International
Progress Report

IPR-02-03

Äspö Hard Rock Laboratory

Prototype Repository

Instrumentation of buffer and backfill for measuring THM processes

Mats Collin
Lennart Börgesson

Clay Technology AB

June 2001

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel +46 8 459 84 00
Fax +46 8 661 57 19

Äspö Hard Rock
Laboratory

Report no.	No.
IPR-02-03	F63K
Author	Date
Mats Collin Lennart Börgesson	2001-06-30
Checked by	Date
Approved	Date
Christer Svemar	2002-04-09

Äspö Hard Rock Laboratory

Prototype Repository

Instrumentation of buffer and backfill for measuring THM processes

Mats Collin
Lennart Börgesson

Clay Technology AB

June 2001

Keywords: Bentonite, buffer, Prototype Repository, instrument, deposition hole, field test, temperature, pressure, total pressure, pore water pressure, saturation, humidity, water content

Abstract

A field experiment with a Prototype Repository will be made at Äspö Hard Rock Laboratory for demonstration of a future deep repository of nuclear waste fuel. The Prototype Repository is located in the drilled part of the very bottom of the laboratory tunnel and occupies approximately 70 m of the tunnel. This report describes the recommended instrumentation of backfill and buffer for study of THM processes in the Prototype Repository.

The recommended instrumentation consists of approximately 650 units of sensors for measuring:

- Temperature
- Total pressure
- Pore water pressure
- Water content

The test period will last five years for an outer section of the tunnel and twenty years for an inner section of the tunnel.

Instrument manufacturers have been invited to give a proposal and estimate for instrumentation of the Prototype Repository.

The Swedish Corrosion Institute has in a report described the corrosivity of different materials offered by manufacturers and used for the exposed parts of the measurement system as sensor housing, protection tubes etc. The conclusion in the report is to use titanium as far as possible for the parts of the instrumentation that are placed in the buffer as well as in the backfill material.

Measuring principles and number of sensors suggested for use in the Prototype Repository as well as the investment costs for the instrumentation are shown in the following table:

Measuring quantity	**Measuring principle**	**Number of sensors in section I**	**Number of sensors in tunnel section II**	**Total number of sensors in tunnel section I and II**	**Investment cost**	**Specific investment cost**
Temperature	Thermocouples	84	78	164	1.15 MSEK	7.0 kSEK/unit
	Fibre optic[1]	8	4	12	1.60 MSEK	133.4 kSEK/unit
Total pressure	Vibrating wire	38	36	74	1.65 MSEK	22.3 kSEK/unit
	Piezoresistive	38	36	74	2.40 MSEK	32.5 kSEK/unit
Pore water pressure	Vibrating wire	26	24	50	1.00 MSEK	20.0 kSEK/unit
	Piezoresistive	26	24	50	1.50 MSEK	30.0 kSEK/unit
Water content	Relative humidity (capacitive method)	74	74	148	2.75 MSEK	18.6 kSEK/unit
	Soil psychrometer	45	32	77	0.65 MSEK	8.45 kSEK/unit
Total		339	310	649	12.70 MSEK	
Additional sensors, planning, installation, commissioning etc. (25 %)					3.20 MSEK	
Total investment cost					15.90 MSEK	

---

[1] Number of sensors is represented by the number of cables.

Sammanfattning

Vid Äspö Hard Rock Laboratory kommer ett fältförsök med ett prototypförvar att genomföras för demonstration av ett framtida djupförvar för använt kärnbränsle. Prototypförvaret kommer att uppföras längst ned i den borrade delen av laboratoriets tunnel och uppta ca 70 m av tunneln. Denna rapport beskriver förslag till instrumentering av återfyllningsmaterial och buffertmaterial för kartläggning av THM-processer i prototypförvaret.

Förslaget till instrumentering omfattar ca 650 st givare för:

- Temperature
- Total pressure
- Pore water pressure
- Fukthalt

Försökstiden är fem år för en yttre sektion av prototypförvaret och tjugo år för en inre sektion.

Instrumenttillverkare har erbjudits tillfälle att lämna förslag och budgetpriser på mätutrustning.

Korrosionsinstitutet har i en rapport kommenterat korrosionsbenägenheten hos de olika material hos givare etc som tillverkare anser sig kunna leverera. Med utgångspunkt från rapporten är titan det material som i första hand kommer att användas för de komponenter av mätutrustningen som placeras i buffert och återfyllning.

Mätprinciper, antalet givare och investeringskostnader för den instrumentering som föreslås i rapporten framgår av följande tabell:

Mätstorhet	**Mätprincip**	**Antal givare i sektion I**	**Antal givare i sektion II**	**Totalt antal givare i sektion I och II**	**Investerings-kostnad**	**Specifik investerings-kostnad**
Temperatur	Termoelement	84	78	164	1.15 MSEK	7.0 kSEK/st
	Fiberoptik	8	4	12	1.60 MSEK	133.4 kSEK/st
Totaltryck	Vibrerande sträng	38	36	74	1.65 MSEK	22.3 kSEK/st
	Piezoresistiv	38	36	74	2.40 MSEK	32.5 kSEK/st
Porvatten-tryck	Vibrerande sträng	26	24	50	1.00 MSEK	20.0 kSEK/st
	Piezoresistiv	26	24	50	1.50 MSEK	30.0 kSEK/st
Vatteninne-håll	Relativ fuktighet (kapacitiv metod)	74	74	148	2.75 MSEK	18.6 kSEK/st
	Jord-psykrometer	45	32	77	0.65 MSEK	8.45 kSEK/st
Totalt		339	310	649	12.70 MSEK	
Tillkommande givare, projektering, installation, idrifttagning etc (25 %)					3.20 MSEK	
Total investeringskostnad					15.90 MSEK	

Contents

1 Background and basic conditions

A field experiment with a prototype repository will be made at Äspö Hard Rock Laboratory, north of Oskarshamn in Sweden, for demonstration of a future deep repository of nuclear waste fuel. The underground part of the laboratory consists of a main tunnel blasted as spiral and with the length 3,6 km down to a depth of 450 m in the bedrock. A length of 400 m at the end of the tunnel is drilled by means of a TBM (tunnel boring machine). The Prototype Repository will use 70 m of the very end of the drilled tunnel part.

The purpose of the Prototype Repository is to study thermal, hydraulic and mechanical processes, which are expected to occur in a future deep repository of nuclear waste fuel. In the Prototype Repository the nuclear fuel is replaced by electrical heaters that will simulate the heat energy flow (1800 W) developed in the real case. In Figure 1, a picture of the tunnel with deposition holes that is used for the Prototype Repository is shown. The nuclear fuel, in this case the electrical heater, is placed in a canister consisting of a jacket of cupper and a core of steel with boxes for the fuel, i.e. the electrical heaters.

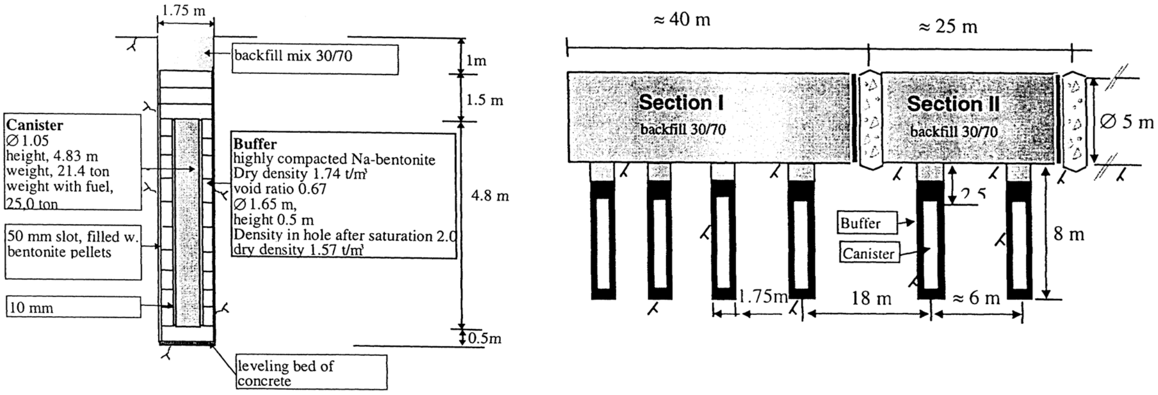


Figure 1 *Deposition holes and tunnel in the Prototype Repository /1-1/.*

The main part of the instrumentation for the Prototype Repository consists of measuring devices for:

- Temperature
- Total pressure
- Pore water pressure
- Moisture content

The installation of the instrumentation is planned to start in the beginning of 2001.

Measurements will be made in backfill, buffer and surrounding rock. This report describes instrumentation in backfill and buffer. The number of measuring devices is about 650 units and has been chosen as a result of what is commercially available on the market, the limits of the budget and what gives the possibility of an adequate analyse and modelling. The test period is five years for the outer section of the tunnel and up to twenty years for the inner section.

The experience from the following similar field tests has been of help when selecting the instrumentation:

- Buffer Mass Test and French Clay Test at Stripa, Sweden
- Long Term Test of Buffer Material and Backfill and Plug Test at Äspö Hard Rock Laboratory, Sweden
- FEBEX at Grimsel, Switzerland
- Buffer Container Experiment at URL, Canada
- Kamaishi THM Experiments at Kamaishi, Japan
- HADES at Mol, Belgium

Backfill and buffer are continuously fed with saline ground water by natural fractures in the rock and will in time goes be moisture saturated. The buffer material, which consists of high compacted bentonite clay, has after saturation expanded and developed such a high swelling pressure towards the surroundings that an effectively casing of the canister has been established.

The salt content in the water is 1,2-1,5 %. The temperature is expected to be 20-30 °C with exception of the buffer where the temperature will reach 90 °C. The total pressure can be as high as 15 MPa and the pore water pressure as high as 5 MPa.

The Swedish Corrosion Institute has in a report described the corrosivity of different materials offered by manufacturers for use in parts of the instruments as sensor housing, protection tubes etc which will be placed in the buffer and the backfill. The selection of material is determined by the location of the sensor with respect to temperature, pressure and salinity. The conclusion in the report is to use titanium as far as possible for the parts of the instrumentation that are placed in the buffer as well as in the backfill.

Manufacturers were initially invited to choose from the following materials in their proposals:

1. SS 2343 (AISI 316)
2. SS 2378 (AVESTA 254 SMO)
3. Inconel
4. Titanium
5. Platinum
6. Plastic material (e.g. PEEK)

Finally it was decided to use titanium for all exposed parts of the instruments as far as possible.

2 Recommendation for study of THM processes

2.1 General

Buffer and backfill will during the test period in the Prototype Repository absorb water from the rock, swell and thus exert pressure on the rock and the canister. The temperature increase and the temperature gradient will cause a transport of vapour with a drying near the canister as a result before the water from the rock reaches the canister. In order to analyse these processes, the THM (thermo, hydraulic and mechanical) processes in buffer and backfill have to be measured.

The following classification of the instrumentation can be made:

1 **Thermo, hydraulic and mechanical measurements**

- 1A "Standard measurements in a sparse and evenly distributed network
- 1B "Standard measurements" concentrated to certain locations where detailed studies of THM processes are of interest
- 1C "Special measurements"

2 **Other measurements as geochemical, biochemical etc**

This recommendation includes measurements of class 1A, i.e. standard measurements in a sparse network, but in some extent also class 1B and 1C.

2.2 1A "Standard measurements" in a sparse and evenly distributed network

The following variables are the most important:

- Temperature
- Water content
- Pore water pressure
- Total pressure

A relatively great number of sensors will be installed since it is possible to measure these variables with "standard" equipment. The purpose of these measurements is to have an overall sparse instrumentation but with concentrated measurements in certain regions. Because it is possible that the water inflow from the rock is unevenly distributed in a deposition hole, measurements will be made in different vertical sections around the canister. In order to compare the measurements in the different deposition holes, it is recommended to use equivalent instrumentations in all the holes.

The main measurements are, in the deposition holes, made on three horizontal planes. Two of these are located just above and under the canister. The reason for this is that the bentonite, located under and above the canister, is last saturated. It has been possible to choose a long distance between the horizontal planes because the rock fractures are mainly oriented vertically and are therefore not expected to cause large differences of water supply along the canister

Measurements will be made in four vertical sections A, B, C and D (as seen in Figures 2 and 3), of which two are oriented in the axial direction of the tunnel and two oriented at right angles or at an angle of 60 degrees to the tunnel axis. The two alternative orientations of the vertical sections are shown in Figure 2. The idea of alternative 2 is to only measure temperature in section D so that almost half the hole will not be instrumented and the saturation process not affected by instrumentation since cables from temperature sensors can be led out through the buffer from sections B and C.

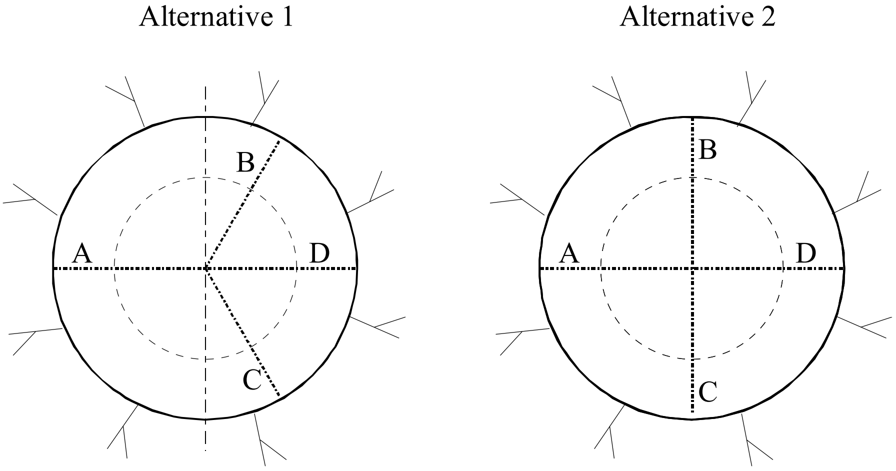


Figure 2 *Vertical sections in a deposition hole.*

The position of sensors in the deposition hole is shown in Figure 3. A vertical section A and a horizontal section just in front of the canister are instrumented more than the others for study of the distribution axially and radially respectively. The vertical section D is instrumented with only temperature sensors which reduces the number of sensors in this section but still gives adequate information.

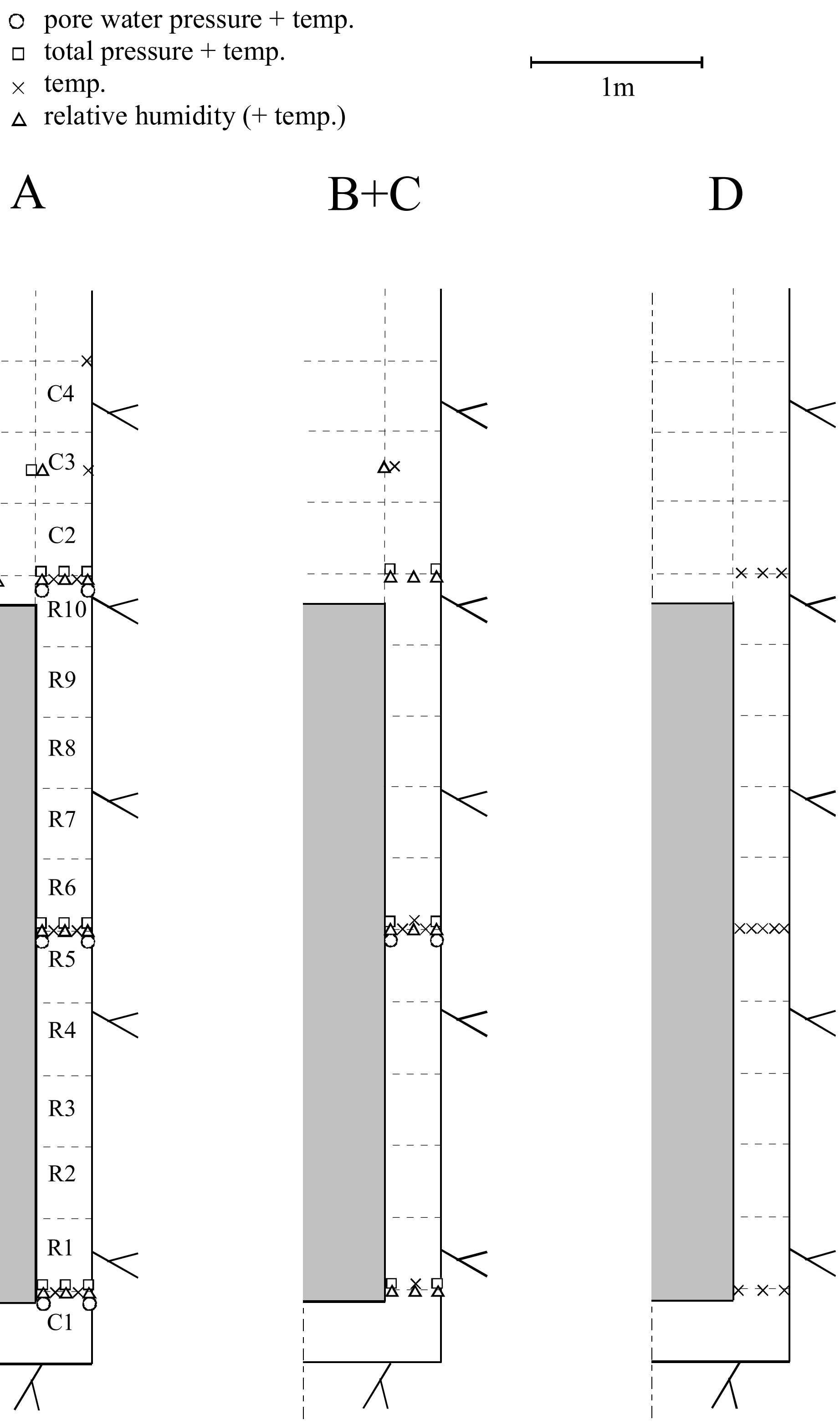


Figure 3 *Sensor positions in a deposition hole.*

Two different types of moisture sensors are installed in some measuring points. The reason for this is that the two measuring principles, that are recommended (capacitive sensor and psychrometer), have overlapping measuring ranges and therefore are complementing each other. Furthermore, a distributed fibre optic temperature measurement system will be used for determination of surface temperature of the canister.

The backfill will be instrumented in vertical sections straight above and between the deposition holes, which is seen in Figure 4. This gives information about the propagation both axially and radially around the holes. The areas between the outer holes and the plugs are expected to be less interesting and therefore sparsely instrumented.

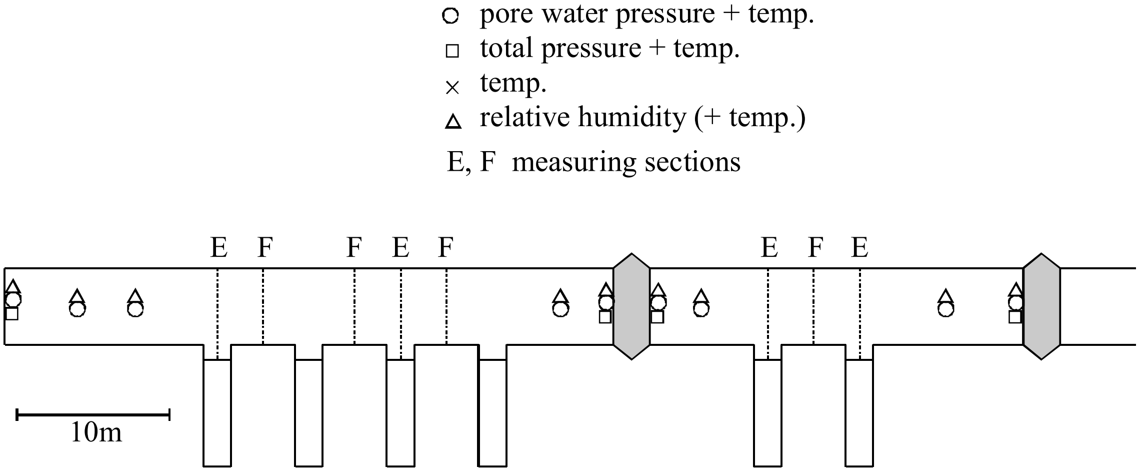


Figure 4 *Instrumentation of backfill in the tunnel.*

The sensor positions in sections E and F are shown in Figure 5.

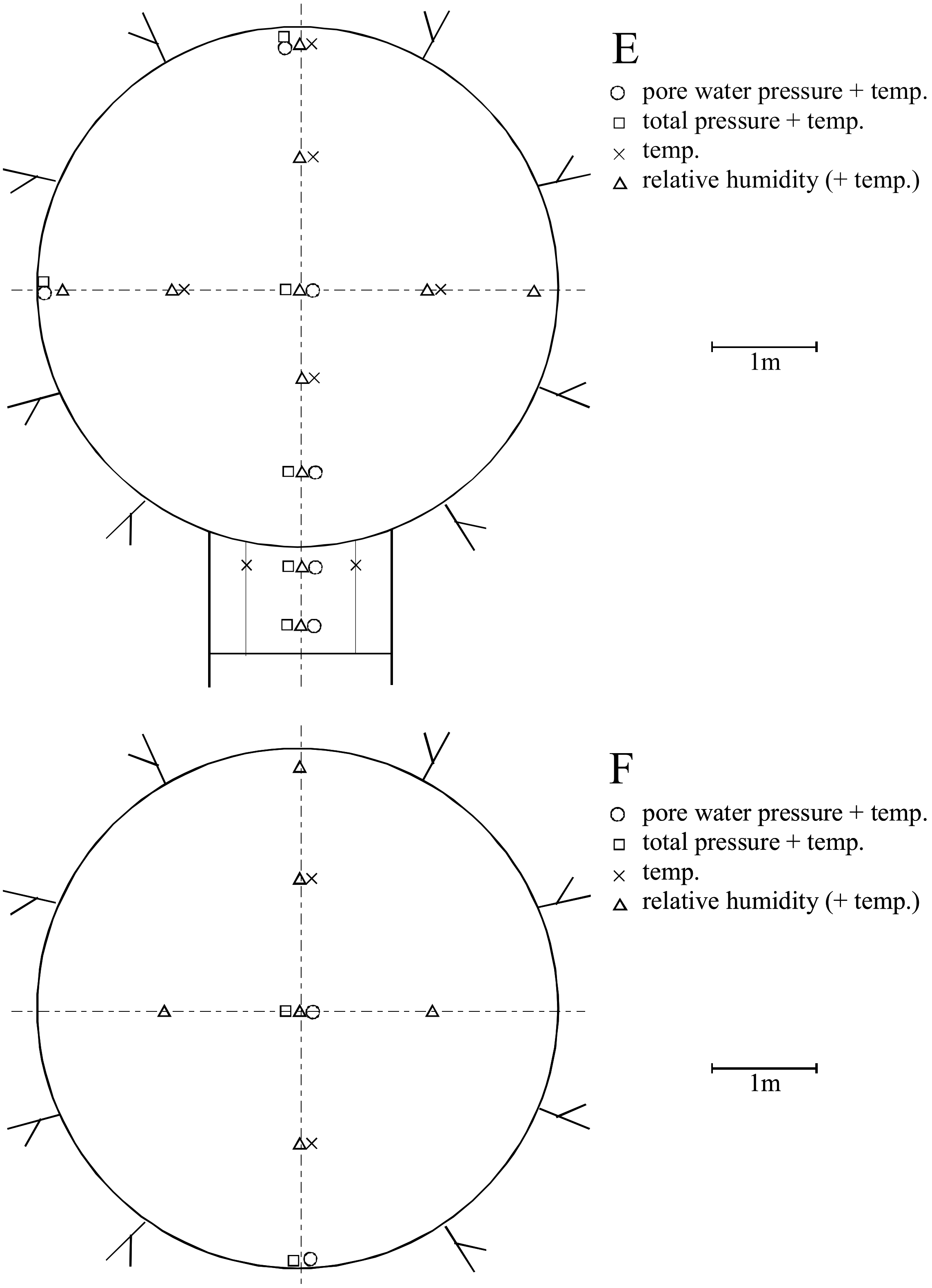


Figure 5 *Sensor positions in the tunnel.*

2.3 1B Standard measurements concentrated to regions of special interest

The following special studies, which are not analysed in this report, may be of interest:

- Water saturation process in buffer and backfill around water bearing fractures
- Temperature progression over openings at bentonite blocks
- Drying out effects near the canister

Installation of sensors sufficiently close to each other, e.g. radially between canister and rock, make it possible to obtain information which can be compared with predictions. A special test program has to be prepared for each study.

2.4 1C Special measurements

The following measurements are not discussed in this report but nevertheless of interest:

- Displacement
- Air and gas pressure

Especially the following displacements are of interest:

1. Movement of the canister
2. Swelling of bentonite towards the backfill
3. Swelling and shrinkage of bentonite blocks due to water transport

The techniques for measuring these displacements have to be studied further. Of these measurements, measuring movement of the canister will be carried out.

The rate of water supply, especially in the backfill, is affected by entrapped air, which is compressed when pressurized. Understanding of the water saturation process requires knowledge about how the entrapped air is affected. A study of the water saturation process requires measurement of the air pressure variation.

3 Basic requirements for the measuring equipment

3.1 Temperature

Temperature is generally measured by means of a thermocouple, type T, J, K or equivalent. Other methods as e.g. optical fibre system or resistance thermometers are also possible.

The required measurement range is 0-200 °C.

The sensor is placed in a housing or sheath made of corrosion-resistant material.

The maximum length of the temperature sensor including cabling is about 100 m. The average length is 75 m. Extension cables are placed in protection tubes, which are sealed against the surroundings. A sheath type of sensor is protected all the way from the measuring point to the data collecting equipment by the sheath itself.

The total number of temperature measuring devices that will be used in the Prototype Repository is about 210 units.

3.2 Total pressure and pore water pressure

Total pressure and pore water pressure can be measured indirectly, i.e. by means of a hydraulic measuring system, or with the pressure gauge directly placed in the test volume.

The pressure gauge can in both cases be of vibrating wire type or piezoresistive type.

The required measuring range is 0-5 MPa for pore water pressure and 0-15 MPa for total pressure.

The pressure gauge must work in the following temperatures:

0-40 °C in backfill

0-120 °C in buffer

The maximum distance between the pressure gauge and the data acquisition system is 100 m. If possible, the electronic unit of the measuring system is placed outside the tunnel. In other case, the electronic unit is placed together with other equipment in a waterproof cabinet or chest.

The measuring system includes gauges, signal cables, electronic units and necessary equipment for data processing and shall produce a complete and analysed result in the form of an output signal of 4-20 mA or a binary signal through a serial communication device.

Electrical and signal cables shall either resist the specified pressure and protect against water leakage after moisture saturation or be placed in tubes which protect against mechanical damage and water leakage. Gauges are protected against mechanical damage from surrounding material.

Total number of gauges in the Prototype Repository is approximately:

Total pressure	180 units
Pore water pressure	120 units

3.3 Moisture content

Moisture content can be measured by means of the following four methods:

1. Capacitive sensor measuring relative humidity in the pore system
2. TDR (Time Domain Reflectometry) measuring volumetric water content
3. Psychrometer measuring relative humidity in the pore system
4. Resistive sensors measuring the volumetric water content.

The psychrometer is used in the backfill at a relative humidity of 95-100 %. This method may also be useful when the buffer is close to water saturation.

The measuring range, which seems to be possible to achieve with the different measuring methods is:

Capacitive sensor	0-100 % relative humidity
TDR	0-100 % volumetric water content
Psychrometer	95-100 % relative humidity
Resistive sensor	0-100 % relative humidity

The gauge must work in the following temperatures and pressures:

- 0-40 °C in backfill
- 0-120 °C in buffer
- 0-15 MPa total pressure
- 0-5 MPa pore water pressure

The maximum distance between the sensor and the data acquisition system is 100 m. If possible, the electronic unit of the measuring system is placed outside the tunnel. In other case, the electronic unit is placed together with other equipment in a waterproof cabinet or chest. Information about the allowed maximum cable length shall be given in the proposal.

The measuring system includes gauges, signal cables, electronic units and necessary equipment for data processing and shall produce a complete and analysed result in the form of an output signal of 4-20 mA or a binary signal through a serial communication device.

Electrical and signal cables must either resist the specified pressure and protect against water leakage after moisture saturation or be placed in tubes which protect against mechanical damage and water leakage. The gauges are protected against mechanical damage from surrounding material.

Total number of measuring devices in the prototype repository is:

Number of sensors in the tunnel	100
Number of sensors in the deposition holes	190

3.4 Laying of cables and tubes

Protection tubes of titanium are used in the buffer where the temperature is expected to be up to 100 °C. Fittings are of type Swagelok and made of titanium. Signal cables may be laid in protection tubes of Tecalan (polyamide 1 and 12) in the tunnel and also in the lead-throughs out from the tunnel.

As far as possible, one single signal cable is used for connecting the sensor to the data collecting equipment outside the tunnel. Some measurement systems cannot use too long cables. Therefore, some electronically equipment has to be encased in waterproof cabinets made of corrosion-proof material and placed in the tunnel. This is primarily the case for moisture measurement equipment as the capacitive sensor and TDR.

Lead-throughs for cables and tubes are made in the rock between the Prototype Repository tunnel and the G tunnel. The lead-throughs are sealed by flange joints in the same way as in the project Backfill and Plug Test, or by means of some sort of sealing compound.

The laying of cables from the deposition hole and to the tunnel can be made as follows:

A. Protection tubes (one for each sensor) are laid straight up from the deposition hole and evenly distributed over the surface of the bentonite block in the gap between bentonite block and rock surface.

B. Protection tubes (one for each sensor) are laid straight up from the deposition hole and evenly distributed over the rock surface.

C. Protection tubes (one for each sensor) are laid straight up from the deposition hole and collected in vertical slots in the rock wall (in all three slots, one for each instrumented level).

D. Protection tubes (one for each sensor) are laid in lead-throughs from the instrumented level and diagonally up to the tunnel (in all three slits, one for each instrumented level).

4 Selection of material

The Swedish Corrosion Institute has in a report described the corrosivity of different materials offered by manufacturers and used for the parts of the instruments as sensor housing, protection tubes etc which will be placed in the buffer and the backfill. According to the report, titanium is the only material of the proposed ones that is resistant in seawater up to 120 °C. Other materials that have acceptable resistance against corrosion are nickel-based alloys as Inconel 625. The conclusion is to use titanium, grade 2 or preferably grade 12, as far as possible for the instruments used in the Prototype Repository. Other materials are possible when the sensors are protected by a housing of titanium, as is the case with e.g. the capacitive sensor for relative humidity measurements.

5 Suppliers of measuring equipment

Table 1 shows a list of suppliers of measuring equipment and the different measuring principles, which are suitable for the experiment.

Table 1 List of suppliers of measuring equipment

Measuring quantity	Measuring principle	Supplier	Country	Representative in Sweden
Temperature	Vibrating wire	Geokon	USA	Bemek
	Thermocouple	Roctest	Canada	
		Geokon	USA	Bemek
		Pentronic	Sweden	
		Glötzl	Germany	
		Fisher-Rosemount	Sweden	
		BICC Thermoheat	England	
	Resistive temperature sensor	Rotronic	Switzerland	
		Glötzl	Germany	
	Fibre optic	Roctest	Canada	
		BICC Thermoheat	England	
		York Sensors	England	
Total pressure and pore water pressure	Hydraulic pressure cells	Glötzl	Germany	
	Piezoresistive sensors	Geokon	USA	Bemek
		Kulite	Holland	Sensotest
		Roctest	Canada	
	Vibrating wire	Geokon	USA	Bemek
		Roctest	Canada	
		Glötzl	Germany	
		Geonor	Norway	
	Fibre optic sensors	Glötzl	Germany	
		Roctest	Canada	

Measuring quantity	Measuring principle	Supplier	Country	Representative in Sweden
Water content	TDR	Nagra	Switzerland	
		Environmental Sensors	Canada	
		Soilmoisture Equipment	USA	Geologic
	Capacitive sensors	Rotronic	Switzerland	
		Vaisala	Finland	Vaisala
	Soil psychrometer	Wescor	USA	
	Resistive sensors	Clay Technology and LTH	Sweden	

6 Measuring principles

6.1 Temperature

6.1.1 Vibrating wire

The vibrating wire temperature-measuring device uses a sensor body and a wire with different thermal coefficients of expansion. This means that when the temperature changes, the frequency of the wire changes as well. The vibrating wire measuring principle is described in more detail in the chapter describing pressure measurements.

6.1.2 Thermocouple

The thermocouple consists of two leaders of different metals or alloys, which are joined together at one of the ends. A potential (electromotive force) is produced at the contact surface between the two metals and is the measure of the temperature. When the leaders are connected to a reading device a potential is also produced at its contacts. The result is that the reading device will measure the difference between the two potentials. Therefore, the temperature of the reading device, i.e. the reference temperature, has to be known in order to obtain a temperature value at the joint (the measuring point). The reference temperature is often measured by means of a resistance temperature sensor.

Common thermocouple types are shown in Table 2.

Table 2 Common thermocouple types

Material	Type	Range
Copper-Constantan	T	-200 - 400 °C
Chromel-Constantan	E	-200 - 900 °C
Chromel-Alumel	K	-200 - 1200 °C

A non-calibrated thermocouple has a measuring uncertainty of ± 3 °C at the temperatures expected in the Prototype Repository.

6.1.3 Resistive temperature detectors

Resistive temperature detectors or RTDs are normally made of platinum (Pt 100 sensors) or semiconductor material.

The correlation between resistance, R_t, and temperature, t, for the Pt 100 sensor is approximately following a quadratic equation within a large temperature range (0 - 600 °C) as follows:

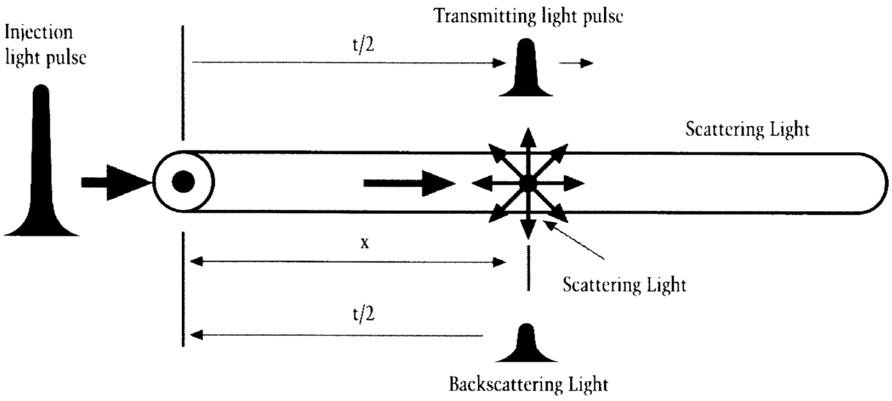
$$R_t = R_0(1 + At + Bt^2)$$

A temperature sensor of semiconductor type is often called thermistor but also PTC or NTC resistance. PTC stands for "positive temperature coefficient" and NTC for "negative temperature coefficient ". The measuring range for the semiconductor sensors stretches from almost absolute zero to 300 °C.

6.1.4 Fibre optic

Optical fibre temperature measurement systems are often called Distributed Temperature Sensing (DTS) or Fibre Temperature Laser Radar (FTR).

The measuring principle is shown in Figure 6. A laser light source sends a light pulse into one of the ends of an optical fibre. Most of the light is transported all the way through the fibre and exits the fibre in the other end. A smaller part of the light is scattered and reflected through all the fibre backwards in the direction to the light source. The backscattering light is called Rayleigh scattering light and is a result of density variation in the fibre material. The backscattering light is analysed with respect to the Raman scattering spectrum, which consists of a shorter wavelength (Stokes light) and a longer wavelength (Anti-Stokes light) than the original laser light wavelength. The intensity ratio between the Stokes light and the Anti-Stokes light is a measure of the temperature. The time it takes for the backscattering light to return to the light source is a measure of the position along the fibre. As a result a temperature profile is achieved along all the cable length.



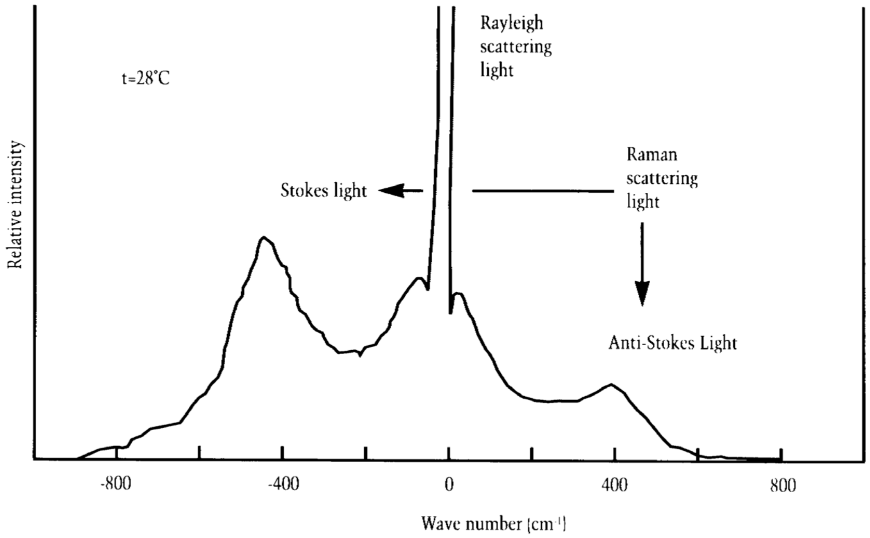


Figure 6 *Backscattering light generation in an optical fibre (upper part). The Raman scattering spectrum in an optical fibre (lower part).*

The measurement is completely insensitive to electromagnetic interference, which is an advantage.

Since a time integration of the measurement signal, which can be regarded as a stochastic variable, has to be done, the measurement result is equal to an average temperature along a distance of the cable. A special sensor called spot sensor, made of several meters of cable, which are coiled and encapsulated, is used where a more precise location of the measuring point is required.

The spatial resolution is defined as the distance along which the measuring signal changes from 10 % to 90 % of the actual temperature difference at a stepwise temperature change as can be seen in Figure 7. The average temperatures achieved are shown in Table 3.

Table 3 Average temperatures along the optical fibre

Distance a-b in graph A	t_0
Distance c-d in graph B	t_0+plus 10 % of the difference between t_1 and t_0
Distance e-f in graph C	t_0+plus 90 % of the difference between t_1 and t_0
Distance g-h in graph D	t_1

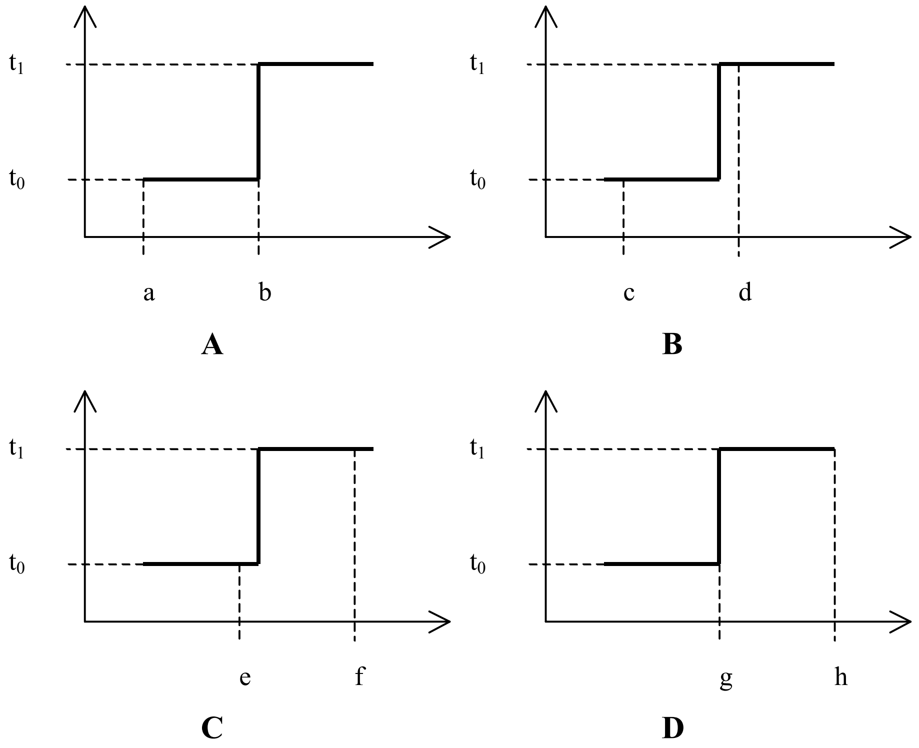


***Figure** 7 Definition of the spatial resolution, which in these graphs is equal to the distance between position c and e.*

Figures 8 and 9 show how two optical fibre cables placed on the canister surface.

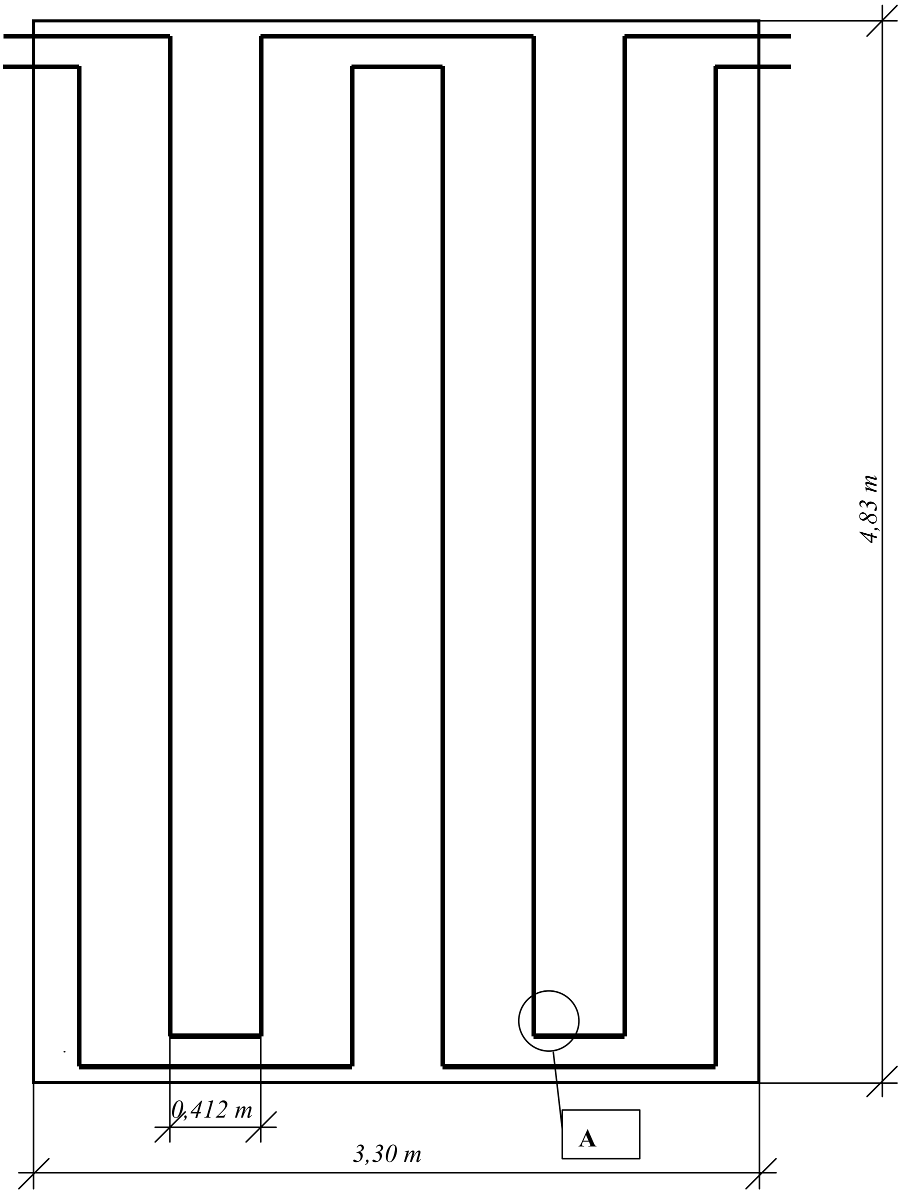


Figure 8 *Laying of two optical fibre cables with protection tube of Inconel 625 (outer diameter 2 mm) for measurement of the canister surface temperature (surface unfolded). With this laying the cable will enter and exit the surface at almost the same position. Bendings are shaped as a quarter circle with a radius of 20 cm. The cable is placed in a milled out channel on the surface. The channel has a width and a depth of just above 2 mm*

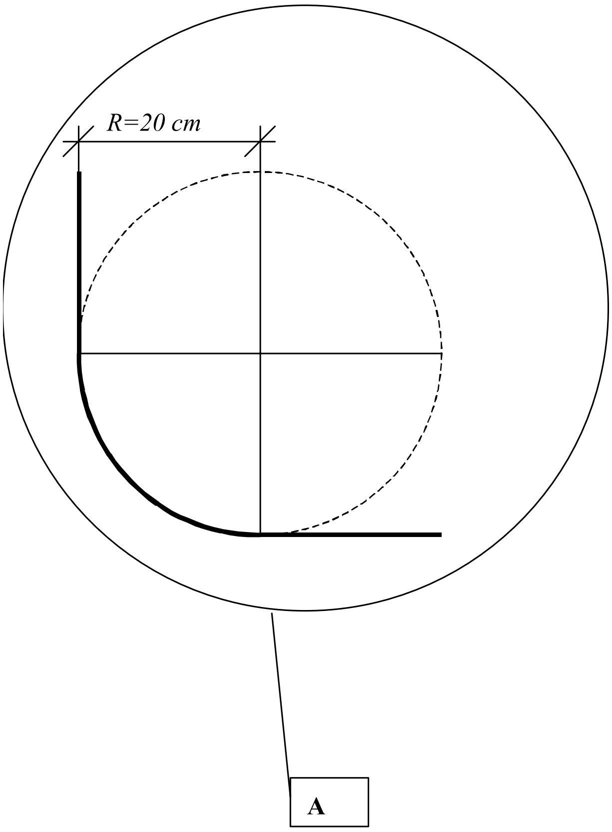


Figure 9 *Design of the cable bendings with a minimum radius of 20 cm.*

The Fabry-Pérot interferometer, which is built inside each sensor (see a description of this principle in chapter 6.2.4), can also be mentioned as one among other measuring principles using fibre optic.

6.2 Total pressure and pore water pressure

6.2.1 Hydraulic pressure cells

The hydraulic pressure measurement system consists, in case of total pressure measurement, of an oil or gas filled pressure cell which is embedded in the material of which the pressure shall be measured, an oil filled pump circulation system, a control valve and a pressure gauge. The control valve, which regulates the oil flow in the system, is equipped with a diaphragm connected on one side to the pressure cell and the other to the circulation system. The measuring sequence begins with starting the pump. The pressure increases on the side of the diagraphm connected to the outlet pipe from the pump. The valve opens when the pressures are equal on both sides of the diaphragm. Thus, the pressure change measured in the outlet pipe is equal to the pressure in the surrounding material of the cell.

When pore water pressure is measured, the pressure cell is replaced by a ceramic or metallic filter assembled outside the diaphragm of the valve.

6.2.2 Piezoresistive sensors

The piezoresistive sensor uses a strain gauge of semiconductor material. The strain gauge is bonded to a diaphragm, which is in contact with the surrounding material. The resistance of the strain gauge is measured and represents the pressure of the surrounding material.

6.2.3 Vibrating wire

A vibrating wire sensor uses a wire, which in one end is attached to the backside of a pressure diaphragm and held under tension. Pressure acting on the other side of the diaphragm causes wire tension and thus the natural frequency of the wire to change.

There are two different types of vibrating wire sensors as follows:

- Pluck and read
- Auto resonant

The pluck and read type uses a voltage pulse applied to an electromagnetic coil to pluck the wire, i.e. draw the wire to one side and release it. The sensors also use a permanent magnet, which together with the vibrating wire induces a sinusoidal voltage in the coil. The frequency of the voltage is measured and is a measure of the pressure. The pluck and read type is shown in Figure 10.

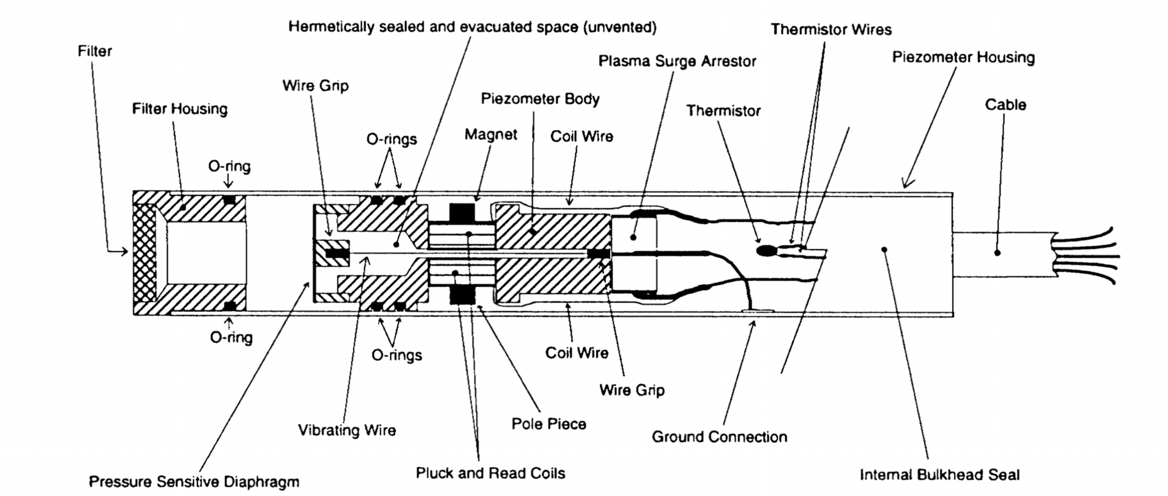


Figure 10 *Pressure sensor of vibrating wire type using the pluck and read method.*

The auto resonant type uses an electromagnetic coil that causes the wire to continuously vibrate at its natural frequency. A second coil is used to measure the frequency of the wire and thus the pressure.

6.2.4 Fibre optic

Fibre optic measuring principle is primarily based on the following techniques:

- Intensity modulation
- Bragg gratings
- Fabry-Pérot interferometer

Change of the light amplitude (i.e. intensity modulation) is the oldest of the three techniques. One disadvantage with this technique is that the amplitude is also affected by ageing.

A Bragg grating sensor consists of an optical fibre, which has been processed by UV radiation to obtain a repeated change from one refractive index to another along the fibre. The working principle is shown in Figure 11. At each change from the one refractive index to the other a smaller part of the incoming light is reflected back. The reflected light has its maximum intensity at the wavelength λ_β, which is equal to $2n\Lambda$ where n is the average of the two different refractive indexes and Λ is the distance between two adjacent pair of indexes. A pressure sensor is designed in such a way that the pressure to be measured affects the characteristic of the grating and thus the wavelength of the reflected light.

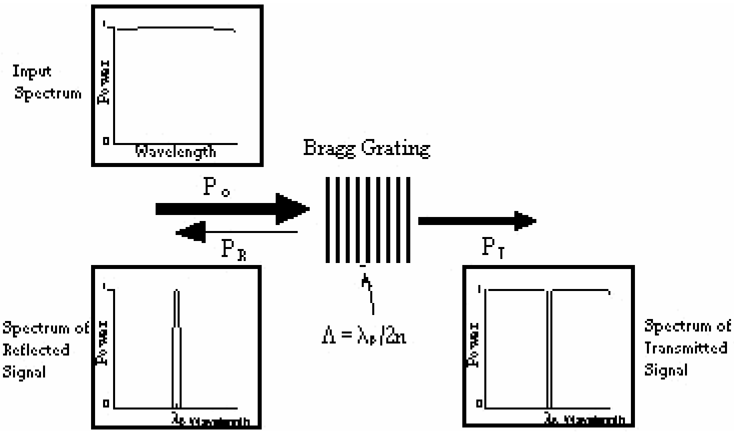


Figure 11 *Principle of the Bragg grating*

The working principle of the Fabry-Pérot interferometer is as follows (see Figure 12):

1. White light is sent through an optical switch to the sensors where the Fabry-Pérot interferometer is located. In principle, the Fabry-Pérot interferometer is made of two standard multimode optical fibres with the end tips directed towards each other. The tips are covered with a semi-reflecting mirror and have a distance or cavity length between each other, which are affected by the pressure of interest.

2. The wavelength-modulated light is reflected back and transported via the switch and through the lens into the analyser which functions as an optical cross-correlator.

3. The modulated light is focused by means of the cross-correlator on a certain pixel on a CCD array. This also means that each pixel on the CCD array is associated with a predefined cavity length and thus a pressure.

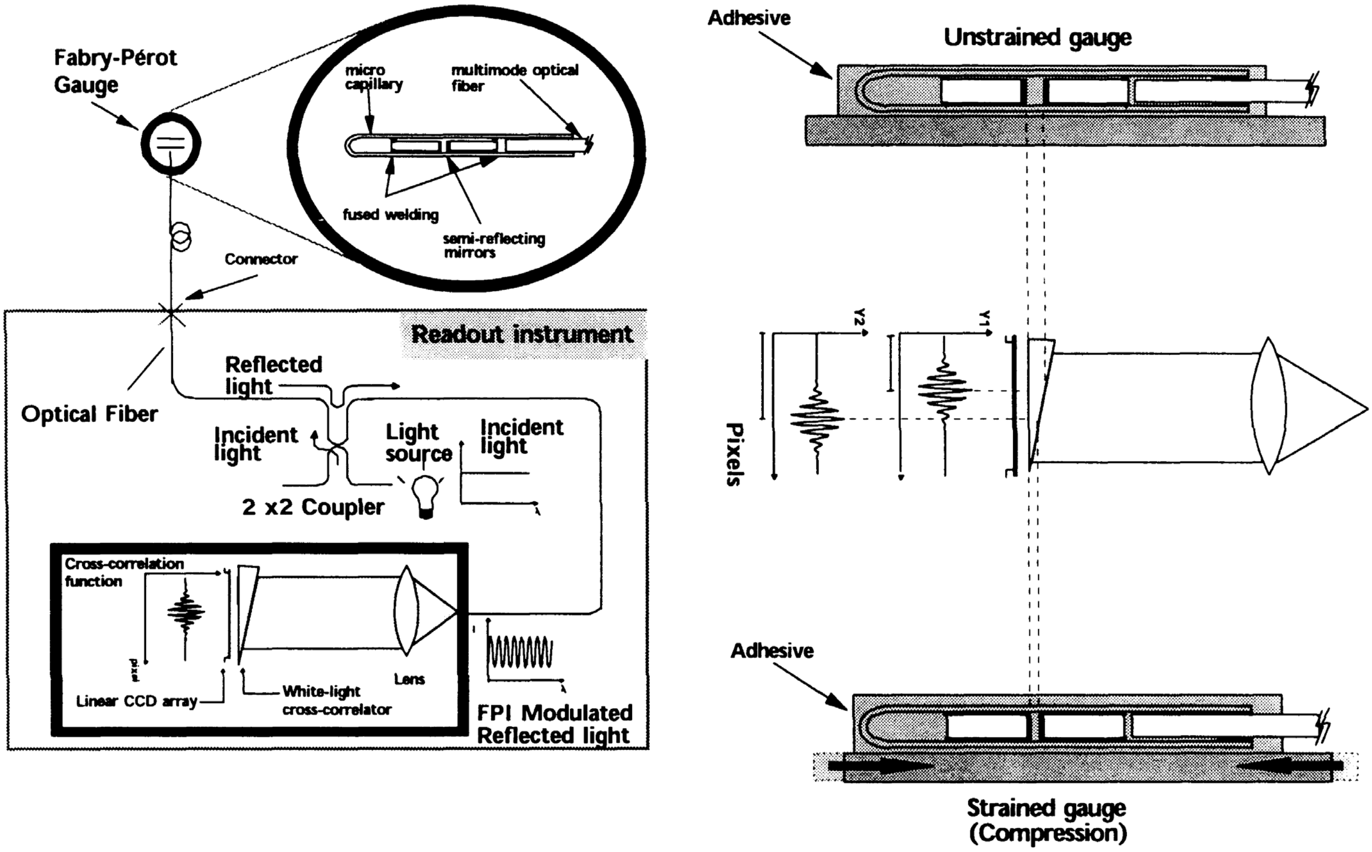


Figure 12 *Working principle of the Fabry-Pérot interferometer used for pressure or strain measurements.*

6.3 Water content

6.3.1 TDR (Time Domain Reflectometry)

The TDR measurement system mainly consists of the following components:

- A time domain reflectometer (network cable test analyser).
- In-situ probe designed as a wave-guide
- Coaxial cable connecting the reflectometer with the wave-guide

The advantages of the TDR measurement system are:

- Uses an in-situ probe, which is robust and durable.
- The long-time stability is very good.
- The sensitivity is high within the entire measuring range of 0-100 %.
- Directly measuring of the volumetric water content in a material, i.e. the quantity of water in a specific volume of the material.

The measuring principle is as follows. A voltage pulse is sent out from the reflectometer, through the coaxial cable and to the wave-guide, which is embedded in the material in which the water content is to be measured. When the pulse reaches the wave-guide, an electromagnetic wave is produced in the surrounding material. At the end of the wave-guide, the voltage pulse is reflected back to the source. The travel time it takes for the pulse to be transported forward and backward along the wave-guide is a function of the permittivity in the surrounding material. Since the water has a significant higher permittivity than soil and rock material, the time will be a measure of the water content in the material.

The relationship between travel time t, length of the wave-guide l, light velocity in vacuum c_0 and permittivity in the surrounding material ε_r can be formulated into the following equation:

$$t = \frac{2l}{c_0} \cdot \sqrt{\varepsilon_r}$$

By means of the above equation, the permittivity can be calculated ε_r. The volumetric water content can then be calculated by means of an empirical correlation between the permittivity ε_r and the volumetric water content θ_v. An example of such a correlation is the following equation:

$$\varepsilon_r = 3{,}03 + 9{,}3\theta_v + 146\theta_v^{\,2} - 76{,}7\theta_v^{\,3}$$

The following factors are affecting the accuracy of measurement and applicability of the TDR measurement method:

- Measurements in a small limited volume of material (lead to weak signal levels).
- Density variation in the surrounding material.

- Presence of air space between the wave-guide and the surrounding material (must be avoided).
- Temperature dependency.
- High salinity content in the surrounding material (weakens the measuring signal but can be handled by covering the wave guide with some plastic material, e.g. PVC).

6.3.2 Capacitive method

By using the capacitive method, relative humidity in the pore volume of a material can be measured.

The sensor consists of a pair of electrodes, which are separated by a polymer film. The quantity of moisture, which is absorbed by the polymer film, is affected by the relative humidity in the surrounding air. The capacitance is affected by the absorbed water quantity and is equivalent to the relative humidity and thus the water content in the surrounding material.

6.3.3 Soil psychrometer

The soil psychrometer is used for measurement of the dry and the wet temperature in the pore volume of a material.

The sensor consists of two thermocouples of which one is used for cooling by the Peltier effect and the other for temperature measurement. The sensor is cooled down below the dew point after which the cooling is interrupted. The knowledge of the wet temperature, which can be read when the condensed water evaporates, and the dry temperature gives the relative humidity and thus the water content in the surrounding material.

6.3.4 Resistive sensors

The resistivity in a soil material is a function of water content and salinity in the material. A resistive sensor consists of four isolated electrodes mounted along a rod of polyurethane. A known current is applied to the two outer electrodes while the voltage between the two inner electrodes is measured. The current and the voltage are then used for calculation of the resistivity and thus the water content.

The measuring principle is described further in the report SKB TN-98-04f, Backfill Instrumentation /6-1/.

7 Selection of instrumentation

When selecting instrumentation for the Prototype Repository, the following conditions have to be considered:

- Two tunnel sections, I and II, will be instrumented.
- The tests will be terminated in section II after 5 years and in section I after 15-20 years.
- The conditions regarding temperature, pressure, corrosiveness is completely different in the tunnel and the deposition holes.
- The number of deposition holes is four in tunnel section I and two in section II.
- Two of the deposition holes in tunnel section I will be instrumented with a minimum of sensors (i.e. with optic fibres on the canister surface for temperature measurement) and will be used for comparison with the others after the end of the experiment. In this way it may be possible to evaluate if the instruments and the cabling, which may affect the water flow, have had physical or chemical effects on the processes in the buffer material.
- Two different measuring principles or manufactures should be used in order to increase the availability and the reliability of the measurements.

Since two different measuring principles or manufactures will be used in every deposition hole and every part of the tunnel sections and since the sensors will be equally distributed in the deposition holes and the tunnel sections respectively the following advantages apply:

- The progress of the processes in the different deposition holes can directly be compared since the same measuring principles are used in all deposition holes.
- If one of the measuring principles is not reliable, analysis can still be made by means of the principle that is still functioning.
- Temperature, pressure and moisture profiles are measured with high resolution.
- The reliability of the measurement result is improved if both of the measuring principles give the same result.

The number of measuring points distributed among different measuring quantities in tunnel and deposition holes is shown in Table 4. Temperature measurements with the distributed optical fibre measurement system, DTS/FTR, measure the average temperature along a line rather than in a point.

Table 4 Number of measuring points and their distribution among different measuring quantities

	Tunnel	Deposition holes	Total number
Section I			
Temperature	20	64	84
Total pressure	20	54	74
Pore water pressure	23	28	51
Water content	45	74	119
Total number	*108*	*220*	*328*
Section II			
Temperature	16	64	80
Total pressure	16	54	70
Pore water pressure	18	28	46
Water content	32	74	106
Total number	*82*	*220*	*302*
Section I and II together			
Temperature	36	128	164
Total pressure	36	108	144
Pore water pressure	41	56	97
Water content	77	148	225
Total number	*190*	*440*	*630*

If possible, two measuring principles are used for every measuring quantity both in the tunnel and the deposition holes. Some measuring principles for moisture measurements are not suitable in certain cases. The capacitive sensor for relative humidity measurements has a high uncertainty in the range 95 to 100 % relative humidity. Using this measuring principle when the backfill and buffer are close to saturation results in measurement result with low accuracy. The soil psychrometer is on the other hand not suitable for use in dryer materials where the relative humidity is lower than 95 %. TDR may be difficult to use for measurement of water content gradients because of the probe design.

The two measuring principles for temperature measurements that are recommended are the distributed optical fibre temperature measurement system (DTS/FTR) and thermocouples. Temperature sensors are also built into pressure and relative humidity sensors.

It is recommended that the optical fibre system is equipped with a number of optical fibre cables. Otherwise, the measurements are completely disrupted in case of cable breakdown. The suggestion is to use two cables on each canister surface. A calculation of the required cable length of the optical fibre is presented in Table 5. The two cables, with a distance of 0,5 m from each other, are vertically laid on each canister surface.

Table 5 Calculation of cable lengths for an optical fibre optic temperature measurement system DTS/FTR

Number of cables	Section I	Section II
Number of deposition holes	4	2
Number of cables on each canister surface	2	2
Total number of cables	8	4
Deposition hole		
Cable spacing, m	1	1
Hole depth, m	8	8
Hole diameter, m	1,75	1,75
Canister length, m	4,8	4,8
Canister diameter, m	1,05	1,05
Number of parallel slots on canister surface	4	4
Cable length on the canister surface, m	22,50	22,50
Additional cable length	200	200
Total cable length, m	222	222
Total		
Total length of cable, m	1780	890

An estimation of the investment cost, installation cost excluded, for different sensors is made in Table 6 where also the material selection is specified.

Table 6 Estimated costs for different measuring methods with installation costs excluded

	Material in sensor	Number of sensors	Cost
Temperature			
Thermocouple	Cupro-nickel	164	1.15 MSEK
Fibre optic (DTS/FTR)	Inconel 625	12 (cables)	1.60 MSEK
Total pressure			
Vibrating wire	Titanium in deposition holes and AISI 316 in tunnel	74	1.65 MSEK
Piezoresistive sensors	Titanium	74	2.40 MSEK
Pore water pressure			
Vibrating wire	Titanium in deposition holes and AISI 316 in tunnel	50	1.00 MSEK
Piezoresistive sensors	Titanium	50	1.50 MSEK
Water content			
Relative humidity (capacitive method)	Protection tubes of titanium	148	2.75 MSEK
Soil psychrometer	Protection tubes of titanium	77	0.65 MSEK

The following approximate costs for cables with and average length of 75 m and protection tubes are included in investment costs specified in table 6:

Protection tube of Tecalan	40 SEK/m
Signal cable (high temperatur)	65 SEK/m
Signal cable (low temperatur)	25 SEK/m
Fibre optic cable in protection tube of Inconel 625	85 SEK/m

The measuring principles, which are recommended to be used in the Prototype Repository and the distribution of sensors among the different principles, are shown in Table 7.

Table 7 Measuring principles suggested to be used for instrumentation of the Prototype Repository

Measuring quantity	**Measuring principle**	**Number of sensors in section I**		**Number of sensors in section II**		**Total number**
		Tunnel	**Deposition hole**	**Tunnel**	**Deposition hole**	
Temperature	Thermocouple	20	64	16	64	164
	Fibre optic (DTS/FTR)	0	8	0	4	12
Total pressure	Vibrating wire	10	28	8	28	74
	Piezoresistive	10	28	8	28	74
Pore water pressure	Vibrating wire	12	14	10	14	50
	Piezoresistive	12	14	10	14	50
Water content	Relative humidity (capacitive method)	0	74	0	74	148
	Soil psychrometer	45	0	32	0	77
Total		109	230	84	226	649

The selection of measuring principles is motivated as follows:

Measuring principle	Motive
Thermocouples	1. Reliable technique 2. Low cost 3. Sufficiently long-term stable at the temperatures expected in the Prototype Repository 4. The sensor (i.e. joint) and thermocouple wire are covered by a metal sheath which protects against water leakage and in some extent from electromagnetic fields 5. The sheath is made of Cupro-Nickel which probably is sufficiently corrosion-resistant in the environment expected in the Prototype Repository
Optical fibre temperature measurement system, DTS/FTR	1. Temperature profiles can be monitored easily 2. Small dimensions 3. Gives a large amount of information in relation to the number of cables 4. Protection tube is made of Inconel 625 which probably is sufficiently corrosion-resistant in the environment expected in the Prototype Repository 5. Insensitive to electromagnetic interference
Vibrating wire for total pressure and pore water pressure	1. Reliable technique 2. The sensor housing and pressure diaphragm can be made of titanium 3. The measuring signal is composed of a frequency of a varying voltage and is completely insensitive to electromagnetic interference 4. The sensor has no built-in electronics 5. Long-term stable 6. The sensor can be equipped with a built-in thermistor

Measuring principle	Motive
Piezoresistive for total pressure and pore water pressure	1. The sensor housing and pressure diaphragm can be made of titanium 2. The method is probably long-term stable 3. The sensor has small dimensions 4. The cable has a small dimension and be laid in a protection tube made of Inconel 625
Capacitive sensor for measuring relative humidity in pore volume	1. The probe contains limited or no electronics 2. The probe has small dimensions 3. The probe can be equipped with a built-in temperature sensor of type Pt 100 4. Large measuring range (however slightly less accurate in the range of 95-100 % relative humidity)
Soil psychrometer for measuring dry and wet temperature in pore volume	1. Low cost 2. High accuracy at high relative humidity expected in the backfill material

In Table 8, the investment costs for the recommended instrumentation of the Prototype Repository are shown.

Table 8 Costs for instrumentation of the Prototype Repository

Measuring quantity	**Measuring principle**	**Total number of sensors in section I**	**Total number of sensors in section II**	**Total number of sensors in section I and II**	**Cost**	**Specific cost**
Temperature	Thermocouples	84	80	164	1.15 MSEK	7.00 SEK/unit
	Fibre optic (DTS/FTR)	8	4	12	1.60 MSEK	133.4 SEK/unit
Total pressure	Vibrating wire	38	36	74	1.65 MSEK	22.3 SEK/unit
	Piezoresistive	38	36	74	2.40 MSEK	32.5 SEK/unit
Pore water pressure	Vibrating wire	26	24	50	1.00 MSEK	20.0 SEK/unit
	Piezoresistive	26	24	50	1.50 MSEK	30.0 SEK/unit
Water content	Relative humidity (capacitive method)	74	74	148	2.75 MSEK	18.6 SEK/unit
	Soil psychrometer	45	32	77	0.65 MSEK	8.5 SEK/unit
Sum		339	310	649	12.70 MSEK	
Additional sensors, design, installation, commissioning etc. (25 %)					3.20 MSEK	
Total cost					15.90 MSEK	

8 Collecting and presentation of measurement result

As far as possible, intelligent measuring units as such as Datascan will be used for collection of measurement results. There are two types of Datascan units, one for analogous channels and one for digital channels. The maximum number of analogues channels per unit is 16. Several units can be connected to each other, forming a data acquisition system for 1,000 channels. A PC is communicating with the system by means of the RS-232 or RS-485 port. Thermocouples, Pt 100 sensors, piezoresistive pressure sensors etc. can directly be connected to a Datascan unit.

A software program, Orchestrator, is used for storing and presentation of measurement result. The standard version of Orchestrator contains a driver for communication with a Datascan system. Drivers are also available for other manufactures such as Campbell Scientifics loggers of type CR7 and CR10, which are often used in combination with soil psychrometers and vibrating wire pressure sensors, which require some control. It may be necessary to develop drivers or software components for other measuring equipment.

Special measuring system as optical fibre measurement systems may require a special software for configuration of the measurements. The software may also include specialized tools for graphical presentation of the measurement result. This type of software is to be regarded as a complement to Orchestrator, which still is used for collecting and storage of data.

The final data acquisition system will probably consist of a number of Windows NT or Windows 95/98 computers forming a workgroup. Techniques as NetDDE and DCOM are used for interprocess communication between different computers in the network.

References

/1-1/ Dahlström L-O, 1998. Test Plan for the Prototype Repository