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Installation, monitoring, dismantling and initial analyses of material from LOT test parcel S2 and A3

Results from field test

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Update notice

The original report, dated June 2020, was found to contain both factual and editorial errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2020-10

Location	Original text	Corrected text
Page 8, Section 1.3, No 1	Report: Examination of copper components from the field tests LOT/S2 and LOT/A3, SKB TR-20-14 (in preparation).	(Johansson et al. 2020).
Page 11, Table 2-2	*Wrong data in table*	*Table updated with correct data*
Page 53, References	*New reference*	Johansson J, Svensson D, Gordon A, Pahverk H, Karlsson O, Brask J, Lundholm M, Malmström D, Gustavsson F, 2020. Corrosion of copper after 20 years exposure in the bentonite field tests LOT S2 and A3, SKB TR-20-14. Svensk Kärnbränslehantering AB.

Abstract

Bentonite clay is an important part of the Swedish KBS-3V design for final repositories of spent nuclear fuel. The spent nuclear fuel is encapsulated in copper canisters which are deposited in vertical deposition holes in crystalline rock at a depth of 400–700 meters. Between the canisters and the rock, compacted bentonite blocks are emplaced as buffer material to protect the canisters and limit the flow of water. The bentonite absorbs water and develops a swelling pressure that will keep the canister in place and the microbiological activity low. The plasticity of the clay should be high enough to not transfer any force from the rock to the canister in case of rock displacements.

The LOT test series can be described as a multi-task experiment in which relatively small test parcels are exposed to field conditions. The test series include in total seven test parcels of which three have been exposed to conditions similar to those in a KBS-3 repository and four parcels have been exposed to conditions with accelerated alteration processes (increased temperature). The test parcels contain prefabricated bentonite blocks placed around copper tubes, which are placed in vertical boreholes in granitic rock. After exposure to field conditions for a defined period, a test parcel has been extracted by overlapping drilling outside the original test hole. The whole test parcel including surrounding rock, has thereafter been lifted and transported to a laboratory where it has been divided. Material from defined positions in the parcel, and reference material, have thereafter been examined by well-defined tests and analyses in order to provide data for the different objectives.

Four test parcels have been dismantled earlier. This report describes the dismantling of additional two test parcels i.e. one test parcel in this test series is still running.

Sammanfattning

Bentonitlera är en viktig del i det svenska KBS-3V konceptet för slutförvaring av utbränt kärnbränsle. Det utbrända kärnbränslet placeras i kopparkapslar som deponeras i vertikala deponeringshål i kristallint berg på ett djup av 400–700 meter. Mellan kapslarna och berget placeras kompakterade bentonitblock för att skydda kapseln och för att begränsa vattenflödet. Bentoniten absorberar vatten och utvecklar ett svälltryck som kommer att hålla kapseln på plats och även begränsa mikrobiologisk aktivitet. Plasticiteten hos leran är tillräckligt hög för att inte kunna överföra eventuella krafter från berget till kapseln vid eventuella rörelser i berget.

LOT testerna kan beskrivas som ett försök där flera olika saker undersöks i relativt små testpaket som är exponerade för fältförhållanden. I testserien ingår total sju testpaket varav tre är exponerade för liknande förhållanden som de förväntade i ett KBS-3 förvar och fyra testpaket är exponerade för förhållanden där hastigheten hos omvandlingsprocesserna har ökats (ökad temperatur). Testpaketen består av kompakterade bentonitblock som har staplats runt kopparrör vilka är placerade i vertikala borrhål i granitiskt berg. Efter att ha exponerats för fältförhållanden under en bestämd tid har ett testpaket frigjorts genom borrning av överlappande borrhål i berget utanför själva testhålet. Hela testpaketet, inklusive omgivande berg, har därefter lyfts upp och transporterats till ett laboratorium där det har delats och provtagits. Material från definierade positioner, samt referensmaterial, har därefter undersökts genom olika väldefinierade tester och analyser för att kunna leverera data till olika ändamål.

Fyra testpaket har brutits och undersökts tidigare. I denna rapport beskrivs brytningen av ytterligare två testpaket dvs. endast ett testpaket i denna testserie är fortfarande igång.

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1 Introduction

1.1 The Swedish KBS-3 design

Bentonite clay is an important part of the Swedish KBS-3V design for final repositories of spent nuclear fuel. The spent nuclear fuel is encapsulated in copper canisters which are deposited in vertical deposition holes in crystalline rock at a depth of 400–700 meters. Between the canisters and the rock, compacted bentonite blocks are emplaced as buffer material to protect the canisters and limit the flow of water. The bentonite absorbs water and develops a swelling pressure that will keep the canister in place and the microbiological activity low. The plasticity of the clay should be high enough to not transfer any force from the rock to the canister in case of rock displacements.

An important function of the bentonite buffer is to minimise water flow over the deposition holes. The transport through the buffer is expected to be reduced and to be controlled principally by diffusion, both with respect to corrosive components in the groundwater, to corrosion products and regarding escaping radionuclides in case of a canister failure.

The decaying spent fuel in the High Level Waste (HLW) canisters will increase temperature and initially give rise to a thermal gradient over the bentonite buffer by which original water will be redistributed in parallel to an uptake of water from the surrounding rock.

1.2 LOT test program

1.2.1 General description

The Long Term Test of Buffer Material, LOT, test series has focused on the long term performance of the bentonite buffer, i.e. the conditions after water saturation, and on buffer related processes in a water saturated bentonite buffer concerning microbiology, cation transport, and copper corrosion.

The complete test series includes seven different tests, Table 1-1. The status of the test series can be compiled as follows:

- **A1 and S1**. Pilot tests that were installed in the end of 1996. Both tests were dismantled in March 1998. The results are reported by Karnland et al. (2000).
- **A2**. Installed in October 1999 and dismantled in January 2006. The results are reported by Karnland et al. (2009).
- **A0**. Complementary test to A1. The test was installed in December 1999 and dismantled in November 2001. The results are reported by Karnland et al. (2011).
- **A3 and S2**. Installed in September–October 1999. The tests were dismantled in September 2019 and results from dismantling and initial material investigations are presented in this report.
- **S3**. Installed in September 1999 and still running.

Table 1-1 The complete test program of the LOT test series.

Test	Max T, °C	Controlled parameters	Test duration, years	Remark	Installed	Terminated
A1	130	T, [K+], pH, am	1.3	pilot test	Nov 1996	Mars 1998
A0	120–150	T, [K+], pH, am	1.9	A1 complement	Dec 1999	Nov 2001
A2	120–150	T, [K+], pH, am	6.1	main test	Oct 1999	Jan 2006
A3	120–150	T	20	main test	Oct 1999	Sep 2019
S1	90	T	1.4	pilot test	Oct 1996	Feb 1998
S2	90	T	20	main test	Sep 1999	Oct 2019
S3	90	T		main test	Sep 1999	

A = Adverse conditions, S = Standard conditions, T = Temperature, [K+] = potassium concentration, pH = high pH from cement, am = accessory minerals added.

1.2.2 Objectives of the LOT test series

The main objectives of the LOT test series are described in detail by Karnland et al. (2009). Here are also descriptions of the different processes and models in the canister-buffer-rock system provided.

The general objectives of the current two test parcels in the LOT test series may be summarised in the following items:

- Collect data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, hydraulic conductivity and rheological properties.
- Check of existing models concerning buffer degrading processes, e.g. mineral redistribution and montmorillonite alteration.
- Check of existing models concerning cation diffusion in bentonite.
- Check of calculated data concerning copper corrosion and collect information regarding the character of possible corrosion products.
- Collect information, which may facilitate the realisation of the full-scale test series (e.g. the Prototype project) with respect to clay preparation, instrumentation, data handling, termination, retrieval and evaluation.

1.3 This report

This report concerns the termination of the A3 and S2 test parcels and describes the:

- background to the LOT test series,
- the main objectives with the tests,
- design of the test parcels,
- field operation including preparation and installation,
- results from monitored data,
- dismantling of the test parcels,
- initial analyses of the bentonite.

In addition to this report, separate reports will be made describing:

1. The results from investigations of copper corrosion (copper coupons and the central copper tube). (Johansson et al. 2020).
2. The investigation of the bentonite regarding chemical and physical properties and regarding the mineralogical stability of the bentonite clay.

2 Design of the test parcels

2.1 General

The LOT test series can be described as a multi-task experiment in which relatively small test parcels are exposed to field conditions at Äspö Hard Rock Laboratory (HRL). The experiment includes a total of seven test parcels. Each test parcel consists of a central copper tube with an electrical heater inside. Prefabricated ring-shaped bentonite blocks are placed around the copper tube. The test parcels were placed in a vertically drilled 4-meter deep borehole in granitic rock, 450 meters below ground surface at Äspö HRL.

Different types of instruments were placed in the bentonite measuring, total pressure, pore pressure, relative humidity and temperature. The thermocouples, measuring the temperature, were also used to regulate the applied power during the initial heating.

The two current test parcels, S2 and A3, also contained equipment used for special measurements: ^{60}Co tracer doped plugs placed in one block to study radionuclide migration in compacted bentonite, copper coupons which can be used to quantify total corrosion with accurate methods (i.e. gravimetric analysis), which is not possible for the large copper tube (see further TR-20-14).

After exposure to field conditions for a defined period, a test parcel was extracted by overlapping drilling outside the original borehole, and the whole test parcel was lifted and transported to a laboratory where it was divided. Material from defined positions in the parcel and reference material were thereafter examined by well-defined tests and analyses in order to provide data for the different objectives listed in Section 1.2.

The dimensions of the test parcels were kept considerably smaller, especially the diameter, compared to a KBS-3 deposition hole in order to:

- shorten the water saturation period and thereby have saturated conditions during a substantial part of the test period,
- achieve a higher temperature gradient over the buffer material,
- facilitate sampling, i.e. release and lift the exposed test parcel in one piece.

2.2 Test site

2.2.1 General

The two pilot test parcels were installed in a niche at the −420 level, positioned opposite the elevator, while the main test series, five tests, were installed in the G tunnel situated in the western part of the Äspö HRL, Figure 2-1. The depth from surface is around 450 m and the rock consist mainly of Äspö diorite, which is crossed by some pegmatite dikes and bands of fine-grained granite. A few water-bearing fractures are visible, but the tunnel may be considered relatively dry compared to the average Äspö rock volume.

2.2.2 Pilot boreholes for the main test series

Five 76 mm vertical pilot holes were drilled in line on the northern side of the G-tunnel between 2nd March and 4th March 1999. The holes were approximately 8 m deep and with a relative distance of 4.5 m. The holes were termed KG0033G01, KG0037G01, KG0042G01, KG0046G01 and KG0051G01, where K denotes core-drilled, G denotes the G-tunnel, 0033 denotes the length in meters from tunnel entrance, and G denotes floor position. The KG0042G01 hole and the KG0046G01 were used for the A3 and S2 test parcels respectively.

No definite suitability criteria were defined for the test holes, but the water pressure in the holes must be higher than the vapor pressure at the chosen test temperature to avoid boiling (0.36 MPa for 140 °C). Further, water inflow had to be low enough to allow the installation of the test parcels and to exclude the risk of piping and erosion after closure.

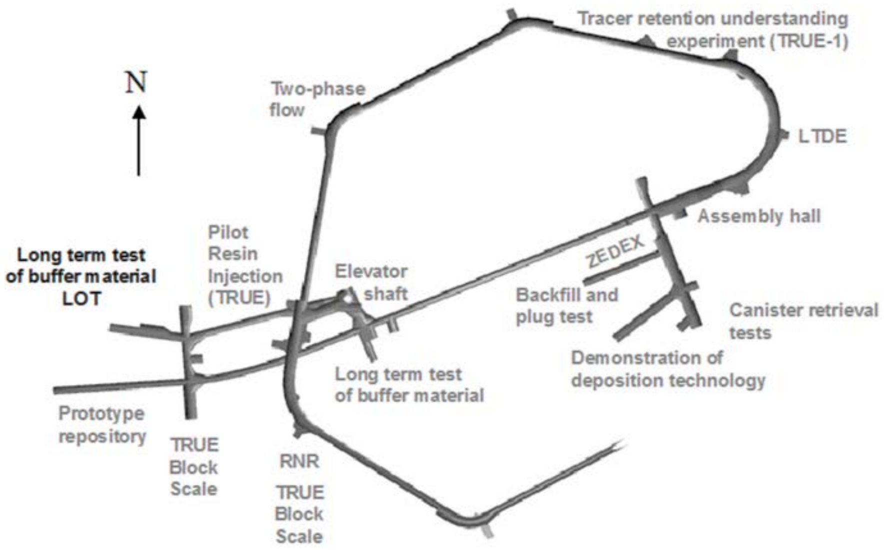

Figure 2-1. The LOT test site is located in the G-tunnel in the western part of the research area, and close to the lowest part of the Äspö tunnel.

Water inflow

The water inflow rates were measured at different depths in the five boreholes. The flow measurements were made by use of double packers with 1 m spacing in the upper 4 m and a single packer was used for the bottom part (4 m to 8 m). With this equipment it was possible to measure the water inflow to a decided section of the boreholes. The results of these measurements are presented in Table 2-1.

Table 2-1 Flow rates (ml/min) measured in intervals of the five pilot boreholes for the LOT tests in the G-tunnel of ÄSPÖ HRL, April 1999.

	Test parcel/pilot borehole				
	A0	**A2**	**A3**	**S2**	**S3**
Section	**KG0033G01**	**KG0037G01**	**KG0042G01**	**KG0046G01**	**KG0051G01**
1.4–8.05	0.025	0.02	−0.12	1.3	0.025
1.00–2.00	0.07	0.09	±0	0.1	0.07
2.00–3.00	0.07	0.07	0.04	0.14	0.01
3.00–4.00	0.06	0.14	0.05	0.08	0.07
4.00–8.05	0.01	0.06	0.01	0.60	0.01

The average water inflow to the borehole where test parcel S2 should be installed was nearly two orders of magnitude higher compared to the other boreholes. The general conclusions from the pilot hole characterisation program were that the water inflow was low, and that the water inlet points were few in all holes. The test time was therefore expected to be much longer than acceptable. Instead of abandoning the site it was decided to add external groundwater into the test holes during the test period. A water supply hole (HG0038B01) was drilled into the northern wall where a water-bearing fracture was found a few meters into the rock. The water pressure was determined to be around 1.2 MPa and the flow was more than enough to support all test holes. A mechanical packer was placed in the borehole. Water was led through the packer into a system of titanium tubes which were used to inject water into each of the five test holes during the entire test period, see also description in Section 3.2.2.

Rock formation water

The water composition has repeatedly been measured in borehole HG0038B01 by use of the "class 5" quality (highest) according to the Äspö HRL nomenclature and the typical composition of main ions is given in Table 2-2.

Table 2-2 Main composition of the formation water in water supply bore hole HG0038B01 (concentrations in mM).

HG0038B01 Units	Na^+ mM	K^+ mM	Ca^{2+} mM	Mg^{2+} mM	HCO_3^- mM	Cl^- mM	SO_4^- mM	Br^- mM	F^- mM	Si mM	HS^- mM	pH	E.C. mS/m
2000-04-14	98.7	0.24	43.4	2.21	0.85	185	4.84	0.50	na	0.18	na	7.4	1750
2001-09-26	104	0.25	49.6	2.15	0.71	195	4.94	0.62	0.13	0.20	0.0006	7.4	1930
2006-10-02	98.7	0.26	56.6	1.90	0.21	219	5.57	0.62	0.08	0.21	0.0003	7.6	2170
2012-05-08	104	0.22	56.6	1.83	0.22	205	5.10	0.55	0.09	0.21	< 0.0006	7.7	2080
2018-11-06	132.7	0.30	75.6	1.45	0.13	266	5.78	0.83	0.09	0.17	< 0.0006	7.8	2553

2.2.3 Test holes

The five pilot holes were enlarged to a diameter of 300 mm to a depth of 4 m. The enlargement was made by percussion drilling because this technique was thought to best simulate the core TBM-type drilling with respect to surface damage and thereby to water conductivity. The test holes were named according to the standard Äspö database nomenclature; HG0033G01, HG0037G01, HG0042G01, HG0046G01 and HG0051G01. The HG0042G01 hole and the HG0046G01 were used for the A3 and S2 test parcels respectively.

After enlarging the test holes, the diameter and the straightness were checked. There was a certain variation in diameter. In some parts of the boreholes, the diameter was exceeding 300 mm by up to 10 mm.

2.3 Test parcel construction

2.3.1 General

The basic demand for the test parcel construction was to keep a defined maximum temperature in the central part of the clay column during the test time span. An important part of the system was therefore the temperature measurement and the power regulation system. A central heater inside an open tube was chosen, as this allows for heater change during the test period in case of a failure. The central tube was made of copper in order to simulate the KBS-3 copper canister, and thereby keep as realistic chemical conditions as possible.

Schematic drawings showing the principal design of the two test parcels S2 and A3 are provided in Figure 2-2 and Figure 2-3. The test parcels contained heaters, central tubes, bentonite blocks and different type of sensors, which are described in the following sections.

2.3.2 Heaters

Specially designed electric heaters from Backer Elektro-värme AB, Sösdala, Sweden were used. The total length was 4650 mm, and the active bottom part had a length of 2000 mm. Three individual stainless steel (SS2348) elements with a diameter of 14 mm were brazed into a stainless steel (SS2343) flange, which was designed in order to let the heater hang down from the top of the copper tube. The maximum power was 2 kW (230/400 V, AC), i.e. each element had a maximum power of 667 W (230 V) corresponding to 0.7 W/cm^2. The expected power need was based on the results from previously performed pilot tests A1 and S1, which agreed with scoping calculations.

2.3.3 Central copper tubes

The copper tubes (SS 5015-04), simulating the canister, had a length of 4700 mm, an inner diameter of 100 mm and a wall thickness of 4 mm. The outer diameter of the tubes is thus 108 mm. With a nominal borehole diameter of 300 mm, the thickness of the buffer will after saturation be 96 mm. At the bottom end of each tube, a copper plate and 4 copper reinforcement parts were brazed by use of soldering silver. A detachable lifting device was placed at the top of the tube during the installation. The maximum possible external pressure acting on the outside of the central tube was expected to be less than 10 MPa (bentonite swelling pressure plus hydrostatic water pressure), which results in a maximum compression stress of the tube of 140 MPa. The used hard-drawn copper quality has a yield point exceeding 200 MPa, which consequently was sufficient.

The upper part of the copper tube was open to the Äspö tunnel and the interior of the tube has thus been filled with air during the entire exposure period. Since no leakage of water/steam or air between the Äspö tunnel and the buffer material in LOT could be accepted, with respect to both the heater function and the mass transport conditions, the impenetrability was tested after the soldering by use of a helium source inside the copper tube and an external detector.

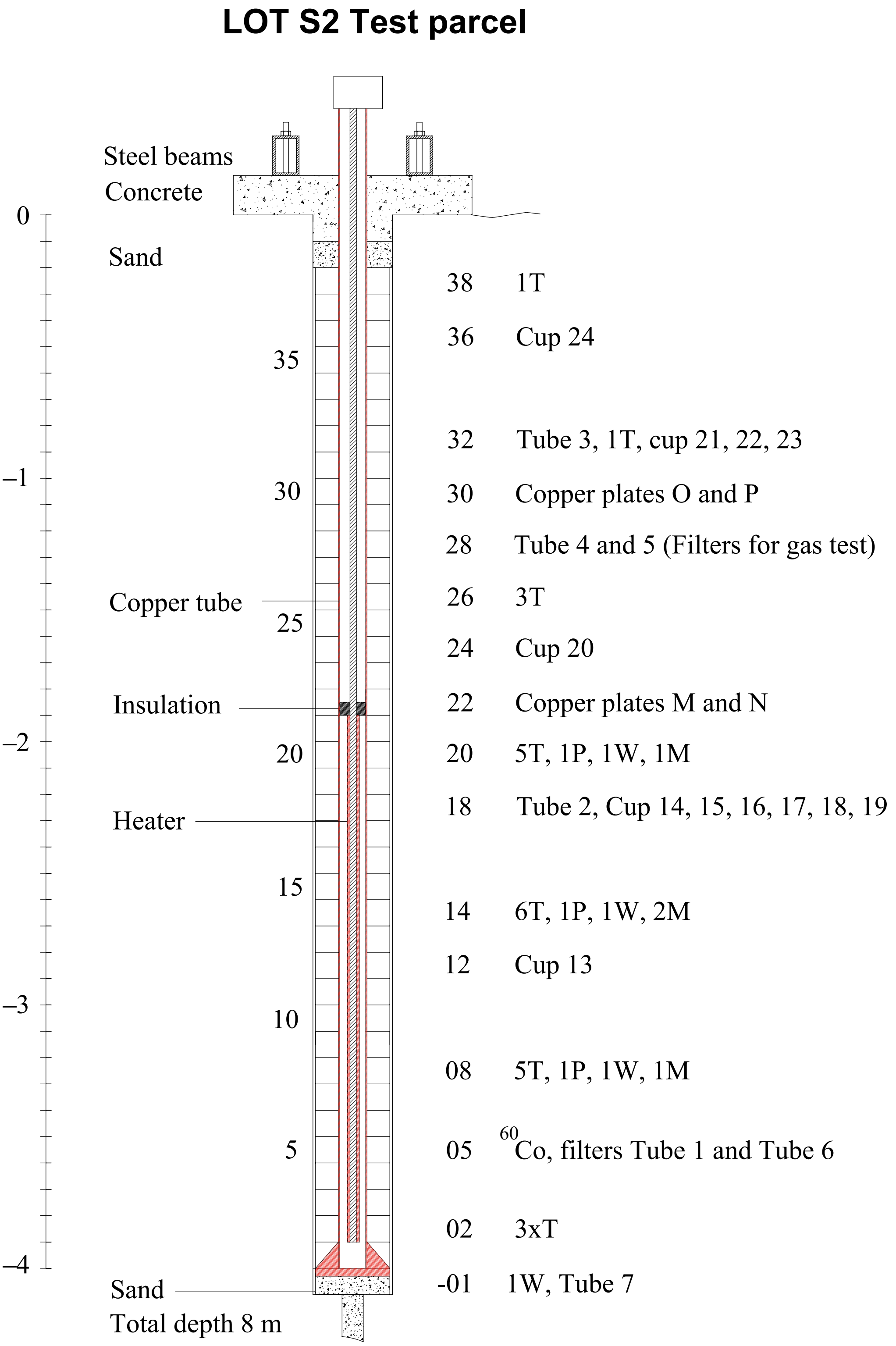

Figure 2-2. *Schematic drawing showing the principal design of Test parcel S2. The type of instruments in the different blocks is described to the right (abbreviations are explained in the text). The block numbers (counted from bottom) are given together with the depth of the test hole.*

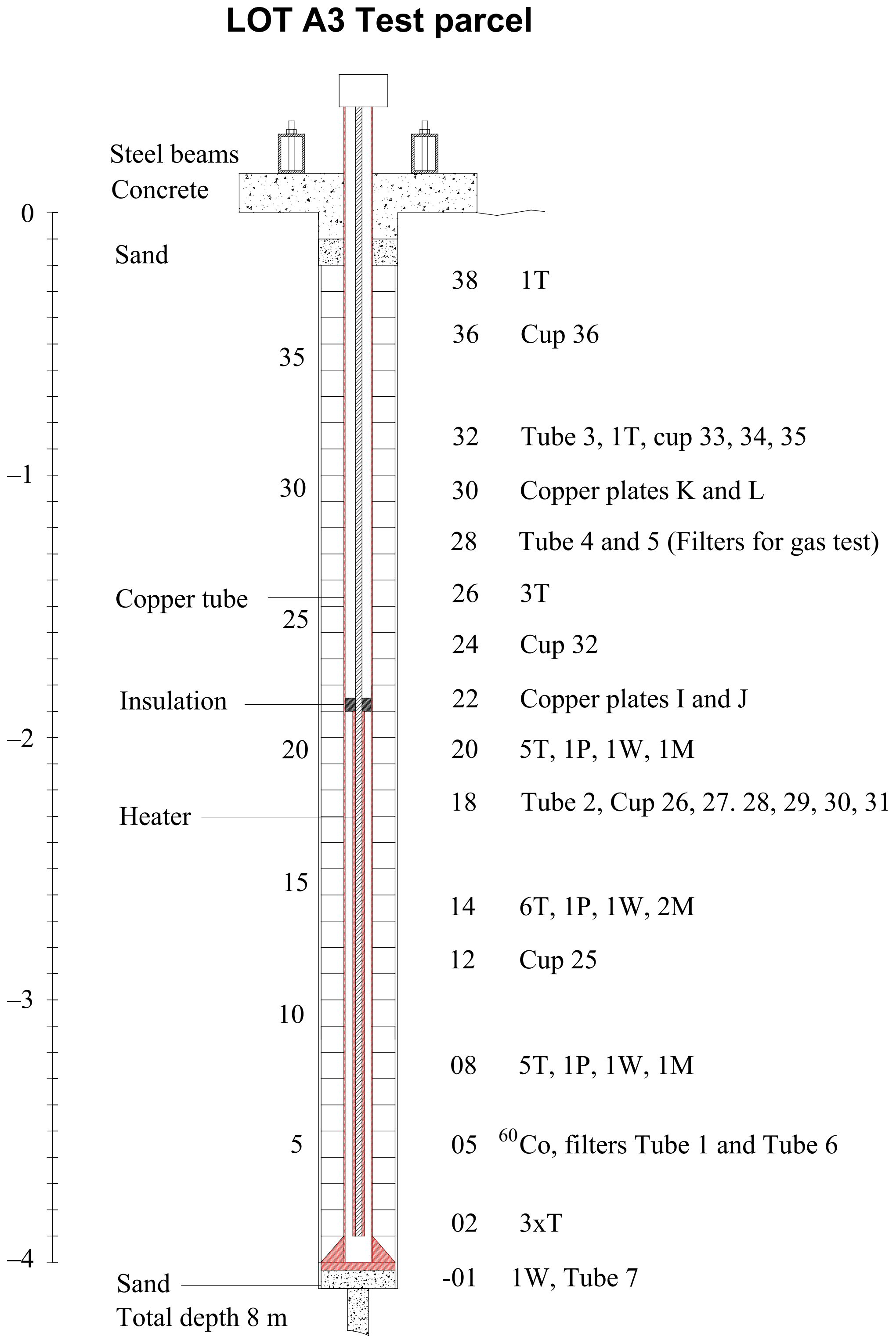

Figure 2-3. *Schematic drawing showing the principal design of Test parcel A3. The type of instruments in the different blocks is described to the right (abbreviations are explained in the text). The block numbers (counted from bottom) are given together with the depth of the test hole.*

2.3.4 Blocks

Wyoming bentonite with the commercial name MX-80 was the source material for all bentonite components in the system. It was delivered by Askania AB and manufactured by Volclay LTD, Mersyside, UK. The material was delivered in 25 kg sacks in one consignment.

The material is dominated by natural mainly sodium montmorillonite clay (~ 80 % by weight). Accessory minerals are quartz (~4 %), tridymite (~4 %), cristobalite (~3 %), feldspars (~4 %), muscovite/illite (~4 %) sulphides (~0.2 %), and small amounts of several other minerals and organic carbon (~0.4 %). Dispersed in distilled water the clay fraction (grain size < 2 µm) makes up around 80 %. The mean mineralogical composition of the montmorillonite part is given by:

$(Si_{7.92}\,Al_{0.08})\,(Al_{3.10}\,Fe^{3+}_{0.4}\,Fe^{2+}_{0.02}\,Mg_{0.48})\,O_{20}(OH)_4\,Na_{0.48}\,Ca_{0.04}\,Mg_{0.02}$

The cation exchange capacity is around 0.75 eq/kg bulk material and around 0.85 eq/kg clay in the minus 2 µm fraction. The natural exchangeable cations are sodium (~70 %), calcium (~20 %), magnesium (~ 6 %) and small amounts of potassium (~2 %). The specific surface area is around 5.5×10^5 m^2/kg material and the particle density around 2 750 kg/m^3 (Karnland et al. 2006).

The various blocks and plugs produced for the S2 and A3 test parcels may be divided in the following groups:

- Standard blocks with maximum original diameter of 281 mm and a height of 100 mm.
- Special blocks, which were prepared from standard blocks, with excavations for reinforcements, instruments and copper plates.
- Bentonite plugs with a diameter of 20 mm. These plugs were used for the tracer tests.

The choice of block compaction technique was based on experiences from previous SKB projects concerning block production (Johannesson et al. 1995). A uniaxial compaction device was constructed in order to make it possible to produce blocks with the accurate dimensions, density and composition. A slight axial conic form and chamfered edges between mantle and end sides were used in order to facilitate the expulsion after compaction and to avoid subsequent stress induced cracks. A small amount of molybdenum sulfide grease was used to smear the mantel surfaces in order to reduce friction.

The bentonite material was compacted without pre-treatment. Water content was measured in each 25 kg sack in order to determine the amount of solid bentonite needed in each block batch. The governing figure for the production was the final density in the test hole after expansion by water uptake. The reference KBS-3 bentonite bulk density is 2 000 kg/m^3 with an accepted divergence of ± 50 kg/cm^3. The accomplished calculations were made by use of a bentonite particle density of 2 750 kg/m^3, a mean block radius of 139.3 mm and an inner radius of 55 mm, a borehole radius of 150 mm and copper tube radius of 54 mm. Extra blocks were made in the production series in order to be divided and analysed with respect to homogeneity. For each produced block, approximately 250 g of the same material, i.e. from the same 25 kg sack, was marked and stored as reference material for background analyses.

After installation of bentonite parcels in the test holes, there was a remaining air-filled annular gap between bentonite blocks and rock surface with a width of approximately 10 mm and another air-filled annular gap between bentonite blocks and the central copper tube with a width of approximately 1 mm. These gaps were later filled with water in conjunction with the test start. It should be noted that there were variations in the test hole diameter, see Section 2.2.3.

The blocks predestined for instruments were made from standard blocks by drilling and carving out the necessary volume. The bentonite material is well suited for this technique and the produced unintentional gaps between the sensors and the bentonite are small and insignificant with respect to the final buffer density

The special blocks produced for the S2 and the A3 test parcels had the following modifications:

Block no.	**Modifications/excavations for**
01	copper bottom-plate reinforcements
02	3 thermocouples
05	20 mm cylindrical holes for tracer tests, 2 filters/tubes
08	5 thermocouples, 1 total pressure sensors, 1 water pressure gauge, 1 relative humidity gauge
12	1 water sampling cup
14	5+1 thermocouples, 1 total pressure sensors, 1 water pressure gauge, 2 relative humidity gauge
18	6 water sampling cups and 2 tubes with filters
20	5 thermocouples, 1 total pressure gauge, 1 water pressure gauge, 1 relative humidity gauge
22	2 copper plates
24	1 water sampling cup
26	3 thermocouples
28	2 tubes with filters
30	2 copper plates
32	1 thermocouple, 3 water sampling cups, 1 tube with filter
36	1 water sampling cup
38	1 thermocouple

All blocks were designed for defined positions in the test parcels and given a specific denomination. The blocks were theoretically partitioned in 9 sections in order to get a system for instrumentation and sampling. The first section ranging from the inner mantel surface and 2 cm outwards was termed section 1, and the following volume, i.e. between 2 and 4 cm from the inner mantel surface, was termed section 3, etc. The last section was consequently 9, and this section only had an initial extension outward of ~1 cm. After swelling, due to water uptake, section 9 represented the volume between 8 and ~10 cm (rock wall). Furthermore, the point of the compass was used to describe the horisontal orientation. The denomination of a specific point (centre of a volume) is according to the example 08ASE3 where

08	block number (counted from the bottom of the parcel),
A	vertical level in the block,
SE	direction of compass in the test hole,
3	radial distance in centimeter from the inner mantel surface to the center of the specimen.

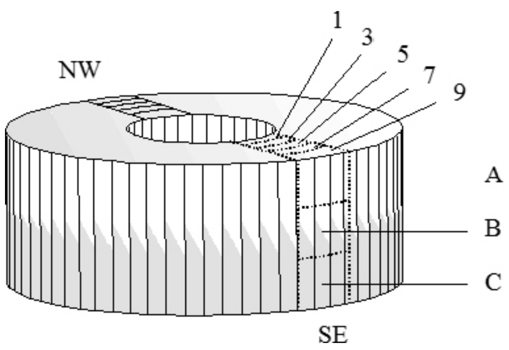

Figure 2-4. *Schematic block partition. SE and NW denote the directions of compass in the test-hole, figures denote the center of the specimens expressed in centimeters measured from the block inner mantel surface, and A, B and C denotes the three vertical positions in the blocks.*

The reference material was related to an imaginary point. Reference material from a specific block was termed according to the example A209R where

R	reference material,
A2	parcel type and number,
09	block number (counted from the bottom of the parcel).

The layout of all special blocks is schematically shown in Appendix 7 to 16.

2.3.5 Tracer doped plugs, copper coupons and water sampling cups

Tracer doped plugs

Plugs made of bentonite were manufactured in laboratory. The plugs had a cylindrical form with a length and diameter of 20 mm. They were compacted in a laboratory compaction device working by the same principle as the block compaction device, but no grease was used. The plugs were compacted to a density corresponding to the standard density of 2 000 kg/m^3 after full water saturation. The compaction was accordingly controlled by the final sample volume and not by the maximum compaction pressure.

A few cubic millimeters of bentonite were ion-exchanged to contain 1 MBq of ^{60}Co. The prepared material was placed in the center of two bentonite plugs. Cylindrical holes were drilled from the north and south side into the mantle surface in block S205 and A305 respectively. The diameter of the holes was 21 mm and the depth 50 mm, meaning that the doped part was placed close to the center of the bentonite, halfway between the rock and the copper tube. The tracer-doped plugs were placed into the block during the submerging of the parcels.

Copper coupons

The copper coupons were placed in tiny slots drilled and sawed from the upper side of the blocks (block no. 22 and 30 in both test parcels, see detailed drawings provided in Appendix). The copper coupons were placed in the blocks during the pile up of the bentonite column. The samples were pre-characterised and marked with letters for identification.

Water sampling cups

Special manufactured titanium cups (d=22 mm, h=20 mm) with a titanium filter at the top were placed in several blocks in each of the test parcels (1 cup in block 12, 6 cups in block 18, 1 cup in block 24, 3 cups in block 32 and 1 cup in block 36) i.e. in total twelve cups in each test parcel. The cups were installed with the purpose to collect free water that could be analysed after termination of the tests.

2.4 Instrumentation

2.4.1 General

The basic aim for the field activity in the LOT tests is to expose the bentonite clay to conditions similar to those in a KBS-3 repository, and to expose the clay to adverse physical-chemical conditions, mainly by an increased temperature. A fundamental demand was therefore to measure the temperature in order to regulate power, and to register the obtained temperature distribution along the test parcels. Relative humidity, porewater pressure and swelling pressure reveal the state of saturation and were therefore also measured. An additional objective with the LOT series was to test equipment for the subsequent full-scale buffer tests at Äspö. These demands in combination with the relatively limited volume in the clay and the potential risk for artifacts due to the instrumentation led to the following compromise concerning instrumentation of the test parcels:

- 24 thermocouples
- 3 total pressure sensors
- 3 water pressure sensors (and additional 3 tubes are equipped with external pressure sensors)
- 4 titanium tubes with filter tips
- 4 relative humidity sensors

The sensors were placed in the parcels as shown in Figure 2-2 and Figure 2-3. Detailed description of the position of each instrument in the blocks is provided in Appendix 7 to 16.

The equipment was termed in accordance with the following example:

A3084P	where
A3	parcel type and the number of the test,
08	block number counted from the bottom,
4	position in the block (according to Section 2.3.4),
P	type of measuring equipment.

The following abbreviations of measuring equipment was used:

M	relative humidity sensors,
P	total pressure sensors,
T	thermocouples,
W	water pressure sensors.

2.4.2 Thermocouples

Temperature was generally measured by thermocouples with a hot junction type J according to IEC 584 standard. Additional temperature information was given by the humidity sensors, which had Pt-100 sensors built-in. The thermocouples were delivered by BICC Thermoheat Limited, England. The soldering spots were isolated by cupro-nickel alloy, which also jackets the wires up to the tunnel and into the measuring cabinet.

The placing strategy was to concentrate the thermocouples in the clay volume around the heater in order to monitor the temperature gradient over the bentonite in detail. Thermocouples were placed in position 1, 3, 5, 7, and 9 in the blocks 08, 14, and 20. In block 14 there was an additional sensor on the copper surface. Below the most interesting sections, three thermocouples were placed in position 1, 5 and 9 in block 02. And above, three thermocouples were placed in position 1, 5 and 9 in block 26. One thermocouple was placed in position 4 in block 32 and 38, respectively. All measuring soldering points were placed from the upper surface of the blocks, into pre-drilled holes, down to a depth of 35 mm.

Calibration is generally not needed for thermocouples; however, a function control was made by connecting all thermocouples to the actual data collecting system and check that they showed the prevailing temperature before installation.

2.4.3 Pressure sensors

Two types of pressure sensors were used to obtain redundancy for the pressure measurements. The placing strategy was to place optical sensors in block 08 and 20, and in between vibrating wire sensors in block 14.

The optical sensors, model FOP, were manufactured and delivered by Roctest Ltd, Canada. The sensors were delivered with signed individual calibration data sheets and traceability numbers.

The vibrating wire sensors, model no. 4500TI-1500, were manufactured and delivered by Geokon Inc., USA. The sensors were delivered with signed individual calibration data sheets and traceability numbers according to ANSI Z540-1.

The water pressure was also measured by leading water in titanium tubes to external sensors placed in the tunnel above the parcels. The sensors were manufactured by Druck Limited, England. Individual data sheets, including gauge serial no, were delivered with the sensors.

The factory calibrations and temperature compensations were used for all three types of pressure sensors.

2.4.4 Relative humidity sensors

The measuring principle for the humidity sensors was electrical capacity change which gives a large measuring span and sufficient accuracy in order to follow the water uptake. The sensors were manufactured by Vaisala Oyj, Finland. The sensors were delivered with signed individual calibration data sheets. Traceability is guaranteed by the Vaisala Oyj.

The sensors were individually calibrated in order to check the delivery calibration data both with respect to relative humidity and to temperature dependence. The sensors were connected to the actual data collecting system, including all cables etc. The sensors were placed in specially designed plastic boxes, which were partly filled with different saturated salt solutions. Saturated solutions of $(NH_4)_2SO_4$, KCl, $BaCl_2$ and KH_2PO_4 were used. The temperature was kept at 22 °C and the equilibrium relative humidity 81.2, 84.8, 90.4 and 94 %, respectively, were used for the calibration.

The $BaCl_2$ solution was also used for the temperature compensation calibration, since the humidity equilibrium is relatively stable in the examined temperature range. Temperatures close to 40, 50 and 60 °C were used and a linear function, describing apparent RH as a function of T, was determined for each sensor. No significant differences between the factory calibration and the Clay Technology laboratory calibration were noticed with respect to relative humidity. The factory calibration and temperature compensation were therefore used in the following presentation of results.

2.4.5 Data acquisition

All sensors were connected to DATASCAN units, which in turn were connected to a computer working under Windows NT placed in a cabin close to the test site. The software was named Orchestrator and was manufactured by Eurosoft Technology, UK. MSS AB, Åkersberga, delivered the software and DATASCAN units. The program has a range of output/input drivers and real time data acquisition which i.e. admitted the use of event-governed logging in addition to periodic logging and alarm functions. The standard logging interval was set to 1 hour during the entire test period. The alarm system was used in order to detect overheating, and the system was connected to the control room at the CLAB facility at the nearby nuclear power plant for 24 h supervision.

A standard interval of 1 hour was used for all collection of data since the course of events was expected to be relatively slow. In addition, an event governed data collection was programmed for each type of measuring equipment. The triggering measuring event was exceeding or falling short of a fixed value, or a fixed interval related to the previous measured value. The configuration was made in such a way that all channels related to the test were read if an event-triggered measurement was started by a single instrument.

The recording and real time handling of data may be divided in three levels of importance. The handling of data used for regulating the system was of course most important since a malfunction may have led to a fast destruction of the system. Of second most importance were the data needed for the evaluation of the test conditions, and finally there is a group of data which is of general interest, but which is not necessary for the accomplishment of the test. In consequence, several levels of alarm function were used in the monitoring system. Depending on the type of released alarm different measures were stipulated, ranging from simple notes to immediate actions from the safety guard at the nuclear power plant.

All recorded data were stored in the specific project computer and backup was regularly made at Äspö HRL. The standard recorded data concerning temperature, pressure and humidity were copied approximately once a month from Clay Technology and stored in an SQL-database (Structered Query Language. This is a standardised programming language for retrieving and modifying data in a database). The data were processed by means of MS EXCEL and thereafter stored in the SICADA database at Äspö.

3 Field operation

3.1 Preparation

3.1.1 Parcel assembly

The entire parcel systems were prepared and checked in laboratories in Lund, dismantled and loaded on to a lorry for transport to Äspö HRL. At the test site, the water in the test hole was pumped and the bottom part was filled with sand up to approximately 100 mm from the bottom. The central 8 m deep pilot hole with a diameter of 76 mm was thereby also filled with sand. The test hole was covered with a building board and the copper tube was vertically fixed at a bottom support right on top of the test hole. The predestined ring-shaped bentonite blocks were threaded onto the copper tube from above one by one from a scaffold, Figure 3-1 .

The sensors were placed in the prepared cavities before the successive block was placed. The instruments were fixed in position only by overlying blocks without additional equipment. The tubes from each instrument were placed in tracks excavated in the outer mantle surface of the blocks above the instrument. The tubes were fixed during the construction of the parcels but released during the parcel submersion in order to admit movements during the subsequent swelling of the bentonite. A few thin copper wires were left, though, to keep the tubes in place during the placement. The tracer test plugs were the last to be placed in order to minimise the risk for contamination with ^{60}Co, see right photo provided in Figure 3-1. The entire mounting procedure of the A2 parcel at the test site was achieved within two days (although quite long days) since the parcel was constructed as a ”building kit”.

Figure 3-1. *Left: Finalising the construction of a LOT test parcel at test site, note the large number of tubes from sensors. Right: Insertion of the plug containing ^{60}Co during lowering the parcel into the test hole. Note the lack of disturbing sensor tubing in the lower hot section.*

3.1.2 Installation

The S2 and A3 test parcels were installed on 22nd September and 13th October,1999 respectively. For each parcel, the top of the copper tube was connected to the lift device mounted in the roof above the test hole. The parcel was slightly heaved and the bottom support and building board removed. The test hole was again emptied on water and the parcel was carefully centered and slowly lowered into the test hole. The total submergence procedures took approximately 15 minutes. The upper slot between the bentonite and the rock was sealed with mineral insulation (Rockwool) in order to avoid sand to penetrate downwards. An approximately 100 mm thick sand layer was placed on top of the bentonite block column and the tubes from all sensors and filters were brought together above the bentonite and fixed. The uppermost 100 mm of the test-hole and a square-formed reinforced concrete top plug were cast, Figure 3-2. After hardening, the plug was prevented from heaving, due to bentonite swelling and water pressure, by use of two steel beams, which in turn were fixed by four rock bolts. The sensor and heater cables were connected to measuring and regulating equipment placed in cabinets on top of the test hole, and the cabinets were covered by a simple drip shelter. The measuring equipment was connected to computers in a container placed about ten meters from the test holes. These computers were in turn connected to the general backup system at the Äspö HRL.

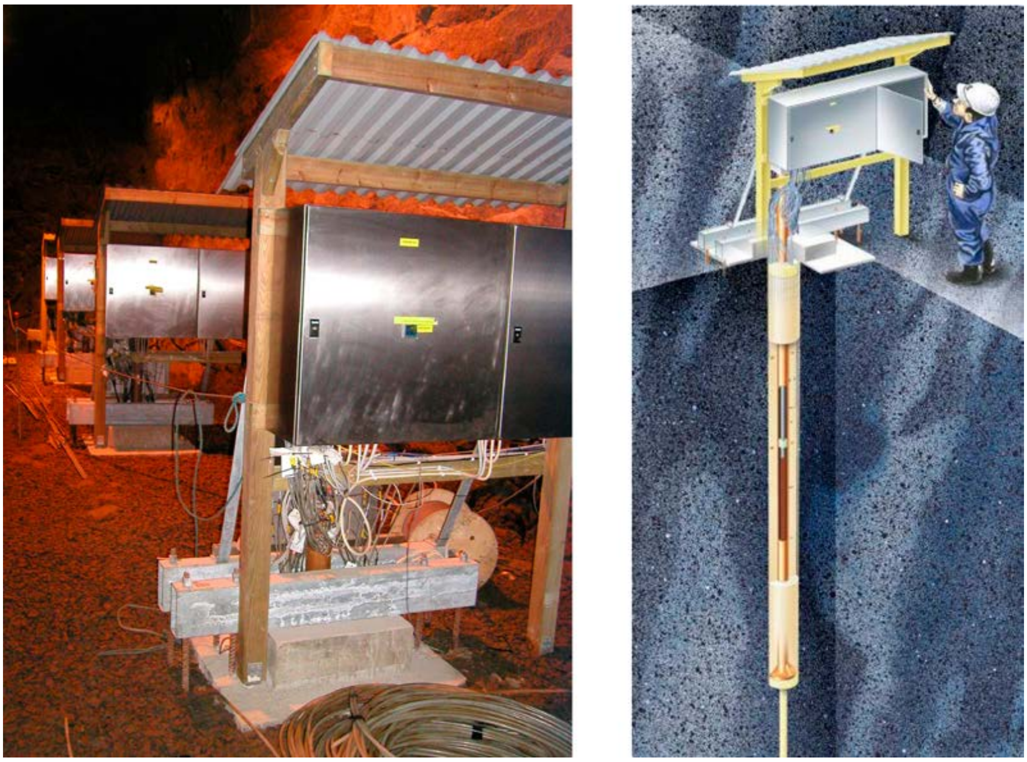

Figure 3-2. *Left: Picture of the test site with parcel A2 in the front. Right: Schematic drawing of the final appearance of a LOT test parcel after installation.*

3.2 Heating phase

3.2.1 Temperature control

There are in principle two main options to control the temperature in this kind of tests, either regulation of the heater power to a fixed value or to regulate the power to give a defined temperature at a certain position. Constant power simulates best the heat production of spent fuel and constant temperature excludes overheating. The power was first turned on 2nd February, 2000, and regulated to give a constant maximum temperature of 50 °C. A mean value of the three thermocouples S208T1, S214T1 and S220T1 (corresponding block for test parcel A3) were initially used to govern the power in order to ensure that no overheating took place. The maximum temperature target was thereafter increased in steps of 10 °C. The 19th March (S2) and the 16th June (A3), 2000 the regulation was changed to a fixed power of 480 W. The power was thereafter increased in steps to a final power of 500 W for test parcel S2 and 800 W for test parcel A3.

3.2.2 Water supply

After installation of bentonite parcels in the test holes, there was a remaining air-filled annular gap between bentonite blocks and rock surface with a width of approximately 10 mm and another air-filled annular gap between bentonite blocks and the central copper tube with a width of approximately 1 mm. These gaps were slowly water filled on February 2, 2000 in parallel with the onset of heating. The filling was made with groundwater from the adjacent borehole (HG0038B01) by use of the fixed installed titanium tube and bottom filter placed in the sand below the parcel and close to the rock wall. The valve connected to the bottom filter was closed at the time when the groundwater had reached the uppermost filter (filter in block 32), which so far was open to air. This filter was then instead connected to the ground-water supply (~1.2 MPa). This inflow point is assessed to simulate a point inflow from a water bearing fracture in the rock. The test parcels have had access to pressurised water from this point inflow during the entire test duration.

3.3 Compilation of data from the installation

A compilation of data regarding the dates for installation and test start is provided in Table 3-1. As shown in the table, test parcel S2 and S3 were installed during September 1999, test parcel A2 and A3 during October 1999 and test parcel A0 during December 1999.

The two test parcels described in this report, S2 and A3, were started 133 and 112 days after installation, respectively. Test start meant that the heating was turned on and water was injected to fill up all empty voids.

Table 3-1. Compilation of data from the installation of all LOT test parcels.

	Test parcel				
Activity	**S2**	**S3**	**A0**	**A2**	**A3**
Date of installation	1999-09-22	1999-09-02	1999-12-16	1999-10-29	1999-10-13
Date of start heating	2000-02-02	1999-09-16	2000-02-02	2000-02-02	2000-02-02
Date of stop heating	2019-08-06	Running	2001-10-23	2005-12-04	2019-08-06
Date of first registered data	1999-10-29	1999-09-16	2000-01-01	2000-02-02	1999-10-27
Time from installation to test start, days	133	14	48	96	112

Since the LOT-tests also includes analyses of corrosion of copper, a number of clarifications are made below regarding the access to oxygen after installation:

1. After installation of the test parcels in the test holes, there were large air-filled voids present. The outer gap between bentonite blocks and rock had a volume of approximately 36.3 liters and the inner gap between blocks and copper tube had a volume of approximately 1.3 liters. The total volume of gaps was thus approximately 37.6 liters.
2. The test parcels were resting on sand, filling up about four meters of the pilot hole (d=76 mm) and about 100 mm of the test hole (d=300 mm). The voids in the sand filling is estimated to approximately 10.1 liters. The sand filling above block number 38 had a void volume of 2.5 liters. A porosity of 40 % in the sand has been used in the calculations, see e.g. Larsson (2008).
3. In total seven titanium tubes (OD=6 mm, ID=4 mm), equipped with filter tips in the ends, were led down in each test hole from the surface. All tubes were equipped with valves that were open during the time between installation and test start. The position of the tubes is shown in the test layout drawings provided in Figure 2-2 and Figure 2-3. The position can also be seen in the drawings of individual blocks provided in Appendix 7 to 16. The seven tubes are positioned according to the following:
    a. Tube 1: Outer periphery of block 5. This tube has been used to measure the pore water pressure.
    b. Tube 2: Outer periphery of block 18. This tube has been used to measure the pore water pressure.
    c. Tube 3: Outer periphery of block 32. This tube has been used in two ways: 1) the tube was initially used for deairing during the water filling and 2) a water pressure, simulating a point inflow, was applied during the entire test time, see also description in Section 3.2.2.
    d. Tube 4: Outer periphery of block 28. This tube has been used to measure the pore water pressure.
    e. Tube 5: Inner periphery of block 28. This tube has not been used.
    f. Tube 6: Inner periphery of block 5. This tube has not been used.
    g. Tube 7: The filter tip was positioned in the sand below the bottom plate of the test parcel. The tube was used to fill up all voids with water in conjunction with the test start.
4. During the time between installation and test start, there was an inflow of water from the rock into the test holes. This means that parts of the voids in the sand filling and the gaps around the test parcel may have been filled with water during this time.
5. In conjunction with the test start, water was filled up from the bottom of the test hole (one titanium tube was ending in the sand filling below the bottom plate). Another titanium tube, positioned at the level of block 32, was used for de-airing and thereby facilitated the water filling of all gaps. This tube was then used to inject water coming from an adjacent borehole, see description in Section 2.2.2.
6. It should be noted that after test start there were still air present in the unsaturated bentonite blocks.

4 Heating and data acquisition

4.1 General

4.1.1 Heating

The power regulating system worked very well during the entire twenty years test duration. In September 2014, the system was updated with new components and this resulted in a small drop in the registered temperature for both test parcels. The drop was clearer for test parcel S2.

No overheating or major temperature drops took place during the test time.

4.1.2 Data acquisition and instruments

Data acquisition

The data acquisition system worked very well during the entire twenty years test duration. Minor incidents with logging units and service stops in logging can be seen in the recorded data. It can also be noted that the recorded data from the pressure measurements and from the relative humidity sensors, includes a lot of noise.

In order to facilitate the reading of the presented data, unrealistic registered data such as zero-readings, spikes etc. have been removed (mainly from the graphs presenting the registered temperature).

In all graphs presenting registered data from the tests, day zero is set to 1st September 1999, i.e. the month where the first test parcels in this test series were installed.

Temperature

The temperature has mainly been measured using thermocouples. These measurements have been working very well during the complete test duration. There have been some minor interruptions in the data registration but only one thermocouple, out of a total of 48 installed in these two test parcels, had stopped working during the test time.

The temperature was also registered by the relative humidity sensors. These measurements have been much noisier, probably since these sensors after full saturation of the surrounding bentonite, have been contaminated of saline water, resulting in erroneous measurements.

Total pressure

Two types of total pressure sensors with different measuring principles were used in the tests, optical pressure sensors and vibrating wire sensors. The vibrating wire sensors have in general worked well during the entire test period. The optical pressure sensors worked well during about 13 years but after that time the logger system started to fuss and after 14 years the logger system stopped working. After this time no data were collected from these sensors.

Pore water pressure

The pore water pressure was also measured with the same two types of sensors as used for the total pressure measurements i.e. optical and vibrating wire. The vibrating wire sensors have worked well while the optical system stopped working after 14 years. In addition, water was transferred by titanium tubes equipped with filter tips from three levels in each of the test parcels. The water pressure in the tubes was measured by external sensors placed in cabinets in the tunnel above the parcels. No problems have occurred during the test time with these sensors.

Relative Humidity

High quality moisture measurements are difficult to perform over long time, especially in the very harsh environment in bentonite at high temperature. When the bentonite is completely saturated, the fragile moisture sensors normally get contaminated of the saline water. This commonly leads to subsequent erroneous results, which however is a good indication of full water saturation.

All relative humidity sensors have thus worked a certain time after installation but after having been contaminated with saline water the registered data is judged to be unreliable.

4.2 Monitoring results from Test Parcel S2

4.2.1 General

All sensors have a specific name. For example, S2020T where

S2	test parcel
02	block number (counted from bottom)
0	radial distance from the copper tube (between 0 and 9, see Figure 2-4)
T	Temperature (P-total pressure, W-water pressure, M-relative humidity sensors)

4.2.2 Temperature

The results from the temperature measurements in test parcel S2 are presented in Figure 4-1 to Figure 4-5. In each graph, the measured temperatures from all thermocouples in a specific block are presented, except for Figure 4-5 where data from three different blocks are presented.

Except for the exchange of power regulators in September 2014 (see description in Section 4.1), which resulted in a small decrease in temperature, there have also been some minor drops in temperature registered during test time. However, it is judged that most of these are not real temperature reductions, instead they are probably related to problems with the data collection system.

There have been interruptions in the data registration for some thermocouples e.g. S2086T and S2088T. In block 20, see Figure 4-4, there have been some problems with the two thermocouples closest to the heater during long time. It has not been possible to clarify what caused this.

There was a clear annual cyclic variation in the registered temperature. This can be correlated to the temperature in the ventilated tunnel and represents the combined effect of the thermal conductivity of the bentonite, copper tube and surrounding rock.

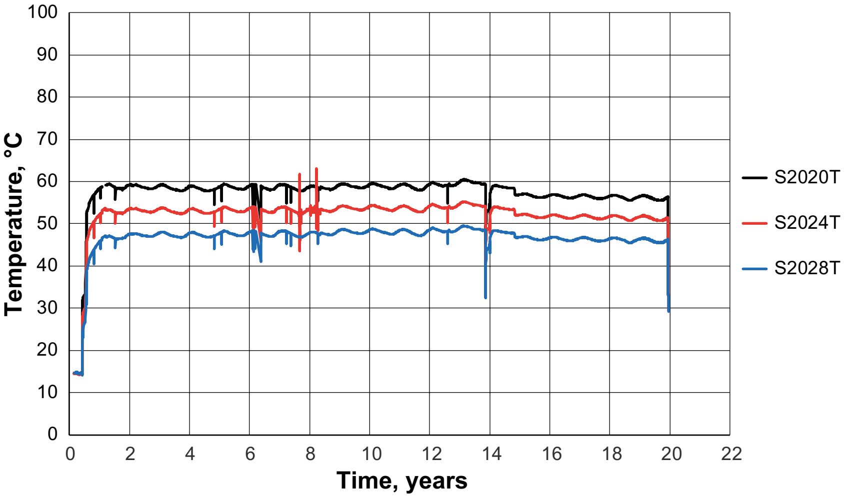

Figure 4-1. *Registered temperature plotted versus time for three sensors positioned in test parcel S2, block 02.*

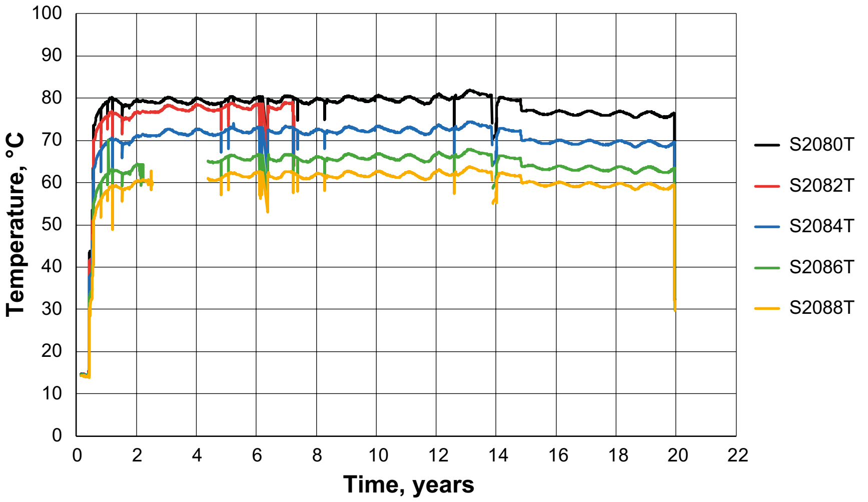

Figure 4-2. *Registered temperature plotted versus time for five sensors positioned in test parcel S2, block 08.*

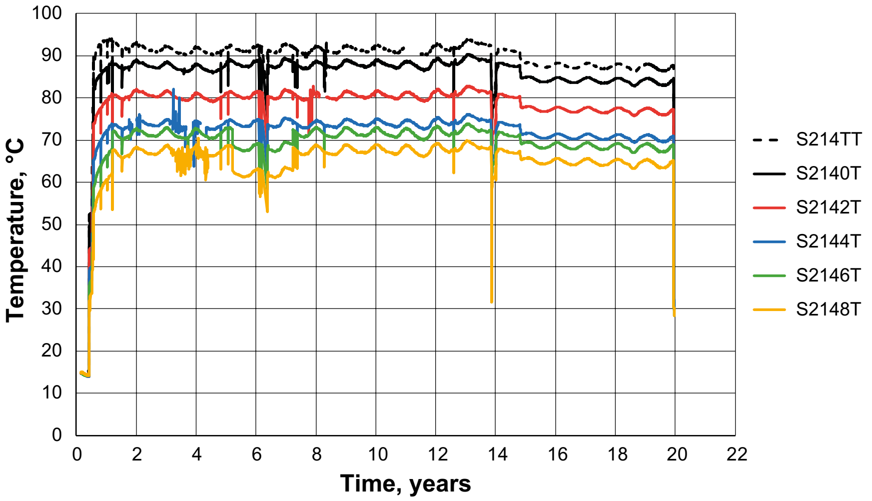

Figure 4-3. *Registered temperature plotted versus time for six sensors positioned in test parcel S2, block 14.*

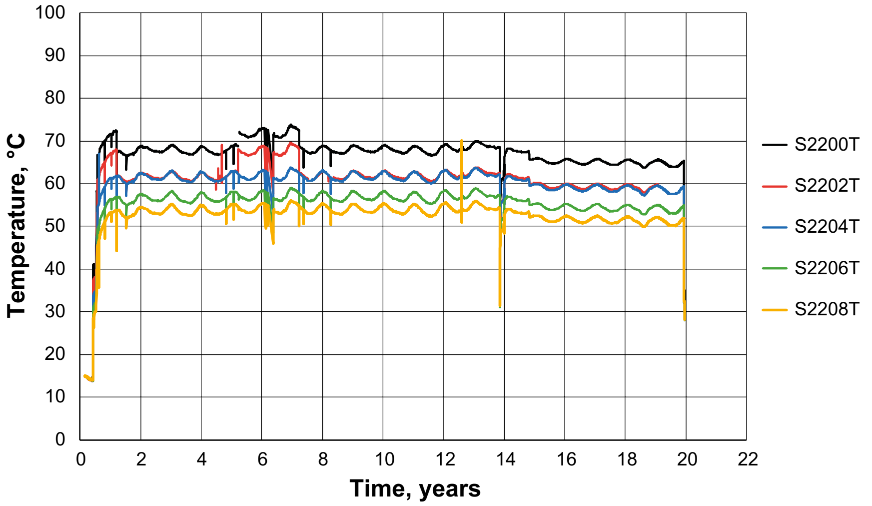

Figure 4-4. *Registered temperature plotted versus time for five sensors positioned in test parcel S2, block 20.*

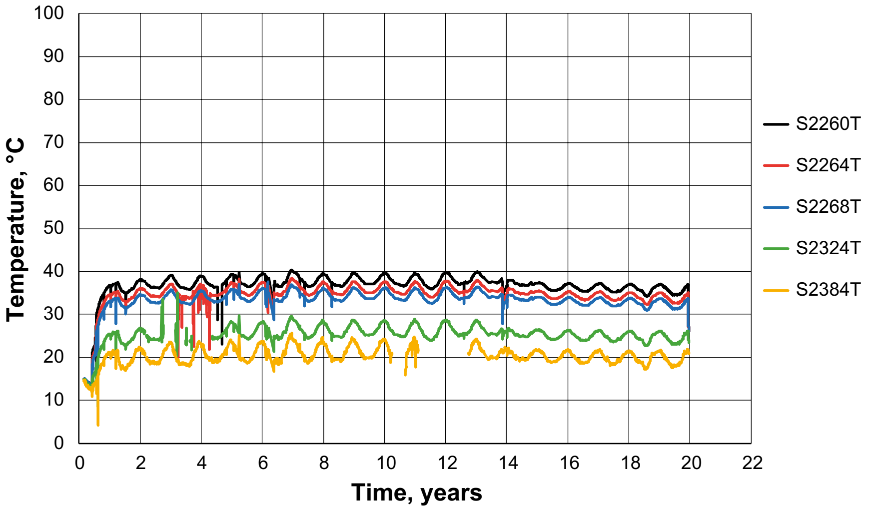

Figure 4-5. Registered temperature plotted versus time for five sensors positioned in test parcel S2, block 26, 32 and 38.

4.2.3 Total pressure and pore water pressure

As described earlier, two types of pressure sensors with different measuring principle were used in the tests, optical pressure sensors and vibrating wire sensors. The optical pressure sensors were placed in block 8 and 20, and in between the vibrating wire sensors were placed in block 14.

The vibrating wire sensors placed in block 14 has worked well during the entire test period, Figure 4-6. The total pressure started to increase about eight months after test start and had after about four years reached 4 MPa. There is a dip in pressure after about 14 years test duration. This dip can also be seen in the registered temperature and is related to the exchange of the power regulators.

The registered pore water pressure in block 14 has been close to 0.25 MPa during the entire test period.

The optical pressure sensors placed in block 8 and block 20 worked well during about 13 years but after that time the logger system started to fuss and after 14 years the logger system stopped working, Figure 4-7. After this time no data were collected from these sensors.

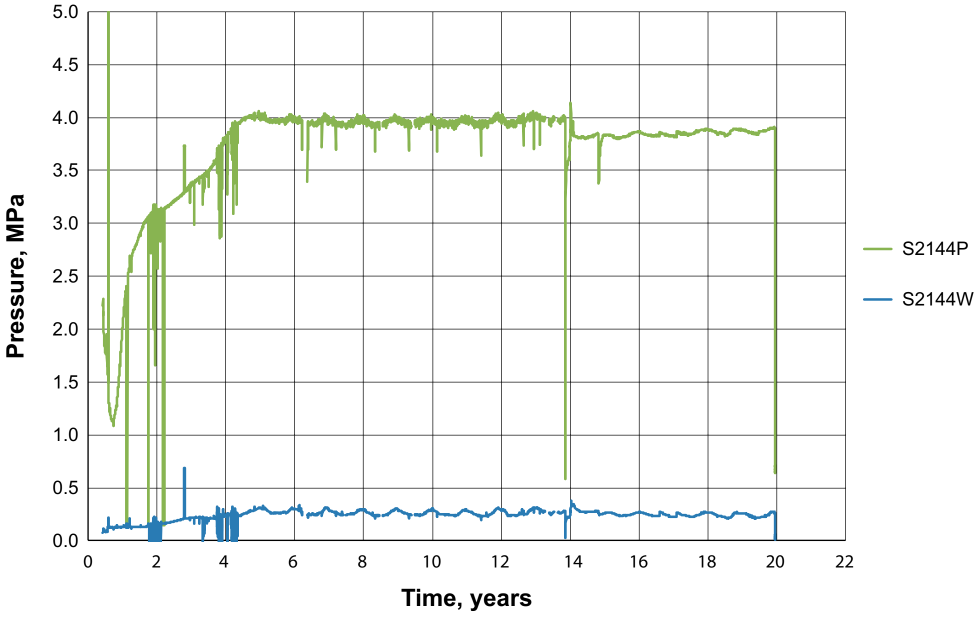

Figure 4-6. Registered total pressure (S2144P) and water pressure (S2144W) by vibrating wire sensors and plotted versus time for the sensor positioned in test parcel S2, block 14.

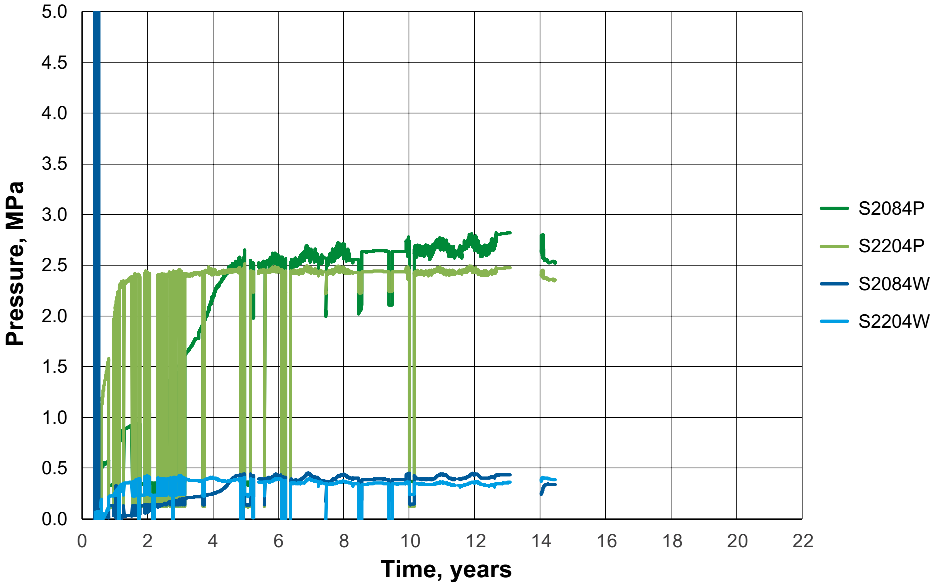

***Figure 4-7.** Registered total pressure (S2084P and S2204P) and water pressure (S2084W and S2204W) by the optical sensors and plotted versus time for the sensors positioned in test parcel S2, block 8 and 20.*

The registered total pressure in block 20 increased rather fast and had after about one year reached 2.4 MPa. This pressure was then rather constant until the sensors stopped working. The pressure in block 8 increased in a similar way as in block 14 i.e. it took over four years to reach the maximum. The maximum pressure registered in block 20 was about 2.8 MPa.

The registered water pressure in block 8 and 20 was about 0.4 MPa during the measuring period.

The annual cyclic variation that could be seen in the registered temperature could also be seen in the pressure measurements.

The pore water pressure was also measured via titanium tubes leading water from three different levels in the test parcel (block 5, 18 and 28). The water pressure was measured by external sensors placed in the tunnel above the parcels.

The pore water pressure measured with these sensors have been in the same range as the pressure measured with the optical sensors and the vibrating wire sensor, roughly between 0.15 and 0.4 MPa with the higher pressure in block 5, Figure 4-8.

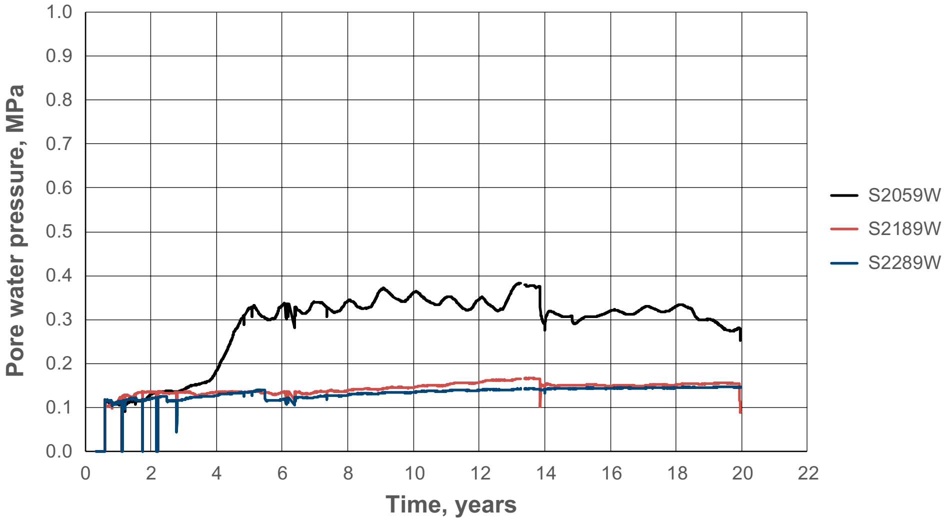

***Figure 4-8.** Registered pore water pressure measured at three different levels in test parcel S2 (block 5, 18 and 28).*

4.2.4 Relative Humidity

The results from the measurements of relative humidity and accessory temperature from the sensors positioned in block 8, 14 and 20, are provided in Figure 4-9 to Figure 4-11. There was one sensor in block 8 and one in block 20, positioned in the middle of the bentonite i.e. approximately between the central copper tube and the rock, see detailed drawings in Appendix. In block 14 there were two sensors, positioned so that they are evenly distributed between the copper tube and the rock surface.

All sensors indicated a rather fast increase in humidity within the first half year. The relative humidity sensor in block 20 delivered reasonable data for only a few months after test start but started after that time to give strange values. The sensors in block 8 and block 14 registered values for about 4 years before reaching 100 % i.e. full water saturation was reached. These results are consequently in good agreement with the indications from the pressure sensors, see graphs provided in Figure 4-6 and Figure 4-7, with respect to the time needed to reach full water saturation.

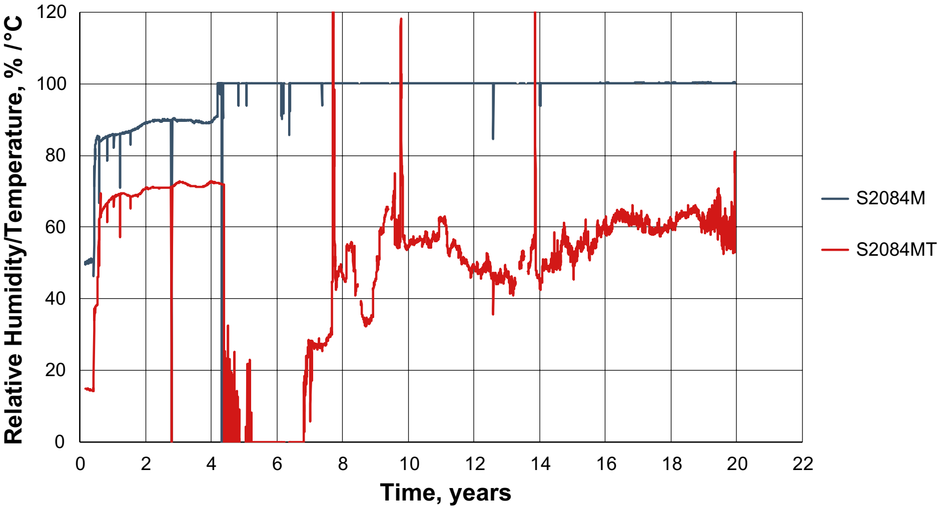

Figure 4-9. Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel S2.

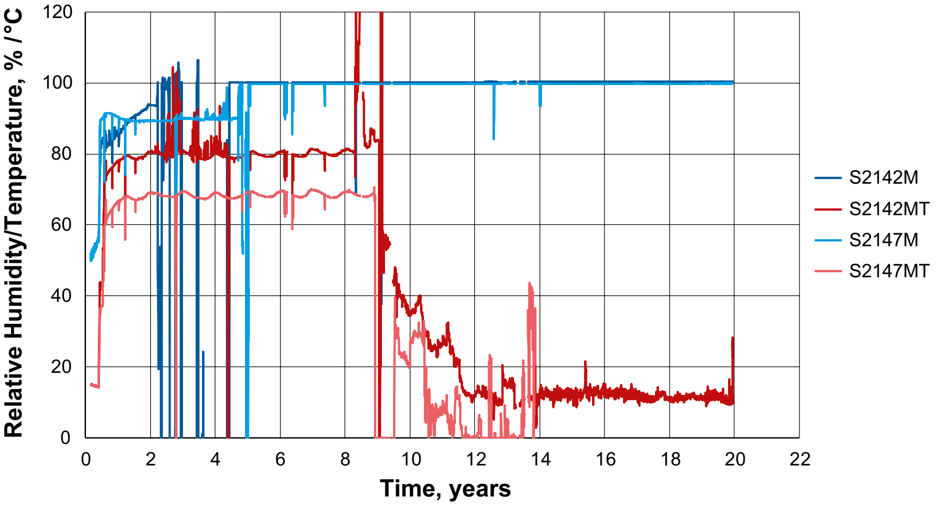

Figure 4-10. Registered relative humidity and temperature plotted versus time for sensors positioned in block 14 in test parcel S2.

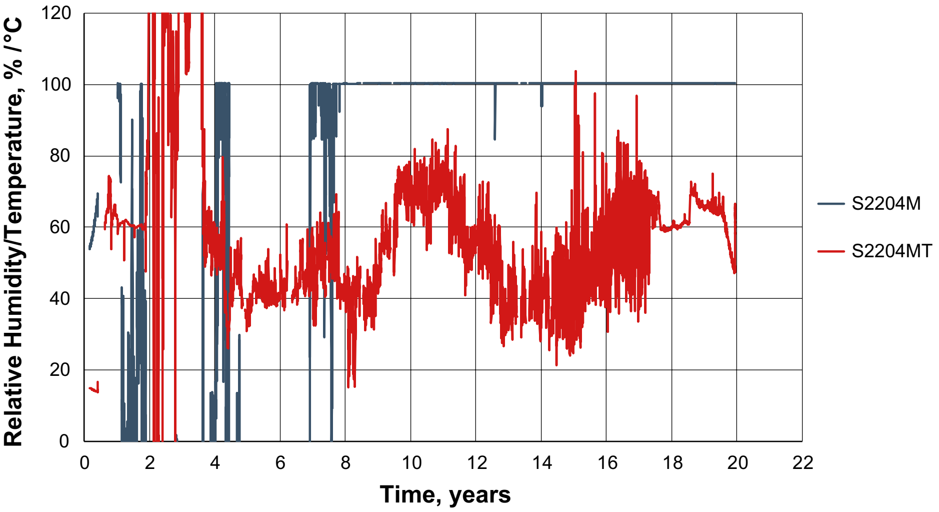

Figure 4-11. Registered relative humidity and temperature plotted versus time for sensor positioned in block 20 in test parcel S2.

In order to facilitate reading of the changes in relative humidity and temperature both after installation but also in conjunction with the test start (test start meant that the heating was turned on and water was injected to fill up all empty voids) graphs have been produced showing the development in relative humidity and temperature during the first 400 days, Figure 4-12 to Figure 4-14. Day 0 in the graphs corresponds to the date of installation. The test, S2, was started 133 days after installation.

The graphs show that the conditions were rather constant during the time after installation and until the test was started, Figure 4-12 and Figure 4-13. The test start, day 133, can be seen very clearly in the graphs. Both the temperature and the relative humidity starts to increase. The relative humidity increases from between 50 and 60 % up to between 85 and 90 % within a few days. Unfortunately, there is some data missing during this period for the sensor positioned in block 20, Figure 4-14.

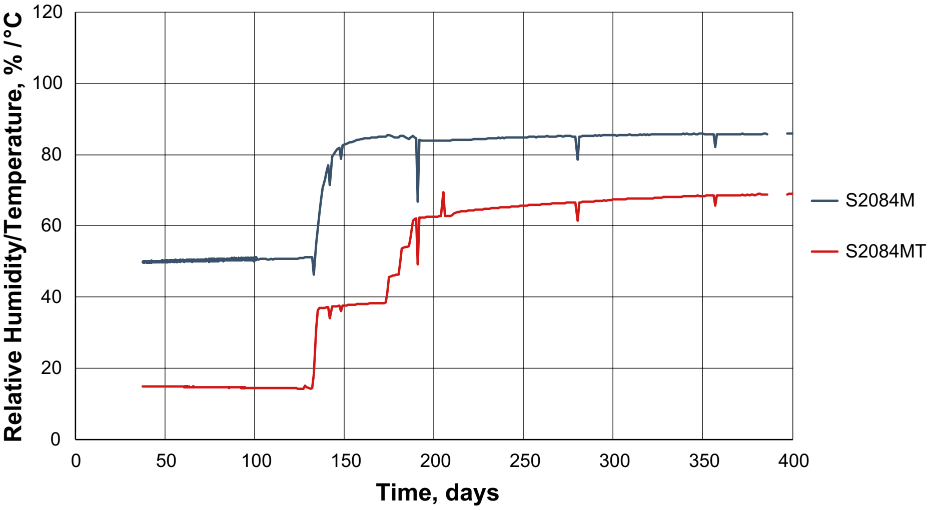

Figure 4-12. Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel S2. The graph shows the registered data during the first 400 days after installation.

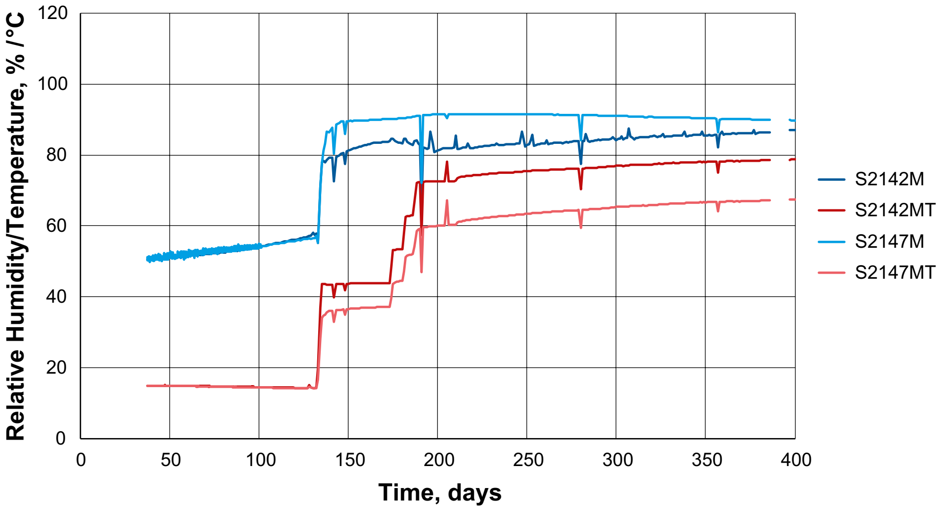

Figure 4-13. *Registered relative humidity and temperature plotted versus time for sensors positioned in block 14 in test parcel S2. The graph shows the registered data during the first 400 days after installation.*

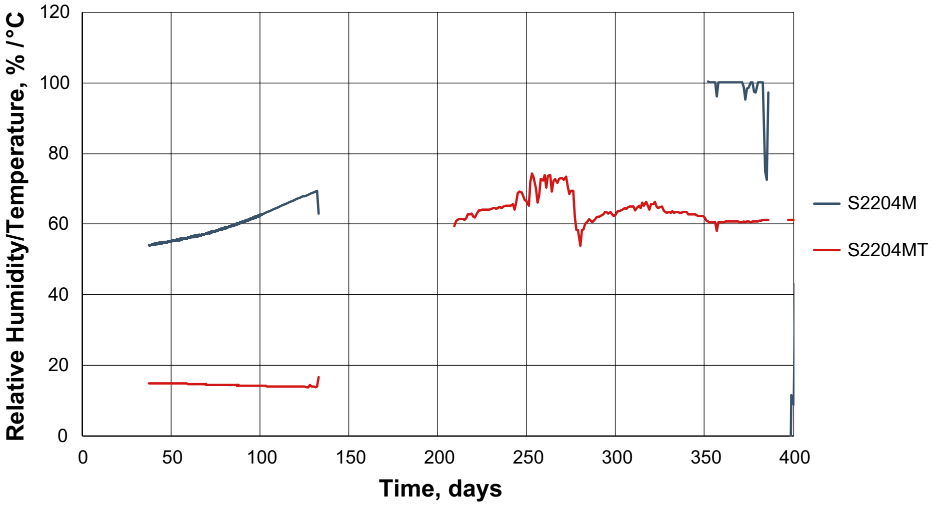

Figure 4-14. *Registered relative humidity and temperature plotted versus time for sensor positioned in block 20 in test parcel S2. The graph shows the registered data during the first 400 days after installation.*

4.3 Monitoring results from Test Parcel A3

4.3.1 General

All sensors have a specific name. For example, A3020T where

A3	test parcel
02	block number (counted from bottom)
0	radial distance from the copper tube (between 0 and 9, see Figure 2-4)
T	Temperature (P-total pressure, W-water pressure, M-relative humidity sensors)

4.3.2 Temperature

The results from the temperature measurements in test parcel A3 are presented in Figure 4-15 to Figure 4-19. In each graph, the measured temperatures from all thermocouples in a specific block are presented, except for Figure 4-19, where data from three different blocks are presented.

Except for the exchange of power regulators in September 2014 (see description in Section 4.1), which resulted in a small decrease in temperature, there have also been some minor drops in temperature registered during test time. However, it is judged that most of these are not real temperature reductions, instead they are probably related to problems with the data collection system.

Between 2 January 2012 and September 2012 no temperature data was registered for this test parcel due to problems with the data loggers. There have also been some rather long interruptions in the data registration for some thermocouples e.g. A314TT, A3144T and A3260T.

As in test parcel S2, there has been a clear annual cyclic variation in the registered temperature.

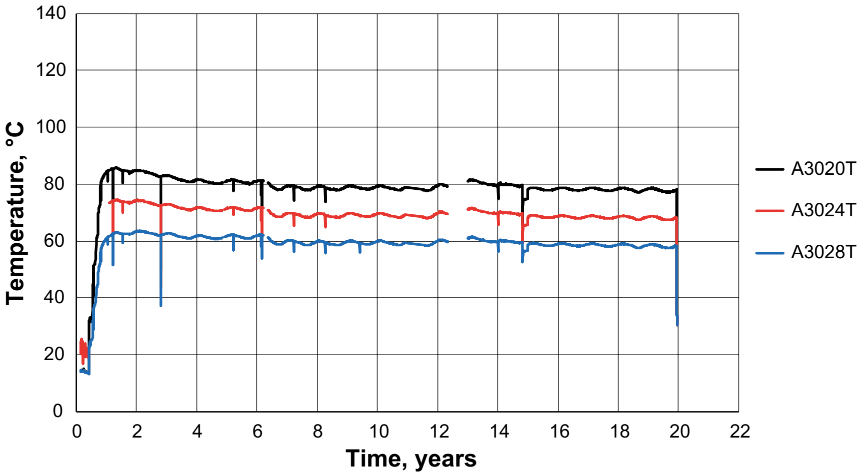

Figure 4-15. Registered temperature plotted versus time for three sensors positioned in test parcel A3, block 02.

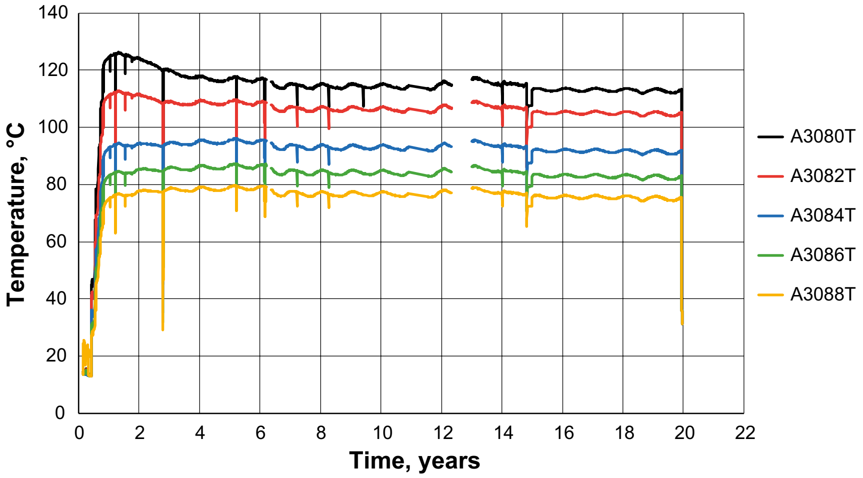

Figure 4-16. Registered temperature plotted versus time for five sensors positioned in test parcel A3, block 08.

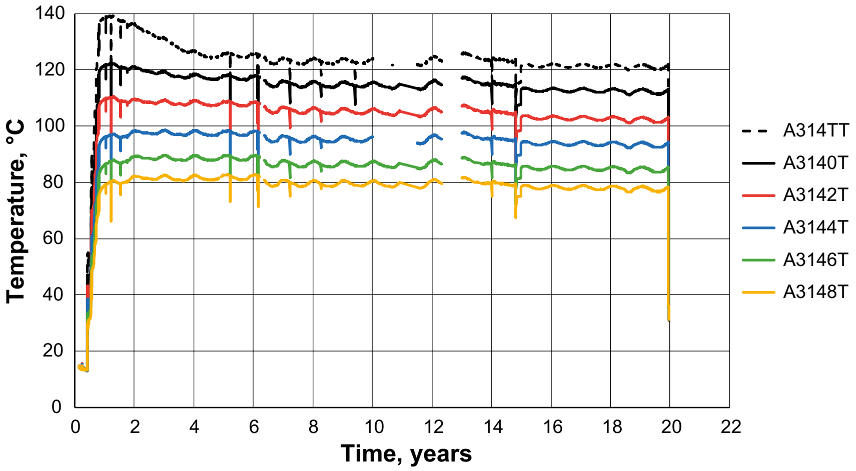

***Figure 4-17.** Registered temperature plotted versus time for six sensors positioned in test parcel A3, block 14.*

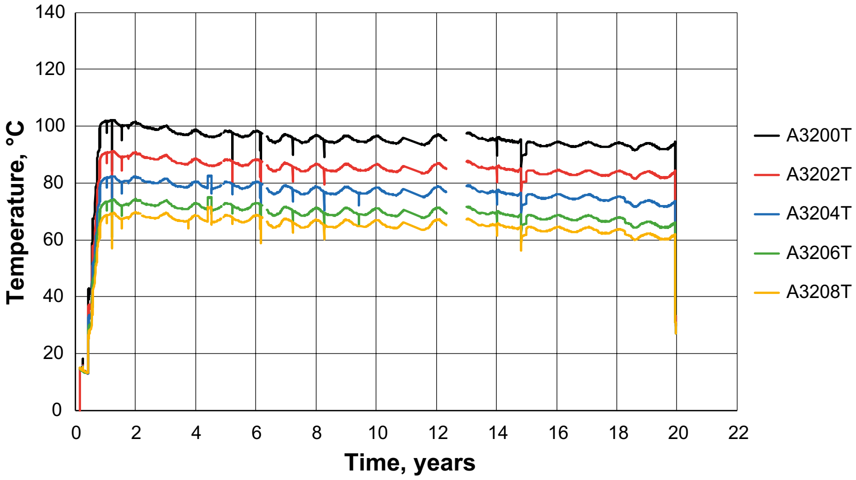

***Figure 4-18.** Registered temperature plotted versus time for five sensors positioned in test parcel A3, block 20.*

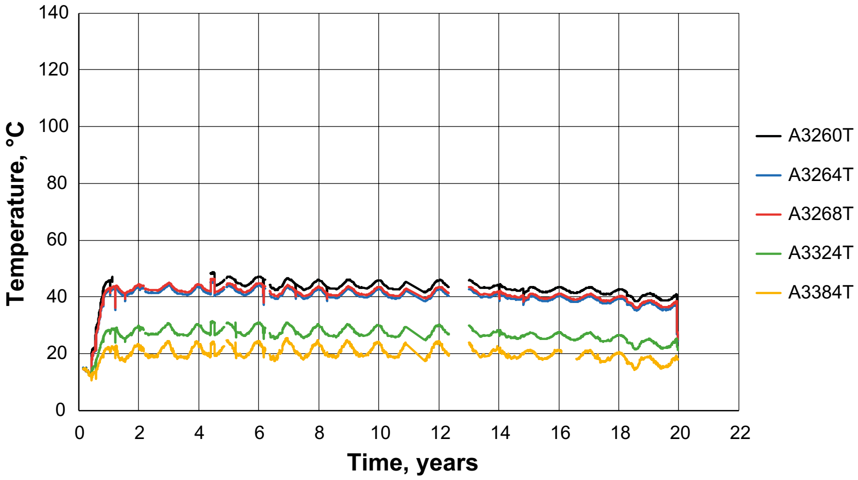

***Figure 4-19.** Registered temperature plotted versus time for five sensors positioned in test parcel A3, block 26, 32 and 38.*

4.3.3 Total pressure and pore water pressure

The same types of pressure sensors as in test parcel S2 were also used in this test parcel i.e. optical pressure sensors and vibrating wire sensors. The optical pressure sensors were placed in block 8 and 20, and in between the vibrating wire sensors were placed in block 14.

The vibrating wire sensor placed in block 14 registered an increasing total pressure for almost four years, reaching a maximum pressure of about 3.9 MPa, Figure 4-20. This pressure increase rate, and the reached maximum pressure, was almost the same as what was registered in test parcel S2 in the same block number. Unfortunately, the sensor stopped working after about four years.

The registered water pressure in this position has been close to 0.25 MPa during the entire test duration.

As for test parcel S2, the optical pressure sensors placed in block 8 and block 20 worked well during about 13 years but after that time the logger system started to fuss and after 14 years the logger system stopped working. After this time no data were collected from these sensors.

The registered total pressure in block 20 increased rather fast and had after about one year reached 1.6 MPa, Figure 4-21. This pressure was then rather constant until the sensors stopped working. The pressure in block 8 increased in a similar way as in block 14 i.e. it took long time to reach the maximum pressure, about six years. The maximum pressure registered in block 20 was about 1.6 MPa

The registered water pressure in block 8 and 20 was about 0.2 MPa during the entire test duration.

The annual cyclic variation that could be seen in the registered temperature could also be seen in the pressure measurements.

The pore water pressure was also measured via titanium tubes leading water from three different levels in the test parcel (block 5, 18 and 28). The water pressure was measured by external sensors placed in the tunnel above the parcels.

The pore water pressure measured with these sensors have been in the same range as the pressure measured with the optical sensors and the vibrating wire sensor, roughly between 0.15 and 0.2 MPa in block 5 and 18, and somewhat higher in block 28, mainly between 0.4 and 0.7 MPa, Figure 4-22. The same problem with the data loggers that occurred for the thermocouples between 2 January 2012 and September 2012 i.e. no data was recorded during this time, could also be seen for these sensors.

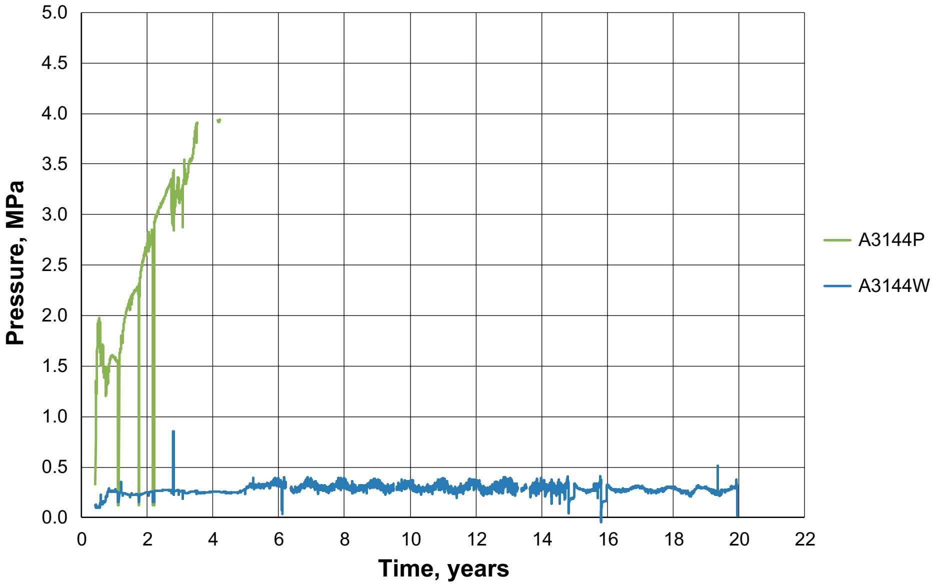

Figure 4-20. *Registered total pressure (A3144P) and water pressure (A3144W) by the vibrating wire sensors and plotted versus time for the sensor positioned in test parcel A32, block 14.*

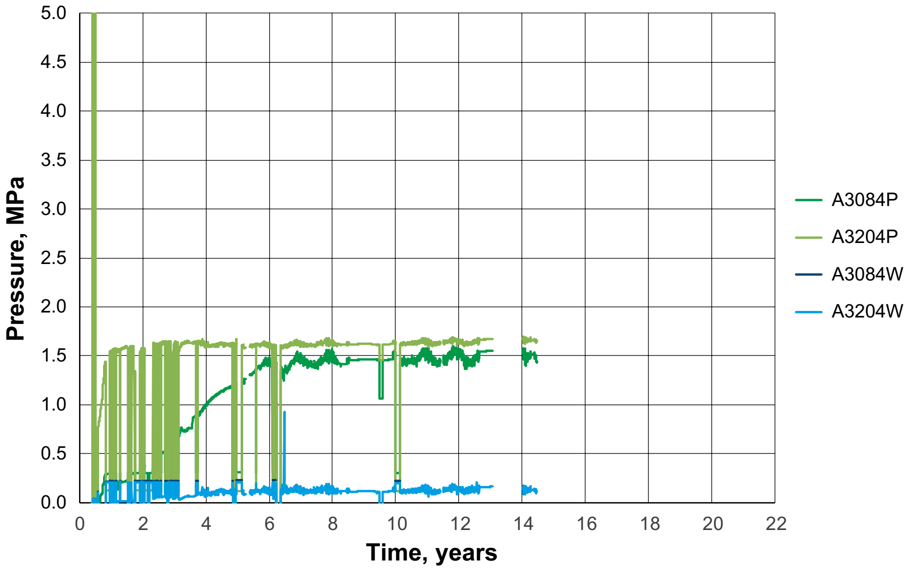

Figure 4-21. Registered total pressure (A3084P and A3204P) and water pressure (A3084W and A3204W) by the optical sensors and plotted versus time for the sensors positioned in test parcel A3, block 8 and 20.

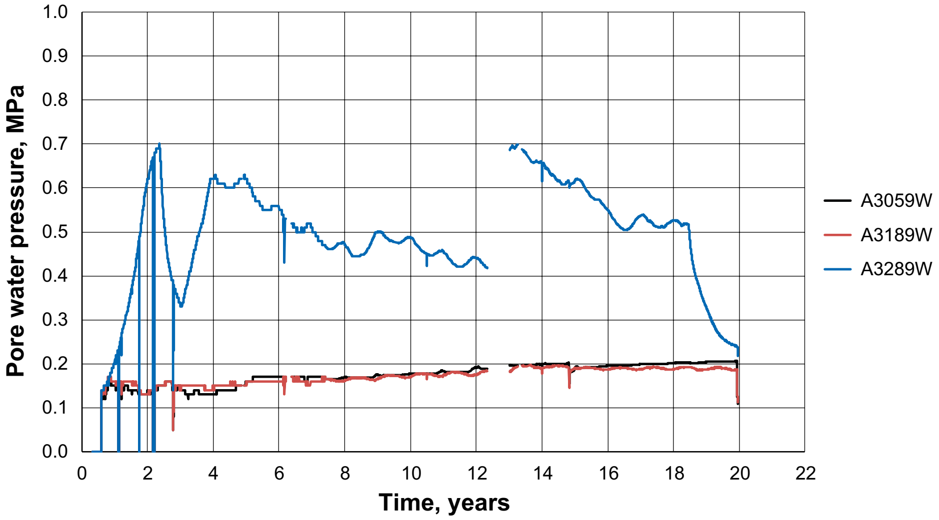

Figure 4-22. Registered pore water pressure measured at three different levels in test parcel A3 (block 5, 18 and 28).

4.3.4 Relative Humidity

The results from the measurements of relative humidity and accessory temperature from the sensors positioned in block 8, 14 and 20, are provided in Figure 4-23 to Figure 4-25. There was one sensor in block 8 and one in block 20, positioned in the middle of the bentonite i.e. approximately between the central copper tube and the rock, see detailed drawings in Appendix. In block 14 there were two sensors, positioned so that they are evenly distributed between the copper tube and the rock surface.

All sensors indicated a rather fast increase in humidity within the first half year. After two to three years, all sensors are registering large variations in both relative humidity and temperature which indicates that water has reached the sensors that have been contaminated of the saline water. This is, however, a good indication of complete saturation of the bentonite.

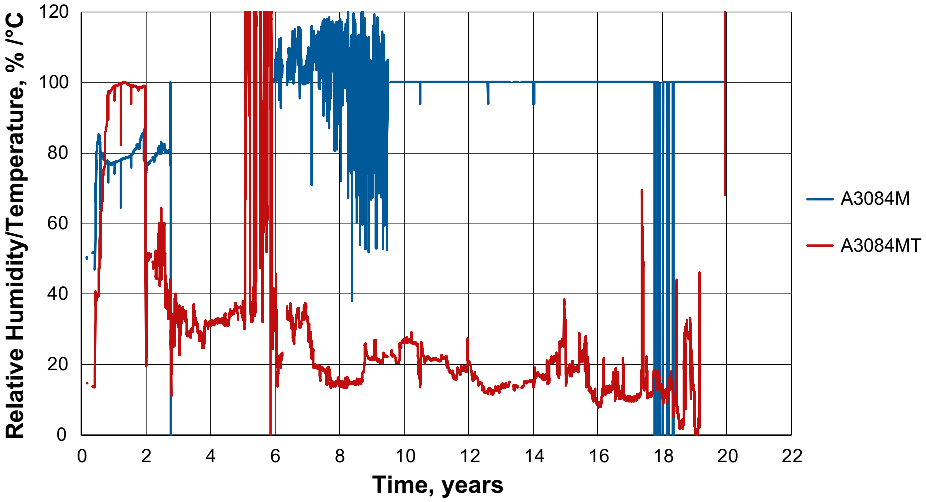

Figure 4-23. Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel A3.

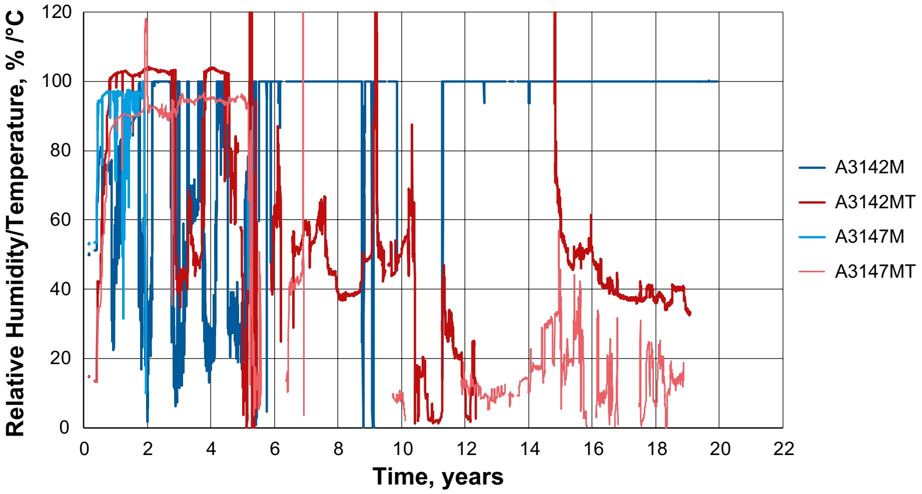

Figure 4-24. Registered relative humidity and temperature plotted versus time for sensor positioned in block 14 in test parcel A3.

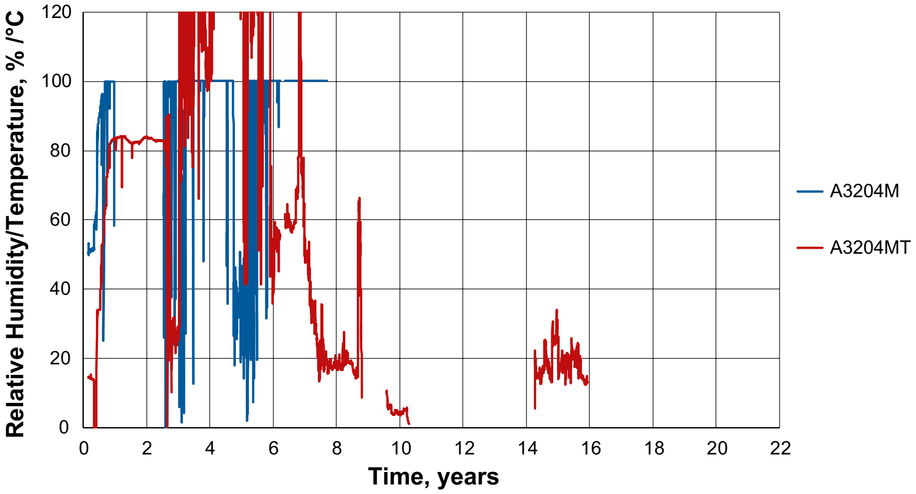

Figure 4-25. Registered relative humidity and temperature plotted versus time for sensor positioned in block 20 in test parcel A3.

In order to facilitate reading of the changes in relative humidity and temperature both after installation but also in conjunction with the test start (test start meant that the heating was turned on and water was injected to fill up all empty voids) graphs have been produced showing the development in relative humidity and temperature during the first 400 days, Figure 4-26 to Figure 4-28. Day 0 in the graphs corresponds to the date of installation. The test, A3, was started 112 days after installation.

The graphs show that the conditions were rather constant during the time after installation and until the test was started even if there are some data missing during this period. The test start, day 112, can be seen very clearly in the graphs. Both the temperature and the relative humidity starts to increase. The relative humidity increases from between 50 and 60 % up to between 75 and 90 % within a few days.

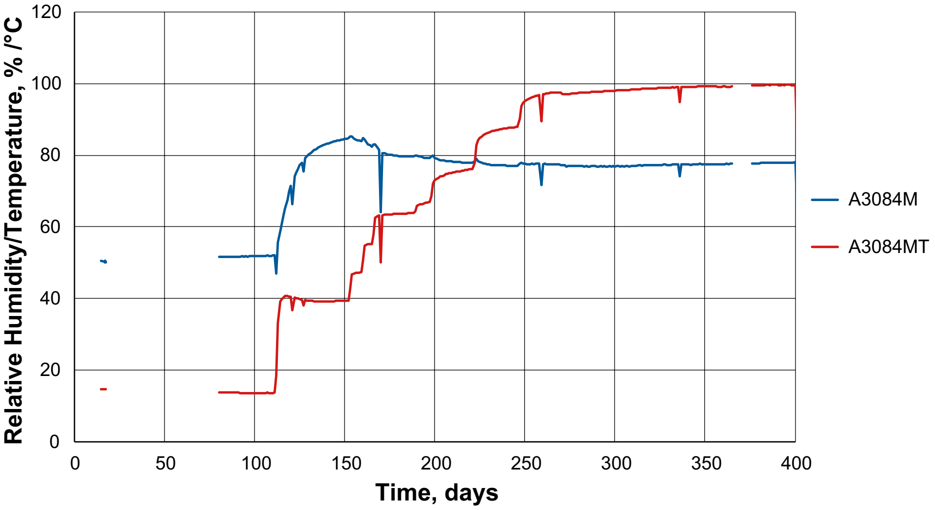

***Figure 4-26.** Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel A3. The graph shows the registered data during the first 400 days after installation.*

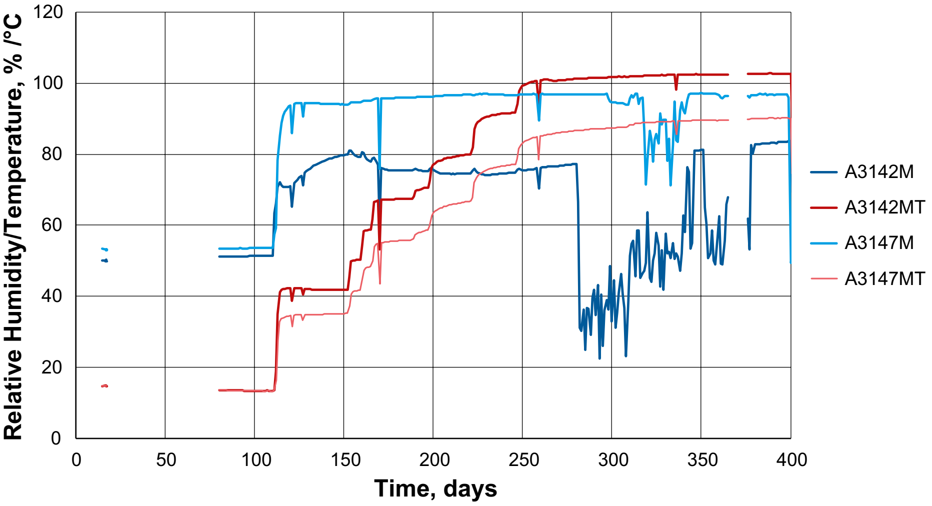

***Figure 4-27.** Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel A3. The graph shows the registered data during the first 400 days after installation.*

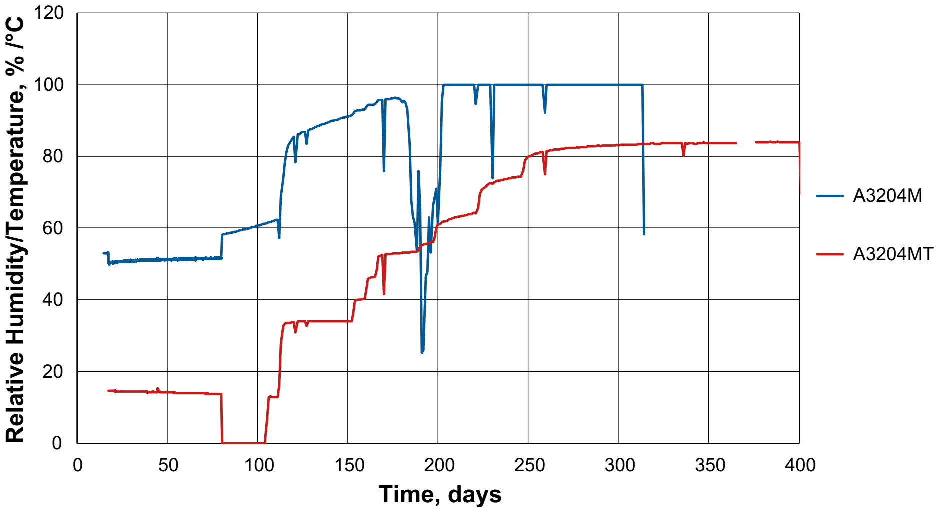

Figure 4-28. *Registered relative humidity and temperature plotted versus time for sensor positioned in block 8 in test parcel A3. The graph shows the registered data during the first 400 days after installation.*

4.4 Comments and conclusions

4.4.1 Temperature

The temperature recordings are of high importance as this parameter is influencing the reaction rate of chemical processes. The large number of thermocouples gave a clear picture of the temperature distribution within both of the test parcels. Contour plots of the measured temperature have been made using an interpolation program, see graphs provided in Figure 4-29. The temperature readings used for the graphs were made the 5th August 2019 i.e. the day before the heaters were stopped.

The active part of the electrical heaters was positioned in the lowest two meters inside the central copper tubes. The temperature measurements show that the warmest section in test parcel S2 was between 700 and 1 800 mm from the bottom. In this area the temperature has been between 70 and 90 °C close to the heater and between 60 and 70 °C closer to the rock. The warmest section in test parcel A3 was between 600 and 1 700 mm from the bottom. In this area the temperature has been between 100 to 120 °C close to the heater and between 70 and 90 °C closer to the rock.

There was a minor decrease in temperature in the innermost positions during the first three to four years (especially clear for test parcel A3). This is a strong indication of how the water saturation process has proceeded (the thermal conductivity of the bentonite increases with increased degree of saturation).

4.4.2 Total pressure and pore pressure

The two types of pressure sensors, i.e. optical sensors in block 08 and 20 and vibrating wire sensors in block 14 has in general worked well. However, after about thirteen years the logger system for the optical sensors started to fuss and after fourteen years the logger system stopped working. After this time no data were collected from the optical sensors.

The pressure sensors show similar results in the two test parcels. The total pressure varies between 1.5 and 4 MPa and the pore pressure between 0.2 and 0.4 MPa. The time to reach steady state for all pressure sensors was more than four years in test parcel S2 and six years in test parcel A3.

4.4.3 Relative Humidity/Saturation

As mentioned earlier, high quality moisture measurements are difficult to perform over long time, especially in the very harsh environment in bentonite at high temperature. When the bentonite is completely saturated, the fragile moisture sensors normally get contaminated of the saline water. This commonly leads to subsequent erroneous results, which however, is a good indication of full water saturation.

The time to reach complete saturation in the measuring points was more than four years in test parcel S2. This time corresponds very well with the time to reach steady state regarding the total pressure, see results from pressure measurements in Section 4.2.2. The time to reach complete saturation (in the measuring points) was shorter in test parcel A3, between 0.5 to 2.5 years. This should be compared with the time to reach steady state regarding the pressure measurements, about six years according to the measurements, see results provided in Section 4.3.2. It should be noted that even if the bentonite is completely saturated, there can still be a homogenisation process ongoing which may result in an increasing swelling pressure locally.

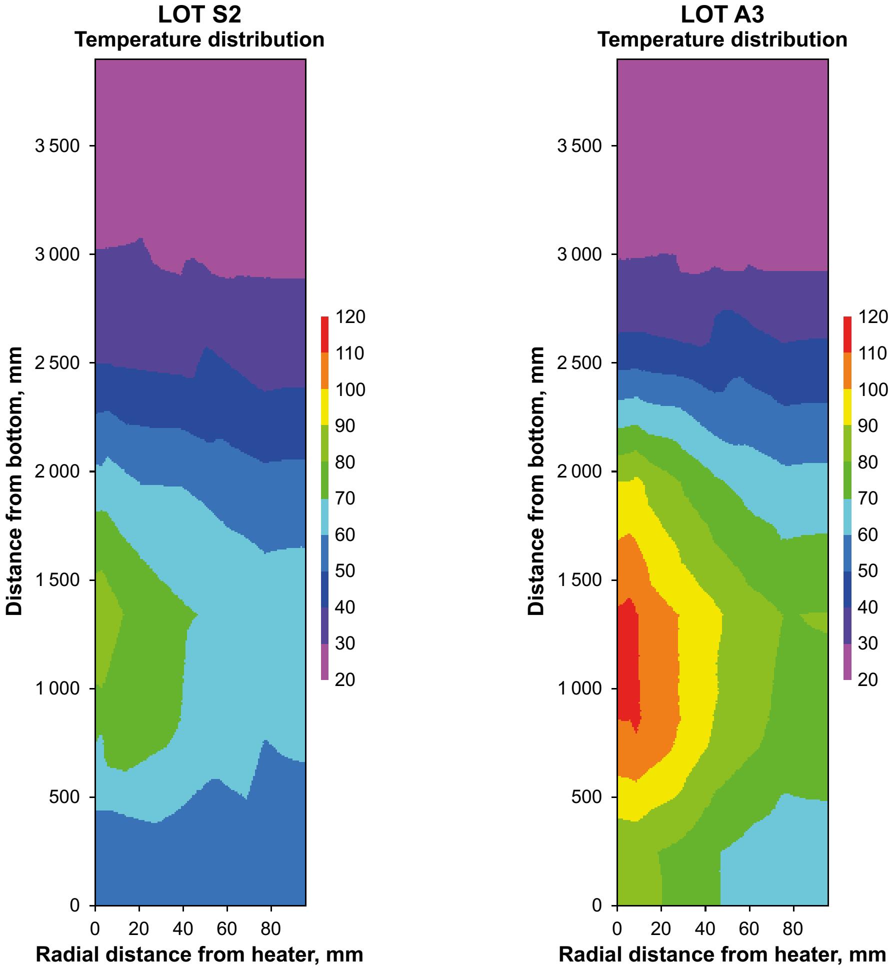

Figure 4-29. Contour plots showing the temperature distribution in test parcel S2 (left) and test parcel A3 (right).

5 Dismantling

5.1 General description of termination, drilling and uplift

The two test parcels were terminated and released from the surrounding rock using the same technique as had been used for earlier test parcels in the LOT series, see e.g. Karnland et al. (2009).

The test parcels were released by overlapping percussion drilling in the surrounding rock. The diameter of the boreholes was 89 mm diameter and the depth around 4.5 m. The final part of the circumference was core drilled with a diameter of 280 mm, Figure 5-1. The choice of percussion technique was motivated partly by economic reasons, but mostly by the fact that no cooling water was necessary. The core drilling technique was used to finalise the slot around the parcel, since the rock support normally is poor at this stage which makes the steering of a percussion boring head cumbersome. The large diameter of the core drilled holes was motivated by the wire sawing equipment which was used to release the bottom of the rock column.

In conjunction with the drilling of the surrounding slot, large efforts were made to ensure that no water, either natural from the rock or cooling water from the drilling machines, could reach the bentonite parcel via e.g. fractures in the rock, since this may influence the bentonite that could swell and make the surrounding rock cover crack. Pumps were used continuously to keep the water level in the boreholes surrounding the test parcels at a low level. In addition, alarms were installed to monitor the water level also during non-working hours.

The released test parcel including rock-cover was lifted by a crane lorry and transported to the ground surface and then further to the laboratory at Äspö, Figure 5-2. The total weight of the rock/bentonite parcel was about 4 500 kg, and the diameter was 650 to 700 mm. i.e. the rock cover of the test parcel was 150 to 200 mm.

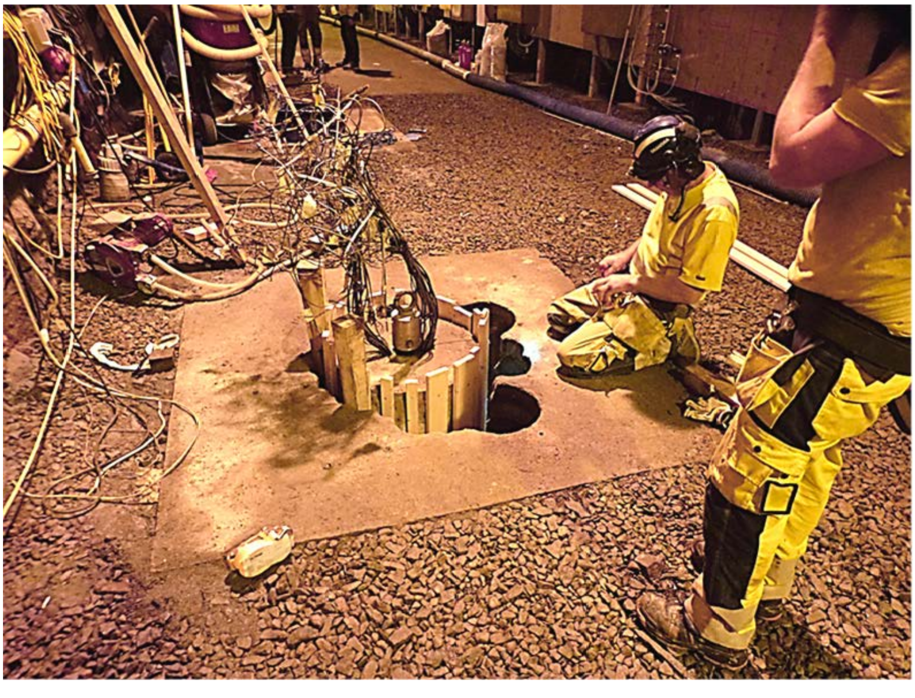

***Figure 5-1.** The released test parcel ready to lift (A3). Note the surrounding slot made by overlapping percussion drilled holes and the larger core drilled holes.*

Figure 5-2. The entire test parcels, including rock-cover, were being placed on a lorry for transport to the ground surface.

5.2 Summary of field activities

The termination of the two test parcels S2 and A3 was performed during August to October 2019 and was divided into several activities:

- 6th August. The power to the heaters was turned off. The temperature drop was relatively fast and after one week, the maximum temperature was 30 °C.
- 12th August. The data acquisition system was stopped, and all sensors disconnected.
- 13th August. Radiological review of the test area was done. Since the two test parcels included ^{60}Co-tracer doped plugs, placed in one bentonite block in each parcel, a radiological control of the test area was performed. The remaining activity in the test parcels was calculated to be below 300 kBq, which from an emission point of view is low, but for personal security still associated with certain risks. No contamination was detected in the test niche.
- 14th August. Dismantling of steel beams and cabinet above the test holes was done.
- 16th to 20th August. Core drilling of the steel rods that have been used to secure the beams over the test parcel was carried out. Some of the steel rods would interfere with the percussion drilled slot and it was therefore decided to remove them. To facilitate the later overlapping percussion drilling, which is dependent on the material being solid to increase the accuracy, the boreholes were filled with concrete after removal of the steel rods.
- 27th August. The percussion drilling of test parcel A3 was started. After finishing, the two larger core drilled holes were performed. Problems occurred during the work with reinforcement bars that were placed in the upper concrete plate. This influenced the accuracy of the percussion drilling and resulted in that all boreholes didn't overlap each other completely. Several extra core drilled holes had to be drilled to remove remaining rock between the percussion drilled boreholes.
- 10th September. Test parcel A3 was lifted and transported to the laboratory.

- 11th September. Radiological control of test parcel A3 was done. Increased levels were noted on several positions along the test parcel but after completing analysis it was concluded that these originated from radioactive elements, naturally occurring in rock and water. All material, except block 4, 5 and 6 (block 5 contained ^{60}Co tracer doped plugs, see further description in Section 5.3.2), was radiologically cleared and could be handled without any restrictions.
- 12th September. The percussion drilling of test parcel S2 was started. After finishing, the two larger core drilled holes were performed. Only minor problems occurred with remaining rock between the percussion drilled boreholes.
- 16th September 2019. The division of test parcel A3 was started.
- 1st October. Test parcel S2 was lifted and transported to the laboratory and a radiological control was made. All material, except block 4, 5 and 6 (block 5 contained ^{60}Co tracer doped plugs, see further description in Section 5.3.2), was radiologically cleared and could be handled without any restrictions.
- 2nd October. The division of test parcel S2 was started.

5.3 Sampling of the test parcels

5.3.1 Removal of rock cover and rough division of the blocks

The covering rock was successively removed from the test parcels. Natural occurring fractures and weaknesses in the rock were used together with drilling and wedges to loosen rock pieces from the test parcels, Figure 5-3 and Figure 5-4. The approximate position of the original block interfaces was identified in the exposed bentonite by measuring the distance from the bottom plate but also by use of different tubes going in to defined positions. The north direction of the test parcel was checked and marked on the bentonite. The bentonite blocks were cut by using a saber saw, Figure 5-5 and Figure 5-6. To facilitate removal of the blocks from the central copper tube it was often necessary to also do a cut in the blocks along the test parcel. The removed blocks, often two or three together, were marked and temporarily placed in plastic bags to minimise the risk of drying.

Figure 5-3. *Photo showing the removal of the rock cover from the test parcels. Wedges were used to create fractures in the rock.*

***Figure 5-4.** Large pieces of rock were removed from the test parcels.*

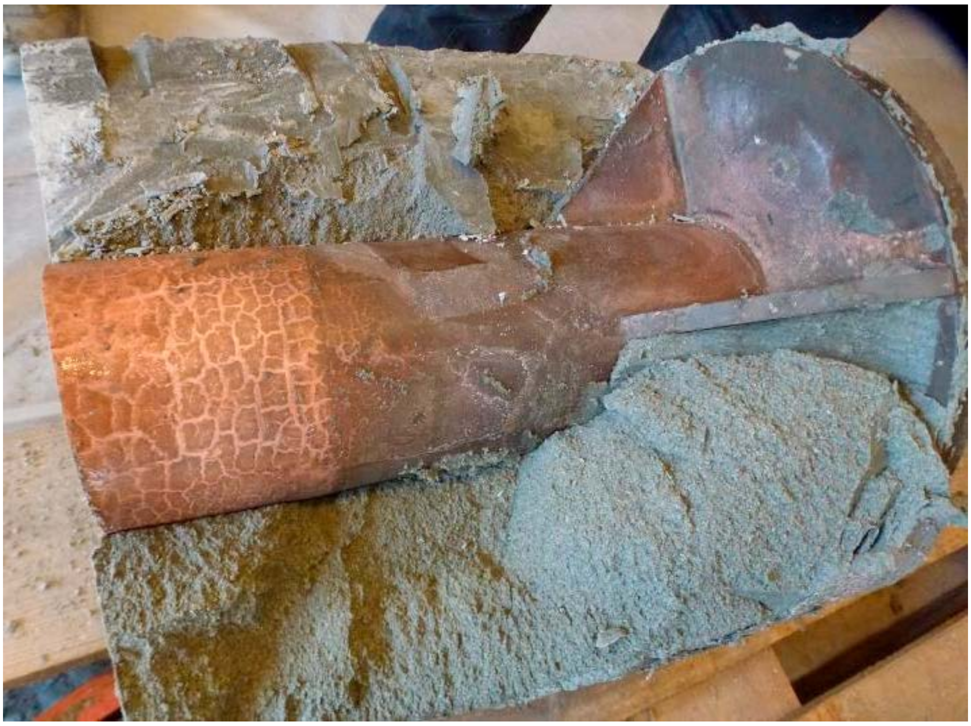

***Figure 5-5.** The bottom part of the central copper tube, including the bottom plate, was cut of together with three bentonite blocks (photo from test parcel S2).*

__Figure 5-6.__ A saber saw was used to cut of blocks from the test parcel. The cuts were made approximately at the original block interfaces. The lines along the parcel that can be seen on the bentonite surface originate from thermocouples and other tubes that had been placed on the test parcel periphery (photo from test parcel A3).

5.3.2 Blocks with tracer doped plugs

In both test parcels ^{60}Co tracer doped plugs were placed in block 5. Packages including block 4, 5 and block 6 were cut off from each of the test parcels. The packages included both bentonite blocks and the central copper tube. The packages were placed in alumina bags that were evacuated from air and then placed in special transport boxes. The box containing blocks from test parcel A3 was transported to Chalmers, Gothenburg for further analyses on the ^{60}Co tracer and the box containing blocks from test parcel S2 was transported to CLAB (Central Interim Storage for Spent Nuclear Fuel) for storage.

5.3.3 Copper coupons

Copper coupons were emplaced in bentonite block no. 22 and 30 in both current test parcels. Since it was important to not damage the coupons by e.g. cutting or scratching in them during excavation it was decided to use a special procedure to find their exact location:

1. The North direction was marked on the blocks (the copper coupons were positioned in the north and south directions of the test parcels).
2. In conjunction with the initial division of the bentonite, the theoretical (initial) positions of the emplaced copper coupons were determined. The current blocks, no. 22 and 30, including one extra block on each side, were thereafter removed from the central copper tube.
3. A metal detector was used to roughly verify the positions of the copper coupons.
4. The blocks were carefully divided into smaller pieces. The division was made using small wedges of wood. Between every division, the metal detector was used to verify in which bentonite piece the copper coupon was positioned.

All copper coupons, four in each test parcel, were found undamaged. The work and results from the investigations on the coupons are described in a separate report.

5.3.4 Water sampling cups

In total twelve water sampling cups were installed in each test parcel. In conjunction with the division of the bentonite, eight cups were found in the A3 test parcel and four in the S2 test parcel. No efforts were made to find the remaining cups. These are still embedded in the bentonite blocks and it is judged that they easily can be found later.

In order to get an indication whether there was water in the cups, all cups that were found, were weighed. The weight was between 21.5 and 22.1 g. The weight of a reference cup was 22.4 g. This indicates that there was no water present in the cups. The found cups were packetised and placed in the storage at Äspö.

5.3.5 Initial sampling of the bentonite

The water content and density were determined on several positions in the two test parcels. Two slices were cut out from each bentonite block, Figure 5-7. From one of the slices, samples were taken at the mid-height of the blocks at five different radial distances from the heater, The measurements were made on every block except no. 4, 5 and 6 (in block no. 5 there was ^{60}Co-tracer doped plugs and this block together with the neighboring were sent for special analyses). In total 180 samples were analysed from each test parcel.

The second slice was saved for future sampling. The slices were sawed out in different directions, see tables provided in Appendix 1 to 6.

5.3.6 Final packetising

The final packetising was made using special alumina bags. The air was evacuated by use of a vacuum pump, and the bags were then sealed by welding. All material from the two test parcels were, after packetising, stored in the laboratory at Äspö with the following exceptions:

1. Pieces from block 22 and 30, both test parcels. These blocks contained the copper coupons. After having found the coupons they were either left partly embedded in the bentonite block pieces or removed from the bentonite and wrapped up in paper before packetising in alumina bags. The material was then transported to Rise KIMAB, Kista for further examination of the copper coupons.
2. Block 4,5 and 6, both test parcels. These three blocks were handed as one piece including the central copper tube from both test parcels. The blocks were packetised and placed in special transport boxes. The box containing blocks from test parcel A3 was transported to Chalmers, Gothenburg for further analyses on the ^{60}Co tracer and the box containing blocks from test parcel S2 was transported to CLAB (Central Interim Storage for Spent Nuclear Fuel) for storage.

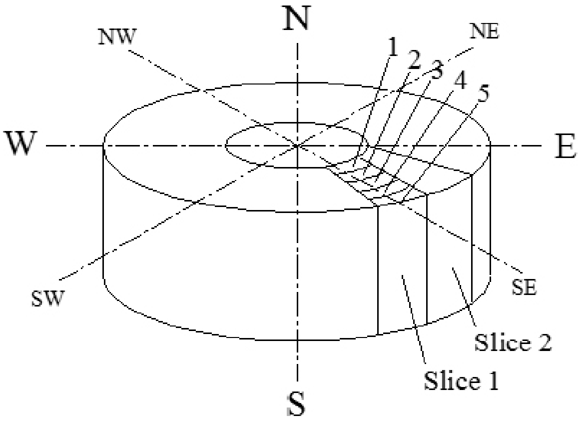

Figure 5-7. Two slices were cut from each bentonite block. One slice was used for the initial determination of water content and density and the other slice was saved for future sampling.

6 Initial analyses

6.1 General

Basic properties of the bentonite test material were measured in many positions in the two test parcels to achieve a picture of the water content and density distribution. This data was then used to calculate the degree of saturation. Samples were taken at the mid-height of the blocks at five different radial distances from the heater. The measurements were made on every block except no. 4, 5 and 6 (in block no. 5 there was ^{60}Co-tracer doped plugs and this block together with the neighboring were sent for special analyses).

In total 180 samples were analysed from each test parcel.

6.2 Method

6.2.1 Water content

The water content (w) is defined as mass of water (m_w) per mass of dry substance (m_s). The dry mass is obtained by drying the wet specimen at 105 °C for 24 hours. The water content was determined on a sample of about 50 g.

The sample was placed in an aluminum tin and the bulk mass (m_b) of the sample was determined by use of a laboratory balance. The sample was then placed in an oven for 24 h at a temperature of 105 °C. The dry mass of the sample (m_s) was determined immediately after taking it out. From these measurements the mass of water (m_w) was calculated:

$$m_w = m_b - m_s \tag{6-1}$$

and the water content (w) of the sample determined:

$$w = \frac{m_w}{m_s} \tag{6-2}$$

6.2.2 Bulk density, dry density and degree of saturation of single pellets

Bulk density

The bulk density (ρ_b) is the ratio of the total bulk mass (m_b) to the total volume (V). The volume was determined by hanging a sample in a thin thread under a balance. The sample was then weighed, first in air (m_b) and then again when submerged into paraffin oil (m_{bp}) with known density (ρ_p). The volume of the sample was then calculated:

$$V = \frac{m_b - m_{bp}}{\rho_p} \tag{6-3}$$

The bulk density of the sample was then calculated as:

$$\rho_b = \frac{m_b}{V} \tag{6-4}$$

Dry density

Dry density (ρ_d) is the mass of solids per unit volume. After determining the water content and the bulk density of each sample it was possible to calculate the dry density:

$$\rho_d = \frac{\rho_b}{1 + w} \tag{6-5}$$

Degree of saturation

The degree of saturation (s_r) is the ratio of the volume of water to the total volume of void space.

The density of the particles (ρ_s) i.e. the ratio between the mass of solids and the volume of the solids, is known (a value of the particle density of 2 780 kg/m^3 have been used) and also the density of the water (ρ_w), which means that the degree of saturation can be calculated:

$$Sr = \frac{w \cdot \rho_b \cdot \rho_s}{(\rho_s \cdot (1+w) - \rho_b) \cdot \rho_w} \qquad 6\text{-}6$$

6.3 Results

Contour plots of the measured and calculated variables water content, dry density and degree of saturation were made using an interpolation program. It was judged that due to the long test time there was rotational symmetry which means that all results are plotted as function of depth and radius only (the sampling direction and the exact coordinates for each measuring position are specified for each measuring point together with the determined values in the tables provided in Appendix 1 to 6).

The results from the initial analyses on the bentonite from the two test parcels are presented in Figure 6-1 (water content), Figure 6-2 (dry density) and Figure 6-3 (degree of saturation).

The results show that both test parcels had a similar water content and density distribution. The water content varied between 27 and 42 %. The highest values were at the lower part, about 0–0.3 m, and at the top, about 3.4–3.9 m, Figure 6-1.

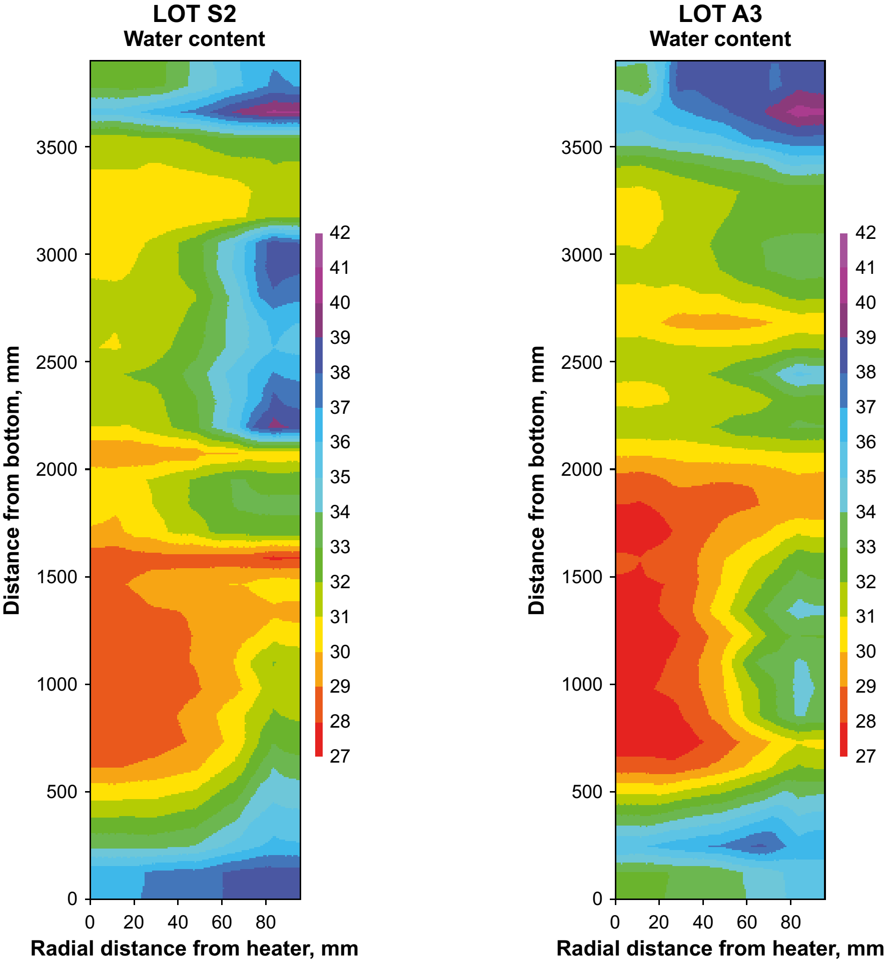

Figure 6-1. *Water content distribution for test parcel S2 (left) and test parcel A3 (right).*

The density was significantly lower in the bottom part and at the top of both parcels, mainly below 1 450 kg/m^3, while the density in the hottest part was rather high, typically between 1 500 and 1 550 kg/m^3, Figure 6-2.

There are two explanations for the rather large differences in density and water content along the test parcels.

Lower part of the test parcels

The test parcels were installed resting on a sand filling placed in the bottom of the borehole. This sand filling was placed both to fill up the smaller pilot hole but also to provide a stable ground for the test parcels. The sand filling was also later used during the water filling in conjunction with the test start. A titanium tube with a filter tip was then placed in the sand filling and water was injected so that the initial gaps between blocks and rock surface were filled with water from the bottom of the test holes, see Section 3.2.2. The sand has thus served as a filter, where inflowing water to the pilot hole has been distributed upwards through the annular gap around the bottom plate and further up to the bentonite. It is likely that this access to water from the bottom has led to an early swelling of the lower part of the test parcel.

The upper part of the test parcels

In each of the test parcels, a sand filling with a thickness of about 100 mm was positioned between the uppermost bentonite blocks and the concrete top plugs. This has probably resulted in that the blocks at the top has swelled and compacted the sand filling upwards.

These early swelling at the bottom and at the top has resulted in density gradients in the bentonite that were still present also after twenty years test duration.

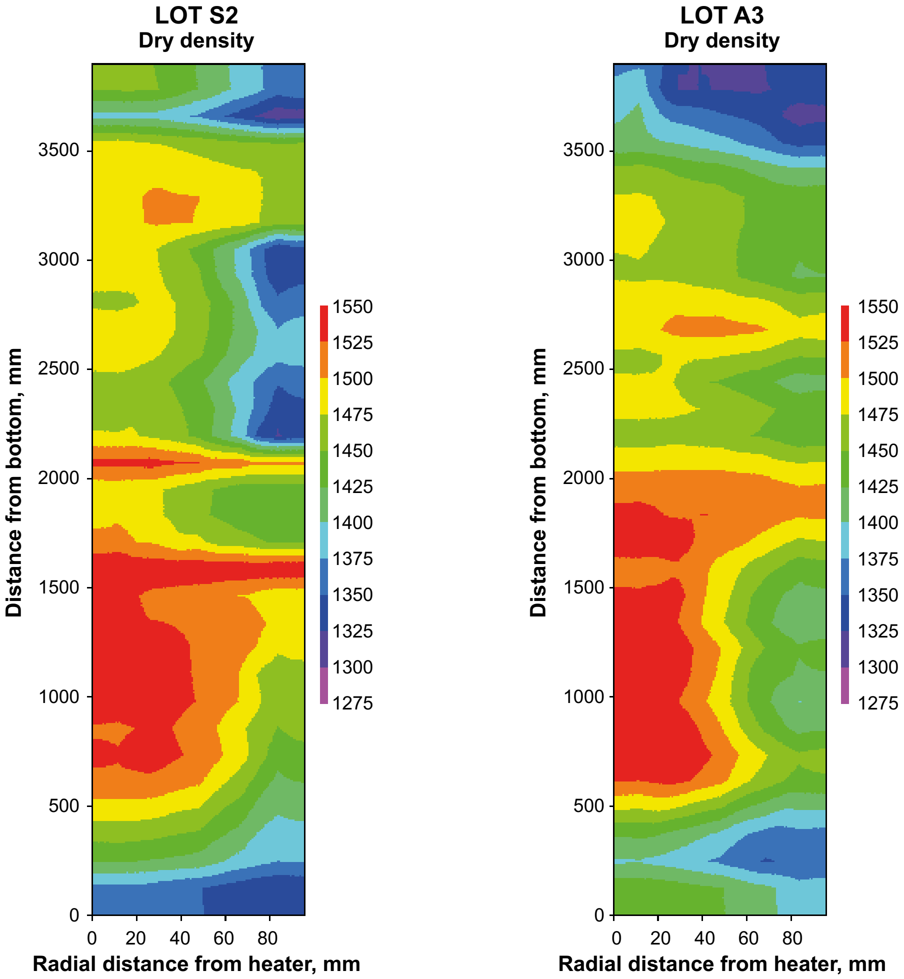

***Figure 6-2.** Dry density distribution for test parcel S2 (left) and test parcel A3 (right).*

There is also, for both test parcels, a strong radial density gradient. All bentonite blocks have swelled in radial direction and after twenty years test duration there are still a clear difference in density between the inner parts at the central copper tube and the outermost parts close to the rock. There is a homogenisation process ongoing in the bentonite. Differences in density are, however, expected also after long time when homogenisation has occurred, depending on inner friction in the bentonite.

The degree of saturation was close to 100 % in most positions in both test parcels, Figure 6-3. In test parcel A3, the right graph, there was a small difference in degree of saturation in the hottest part i.e. between 500 and 2 000 mm from the bottom compared to the parts with lower temperature. In the hottest part, the degree of saturation was somewhat lower, roughly between 94 and 97 % compared to between 97 and 100 % in the parts with lower temperature. The difference is thus rather small but still clear. The difference depends probably on the thermal expansion of water during the heating phase. When the power was turned off and the temperature decreased, the water took up less space which means that additional water was needed to again reach full saturation. Since the time from turning of the power to the lift of the test parcel was rather short, there was not enough time to restore the saturation.

Example: Water has a density of 943 kg/m^3 at a temperature of 120 °C (at saturation pressure). Assuming that the bentonite is completely saturated at this temperature and then the temperature is decreased to 20 °C. The density of the water will then increase to approximately 1 000 kg/m^3. For a saturated bentonite sample this results in a decreased degree of saturation to approximately 94 % i.e. additional water is needed to again reach 100 % degree of saturation.

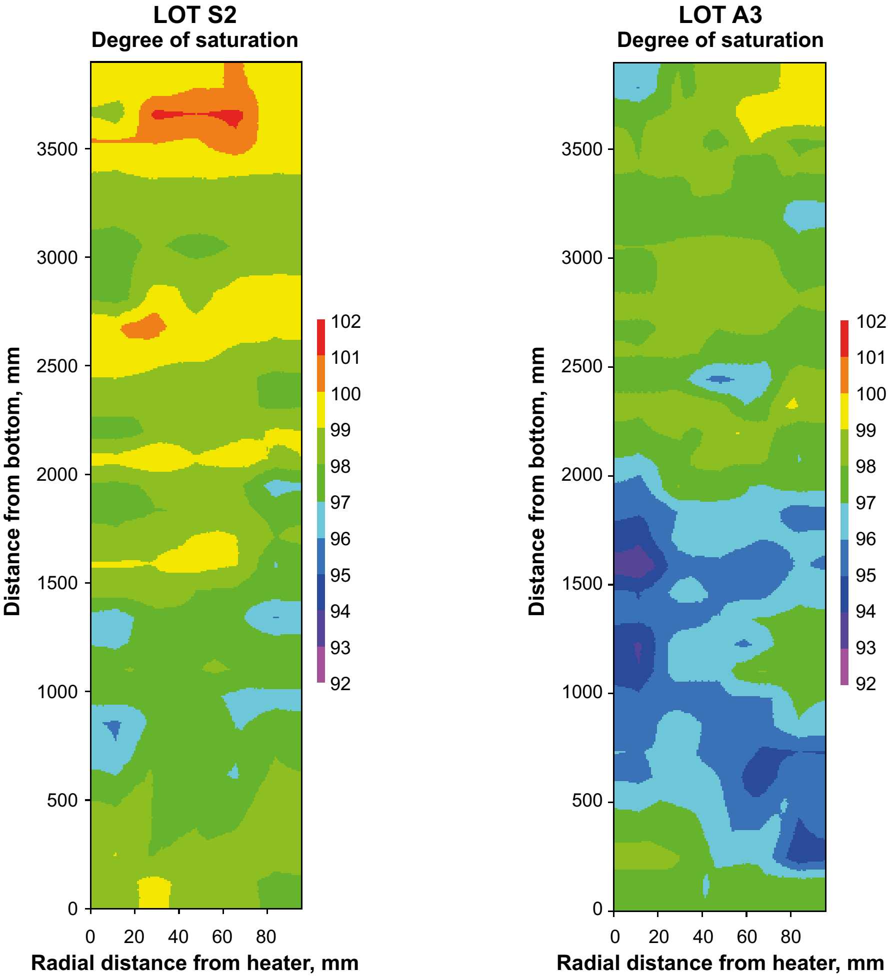

Figure 6-3. Degree of saturation for test parcel S2 (left) and test parcel A3 (right).

7 Performance of instrumentation

The two test parcels had been running for about twenty years. During this time, most of the pressure sensors and all relative humidity sensors had stopped working, see Table 7-1. However, all but one thermocouple, were still working when the heaters were disconnected.

Table 7-1. Status of the different sensors after twenty years test duration.

Sensor type	Test parcel S2		Test parcel A3	
	Installed number of sensors	Sensors working after 20 years	Installed number of sensors	Sensors working after 20 years
Thermocouples	24	23	24	24
Total pressure sensors (optical)	2	0	2	0
Total pressure sensors (vibrating wire)	1	1	1	0
Pore pressure sensors (optical)	2	0	2	0
Pore pressure sensors (vibrating wire)	1	1	1	1
Relative humidity sensors	4	4*	4	4*

* The relative humidity sensors do not work after being contaminated with saline water. This is, however, a good indication of complete water saturation.

Prior to the termination of the two test parcels it was decided to prioritise the retrieval of the copper coupons and the sampling of the bentonite. Besides the sensors that had stopped function during the test time, several of the other sensors, or their cabling, were damaged during the dismantling of the test parcels. Function control after dismantling has thus only been performed on thermocouples. Out of a total of 48 thermocouples (24 in each test parcel) it was possible to perform a function control on 30 thermocouples.

The function control was performed by connecting a single thermocouple to a handheld thermocouple reader (ET-959) and then measure the temperature, both in the room but also after lowering the thermocouple into a hot bath (heated circulated bath). Reference measurements were performed using both analogue and digital thermometers.

The results from the function controls are provided in Table 7-2. As shown in the table, all tested thermocouples show a high accuracy when measuring the temperature in a hot bath. The variation in temperature was somewhat higher when measuring in the room but this is judged to depend on difficulties to provide an even environment.

Table 7-2. Compilation of data from the function test on thermocouples after retrieval.

Test parcel LOT S2			Test parcel LOT A3		
Sensor no.	**Room Temp °C**	**Hot Bath °C**	**Sensor no.**	**Room Temp °C**	**Hot Bath °C**
Ref.	21.3	90	Ref.	22.7	90
S2020T	23.1	90.0	A3024T	22.5	90.2
S2024T	21.5	90.0	A3028T	22.3	90.0
S2028T	21.0	90.0	A3080T	22.8	89.9
S2080T	23.6	90.1	A3082T	22.6	90.1
S2088T	21.8	90.0	A3084T	22.6	90.4
S2142T	20.9	90.0	A3086T	22.6	90.1
S2144T	21.3	90.1	A3146T	22.5	89.9
S2146T	21.0	90.0	A3148T	22.9	90.0
S2148T	20.9	90.2	A314TT	22.6	90.3
S2260T	21.3	90.0	A3200T	22.6	90.0
S2268T	21.9	89.9	A3204T	22.5	90.2
S2384T	20.9	90.0	A3206T	22.6	89.8
			A3208T	22.5	90.2
			A3264T	23.0	90.9
			A3268T	22.6	90.2
			A3324T	22.6	90.1
			A3384T	22.6	90.1
			A3TUT	22.8	90.3

8 Summary and conclusions

8.1 General

The design of the test parcels is judged to be successful. The relatively small dimensions, compared to a full-scale KBS-3 deposition hole, have shortened the time to reach water saturation of the bentonite. It has also been possible to achieve a higher temperature gradient over the buffer material and the dimensions have also facilitated the dismantling of the test parcels and the following sampling of the bentonite.

8.2 Temperature

A basic requirement for the test parcel construction was to keep a defined maximum temperature in the central part of the clay column during the test time. This requirement is deemed to have been fulfilled.

The active part of the electrical heaters was positioned in the lowest two meters inside the central copper tubes. The temperature measurements show that the warmest section in test parcel S2 was between 700 and 1 800 mm from the bottom. In this area the temperature has been between 70 and 90 °C close to the heater and between 60 and 70 °C closer to the rock. The warmest section in test parcel A3 was between 600 and 1 700 mm from the bottom. In this area the temperature has been between 100 to 120 °C close to the heater and between 70 and 90 °C closer to the rock.

The power regulating system worked very well during the entire twenty years test duration. In September 2014, the system was updated with new components and this resulted in a small drop in the registered temperature for both test parcels. The drop was clearer for test parcel S2.

No overheating or major temperature drops took place during the test time.

8.3 Bentonite

8.3.1 Degree of saturation

The degree of saturation was close to 100 % in most positions in both test parcels. In test parcel A3 there was a small difference in degree of saturation in the hottest part i.e. between 500 and 2 000 mm from the bottom compared to the parts with lower temperature. In the hottest part, the degree of saturation was somewhat lower, roughly between 94 and 97 % compared to between 97 and 100 % in the parts with lower temperature. The difference is thus rather small but still clear. The difference depends probably on the thermal expansion of water during the heating phase. When the power was turned off and the temperature decreased, the water took up less space which means that additional water was needed to again reach full saturation. Since the time from turning of the power to the lift of the test parcel was rather short, there was not enough time to restore the saturation.

8.3.2 Density distribution

The density was significantly lower in the bottom part (0–400 mm) and at the top of both parcels (3 500–3 900 mm), mainly below 1 450 kg/m^3, while the density in the hottest part was rather high, typically between 1 500 and 1 550 kg/m^3, Figure 6-2.

An explanation for the rather large differences in density along the test parcels could be that the test parcels were installed resting on a sand filling placed in the bottom of the borehole. This sand filling was placed both to fill up the smaller pilot hole but also to provide a stable ground for the test parcels. The sand filling was also later used during the water filling. A titanium tube with a filter tip was placed in the sand filling and water was injected so that the initial gaps between blocks and rock surface were filled from the bottom of the test holes with water in conjunction with the test start, see Section 3.2.2.

The uppermost part of each test parcel was filled with sand, about 100 mm. This has resulted in that the blocks at the top has swelled and compacted the sand filling above. These early swelling at the bottom and at the top has resulted in density gradients in the bentonite that were still present also after twenty years test duration.

There is also, for both test parcels, a strong radial density gradient. All bentonite blocks have swelled in radial direction and after twenty years test duration there are still a clear difference in density between the inner parts at the central copper tube and the outermost parts close to the rock.

8.3.3 Swelling pressure

The pressure sensors show similar results in the two test parcels. The pressure sensors were placed in block 8, 14 and 20.

The registered total pressure varied between 2.5 and 4 MPa in test parcel S2 with the highest pressure in block 14. The pore pressure varied between 0.25 and 0.4 MPa. This means that the swelling pressure was between 2.1 and 3.75 MPa. To obtain the swelling pressure of the bentonite, the measured total pressure should be reduced by the value of the pore pressure. The time to reach steady state for all pressure sensors was more than four years in test parcel S2.

The registered total pressure varied between 1.5 and 4 MPa in test parcel A3 with the highest pressure in block 14. The pore pressure varied between 0.15 and 0.25 MPa. This means that the swelling pressure was between 1.35 and 3.75 MPa. The time to reach steady state for all pressure sensors was more than six years in test parcel A3

The dry density in the central parts of block no. 8, 14 and 20 i.e. the position of the total pressure sensors, varies between 1 426 to 1 523 kg/m^3. This corresponds to a calculated swelling pressure of between 2.13 and 4.12 MPa during swelling according to Åkesson et al. (2010). These values are thus in good agreement with the measured pressures.

The maximum swelling pressure is reached after approximately between one and four years in both test parcels. These long times depends probably on the fact that all total pressure sensors were positioned in the middle of the blocks which means that it will take long time to reach full saturation around the sensor bodies. After the initial filling with water, the bentonite starts to swell into the water filled gap between rock and blocks. However, to reach full saturation of all bentonite in the parcel, additional water is needed. This water comes partly from the rock and partly from the artificial point inflow positioned at the level of block 32 (titanium tube with filter tip). The transport of water from the rock surface to the inner parts of the blocks will take rather long time depending on the low hydraulic conductivity of the bentonite. Also, after having reached full saturation there is an ongoing homogenisation process that contributes to an increasing swelling pressure during long time.

The final swelling pressure that is reached for a certain position depends on the density of the bentonite, the salinity of the water and the type of adsorbed cations. There is also a strong dependence of the stress path i.e. if the bentonite has been consolidated or if it has swelled. The highest densities in both test parcels were found in the center of the warmest parts i.e. block 14 were also the highest swelling pressures were registered (4 MPa). The density in block 8 and 20 is somewhat lower, and they are positioned on borders of areas with lower density and this could be an explanation for the lower swelling pressure registered in these blocks (1.35–2.5 MPa). There have also been an axial swelling downwards and upwards in the test parcels close to these positions which may have affected the final swelling pressure.

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Appendix 1

Water content distribution in test parcel S2

Water content distribution in test parcel S2, %

Block no.	Direction	Position, mm from central heater				
		10	29	48	67	86
1	West	38.7	39.9	39.5	40.3	39.7
2	West	35.8	36.2	36.5	37.5	37.9
3	West	33.6	33.5	33.9	35.2	36.3
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	East	28.3	28.7	29.3	30.9	33.9
8	East	28.4	28.5	29.1	30.3	33.2
9	East	28.5	28.6	29.3	30.7	32.4
10	West	28.4	28.4	28.9	29.8	32.0
11	West	28.2	28.3	28.8	29.8	31.5
12	West	28.6	28.8	29.3	30.4	33.2
13	South	28.2	28.5	28.9	29.3	30.1
14	South	28.2	28.9	29.1	29.1	29.8
15	South	28.9	29.5	29.8	30.3	31.4
16	West	28.4	28.7	28.6	28.4	27.2
17	West	28.5	28.6	28.6	28.5	28.3
18	East	30.2	31.8	33.4	35.3	35.9
19	East	30.1	30.8	31.9	32.6	32.6
20	East	30.7	31.1	32.1	33.1	32.5
21	North	28.6	28.5	28.4	28.3	28.0
22	North	30.0	31.2	32.6	35.4	38.0
23	North	32.3	32.1	32.9	35.8	41.9
24	East	31.3	31.3	32.9	35.1	37.7
25	East	32.0	32.3	33.4	35.6	37.4
26	North	30.8	31.5	32.7	34.4	36.2
27	North	30.9	31.4	32.4	34.3	36.7
28	North	31.3	31.5	32.0	34.8	36.7
29	North	31.6	31.3	31.8	34.2	38.9
30	North	30.2	31.1	32.5	35.6	39.6
31	North	30.3	31.2	32.5	35.1	39.1
32	South	30.6	30.0	30.3	30.8	32.2
33	South	30.8	30.1	30.3	30.4	31.8
34	South	30.6	29.9	30.1	30.7	31.9
35	West	31.3	31.5	31.9	32.1	32.3
36	West	31.3	31.9	32.2	33.1	32.9
37	West	35.3	36.5	37.5	39.4	40.4
38	West	32.8	33.0	34.8	36.7	38.7
39	West	33.9	31.9	32.8	33.8	34.7

Appendix 2

Dry density distribution in test parcel S2

Dry density distribution in test parcel S2, kg/m^3

Block no.	Direction	Position, mm from central heater				
		10	29	48	67	86
1	West	1 333	1 317	1 309	1 294	1 294
2	West	1 378	1 380	1 368	1 352	1 339
3	West	1 432	1 426	1 419	1 394	1 375
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	East	1 531	1 531	1 515	1 473	1 419
8	East	1 524	1 536	1 521	1 489	1 432
9	East	1 520	1 530	1 516	1 479	1 445
10	West	1 537	1 535	1 524	1 498	1 450
11	West	1 546	1 537	1 526	1 499	1 457
12	West	1 530	1 530	1 520	1 499	1 438
13	South	1 532	1 533	1 525	1 513	1 490
14	South	1 530	1 525	1 522	1 516	1 490
15	South	1 532	1 516	1 506	1 492	1 468
16	West	1 548	1 540	1 544	1 546	1 557
17	West	1 544	1 541	1 548	1 545	1 537
18	East	1 494	1 464	1 430	1 394	1 377
19	East	1 496	1 484	1 460	1 447	1 439
20	East	1 485	1 479	1 458	1 435	1 434
21	North	1 547	1 554	1 550	1 553	1 553
22	North	1 493	1 475	1 443	1 390	1 347
23	North	1 452	1 459	1 444	1 387	1 280
24	East	1 478	1 475	1 444	1 397	1 336
25	East	1 465	1 456	1 428	1 386	1 346
26	North	1 496	1 477	1 453	1 410	1 379
27	North	1 492	1 485	1 461	1 422	1 368
28	North	1 474	1 493	1 465	1 413	1 372
29	North	1 460	1 473	1 457	1 420	1 334
30	North	1 495	1 481	1 452	1 388	1 315
31	North	1 492	1 477	1 443	1 393	1 318
32	South	1 488	1 504	1 499	1 489	1 452
33	South	1 487	1 503	1 500	1 493	1 465
34	South	1 490	1 508	1 501	1 490	1 459
35	West	1 482	1 482	1 472	1 467	1 464
36	West	1 488	1 474	1 467	1 454	1 446
37	West	1 389	1 389	1 369	1 336	1 300
38	West	1 448	1 444	1 414	1 379	1 337
39	West	1 451	1 471	1 452	1 429	1 409

Degree of saturation in test parcel S2

Degree of saturation in test parcel S2, %

Block no.	Direction	Position, mm from central heater 10	29	48	67	86
1	West	99.2	99.7	97.6	97.6	96.1
2	West	97.9	99.1	98.4	98.7	97.9
3	West	99.3	97.9	98.2	98.5	98.7
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	East	96.5	98.0	97.6	96.8	98.3
8	East	95.7	97.8	97.6	97.1	98.0
9	East	95.6	97.2	97.8	96.9	97.3
10	West	97.5	97.2	97.3	96.7	96.9
11	West	98.3	97.4	97.5	96.9	96.4
12	West	97.2	97.8	98.4	99.0	98.8
13	South	96.2	97.4	97.6	97.2	96.7
14	South	96.1	97.8	97.9	97.2	95.8
15	South	98.5	98.4	97.8	97.7	97.8
16	West	99.2	99.0	99.3	99.0	96.2
17	West	98.9	99.0	99.9	99.3	97.2
18	East	97.5	98.4	98.5	98.8	98.0
19	East	97.6	97.8	97.9	98.3	97.3
20	East	97.8	98.1	98.5	98.2	96.2
21	North	99.7	100.4	99.4	99.7	98.5
22	North	96.9	98.2	97.9	98.4	99.3
23	North	98.1	98.4	98.8	99.3	99.3
24	East	98.7	98.4	98.8	98.5	97.0
25	East	99.1	98.8	98.2	98.3	97.6
26	North	99.8	99.4	99.5	98.6	98.9
27	North	99.6	100.2	99.6	99.7	98.8
28	North	98.3	101.4	99.3	100.0	99.4
29	North	97.0	98.0	97.6	99.3	100.0
30	North	97.6	98.7	98.8	98.7	98.8
31	North	97.5	98.2	97.5	98.1	98.0
32	South	98.1	98.3	98.5	98.6	97.8
33	South	98.3	98.6	98.8	98.1	98.4
34	South	98.4	98.5	98.4	98.6	98.1
35	West	99.4	99.9	99.8	99.8	99.8
36	West	100.2	100.2	99.9	101.0	99.2
37	West	98.0	101.3	101.1	101.3	98.7
38	West	99.1	99.2	100.2	100.4	99.5
39	West	103.0	99.8	99.6	99.3	99.1

Water content distribution in test parcel A3

Water content distribution in test parcel A3, %

Block no.	Direction	Position, mm from central heater				
		10	29	48	67	86
1	South	29.2	29.8	30.9	31.4	33.6
2	South	34.4	34.4	34.3	35.5	36.7
3	South	35.8	36.7	37.3	38.5	36.4
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	South	27.7	27.4	28.3	29.6	31.5
8	South	27.4	27.4	28.4	29.7	31.1
9	East	27.5	27.8	29.3	32.1	34.5
10	West	27.7	28.0	29.4	31.7	34.4
11	West	28.2	28.6	30.4	33.5	35.6
12	West	27.5	27.6	29.3	33.2	33.1
13	West	27.5	28.0	29.5	31.1	33.0
14	West	27.8	28.2	30.5	33.1	34.9
15	South	27.8	28.0	30.0	32.0	33.6
16	South	28.1	28.4	30.1	31.4	33.8
17	West	27.5	28.5	29.5	30.4	31.3
18	West	27.0	27.8	28.8	29.3	30.6
19	East	28.1	28.6	28.8	29.0	29.0
20	East	28.3	29.2	29.0	29.0	29.9
21	West	29.9	30.0	30.3	30.5	30.6
22	West	31.4	31.1	31.6	31.6	32.3
23	West	31.7	32.4	32.7	34.1	34.4
24	South	30.3	30.5	30.5	30.2	31.7
25	South	31.2	31.3	32.4	33.6	36.0
26	South	31.7	31.3	31.2	31.4	32.2
27	West	30.6	29.8	29.6	30.0	30.6
28	West	30.0	29.4	29.4	29.4	30.2
29	East	31.3	31.6	32.3	33.4	34.3
30	East	31.3	31.5	31.9	32.8	33.4
31	East	30.8	31.3	32.2	33.0	33.5
32	East	30.7	31.2	31.9	32.4	32.2
33	East	30.9	31.2	31.8	32.3	32.6
34	East	30.1	31.0	31.7	32.3	32.1
35	North	33.0	33.5	34.2	34.5	36.7
36	North	34.8	35.7	36.0	37.7	38.4
37	North	35.5	36.8	37.8	38.9	40.8
38	North	29.9	36.9	37.8	38.3	40.3
39	North	39.3	42.3	41.0	40.3	35.7

Dry density distribution in test parcel A3

Dry density distribution in test parcel A3, kg/m^3

Block no.	Direction	Position, mm from central heater				
		10	29	48	67	86
1	South	1504	1493	1480	1460	1412
2	South	1409	1411	1403	1382	1364
3	South	1382	1362	1342	1321	1337
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	South	1539	1553	1527	1483	1453
8	South	1551	1554	1523	1486	1457
9	East	1541	1547	1498	1436	1399
10	West	1538	1527	1498	1445	1406
11	West	1513	1522	1478	1418	1379
12	West	1534	1552	1508	1440	1438
13	West	1526	1537	1501	1457	1428
14	West	1537	1525	1476	1429	1395
15	South	1531	1538	1488	1440	1415
16	South	1506	1521	1481	1447	1412
17	West	1530	1522	1505	1479	1455
18	West	1546	1544	1519	1504	1477
19	East	1529	1518	1522	1519	1505
20	East	1520	1520	1520	1516	1501
21	West	1494	1499	1498	1493	1482
22	West	1465	1474	1472	1463	1439
23	West	1463	1454	1442	1421	1406
24	South	1500	1498	1495	1485	1472
25	South	1473	1468	1429	1411	1384
26	South	1463	1474	1474	1466	1448
27	West	1487	1507	1510	1503	1482
28	West	1503	1517	1519	1518	1496
29	East	1476	1467	1455	1432	1410
30	East	1464	1470	1462	1444	1424
31	East	1483	1474	1457	1436	1423
32	East	1481	1472	1454	1445	1437
33	East	1478	1475	1460	1447	1442
34	East	1492	1467	1466	1453	1444
35	North	1439	1435	1421	1393	1367
36	North	1396	1389	1370	1352	1331
37	North	1384	1362	1346	1334	1301
38	North	1483	1356	1352	1342	1313
39	North	1309	1274	1282	1291	1377

Degree of saturation in test parcel A3

Degree of saturation in test parcel A3, %

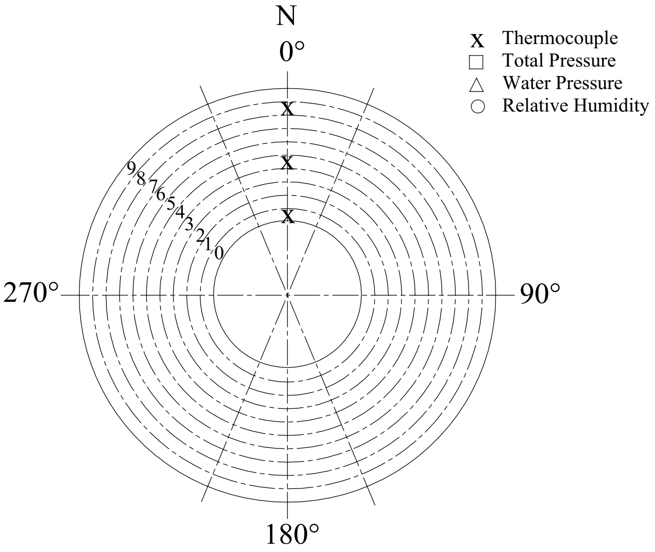
Block no.	Direction	Position, mm from central heater				
		10	29	48	67	86
1	South	95.7	96.0	97.8	96.5	96.5
2	South	98.2	98.6	97.2	97.5	98.3
3	South	98.5	98.1	96.8	96.8	93.7
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	South	95.3	96.2	95.9	94.1	95.8
8	South	96.1	96.4	95.6	95.0	95.1
9	East	95.0	97.0	95.3	95.5	97.1
10	West	95.4	94.9	95.5	95.5	97.7
11	West	93.5	96.3	95.9	97.0	97.5
12	West	93.9	96.9	96.6	99.3	98.6
13	West	93.2	96.4	96.2	95.4	96.7
14	West	95.4	95.4	96.0	97.3	97.5
15	South	94.9	96.4	96.0	95.7	96.9
16	South	92.3	95.4	95.2	94.9	96.9
17	West	93.8	95.9	96.7	95.9	95.6
18	West	94.1	96.6	96.6	96.0	96.5
19	East	95.3	95.8	96.7	97.0	95.2
20	East	95.0	98.1	97.4	96.9	97.5
21	West	96.6	97.7	98.3	98.3	96.9
22	West	97.2	97.6	98.9	97.7	96.3
23	West	97.7	98.9	98.0	99.3	98.0
24	South	98.5	98.9	98.6	96.4	99.3
25	South	97.7	97.3	95.2	96.2	99.3
26	South	98.0	98.2	97.9	97.3	97.2
27	West	97.8	98.1	97.9	98.2	97.3
28	West	98.0	98.2	98.3	98.5	97.7
29	East	98.5	98.1	98.4	98.6	98.2
30	East	96.7	98.3	98.4	98.5	97.5
31	East	98.0	98.2	98.4	98.1	97.5
32	East	97.3	97.5	97.4	97.6	95.9
33	East	97.7	97.9	97.7	97.5	97.6
34	East	97.1	96.4	98.4	98.1	96.4
35	North	98.4	99.4	99.4	96.5	98.8
36	North	97.6	99.0	97.3	99.1	98.0
37	North	97.8	98.1	98.5	99.8	99.8
38	North	95.0	97.7	99.6	99.4	100.3
39	North	97.3	99.6	97.5	97.1	97.4

Appendix 7

LOT S2: Block 02, 05, 08

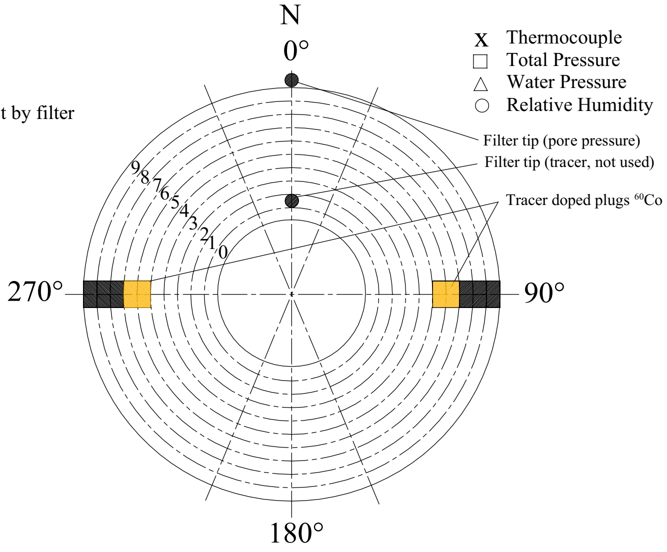
S2 02

Sensors:
S2020T
S2024T
S2028T



S2 05

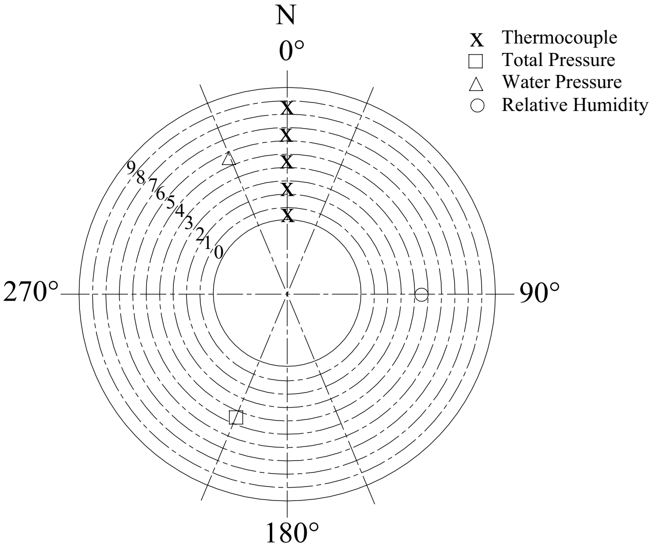
Sensors:
Tracertest by filter



S2 08

Sensors:
S2080T
S2082T
S2084T
S2086T
S2088T

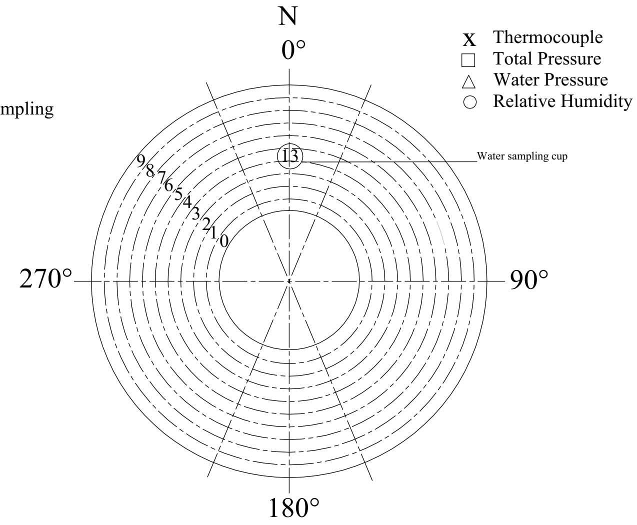
S2084P
S2084W
S2084M



LOT S2: Block 12, 14, 18

S2 12

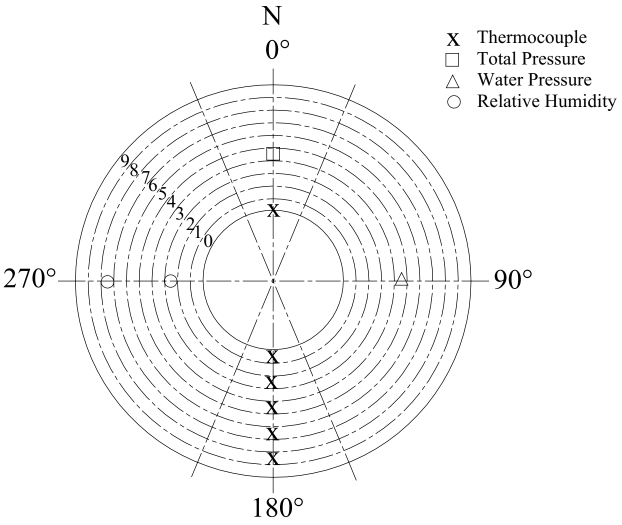
Sensors:
Water sampling



S2 14

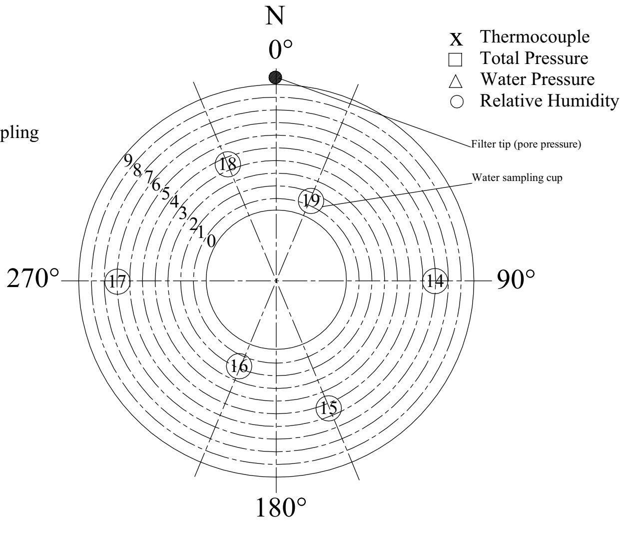
Sensors:
S214TT
S2140T
S2142T
S2144T
S2146T
S2148T

S2144P
S2144W
S2142M
S2147M



S2 18

Sensors:
Water sampling

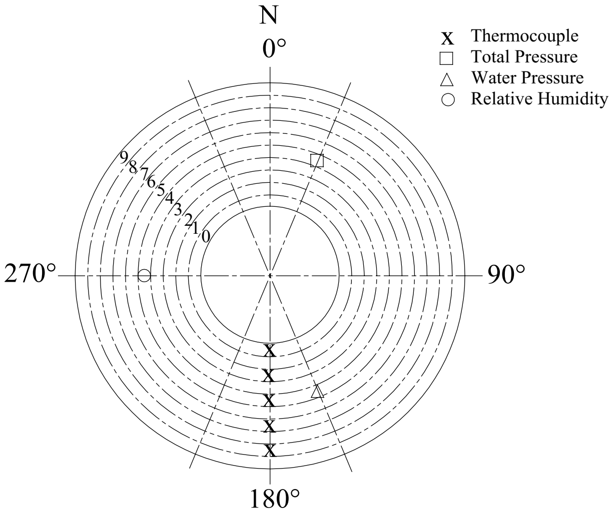


LOT S2: Block 20, 22, 24

S2 20

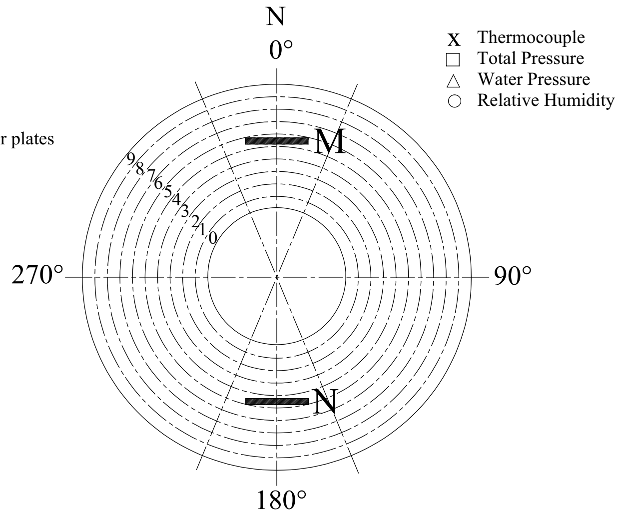
Sensors:
S2200T
S2202T
S2204T
S2206T
S2208T

S2204P
S2204W
S2204M



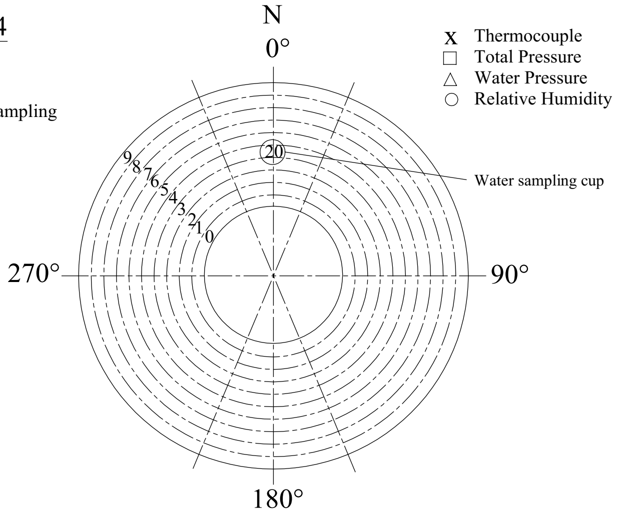
S2 22

Sensors:
2 x Copper plates



A3 24

Sensors:
Water sampling

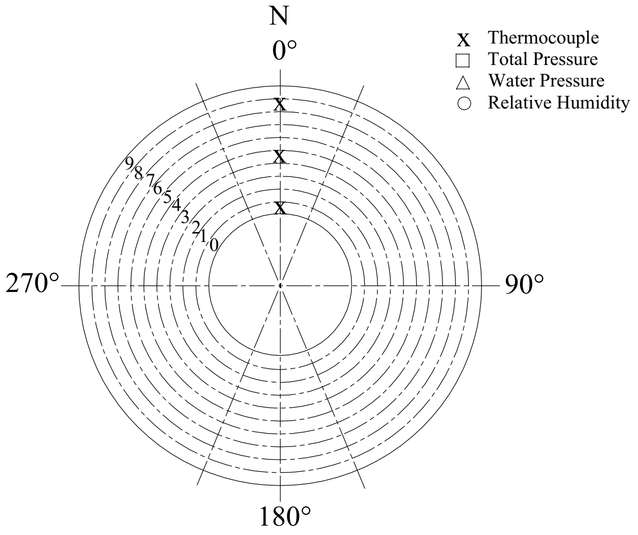


Appendix 10

LOT S2: Block 26, 28, 30

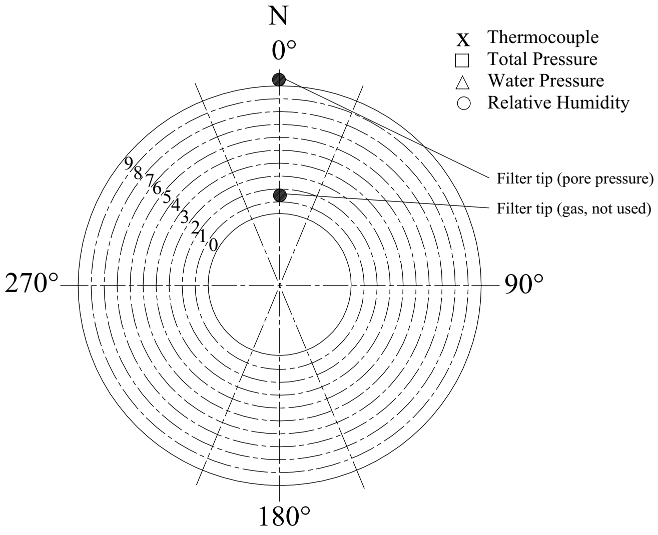
S2 26

Sensors:
S2260T
S2264T
S2268T



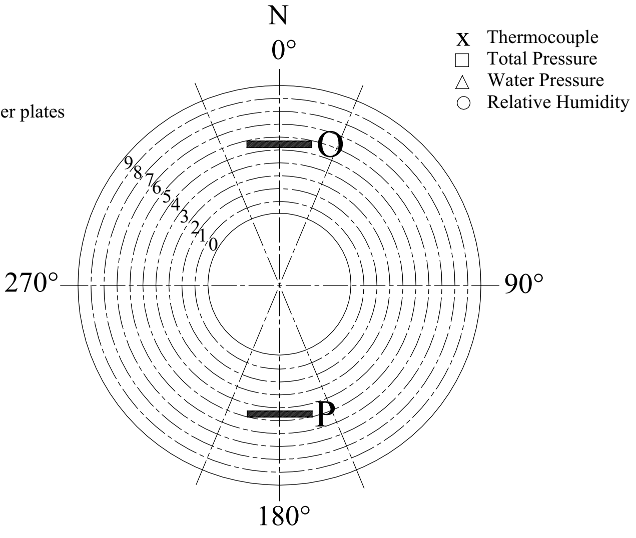
S2 28

Sensors:
Gas test



S2 30

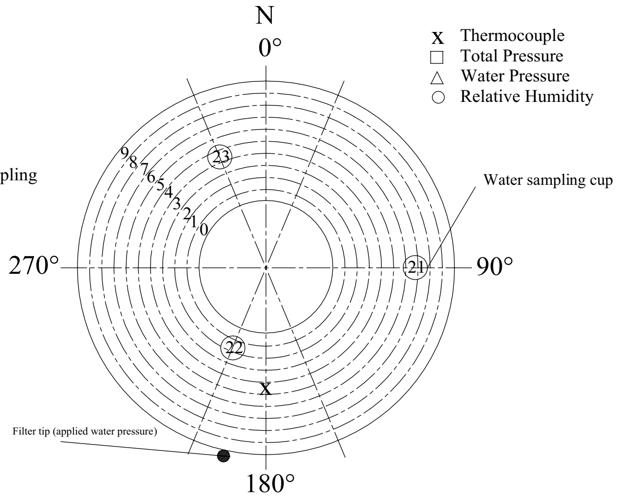
Sensors:
2 x Copper plates



LOT S2: Block 32, 36, 38

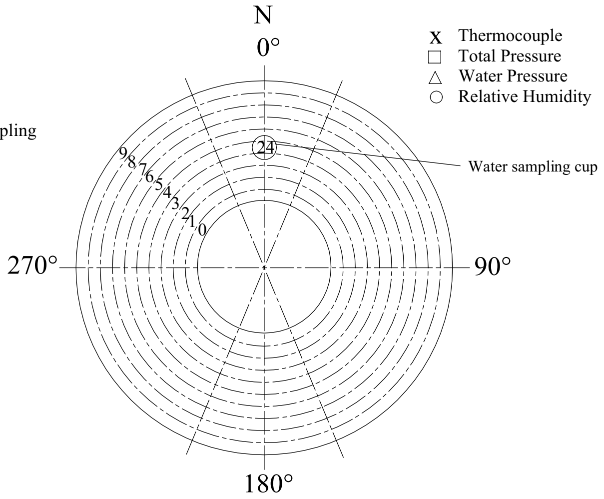
S2 32

Sensors:
S2324T
Water sampling



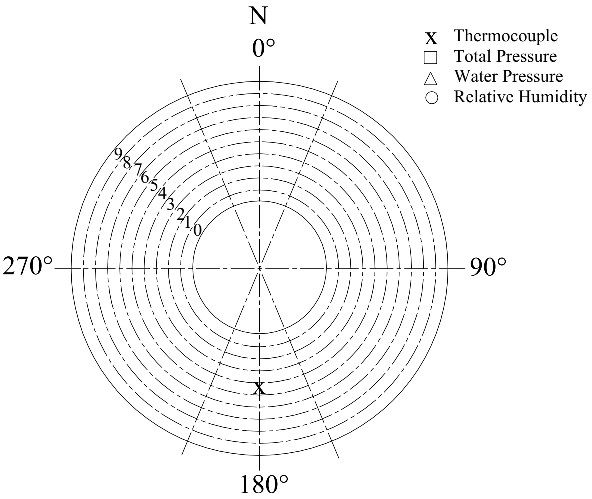
S2 36

Sensors:
Water sampling



S2 38

Sensors:
S2384T

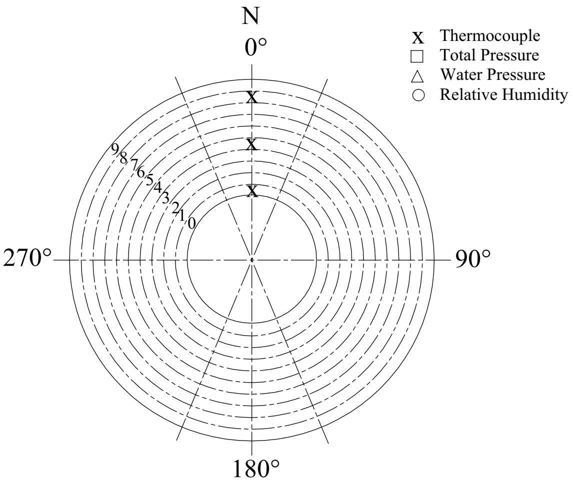


Appendix 12

LOT A3: Block 02, 05 och 08

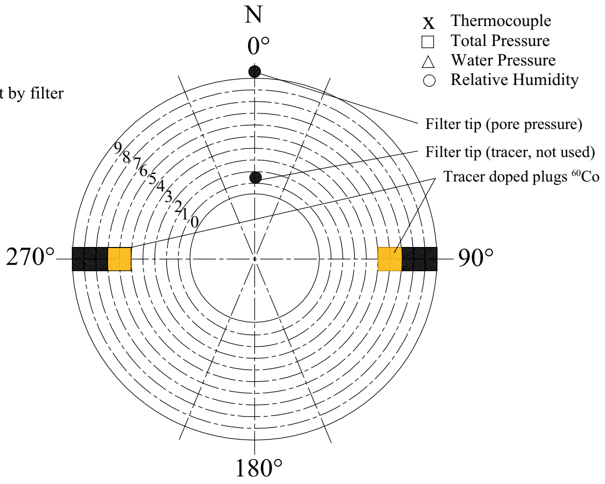
A3 02

Sensors:
A3020T
A3024T
A3028T



A3 05

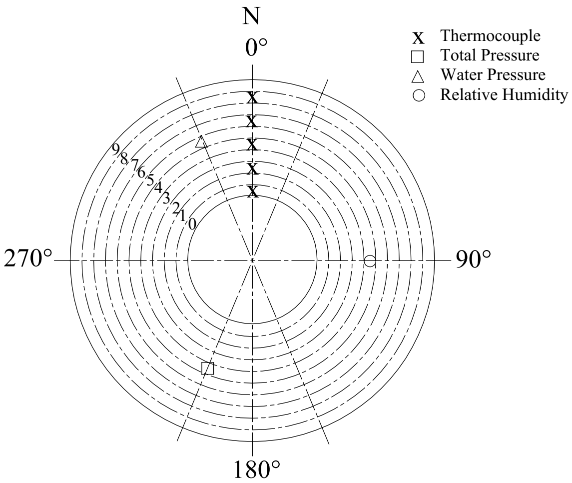
Sensors:
Tracertest by filter



A3 08

Sensors:
A3080T
A3082T
A3084T
A3086T
A3088T

A3084P
A3084W
A3084M

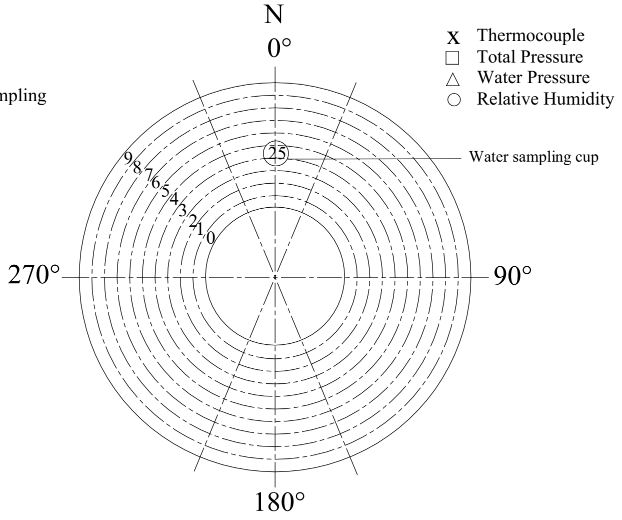


Appendix 13

LOT A3: Block 12, 14 och 18

A3 12

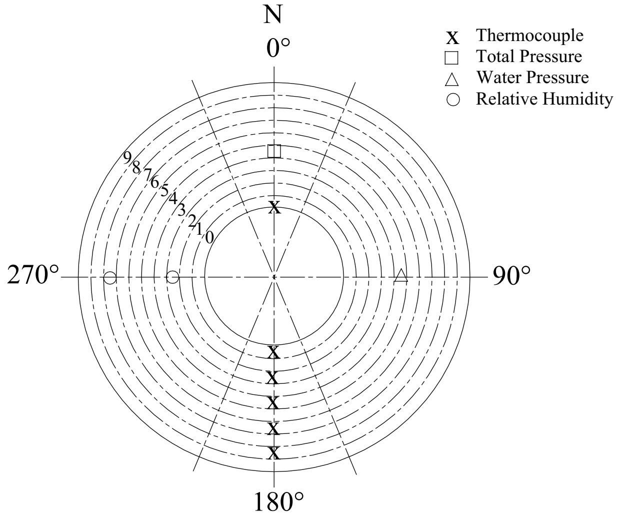
Sensors:
Water sampling



A3 14

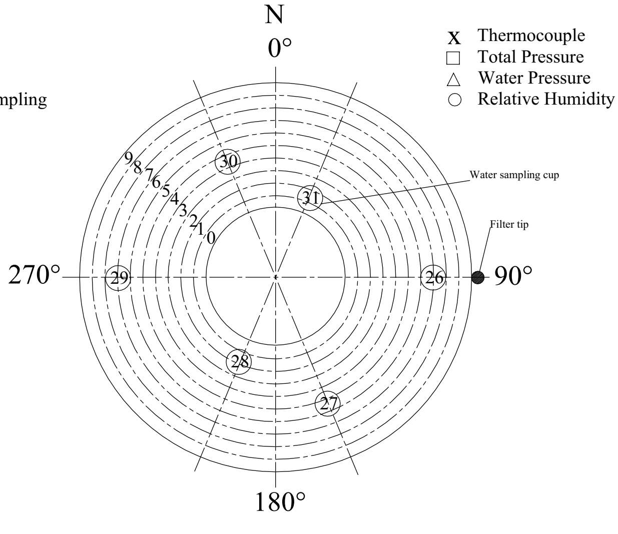
Sensors:
A314TT
A3140T
A3142T
A3144T
A3146T
A3148T

A3144P
A3144W
A3142M
A3147M



A3 18

Sensors:
Water sampling

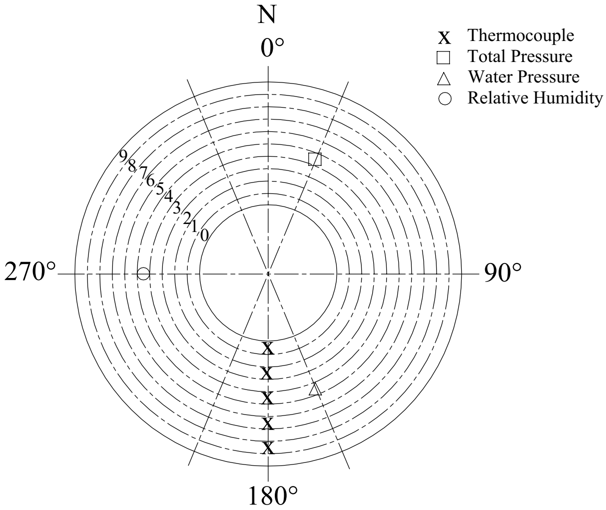


LOT A3: Block 20, 22 och 24

A3 20

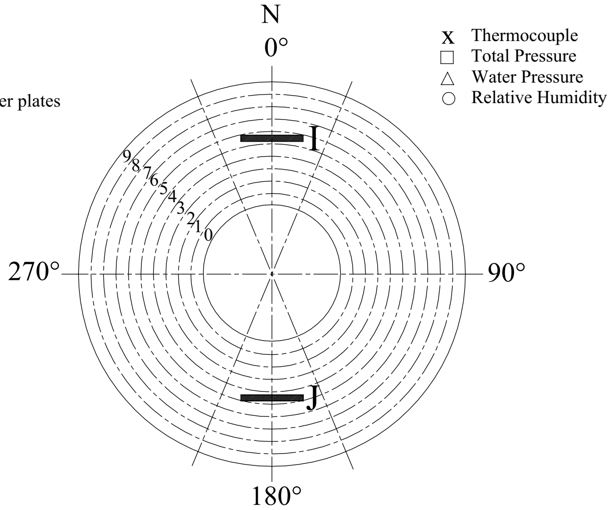
Sensors:
A3200T
A3202T
A3204T
A3206T
A3208T

A3204P
A3204W
A3204M



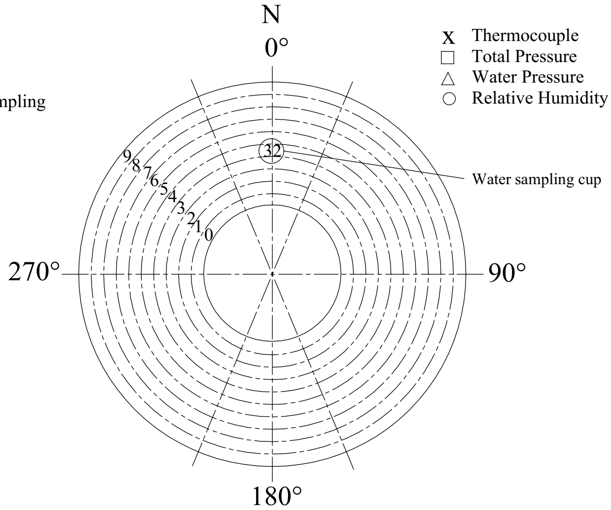
A3 22

Sensors:
2 x Copper plates



A3 24

Sensors:
Water sampling

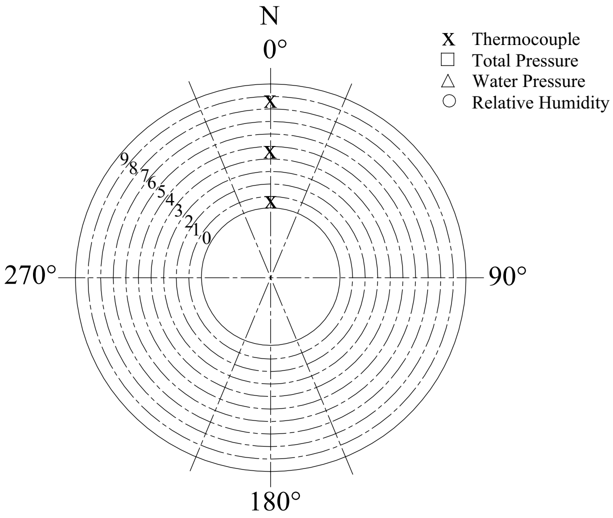


Appendix 15

LOT A3: Block 26, 28 och 30

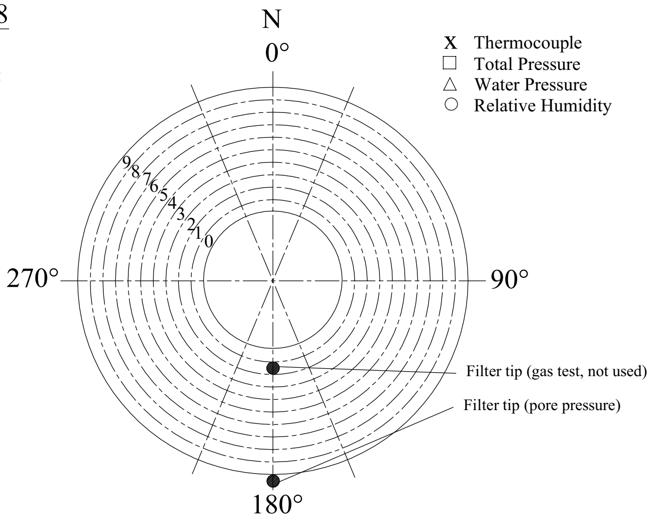
A3 26

Sensors:
A3260T
A3264T
A3268T



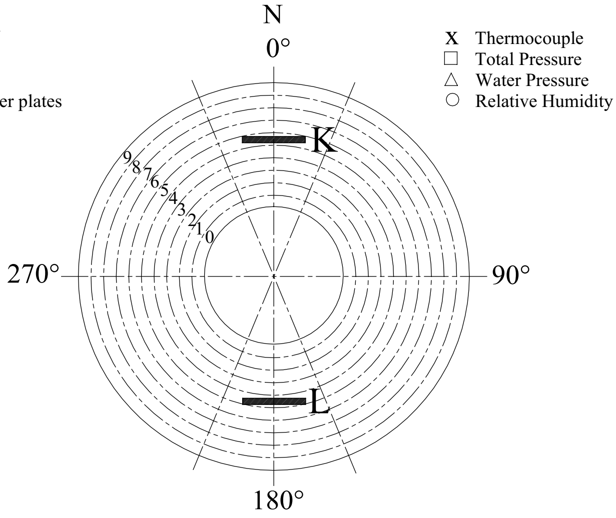
A3 28

Sensors:
Gas test



A3 30

Sensors:
2 x Copper plates

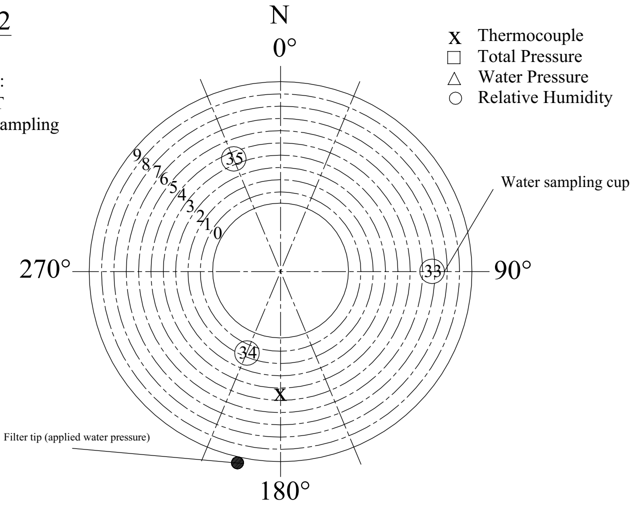


Appendix 16

LOT A3: Block 32, 36 och 38

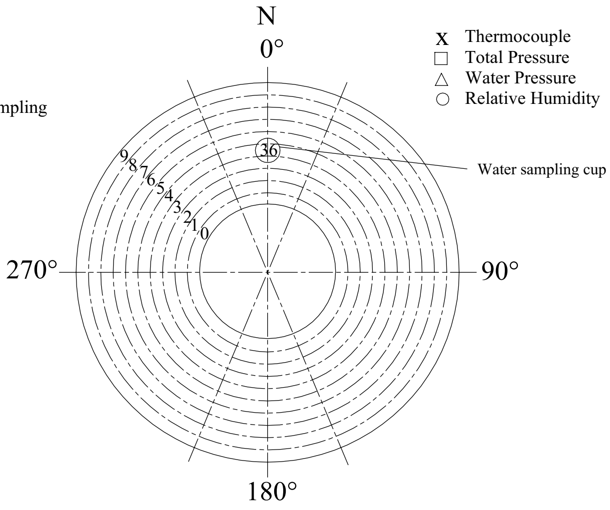
A3 32

Sensors:
A3324T
Water sampling



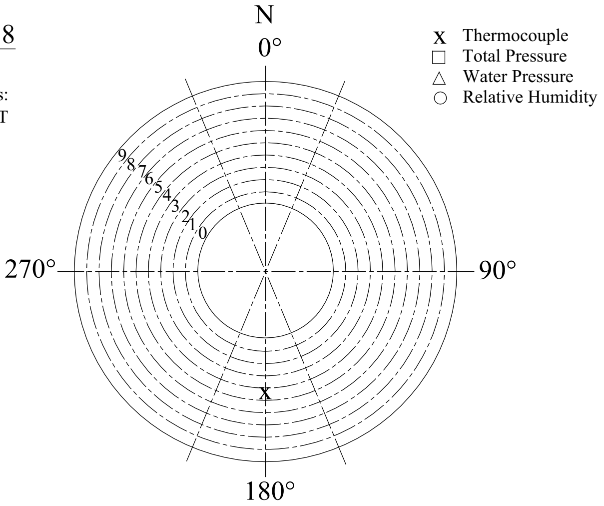
A3 36

Sensors:
Water sampling



A3 38

Sensors:
A3384T



SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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