be explained any further.

![Figure 3 - Production process overview](image-url)
**Single Cavern Completion wells**

Since 2006 these series of wells are not in use anymore, but new caverns get created with so called ‘Single Cavern Completion’ wells. These caverns are completely produced with only one well. This process has a few differences with the series type, but has the advantage that it is cheaper (less wells to be drilled), they are constructed faster and the production is higher.

A SSC well consists of 3 different tubings. The 9 ¾” casing is cemented in the ground. In this casing there are two pipes of 6 5/8” or 7” and 4 ½” diameter. In the annular spacing between the casing and the 6 5/8” tubing there is an oil blanket for protection of the casing and (more important) for controlled production and extension of the cavern.

The oil blanket prevents the water from leaching the roof of the cavern (since vertical development is not wanted in the initial stage where we want to make the cavern as wide as possible). The oil level is kept constant as the cavern diameter increases. However the total height of the blanket is usually only a few centimetres, a single cavern may contain 60,000 to 120,000 litres of oil.

Between the 6 5/8” tubing and the 4 ½” tubing flows the water supply, while in the 4 ½” tubing itself the brine flows back to the surface. The last tubing is positioned lower in the cavern than the other one, since brine has a higher density and is thus located lower in the cavern.
**Construction of a cavern**

The location of the salt cavern is decided based on a few criteria. The caverns are planned so that their maximum allowed diameter will leave a safe pillar between adjacent caverns of at least 40 meters. The depth and height of the different layers are known due to the seismic research which was done before the construction period.

Drilling of the wells is done with a mobile drilling unit. It takes about a month to create a well, including the time required to set up and remove the equipment from the site.

During the drilling the depth and location of the drill bit is measured. Looking at the cuttings from the drilling mud makes it possible to know in which layer the drill is. The mud is prepared with the right density material to prevent pressure differences and blowouts.

Because the target layers consist of a soluble rock type (halite), the mud may start to dissolve the rock, making the drill bit unstable. To prevent this, salt is added to the mud when the drill becomes close to the salt layers, so that the aqueous solution is already saturated, and no leaching will take place during the drilling operation.

When the first salt layer is reached, a report is made every 10 minutes of the progress of the drilling. This makes it possible to know in which sublayer the drill is and if there are any stone layers present.

The drilling is stopped when the drill reaches the bottom of salt A.

After the drilling the first casing (9 ¾”) is installed and cemented. It is located till one meter below the lowest stone bench. When the cement is hardened and the casing is cleaned the top of salt A is located with a Gamma-CCL measurement. After this the rest of the casings are installed together with a system which measures the height of the oil blanket used to control the growth of the cavern.
Measuring the volume of caverns

An important aspect during the development of a cavern is the size and shape of a cavern. Monitoring this ensures that the cavern stays within the safety boundaries and that the risk for subsidence is as low as possible. For storage operations, the shape of a cavern is also important. Storing oil in a cavern of which the roof is highly irregular shaped will result in a lot of the oil being trapped in the roof in the recovery stage.

The volume and shape of caverns is measured with echo measurements. The tool is descended through a well and while the tool turns the cavern volumes are measured.

For multiple wells, echo measurements are done from every well separately (because due to the non-ideal shape of the caverns it isn’t possible to see the whole cavern in full detail with a measurement from just one location).

Below is a picture of how the results of an echo measurement look. Note that this is of a dome structure and the caverns at AkzoNobel are actually more horizontal, therefor the depth is not varied but instead the echo tool also measures vertical lines (the picture in the middle below only shows horizontal lines).

Figure 6 - Overview of echo-tool (From SME Mining engineering handbook)
Another way to measure the volume of a cavern is by using the production values. It is known how much m³ brine there is produced per cavern, and also what the density of that brine was, so from the density and the production, one can calculate how much rock salt has in theory been removed. One of the problems at AkzoNobel is that the echo measurements report a different value from the value calculated by looking at production. Sometimes these values differ in as much as 30%. In order to get more insight in this difference, a new method was used for calculating the volume during the internship.

From the echo data of different wells, the 3D models were exported to a modelling program (Surpac) and combined to one maximum volume from the echo measurements. In this volume the old echo logs are also included, to also include the volume which has been filled on the bottom of the cavern by insoluble parts of the salt.

![3D model of a cavern](image)

Calculating the volume for this model resulted in the following values:

<table>
<thead>
<tr>
<th>Method</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production data</td>
<td>Approximately 280000 m³</td>
</tr>
<tr>
<td>3D model (latest echologs only)</td>
<td>221596 m³</td>
</tr>
<tr>
<td>3D model (combined echologs)</td>
<td>236159 m³</td>
</tr>
</tbody>
</table>

Including the old echo logs does bring the 2 values closer together, however a difference in the different values remains.
Internship focus, project ‘Clovis’

Introduction
In 2012, AkzoNobel wants to have 3 caverns ready for the storage of gasoil (diesel) in salt caverns. This project is being realized together with the North Sea Group. The goal is to create a long-term strategic storage in the underground caverns.

For this project several caverns were selected, with a capacity of minimal 150,000 m³. The first caverns are located at the industrial terrain ‘De Marssteden’, in Enschede. Below is a picture of the storage location. The blue circle indicates where the North Sea Group is located and thus the diesel is stored before it is transferred to the storage area (the red circle). The green circle indicates the current working field of AkzoNobel and the location where the caverns are located. The red circle is the location of ‘De Marssteden’, where the first caverns are located.

Underground storage
Underground storage of products in salt caverns is not new. In the USA, more than 1200 salt caverns are used for storage, containing about 70 million m³ of hydrocarbons. Besides diesel oil, other products can be stored underground, including LPG, Crude oil, Natural Gas, Carbon Dioxide and wastes (permanent storage). (Hartman, SME Mining Handbook, 1992)

For the storage of oil in underground caverns at AkzoNobel, there are several problems to look at:

1. How to get the products underground?
   At the point of filling, the cavern is filled with brine. This brine needs to be replaced with diesel oil.
2. How to make sure the diesel stay in place?
   Nothing of the diesel should leak out to other formations, with the possibility of these formations containing groundwater.
3. How to get the diesel out of the cavern again when they are needed?
   It is important to get as much as possible of the diesel back in a short time.
4. How to make sure that the whole process is safe and won’t damage the environment?
   The process should be safe for both the operators and the environment. No diesel should leak during the filling/emptying operations.

In this report problem 1, 3 and 4 will be looked at. Problem 2 is a separate study and not the focus of this thesis.
Filling the caverns with Diesel fuel oil

At the moment the caverns get filled they are filled with saturated brine (the cavern had a few months of rest so that it has stabilized). To fill the cavern, this brine needs to be pushed out. Because of the difference in specific gravity, this process requires a high pressure.

Problem parameters:

<table>
<thead>
<tr>
<th>Density saturated brine</th>
<th>1201 kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density diesel</td>
<td>860 kg/m³</td>
</tr>
<tr>
<td>Cavern depth (assumed)</td>
<td>475 m</td>
</tr>
</tbody>
</table>

Gauge pressure on Diesel side:

\[ P = \rho \times g \times h = 860 \times 9.81 \times 475 \approx 40 \text{ bar} \]

Gauge pressure on Brine side:

\[ P = \rho \times g \times h = 1201 \times 9.81 \times 475 \approx 56 \text{ bar} \]

Pressure difference is approximately 17 bar \((16.8 \times 10^5 \text{ Pa})\) in the cavern.

To fill the caverns, a pressure of 37 bars is applied with an external pump at the wellhead. With the following parameters we can calculate the flow rate through the 5.5 inch casing used for the filling operation.

| P surface | 37 \times 10^5 \text{ Pa} |
| P bottom  | 56.9 \times 10^5 \text{ Pa} |
| Radius pipe | 0.0625 m |
| Viscosity diesel (min) | 0.00129 \text{ Pa*s} |
| Viscosity diesel (max) | 0.00516 \text{ Pa*s} |
| Friction factor pipe | 0.001 m |

With the formula for flow through a cylinder from ‘Bird, Stewart and Lightfoot, Transport Phenomena’, page 46 and the method of calculating the flow speed of turbulent flows with friction factors (from ‘Fysische transportverschijnselen’, page 223) we can calculate the flow speed \(Q\).

This gives the following result:

| Qmax (m³) | 0.048803156 | 175.6913632 | 0.0195 |
| Qmin (m³) | 0.045946653 | 165.4079495 | 0.022 |

So with these parameters, a flow speed of around 170 cubic meters per hour should be achievable.
Emptying the caverns

During the emptying of the caverns, saturated brine is injected back into the cavern. This is because it is unwanted that the cavern would be leached any further (stability + volume control). The brine is already heavier than the oil, so the diesel will flow out due to the gravity pressure.

We use the same problem parameters as in the previous paragraph.

Gauge pressure on Diesel side:

\[
P = \rho \cdot g \cdot h = 860 \cdot 9.81 \cdot 475 = \sim 40 \text{ bar}
\]

Pressure on Brine side (including the 2 bar pressure that is present in the brine system at the wellhead):

\[
P = \rho \cdot g \cdot h = 1201 \cdot 9.81 \cdot 475 + 2 = \sim 58 \text{ bar}
\]

Pressure difference is approximately 18 bar (17.8 * 10^5 Pa) in the cavern.

There is no extra pressure applied on this process.

\[
\begin{array}{|c|c|}
\hline
\text{P surface} & 1 \cdot 10^5 \text{Pa} \\
\hline
\text{P bottom} & 57.9 \cdot 10^5 \text{Pa} \\
\hline
\text{Radius pipe} & 0.0625 \text{ m} \\
\hline
\text{Viscosity diesel (min)} & 0.00129 \text{ Pa*s} \\
\hline
\text{Viscosity diesel (max)} & 0.00516 \text{ Pa*s} \\
\hline
\text{Friction factor pipe} & 0.001 \text{ m} \\
\hline
\end{array}
\]

Using the same formulas as in the previous section, we obtain the following flow results:

<table>
<thead>
<tr>
<th>Qmax (m³)</th>
<th>per sec</th>
<th>per hour</th>
<th>f (Fanning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.043509953</td>
<td>156.6358</td>
<td>0.0245</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Qmin (m³)</th>
<th>per sec</th>
<th>per hour</th>
<th>f (Fanning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.039799948</td>
<td>143.2798</td>
<td>0.0245</td>
<td></td>
</tr>
</tbody>
</table>

This means that emptying the caverns will be at a slower speed than filling them.

The worksheet containing the method for calculating the flow in the well can be found attached with the report.

Results discussion

The results seem to be in the logical range of a flow speed one would expect with the given pressures. What is noticeable is that the method used to calculate the flow speeds is less accurate for highly turbulent flows. The speed is more depending on the roughness of the pipes (which is hard to determine) than on the actual pressure. Reading the value in tables is also not a very accurate way of determining the speed. Actual results in the field will have to show if the flow speeds measured here can be achieved.
Ensuring the safety of the process

Health and safety are important values within AkzoNobel. For the project ‘Clovis’ several studies have been made concerning Hazards for both the environment and the operators.

Available information shows that from the accidents at underground storage facilities, about 20% happened during operation (Evans, 2008). This is why the HAZOP (Hazard and Operability) study was done. This study focuses on all the hazards involved with the daily operation of the system. It tackles problems from a simple open valve or leaking pipe to the complete destruction of a wellhead due to for example a truck driving over it, but also includes research into the possibilities of earthquakes at the site and the effect of roof collapse.

The problems have been studied and considered in the design of the wellheads. This is to make sure that many operational hazards are already covered by design and won’t require extra attention during the operation. Other points need to be made clear to the workers through documentation of the working progress. The so-called ‘working instructions’ (Dutch: Werkinstructies, shortened to WI from here on) are a detailed documentation of the several stages of the storage process.

The following working instructions have been created:

- Workflow of the overall process in which the steps are set out and their corresponding working instructions, as well which company has the responsibility for the certain step and if a working contract is required.
- WI to create a plan for changes in the flow of the brine from the fields during filling operations (extra flow) and emptying (less flow).
- WI for preparing the caverns before the filling/emptying operation
- WI for unlocking the caverns
- WI for closing the caverns after filling/emptying operation
- WI for locking the caverns
- WI for periodic inspection of the caverns
- Document with possible scenarios of changes in the operation, if for example trucks break down during the transport and the flow is lower for a longer period.
Conclusion
As with many things, solution mining looks easier than it is. Above the surface all you see is a small green shed and if you look inside you only see a wellhead.

Under the surface however, there is a big salt cavern with the size of a football stadium. This cavern produces 25 m³ brine per hour on average, 24 hours a day. Since the cavern is underground, one can’t easy look at the current state of the cavern. A rough image of the cavern shape and size can be obtained with echo measurements, but these are costly and take caverns out of production, and thus can only been done every few years. In the past 10 years the development of underground caverns has gone fast. It is likely that in the future more methods will be available to monitor and control the development and leaching speed of a cavern.

Once a cavern is grown to its maximum size, it can be used for underground storage. It has to meet a lot of requirements to qualify, including the right size, location, stability, shape, roof stability, etc.

Before a cavern can be used for storage a lot of work needs to be done on the environmental aspect in order to get the right permits.

However underground storage means that the resources stored are less accessible than above the ground, it also means that it is stored more secure and cheaper on long term.
**Recommendations**

For future research it would be good to look more into the size and the shape of caverns, such as what causes some caverns to develop in an ideal shape and others to grow in one specific direction (usually upwards on one side). It would also be good to look into optimizing the development process better so that the cavern develops with a flat, or even better, a cone shaped roof which makes the caverns better suitable for storage.

Another thing to look into is the big difference between estimated cavern size from produced cubic meters and the results of the echo measurements. There could also be looked into if phenomena like salt creep play a role in the size reduction on the echo results. The brine produced has to come from somewhere and the current values differ too much to be fully reliable.

As last it would be recommended to look into the recovery of the last bit of diesel fuel oil at the end of the storage period. Investigation should be done in which methods can be used for this (gases such as N² or even CO²) and with which volumes such an operation becomes profitable.
Bibliography
