Advanced Thermal Response Testing and Its Relevance to Complex UTES Arrays

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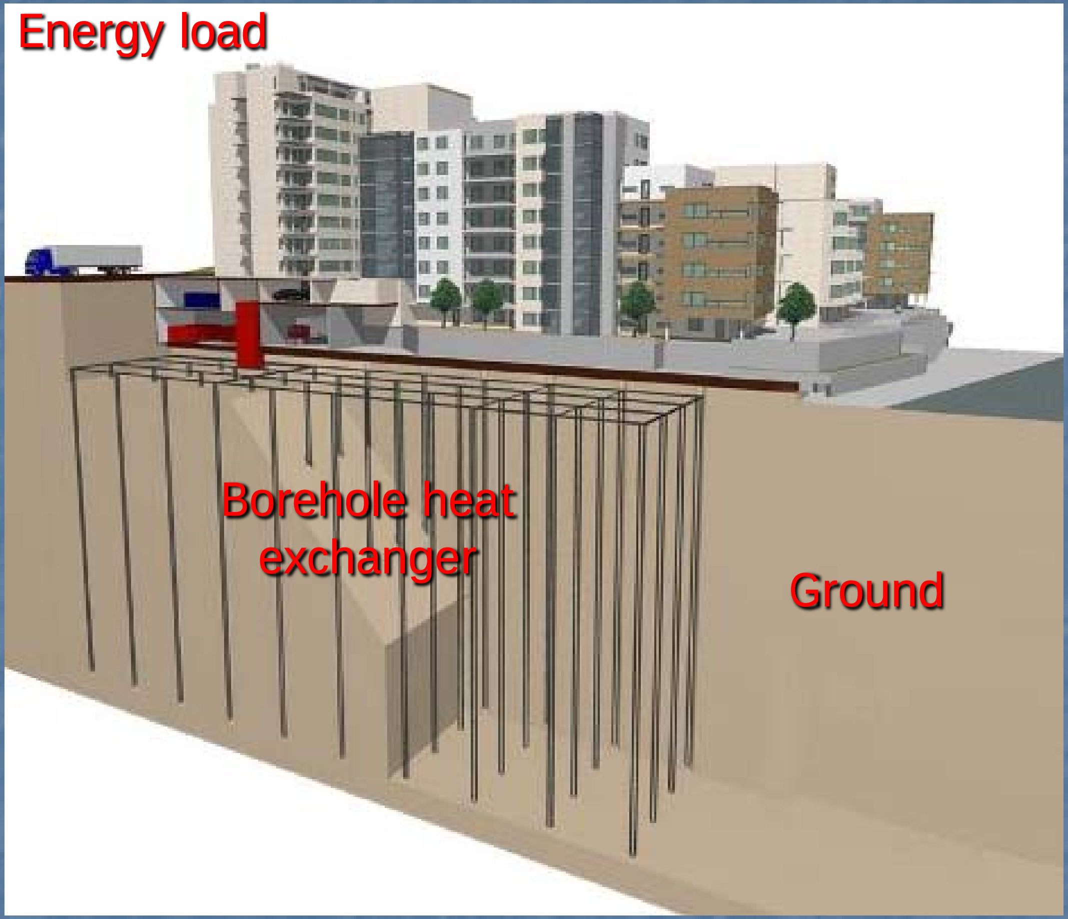
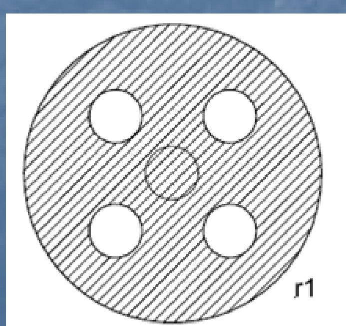
NEO ENERGY

Borehole heat exchanger

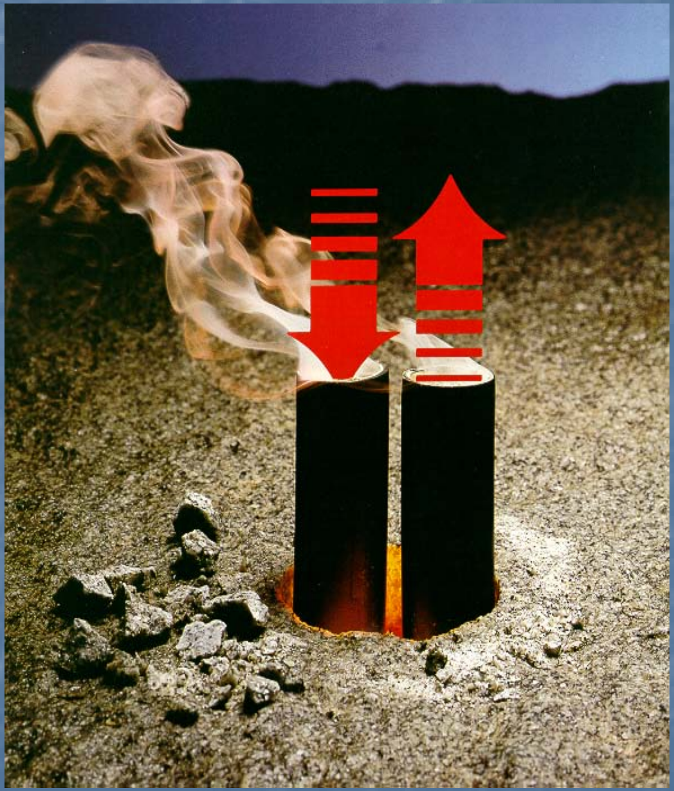


CLOSED LOOP
BOREHOLE HEAT EXCHANGERS

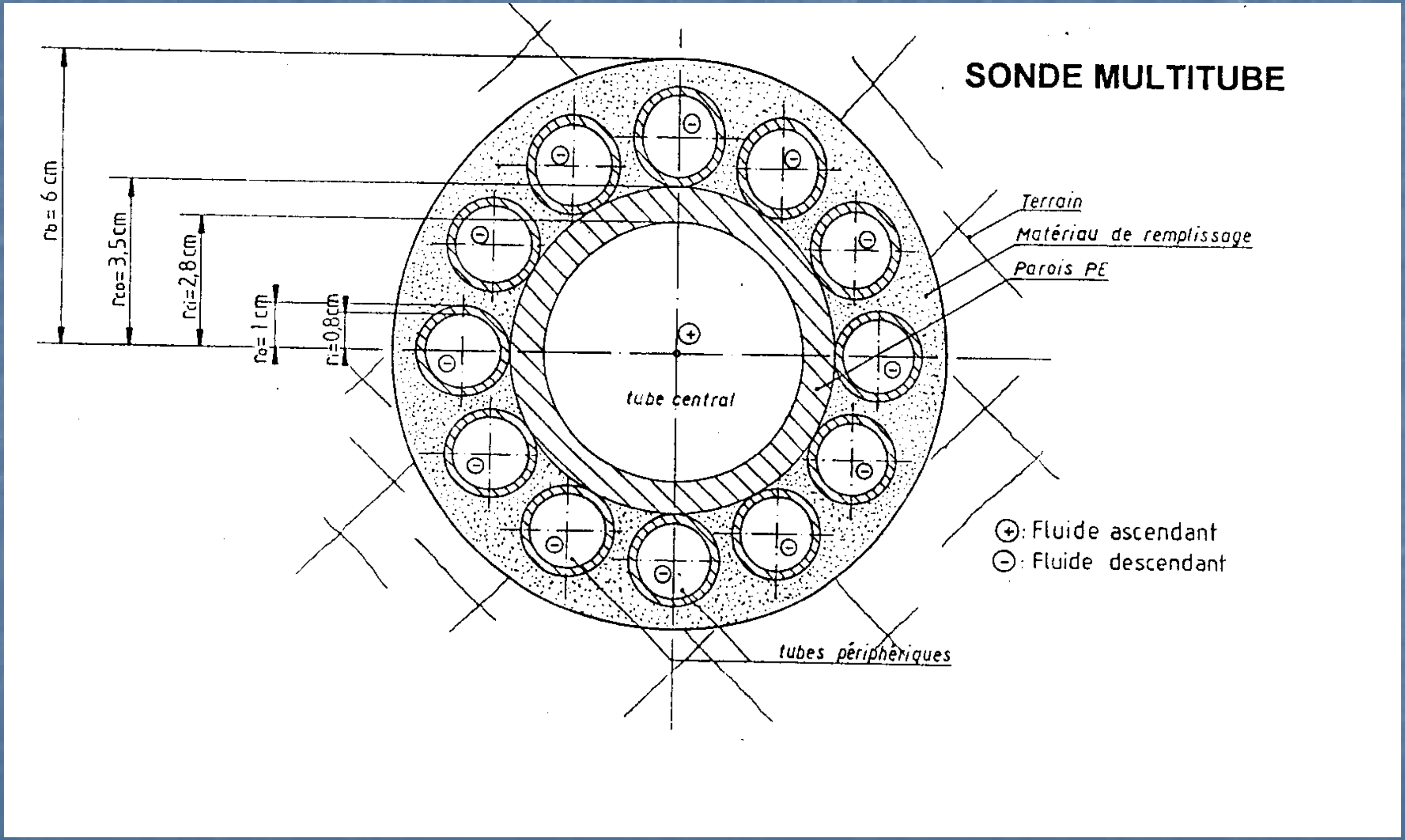
Closed Loop
Vertical BHE Insertion



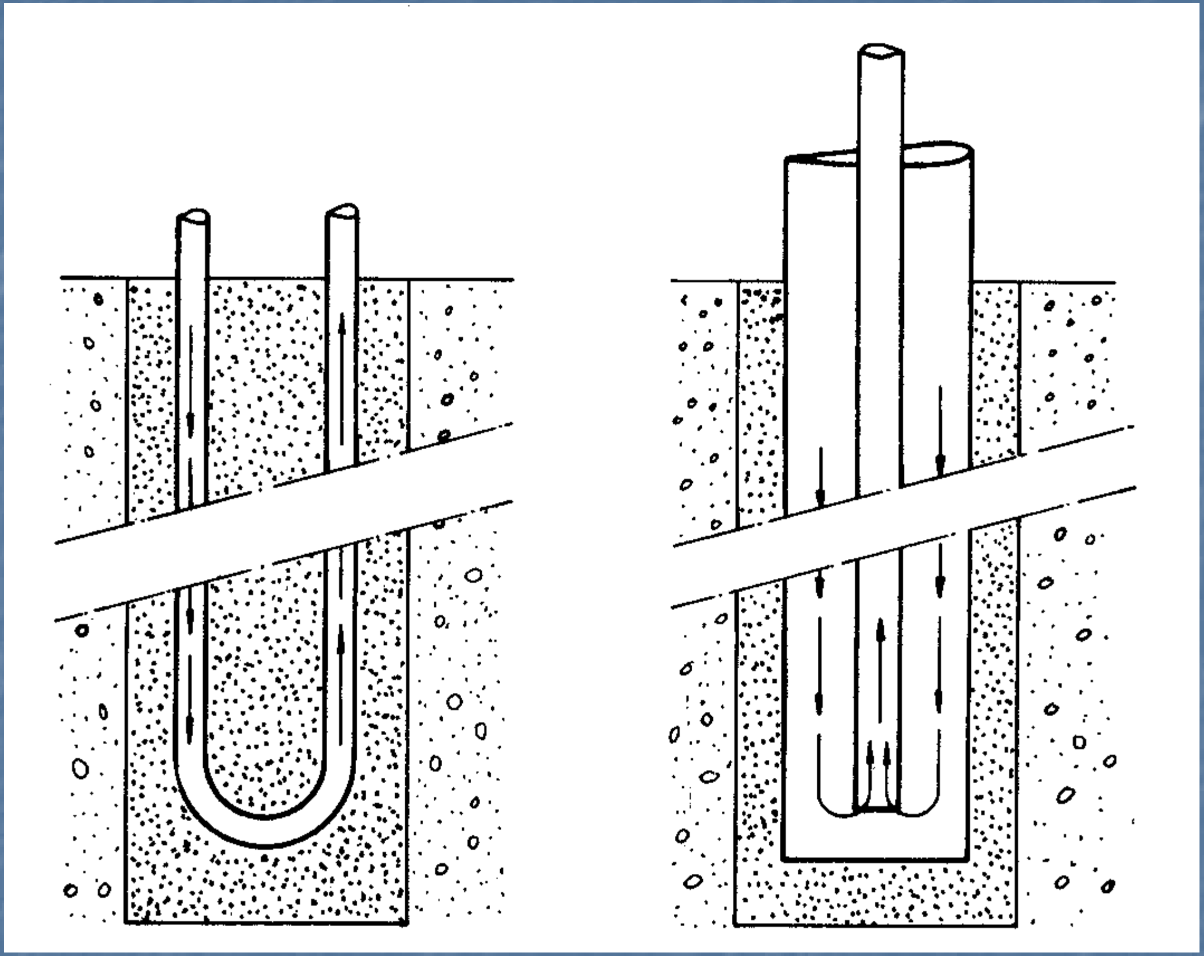
Single U-pipe BHE



Multipipe coaxial type



Basic types of borehole heat exchangers



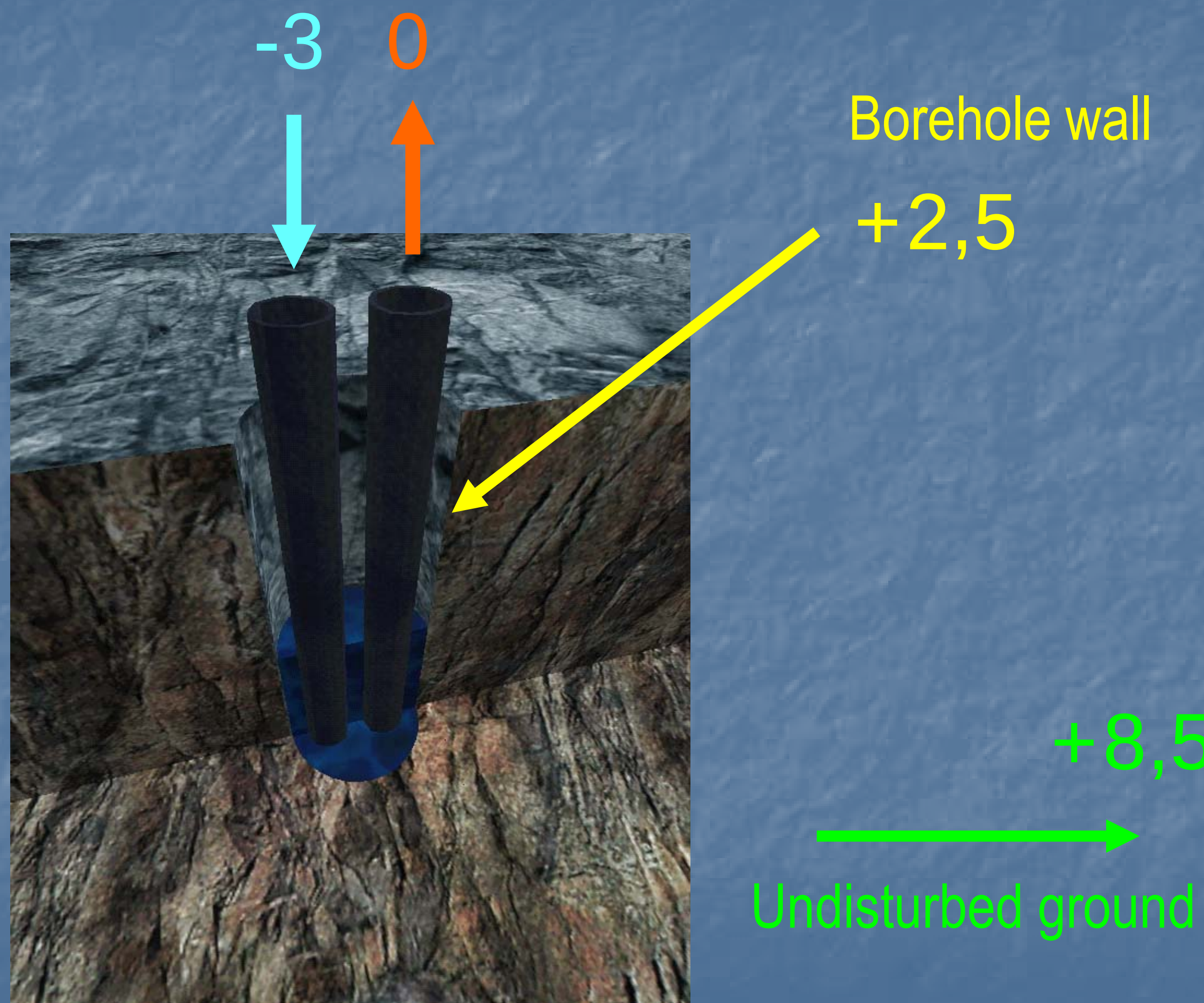
U-tube　　　　　　　　Coaxial

Ground-source heat pump operating conditions

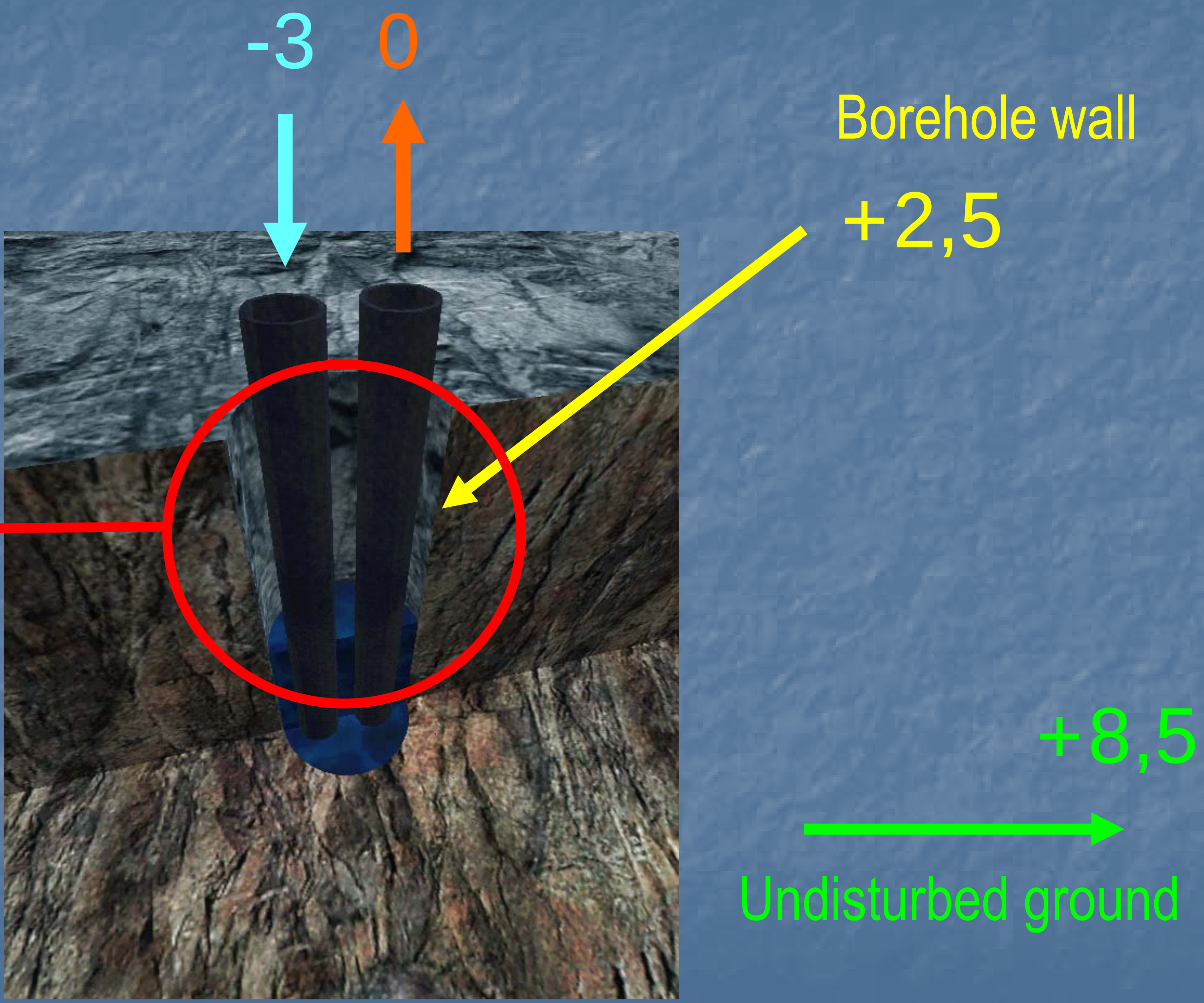
Heat extraction rate

40 W/m

Typical operating conditions in central Sweden

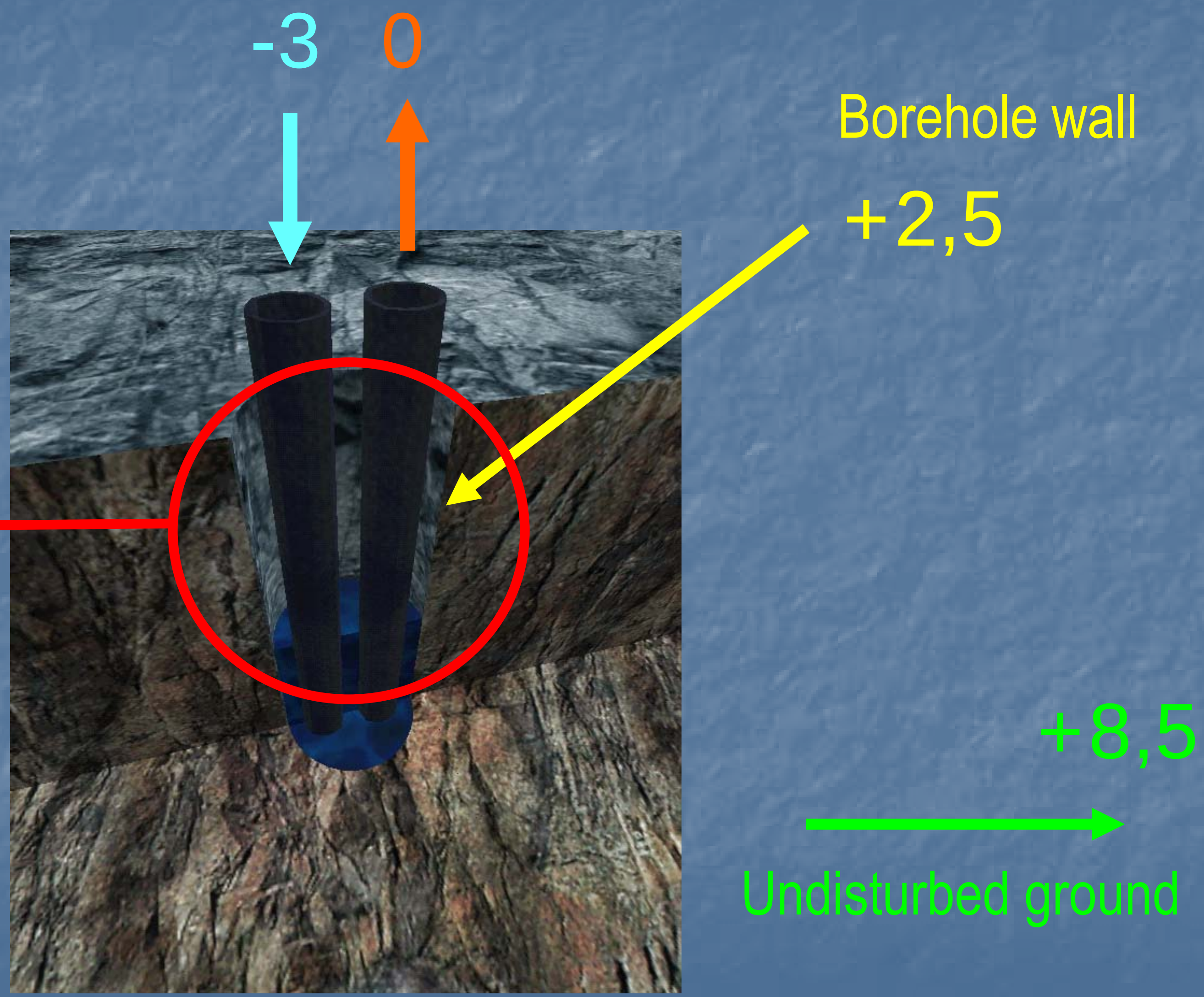


Ground-source heat pump operating conditions



40 % of temperature difference between heat carrier fluid and surrounding ground within the borehole

Ground-source heat pump operating conditions



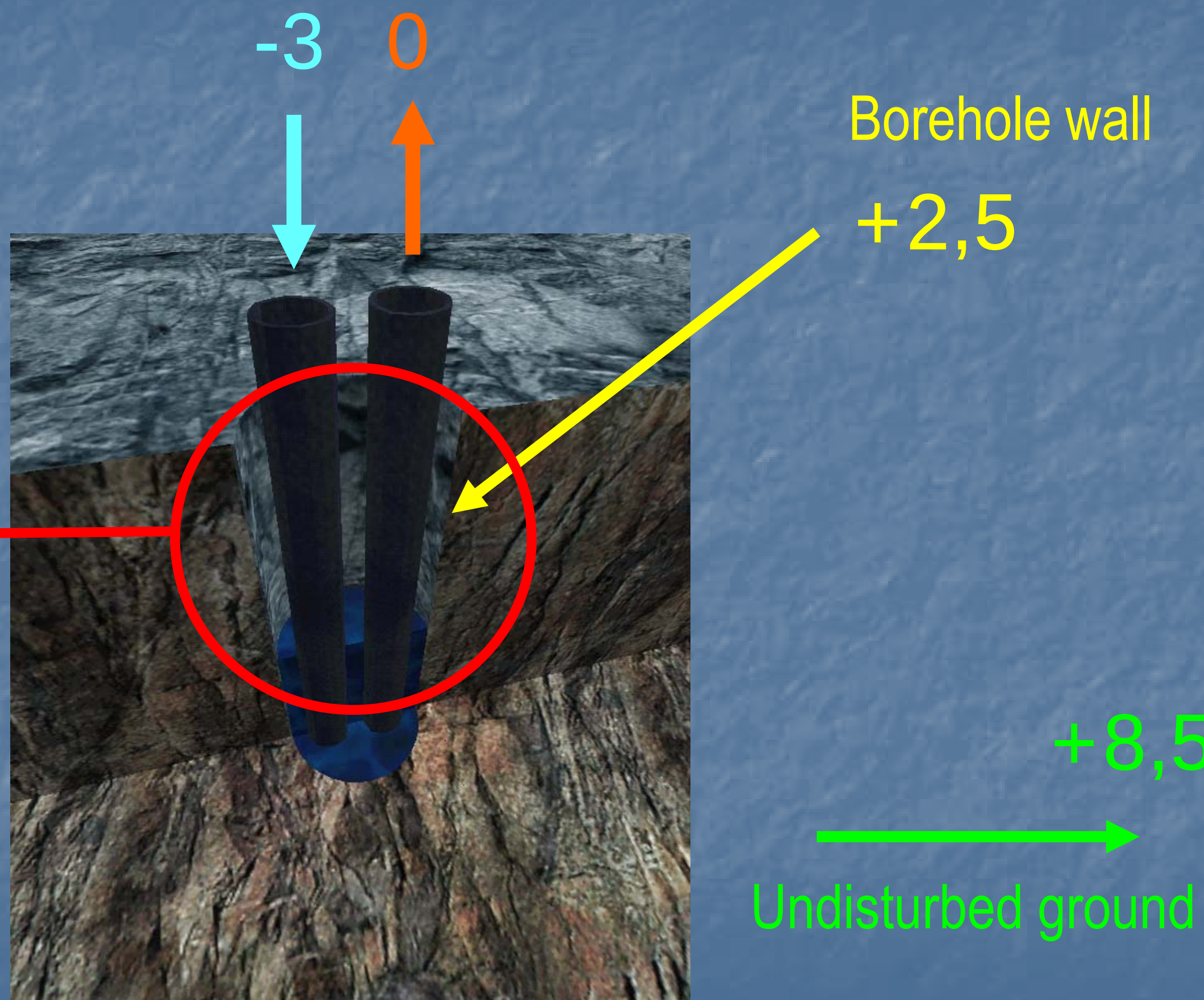
40 % of temperature difference between heat carrier fluid and surrounding ground within the borehole

TRT used to measure performance of borehole heat exchangers

Ground-source heat pump operating conditions

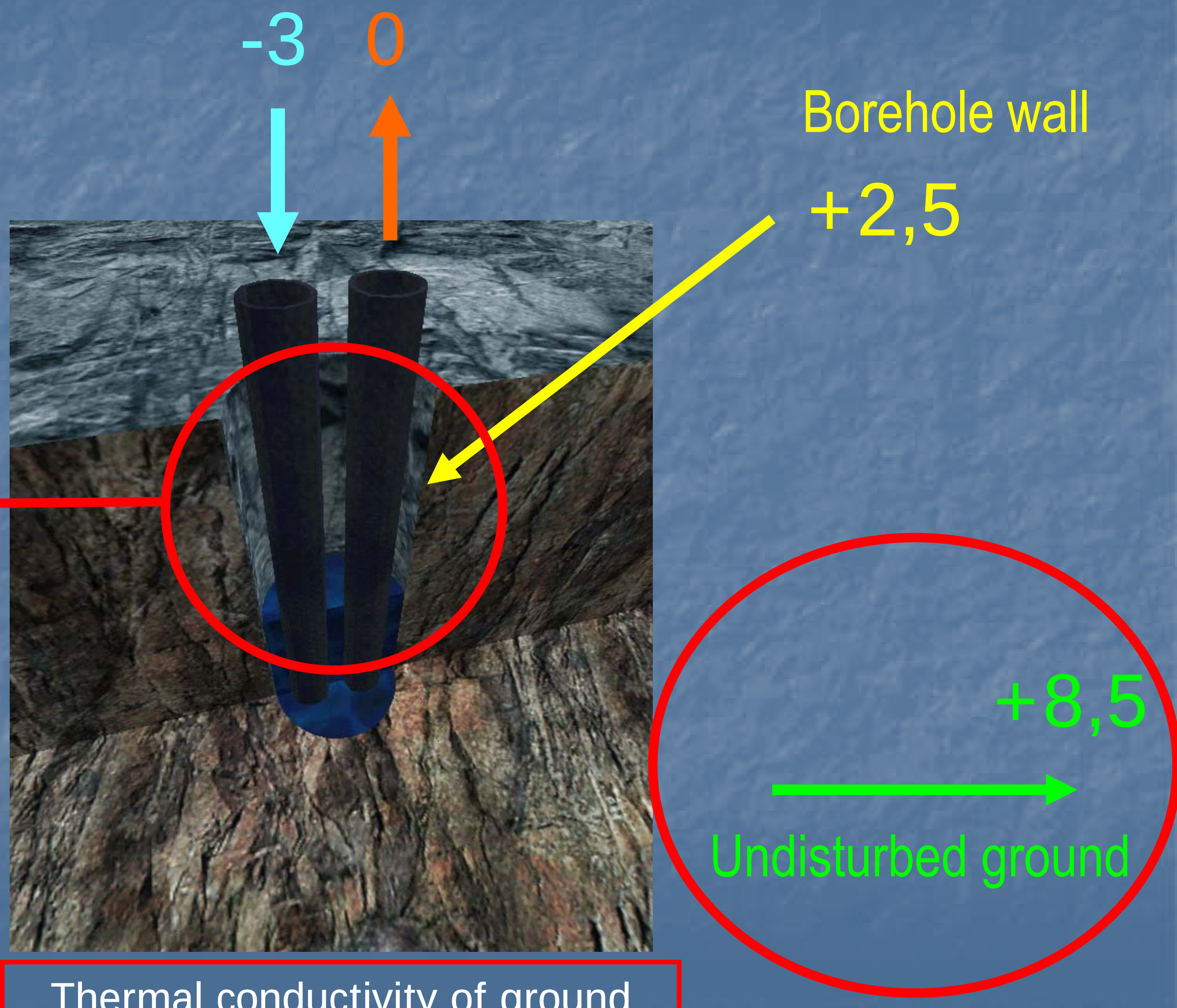
40 % of temperature difference between heat carrier fluid and surrounding ground <u>within</u> the borehole

TRT used to measure performance of borehole heat exchangers



Thermal conductivity of ground

Ground-source heat pump operating conditions



40 % of temperature difference between heat carrier fluid and surrounding ground <u>within</u> the borehole

TRT used to measure performance of borehole heat exchangers

Thermal conductivity of ground

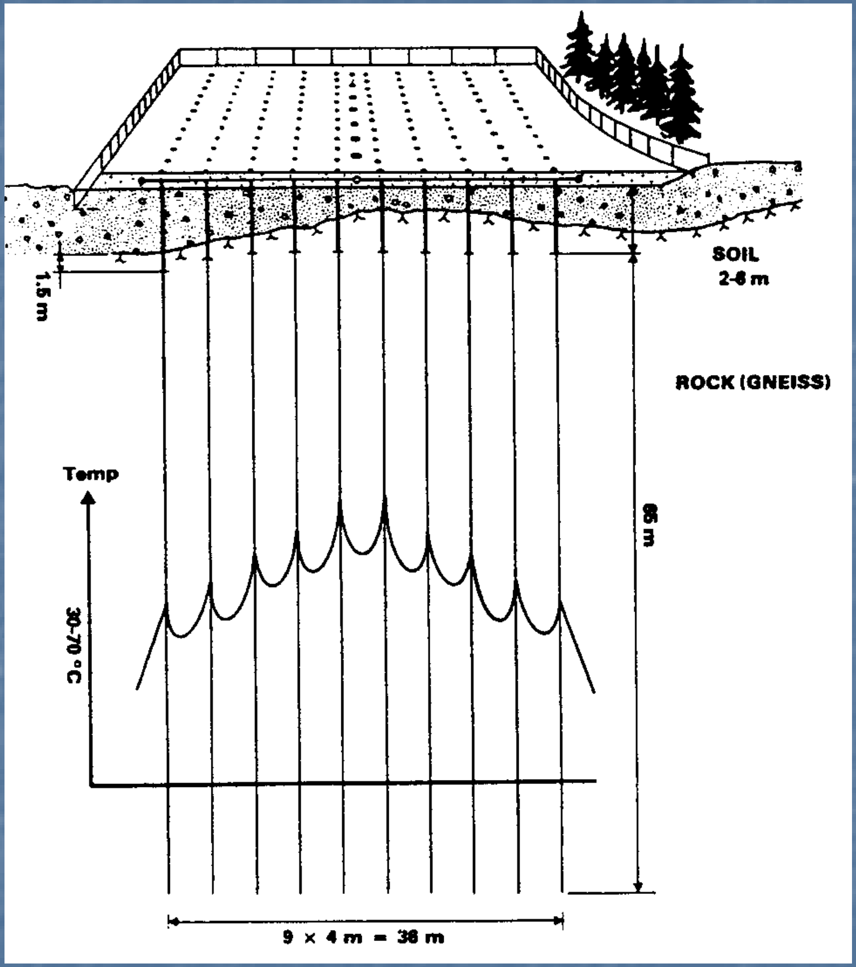
Single U-pipe BHE

Germany, several	bentonite	0,10-0,13
Germany, several	thermal grout	0,06-0,08
USA, several	bentonite	0,13-0,15
USA, several	thermal grout	0,09-0,10
Sweden, several	water, heating	0,06-0,08
Studsvik	ice	0,09

Field measurements of borehole thermal resistance

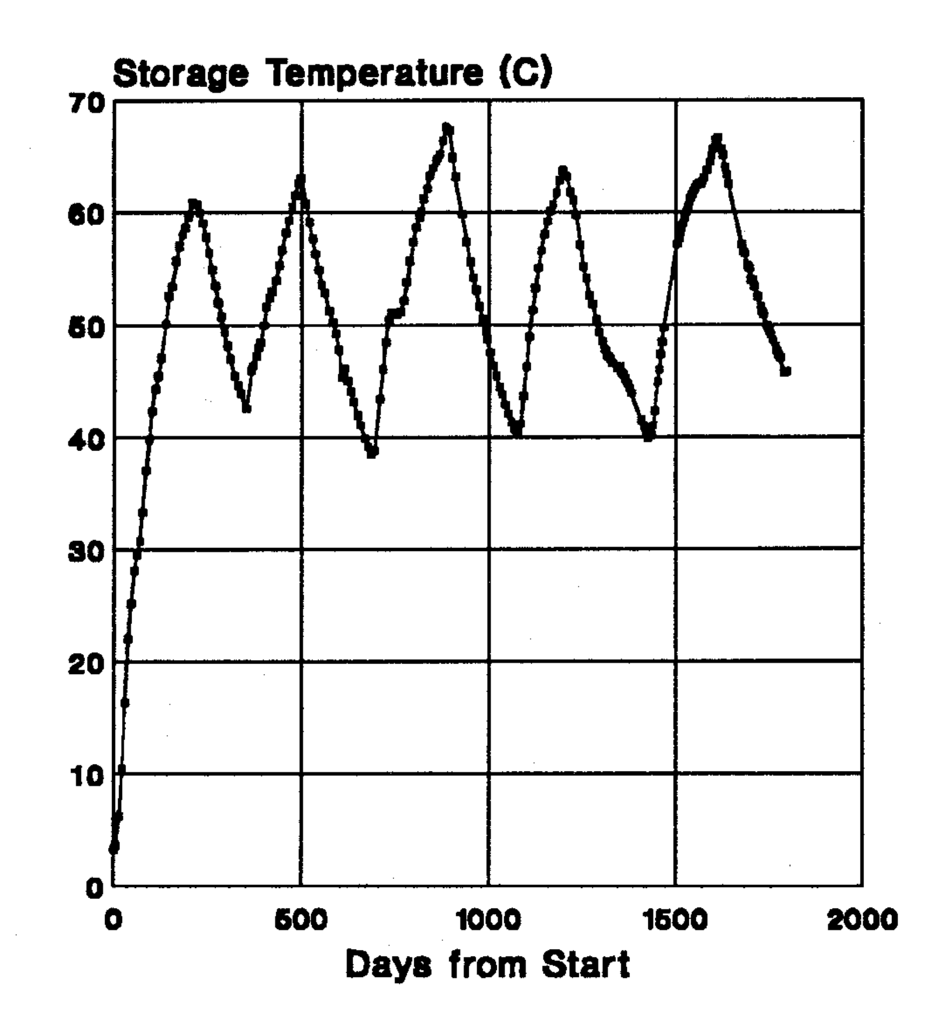
UNDERGROUND THERMAL ENERGY STORAGE

BTES - Luleå



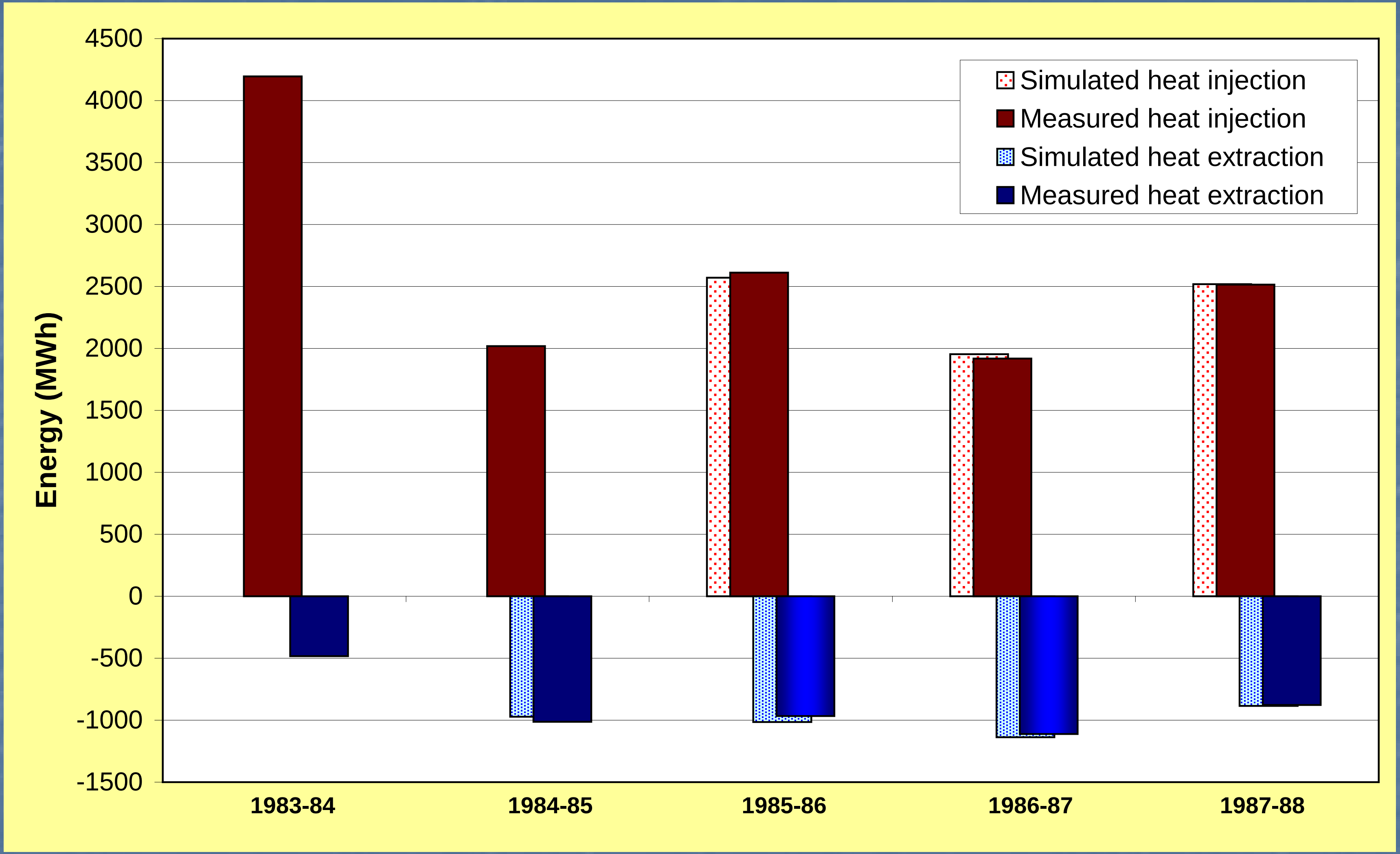
Borehole heat store: 120 boreholes depth 65 m

BTES - Luleå



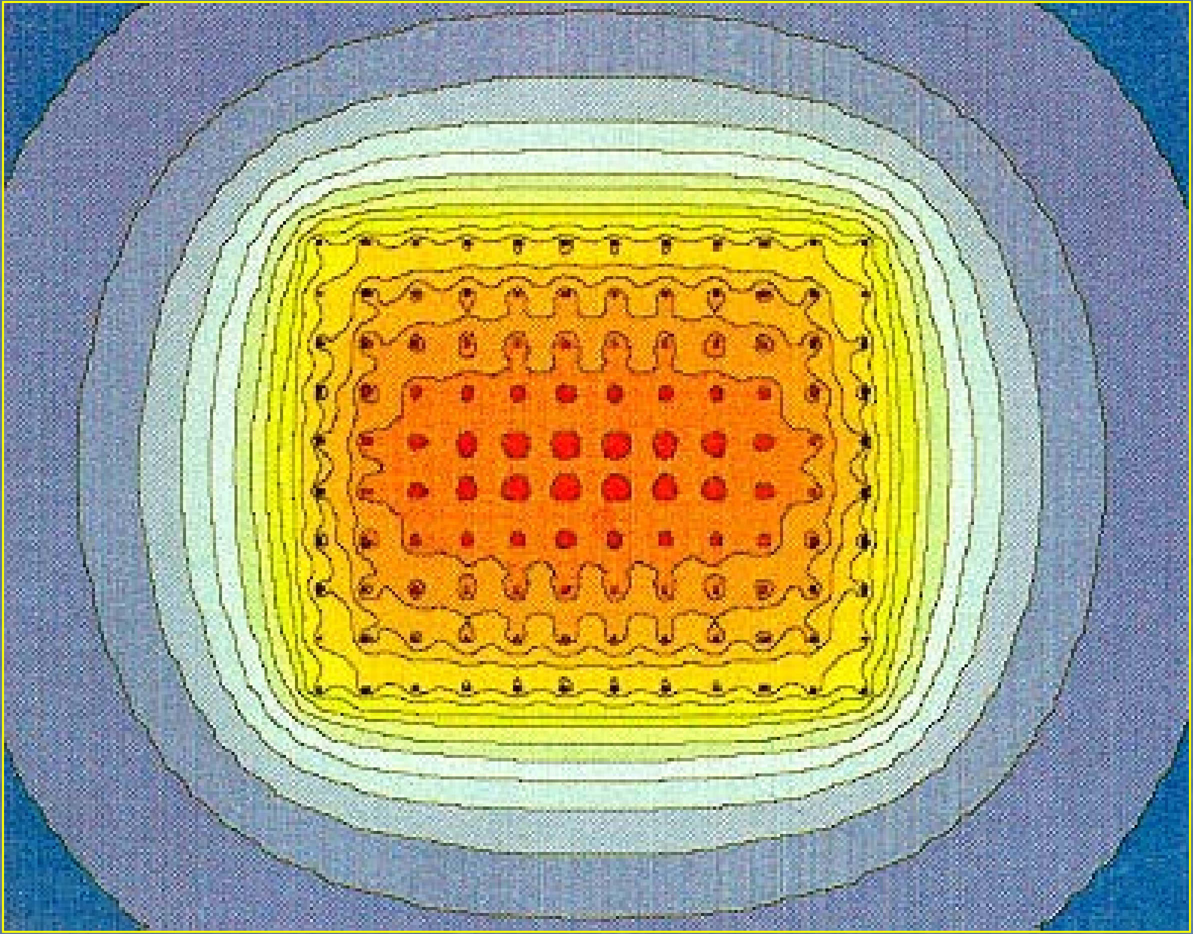
Measured temperature in center of store

BTES - Luleå



Measured and simulated energy balance 1983-1988

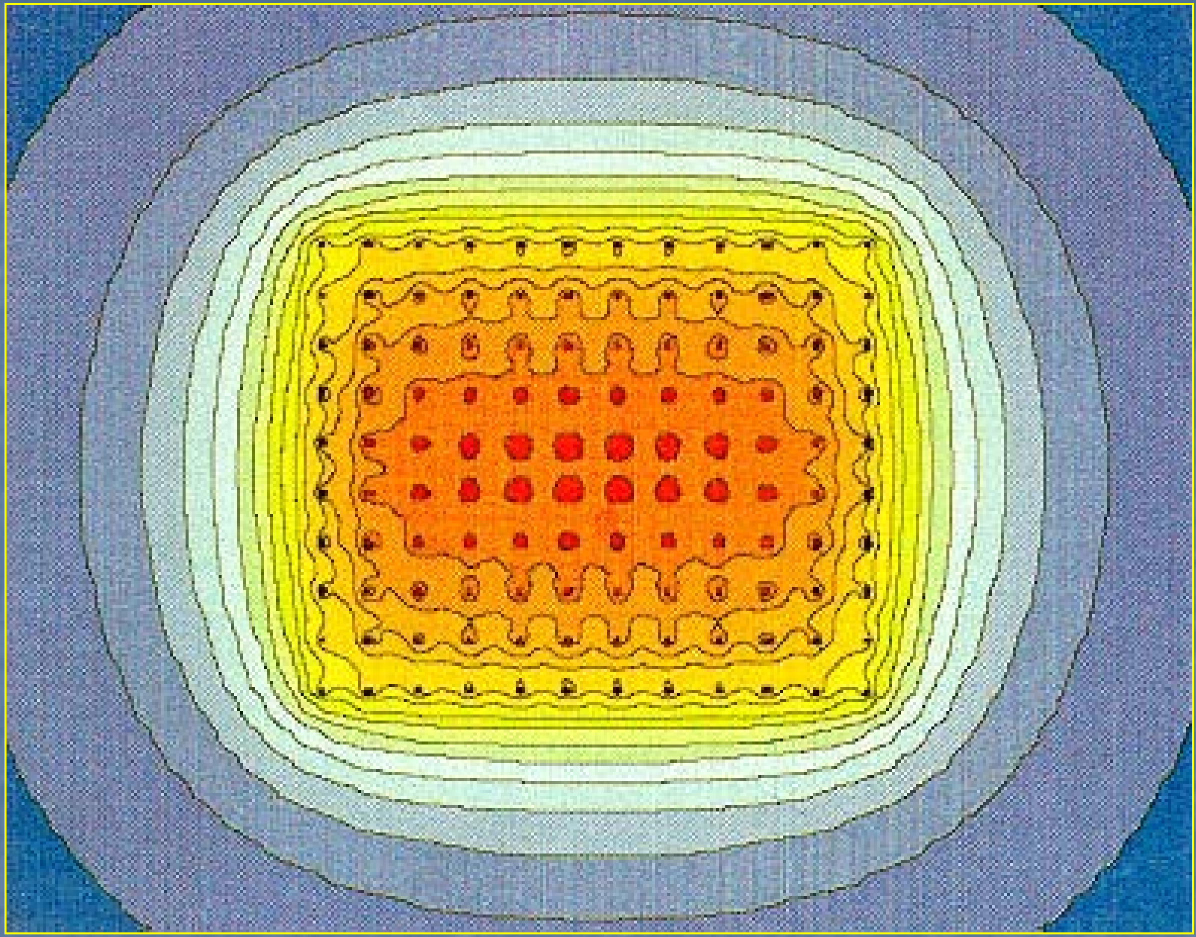
BTES - Luleå



Estimated ground temperature after charging

Heat losses proportional to to thermal conductivity of ground

BTES - Luleå



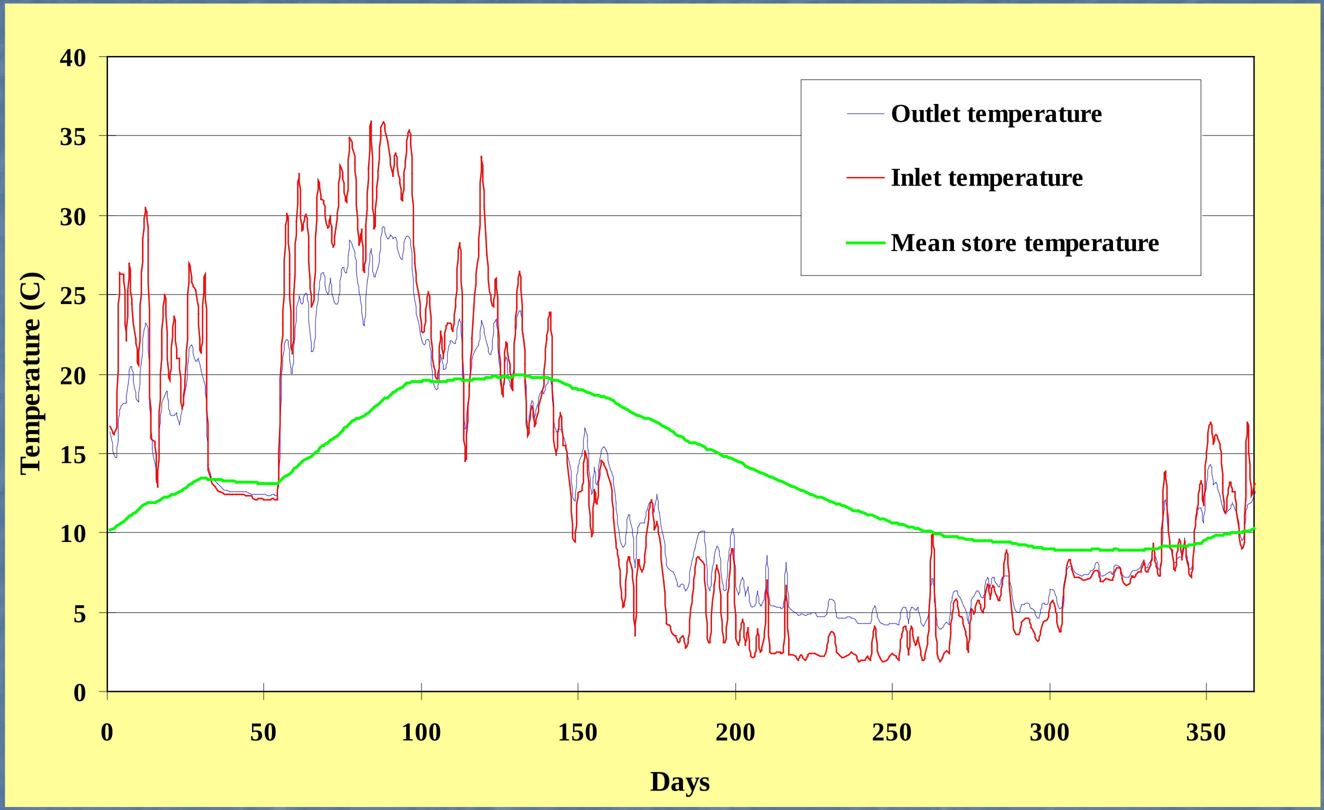
Estimated ground temperature after charging

Heat losses proportional to to thermal conductivity of ground

(Influence of groundwater flow)

THERMAL PROCESSES

Energy load variation



What is the relation between fluid temperatures and heat transfer rates for a specific borehole exhanger design?

Method of analysis

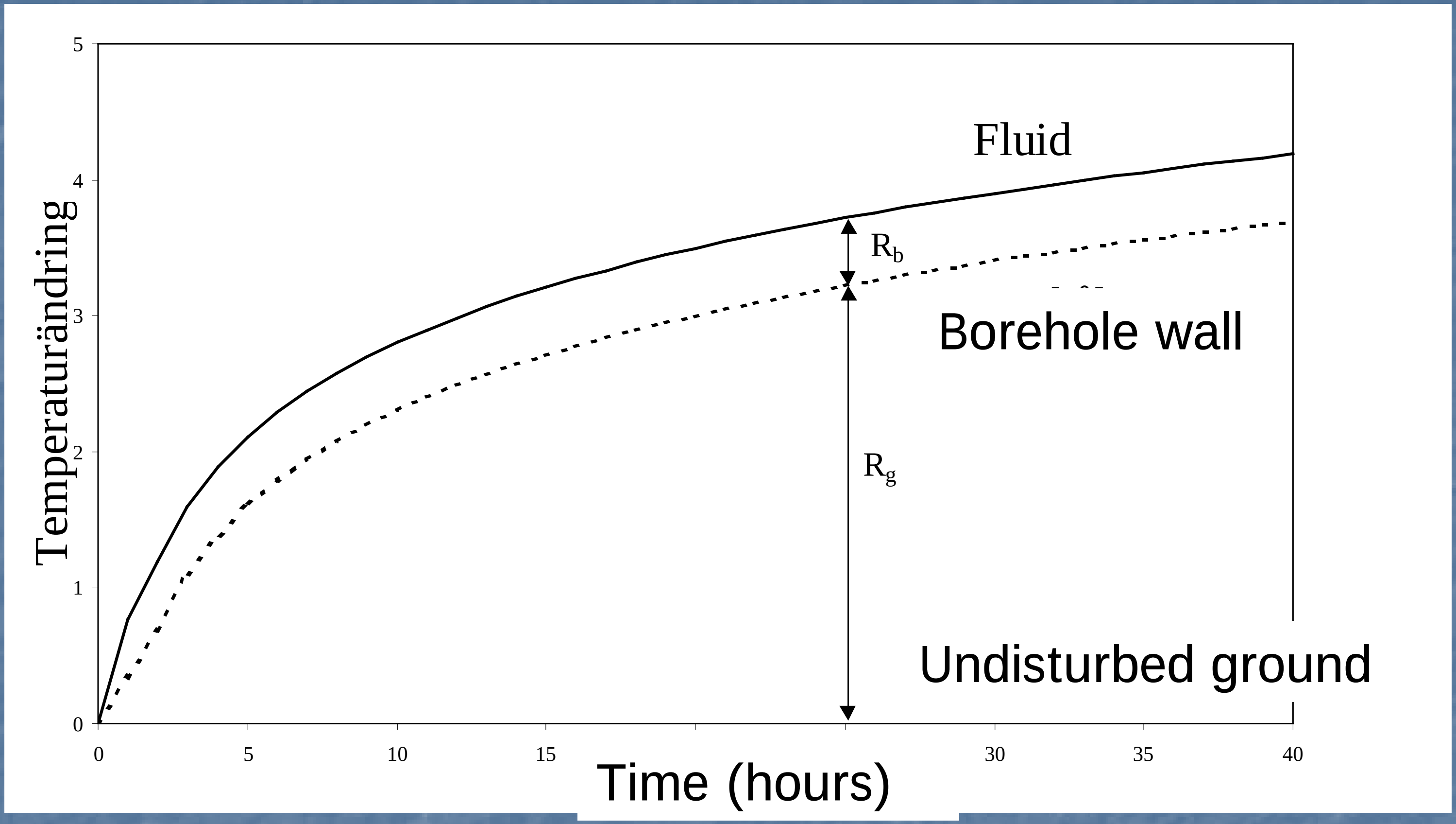
Common approach:

- Determine a thermal response function!

Two basic parts:

- Response of the thermal process in the borehole
- Response of the thermal process in the ground surrounding borehole

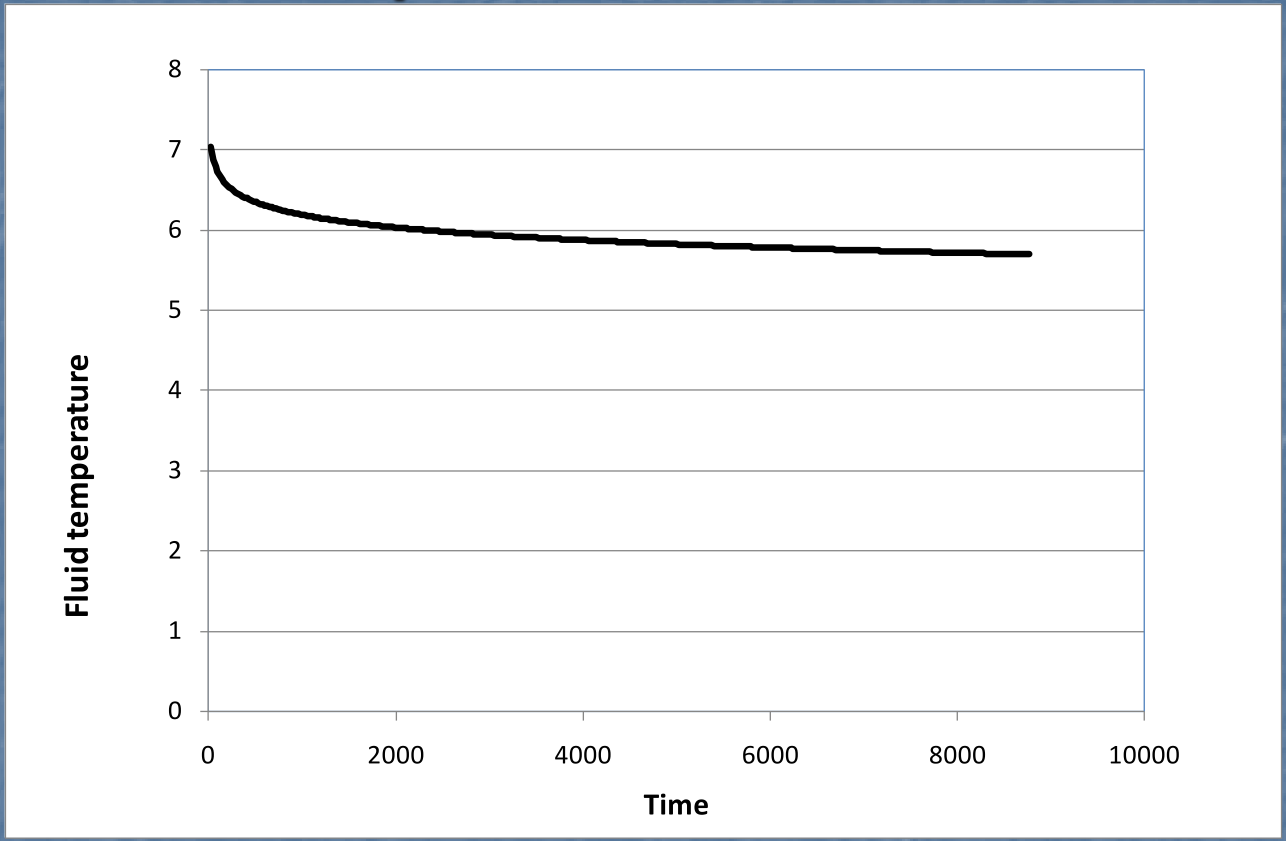
Thermal response



Temperature change when constant heat injection rate is supplied

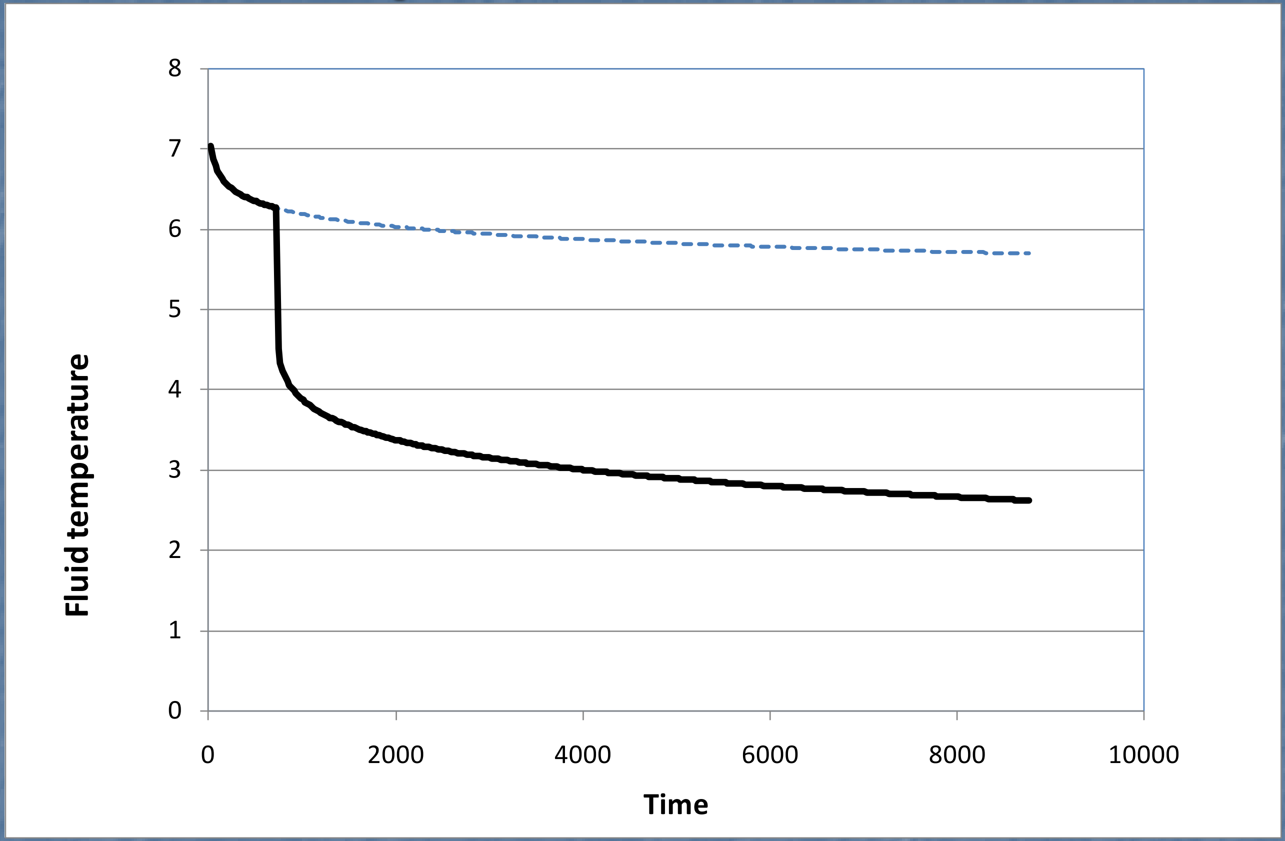
(Similar to thermal response test)

Thermal response



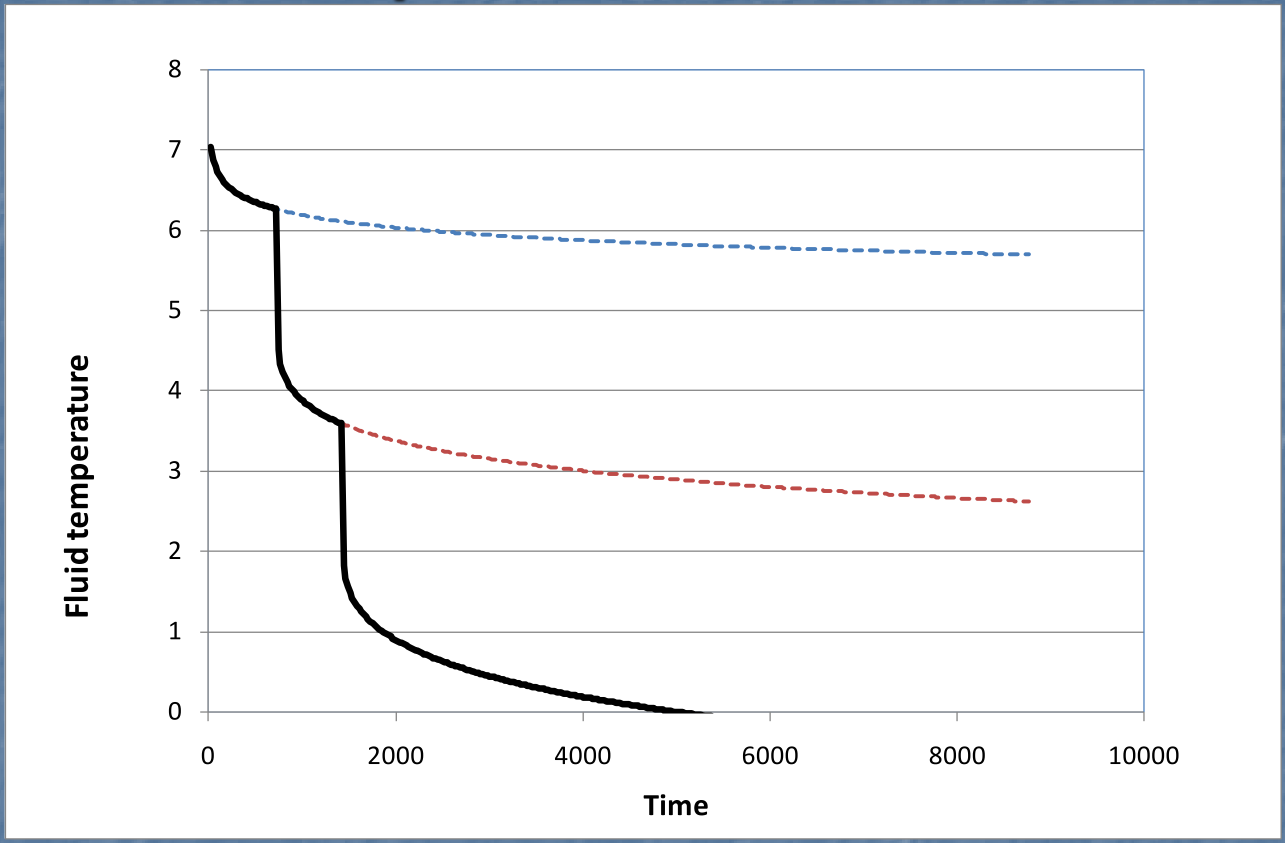
Superpositioning of response functions

Thermal response



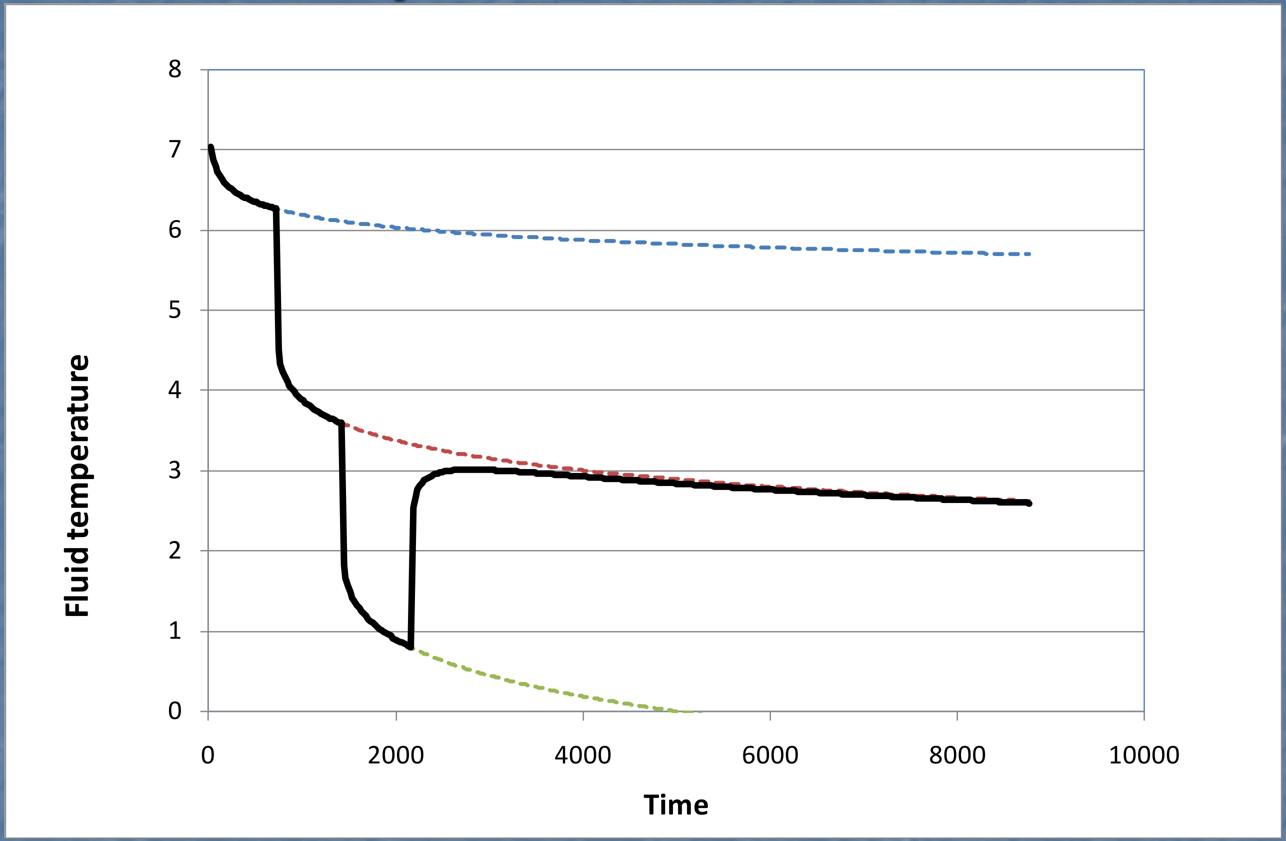
Superpositioning of response functions

Thermal response



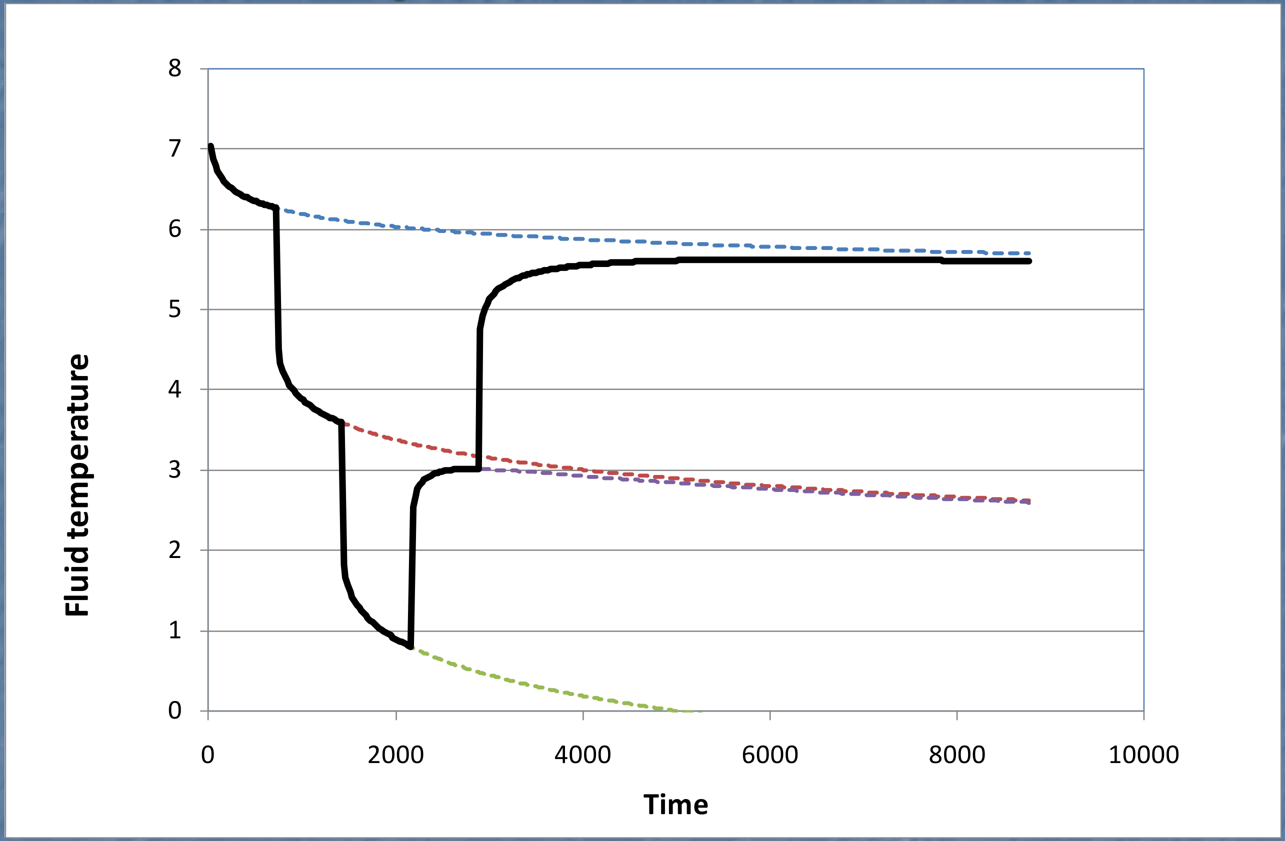
Superpositioning of response functions

Thermal response



Superpositioning of response functions

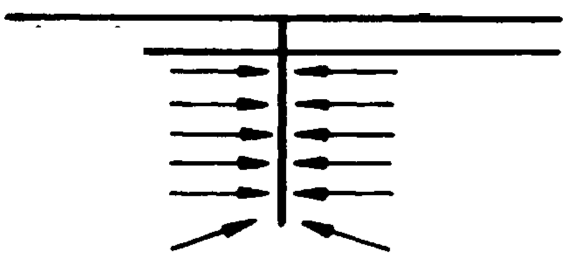
Thermal response



Superpositioning of response functions

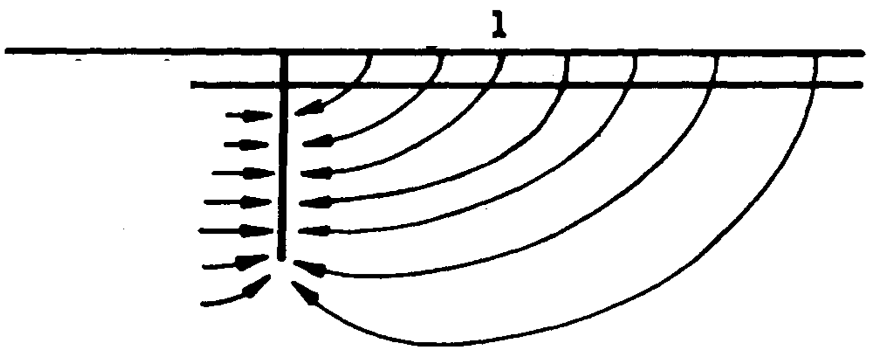
Character of heat transfer process

Short term



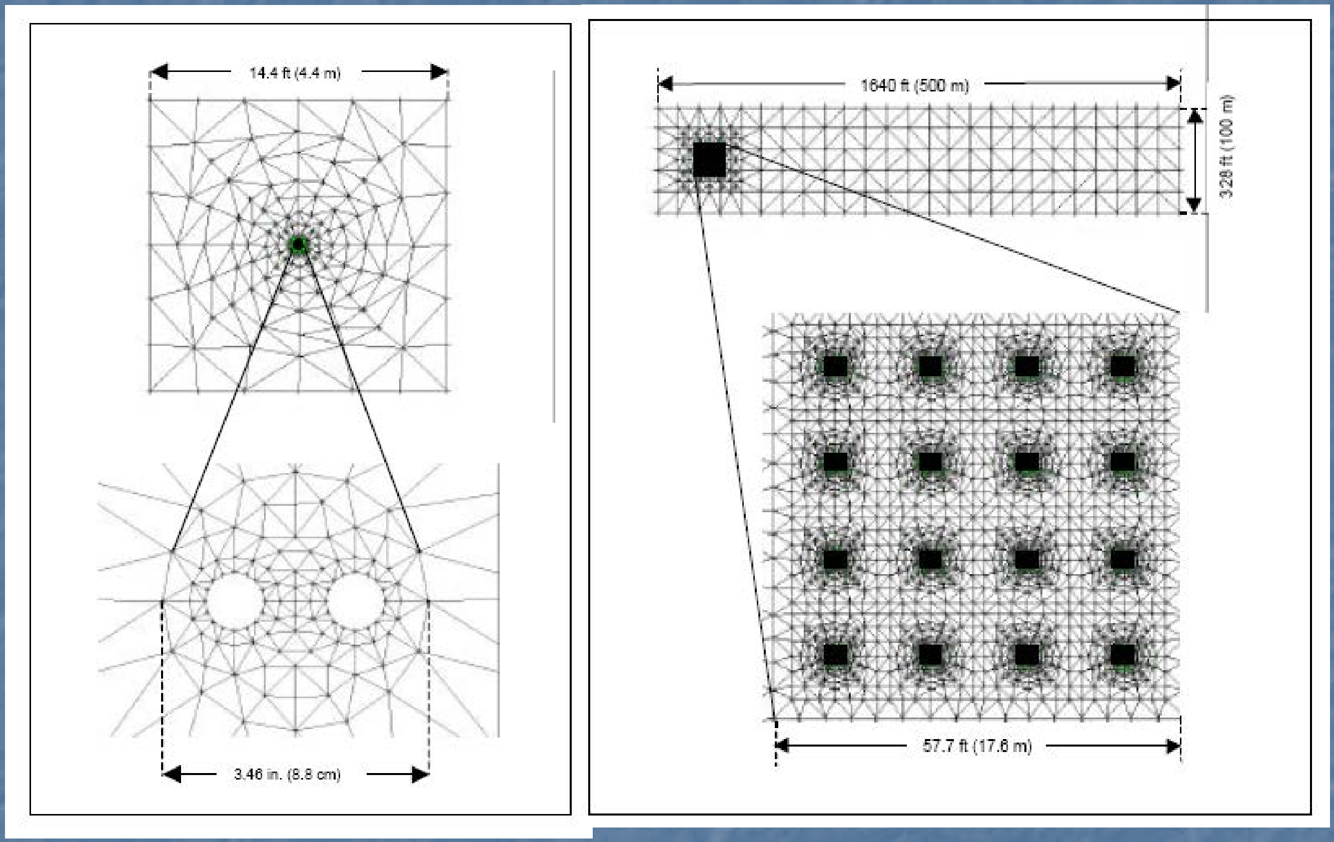
Transient radial heat conduction

Long term



Steady-state heat conduction

Numerical methods



Example of numeric grid (Chiasson)

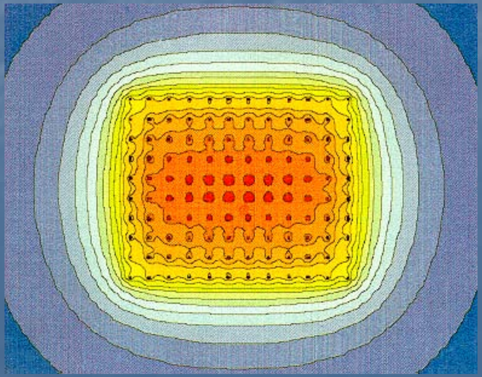
Simulation models

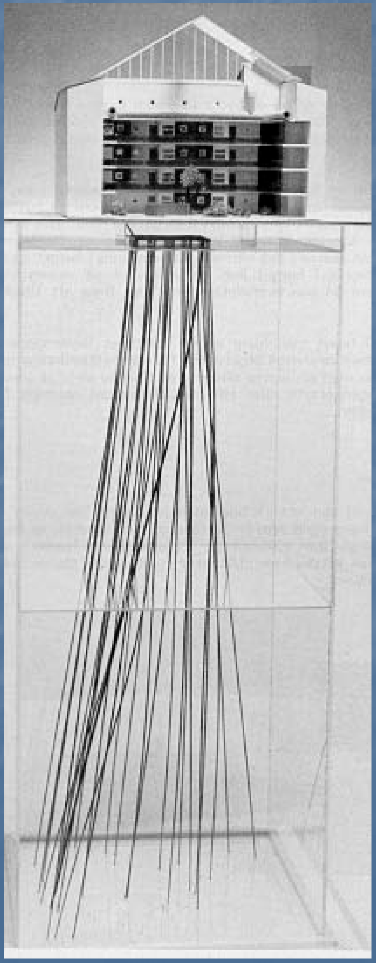
SBM – Superposition Borehole Model

- homogeneous ground properties
- borehole heat exchanger (depth, material, filling material)
- arbitrary placement of boreholes (vertical or graded)
- Validated against field experiments

Results:

- fluid temperature variation
- temperature in the ground
- energy balance





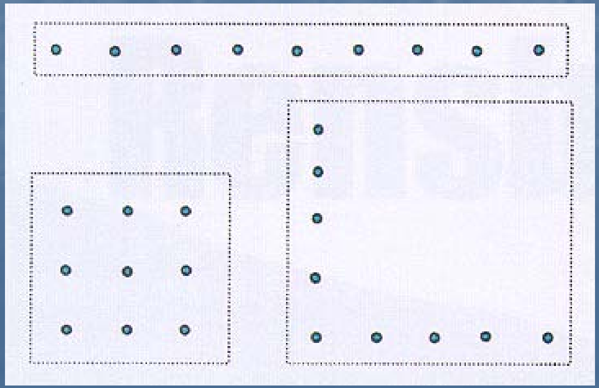
Design tool

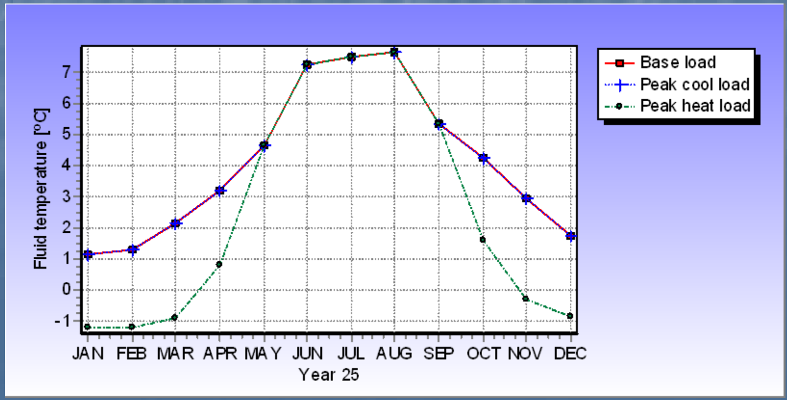
EED – Earth Energy Designer

- easy and fast to use (GUI)
- ground properties
- borehole heat exchanger (type, depth, material, filling material)
- 800 predefined borehole configurations
- heat carrier fluid

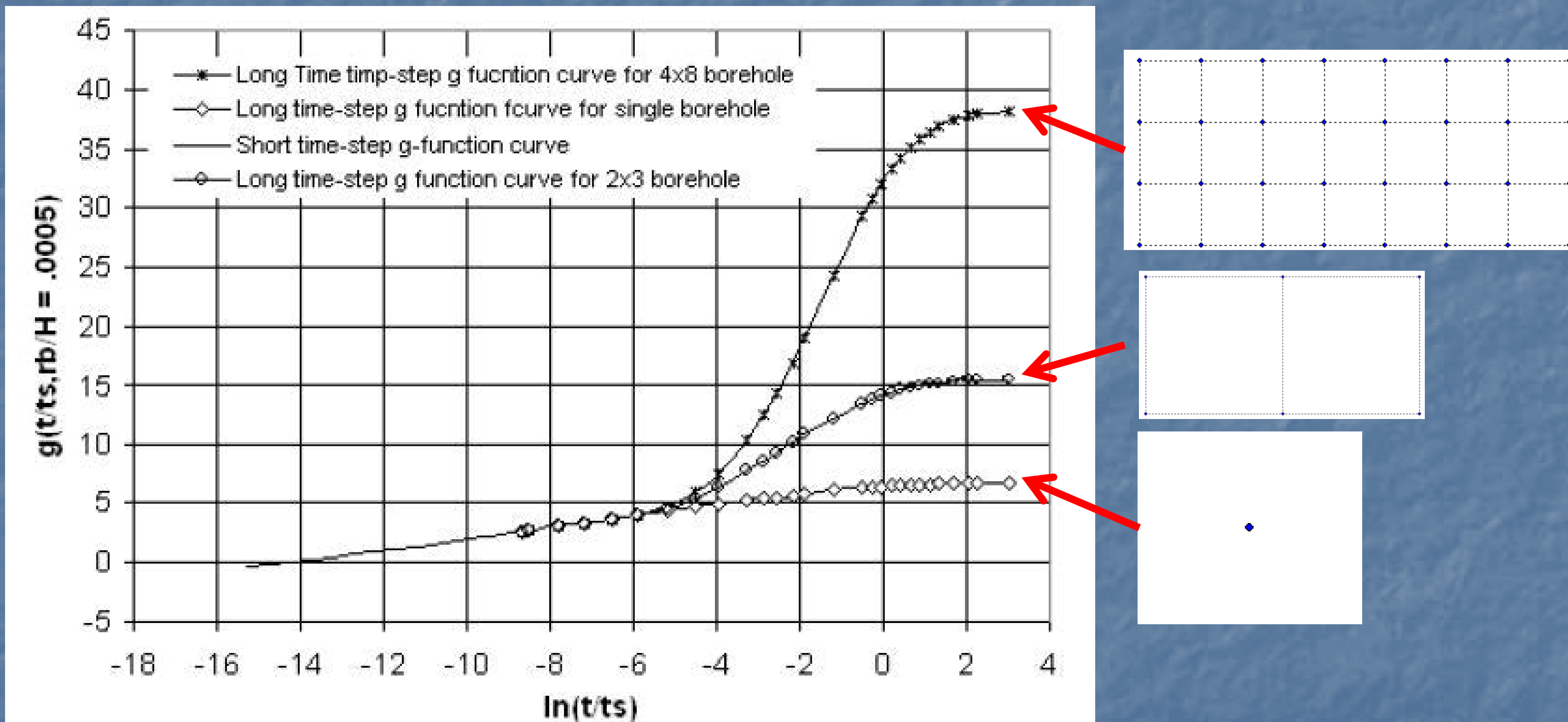
The model provides databases for the input data and also relies on a database of pre-calculated response functions

Results: fluid temperature variation and required borehole length





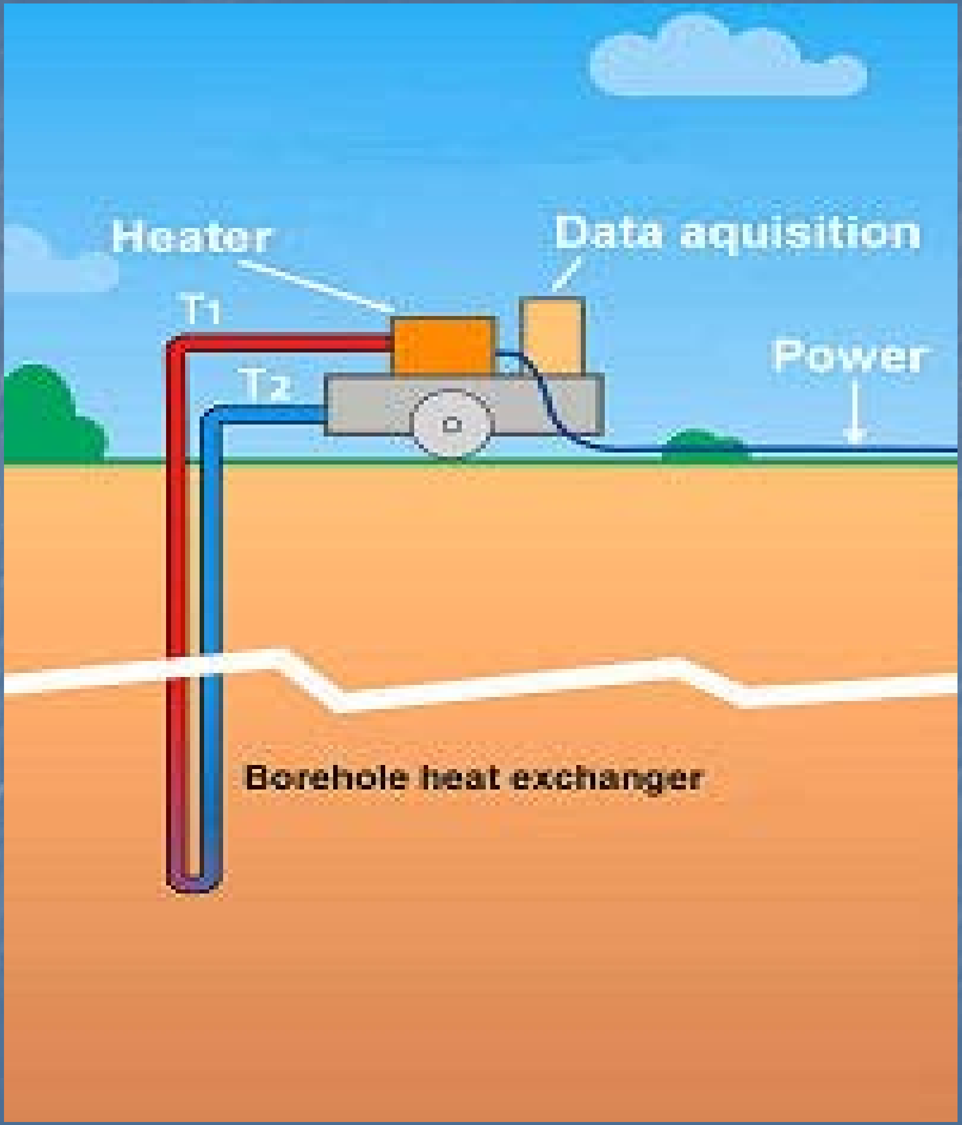
Non-dimensional response functions



Non-dimensional thermal response function – so-called g-functions

THERMAL RESPONSE TEST

Thermal Response Testing (TRT)



Brief history of Thermal Response Testing

- 1975, Gothenburg: GSHP in clay
- 1981, Luleå: 19 borehole pilot trial BTES installation
- 1983, Stockholm: GSHP in rock
- 1984, Luleå: 120 borehole high-temperature BTES installation
- 1986, Stockholm: 25 borehole low-temperature BTES
- 1992, Linköping: 100 U-pipes high-temperature heat storage in clay

- These TRT tests were performed after the installations were already completed to verify ground loop performance
- In order to influence the ground loop sizing it would be desirable to make an in-situ TRT before the detailed design

Mobile thermal response test equipment

First mobile TRT rig (1996)

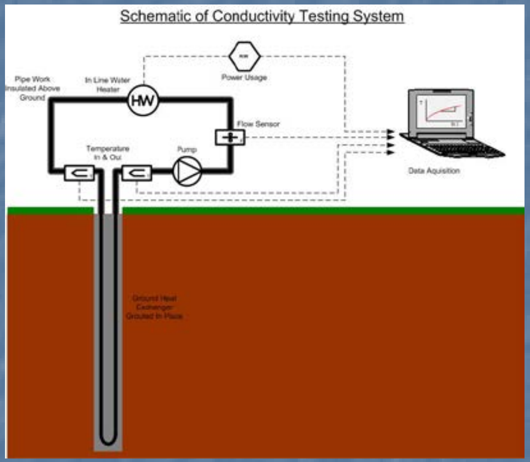
Brief history

- 1996, Sweden: First mobile TRT in operation
- 1998, USA, Independent development

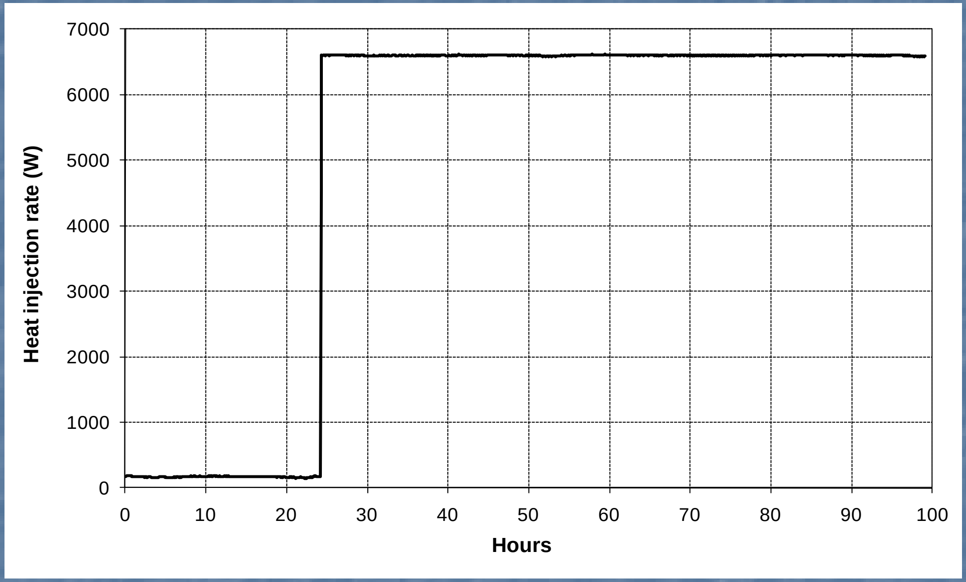
- 1997, Netherlands: Mobile TRT with heat pump
- 2008, Sweden: TRT with optic fibres

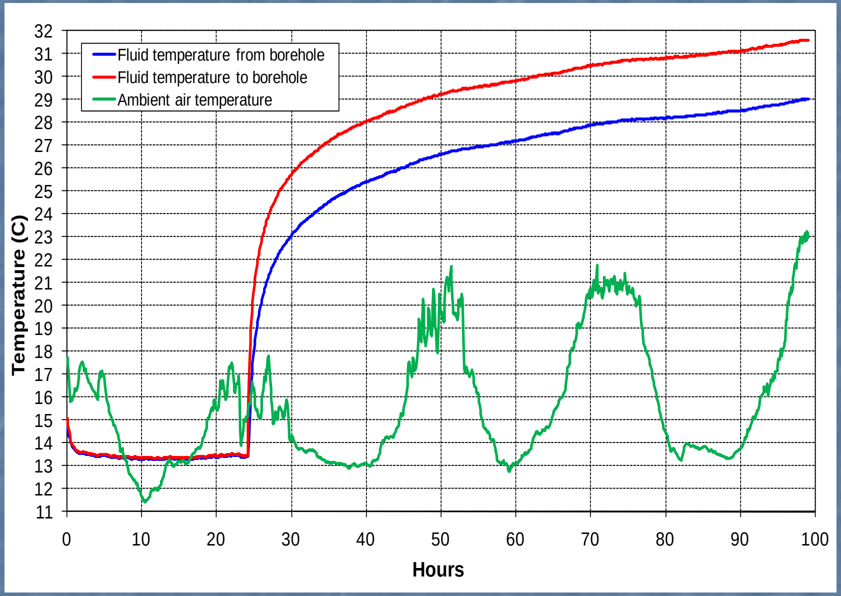
Thermal Response Testing (TRT) - Procedure

- **Test Procedure**
  - Minimum 3Hrs circulation without heating
  - Minimum 50hrs circulation with constant heat input
  - Optional 24hrs recovery with heater switched off
- **Data Logger**
  - Flow rate of carrier fluid (m^3/s)
  - Heat input (kW)
  - Inflow temperature (C) to BHE
  - Return temperature (C) from BHE
  - Ambient air temperature (C)



Thermal Response Testing (TRT)





Measured injection rate, heat carrier fluid temperatures and ambient temperature

Site investigation of heat transfer properties

- Thermal response test (TRT)
  - Estimates the effective thermal conductivity along the borehole
  - Estimates the thermal resistance between heat carrier fluid and borehole wall
- Logging of vertical temperature profile in the borehole
- Geohydrological conditions
  - Groundwater level
  - Permeable layers
- Sampling of cuttings
  - Analysis of mineral composition gives further information on thermal properties of the ground
- Drilling conditions
  - Soil depth, geological stratification, production capability

Thermal response test considerations

- Planning of drilling and TRT test
  - Allow 3-5 days between end of drilling and start of TRT test
  - Allow for initial period with only circulation (no heat input)
  - Test duration at least 50 hours
  - Avoid drilling activities in the vicinity
  - Measure vertical temperature profile before and after test
- Number of boreholes to test
  - For large projects sometimes several test boreholes drilled and number of TRT chosen depending on variability of geology
- Borehole heat exchanger depth and design
  - Should be similar to chosen design
- Heat injection rate and heat carrier flow rate
  - Should be similar to expected load conditions

Evaluation method

- Measured heat input
- Measured average fluid temperature
- Measured ambient air temperature

- Radial heat conduction in rock
- Line-source model
- Two node borehole model
  - Borehole heat capacity included
  - Heat carrier fluid capacity included

- Parameter fitting using Nelder-Mead minimization of quadratic error

- Results: Effective thermal conductivity and borehole thermal resistance

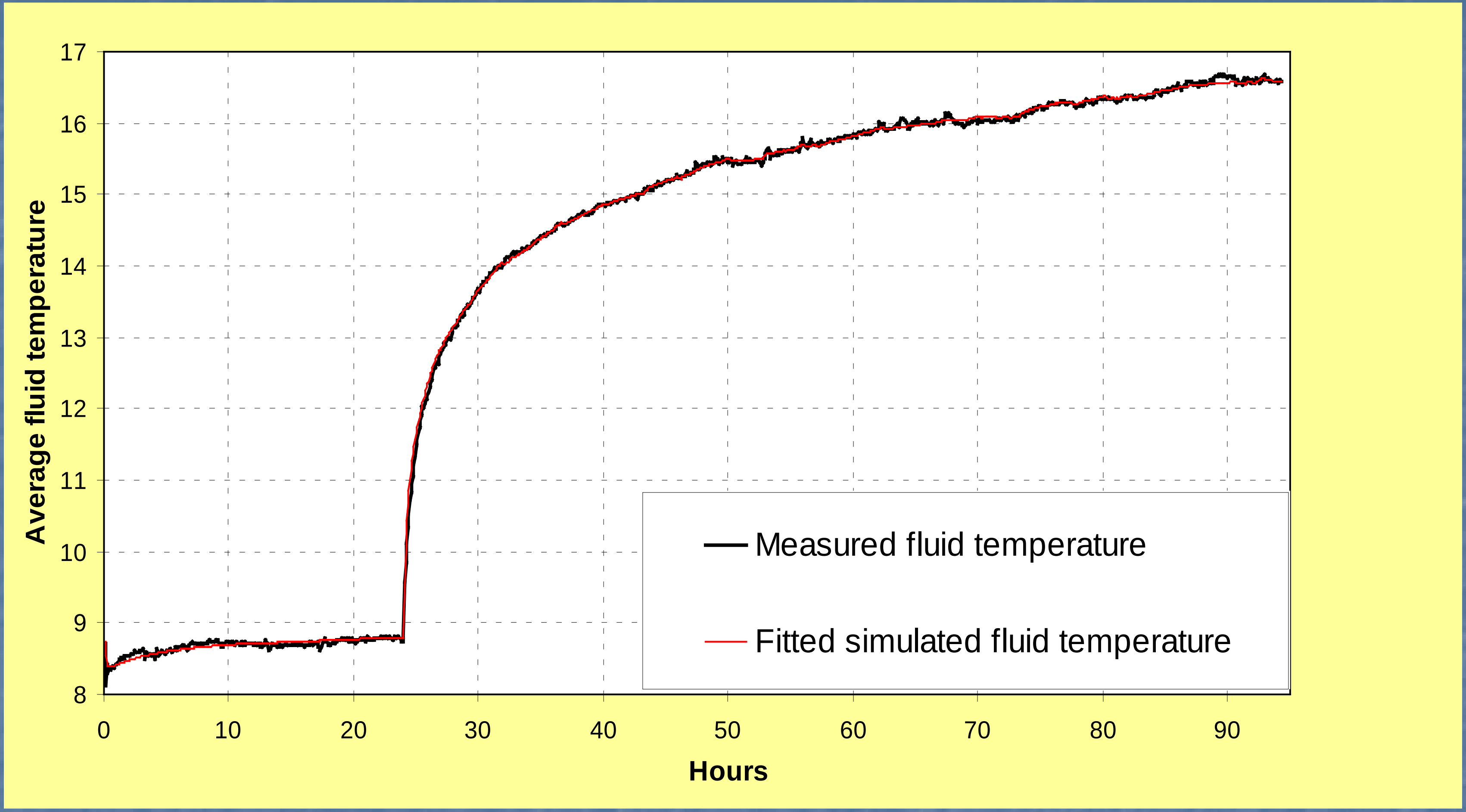
Experiences – equipment

- Electric power from grid
  - Easy to use
  - Sometimes unreliable (power cuts, vandalism, etc)
  - Some diurnal fluctuation
- Electric power from generator
  - Independent of grid (required at undeveloped sites)
  - Stable power
  - Needs refueling
- Heavy rigs difficult to handle outside paved areas
- Thermal insulation of flow path very important
- Full remote control practical

Experiences – evaluation

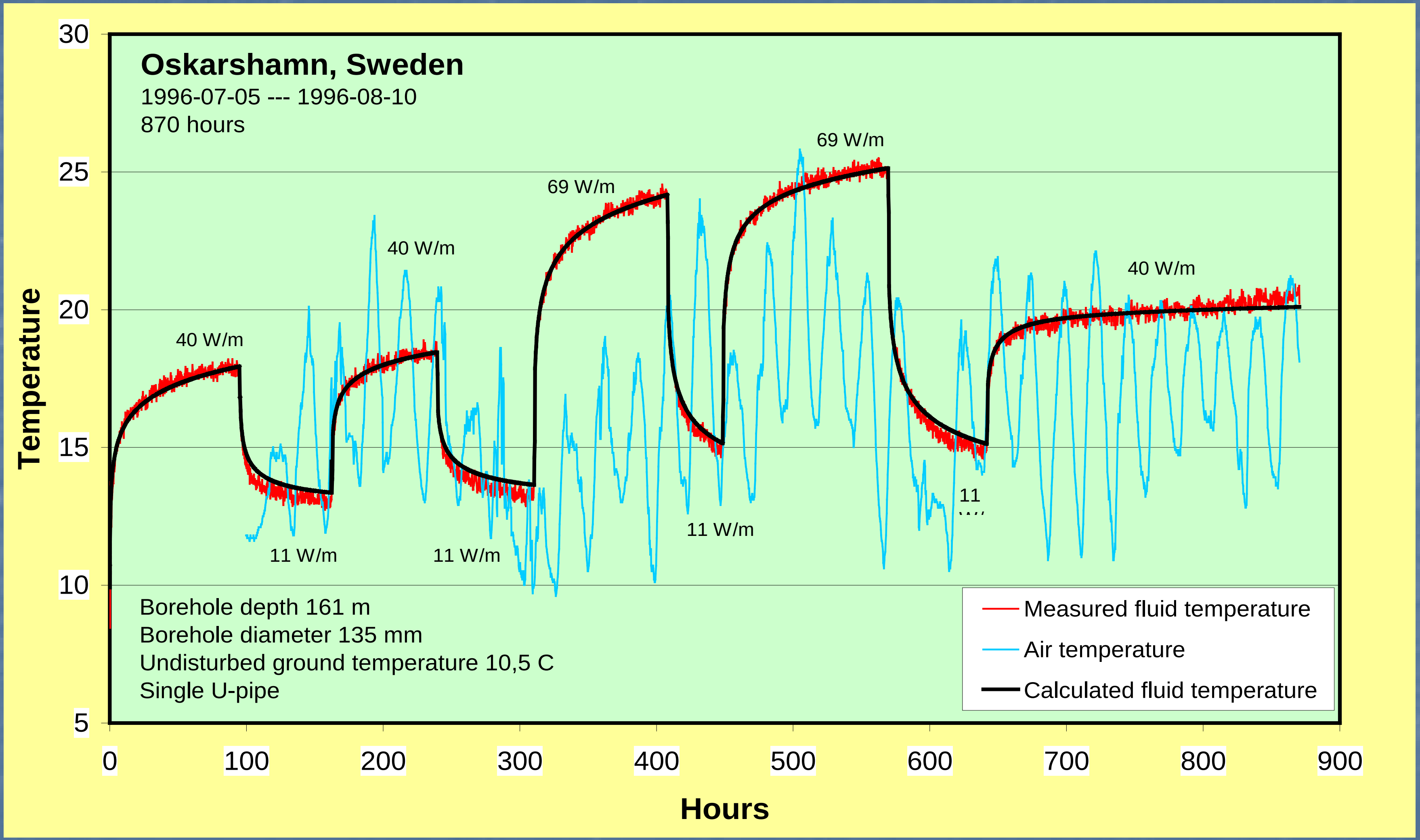
- Evaluation methods used:
  - Line-source method
  - Numerical parameter fitting method with radial heat conduction and heat capacity of fluid and grout
- Important to use the same model and parameters when applying the results to the design case
- Borehole thermal resistance may have to be modified from measured conditions due to changes in flow rate and temperature

Thermal response test evaluation



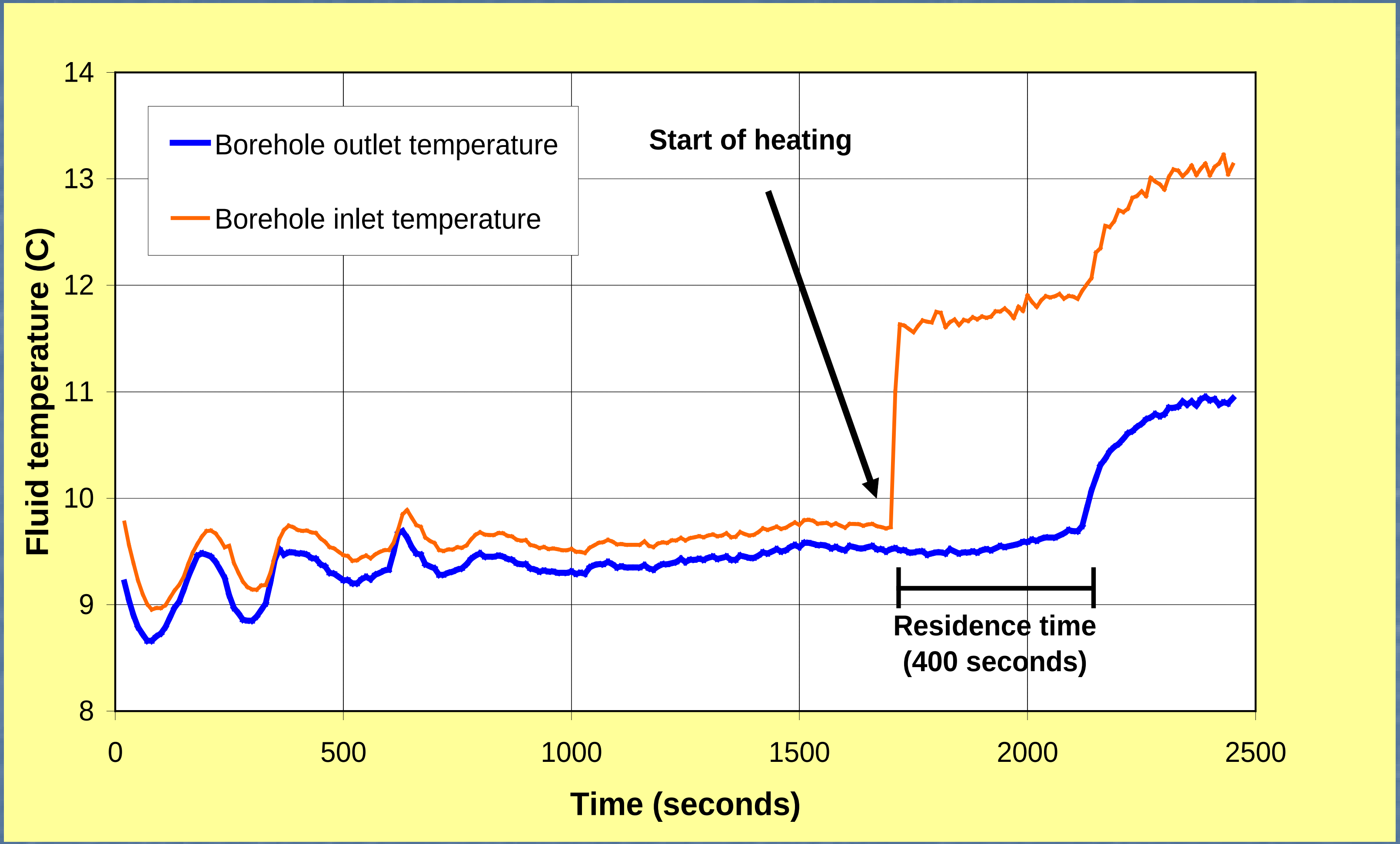
Fitting procedure of measured and calculated fluid temperatures gives effective ground thermal conductivity and borehole thermal resistance

Long-term thermal response test evaluation



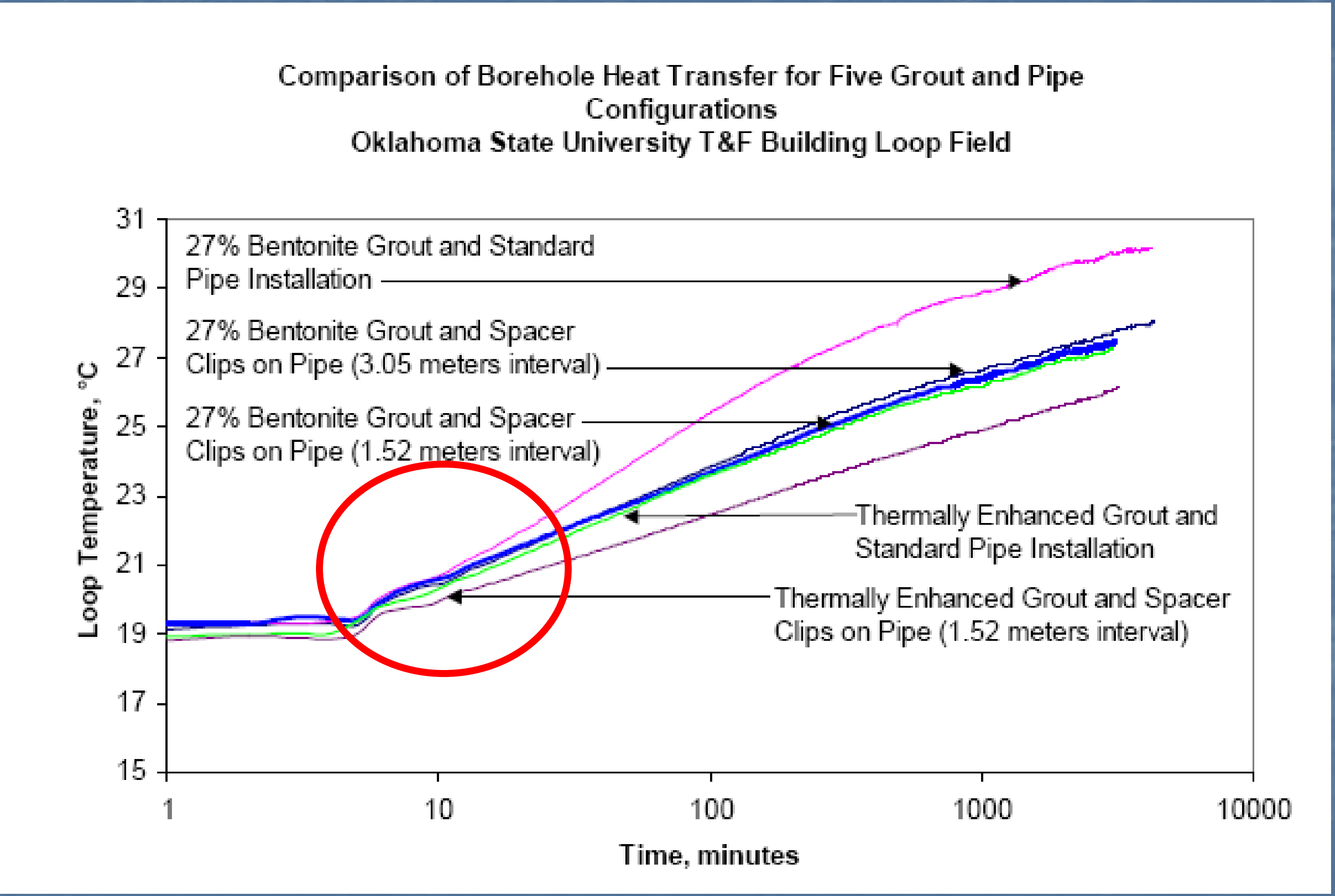
Long-term test (35 days) in Sweden (1996)

Initial thermal response



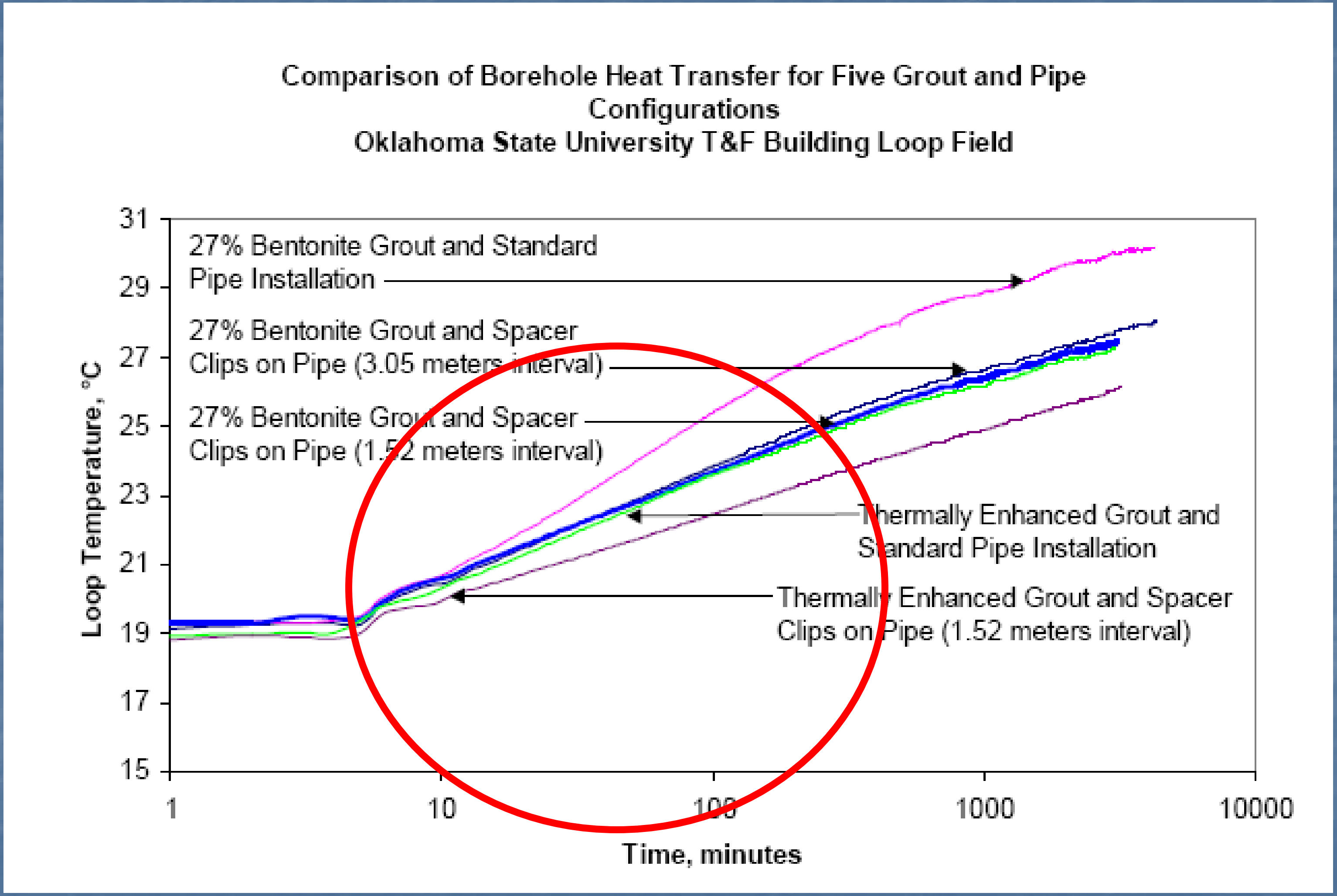
Short-term response (residence time)

Thermal response test



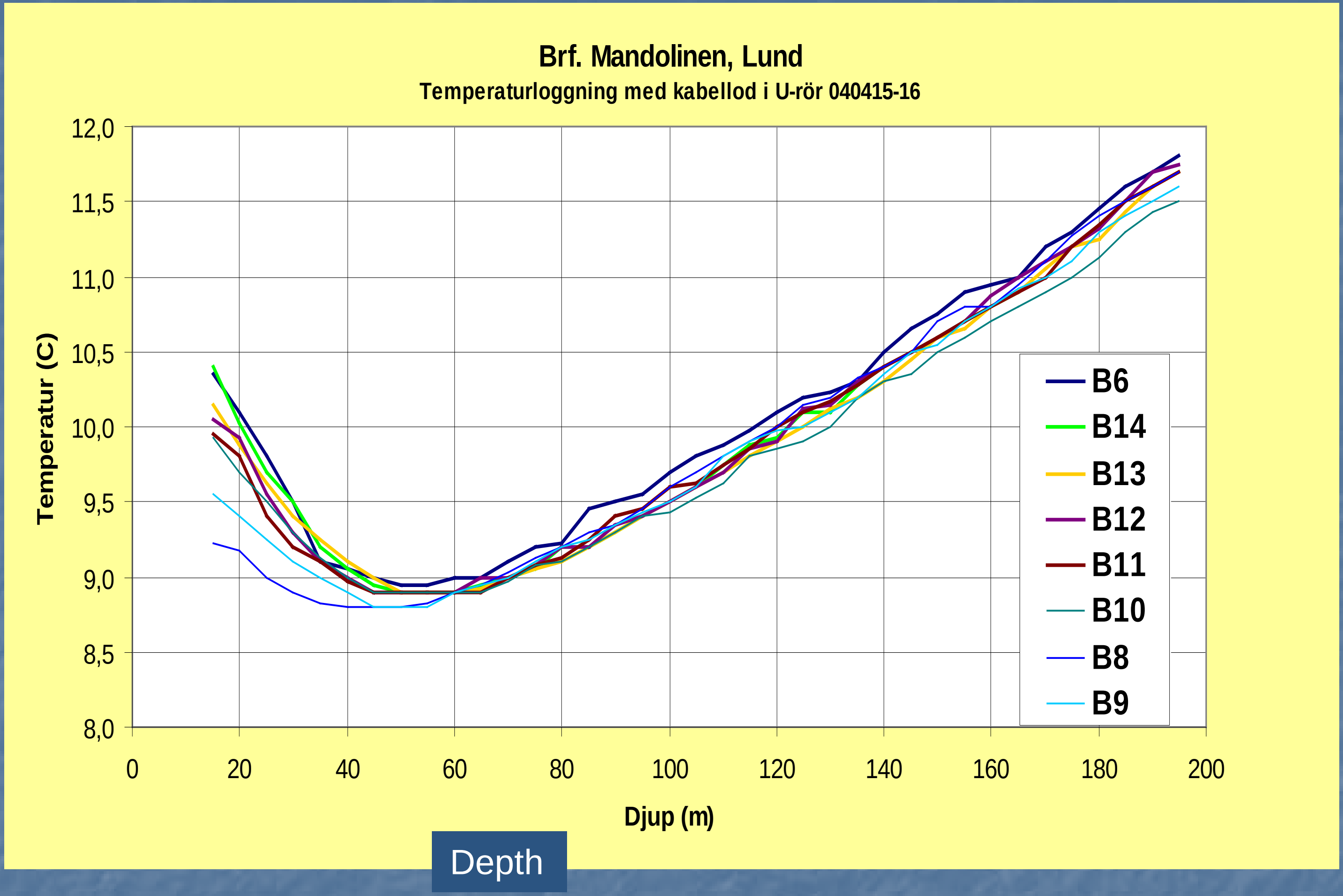
Fluid capacity

Thermal response test



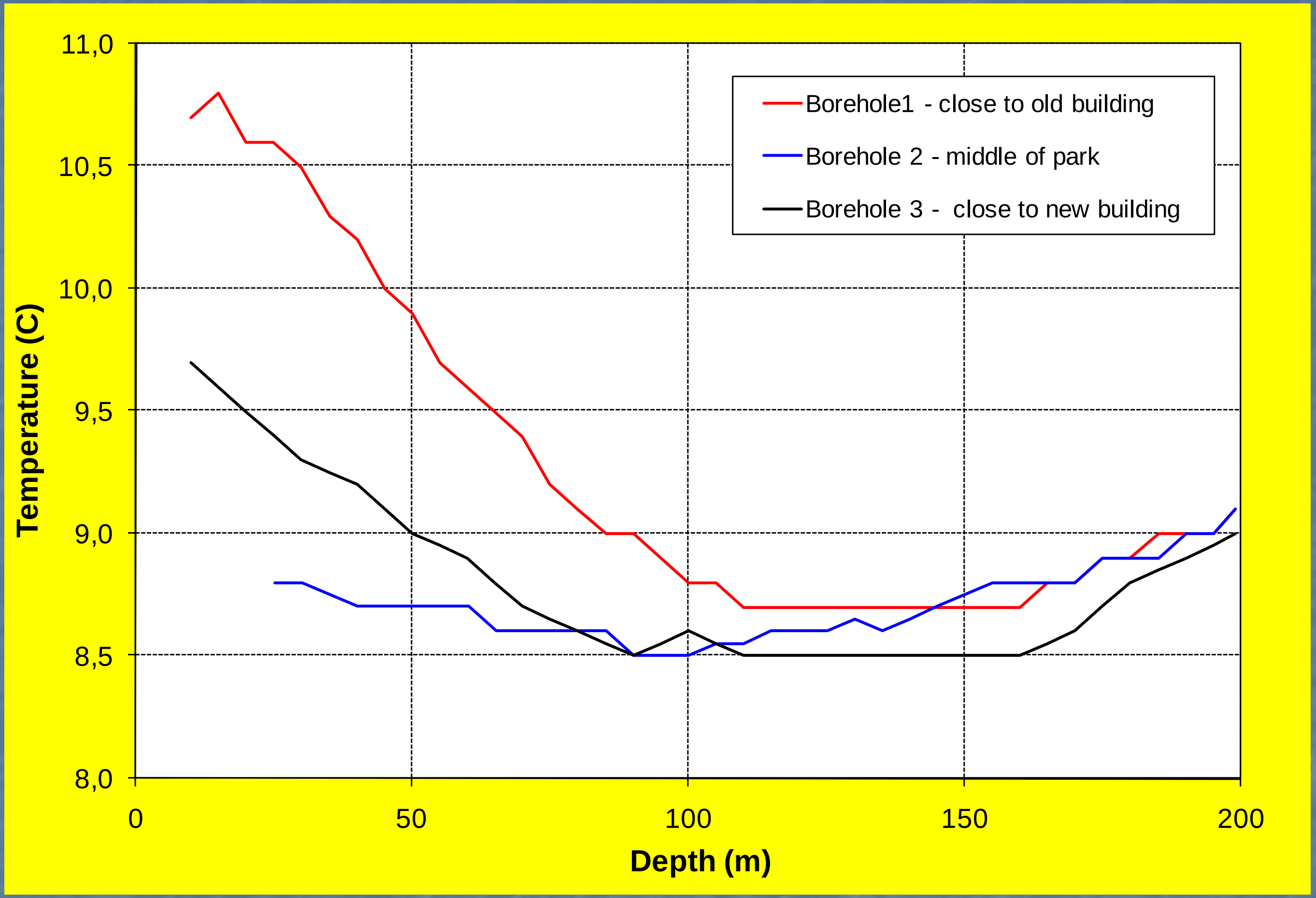
Fluid and grout thermal capacity

Undisturbed ground temperature



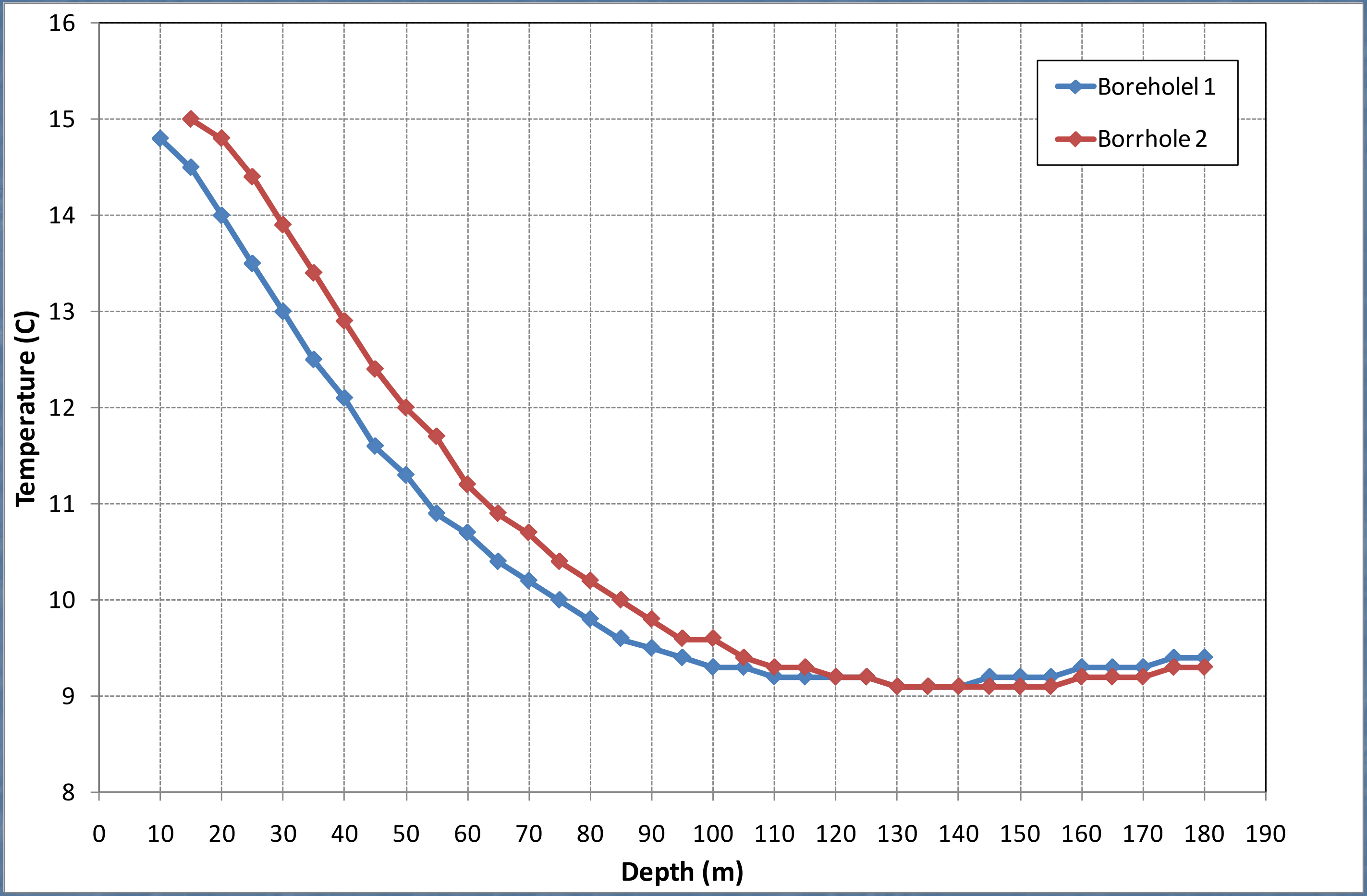
Temperature as function of borehole depth

Undisturbed ground temperature



Temperature as function of borehole depth

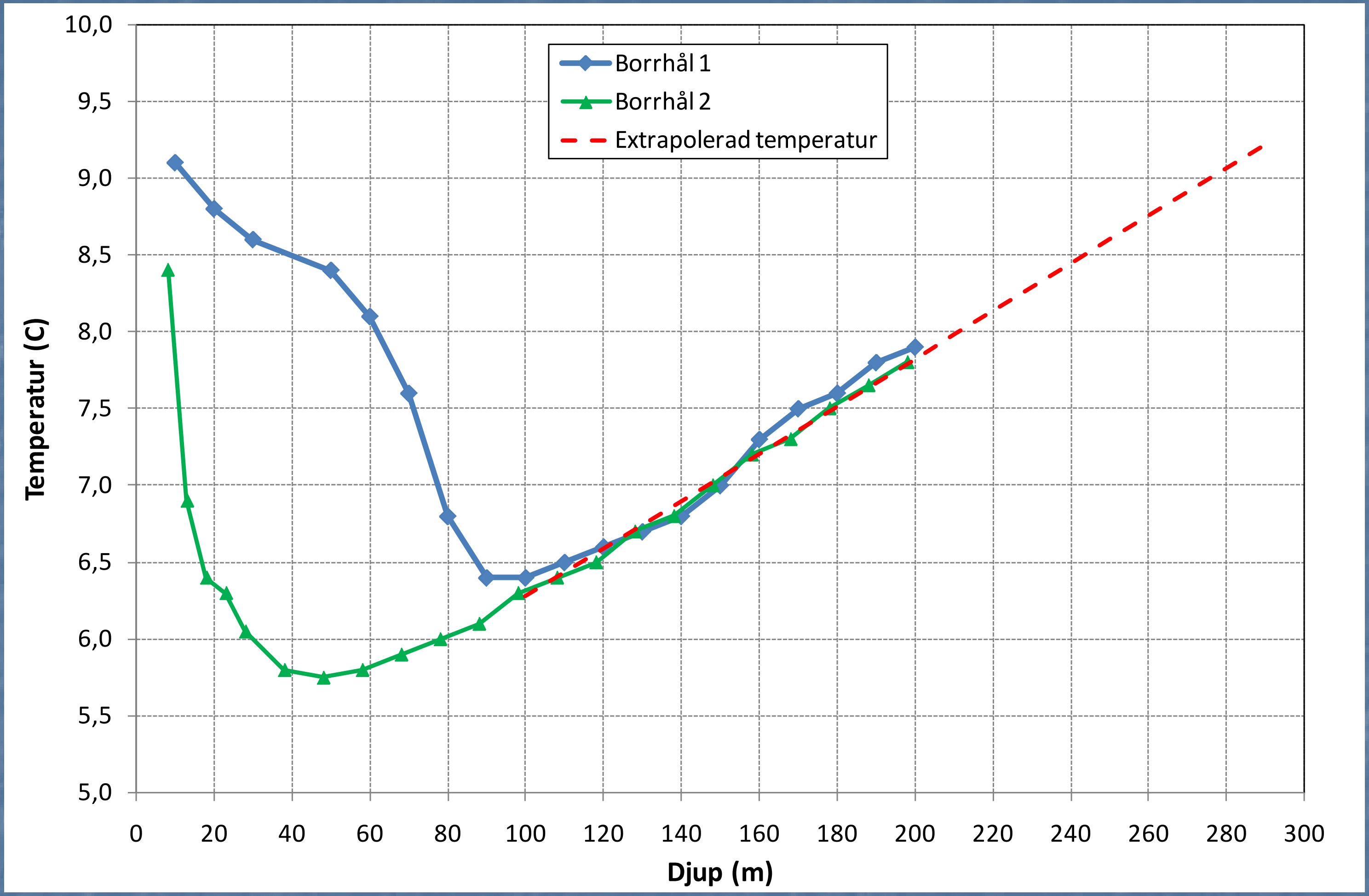
Undisturbed ground temperature



Temperature as function of borehole depth

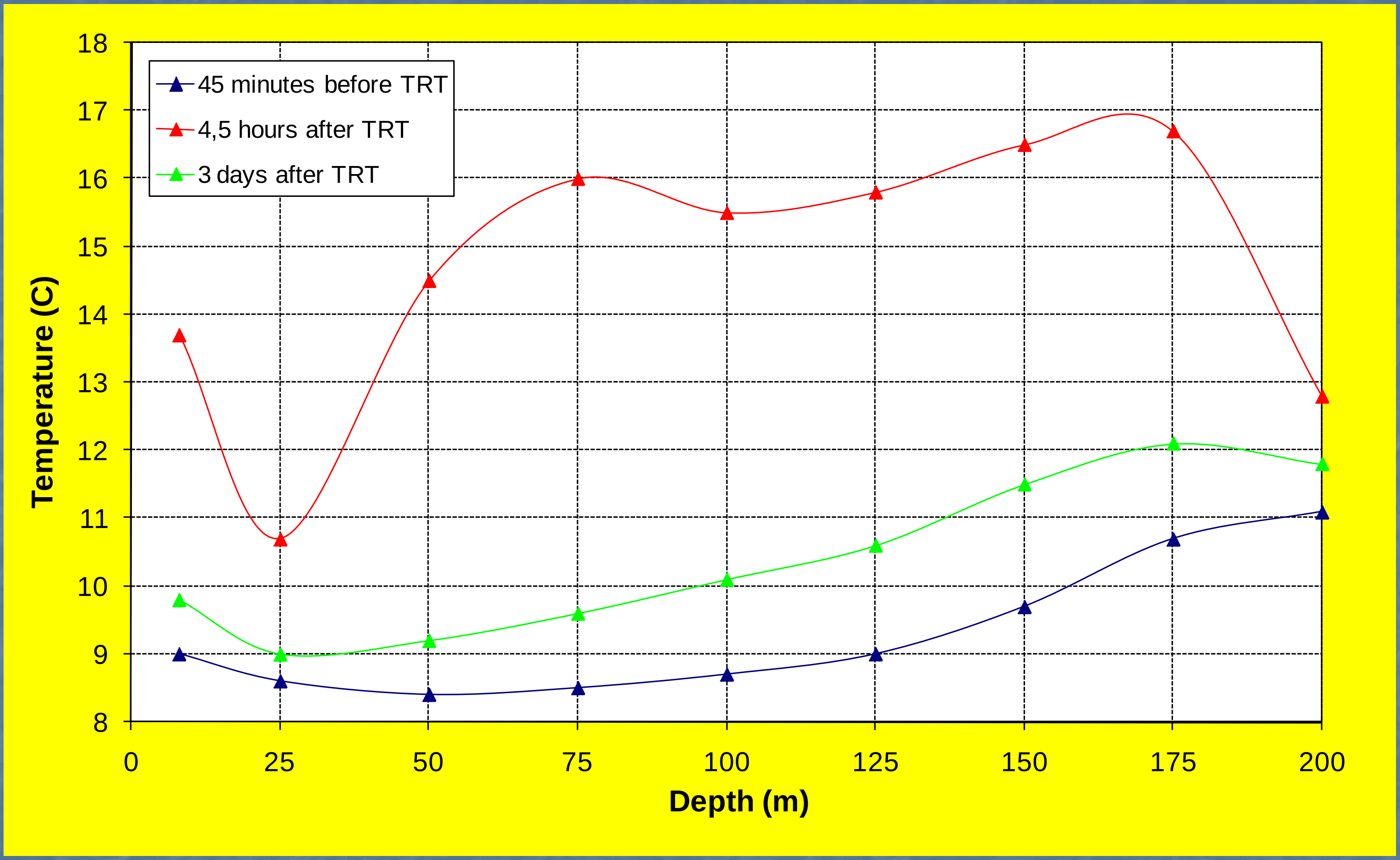
The boreholes are located in the centre of Stockholm

Undisturbed ground temperature



Borehole 1 disturbed by groundwater flow

Temperature profile at different times



Temperature as function of borehole depth

The evolution of the profiles indicate a zone with groundwater flow around 25 m depth

Experiences – effective thermal conductivity

- About 150 measurements performed in Sweden
- About eight of those strongly affected by groundwater flow
  - Values influenced by vertical groundwater flow through borehole
  - At one location the system was changed from borehole heat extraction to groundwater-source heat pump after the TRT result
  - Warning – flow conditions may change with more boreholes in the vicinity
  - Nearby drilling activities disturbs the groundwater flow
- Effective thermal conductivities in the range 2,5-6,8 W/m,K
- Values influenced by vertical groundwater through borehole

Experiences – borehole thermal resistance

- Estimation of borehole thermal resistance requires good estimate of undisturbed ground temperature
- Groundwater-filled boreholes
  - ✓ Borehole thermal resistance depends on heat injection rate and temperature level
- Method to estimate borehole heat exchanger performance
  - ✓ Site-specific conditions may influence values (base reference values on measurements on several boreholes)

Experiences – undisturbed ground temperature

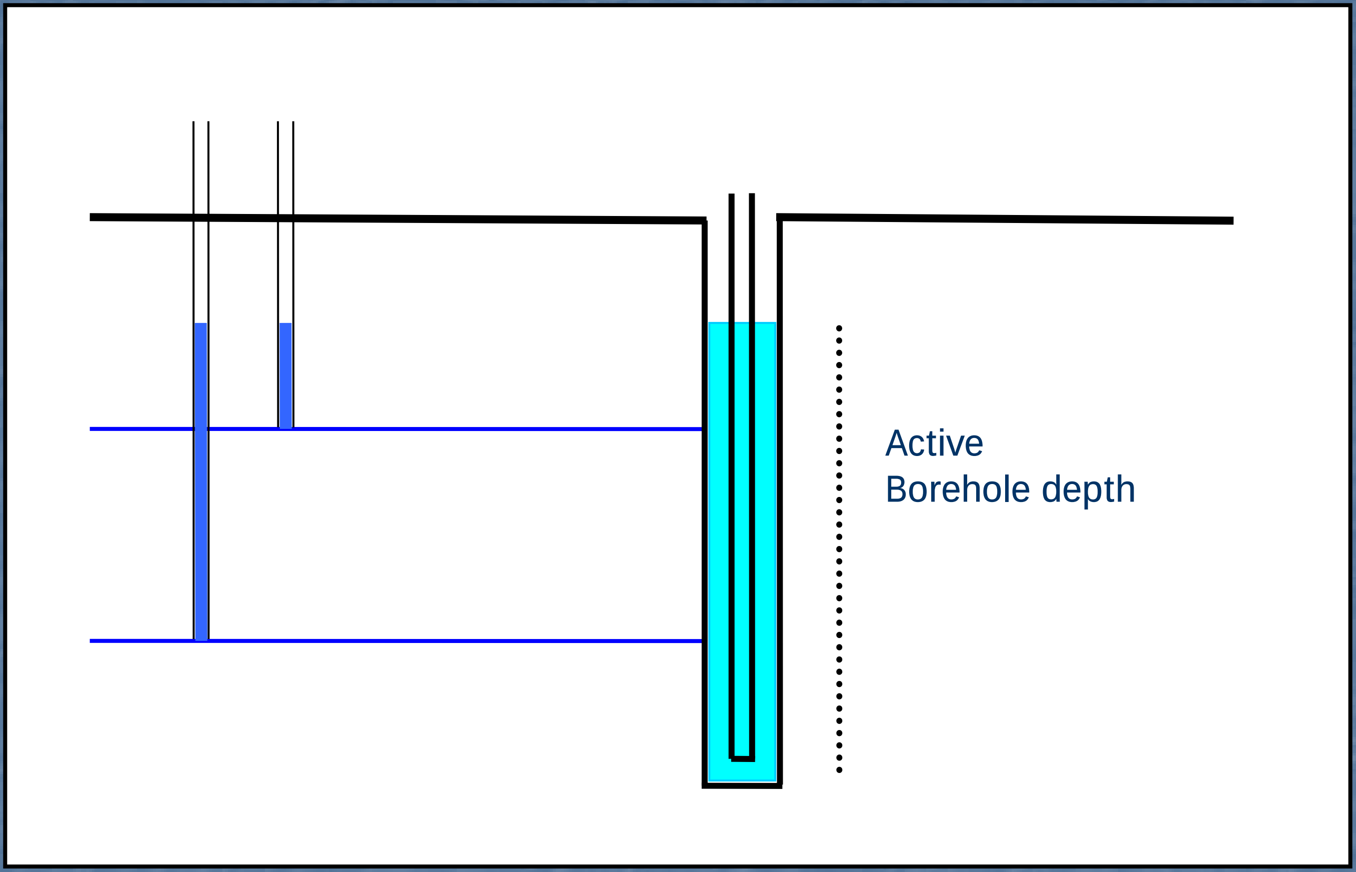
- Measure undisturbed vertical temperature profile
- Estimate undisturbed ground temperature based on initial period with only circulation of heat carrier fluid
- "Undisturbed" ground temperature profile may be disturbed by heat flow from buildings, paved areas and tunnels (and changes in local climate)
  - Interpreting vertical variations in thermal conductivity by using the profile may be difficult
- Measuring vertical temperature profile before and after the TRT may indicate zones of groundwater flow and/or layers with differing thermal conductivity

THERMAL RESPONSE TEST
Groundwater-filled boreholes

Groundwater-filled boreholes

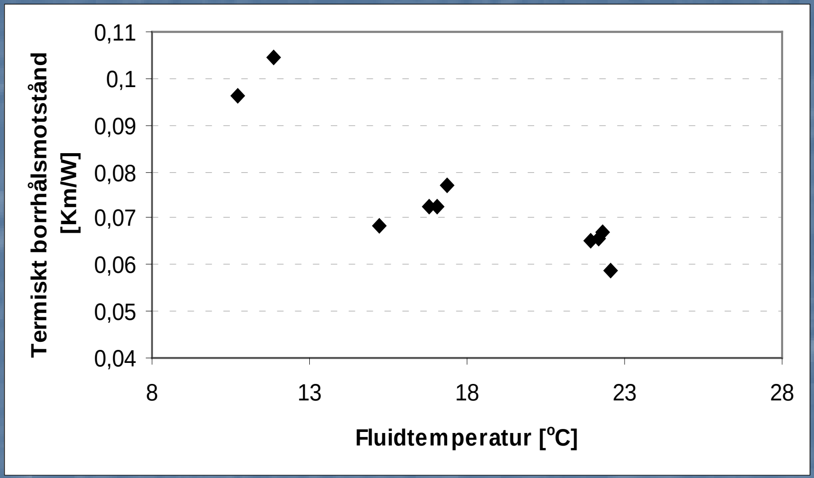
- Better heat transfer than grouted or sand-filled boreholes
- Water movement
  - Natural convection between pipes and borehole wall
  - Vertical flow in borehole
- Freezing of borehole water

Active borehole depth

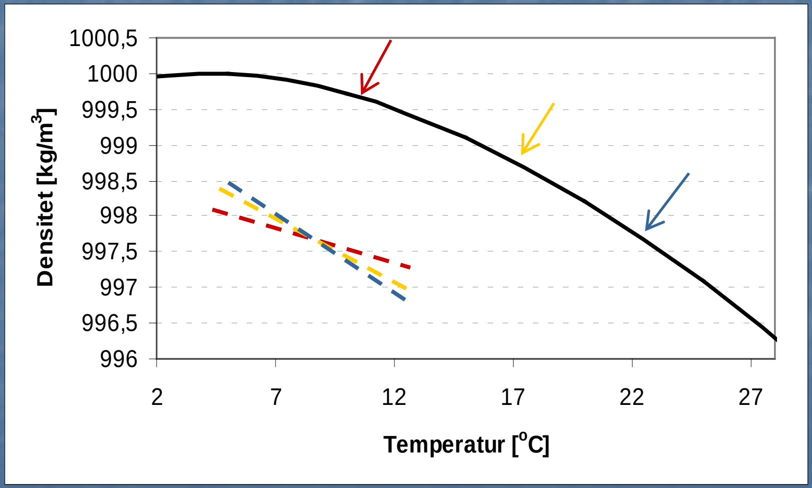


Groundwater-filled part of the borehole

TRT with varying heat injection rates



Case	Power [kW]	Dur [h]	λ_e [W/m,K]	R_b [Km/W]
M1	6	70	3.4	**0.065**
M2	Circulation pump 3 6 Circulation pump	26 98 99 71	 3.2 3.2 3.2	 **0.069** **0.059** **0.104**
M3	Circulation pump 6 3	23 72 96	 3.5 3.5	 **0.067** **0.077**
M4	Circulation pump 6 Circulation pump 3 Circulation pump 3	27 116 53 120 23 307	 3.3 3.3 3.3 3.3	 **0.065** **0.096** **0.073** **0.073**



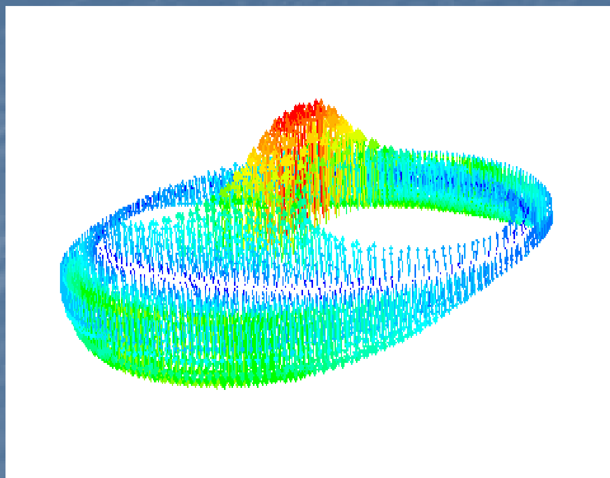
TRT measurements at Luleå

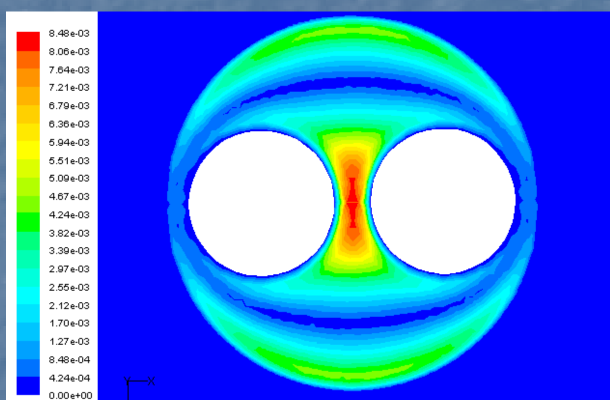
High injection rates and high temperatures give lower borehole thermal resistance due to natural convection within the borehole

Ground-water filled boreholes

LULEÅ TEKNISKA UNIVERSITET

Simulations of natural convection in borehole





Single U-pipe in groundwater-filled borehole

The water close to the pipes will rise during heat injection

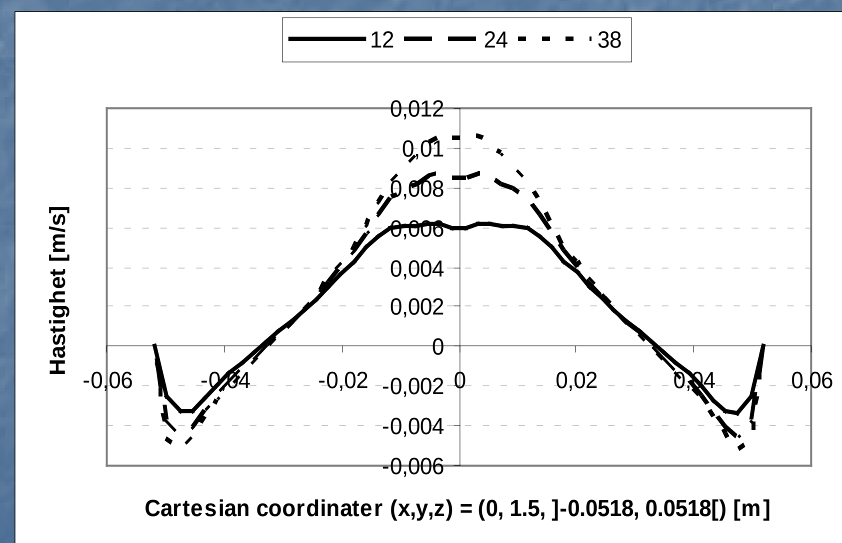
Water velocity depends on temperature (viscosity).

Heat injection rate 75 W/m

12 C results in maximum velocity of 0,006 m/s

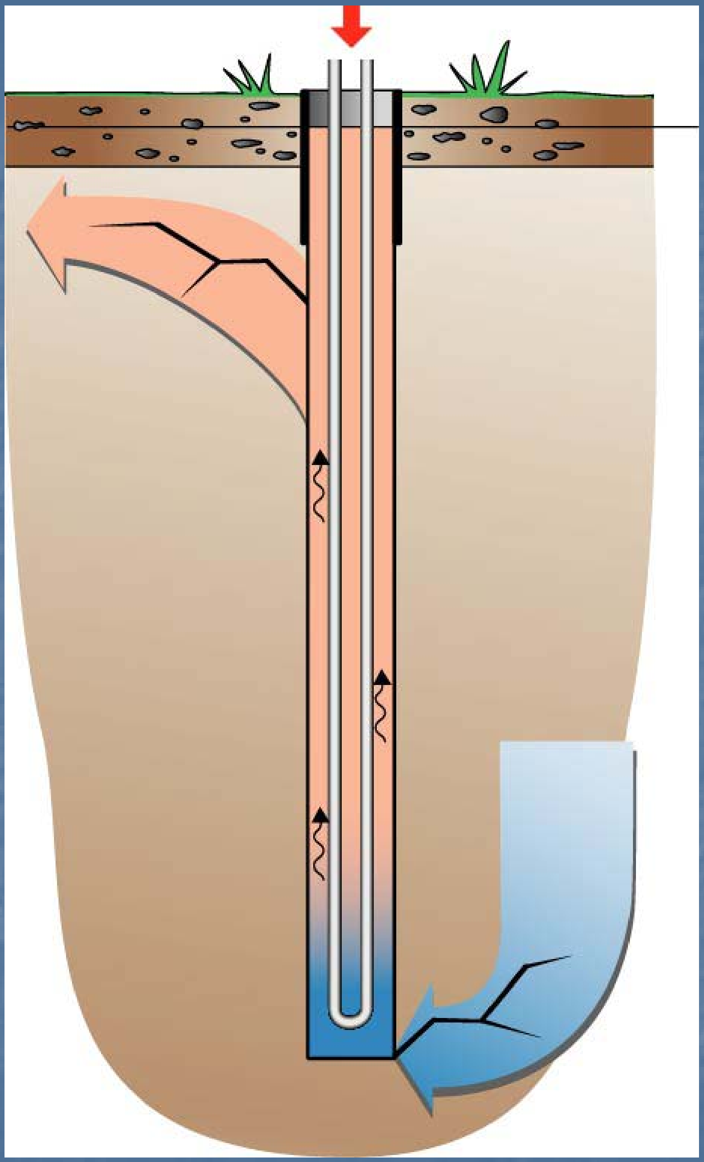
24 C results in maximum velocity of 0,009 m/s

38 C results in maximum velocity of 0,011 m/s

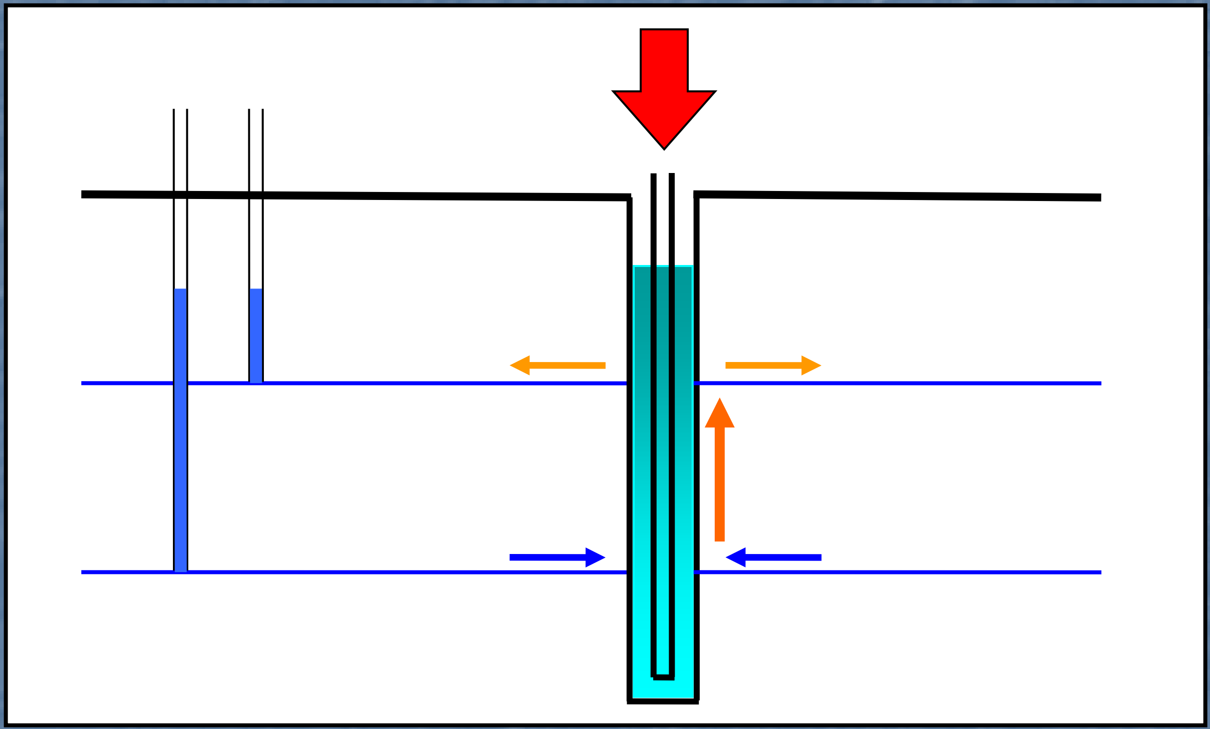


Thermosiphon effect

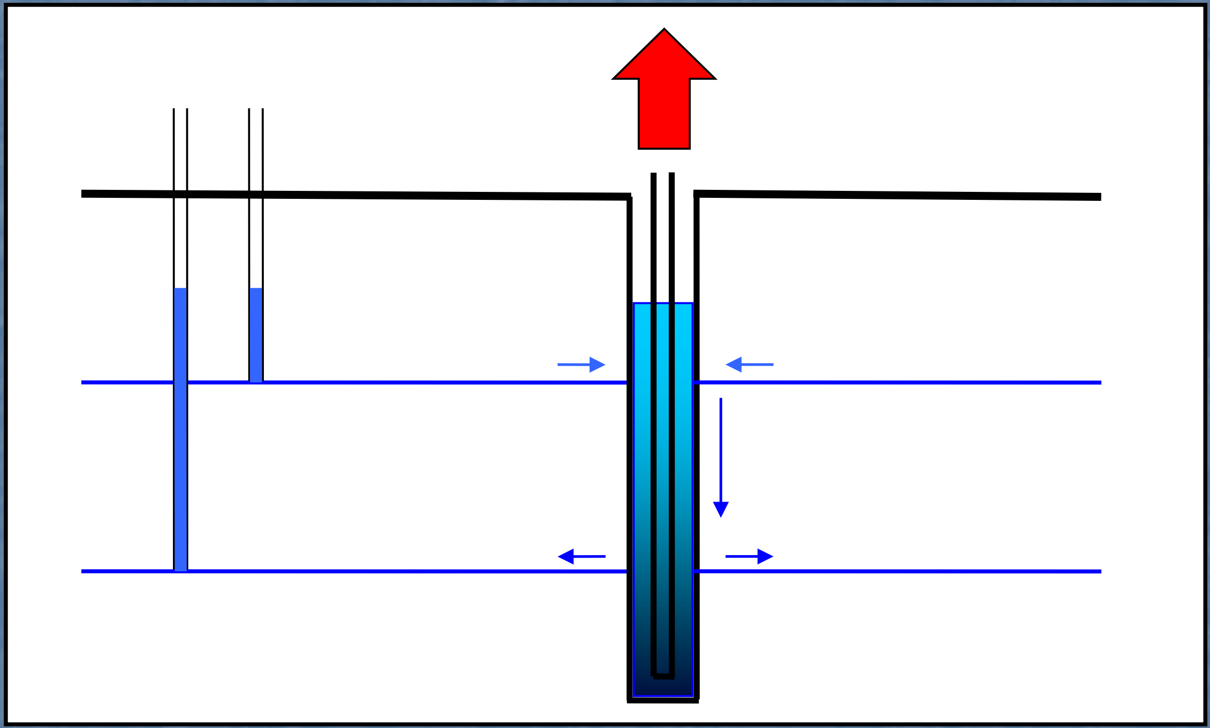
Vertical groundwater flow through borehole due to natural convection



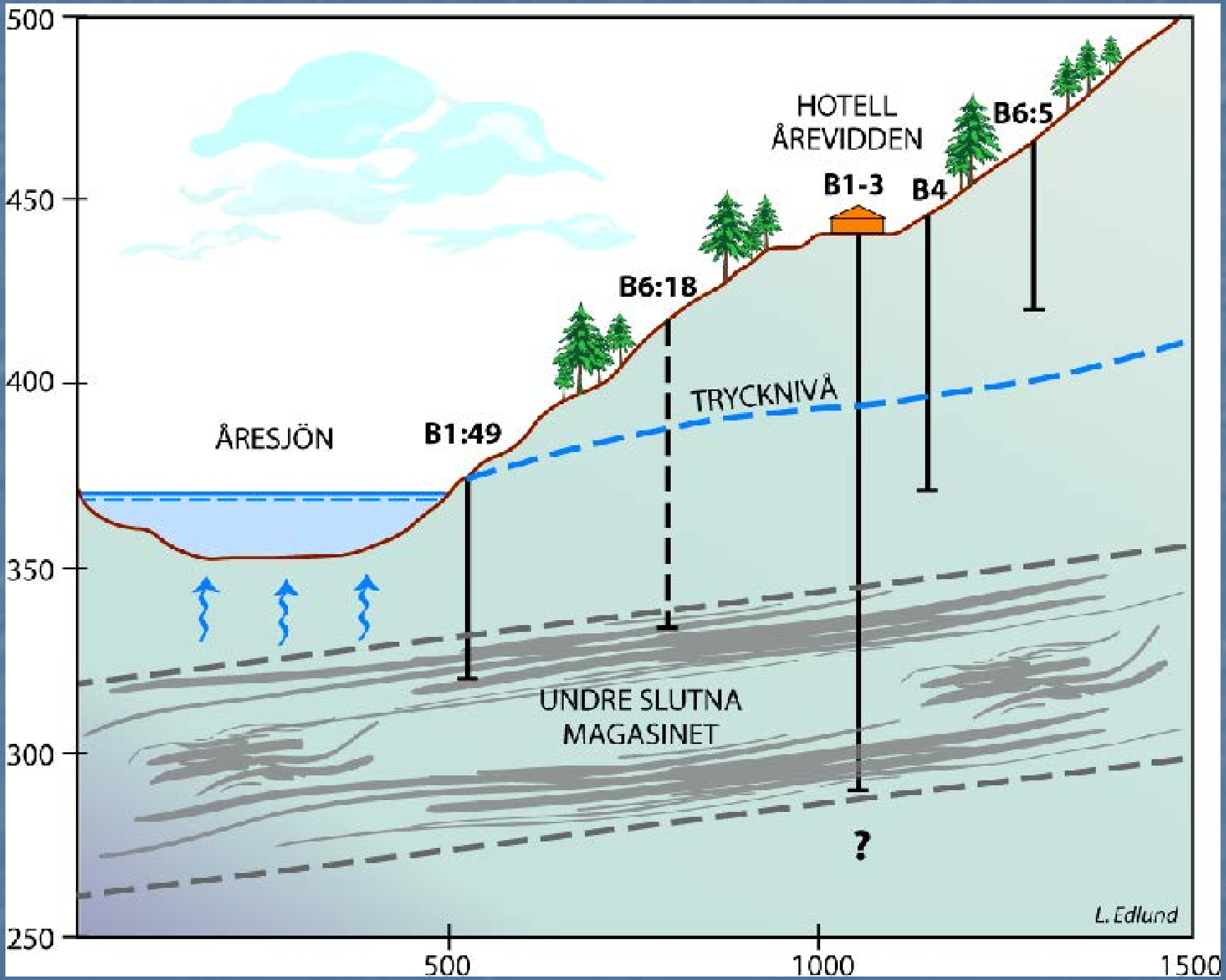
Thermosiphon – heat injection



Thermosiphon – heat extraction

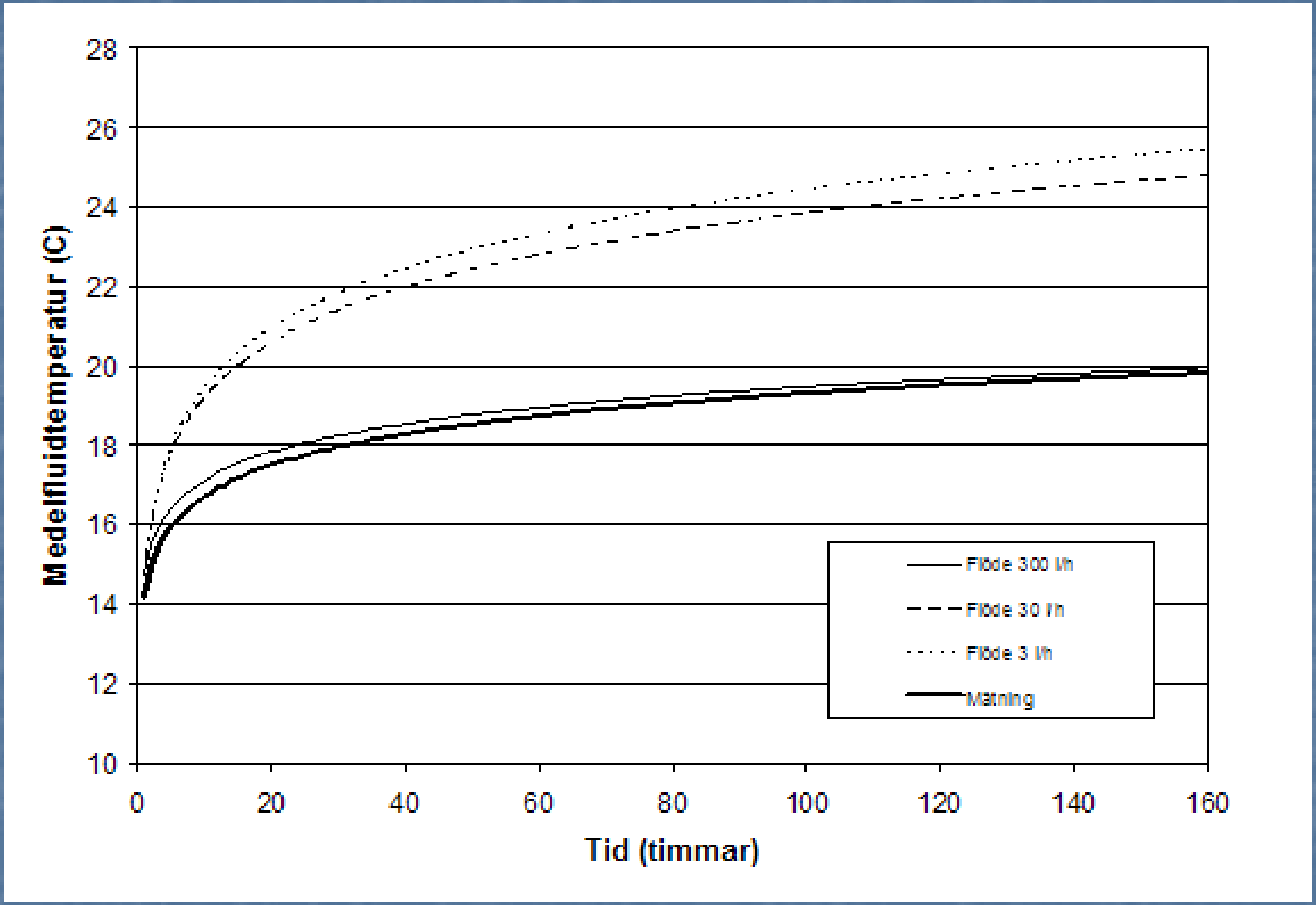


Ground water levels



Groundwater flow between permeable layers with different hydrostatic pressure

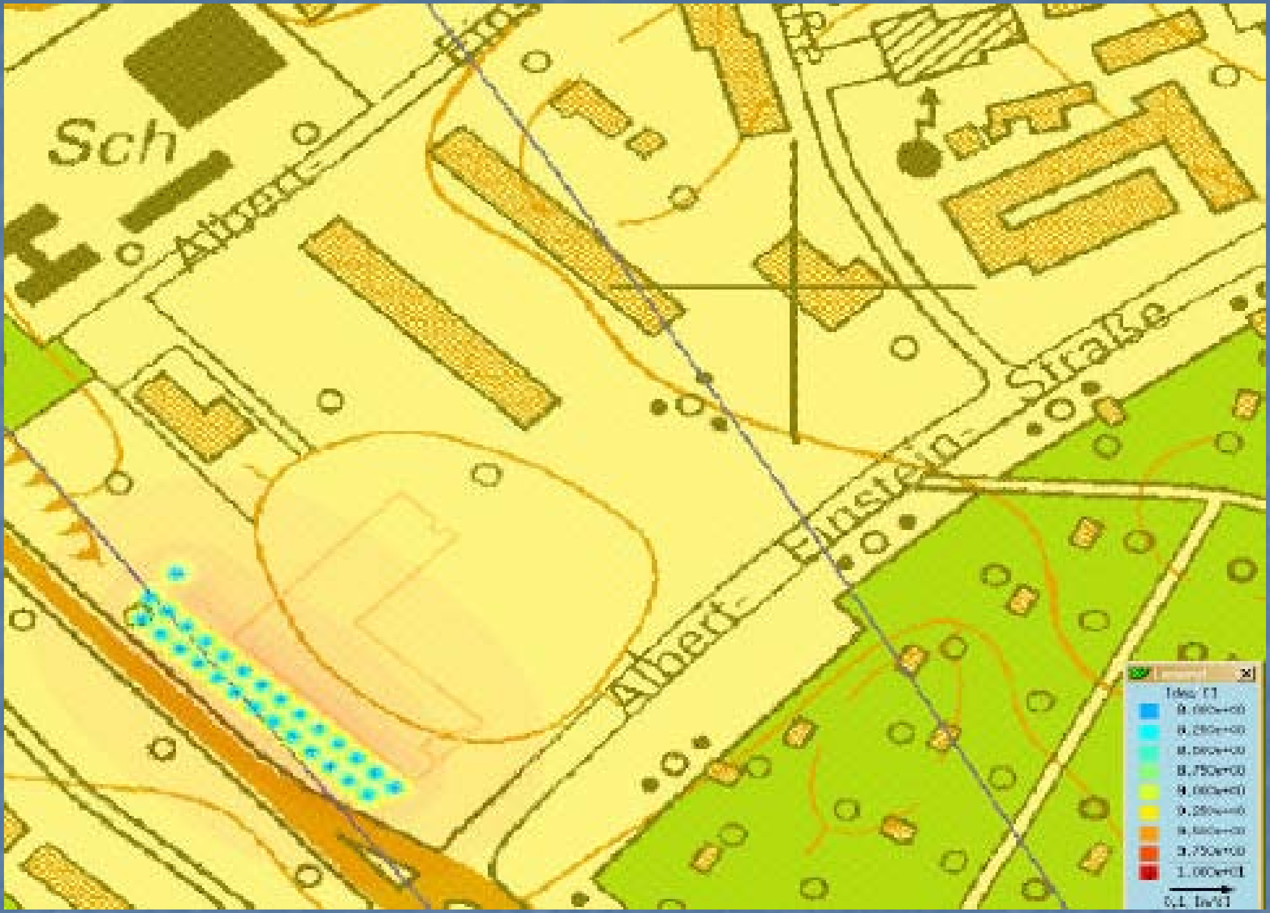
Thermal response test and artesian flow



Thermal response influenced by groundwater flow

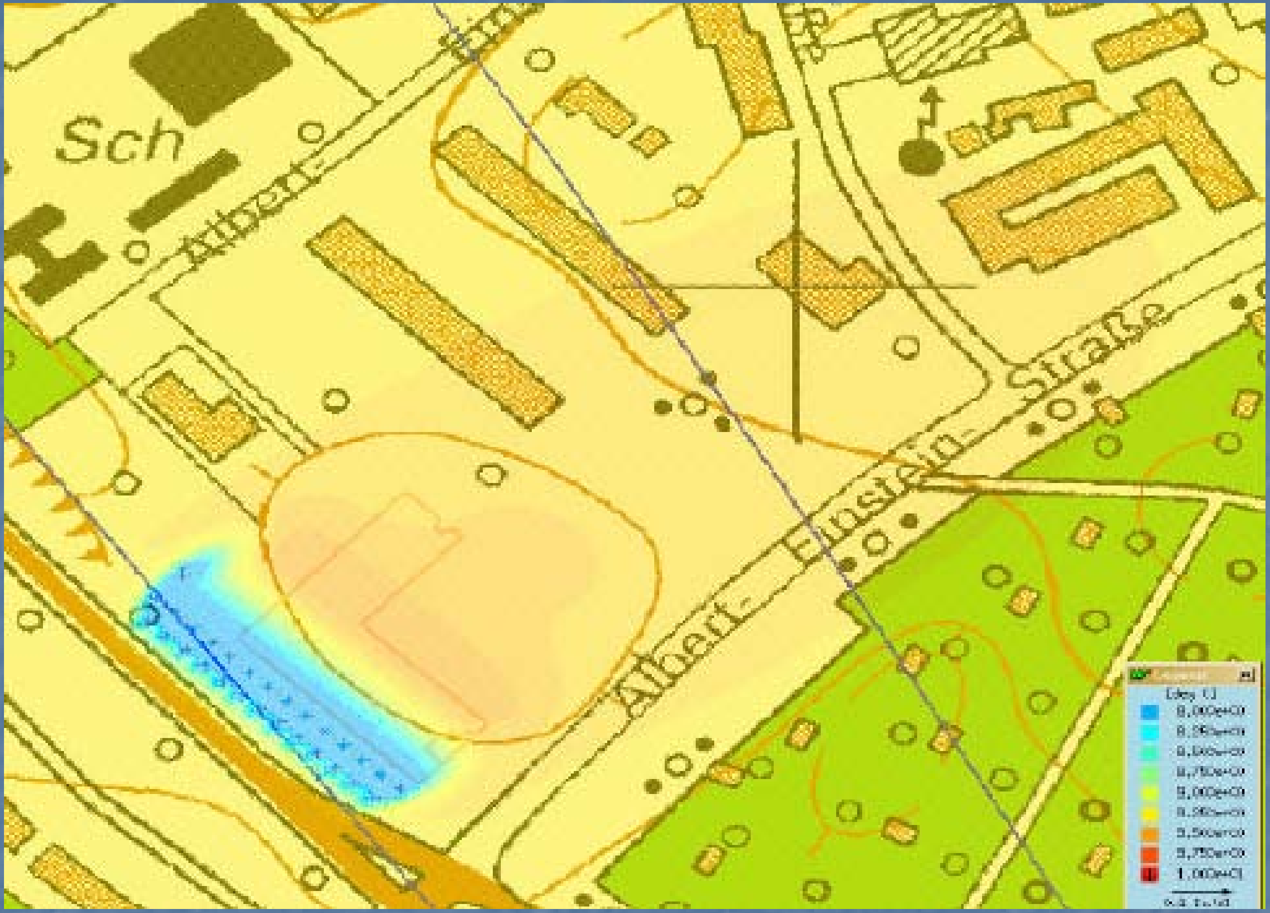
THERMAL RESPONSE TEST
Groundwater flow

Regional groundwater flow



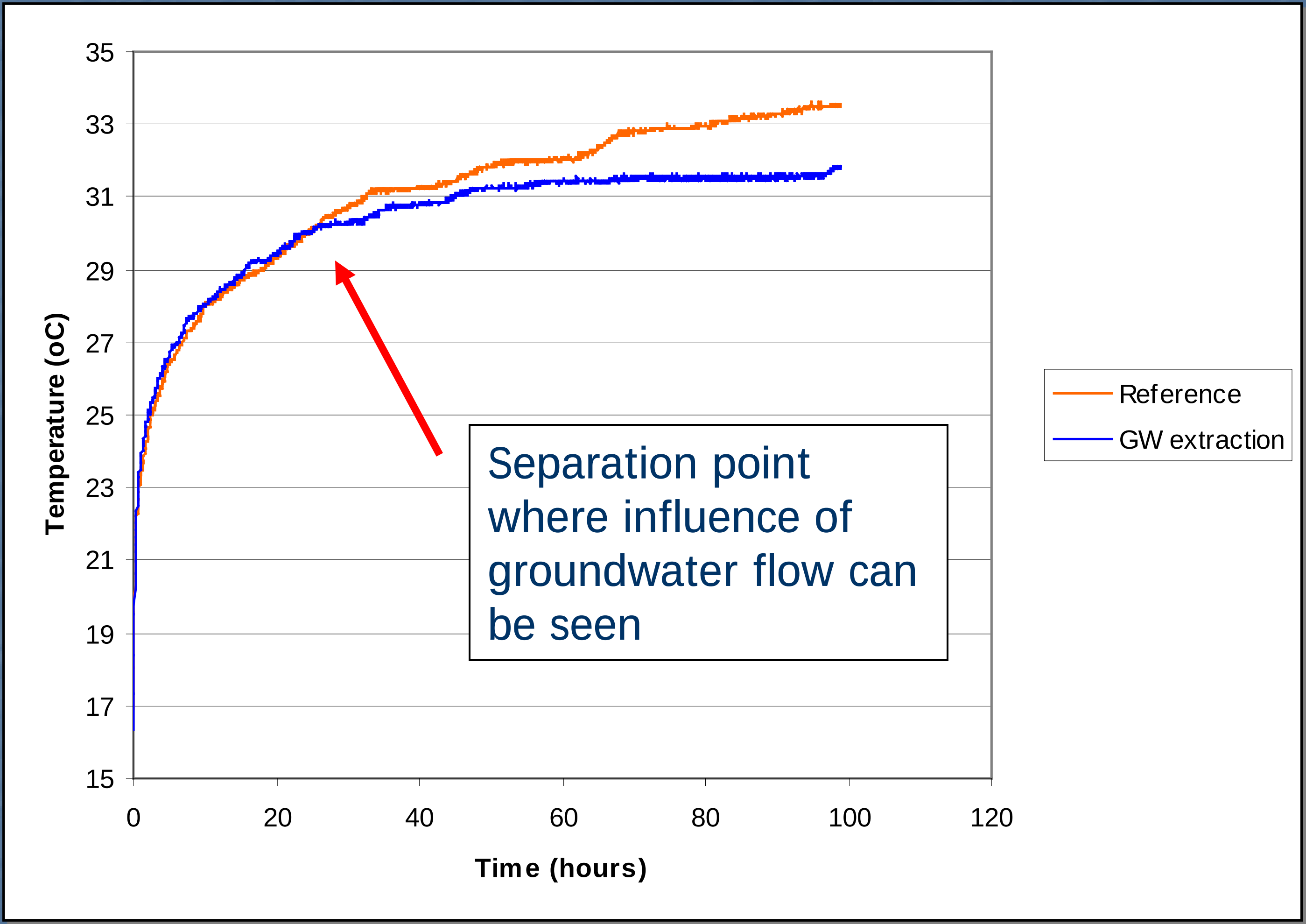
Simulation of thermal process in low permeable layer
(Dähne and Kaiser, 2004)

Regional groundwater flow



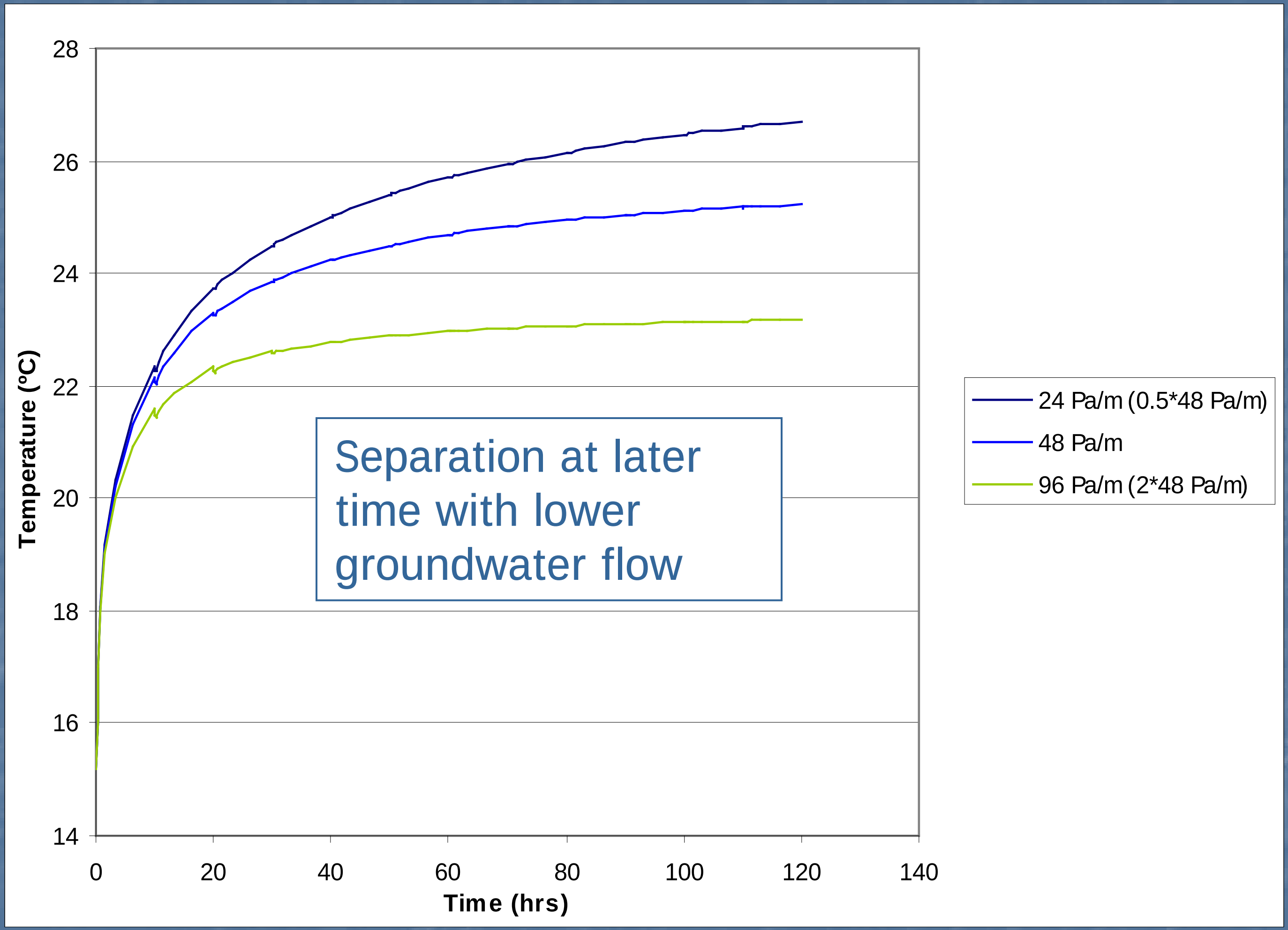
Simulation of thermal process in high permeable layer
(Dähne and Kaiser, 2004)

Thermal response test and groundwater flow



Influence of groundwater flow (Witte, 2001)

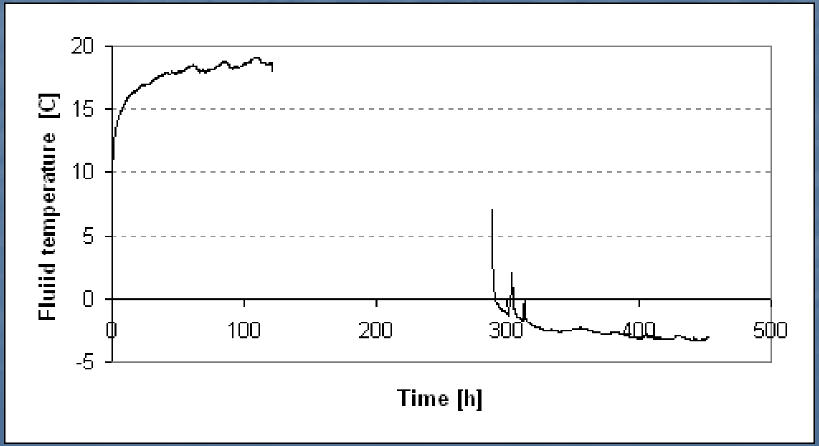
Thermal response test and groundwater flow



Influence of groundwater flow - simulation (Witte, 2001)

THERMAL RESPONSE TEST Freezing boreholes

New TRT equipment



In 2004 a new TRT equipment was built at Luleå Technical University. It contains both an electric heater and a heat pump

Övertorneå

162 m groundwater-filled borehole, single U-pipe

5 days heat injection 12 kW
7 days rest,
6 days heat extraction 7,3 kW

Results

λ_e = 4,2 W/m,K

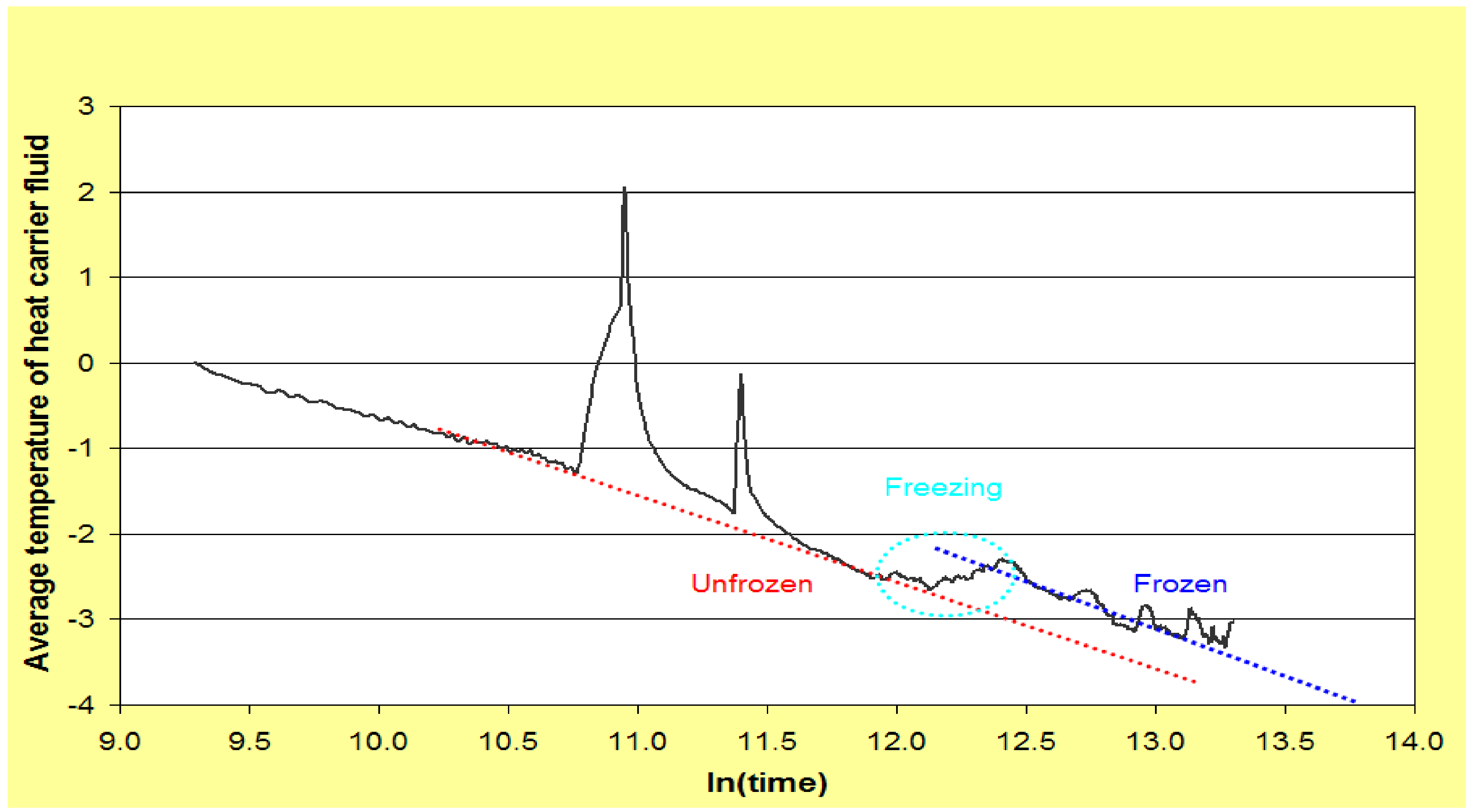
R_{b1} = 0,066 Km/W (heat injection)

R_{b2} = 0,094 Km/W (heat extraction, unfrozen)

R_{b3} = 0,075 Km/W (heat extraction, frozen)

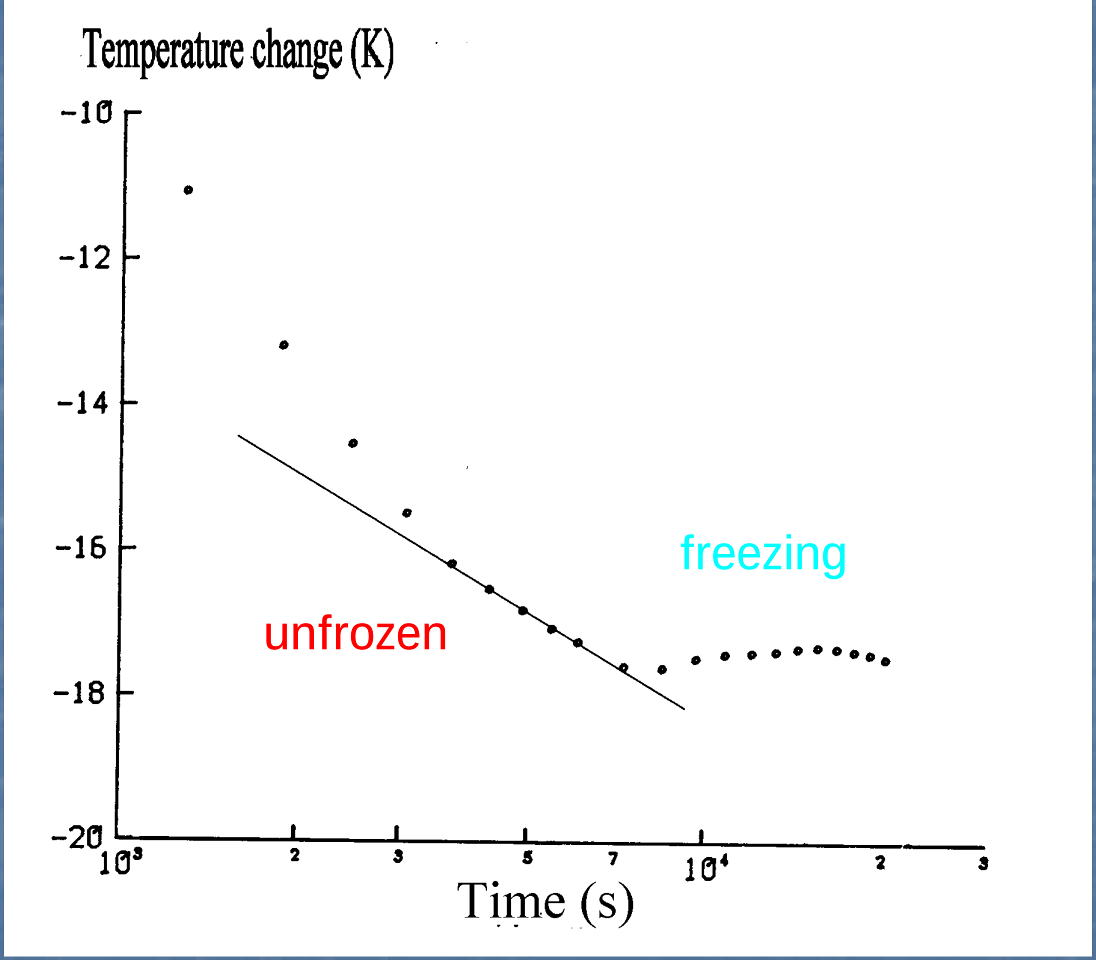
LULEÅ TEKNISKA UNIVERSITET

Thermal response test with freezing



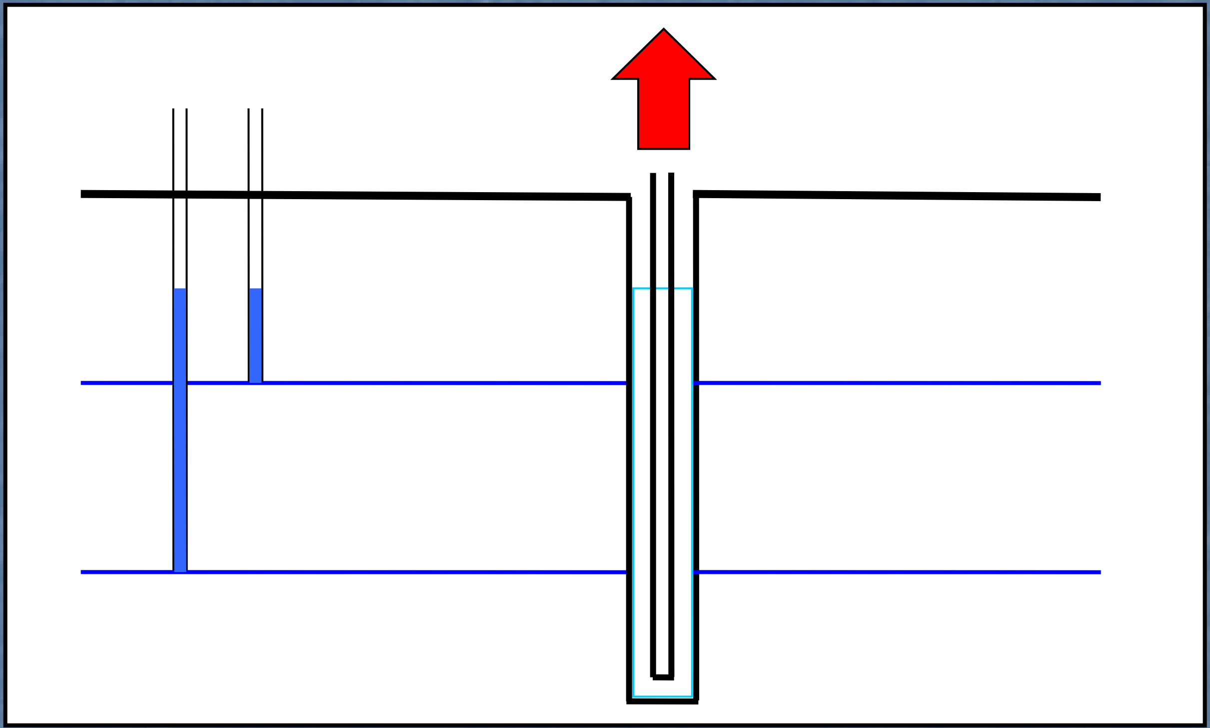
Temperature decrease in heat carrier fluid
with freezing borehole water

Thermal response test with freezing



Stockholm, 1983

Freezing of borehole water

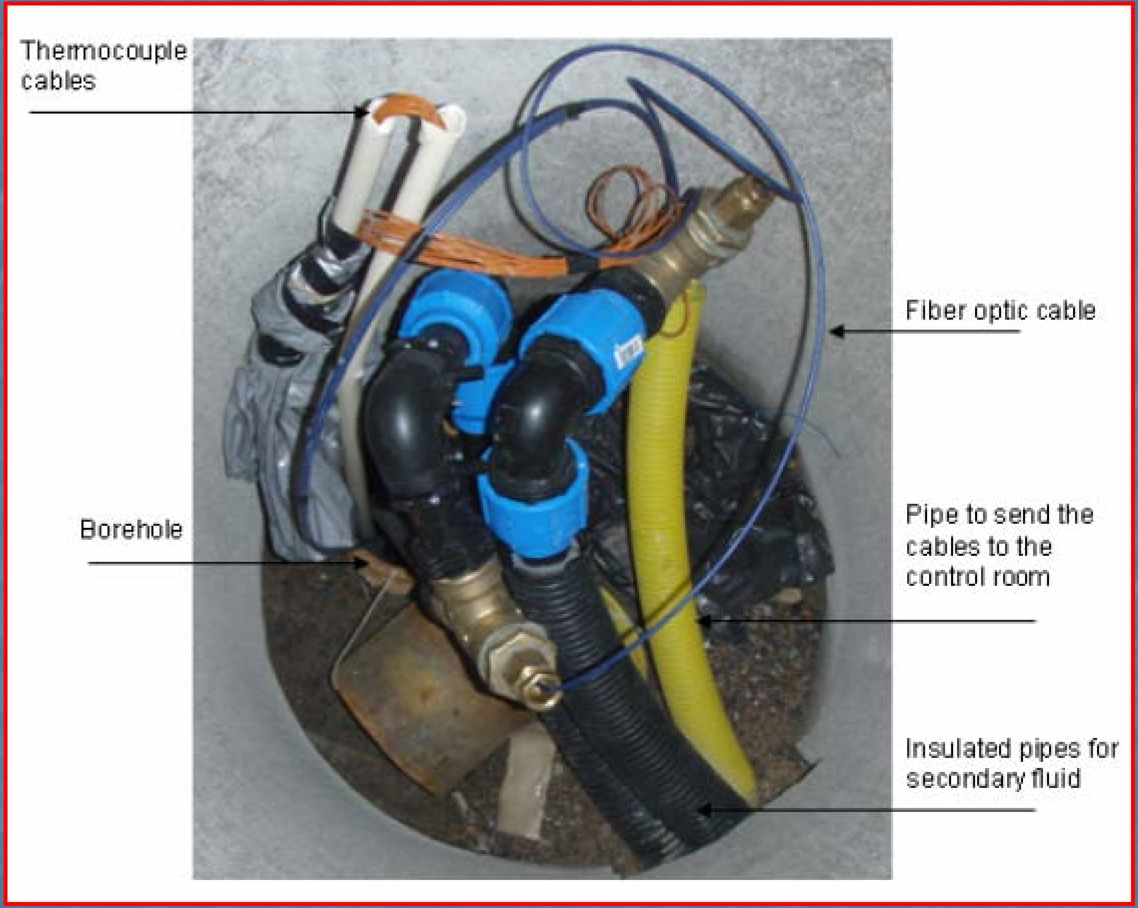


Danger of squeezing the pipe

A survey in Sweden showed that incidence of pipe damage is very small (estimated to 1 in 5,000-10,000)

THERMAL RESPONSE TEST
Optic Fibre

TRT with optic fibre

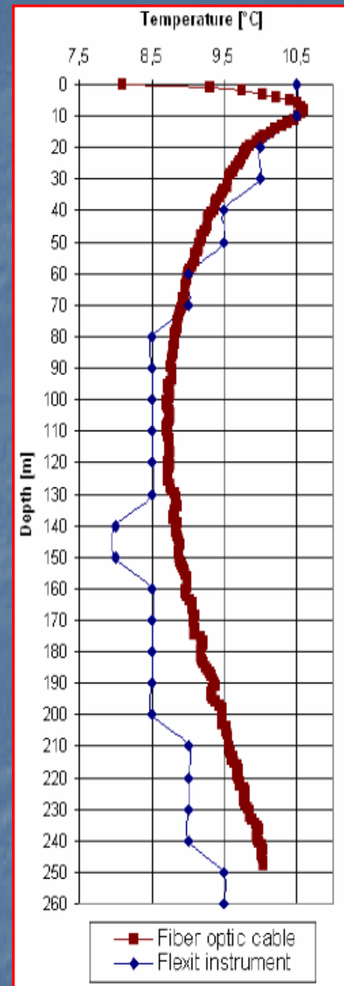


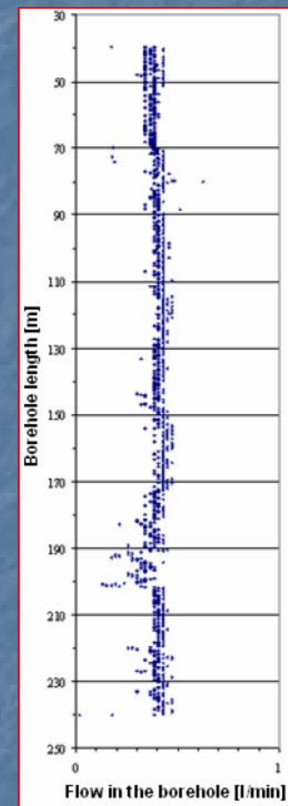
TRT with optical fibre (DTRT)

Acuna, Hill, Mogensen, Palm (Royal Institute of Technology, Stockholm)

TRT with optic fibre

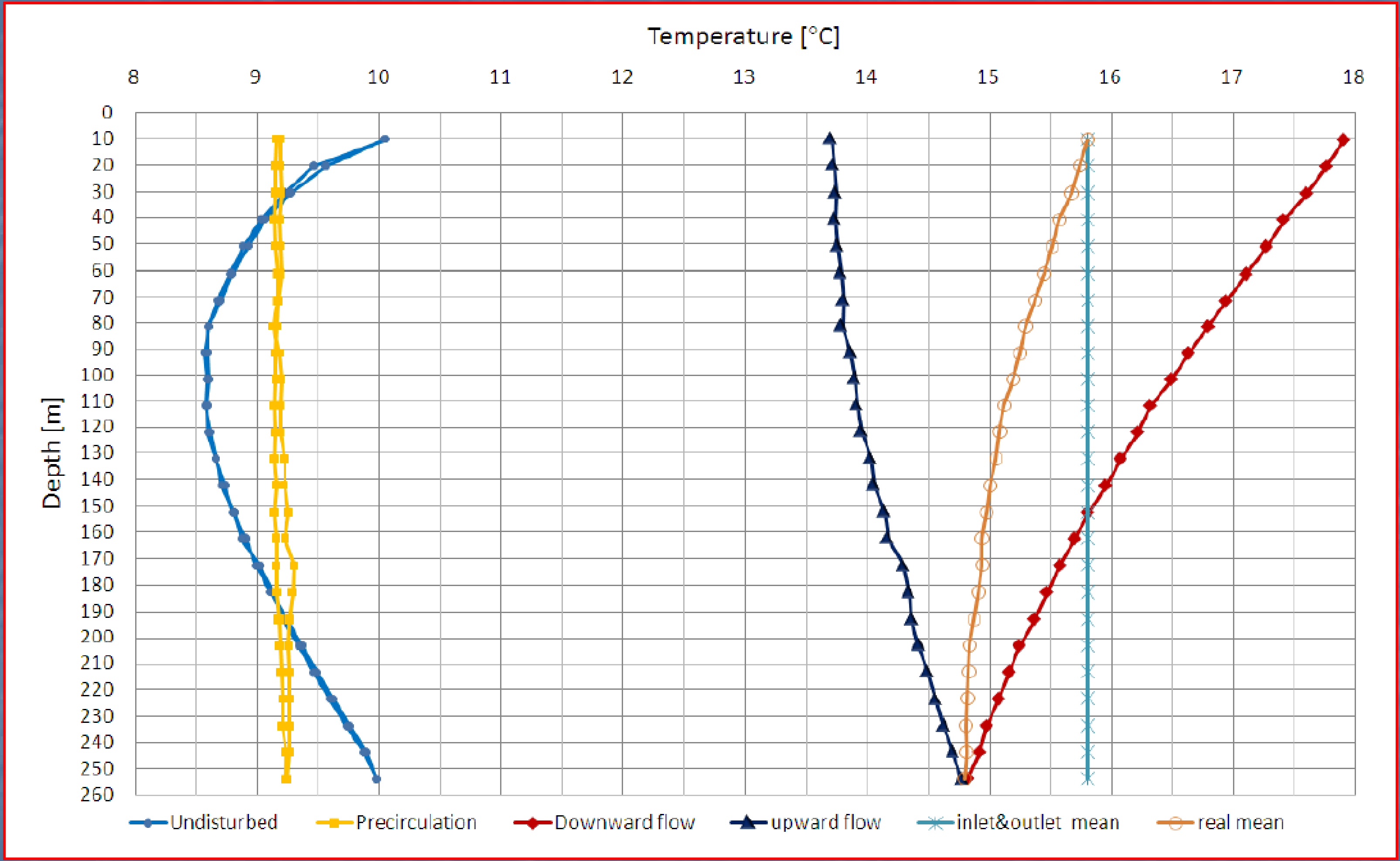
Borehole depth 260 m
Diameter 140 mm
Single U-pipe PE80 40 mm
Ethanol/water mixture (16%)
Flow rate 1,87 m3/h





Temperature profile and flow log

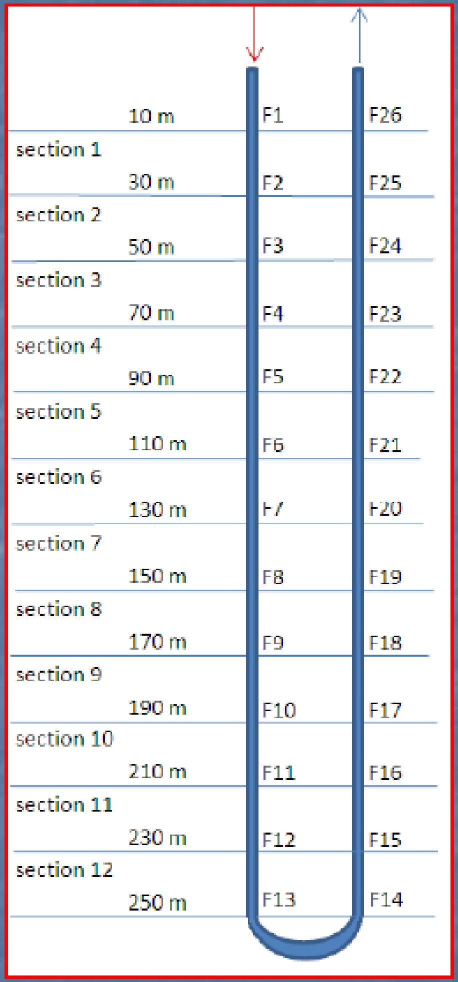
TRT with optic fibre



Vertical temperature profile before and during initial circulation of fluid

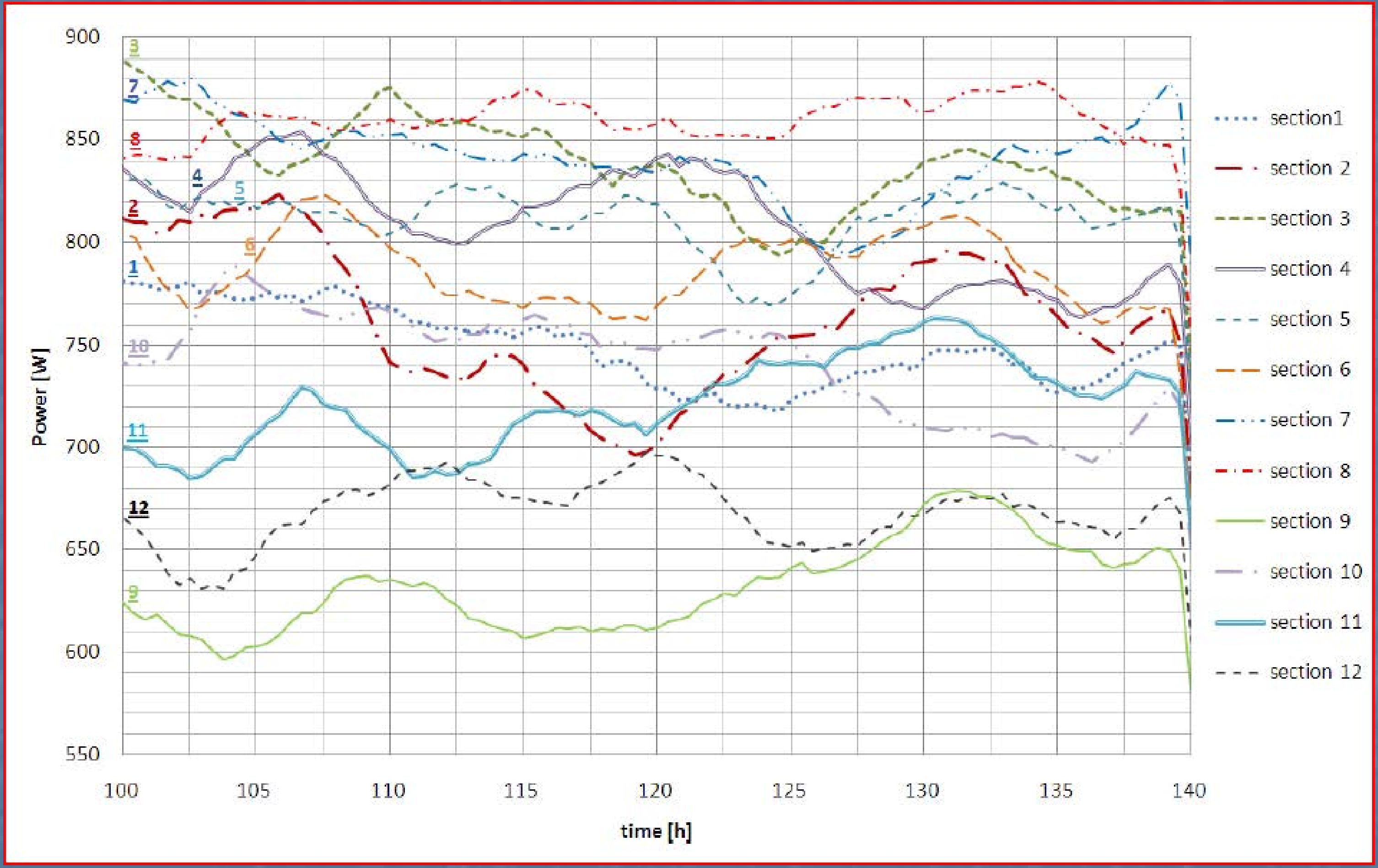
Average fluid temperatures during heating phase

Distributed Thermal Response Test - DTRT



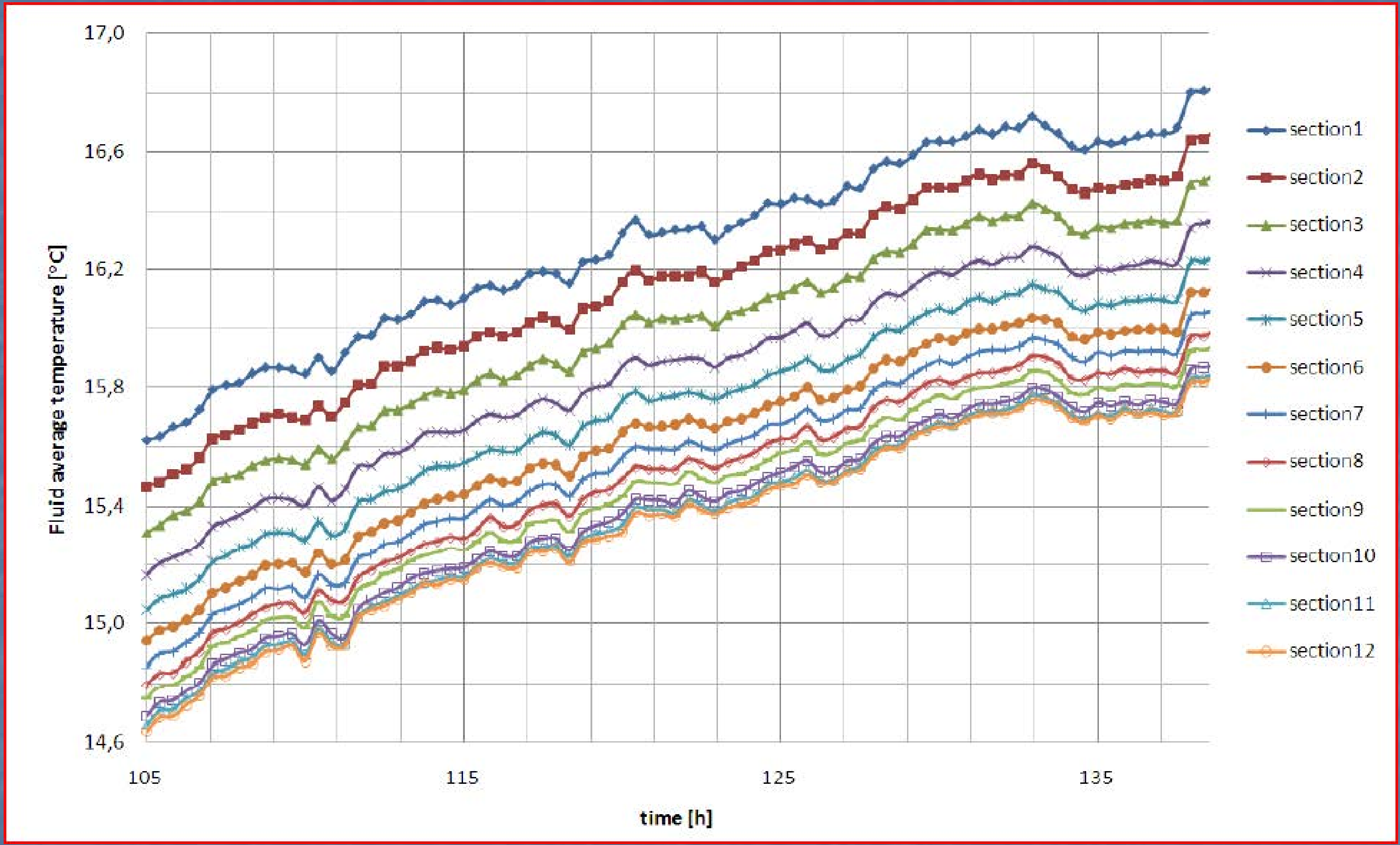
Measurement of heat balance in sections

Distributed Thermal Response Test - DTRT



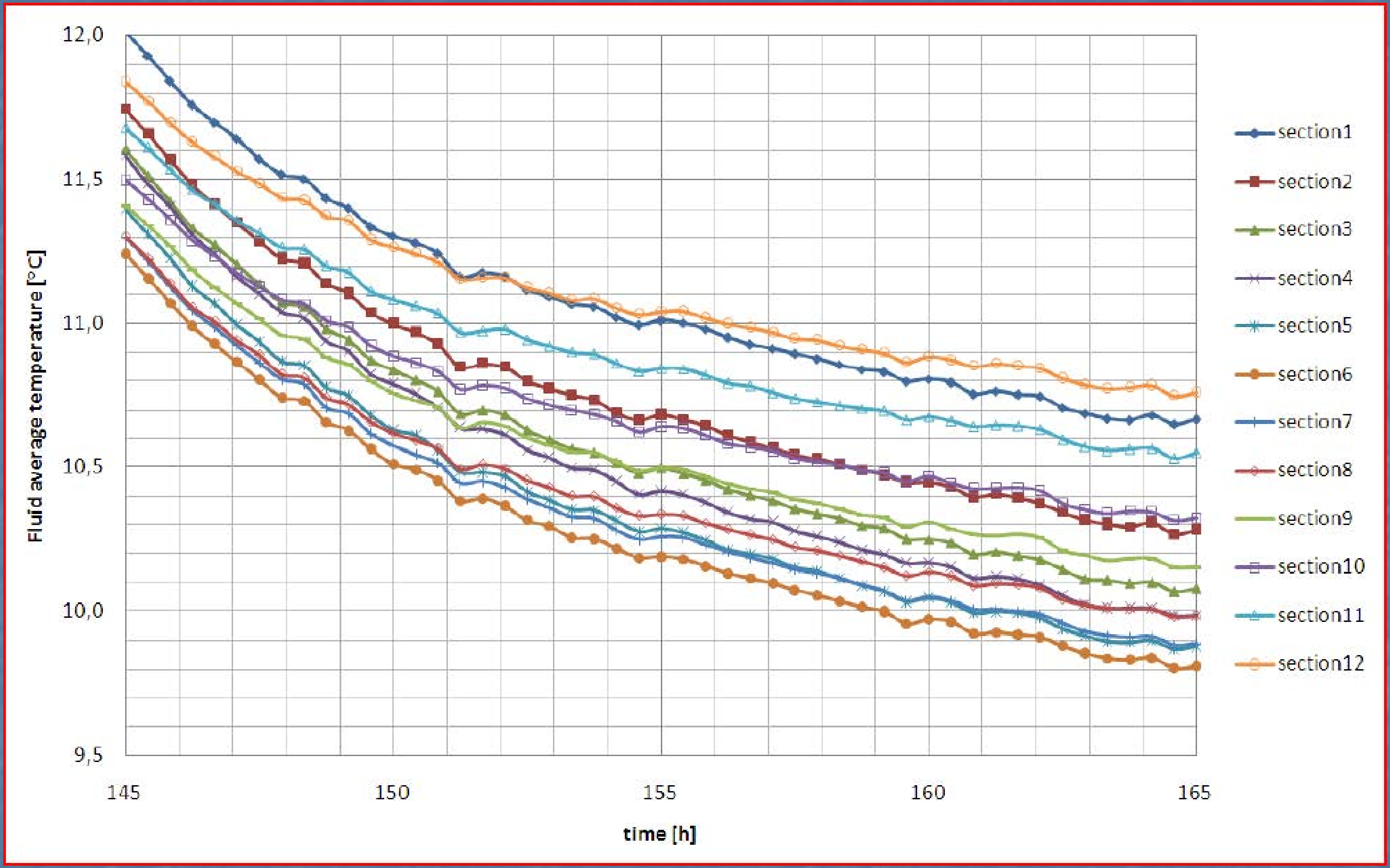
Power supplied in each section of the borehole

Distributed Thermal Response Test - DTRT



Fluid temperatures in each section during injection
(Borehole thermal resistance evaluated from this curve)

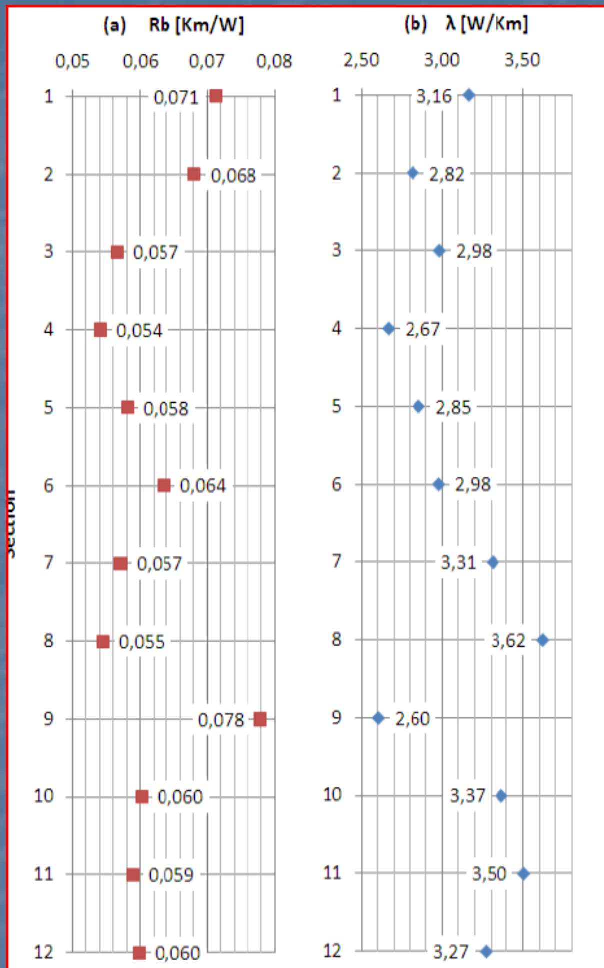
Distributed Thermal Response Test - DTRT



Fluid temperatures in each section during recovery

(Ground thermal conductivity evaluated from this curve)

Distributed Thermal Response Test - DTRT



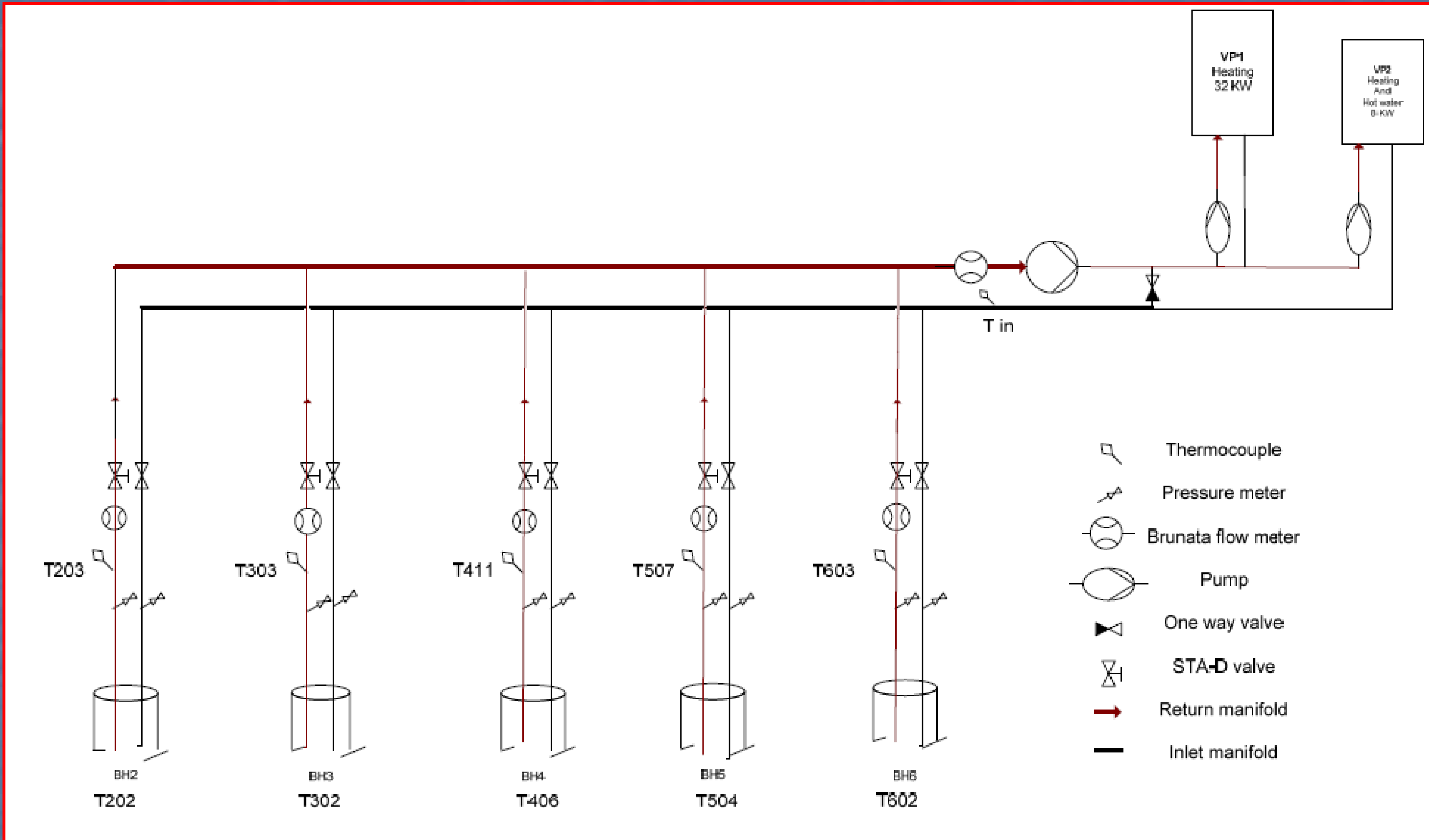
DTRT results (average values)
-Ground thermal conductivity 3,10 W/m,K
-Borehole thermal resistance 0,063 K/(W/m)

TRT results
-Ground thermal conductivity 3,08 W/m,K
-Borehole thermal resistance 0,079 K/(W/m)

Undisturbed ground temperature
-Based on vertical profile 9,10 C
-Based on initial circulation 9,19 C
(Difference attributed to circulation pump work)

Evaluated thermal conductivity and borehole thermal resistance in each section

Borehole heat exchanger comparison



Four different designs tested

(3-pipe, U-pipe with and without spacer, U-pipe with internal turbulence promoter (fins))

Vertical temperature profile

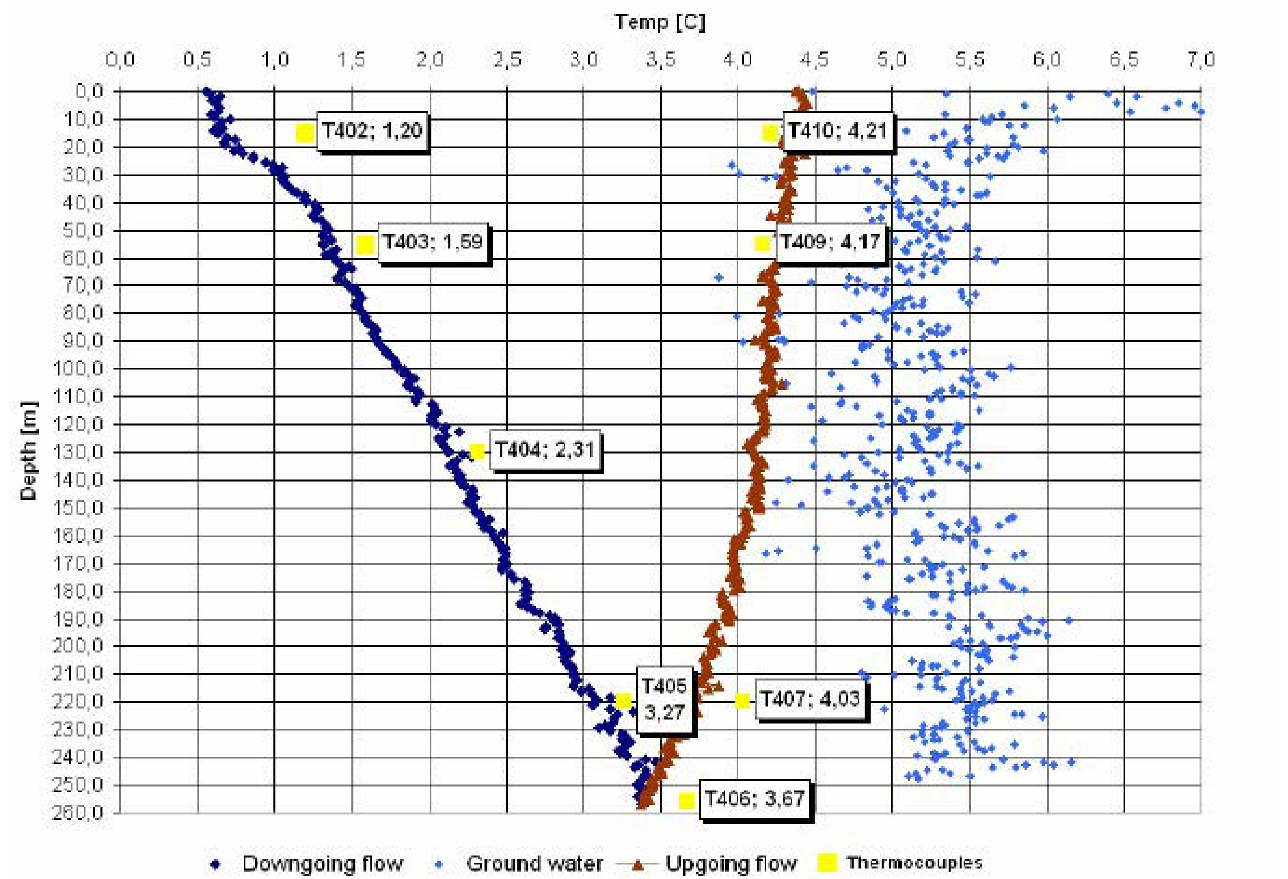


Figure 8: Average temperatures along the borehole during the first month of operation

Single U-pipe: Vertical temperature profile in fluid

(Acuna et al, 2008)

Vertical temperature profile

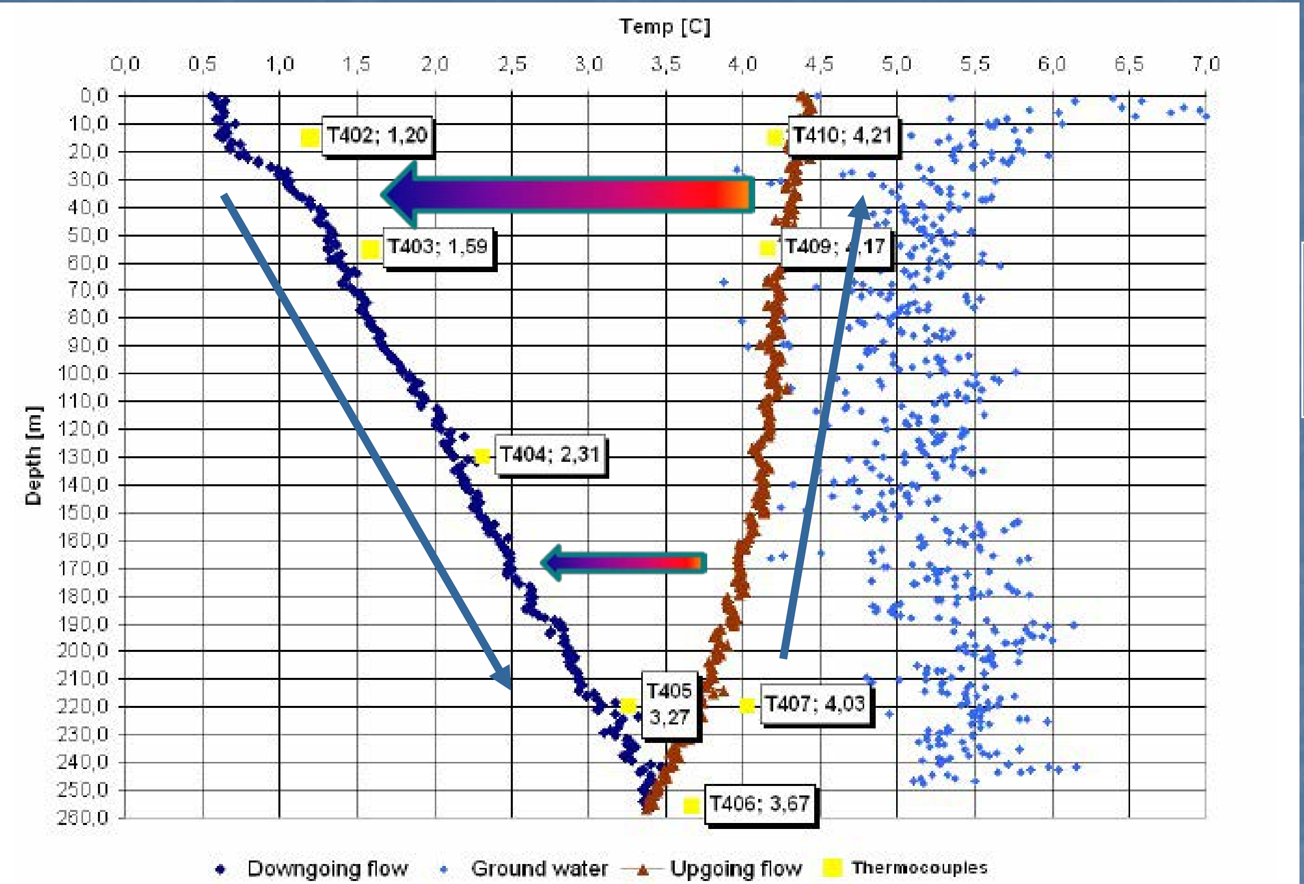


Figure 8: Average temperatures along the borehole during the first month of operation

Thermal short-circuiting

Single U-pipe: Vertical temperature profile in fluid

(Acuna et al, 2008)

Current activities

- Chalmers Technical University, Gothenburg
  - Analytical and numerical modelling of short-term respons
- Royal Institute of Technology, Stockholm
  - Borehole heat exchangers – field measurements using optic fibre
- Luleå Technical University
  - Numerical simulations of groundwater filled borehole heat exchangers

Thermal response test

The thermal response test is an established standard procedure for large projects


O ENERGY
Thank you!