HEATSTORE

DESIGN CONSIDERATIONS FOR HIGH TEMPERATURE STORAGE IN DUTCH AQUIFERS

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HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

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About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority - 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage, which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2019.04.05	Ver. 0 Final report

Table of Content

1 INTRODUCTION

This report present design considerations for high temperature aquifer storage (HT-ATES). It is part of work package 1.1 of the HEATSTORE project.

The design considerations are based on the experience with the HT-ATES project (> 30 °) of the last 25 years in the Netherlands for sedimentary unconsolidated aquifers. In addition to the project experience use as been made of (inter)national scientific research on clogging, scaling and water treatment.

The considerations are given for the key component of HT-ATES like wells, submersible pumps, heat exchangers and water treatment. Furthermore, there will be some more general considerations on corrosion, scaling and well clogging. Thermal efficiency, aquifer selection and well configuration for HT-ATES are outside the scope of this report and dealt with in the State of the art report on HT-ATES (IF Technology, 2018b).

2 EXPERIENCES

In the Netherlands more than 3,000 (licensed) ATES systems have been realized since 1985 (Bakema, 2016). In more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in nine projects.
The main characteristics of these heat storage projects are summarized in Table 1. With exception of the NIOO project all the mid-temperature (< 50 °C) are made in coarse sandy fresh water aquifers. These projects are made under the same design consideration as those for low (< 25 °C) temperature storage (NVOE, 2006). Except from low thermal efficiency no problems where recorded for the main components at these mid-temperature projects. Because of the low thermal efficiency it's advised not to use these coarse sandy aquifer (Permeability > 10 m/d) for future HT-UTES projects (IF Technology, 2018).
In this evaluation, the focus will be on the project NIOO, University Utrecht and Hooge Burgh, Zwammerdam, which are made in medium fine to fine sandy aquifers (mostly salt water). Also the GEOMEC-4P HT-ATES project in Brielle is part of the evaluation although it hasn't been realised so far.

Table 1 Realised HT-ATES

Project	Realization	Flow (m^3/h)	Storage temperature [°C]	Aquifer depth [m bs]	Formation material	Water quality
Office complex, Bunnik	1985	40 (?)	25-30	20 – 50	Coarse sand	Fresh water
Utrecht University	1991	100 charge, 50 discharge	90	220 - 260	Medium fine sand	Brackish water
Heuvelgalerie Shopping Mall Eindhoven	1992	100	32	25 -80	Coarse sand	Fresh water
Dolfinarium Harderwijk	1997	Charge 90, discharge 150	40	75- 125	Coarse sand	Fresh water
Hooge Burch Zwammerdam	1998	Charge 20, discharge 25	88	130 - 150	Medium fine sand	Salt water
2 MW, Haarlem	2002	50	45	90 -120	Coarse sand	Fresh water
NIOO, Wageningen	2011	40	45	225 - 295	Fine sands	Brackish/salt water
Van Duin, Steenbergen	2016	60	40	45-80	Coarse sand	fresh
Koppert-Cress Monster	2017	40	45			
GEOMEC-4P	Only design	450	78	80-190	Medium fine sand	salt

2.1 NIOO Wageningen 2011

The headquarters of the Netherlands Institute of Ecology of the Royal Netherlands Academy of Sciences (NIOO-KNAW) in Wageningen has a high sustainability level.

To enable a sustainable climate control system, two ATES systems have been installed. The first (shallow) groundwater system is a regular (low temperature) ATES system in a coarse sand aquifer. The second (deep) ATES system is a medium-temperature heat storage system in a low permeability aquifer. The medium temperature heat storage system of NIOO consists of a cold and a warm well with infiltration temperatures of respectively 26 ºC and 45 ºC.

Table 3 gives an overview of the key design and construction items. The wells have screens at the Oosterhout formation at a depth of 220 – 290 m bs (Figure 1). Stainless steel screens have been used because of the very fine sand layers. Due to the fact that temperatures remains under the 50 °C, the casing is made of standard PVC-pipe. A submersible pump was selected that is normally used in wells of low temperature aquifer energy storage systems.

The average permeability of the top 40 m is about 0.5 m/d. The lower 30 m has a permeability of less than 0.02 m/d; mainly caused by the high content of fines (< 63 µm) and clay (Table 2).

Table 2 Sieve analyses warm well NIOO

Parameter/depth (m bs)	225	240	256	266
sand > 125 µm (%)	30.7	31.8	27.4	15.8
sand 63 -125 µm (%)	66.3	64.1	69.0	74.5
M 63 Cijfer (µm)	96	95	93	92
Silt (<63 µm) (%)	3.0	4.1	3.6	9.7
Clay (<2 µm) (%)	0.5	0.5	0.5	3.6
permeability (m/d)	0.52	0.54	0.36	0.01

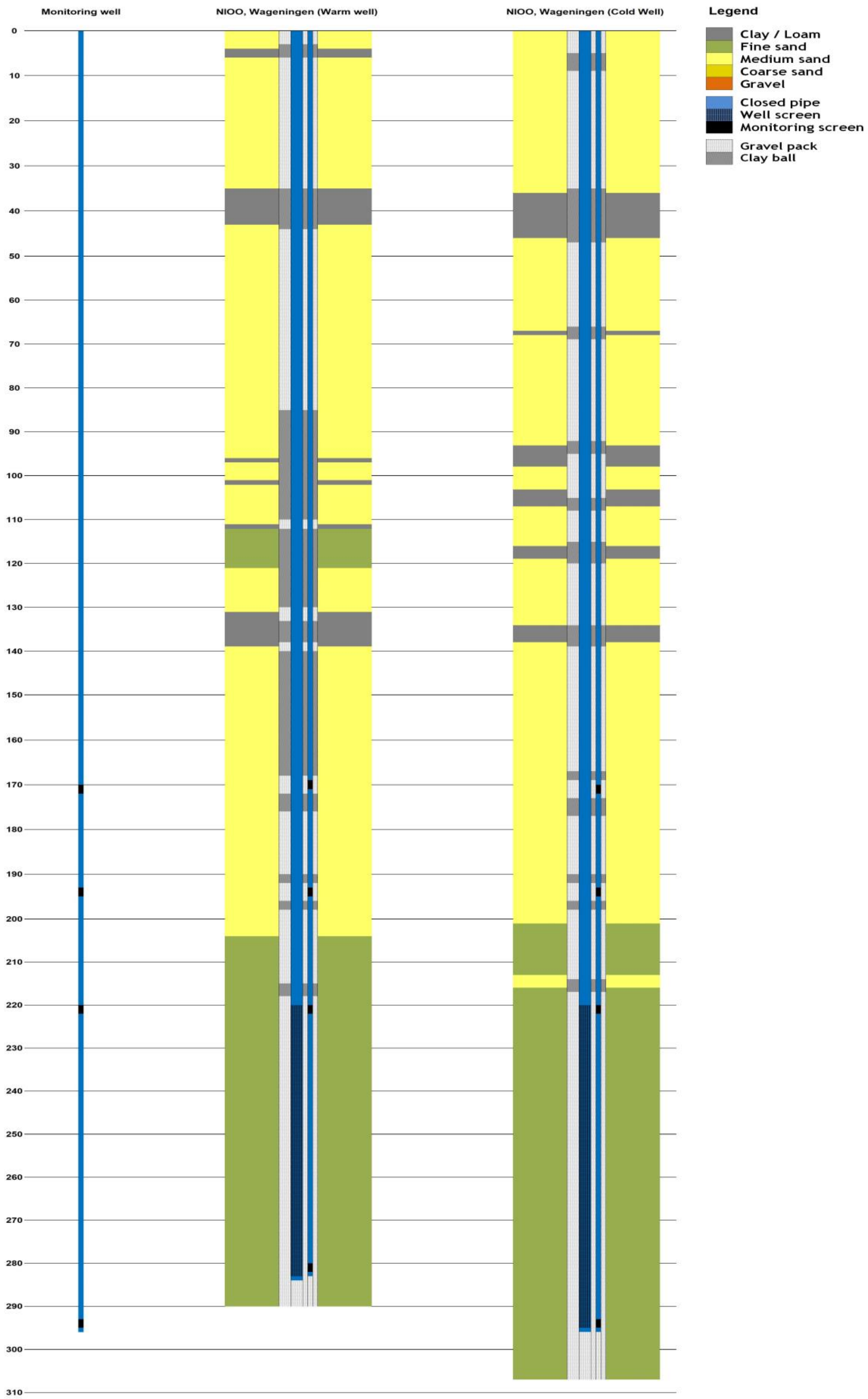

Figure 1 Well data NIOO HT-ATES project

From the different evaluation reports (DWA, 2014, IF Technology 2011 and IF Technology 2018b) the following conclusions can be drawn:

- A test drilling should have been done to verify the hydrogeologic starting points of the design.
- The capacity of the wells is more than 50 % less than expected from the geohydrological design. Mainly caused by the low permeability of the aquifer and skin. Intensive well development hasn't brought sufficient improvement. Maybe the fine sorted gravel pack and small slot size of the screen has negative impact on the productivity;
- The lower part of the screen has a low productivity (see Figure 2). The lower screen between 247-283 m bs (57%) produces 10% of the flow the upper part of the screen 220-247 m bs (43%) produces 90%. Low permeability of the deeper part of the aquifer is one of the main reasons. Also the drilling process might have negative effect on the permeability. It's suggested that during the back-fill process drilling fluids have sunk to the lower part of the wells. Also clay swelling due the intrusion of fresh water (drilling fluids) in a salt water aquifer was mentioned as cause for the low permeability.
- During the period 2011-2018 no decline of well capacity was found.
- With the exception of some broke tubes (PVC) in the monitoring and warm well no problems occurred in the rest of the groundwater systems

Table 3 Design parameters key-components

Drilling method	Reverse rotary with air-lift 600 mm
Well development methods	Sectional cleaning, air surge, chemical treatment (hydrogen peroxide)
Screen	Stainless Steel slotsize 0,1 mm, open screen surface 9,5 %
Casing pipe	PVC
Gravel pack	grainsize 0,2 to 0,63 mm
Back-fill material	Mikolite 300 (strong swell clay pellets), gravel 2 -3 mm. No insulation.
Pumps	Submersible pumps
Water treatment	no

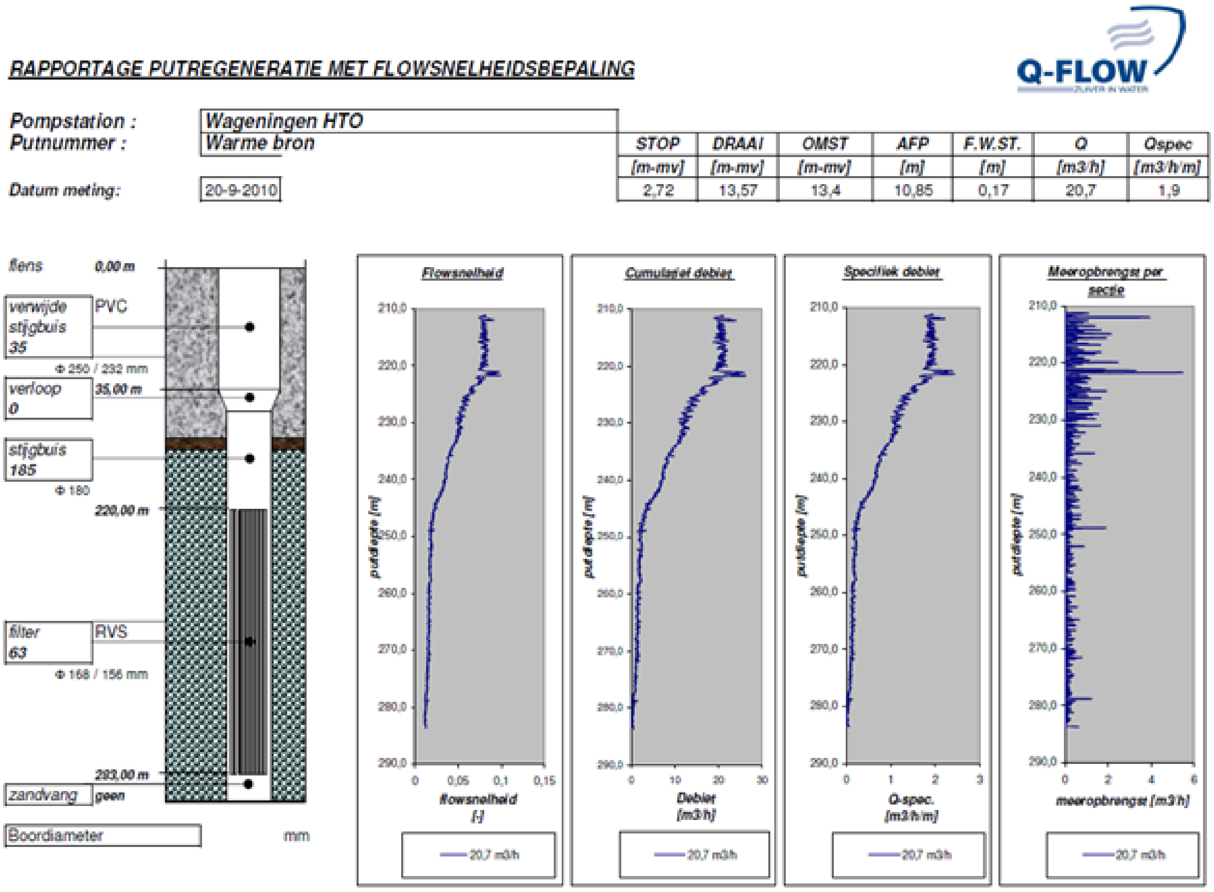

Figure 2 Flow speed measurements

Figure 3 Drilling process NIOO

2.2 University of Utrecht

The heat storage at Utrecht University has been unique in the world as the only high temperature ATES system. The heat storage was put into operation in 1991. In 1999 the warm well was damaged and the storage was taken out of service.

The ATES stored residual heat from the university's combined heat and power plants in the summer period. The heat storage consisted of a cold and a warm well, both in the third aquifer (formation of Oosterhout) at a depth of 220 to 260 mbgl.
In the design phase a test drilling was performed (Heidemij, 1988). The aquifer consist of coarse till medium fine sands with a permeability between 25 and 3 m/d (Figure 4). Because of potential high thermal losses the upper high permeable part of the aquifer was not used. The upper part of the aquifer consists of fresh water (Cl^{-}< 50 mg/l); the deeper part of brackish water (500 mg/l Cl^{-}).

The high storage temperature forces to use glass fiber reinforced epoxy (GRE) or composite casing GRE; because slotting a GRE with small size slots is impossible a stainless steel screen has been used. Suitable and payable high temperature submersible pumps were not at the market in 1991. A line shaft pump (LSP) with the motor on the surface has been used (see Table 4).

The technique of ion-exchange has been put into practice at Utrecht University. The groundwater passes an ion exchanger and calcium from the ground water is absorbed by the resin where it is exchanged by sodium. This reduces (among other things) the calcium concentration in the

groundwater and the calcium carbonate saturation degree. In this way, the precipitation of calcium carbonates can be prevented.
After some time, the resin becomes saturated and has to be regenerated with sodium. After regeneration the resin can be reused.

Table 4 Design parameters key components

Drilling method	Reverse rotary with air lift 600 mm
Well development methods	Sectional cleaning and air lifting
Screen	Houston, Well Screen stainless steel RVS 316L Houston Free 114.3 x 103 mm, wirewrapped slotsize 0.3 mm, open surface 12%
Casing	Wavin, Wavistrong GRE pipe EST 25, Glass fiber reinforced epoxy
Gravel pack	0.5 – 0.8 mm
Back-fill material	Spherlite-cement thermal conductivity of 0.12 W/mK
Pumps	Line Shafts pumps (LSP)
Water treatment	Ca/Na ion-exchanges

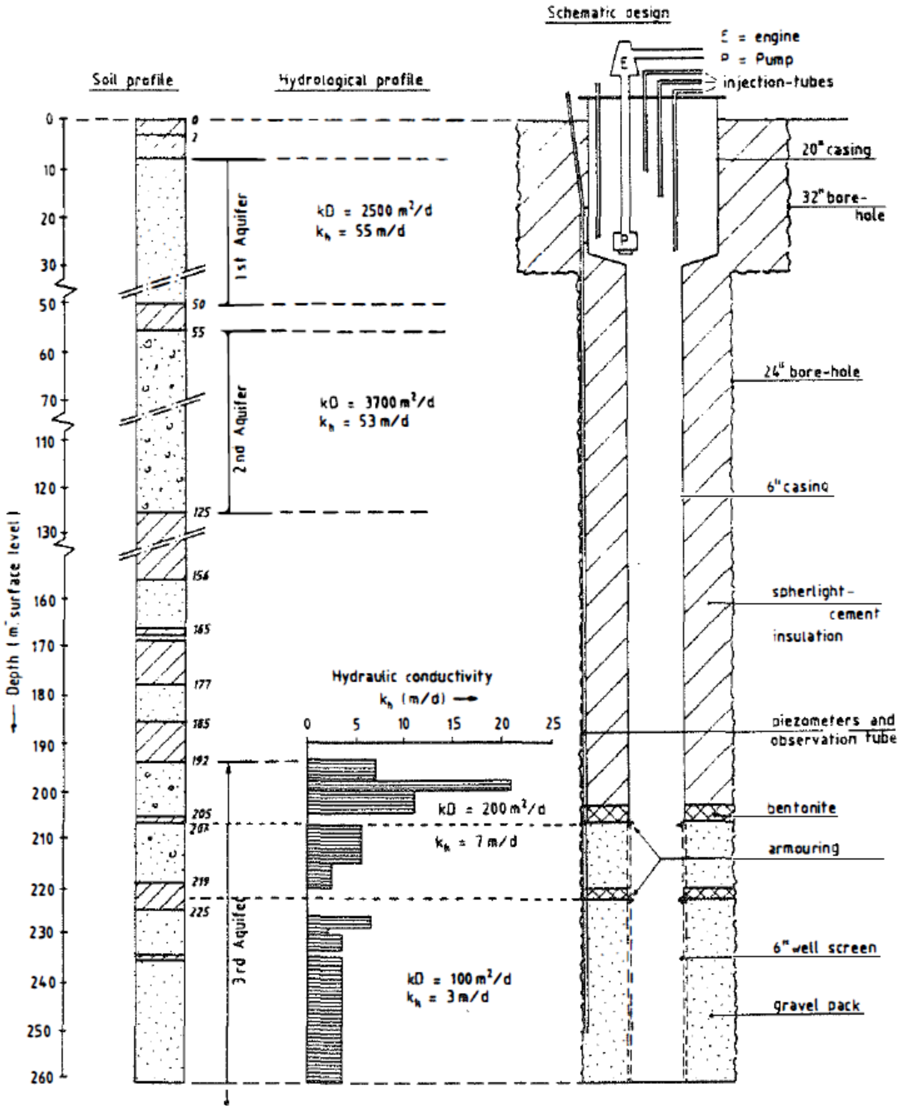

Figure 4 Geohydrological profile and well design HT-ATES University Utrecht

The HT-ATES was abandoned in 1997 due to well problems and low thermal efficiency. The project was extensive evaluated in 2001 (IF Technology, 2001). From this evaluation the main conclusions are listed:

- No corrosion was noticed. The well construction (screens, casing, well head etc) functioned without any problem.
- The warm well got serious (reduction of 85%) clogged after two years of operation. The clogging might have been caused by the water treatment (clay swelling or calcite precipitation). Regeneration of the well with HCl and hypochlorite was effective but the well never reached more than 50 % of its original capacity. During regeneration no fines (clay, sand, slit) were found.
- Due to clogging and misfunctioning of the control system the warm well cracked (1999) and injected warm water flowed to surface. The well wasn't restored.
- The Ca/Na ion-exchanges was very critical in respect to the risk of clay swelling. Manual adjustments had to be made on a regular bases and the installation was out of order during periods in 1994. Clay swelling because of the ion-exchange system has caused clogging of the warm well. Furthermore the ion-exchanges uses large amount of salt (NaCl) for

regeneration. It's was concluded that Ca/Na ion exchanges should not have been used for HT-ATES in Dutch aquifers.

- The shaft-pumps of the warm well functioned well although maintenance was very complicated and expensive. The shaft pump of the cold well broke after five years and has been replaced by a submersible pump. For future project it is advised to use submersible pumps for all wells.
- To prevent thermal losses insulation of wells and terrain piping is necessary. The wells were insulated by using concrete with spherlite around the casings. The production lines within the wells where not insulated.
- HT-ATES is mainly used in aquifers with shallow groundwater level. Water levels in the warm well can raise far beyond surface level causing practical problems during maintenance jobs at wells and pump.

2.3 Hooge Burch Zwammerdam

The Hooge Burch care institution in Zwammerdam has a cogeneration plant (CHP) for electricity production, the generated heat is used for heating. The installation was also equipped with a high temperature heat storage. Heat is stored at 90 ºC when the CHP runs for electricity production and the heat demand is smaller than the heat production. The stored heat can be used later for heat supply to the health care institution. The heat storage consists of a cold and a hot well, both in an aquifer at a depth of 135 to 151 mbgl (Figure 5). The distance between the cold and the hot well is approximately 67 m. The aquifer consists of medium fine sand with a hydraulic conductivity of 5 m/d. The aquifer contains salt water (4,000 mg/l Cl^-).
Because of the high storage temperature, the use of PVC pipes was not possible and glass fiber reinforced epoxy (GRE) was used; because slotting a GRE pipe with small size slots is impossible, a stainless steel screen has been used (see Table 5). The project was designed with line shaft pumps (LSP); during the construction phase the shafts proved to be non-resistant for salt ground water (Timmermans, 2018). Therefore these LSPs have not been installed though submersible pumps were used. Besides some issues with the cables (rubber was affected by the HCL-watertreatment) the pumps functioned well.

The solubility of carbonates is not only dependent on the temperature, but also on the pH. Addition of acid lowers the pH and provides a higher solubility of carbonates. By reducing the pH of the groundwater before the temperature is increased, carbonate precipitation can be prevented. For reducing the pH several acids can be selected. At Hooge Burch hydrochloric acid (HCl) has been used.

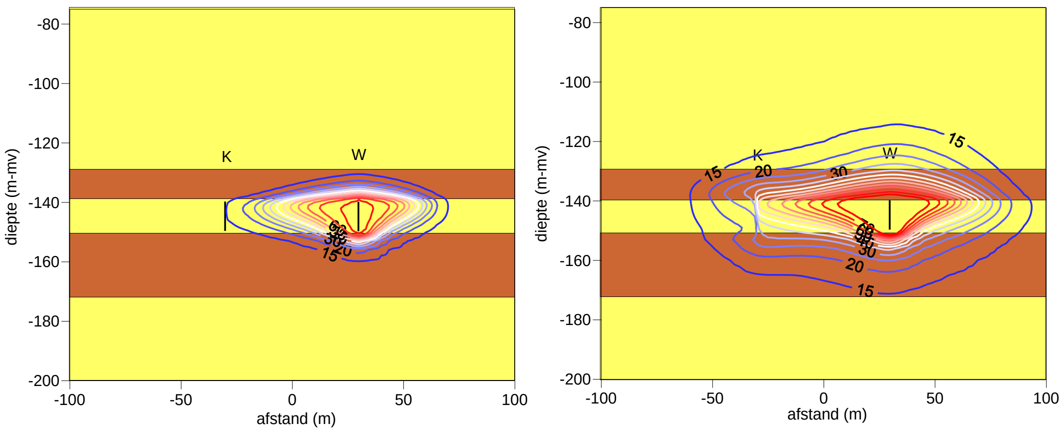

Figure 5 Temperature profile HT-ATES Zwammerdam

Table 5 Design parameters key components

Drilling method	Reverse rotary, 500 mm
Well development methods	Sectional cleaning, air surge and twin pumping.
Screen	Houston, Well Screen RVS 316L Houston Free 114.3 x 103 mm, wirewrapped, Slot size 0.3 mm, open surface 12%
Casing	Wavistrong GRE tube EST 25, DN 100, FB/FS
Gravel pack	Grain size 0.5 to 0.8 mm
Back-fill material	54% spherlite, G-cement Thermal conductivity 0.43 W/m.K
Pumps	Submersible pumps
Water treatment	HCl treatment

The HT-ATES was abandoned in 2003 due to bad economics. The water treatment was extensively evaluated and modelled (IF Technology, 2002a and 2002b, and Drijver, 2012).

In practice, about 50% of the dosage was used that would have been required based on calculations and - after four years of operation – there were no indications for clogging of the wells. It has to be noted, that no mixing of water was encorporated in the calculations, resulting in a higher dosage than predicted based on the calculation method that was used. In 1998-2001 an average acid dosage (30% HCl) of 4,0 ; 3,6 ; 2,9 and 3,2 ml/kWh was used. Although this is only for 4 years, there does not seem to be an increasing dosage. The relatively low dosage in Zwammerdam was based on the measured pH of the extracted water. It has to be noted, that the reliability of the pH-meters was limited. When the measured pH is lower than the value that is expected in case of calcite equilibrium, this indicates some degree of undersaturation. In fact, part of the acid that was added during the previous heat storage period has not been used. As a consequence, a lower dosage is sufficient.

Apparently, in practice less calcite dissolves than was expected based on model calculations. Possible explanations are the presence of layers without calcite (so no calcite can dissolve), natural inhibitors (no precipitation occurs despite some degree of oversaturation), slowness of the dissolution reaction (equilibrium conditions are not reached) and/or mixing of calcite saturated water of different temperatures which leads to undersaturation (this process is known as mixing corrosion, a phenomenon leading to karst features/cave formation, especially in coastal areas). Although the results of the Zwammerdam HT-ATES suggest that a lower dosage may be sufficient, this is not necessarily the case for other projects. Based on measurements in practice, a more accurate dosage can be worked out.

Other experience in the project were:

- The level transmitters in the wells broke down several times due to the high temperatures. No trends of pressure build-up could be measured in the wells. The maintenance firm claimed however no clogging in the wells occurred.
- The cables of the submersible pump in the warm well was affected due to the water treatment with HCl (Timmermans 2018)

2.4 Reichstag Berlin (water treatment)

At the German Parliament building (Reichstag building) two aquifers at different depth are used to store cold (ca. 60 m) and heat (ca. 300 m). The underground storage is operational since 1999, however, the full capacity of the total system and the final operational strategy could not be tested before completion of the energy network and all buildings involved in 2003. Both storage systems, after minor teething problems, performed to satisfaction (Sanner et al., 2005).
The design temperature at the warm well is 70°C while charging. No water treatment is used at the Reichstag building heat store (Sanner, 1999). According to Kranz and Bartels (2010), the storage temperature is limited to 70 °C because of geochemical aspects. They state that the solubility of silicates at higher temperatures is the limiting factor, but this probably should have been carbonates (instead of silicates). Based on the groundwater composition data, the natural groundwater seems to be calcite saturated. Apparently, in this case heating to 70 °C is possible without the necessity of water treatment.

2.5 GEOMEC-4P 2013 (design phase)

In 2013 a HT-ATES was designed for the GEOMEC-4P project. GEOMEC-4P intended to store surplus heat of a geothermal plant to be used in winter time for heating horticulture. Due to economical set-back the system wasn’t built so far. The HT-ATES design of GEOMEC-4p combined all the lessons learned from the former Dutch and international HT-ATES project.

Test drilling proved there was suitable aquifer between 80 and 190 m-bs (Figure 7). The aquifer consists of medium fine sand of the Maassluis formation with a permeability of 8 m/d. The ground water in the aquifer is salty (10.000 mg/l CL^{-}).

In comparison to the older HT-ATES sytems the GEOMEC-4P was significant larger in volume. It was meant to store approximately 800.000 m^3 with a configuration of three warm wells surrounded by a “ring” of three cold wells (see Figure 6).

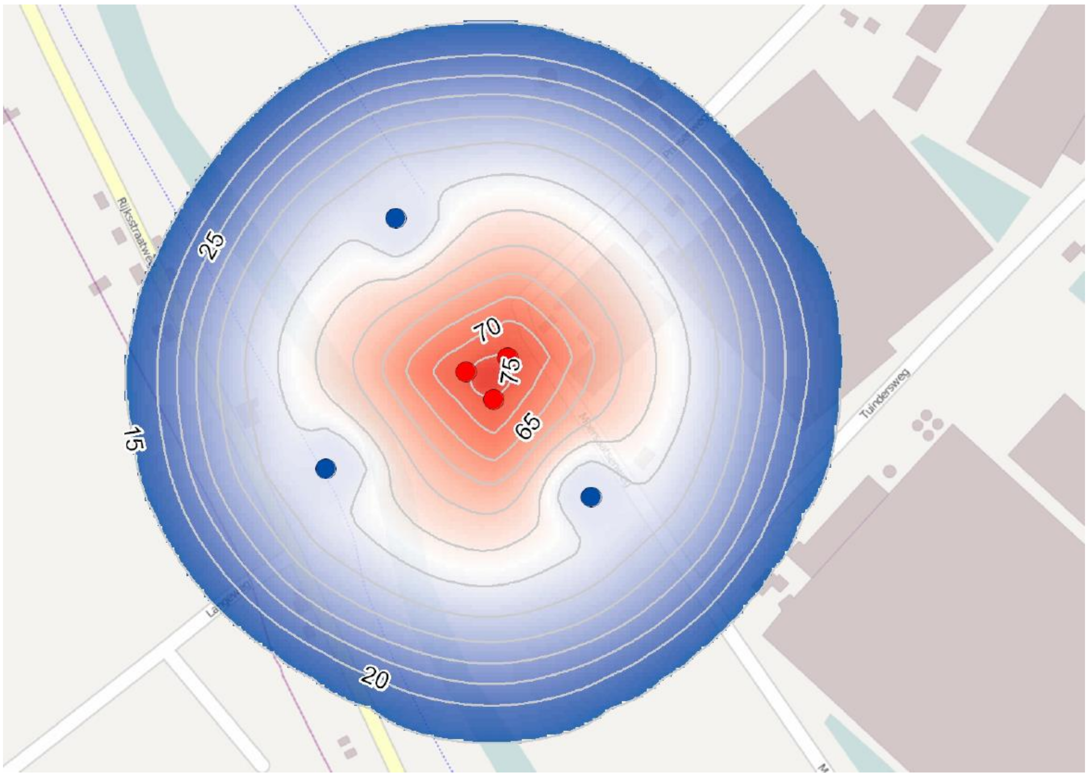

Figure 6 Well configuration HT-ATES GEOMEC

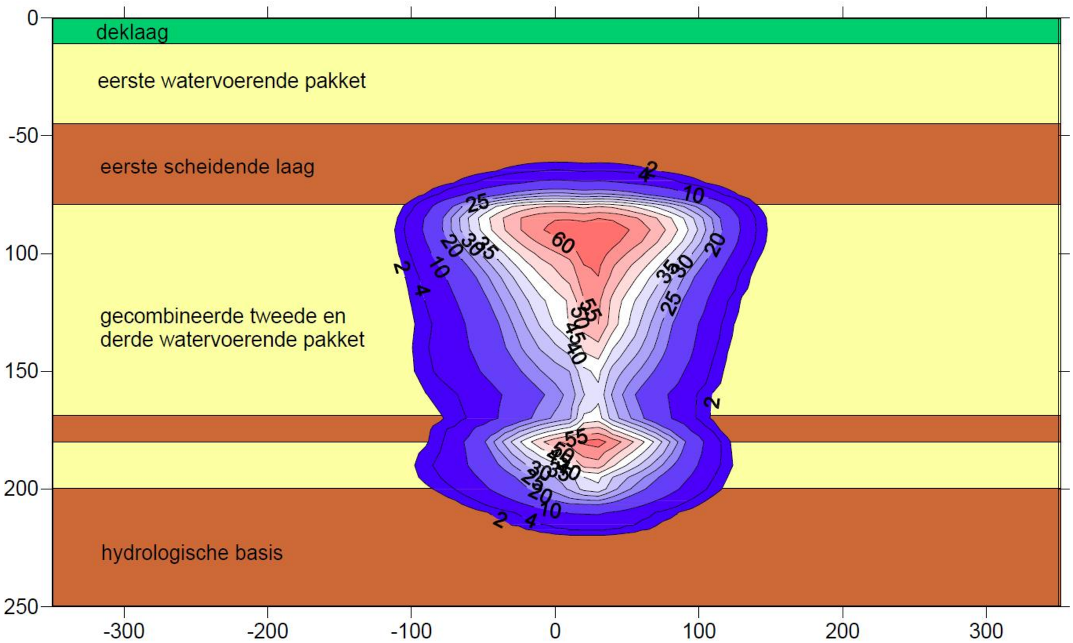

Figure 7 Cross section with HT-ATES after discharging period

Table 6 Design parameters key components

Drilling method	Reverse rotary air lift 700 mm cold well, 500 mm warm well.
Well development methods	Sectional cleaning, air lift and twin pumping.
Screen	Cold wells: PVC slotted 0,4 mm Warm wells: stainless steel, wire wrapped screen, slotsize 0,4 mm
Casing	Cold wells: PVC Warm wells: Wavistrong GRE casing
Gravel pack	Grain size 0,5 tot 0,8 mm
Back-fill material	Mikolite 300 (clay pellets with extra swelling properties), gravel 2 -3 mm. No insulation.
Pumps	Cold wells: standard submersible pumps ,Melotte Warm wells: ESP from oil&gas industry, Schlumberger
Injection valves in wells	Melotte
Water treatment	HCl treatment

The main design consideration of the GEOMEC-4P projects were:

- The cold wells were constructed with PVC screens and casings; the temperature wasn't expected to exceed 60 °C. Cost savings per well up to 70 k€
- The submersible pumps in the cold wells are standard low temperature submersible pumps; in the warm wells specific ESP were to be installed suitable for high temperatures. These ESP's are commonly used in oil&gas or geothermal applications.

2.6 Design considerations form existing projects

The experiences with former or existing HT-ATES leads to the following design considerations:

- HT-ATES systems with a warm well temperature lower than 45 °C can be designed with the same design criteria as for LT-ATES (8 – 25 °C).
- A test drilling should always be applied when designing a HT-ATES.
- Water treatment with ion-exchanges should not be used. HCl-treatment is proven to be a reliable technique to prevent clogging. High HCl consumption is major disadvantage in respect to public acceptance and high operational costs.
- Shaft-pump should not be used. Submersible pumps proved to be reliable and well adjustable to low flows; temperature level and groundwater quality should be considered when selecting a submersible pump.
- As long as oxygen accession is prevented, RVS 316 quality stainless can be used for the main components (pipes, valves, heat exchangers). However instead of RVS, the use of GRE can be a better or comparable solution for some components.
- Insulation of the well casing can minimize heat losses of the store and prevent heating up shallow (fresh water) aquifers.

3 General design aspects.

3.1 Scope of considerations

The design recommendations are concentrating on HT-ATES with temperature levels between 45 and 95 °C. Below 45 °C a standard low temperature ATES design can be used. Systems above 95 °C are considered as highly experimental (TRL below 6) and need different design considerations. The focus is on sedimentary **unconsolidated** aquifers. For the Dutch situation these are the formations of Maassluis, Oosterhout, Breda and Brussel. The standard wells for HT-ATES are vertical; horizontal and radial wells are considered experimental (TRL below 7) and need further development. and demonstration.

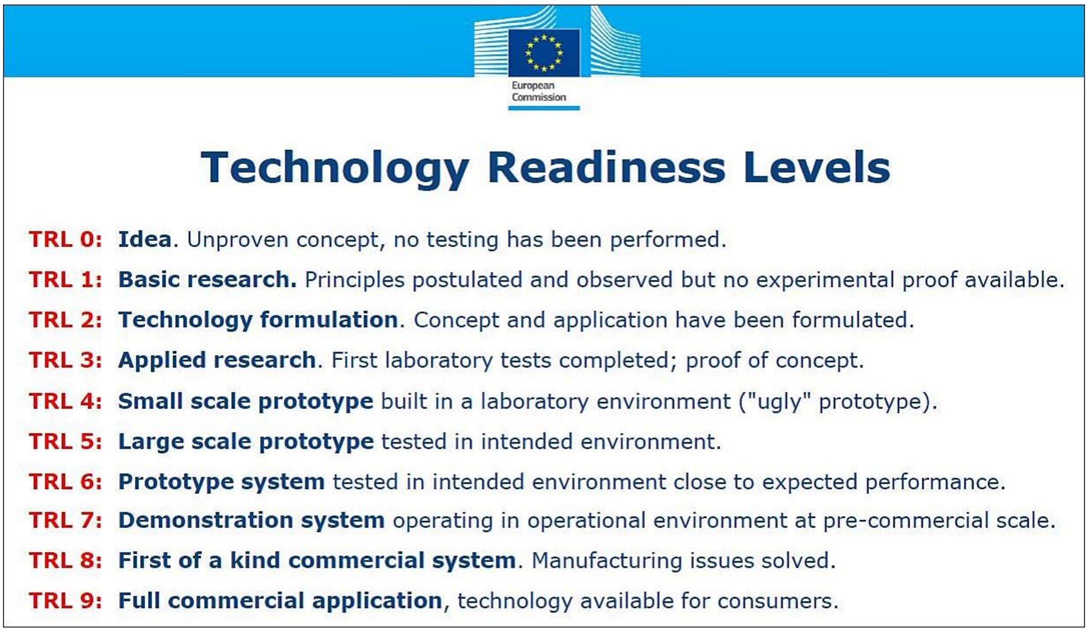

Figure 8 Technical readiness levels

3.1.1 Legal framework

The design considerations need to fit in Dutch regulation on Energy storage in the Underground (ATES). For drilling it's the regulation on mechanical drilling BRL-SIKB 2100 (SIKB 2015) and for design and construction of underground systems the BRL-SIKB 11000 (SIKB 2014). The BRL's consist of process rules and guide lines. Also the BRL demands for certified companies to construct and design ATES systems.

3.1.2 General design criteria

There is limited experience in realization of HT-ATES systems. Therefore the considerations for the designs and realizations of the existing and new HT-ATES systems are mainly based on experiences of many regular ATES systems and on deep geothermal systems. The learning curve will be very steep in the years to come. It is of great importance that before designing new HT-

ATES systems, the experiences of the latest HT-ATES systems should be studied. This information could be very valuable to adjust the design considerations as stated below.

For designing HT-ATES the same design criteria as for LT-ATES will apply. It has to apply the next design criteria:

- Minimum Lifespan of the different component:
  - Wells; 30 years; every five year mechanical (or sometimes chemical) cleaning;
  - Submersible pumps: 5 years;
  - Piping and cables : 30 years;
  - Water treatment: 10 years;
  - Heat exchangers: 10 years;
  - Pumps and valves: 10 years.
- Reliability
  - 97,5 % (one week out of order for maintenance)
  - Number of disturbances (1 hour or more): 10
- Safety
  - Regulations according to:
    - ARBOWET (Dutch law on working conditions)
    - NEN standards
    - CE/PED directives

More specific technical design criteria are:

- No corrosion of piping, heat exchangers, pumps and valves. Use stainless steel of RVS 316L quality or plastics (if possible);
- No erosion and limited pollution/clogging of wells, pumps, heat exchangers etc. The produced water should contain a minimum of non-dissolved particles: silt (MFI < 2.0) and fines (less than 0,01 mg/l);
- No oxide in the water that is produced from the aquifer. Ingress of oxygen/air needs to be prevented by using gas tight systems and by maintaining an overpressure in the system;
- No degassing of the produced water that will be injected again; system pressure is always above gas bubble point (check gasses in produced water during testing the exploration well and take into account possible high gas pressures because of CO_2 treatment);
- No scaling in wells, pumps and heat exchangers. Check water quality during testing the exploration well. Consider water treatment for every project above 50 °C, especially for preventing $CaCO_3$ scaling while heating.

3.2 Design main components

3.2.1 Test drilling

Limited data about the potential formations to be used for HT-ATES (Maassluis, Oosterhout, Breda and Brussel) is available. These formations are not used for drinking water or industrial cooling due to the high salt content and standard ATES applications are mostly applied in less deep aquifers. Therefore drilling and testing an exploration well to obtain more data is highly recommended for all HT-ATES project. In most cases the test drilling can be completed as a monitoring well that will be used during operation.

The key parameters to be investigated during drilling and testing the exploration well are:

- Groundwater composition for designing water treatment and environmental assessment study;
- Horizontal and vertical permeability of the target aquifer for calculating potential flow and thermal efficiency;
- Grain size of the sand of the target aquifer to design slot size of the screen and gravel pack
- Geohydrological structure and characteristics of the top layer (a consistent clay layer is needed) for calculating thermal efficiency and environmental assessment study.
- Drilling issues and risks (for example clay balling, mud/water losses, hard layers etc.) for designing the final wells and determine the best drilling procedures and mud.

Design considerations for drilling and testing the exploration well are:

- Reversed rotary air drilling to get good samples for accurate stratification interpretation.
- Well logging (Gamma and SP) are necessary for information on clay content and coarseness of the sand.
- Sieve analyses on some soil samples in the target aquifer for coarseness of the sand and clay-content. Correlation with the well log.
- Construction of a screen (minimal 200 mm) in the target aquifer to be able to perform a well test.
- A step draw-down test should be performed, followed by a shut in or recovery test. Well testing results will be used to determine the aquifer transmissivity and to predict production capacity of the future wells and model the thermal efficiency of the heat storage. Construct monitoring pipes in the gravel pack to be able to perform water sampling and analyses. Pipes and screens should be of GRE or stainless steel if the test well is made in the > 60 °C influence zone of the future HT system.
- During well testing the produced water will be sampled and analyzed on:
    - bubble pressure of the dissolved gas, dissolved gas quality and quantity;
    - chemical water composition.
- flow velocity measurements in the screen sections.

3.2.2 Maximum production and injection rate

For ATES systems two criteria exist to calculate the maximum allowable well entering velocity (production) and the maximum aquifer infiltration velocity. The idea behind the maximum velocity is for production avoiding sand mobilization and infiltration it is a maximum allowable clogging rate.

In the existing criteria the temperature is assumed to be fairly constant (around 12°C). It is thought that the criteria can be used in the temperature range between 6 and 20°C. The temperature effect in this range is neglectable (+/- 15%). At higher temperatures the effect of the viscosity will be of greater importance and must therefore be taken into account. In the equation below the temperature effect is incorporated into the existing production criterium:

$$\boldsymbol{v_e = 7200 * \frac{\rho_f * g}{\mu} * K_i}$$

v_e maximum extraction velocity [m/h]
7200 a constant [-]
ρ_f density of produced water [kg/m^3]
G gravitational acceleration [m/s^2]
μ viscosity of produced water [kg/(m·s)]
K_i intrinsic permeability [m^2]

The existing Infiltration criterium is based on the following equation:

$$v_{clog} = \frac{2\, MFI_{mea}\, p\, A_f^2}{\rho_w\, g} \frac{t}{t_0} \frac{\mu}{\mu_0} \frac{d_p^2\ 6^2}{D_{50}^2}\ v_{inf}^2$$

p standard pressure, 2E-5 [Pa]
t_0 running hours per year, 8760 [h]
A_f Area of filter, 1.38E-3 [m^2]
μ_0 viscosity of water @10°C, 1.3e-3 [kg/(m·s)]
μ viscosity of water [kg/(m·s)]

t_0 number of hours per year [h]
t full load running hours [h]
g gravitational acceleration velocity [m/s^2]
ρ_w density of water [kg/m^3]
MFI_{mea} measured MFI [s/l^2]
d_p diameter filter pore [m]
D_{50} average grain size [m]
V_{inf} injection velocity [m/h]
v_{clog} clogging velocity [m/a]

$$v_{clog} = \frac{2\, MFI_{mea}\, 2\, 10^5\, (1.38\, 10^{-3})^2}{\rho_w\, g} \frac{t}{8760} \frac{\mu}{1.3\, 10^{-3}} \frac{(0.45\, 10^{-6})^2 6^2}{D50^2} {v_{inj}}^2\, 3600\, 8760\, 10^6$$

$$v_{clog} = 1.6\, 10^{-9}\, MFI_{mea}\, t\, \mu \frac{1}{{D_{50}}^2}\, {v_{inj}}^2$$

When Sheperd (1989) is used to replace D_{50} by a permeability, k in [m/d] the equation changes to:

$$v_{clog} = 1.6\, 10^{-3}\, MFI_{mea}\, t\, \mu \frac{1}{(\frac{k}{150})^{1.2}}\, {v_{inj}}^2$$

This can be rewritten as:

$$v_{inj} = \sqrt{\frac{v_{clog}}{1.6\, 10^{-3}\, MFI_{mea}\, t\, \mu} \left(\frac{k}{150}\right)^{1.2}}$$

The idea behind this criteria is that the pore throat size (see Figure 9) defines the clogging potential of the aquifer and the MFI defines the clogging potential of the water to be infiltrated. When a tetrahedral arrangement of the grains is assumed, the pore throat size is about a sixth of the grainsize.

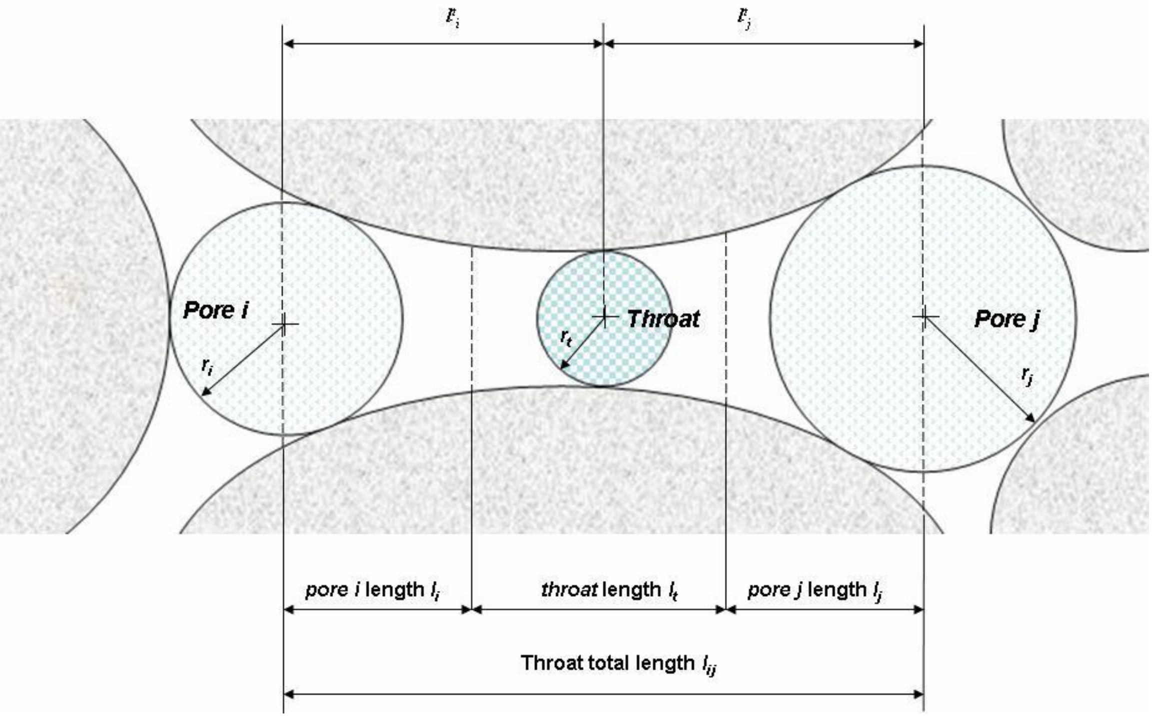

Figure 9 Schematic representation of pore throat

In Figure 10 the workflow of how the pore throat size is determined is shown.

Figure 10 Workflow for relating permeability to pore throat size

The current workflow is a bit cumbersome, also because the permeability in [m/d] depends on the temperature and the salinity of the water. It seems to be better to relate the pore throat size directly to the matrix permeability in [m^2]. In Figure 11 an example of this relation is given. The given relation below is for consolidated sediments. The question is how this relation looks like for unconsolidated sediments.

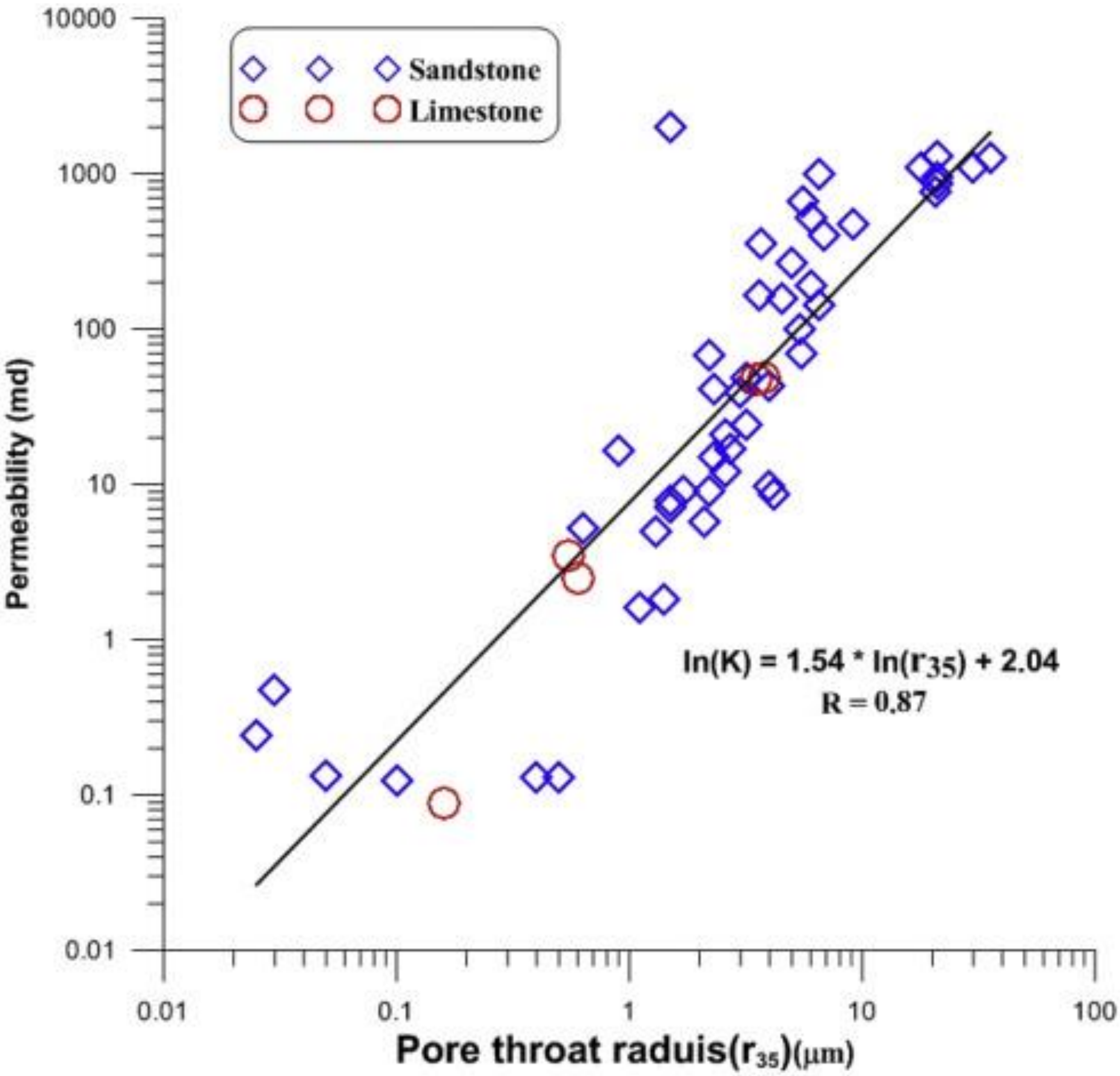

Figure 11 Example of relation between pore throat radius and permeability

Another important aspect is grain size distribution. The more unsorted (large variation in grain sizes) the reservoir the higher the risk on sand production. In reservoirs with a small variation in grain sizes, the risk on sand production is much less. How to incorporate this into design criteria is not clear yet.

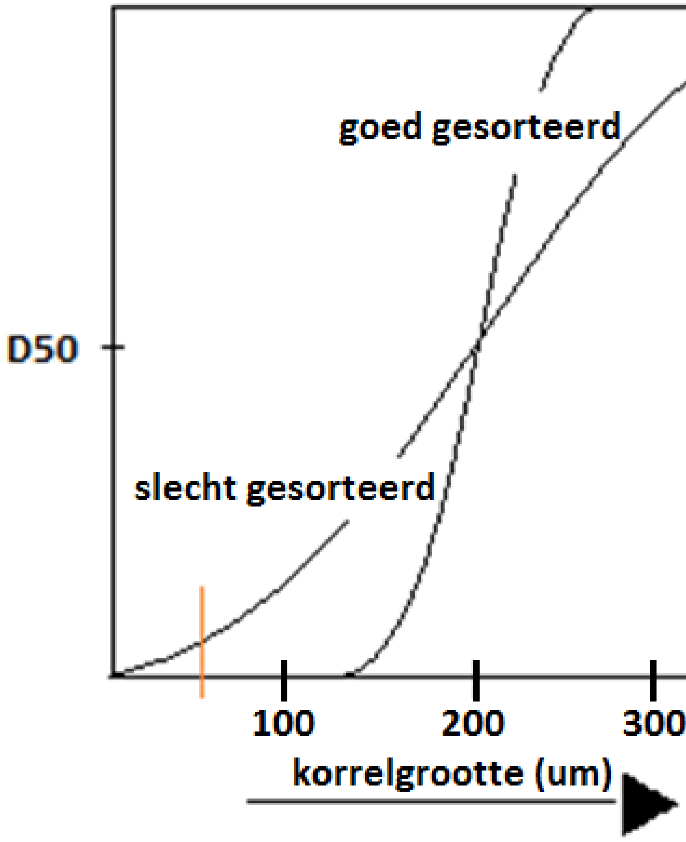

Figure 12 Schematic presentation of grains size distribution

3.3 Realisation of wells in low permeable aquifers

Considerations for realization procedures and methods are divided in: installation of well materials (casing, screen, backfill/cementing), drilling technique and process, and the well development process.

3.3.1 Casing selection

Casings for HT-ATES up to 95°C need to withstand collapse and burst pressures. In most NL HT-ATES projects GRE is and can be used. GRE is also non-corrosive and the risk for scaling is minimal.

Typical ATES wells as described in the BRL are being drilled in one stage from surface to end depth and production casing and screen are installed in one stage in this borehole. HT-ATES wells will be drilled deeper. Drilling risks (as can be experienced during drilling the exploration well, see 4.3) could increase significantly, which could affect the design.

Design consideration:

- For high temperature wells up to 95°C GRE is preferred above steal or stainless steel.
- For temperatures < 45°C, standard PVC can be considered but special attention should be given to decreased collapse and burst pressures because of these high temperatures (40% decrease @ 45°C). PVC could be considered for the cold wells as the injected water is cooled down. Restrictions: HEX needs to be operational and no possibility for bypassing the HEX (f.e. for maintenance or testing operations)
- Good experiences have been experienced using stainless steel wirewrapped screens. Special attention should be given to high load weights during installation (tensile strength on couplings and crossover to steel).
- It is preferred to use a one-stage-approach for drilling the well and installing the casing and screen: first drill the hole to end depth in the target reservoir and then install the total casing, screen and backfill in one stage. In the Netherlands this has been proven to be doable up to depths of more than 500m. Important advantages: 1. it will maximize the borehole diameter at target aquifer and 2. reduce costs significantly.
  The other approach is a telescopic approach. This approach is more common for deep geothermal wells (>1000m): first drill to the sealing clay layer above the target reservoir, then install the casing and cement it. After this first stage, the target reservoir will be drilled into with a smaller diameter. This is a two stage approach, but it could be done in even more stages.
  This telescopic approach could be considered when drilling in complex geohydrological systems. Advantage is that drilling risks can be reduced. After installing a first casing the overlying formations above the aquifer will not influence the drilling in the aquifer anymore (no clay swelling, water losses, borehole collapse). Furthermore different muds can be used for overlying formations and for the target aquifer, as the mud specifications for the target aquifer are not only important for stabilizing the borehole but also for minimizing borehole damage after drilling. The need for a more expensive telescopic approach can be concluded after a test drilling has been performed.
- Wells will be heated during operation and cool down during non-operating periods. With the high temperatures the expansion and shrinkage of the casing and wellhead need to be taken into account in the design to prevent damage during operation. This also accounts for monitoring pipes in or nearby the well. Damage can be prevented to provide enough space for expansion/shrinkage and to use special piping constructions or install compensators that will decrease expansion effects between wellhead and piping connections.

3.3.2 Screen and gravelpack selection

In the HT-ATES wells that have been build sofar wire wrapped screens of stainless steel (SS 316L) with gravel pack are used. No fines production or corrosion is reported in these wells.
There are suppliers for GRE piping that can deliver slotted GRE screens. The percentage of open area of these GRE screens is lower than for RVS wire wrapped screens, however quite similar to PVC applications in low temperature ATES systems in non-consolidated aquifers. In the Netherlands there is no experience with these slotted GRE screens and it could be interesting to investigate this option in more detail.

The Dutch BRL 11001 prescribes:Filter sand should be used as back fill material in the borehole next to the screen. Standard industrial filter sand is heterogenous and classified between a lower and upper grainsize fraction (grainsize distribution curve). The lower grainsize fraction of the filter sand should be maximal factor 4 bigger than the M50 of the sand in the aquifer.

The slot size of the screen should be at least 0.1 mm smaller than the lower grainsize fraction of the filter sand.

Design consideration:

- For the slotsizes the best option in the typical Dutch aquifers and water quality is to use wire wrapped screens of stainless steel 316L. Suppliers of GRE and/or SS 316L wire wrapped screens can deliver crossovers for connecting casing and screen. A SS 316L pipe joint for coupling the screens is laminated in the GRE pipe joint.
- Use filtersand as backfill around the screens to prevent production of fines;
- Use filtersand with a grainsizes fraction less than four times bigger than the M50 of the finest sandlayers in the aquifer. If the aquifer is considered to be very heterogenic, it can be considered to use different filtersand grainsizes.
- Well development is considered more important than risk of sand delivery. The coarser the gravel pack, the better wells can be cleaned and developed, though the more risk on sand delivery.
- Check the manufacturers deviations of slot size and gravel pack grainsizes as this can be very relevant for the small grainsizes to be used for HT-ATES.

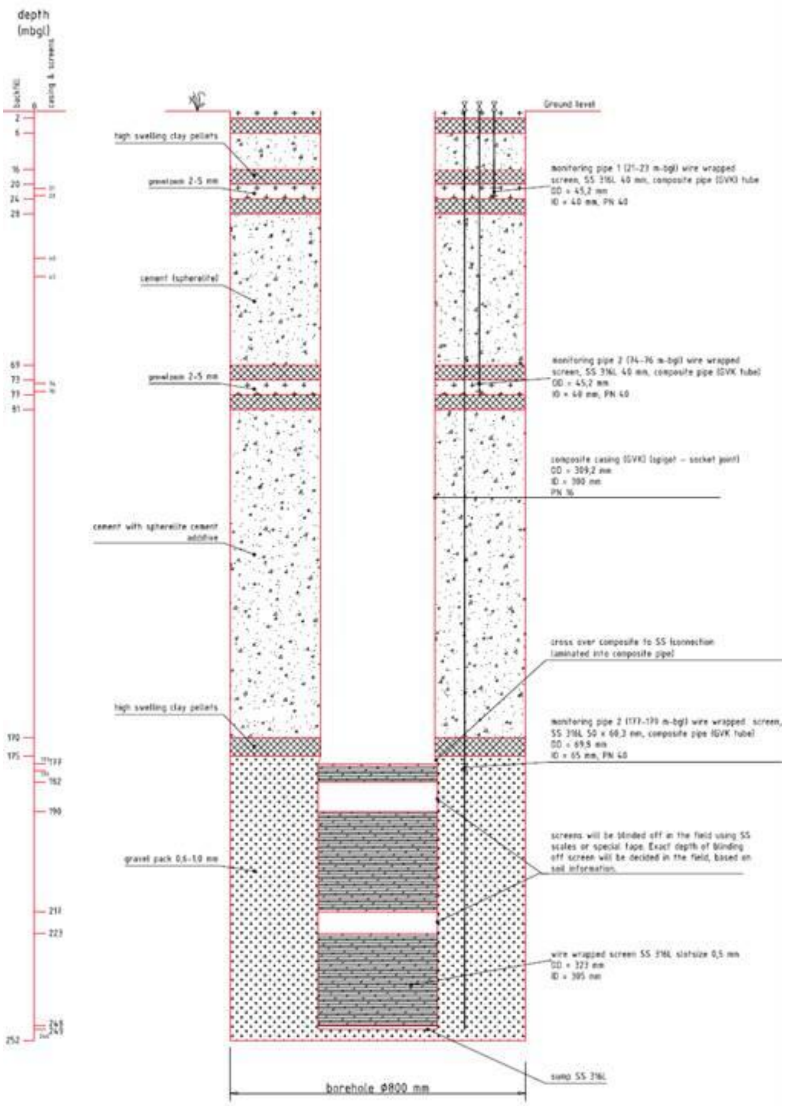

Figure 13 Typical design for an HT-ATES well

3.3.3 Back-fill material (insulation)

Not only the temperature of the target aquifer will be influenced by HT-ATES, but also the formations at more shallow depths surrounding the wells will be affected because of heat radiation from the hot casings. In the Netherlands there is no clear environmental legislation for the need of casing insulation to prevent warming up the direct surroundings of the well. The absolute effect of heat radiation depends on the water temperature that is injected in the well. At high temperatures it has been concluded that the absolute temperature effect on the surroundings of the well can be high, however, it is not expected that this will lead to environmental impact (see AVR 66146/GB for thermal calculations on effect of insulation).

The only insulation used for HT-ATES projects is a special light weight cement (Spherelite). This special cement can reduce heat losses compared to clay pellets as backfill. Spherelite minerals (hollow, fused, pressure-resistant mineral) can be mixed up with cement in different quantities. Most common and practical Spherelite cements at densities of 1.2-1.4 ton/m³ have average thermal conductivities of 0.4-0.5 W/Km. This is circa three times as low as a backfill of clay pellets.

Design considerations are:

- Use of cement with insulating properties should be considered. (e.g. Spherelite). Work out thermal calculations to determine the effect of extra insulationon the impact on temperatures around the wells and to determine the economic advantages during exploitation because of decreased heat loss. These advantages should be outweighed to the disadvantages of using special cement, which leads to extra costs and technical complications compared to standard ATES backfill of clay and sand.
- For insulation of wells Spherelite Cement is proven to be installed successful. However other light-weight cements have not been used before for HT-ATES wells in the Netherlands. Research on costs and technical impact can be considered.

3.3.4 Monitoring lines in HT-ATES wells

In common LT ATES wells monitoring lines (OD/ID of 32/28 mm) are installed in the borehole next to the well casing/screen. These monitoring lines are installed at different depths with screens at different formations in and above the target aquifer. In these monitoring lines groundwater can be sampled to analyse the water quality, gas quality and gas quantity at these depths. But also temperature and water pressure is monitored in these monitoring lines. With this data any possible effect of the target aquifer to the shallower formations can be evaluated (requirement of Dutch legislation).

For monitoring HT-ATES wells the following considerations need to be taken into account:

- Because of heat radiation from the hot well casing to its surroundings, in most cases it is of no use to monitor the temperature in monitoring lines in the same borehole next to the well casing.
- If monitoring pipes are installed in the HT-ATES well, it should be considered to use GRE pipes and GRE or SS316 screens when temperatures in the well exceed 40 C.
- To monitor the heat and water quality in the aquifer, it is advised to install a separate monitoring well at a certain distance to the hot well of the HT-ATES system. Depending on the expected temperatures, it should be considered to use GRE pipes and GRE/SS316 screens in this monitoring well. If a test drilling is done, this borehole could be completed as monitoring well.

- In case the HT ATES well is cemented, monitoring lines above the target aquifer cannot be installed anymore in the annulus between borehole and well casing. These monitoring lines should be installed in a separate nearby monitoring well.
- For monitoring temperature it can be considered to use glasfiber techniques instead of measuring temperatures in the wells or monitoring lines using temperature sensors that are installed from above. Reasons to do so:
  - temperature over depth in the monitoring lines can be influenced by heat convection in these lines (hot water going up);
  - Using a glasfiber cable gives more detailed information (continues measurement over the whole length of the well);
  - Measuring temperatures by hanging in T-sensors in the monitoring pipes is time-consuming especially at great well depths.

3.3.5 Drilling technique and process

Reverse rotary with air-lift is considerate standard technology for HT-ATES because of well diameter and a clean drilling process (see also NVOE, 2006 and SIKB 2015). In addition to the SIKB mechanical drilling protocol the considerations below for realizing HT-ATES wells focus on drilling to large depths (200 – 500 m.bs) and in heterogeneous fine sandy aquifers.
By definition deeper wells will lead to higher drilling risks as drilling to end depth will take longer and more different formations will be drilled through. Both the chance and impact of typical risks are higher when drilling deeper wells, like losing a borehole or stuck pipe after having water losses in highly permeable formations or because of swelling clays .
Furthermore the reservoirs will be less permeable: sandy reservoir with fine to very fine sands. This makes that borehole damage prevention is more important (good quality mud that prevents deep infiltration of fines in the reservoir) and de-sanding during drilling is more important as these fines are more difficult to separate from the mud.

In addition to the Dutch SIKB protocols 2101 and 11001 the following aspects need special attention:

- Check suitability of drilling rig: higher loads, more pressure needed etc.
- Do use heavy weight drilling pipes.
- The salt content will increase at these depths and therefore water levels in deep reservoirs will most likely be lower than less deep reservoirs of <200mbgl. However the reservoir pressures should be evaluated for each case as some deep reservoirs can be pressurized (Artesian) because of former geological processes.
- In the upper North Sea group it is not expected to pass zones with significant shallow gas, though this should always be evaluated before drilling.
- Gasses
- Special attention should be given to drilling mud to prevent typical drilling issues like borehole collapse and stuck-pipe. In most cases a combination of CMC (Antisol) and bentonite will be needed. Concentrations should be limited to prevent too much skin on the borehole wall in the target reservoir. Max. CMC of 0.3 kg/m³ and 1,0 kg/m³ for exceptional cases (Oasen, 2006). Bentonite?50 kg/m³? KCL??
- The mud should be pre-hydrated for at least 24 hours before start drilling. This will ensure a proper aggregation of the bentonite-clay particles.
- It is necessary to use a solid control installation to remove fines from the mud: shakers and/or hydrocyclones (desanders/desilters).
- Mud quality monitoring should be more intensive compared to regular shallow drillings. Consider to use separate mud specialist for making, maintaining and monitoring the

mud. The following parameters should be monitoord: pH (??), viscosity, density, concentration of sand/clay after the solids control installation.

- Mud should be in perfect shape before entering the reservoir. If too much sand/silt is in the mud, it should be circulated and treated until it is improved, or it should be changed out with new clean mud.
- As long as no gravel pack and backfill is being installed, the mud in the annular zone should be circulated to prevent the settling of the mud.

3.3.6 Mechanical engineering considerations

The most important design considerations will be discussed by using a global diagram (Figure 14). For the specific projects the global diagram gives a rough idea of the system layout. This diagram have to be agreed by the involved designers of the backbone installations as well as the designers of the district heating network.

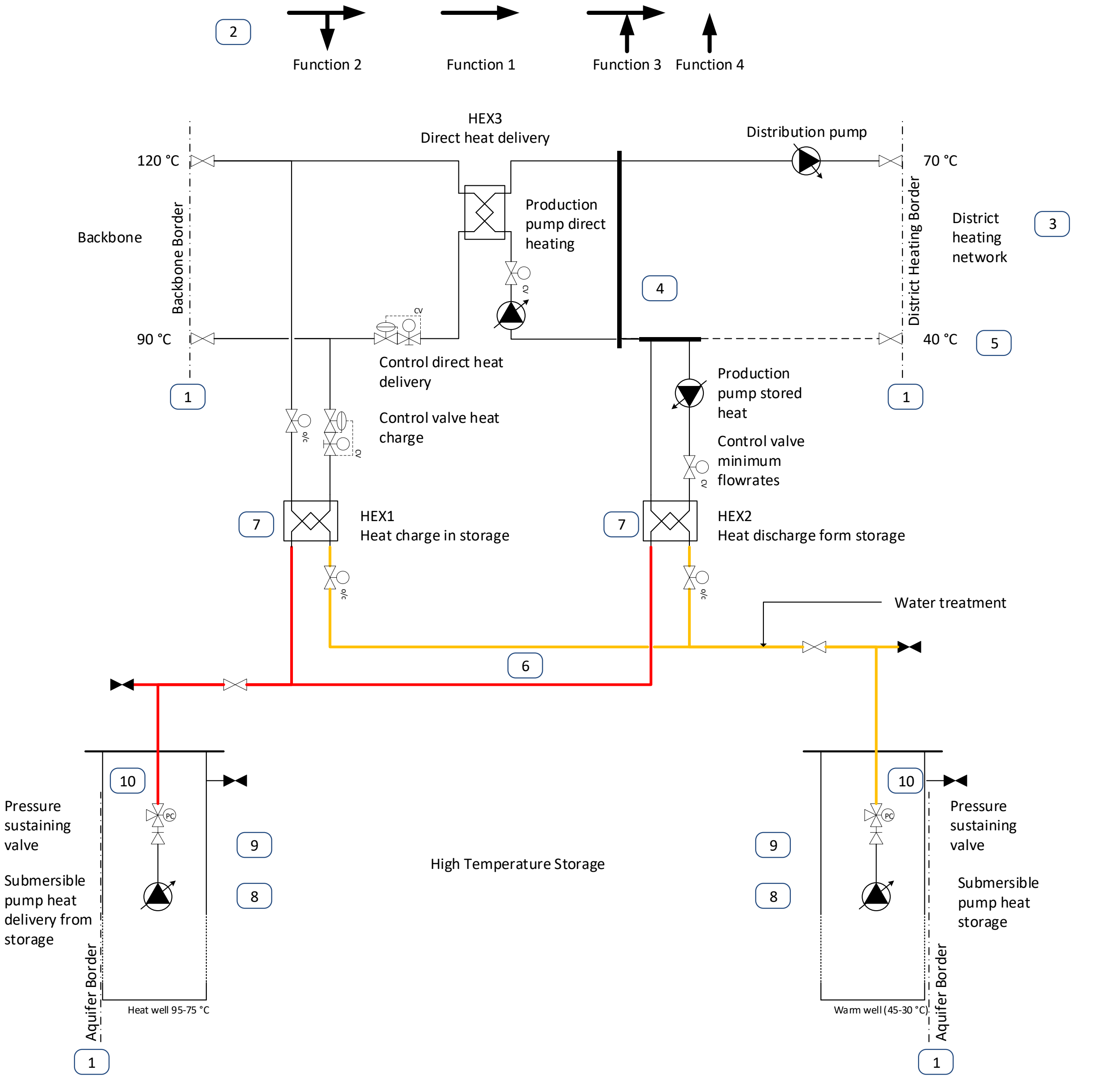

Figure 14 System integration of a HT-ATES

1. System borders

First step is to define the system borders and the design starting points and limitations at that borders: pressures, temperatures, flow's, water levels, water amounts, energy amount, power and other system requirements. In the scope of the High Temperatures Aquifer Thermal Energy Storage (HT-ATES) three borders are relevant: the back bone, which is the source of high temperature energy, the district heating network side which is the demand side of the system and the aquifer which is the location energy will be stored. In between these three borders the energy is exchanged in several ways.

2. Defining the functionality

Regarding the requirements as mentioned above and the global diagram, the functions of the energy system have to be defined. For example:

Function 1 Direct delivery: energy is delivered from the back bone to the district heating network

Function 2 Direct delivery and heat charge: energy is delivered from the backbone to the district heating network and charged in the high temperature storage at the same time

Function 3 Direct delivery and heat discharge: energy is delivered from the backbone to the district heating network and discharged from the high temperature storage at the same time

Function 4 Heat discharge: energy is discharged from the storage and delivered to the district heating network, the back bone connection is not in operation

3. Embedding HT-ATES in the energy system

In contrast to the regular used production units for heating, the HT-ATES will not be able to deliver a constant temperature during winter time (see Figure 15, displayed is the 10th year of system operation). This is of great influence in the choice where the HT-ATES will play its role in the installation.

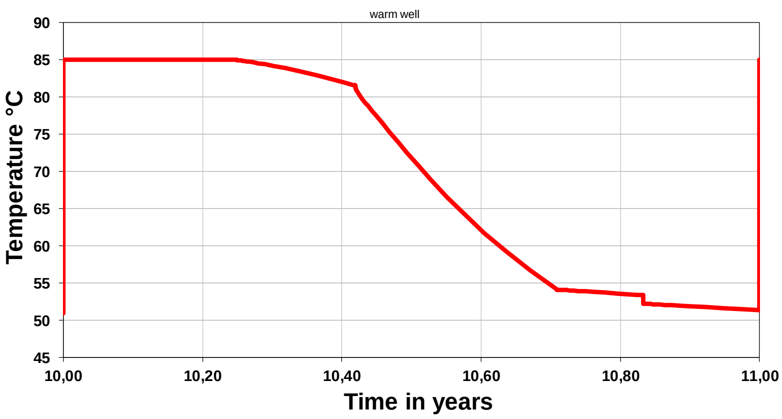

Figure 15 Temperature groundwater from warm well

Usually production units are placed in parallel while producing all the same temperature to fulfil the heating demand (see picture below). The delivery side of the installation frequently split up in several energy consumers with their one required temperature levels. By producing a high temperature at the energy power station, all temperatures can be generated by mixing valves at the delivery level.

In this kind of systems there is a big chance for a relatively small share of the HT-ATES in the energy production because the supply temperature will decrease quickly throughout the winter season and the return temperature may be too high because of the mixed high and low temperature delivery systems.

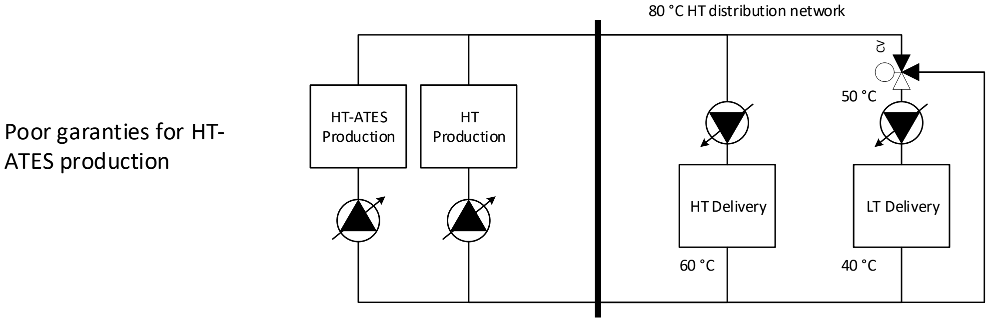

Figure 16 Poor guaranties for HT-ATES production

This situation can be improved by placing the HT-ATES production in serial with the HT production. The chance for a high return temperature form the delivery side is still there, but the possibility of HT-ATES production is improved because it is now possible to heat up the return in two steps. Where the first step is on behalf of the HT-ATES. Important point of attention is the maximum allowed entrance temperature in the HT production.

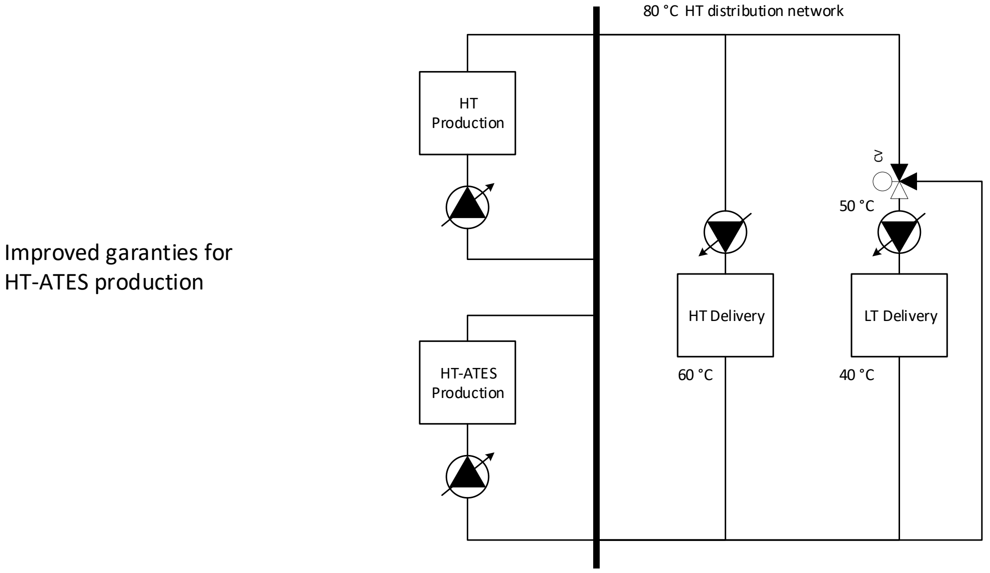

Figure 17 Improved guaranties for HT-ATES production

Better results can be achieved by splitting up the delivery distribution network in a high temperature network and a low temperature network. The HT production contributes to the HT network and the HT-ATES will produce on the LT network.

Best garanties for HT-ATES production

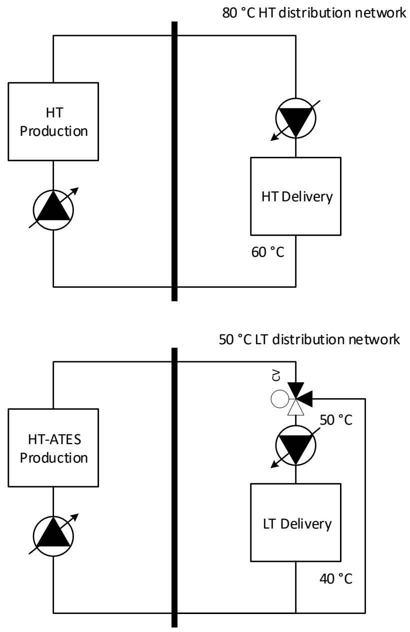

Figure 18 Best guaranties for HT-ATES production

Off course only a low temperature network will suits the best for HT-ATES production.

<u>4. Production configuration</u>
As mentioned above, for having a great share of the energy delivered by the HT-ATES, it is important that the HT-ATES production can be placed in serial with the direct delivery with the back bone. When a high temperature is available the HT-ATES will be able to generate the desired supply temperature. When the temperature from the warm well is decreasing, the HT-ATES is still able to take its part in the power generation in addition to the delivery from the backbone. Important point of attention is the return temperature in the Backbone circuit when HEX2 and HEX3 are placed in serial. Also the minimum capacity of the direct heating is a point of attention.

<u>5. Return temperature</u>
The return temperature from the district heating network is of great influence on the HT-ATES share in the energy production. The measures which are necessary to guarantee these good return temperatures lays at the other side of the border in the district heating network. So this is an important risk which cannot be controlled in the design of the HT-ATES itself, but have to be guaranteed by other parties.

High return temperatures are often caused by short cuts between supply and return pipes in the district heating network. These short cuts are necessary due to the short response times in domestic hot water production. This have to be an important discussion between the engineers of the HT-ATES and the engineers of the district heating network with low return temperatures as the final goal and meeting the requirement with regard to response times.
In each delivery set on the end users location a temperature limitation have to be implemented.

6. Temperature split.

Splitting up de system in two temperature levels might have some advantages in system cost when the low part of the system becomes beneath about 50 °C. At the low temperature side cheaper and more regular components can be selected. Important point of attention is the risk of higher temperatures at the low temperature side with possible component failure as a result. The most of the risks can be eliminated by good system alarming. However in situations with thermal break through between the warm well and the cold well, nothing can be done to protect the warm well for being exposed to high temperatures.

7. Heat exchanger

In all of the Dutch HT-ATES projects plate heat exchangers are used for the energy exchange between groundwater and other circuits. Frequently expansion and shrink of the heat exchanger due to temperature differences gives a risk for leakage at the sealings. For that reason a temperature hold function can be added to the heat exchanger.
Stainless Steel 316L is the commonly used material for the plates (important requirement is the absence of oxygen in the system). Final material choice depends on the water quality and water treatment.
Heat exchanger fouling can be of great influence on the temperatures at both sides of the heat exchanger. An important measure to avoid fouling is the water treatment (described in the next chapter) an the use of strainers in the pipework. Good monitoring with match paired temperature transmitters in combination with reliable flow transmitters (magnetic inductive or ultrasonic) and pressure transmitters makes early detection of heat exchanger fouling possible.

8. HT-ATES Pump

In the past deep shaft pumps were placed at some of the Dutch HT-ATES projects but they have all been replaced by Electrical Submersible Pumps (ESP).
Distinction can be made between de cold and the warm well of the HT-ATES. Normal ATES ESP's (also used for domestic water wells) are suitable up to a temperatures of about 60 °C during pump operation and about 85 °C when not in operation (to be confirmed by the supplier). For motor cooling a water/glycol mixture is used.
At the warm well a pump can be used from the oil and gas industry. These type of ESP's are oil filled and often equipped with down hole monitoring to measure the performance of the pump but also the monitoring for the well. A so called "food-grade" oil is available to avoid environmental damage in case of oil leakage.
Cooling of the motor is always an important issue due to the fact that the motor cooling is performed by the flow of the groundwater.

9. Injection valve

Degassing of groundwater have to be avoided because it may clog the wells very fast. Several types of pressure sustaining options have been practised in ATES-history. At the beginning of ATES injection lines where used. These injection lines consist of several pipes in the pump chamber which generates enough pressure drop at certain flowrates. A big disadvantage of this type is that the flowrate can only be adjusted in fixed values (not stepless). For that reason now a days only back pressure valves are used as pressure sustaining valve. These back pressure valves can be split up in to types: the inline version which is placed in the pump chamber and the normal version which is placed in the well house. The normal ATES versions are suitable for temperatures up to 85 °C (this have to be confirmed by the specific supplier of the valve). Extra point of attention is the control circuit of the valve, especially when this may come in contact with the hot groundwater.

10. Components in pump chamber

The high temperatures in the wells have some consequences for the pump chamber design which have to be taken in to account:

a. Wells will be heated during operation and cool down during non-operating periods. With the high temperatures the expansion and shrinkage of the casing and wellhead need to be taken into account in the design. This also accounts for piping that is connected to the wellhead.
b. Because of heating up the well, the water level in the well will rise significantly. Special attention is needed on pressures (can become artesian when heated), on safety measures to prevent exposure to hot water and on special constructions on the wellhead and procedures for maintenance purposes when wellheads need to be opened (for example regeneration operations or changing pumps etc.).
c. All components have to be suitable for the maximum temperatures which might occur in the pump chamber (even at the cold side of the HT-ATES).
d. Due to degassing of the groundwater, at the top of the pump chamber gas may accumulate just beneath the well head. This is the naturally dissolved gas in the groundwater combined with the gas which might be introduced by the water treatment. It is recommended to place the cables for pumps and transmitters in a stainless steel casing filled with domestic water. Depending on the quality of the gas a safety risk may be introduced in the well house due to small gas leakages at the well head.

3.3.7 Water treatment

One of the main problems that were encountered in TH-ATES projects in the past is mineral precipitation, especially precipitation of carbonates. For most minerals the solubility increases when the temperature rises, but for carbonates this is not the case. The result is well known from daily practice: scaling in kettles or at heating elements in washing machines. In theory a limited rise in temperature of water that is initially saturated with calcite, the most common carbonate ($CaCO_3$), leads to oversaturation and should result in calcite precipitation. In practice however, calcite precipitation does not occur when the temperature rise is limited. In literature different critical temperatures are mentioned, varying from 50 °C (Heidemij, 1987), 40-60 °C (Snijders, 1991, 1994) and 60 to 70 °C (Knoche et. al, 2003). The fact that no precipitation occurs despite significant oversaturation is attributed to the presence of natural inhibitors like phosphate and organic acids (Griffioen and Appelo, 1993; Griffioen, 1992). At the Reichstag Building (storage of 70 °C heat) no water treatment is used (Sanner, 1999). Apparently, the groundwater composition is favorable at this site.

Conclusion is that the risk of carbonate precipitation depends on the degree of carbonate saturation of the original groundwater, the temperature increase and the presence and concentrations of inhibitors. If groundwater is used that is/has been in contact with carbonates (which is likely to be saturated with carbonates), precipitation of calcite is likely in case of HT-ATES if no countermeasures are taken. The necessity to avoid calcite precipitation is illustrated by the initial experiences at the University of Minnesota in St. Paul (USA), where the heat exchanger of an experimental HT-ATES plant had to be cleaned with acid after every 40 hours of operation (Miller and Delin, 2002).

Methods

Precipitation of carbonates occurs because of (significant) oversaturation. For calcite, the degree of saturation is assessed by calculating the calcite Saturation Index (SI_{cc}):

$$SI_{cc} = \log [Ca^{2+}][CO_3^{2-}]/k$$

Here $[Ca^{2+}]$ and $[CO_3^{2-}]$ are the concentrations (or more accurately: the activities) of Calcium (Ca^{2+}) and Carbonate (CO_3^{2-}), and k is the equilibrium constant for calcite. The equilibrium constant is temperature dependent and decreases for increasing temperatures. When $SI_{cc} = 0$, the water is calcite saturated (in equilibrium with calcite: no calcite will dissolve or precipitate). When the Saturation Index is negative the water is undersaturated, which means that more calcite can be dissolved in the water. When the Saturation Index is positive, the water is oversaturated and there is a tendency for calcite to precipitate. However, in practice it appears that some degree of oversaturation is possible without calcite precipitation, which is attributed to the presence of inhibitors.

Based on the above theory, several strategies are possible to prevent clogging by precipitation:

1. Lowering of the temperatures that the water experiences (increases the value of the equilibrium constant);

The most straightforward way is to reduce the storage temperature. However, this option has large consequences for the temperature level of the heat that is recovered. Since storage of high temperatures is the starting point of this project, lowering the storage temperature is not considered as an option.
However, lowering the temperature of the hot water that is used to heat the groundwater will help to minimize scaling potential. When high temperatures are fed into the plate heat exchanger, this will increase the scaling tendency. Using a lower feed temperature reduces the risk of scaling (and/or reduces the required degree of water treatment), but increases the required size of the heat exchanger.

2. Lowering the calcium concentration (reduces the saturation index);

An option to reduce the calcium concentration is the application of ion exchange. This method was used in the Utrecht University HT-ATES plant, but had too many drawbacks (more details in Drijver, 2011).
Another option that reduces the calcium concentration is the use of a complexing agent, that binds part of the dissolved calcium. Because the saturation index is reduced, this may lead to dissolution of carbonates from the storage aquifer (when present) so that treatment may be required each heat storage cycle.

3. Lowering the Carbonate concentration (reduces the saturation index);

A standard technique to reduce the carbonate concentration is lowering the pH by adding acid:

$$H^+ + CO_3^{2-} \Rightarrow HCO_3^-$$

Since the saturation index is reduced, dissolution of carbonates (when present) may occur in the storage aquifer. As a consequence, treatment may be required each heat storage cycle.

Treatment with hydrochloric acid (HCl) can be considered proven technology, since this was successfully used at the Zwammerdam HT-ATES plant. The main disadvantage of HCl is that it is a hazardous fluid and large volumes of HCl are needed in large scale HT-ATES plants. The necessity of frequent transport movements of trucks with HCl is considered undesirable. Another disadvantage is that the salinity of the groundwater will increase. In aquifers that contain carbonates, the addition of HCl will be necessary each cycle, which will eventually result in a significant increase in salinity: in Zwammerdam a rise in chloride concentration from 3900 to 4100 mg/l was calculated for 20 years of operation (Drijver, 2011). For brackish and salt groundwater this rise may not be a problem, but for initially fresh water this will usually not be acceptable.

Another acid that was considered in the past is CO_2. Addition of CO_2 was tested successfully in experiments, but has not been used in full scale plants (Sanner, 2004; Sanner, 1999; Koch and Ruck, 1992). In water treatment systems using membranes (e.g. Reverse Osmosis systems), CO_2-treatment is also known for scaling prevention in other

4. Adding inhibitors

Inhibitors effectively hinder the precipitation process. The presence of inhibitors explains why some degree of oversaturation is possible without precipitation. The idea of adding inhibitors is to further increase the degree of oversaturation that is possible without precipitation. So far, this method has not been used in HT-ATES plants. However, positive experience is available in deep geothermal plants.

5. Controlled precipitation

In the past, experiments have been performed with controlled precipitation of carbonates that are subsequently removed from the system. In 1989, a fluidized bed heat exchanger was installed in the HT-ATES pilot plant SPEOS in Dorigny (Switzerland). This solved the scaling problems in the heat exchanger, but clogging in the drains was still found (Sanner, 1999).

Scaling tests

Satisfying prediction of scaling behavior in heat exchangers by means of conventional geochemical modelling software is not possible. This makes it difficult to assess the necessity of water treatment and the required degree of treatment. Within the Implementing Agreement "Energy Conservation by Energy Storage" Annex 12 "High Temperature Underground Thermal Energy Storage" of the International Energy Agency a mobile test rig (MTR) has been constructed for preliminary investigations on groundwater in respect to troublesome scale formation in above-surface HT-ATES installations, e.g. heat exchangers (Knoche et al., 2003). This mobile test rig has been used on groundwater from eight different locations to find the temperature where scaling starts to occur when no water treatment is used. The same device was also used to perform tests with CO_2 treatment. These tests show that water treatment with CO_2 works to prevent carbonate scaling and can also be used to dissolve scaling that has already formed in a heat exchanger (Sanner, 2004). Unfortunately, the test device has been dismantled and is therefore not available any more (Sanner, personal communication).

For new HT-ATES projects, a first indication of the required degree of water treatment can be obtained by performing geochemical modelling. In these calculations, a certain critical value for the saturation index must be assumed (saturation index above which scaling in the heat exchanger occurs). The right value can be obtained from in-situ tests with the local groundwater from the HT-ATES site (after construction of a test drilling or at least one of the HT-ATES wells). These tests can be extended with water treatment, to find the required dosage. When no tests are done, this may result in overtreatment, with the associated unnecessary costs and environmental impact.

Scaling control system

When scaling occurs in the heat exchanger or in the wells, this can lead to failure of the system and/or irreversible damage to the wells. It is therefore essential to be able to timely register the start of a scaling problem and take the right measures. For the heat exchanger, deterioration of the heat transfer coefficient may be the best indicator. However, tests in practice were not yet successful (Sanner, 2004). For the wells, the specific capacity is usually used as an indicator. Complicating factor for HT-ATES is the influence of the temperature distribution around the well that is tested. It can be considered to lead part of the heated groundwater through a small-scale sand filter and monitor the pressure drop. Another option is the use of coupons.
A standard measure to prevent hydraulic fracturing (resulting in irreversible damage to the wells) is the use of a pressure limit during injection.

Summing up the design considerations for water treatment:

- Consider water treatment at temperatures above 50 °C
- Use of hydrochemical modelling for a first assessment of the necessity of water treatment. In-situ testing with local groundwater recommended.
- HCL treatment is proven technology. Main disadvantage is the use of large volumes of HCl
- CO_2 treatment is a promising technology. To be tested on full-scale
- Automated scaling detection/scaling control system is highly recommended to prevent irreversible damage to the system
- Inhibitors may be worth investigating

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