Bore field sizing : Theory and applications

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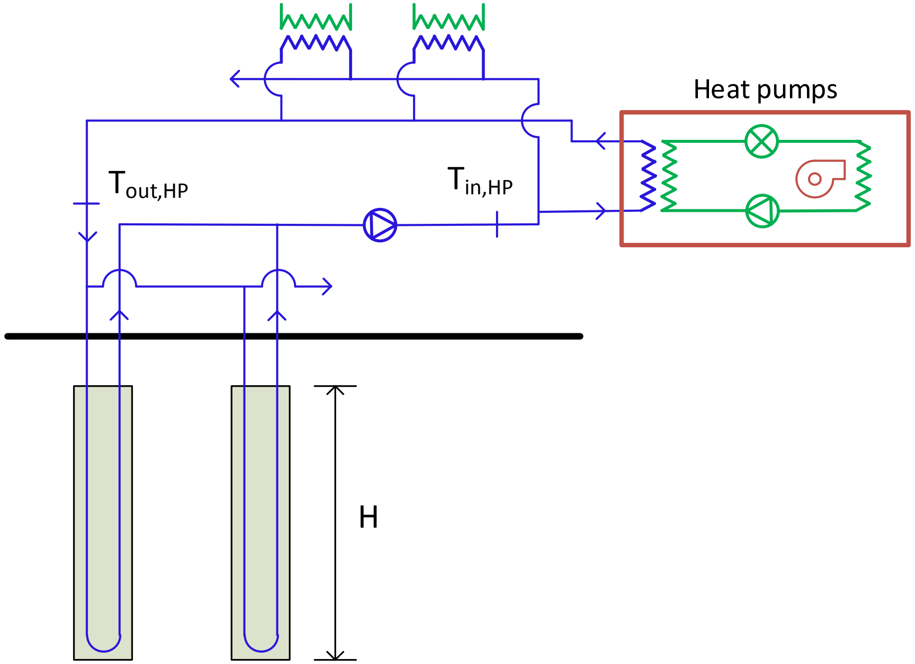
POLYTECHNIQUE MONTRÉAL

OUTLINE

- Introduction
- Sizing of bore fields
  - ASHRAE sizing method
  - Alternative methods
  - Exemple
- Thermal response factors (g-function)
  - Analytical determination
  - Pre-processor
  - Experimental validation
- Other work of interest
  - Thermal capacity in boreholes
  - Freezing around boreholes
  - Drake Landing Solar community
- Research needs
- Question period

INTRODUCTION



Undersized
↓
Operational problem

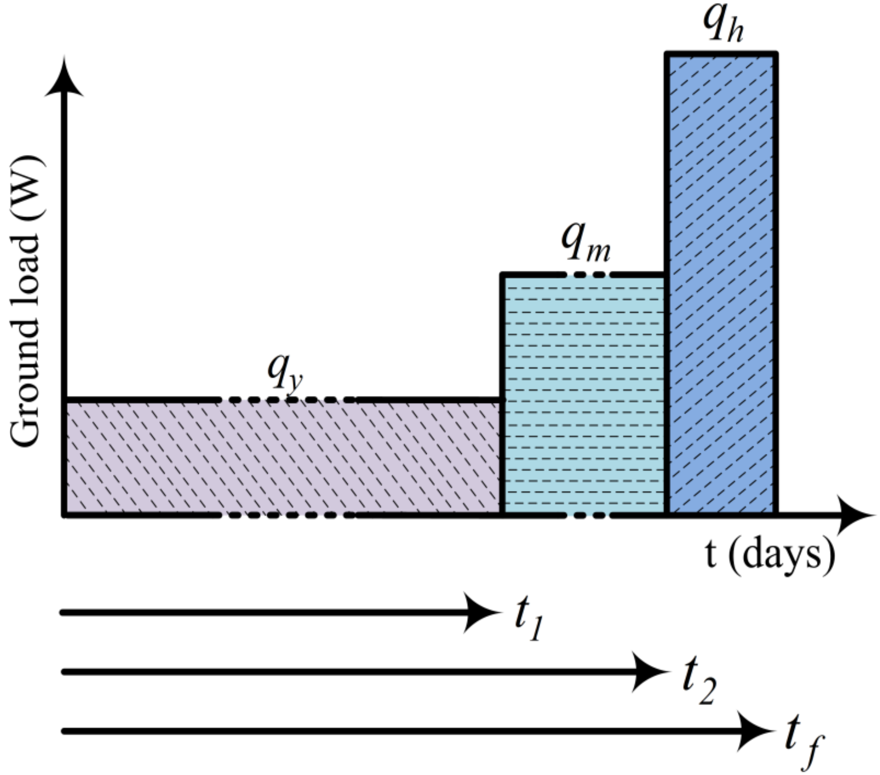
H = ?

Oversized
↓
High first cost

ASHRAE SIZING METHOD

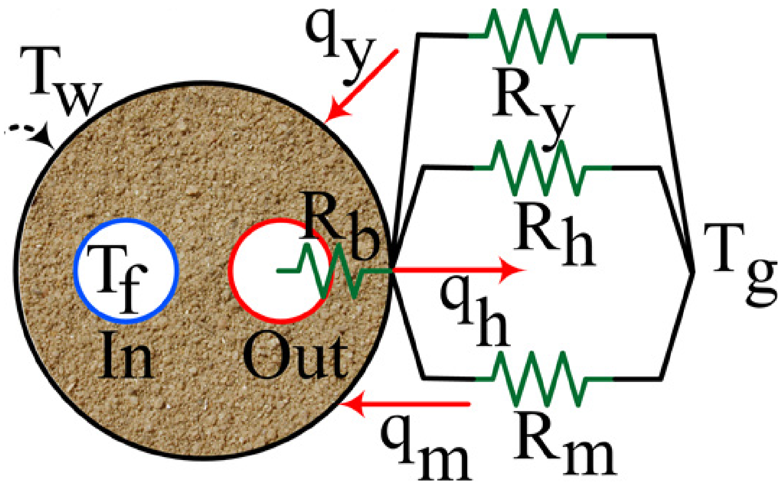
First appeared in the 1995 ASHRAE Handbook

$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$



ASHRAE SIZING METHOD

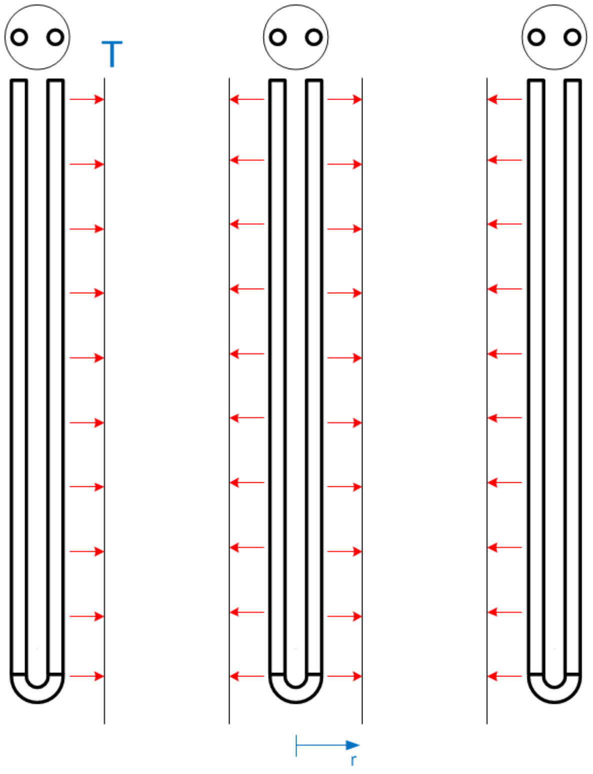
$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$



Schematic representation
(Effective ground thermal resistances are not in parallel)

ASHRAE SIZING METHOD

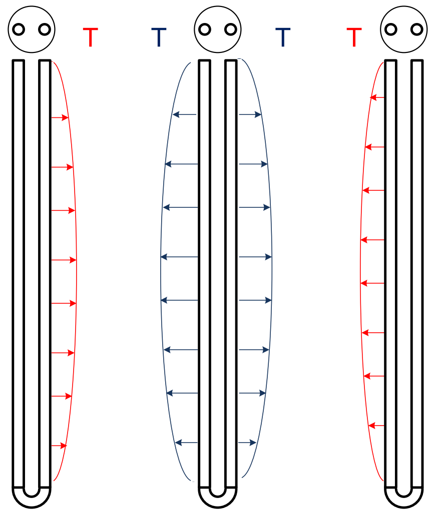
$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$



Obtained using the cylindrical heat source analytical solution

ASHRAE SIZING METHOD

$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$



2-D heat transfer and borehole thermal influence not accounted for

ASHRAE SIZING METHOD

$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$

T_p is introduce to account for thermal interference

…but

- Table for T_p in the Handbook is incomplete
- Limited to a certain number of geometries

Long-Term Temperature Penalty for Worst-Case Nonporous Formations for 10 × 10 grid and 350 kW Load

$EFLH_c$, h/yr	$EFLH_h$, h/yr	$COP_{cooling}$	$COP_{heating}$	T_g, °C	Bore Separation, m	Bore Length, m	$T_{penalty}$, °C
250	1250	5.2	3.6	6	4.5	70	–0.7
		5.2	3.6		6.1	67	–0.4
		5.2	3.6		7.6	66	–0.2
500	1000	4.9	3.7	7	4.5	66	–0.8
		4.9	3.7		6.1	64	–0.4
		4.9	3.7		7.6	63	–0.2
750	750	4.2	4.0	13	4.5	63	1.9
		4.2	4.0		6.1	59	1.0
		4.2	4.0		7.6	58	0.6
1000	500	3.9	4.4	18	4.5	87	3.8
		3.9	4.4		6.1	76	2.1
		3.9	4.4		7.6	70	1.1
1250	250	3.8	4.6	20	4.5	110	5.6
		3.8	4.6		6.1	88	3.2
		3.8	4.6		7.6	78	1.7
0	1500	Not recommended without solar or thermal regeneration					
1500	0	Not recommended without fluid cooler or cooling tower assist					

Note:
k_g = 2.4 W/(m·K), k_{grout} = 1.5 W/(m·K), rated $COP_{cooling}/COP_{heating}$ = 5.9/4.2 (GLHP).

Correction Factors for Other Grid Patterns:

1 × 10 grid	2 × 10 grid	5 × 5 grid	20 × 20 grid
C_f = 0.36	C_f = 0.45	C_f = 0.75	C_f = 1.14

ASHRAE SIZING METHOD–PROPOSED MODIFICATIONS (1)

$$L = \frac{q_y R_y + (q_l - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{fi} + T_{fo})}{2} - T_p}$$

Proposed by Bernier et al. (2006)

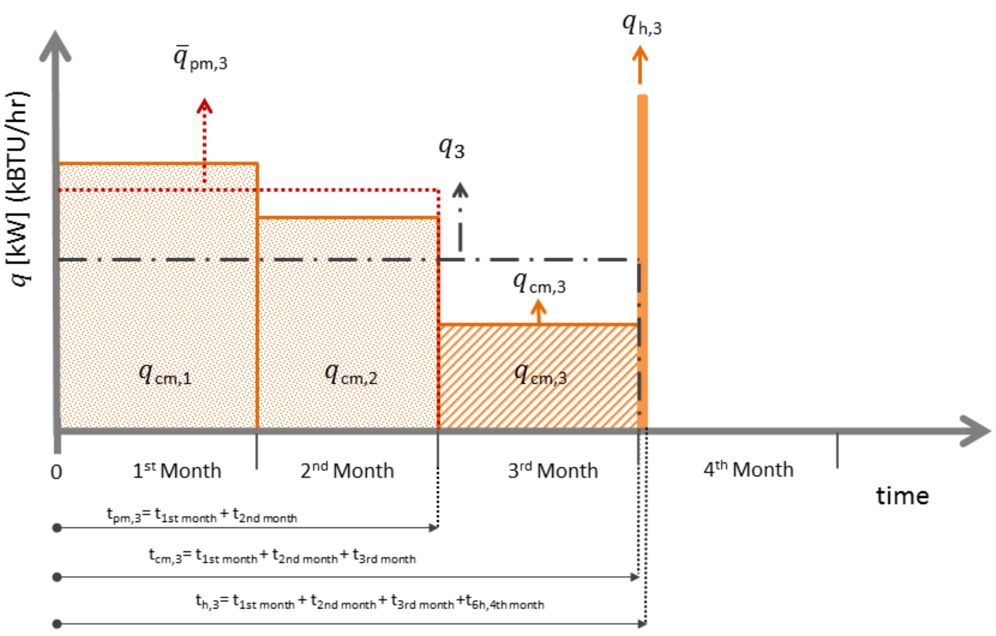
$$L = \frac{q_h R_b + q_y R_y + q_m R_m + q_h R_h}{T_m - (T_g + T_p)}$$

F_{sc} has been eliminated
T_p is calculated based on g-functions

ASHRAE SIZING METHOD–PROPOSED MODIFICATIONS (2)

Modifications to account for the first year of operation

$$L_i = \frac{q_{h,i} \cdot R_b + \bar{q}_{pm,i} \cdot R_{pm,i} + q_{cm,i} \cdot R_{cm} + q_{h,i} \cdot R_h}{T_m - (T_g + T_{p,i})}$$



ASHRAE SIZING METHOD–PROPOSED MODIFICATIONS (3)

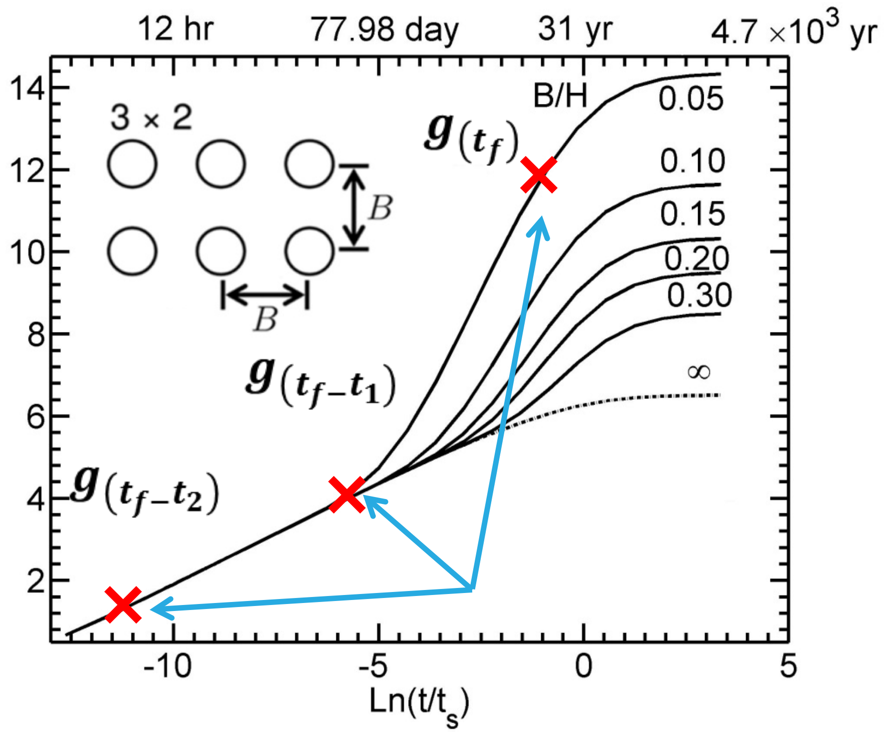
- Iteration procedure is required as L is unknown *a priori*
- g-functions are determined "On fly"
- No interpolation for B/H
- No correction factors for r_b/H

$$L = \frac{q_h R_b + q_y R_{gy} + q_m R_{gm} + q_h R_{gh}}{T_m - T_g}$$

$$R_{gy} = \left(g_{(t_f)} - g_{(t_f - t_1)}\right)/2\pi k$$

$$R_{gm} = \left(g_{(t_f - t_1)} - g_{(t_f - t_2)}\right)/2\pi k$$

$$R_{gh} = g_{(t_f - t_2)}/2\pi k$$



- converges rapidly after **3 to 4 iterations**.
- The method is applicable to **all kind of bore field configurations**

EXEMPLE

Heating and cooling of a building of a building and 3 nearby greenhouses

DETERMINATION OF THE GROUND LOADS

	monthly building cooling load	peak building cooling load	monthly building + greenhouse heating load	peak building + greenhouse heating load	peak hourly ground cooling load	peak hourly ground heating load (with greenhouses)	monthly ground load (with greenhouses)
	kWh	kW	kWh	kW	kW	kW	kW
january	0.0	0.0	112843.5	219.8	0.0	164.9	113.8
february	0.0	0.0	105516.0	219.8	0.0	164.9	117.8
march	0.0	0.0	48361.5	219.8	0.0	164.9	48.8
april	0.0	0.0	20517.0	219.8	0.0	164.9	21.4
may	14655.0	87.9	2931.0	29.3	-109.9	22.0	-21.7
june	23448.0	131.9	0.0	0.0	-164.9	0.0	-40.7
july	29310.0	131.9	0.0	0.0	-164.9	0.0	-49.2
august	26379.0	131.9	0.0	0.0	-164.9	0.0	-44.3
september	23448.0	102.6	2931.0	29.3	-128.2	22.0	-37.7
october	0.0	0.0	23448.0	219.8	0.0	164.9	23.6
november	0.0	0.0	63016.5	219.8	0.0	164.9	65.6
december	0.0	0.0	106981.5	219.8	0.0	164.9	107.8
Totals	117240		486546				
					annual ground imbalance (kW)		
					24.93		

DETERMINATION OF L

$$L = \frac{q_h R_b + q_y R_y + q_m R_m + q_h R_h}{(T_g + T_p) - \frac{T_{out,ground} + T_{in,ground}}{2}}$$

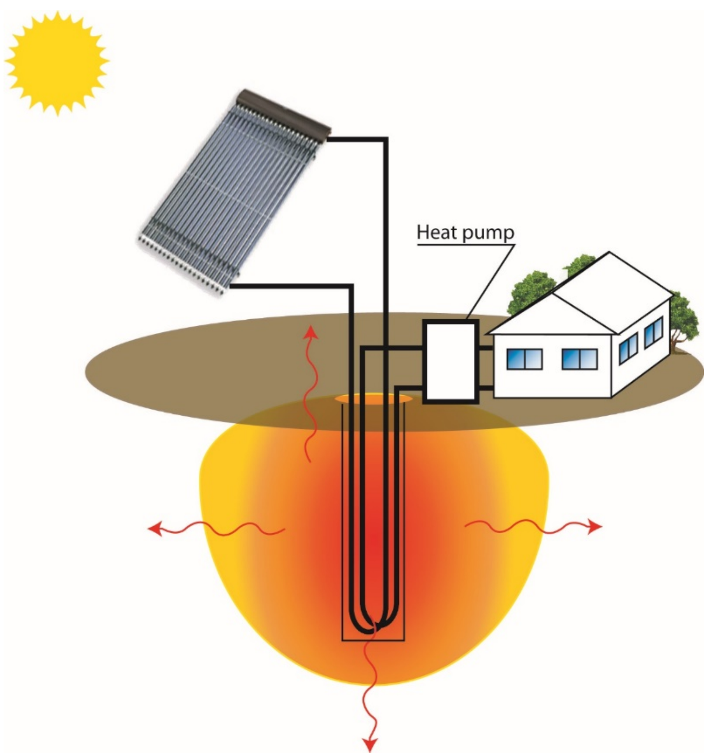
$$L_{ch} = \frac{(164870 \times 0.100) + (24930 \times 0.137) + (117800 \times 0.152) + (164870 \times 0.101)}{(10.80 + -3.5) - (0.0 + -3.7)/2} = \mathbf{5917\ [m]}$$

24.9 kW of thermal imbalance causes an "equivalent" 3.5 °C ground temperature decrease after 5 years

Too long !

SOLAR INJECTION

What if the 24.9 kW of ground thermal imbalance was compensated with solar energy with a double U-tube with 2 independent circuits



LENGTH WITH SOLAR INJECTION

Without solar injection

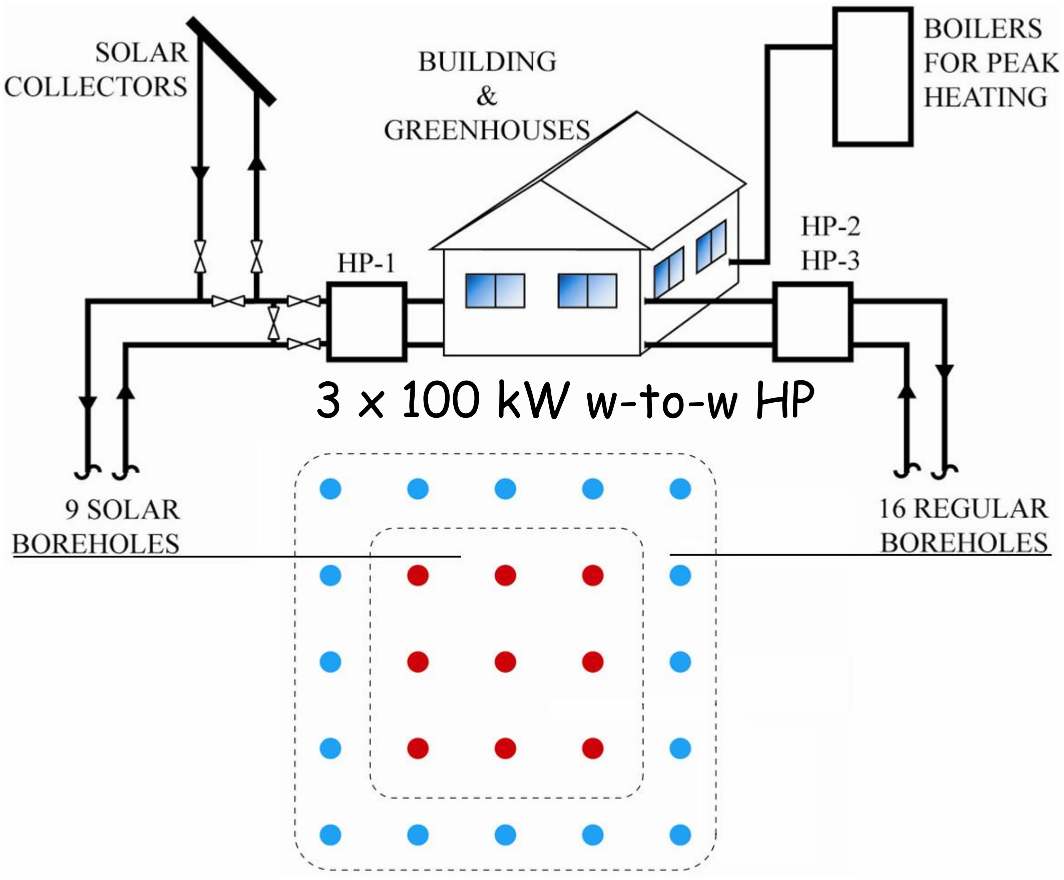
$$L_{ch} = \frac{(164870 \times 0.100) + (24930 \times 0.137) + (117800 \times 0.152) + (164870 \times 0.101)}{(10.80 + -3.5) - (0.0 + -3.7)/2} = \mathbf{5917\ [m]}$$

36%

With solar injection

$$L_{ch} = \frac{(164870 \times 0.100) + (0 \times 0.137) + (97300 \times 0.152) + (164870 \times 0.101)}{(10.80 + 0.0) - (0.0 + -3.7)/2} = \mathbf{3783\ [m]}$$

OTHER PROPOSED METHOD



Field restriction:
25 boreholes

Borehole depth = 146 m

Total length = 3650 m
(≅ 62% of the length calculated without considering solar injection)

The goal: Trap heat in the middle to use it for heating

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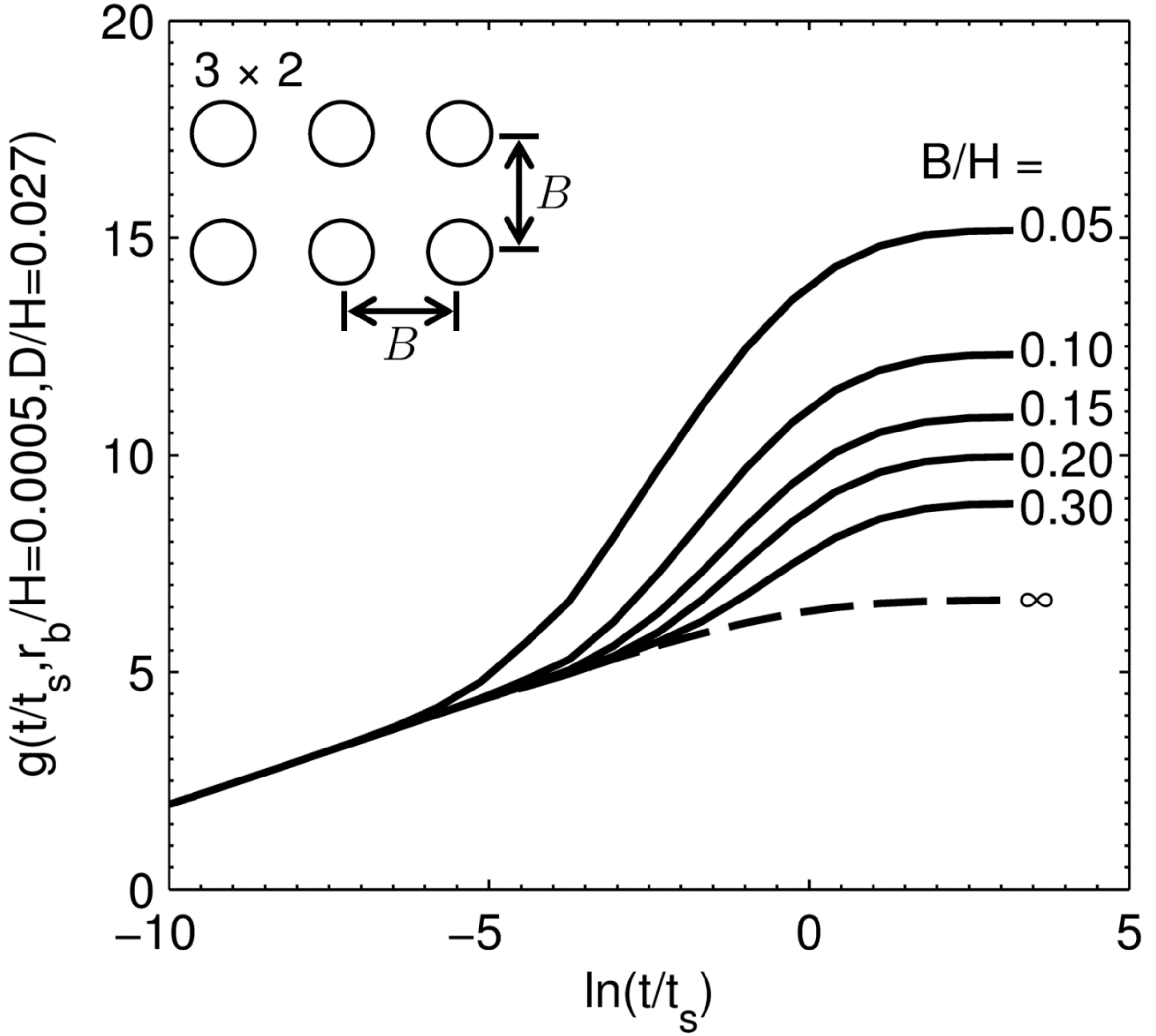
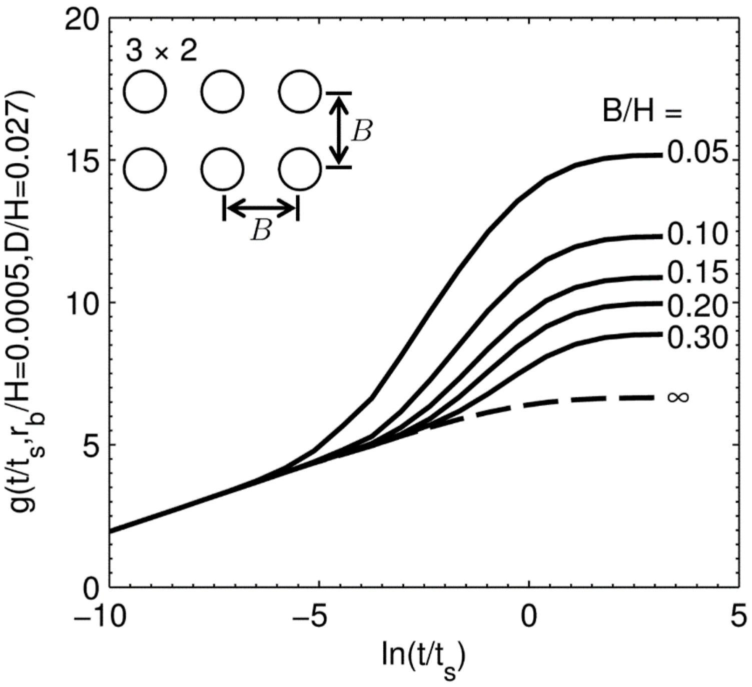
THERMAL RESPONSE FACTORS

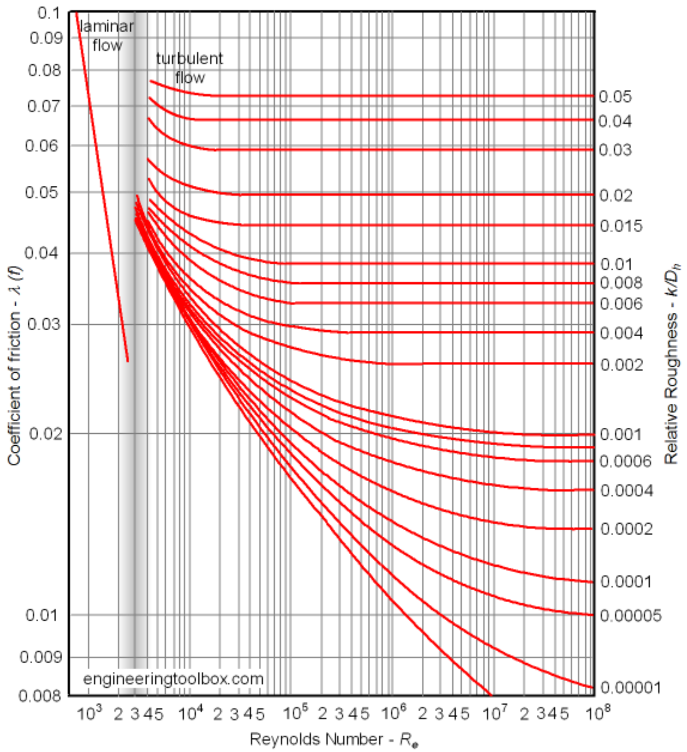
Also known as “g-function”



THERMAL RESPONSE FACTORS

Similar in concept to the Moody diagram

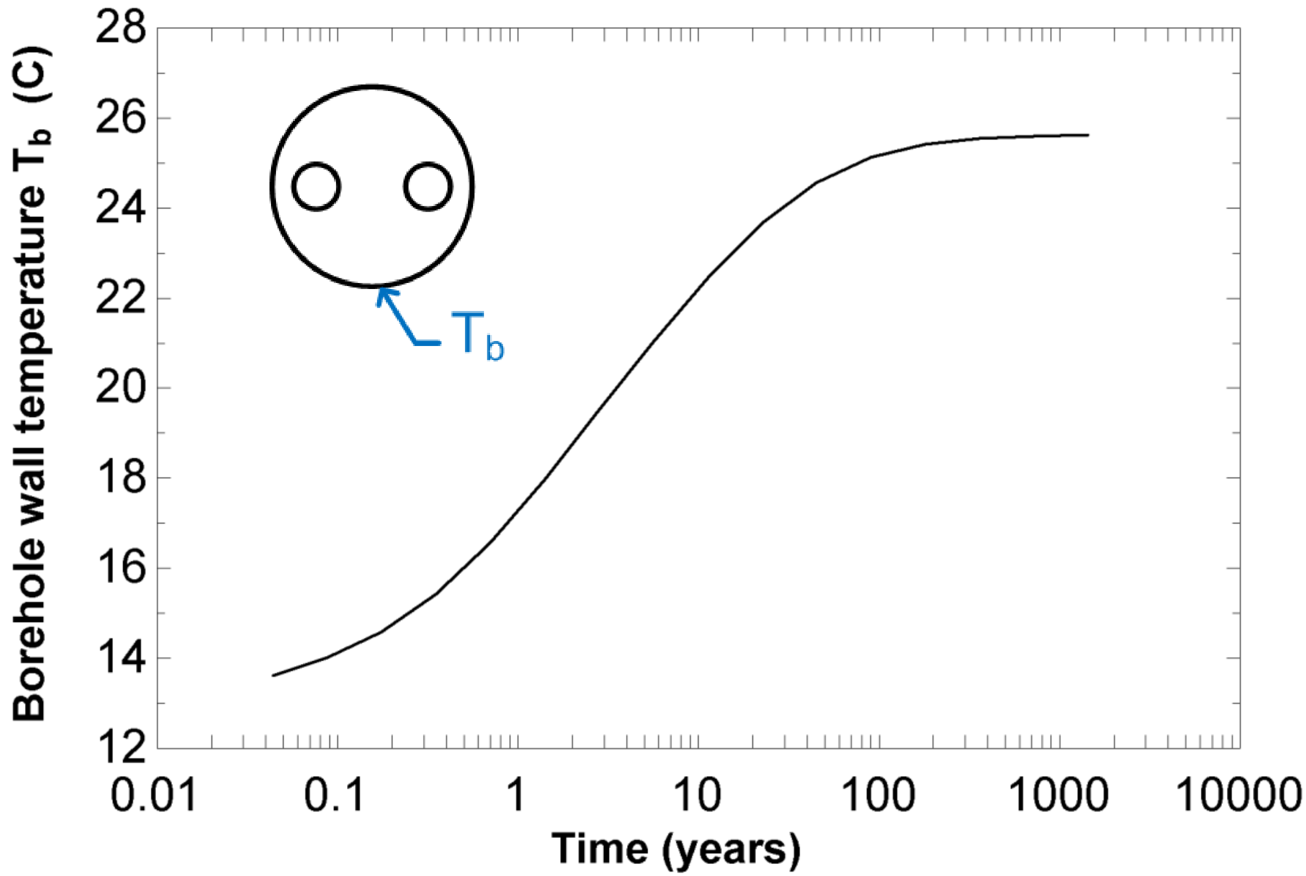




http://www.engineeringtoolbox.com

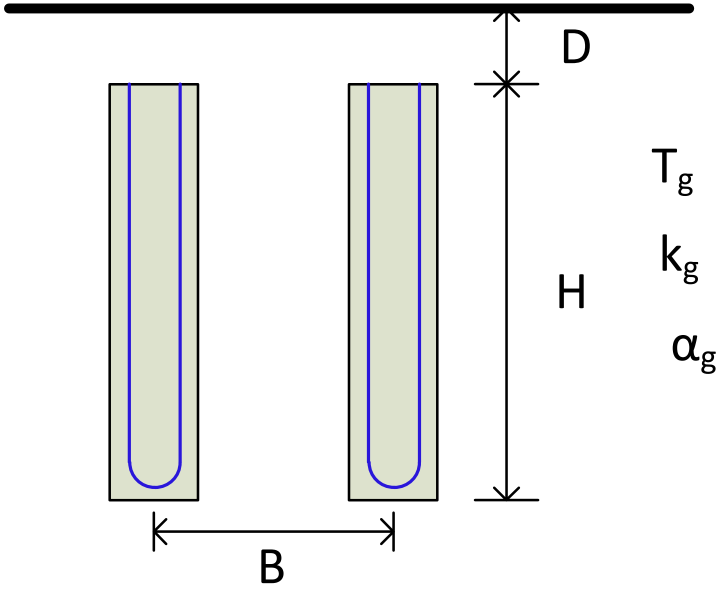
THERMAL RESPONSE FACTORS

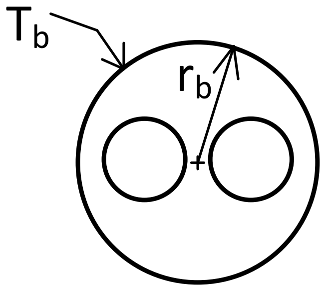
Gives the borehole wall temperature, T_b , as a function of time



Curve shown is only valid for a particular geometry and ground temperature

DEFINITIONS





Eskilson determined that for a given bore field geometry and for deep boreholes, the thermal response of a bore field depends on 3 non-dimensional parameters:

$$B/H$$

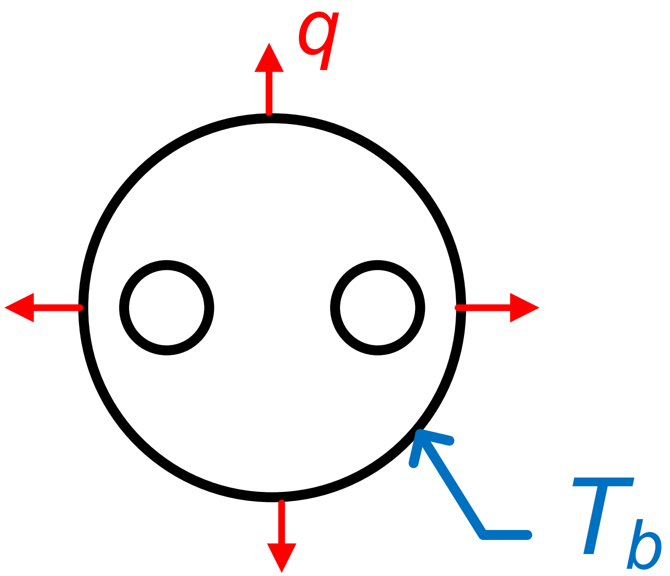
$$t/t_s \quad (t_s = H^2/9\alpha_g)$$

$$r_b/H$$

There is actually a fourth ND parameter

$$D/H$$

DEFINITIONS

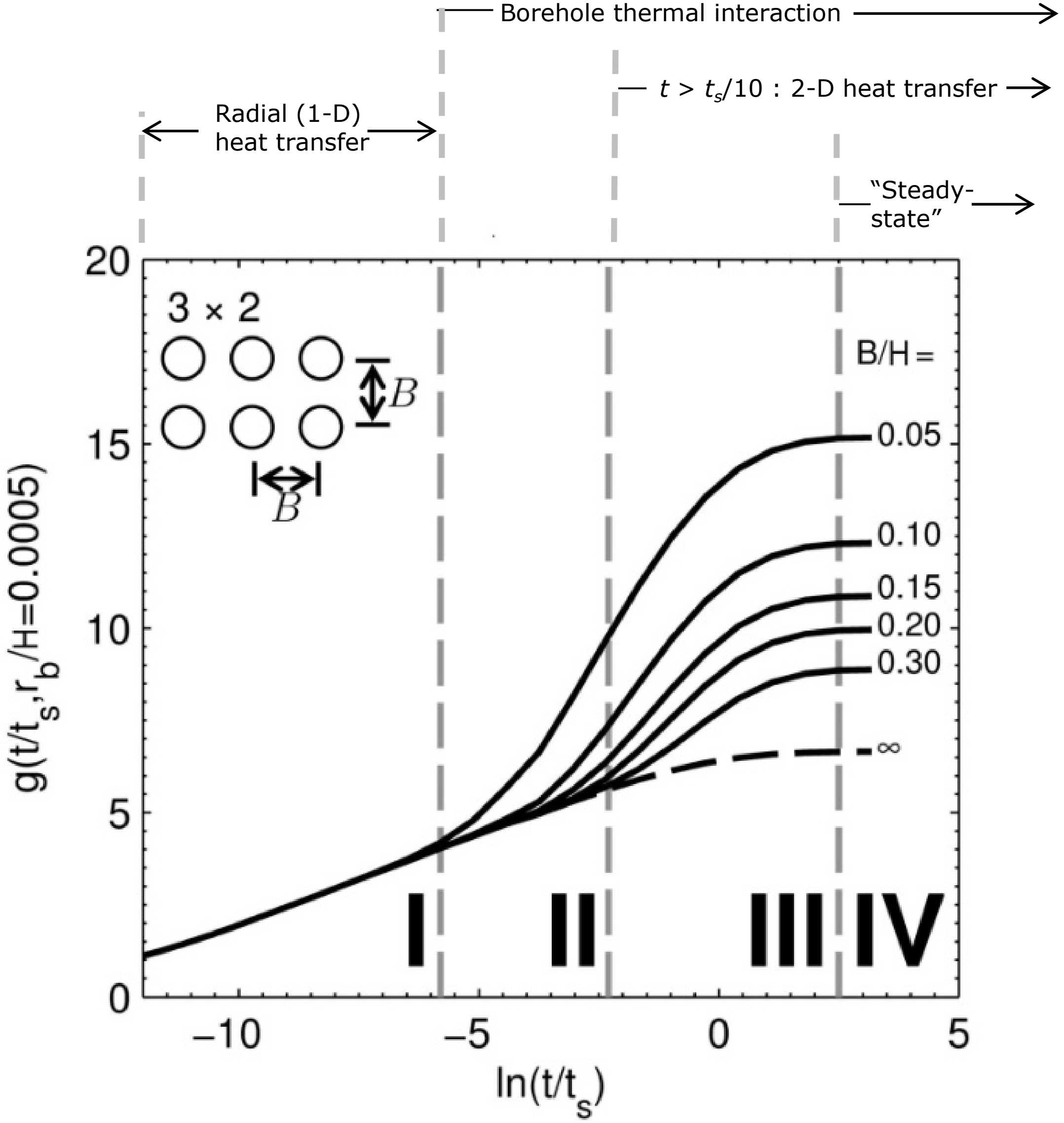


T_g

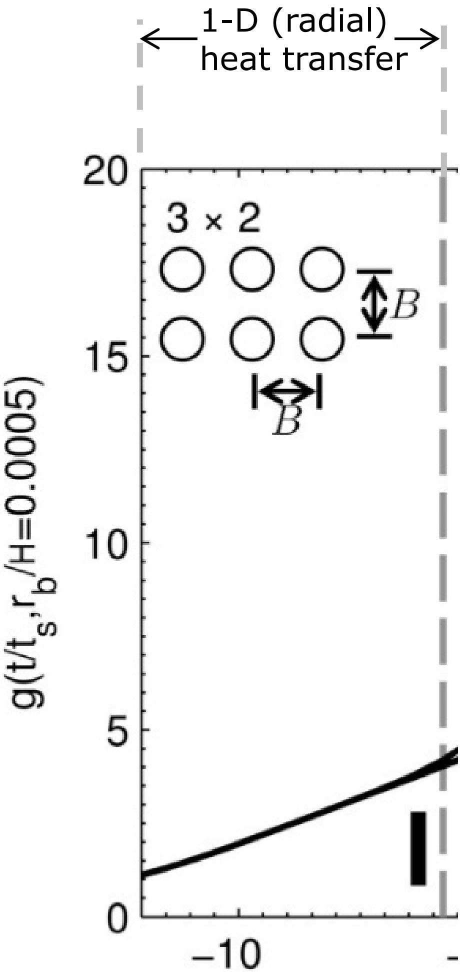
k_g

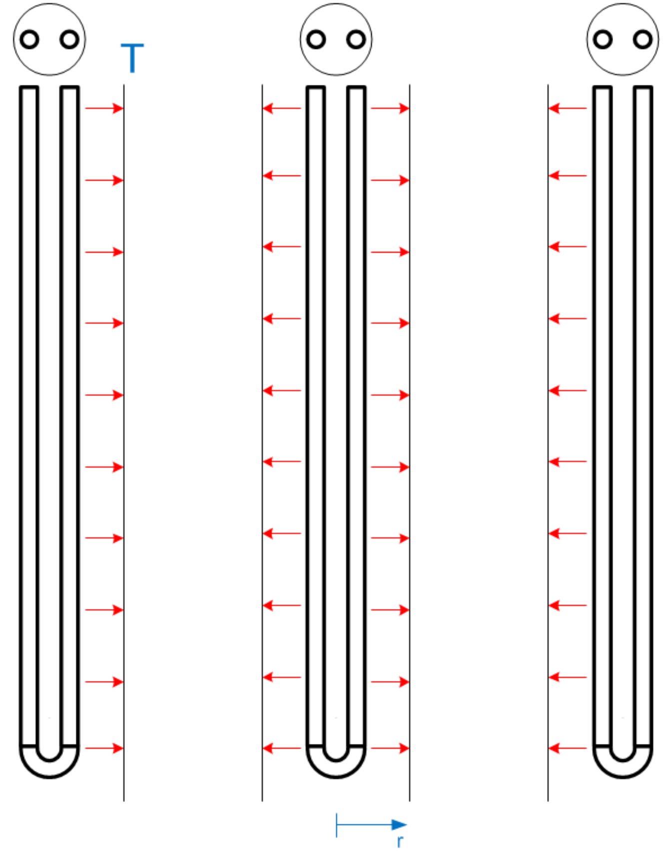
$$T_b = T_g - \frac{q}{2\pi k_g} \cdot g$$

FOUR REGIONS



REGION I : 1-D (RADIAL) HEAT TRANSFER

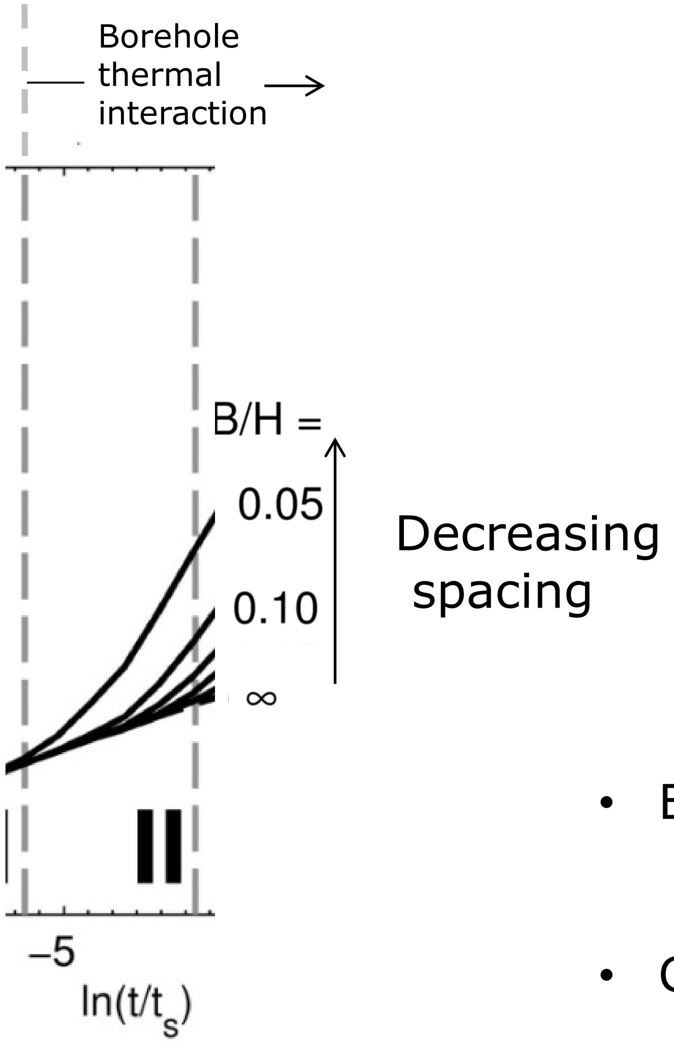


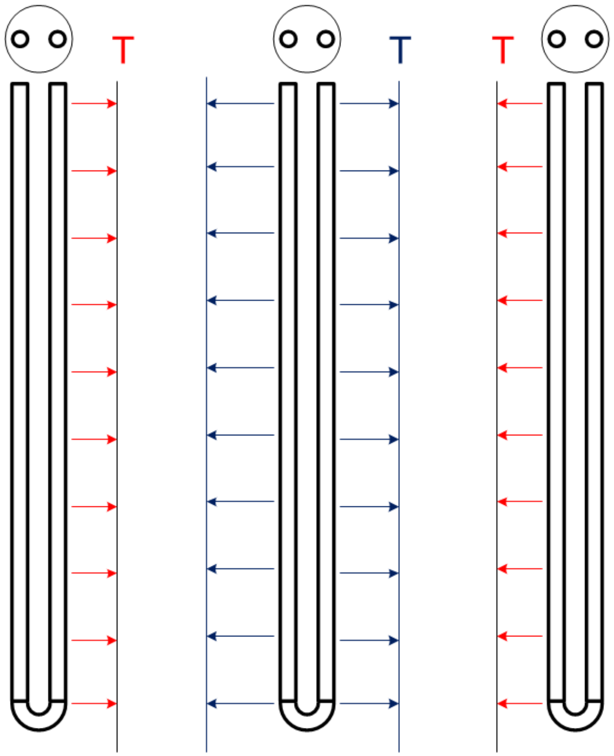


-Temperature is uniform along the height; it varies only in the radial direction

-Independent of borehole spacing

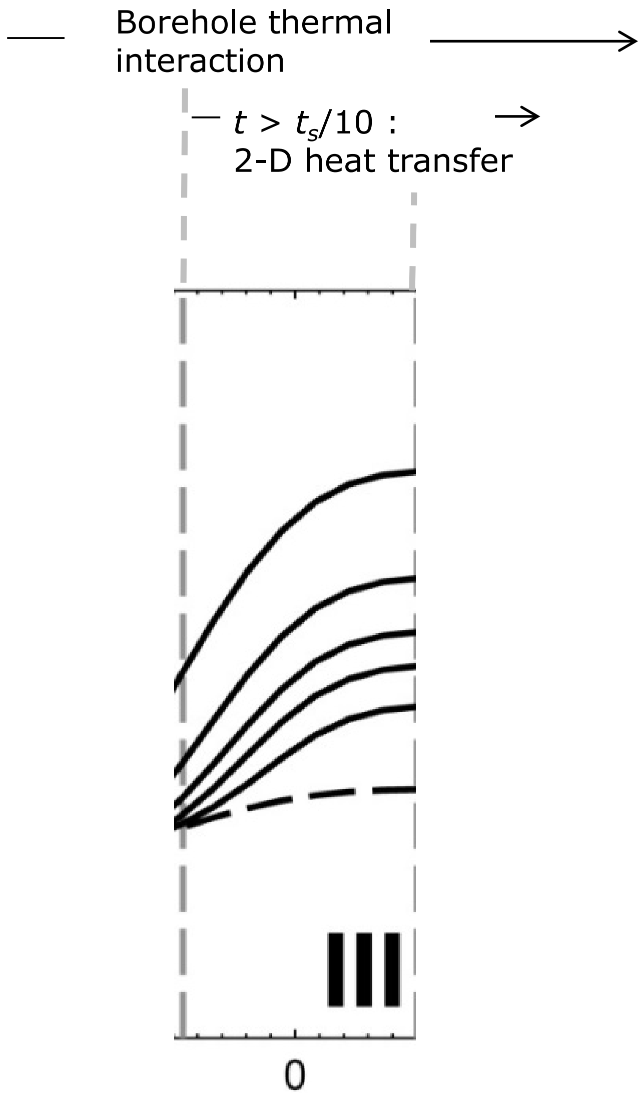
REGION II : BOREHOLE THERMAL INTERACTION

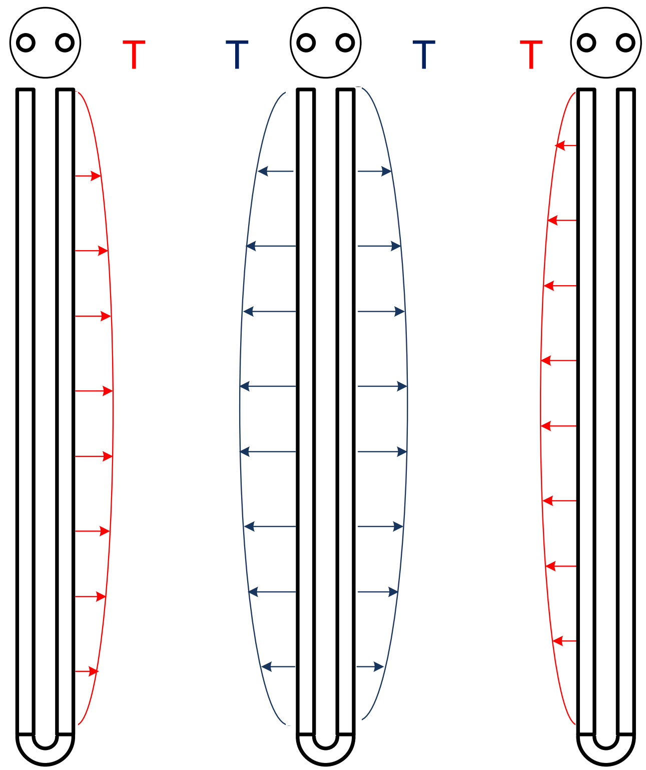




- Boreholes will start to interfere with each other after a few months of operation.
- Center boreholes will be more affected.

REGION III: START OF 2-D HEAT TRANSFER

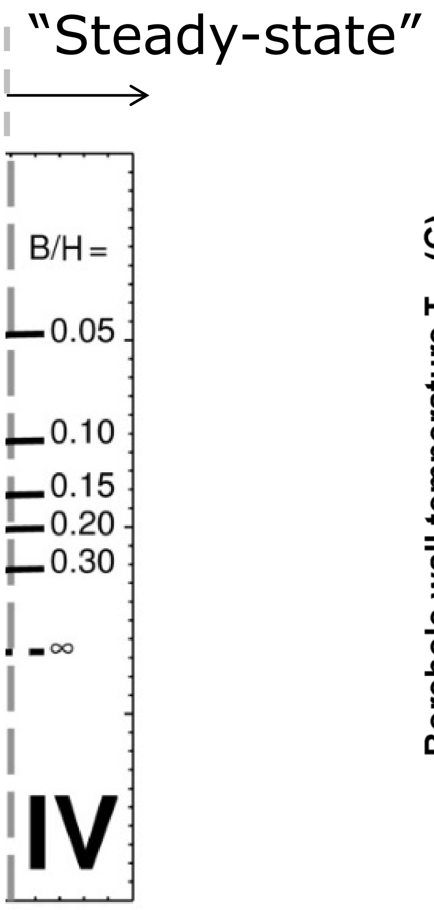


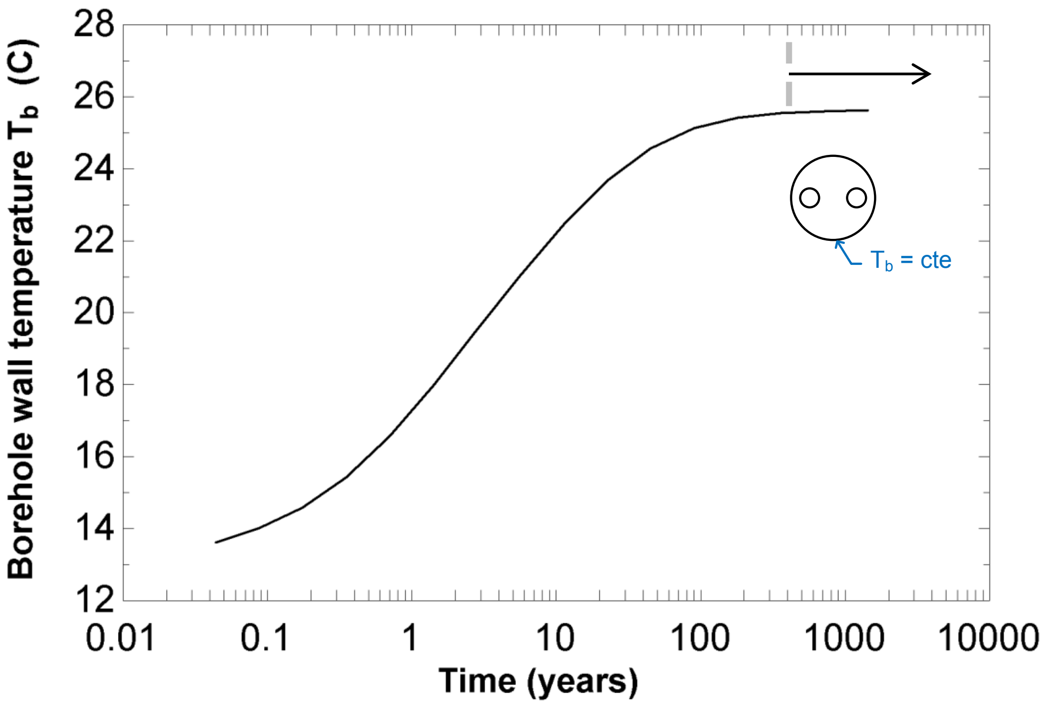


- 2-D heat transfer (radial and axial). "Ellipsoid" temperature profile.

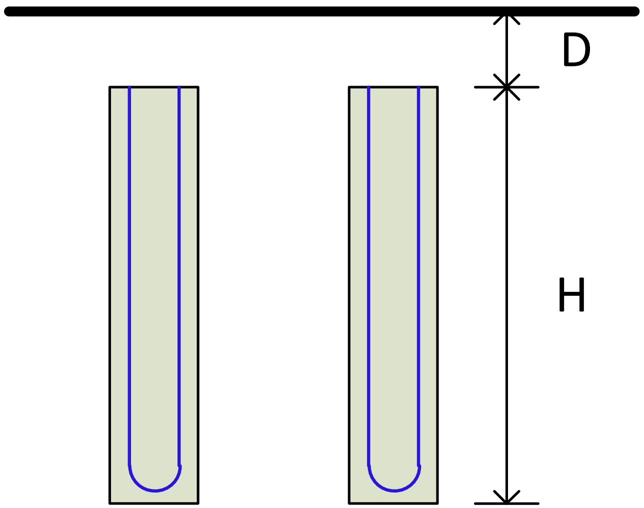
- Borehole thermal interaction continues.

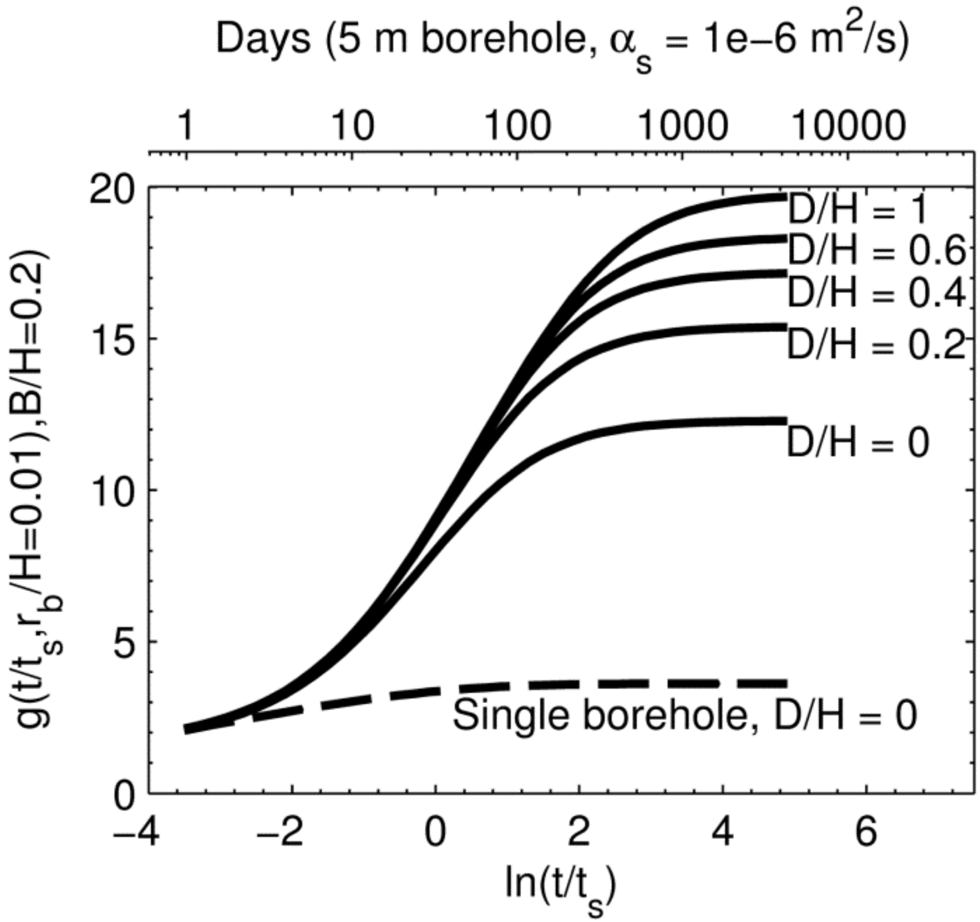
REGION IV : STEADY-STATE HEAT TRANSFER





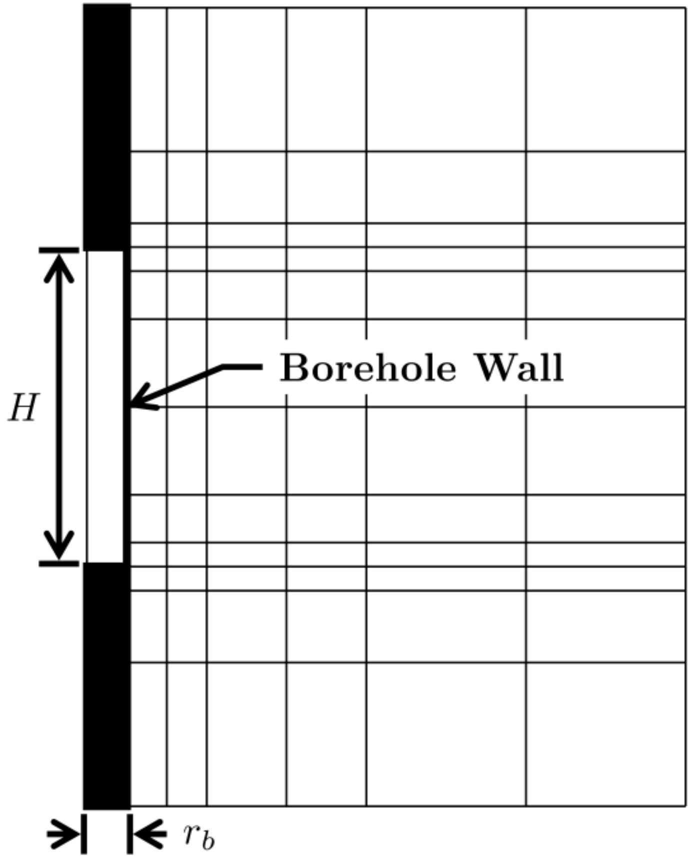
SHORT BOREHOLES



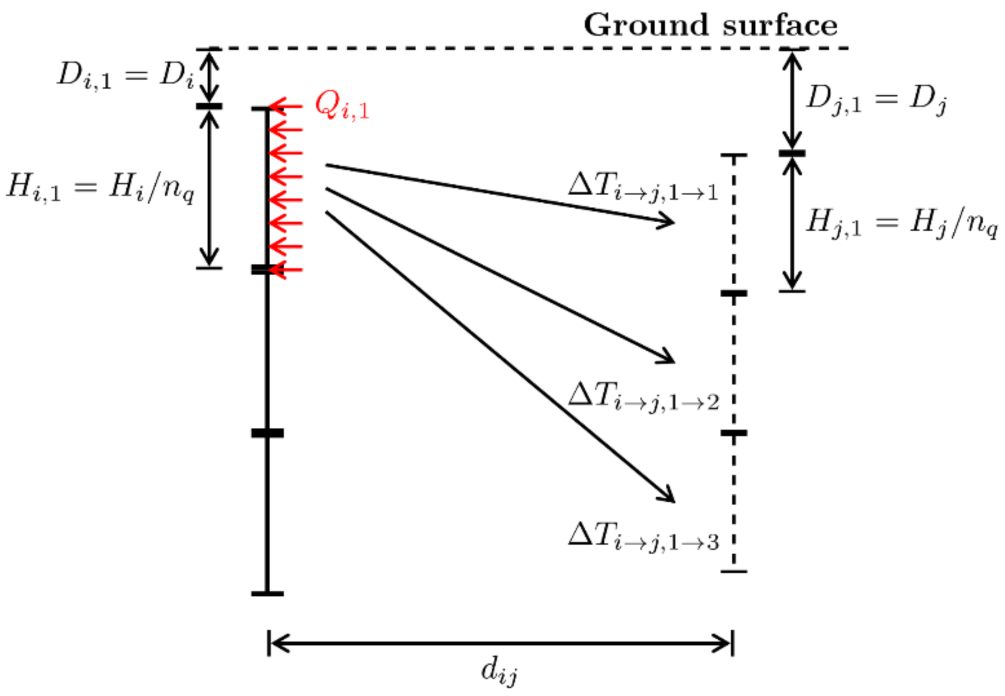


6×4 bore field with *H* = 5 m, *B* = 1 m, and r_b = 0.05 m

DETERMINATION OF G-FUNCTIONS

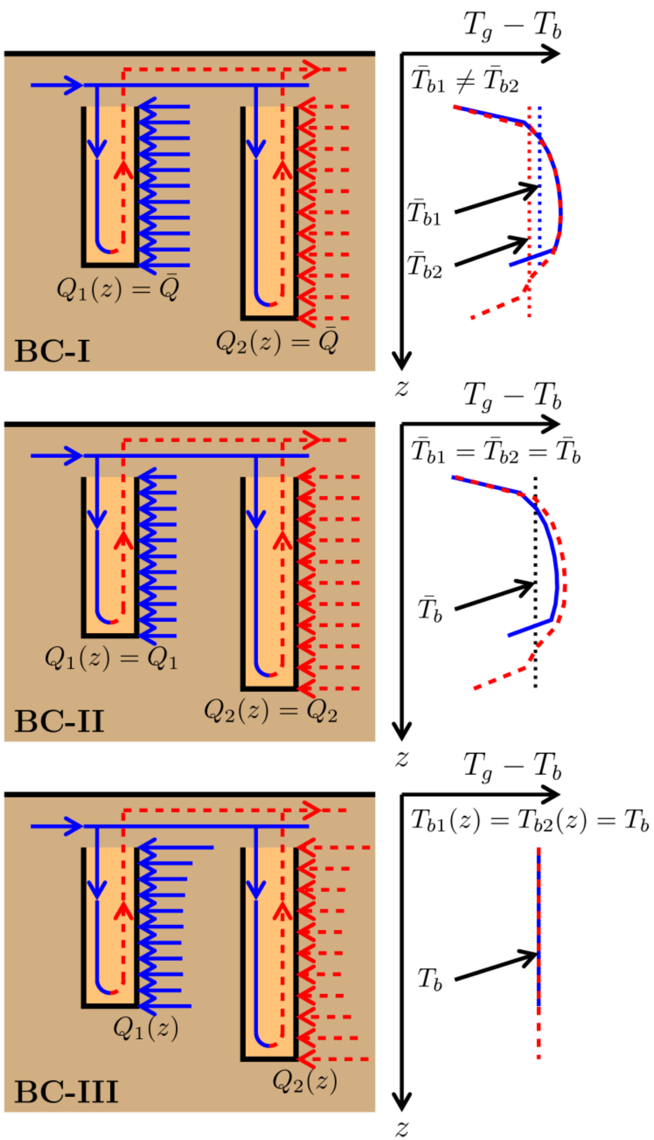


Numerically



Analytically using the Finite Line Source solution (see Cimmino and Bernier, 2014)

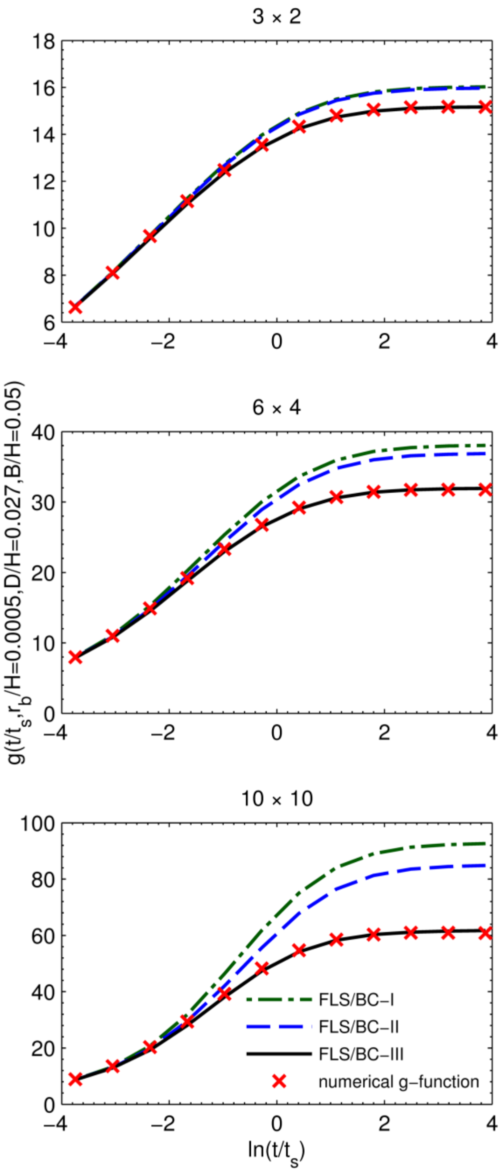
CALCULATION OF THERMAL RESPONSE FACTORS
BOUNDARY CONDITIONS AT THE BOREHOLE WALL



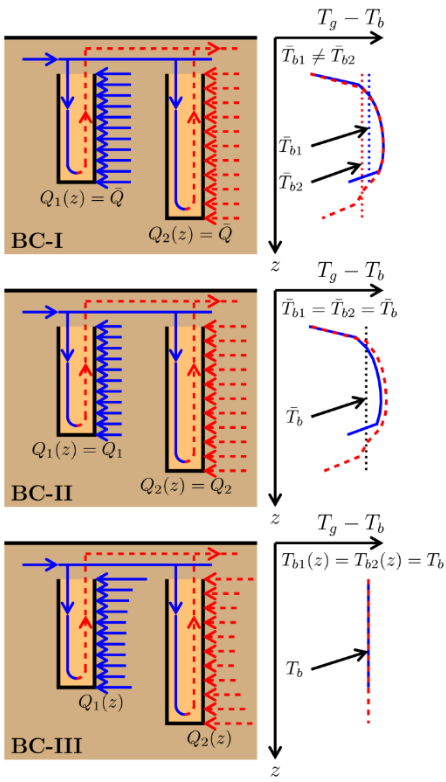
3 boundary conditions at the borehole walls are considered:

- BC-I :
  - **Uniform** heat extraction rate
  - Heat extraction rate **equal** for all boreholes
- BC-II :
  - **Uniform** heat extraction rates
  - Average borehole wall temperature **equal** for all boreholes
- BC-III :
  - **Uniform** borehole wall temperature
  - Borehole wall temperature **equal** for all boreholes

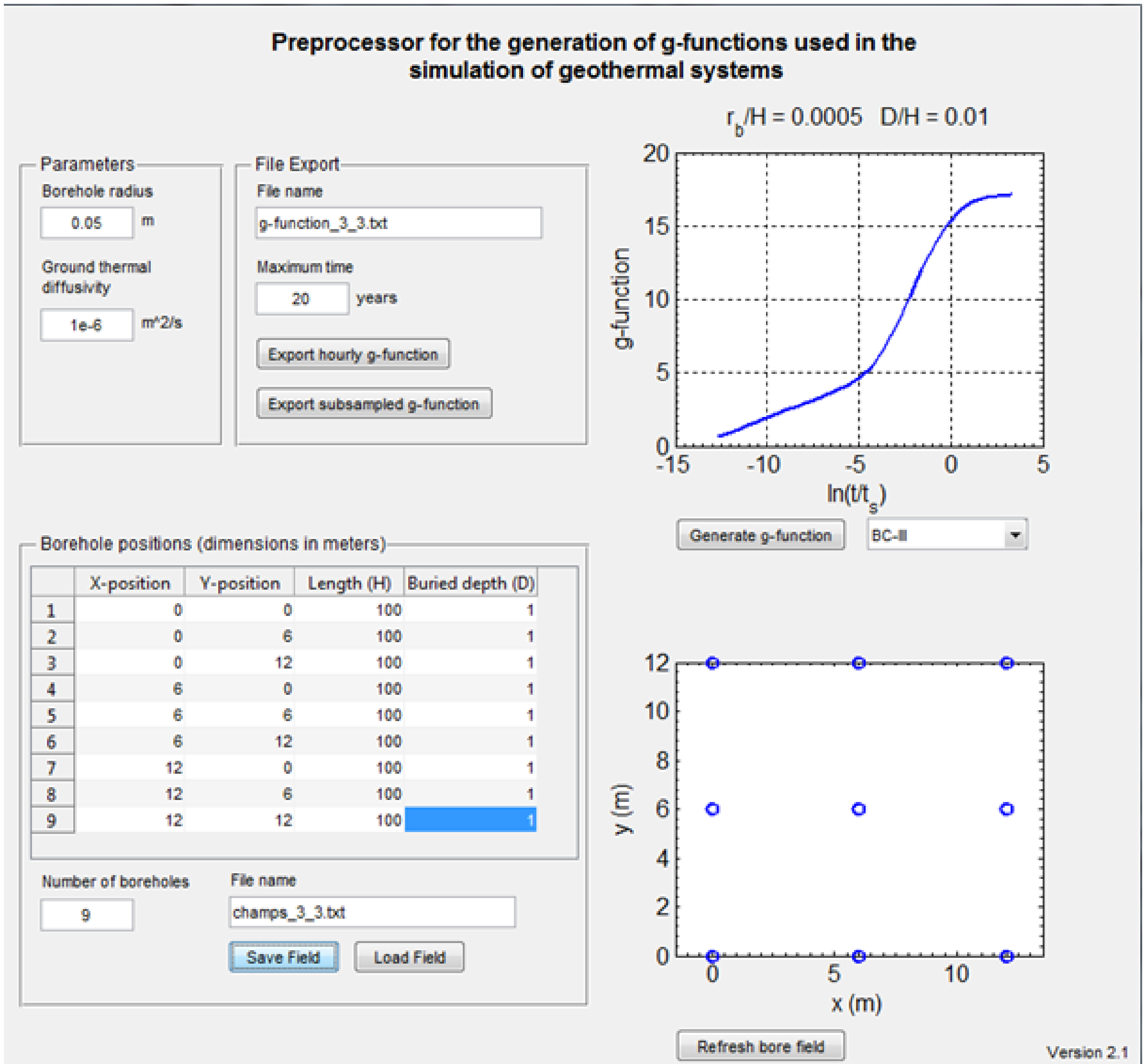
CALCULATION OF THERMAL RESPONSE FACTORS RESULTS (G-FUNCTIONS)



g-functions are compared to numerical g-functions obtained using Eskilson's model.



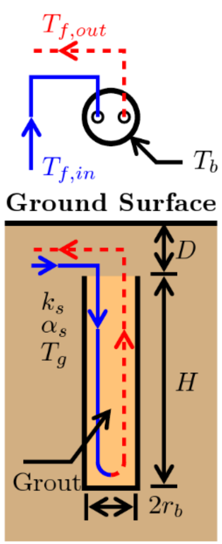
PRE-PROCESSOR OF G-FUNCTIONS

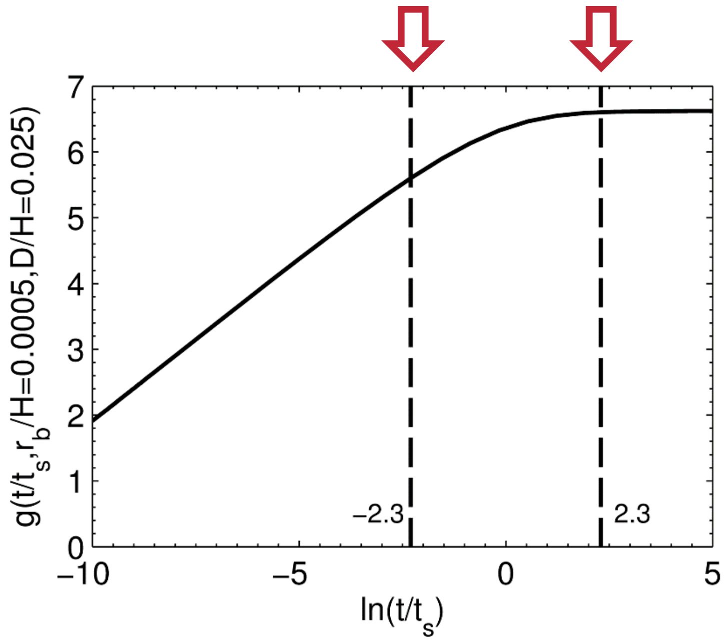


EXPERIMENTAL DETERMINATION OF G-FUNCTIONS SCALE REDUCTION

- For a single borehole:

8 years 800 years ⇦ 150 m borehole

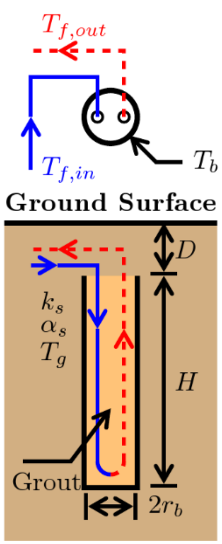


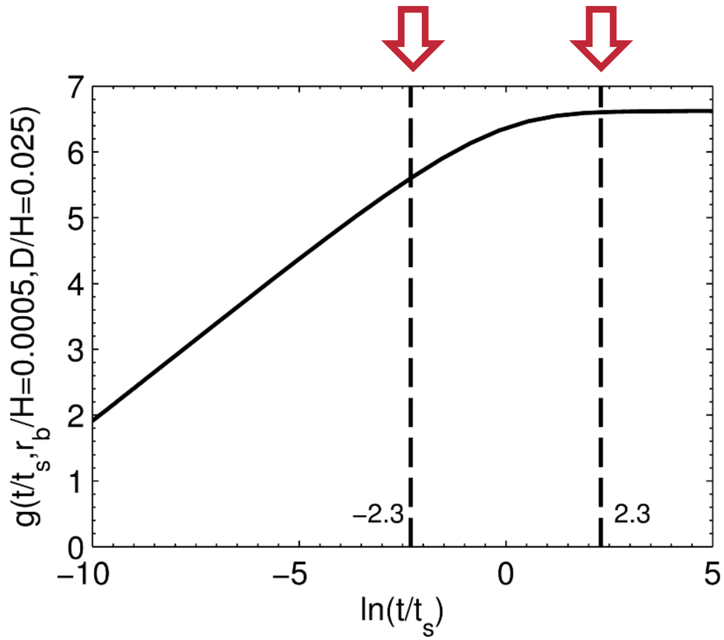


EXPERIMENTAL DETERMINATION OF G-FUNCTIONS SCALE REDUCTION

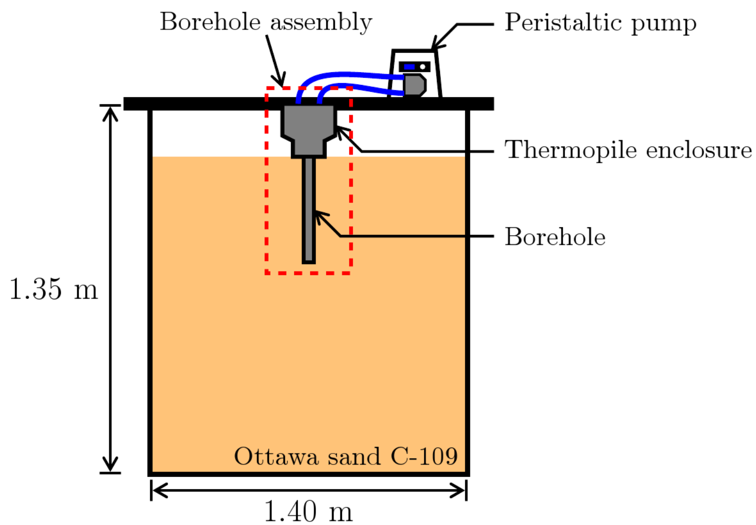
- For a single borehole:

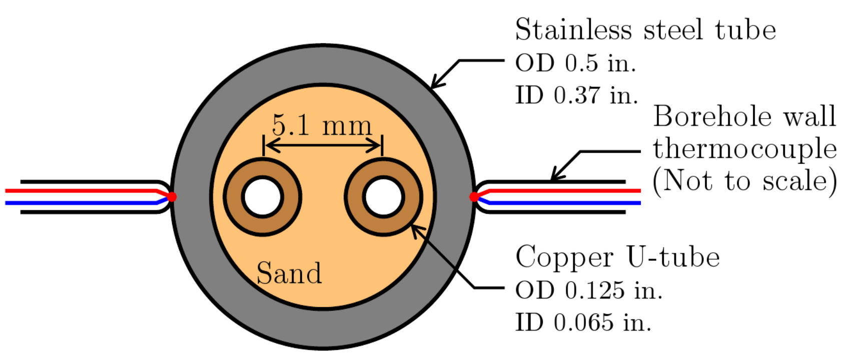
90 min   1 week   40 cm borehole

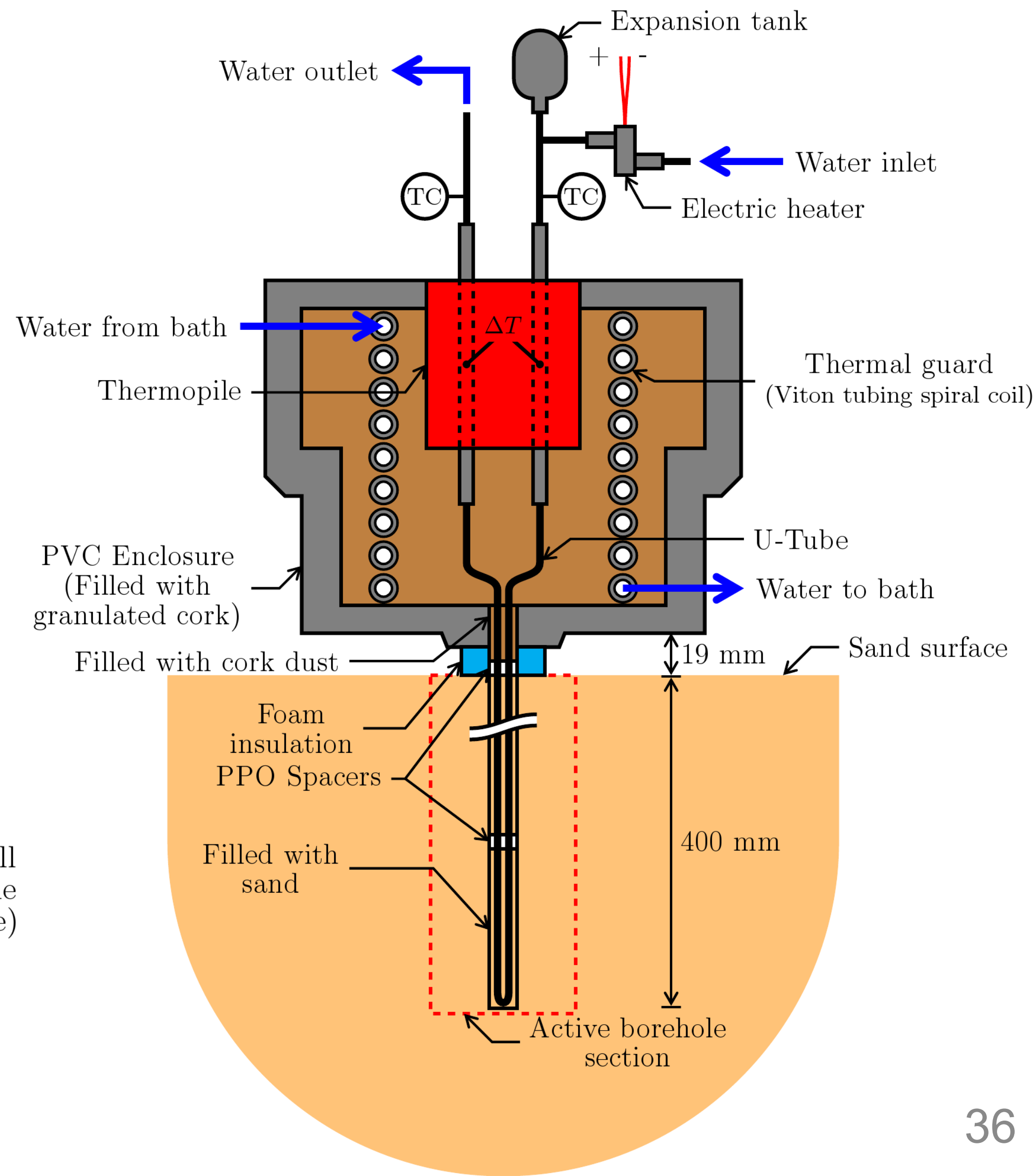




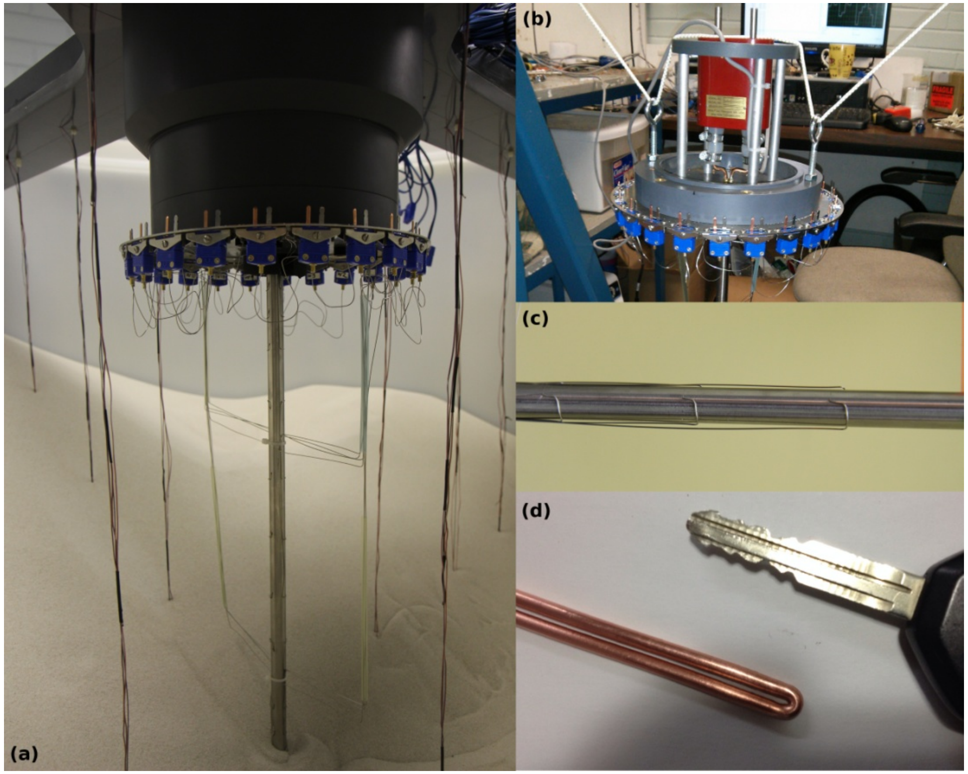
EXPERIMENTAL DETERMINATION OF G-FUNCTIONS
EXPERIMENTAL SET-UP (DIAGRAMS)

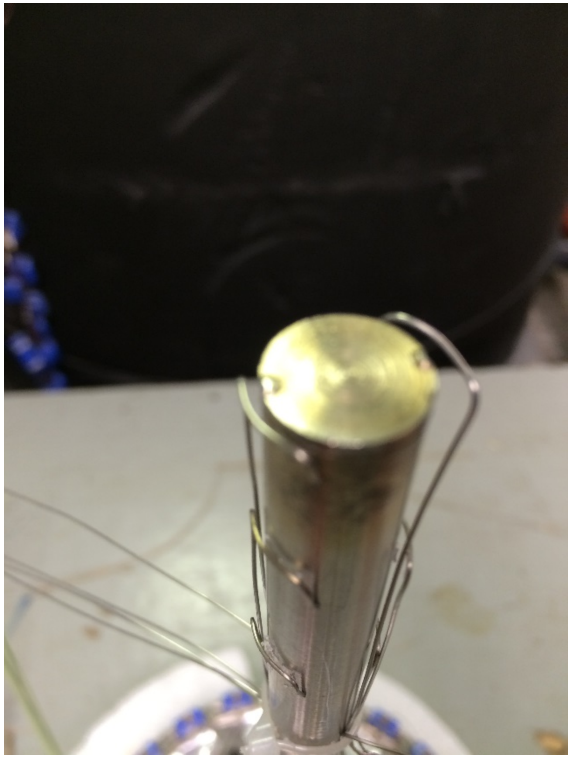




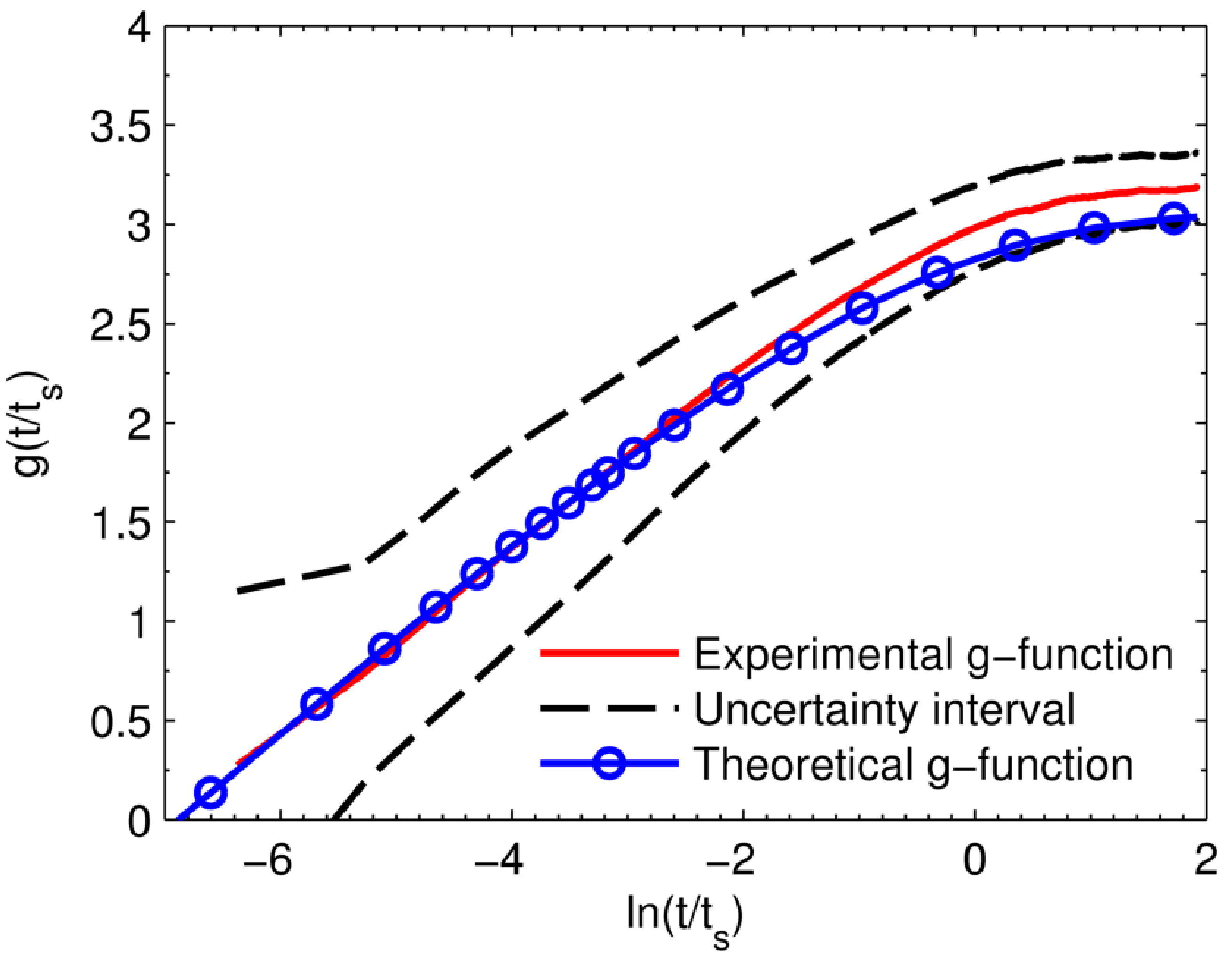


EXPERIMENTAL DETERMINATION OF G-FUNCTIONS





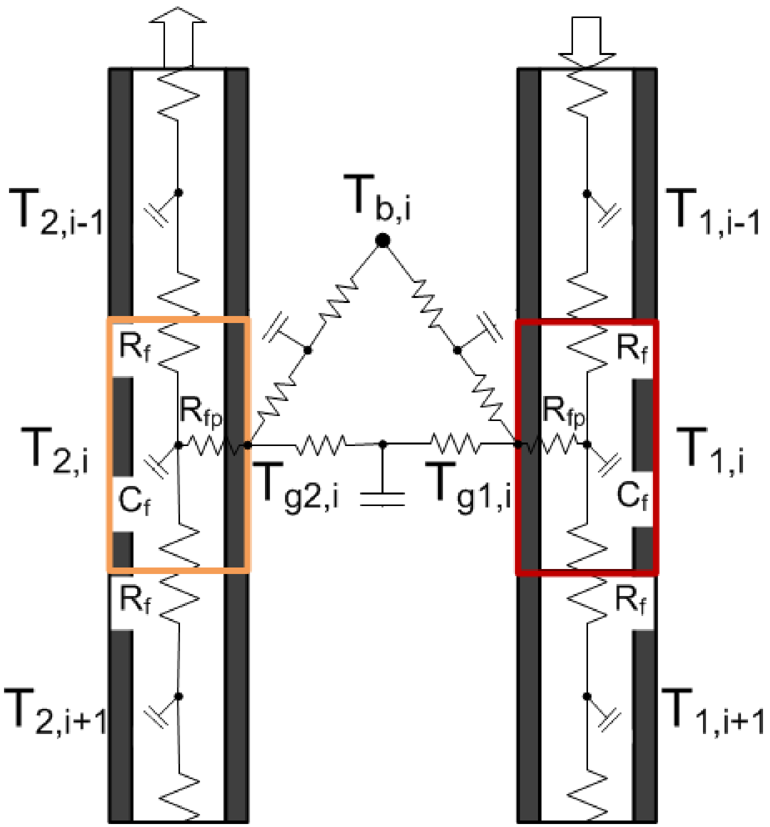
EXPERIMENTAL DETERMINATION OF G-FUNCTIONS

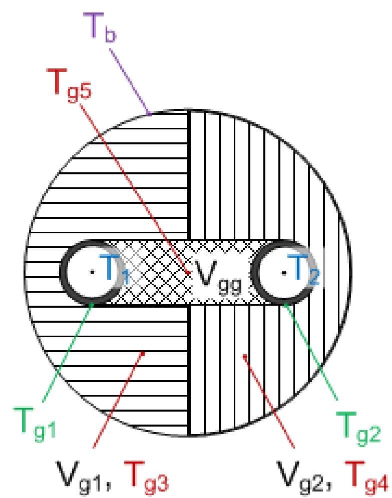


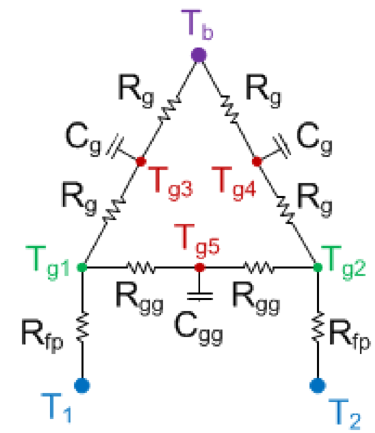
OUTLINE

- Introduction
- Sizing of bore fields
  - ASHRAE sizing method
  - Alternative methods
  - Exemple
- Thermal response factors (g-function)
  - Analytical determination
  - Pre-processor
  - Experimental validation
- Other work of interest
  - Thermal capacity in boreholes
  - Freezing around boreholes
  - Drake Landing Solar community
- Research needs
- Question period

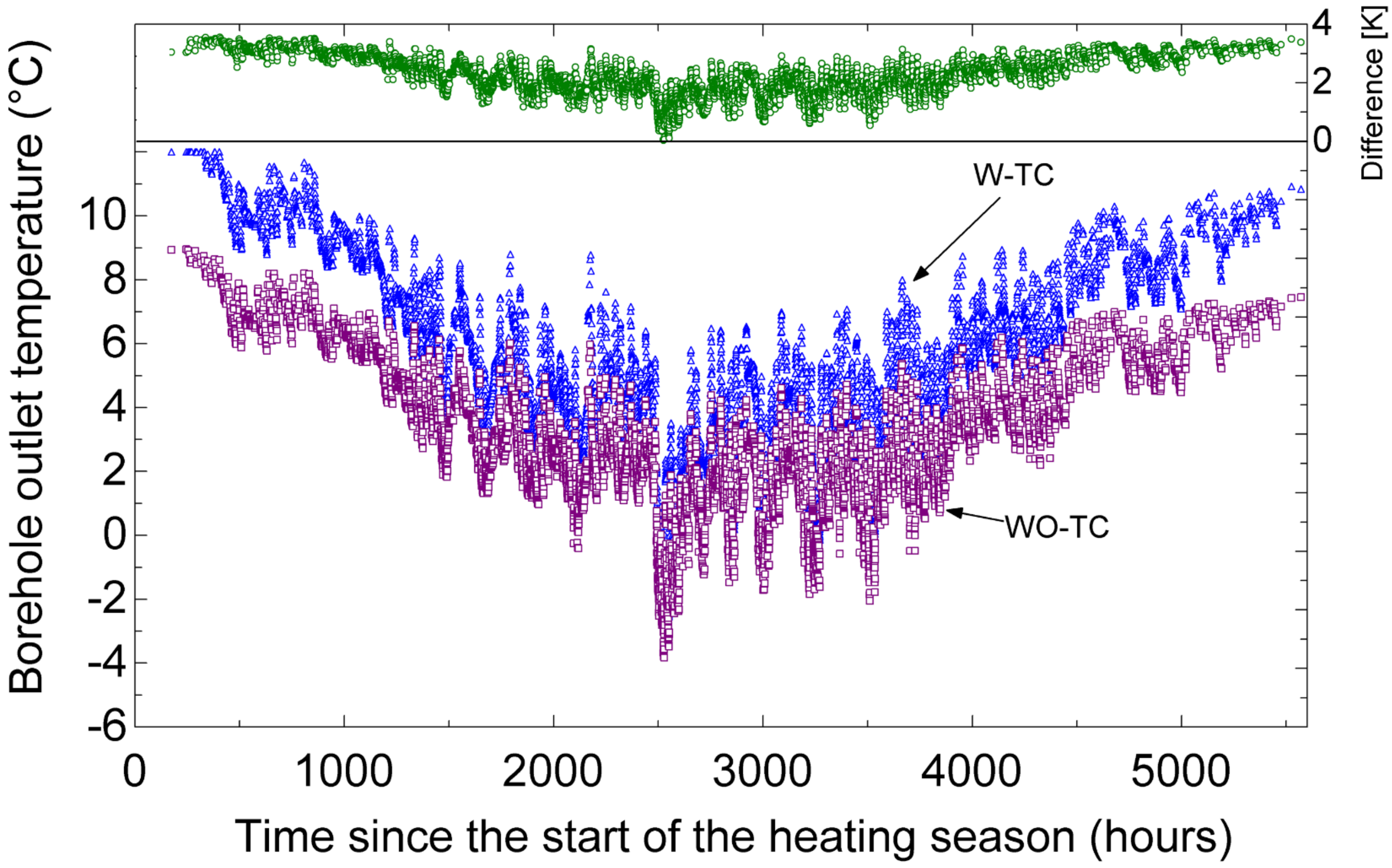
THERMAL CAPACITY IN BOREHOLES



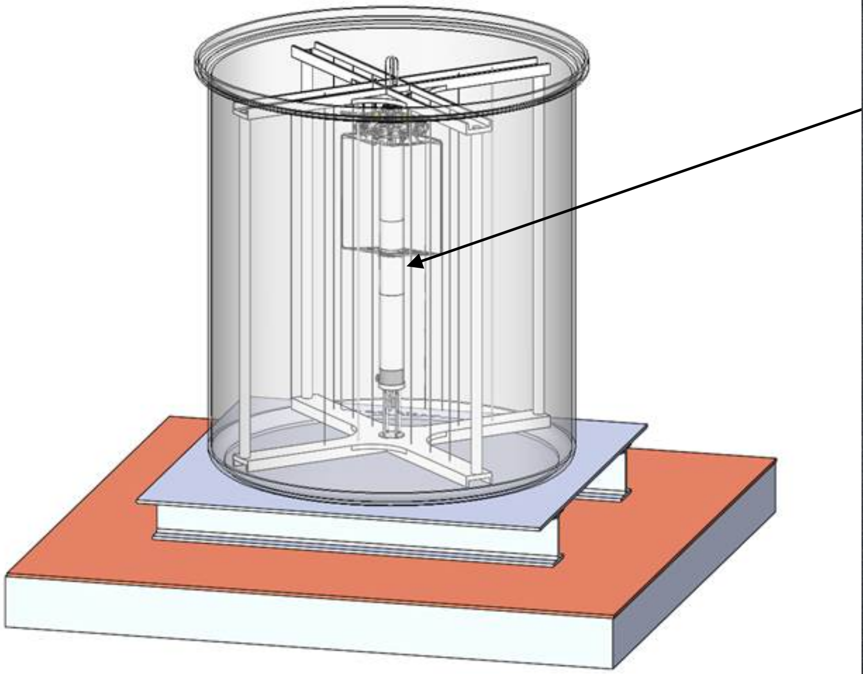


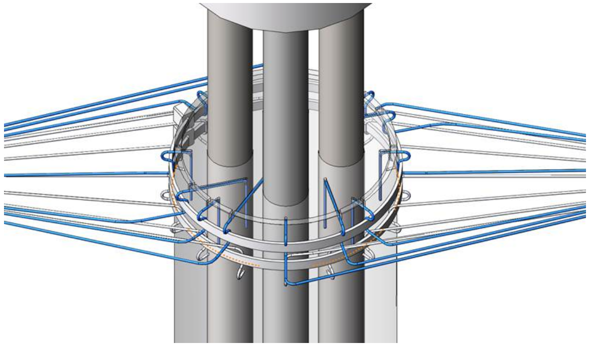


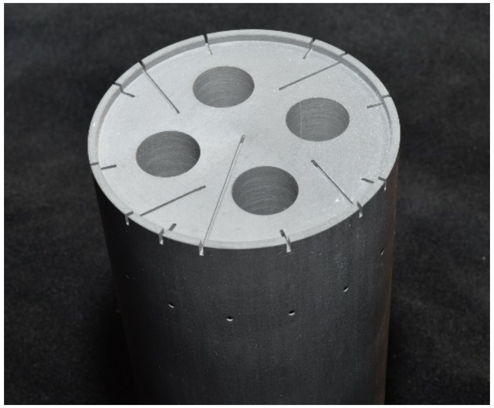
THERMAL CAPACITY IN BOREHOLES



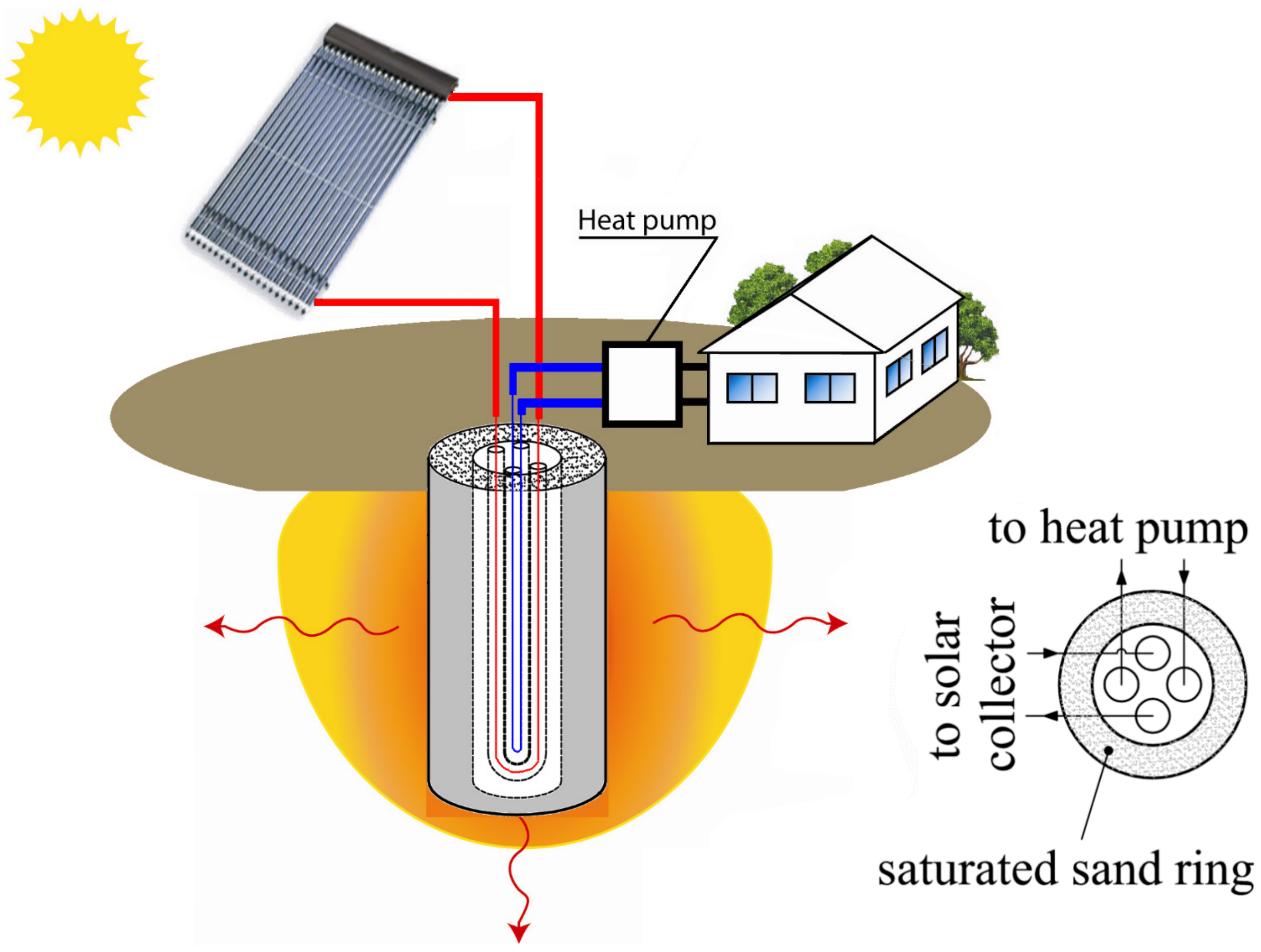
UPCOMING EXPERIMENTAL WORK ON TRANSIENT HEAT TRANSFER IN BOREHOLES



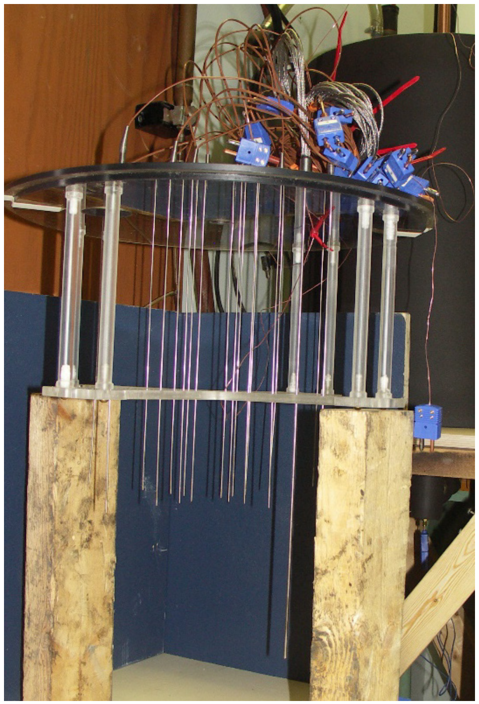


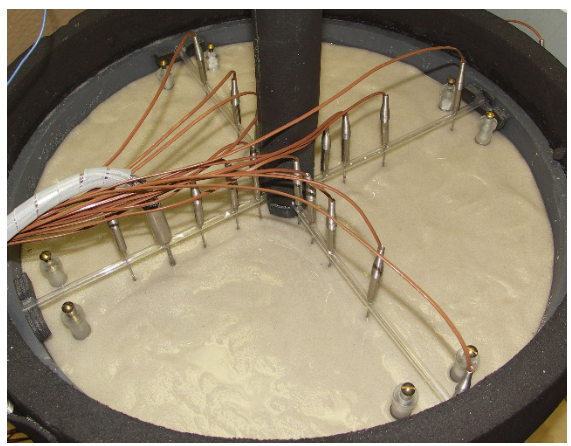


FREEZING OF GEOTHERMAL BOREHOLES

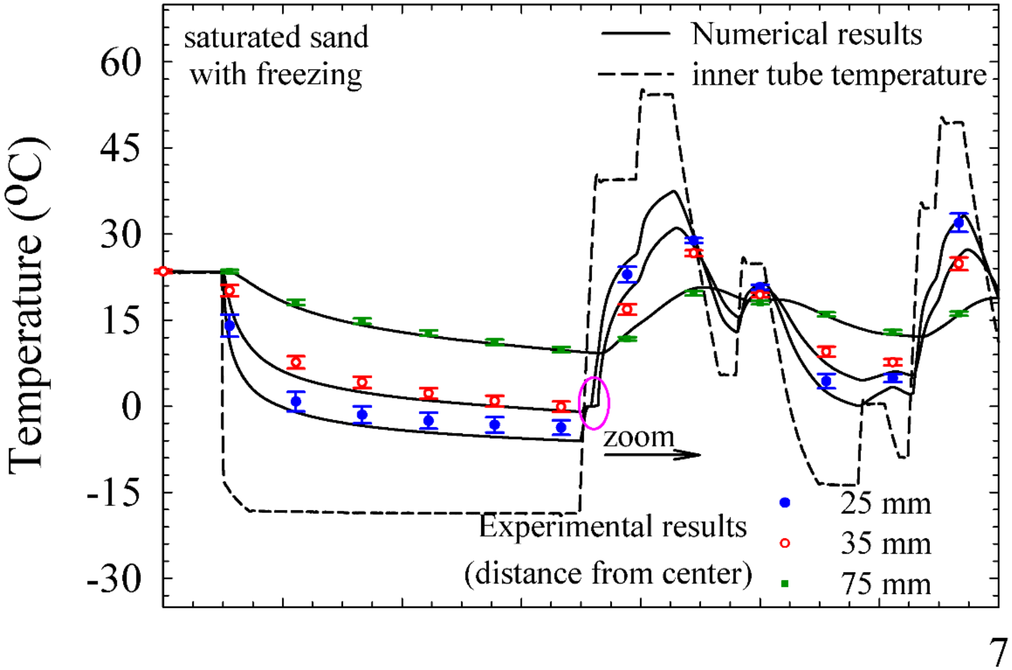


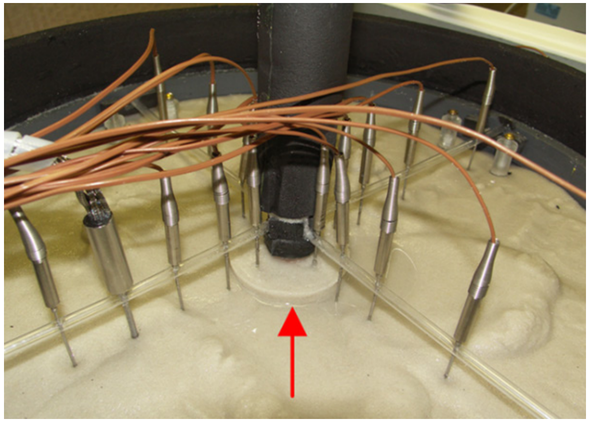
FREEZING OF GEOTHERMAL BOREHOLES

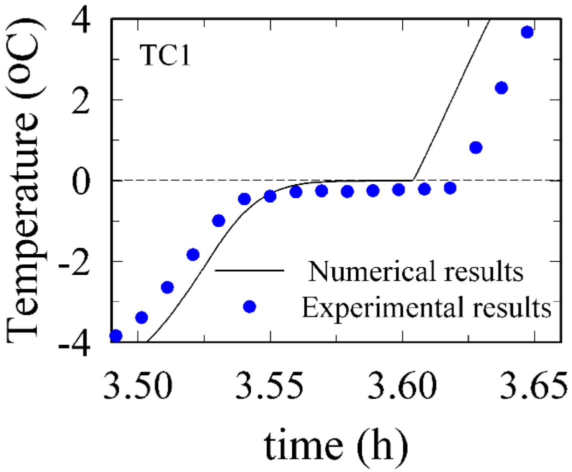




FREEZING OF GEOTHERMAL BOREHOLES

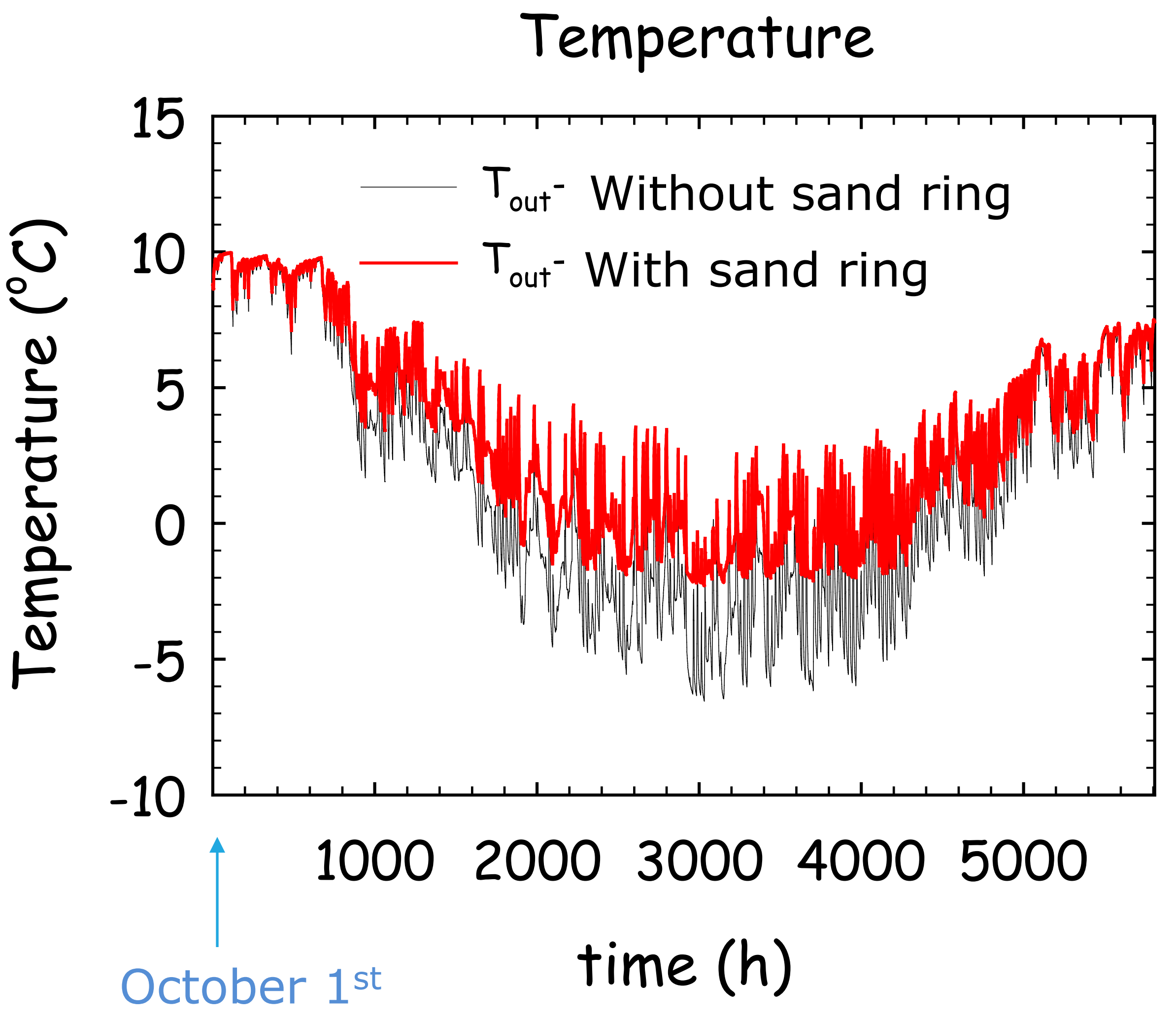






(b)

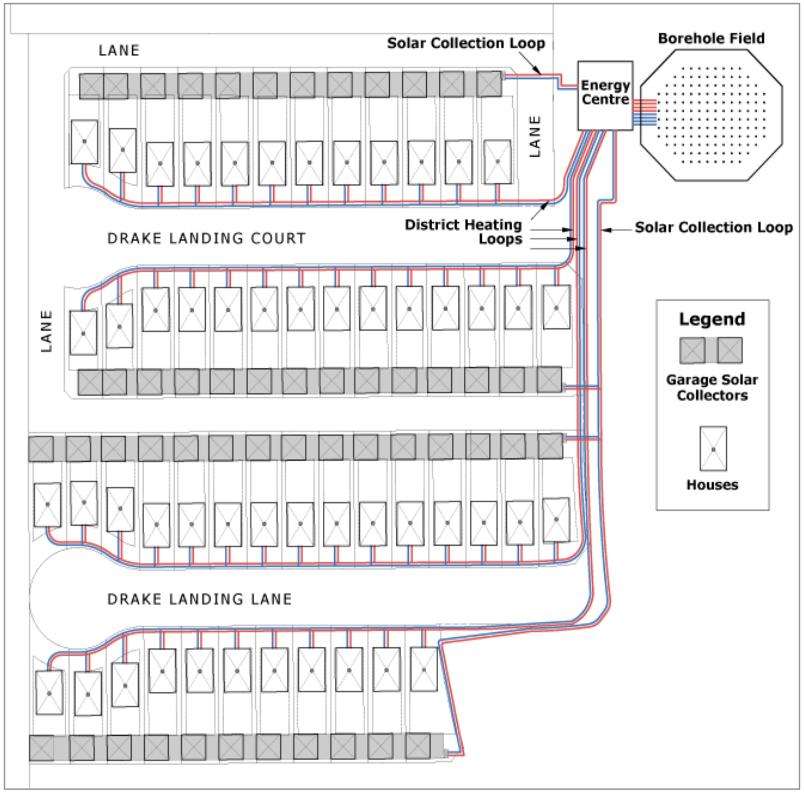
FREEZING OF GEOTHERMAL BOREHOLES



Can reduce borehole length by 38% in low k grounds

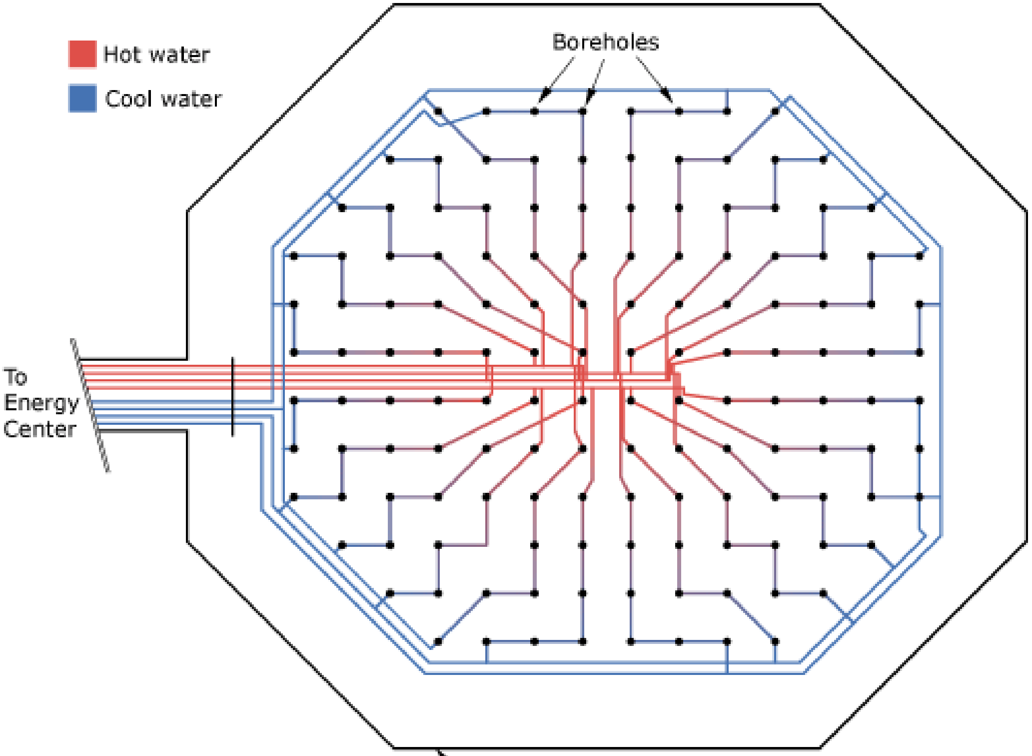
BOREHOLE THERMAL ENERGY STORAGE

Drake Landing Solar Community

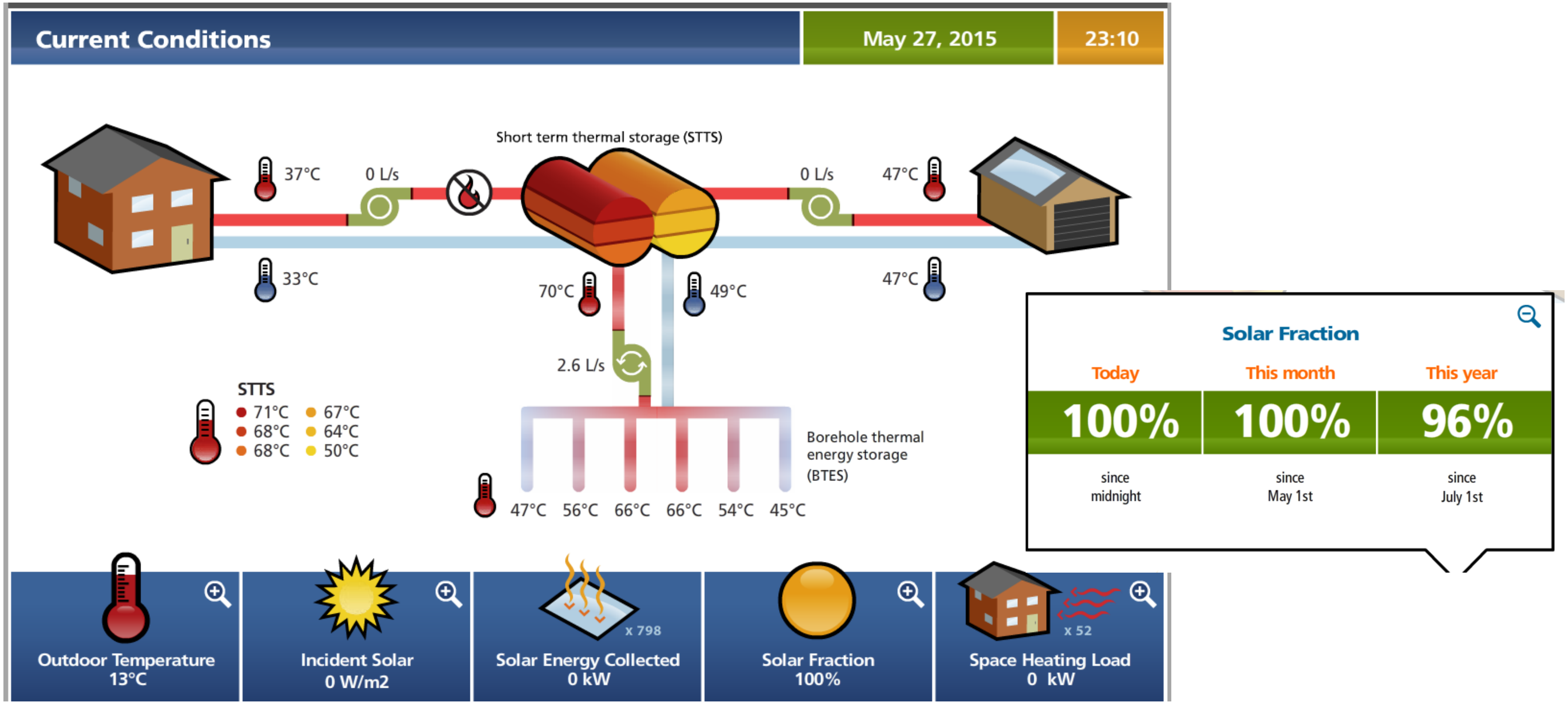


Source : dlsc.ca

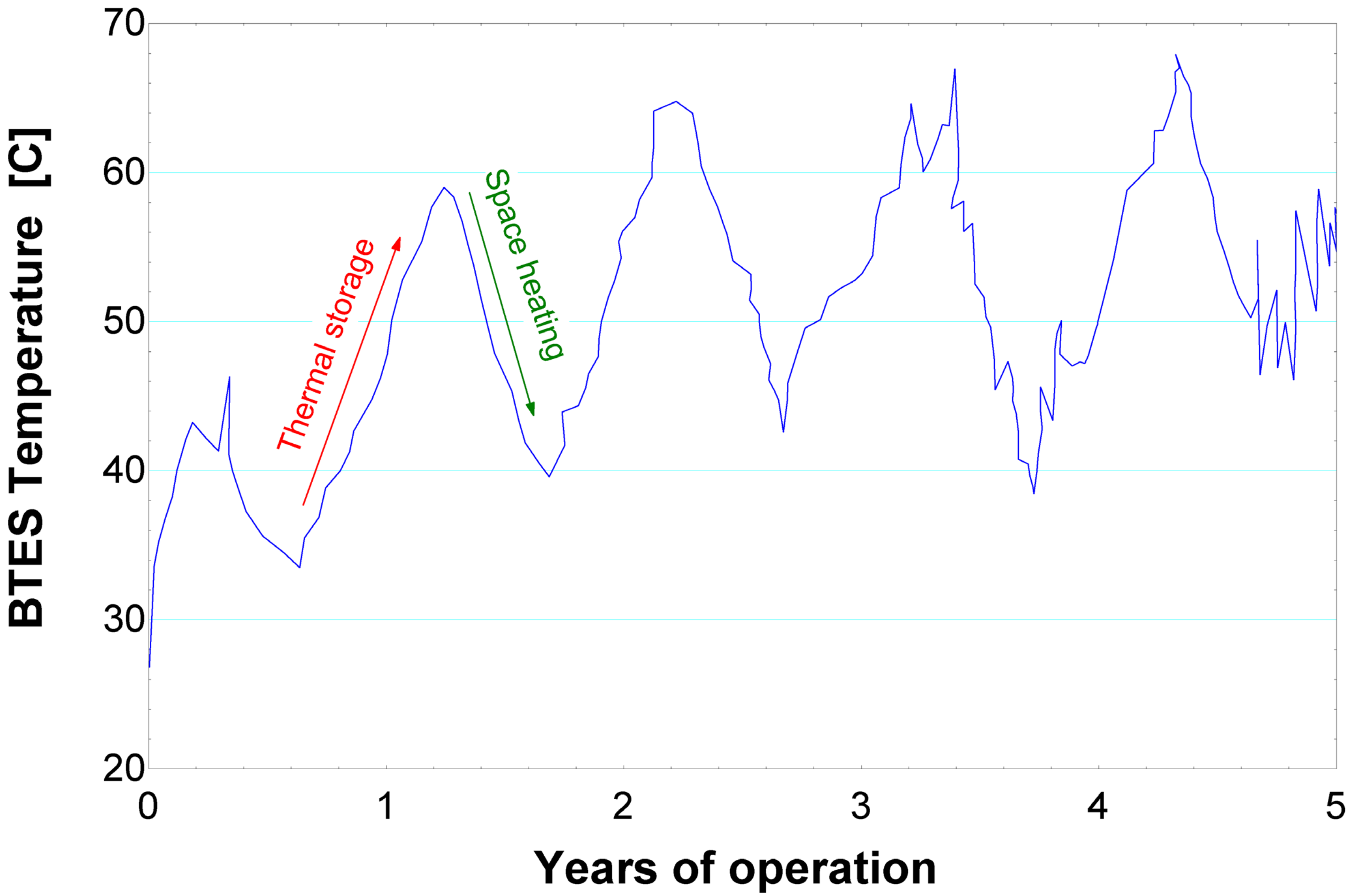
BOREHOLE THERMAL ENERGY STORAGE



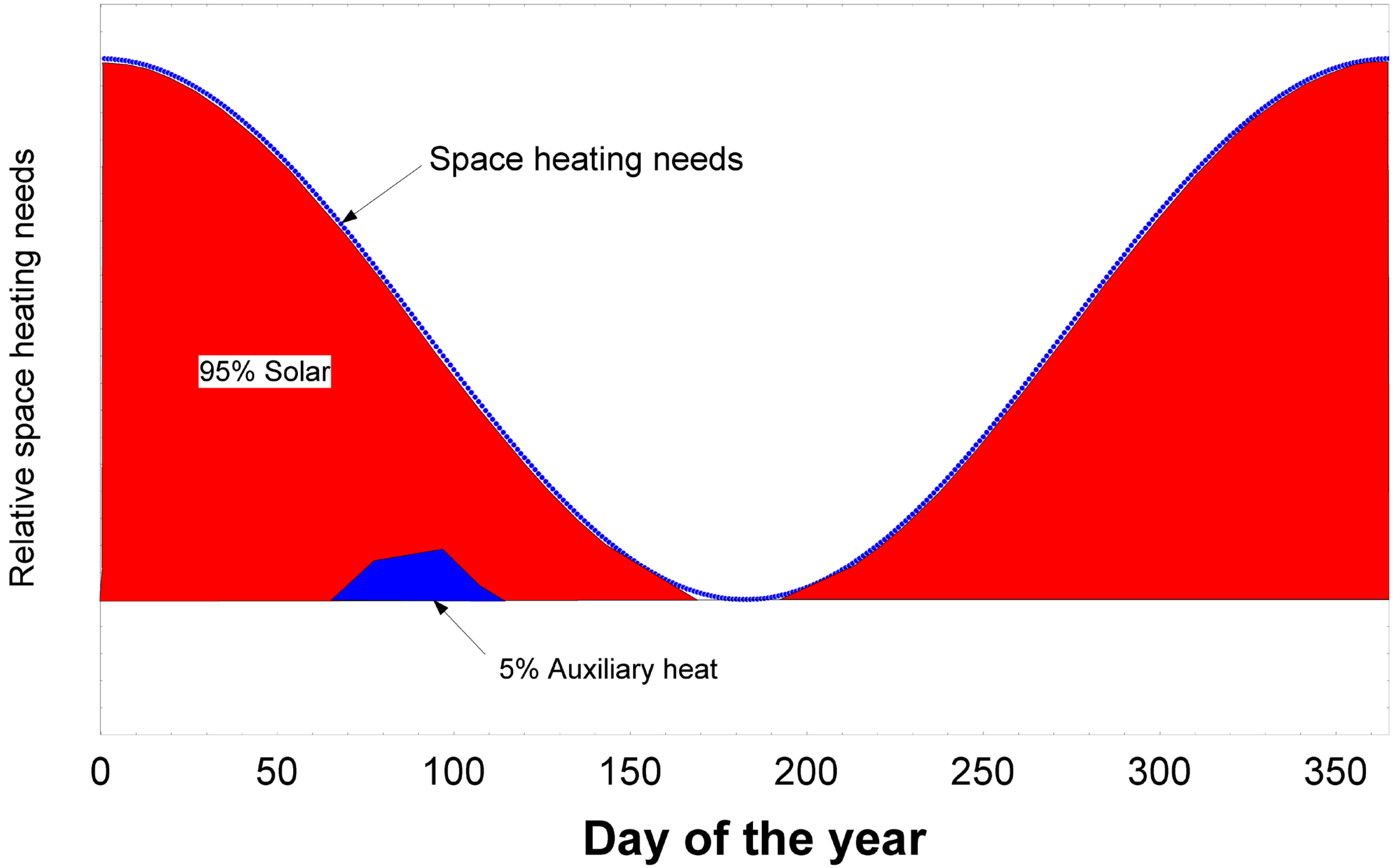
DLSC –CURRENT CONDITIONS



DLSC – MEASUREMENTS

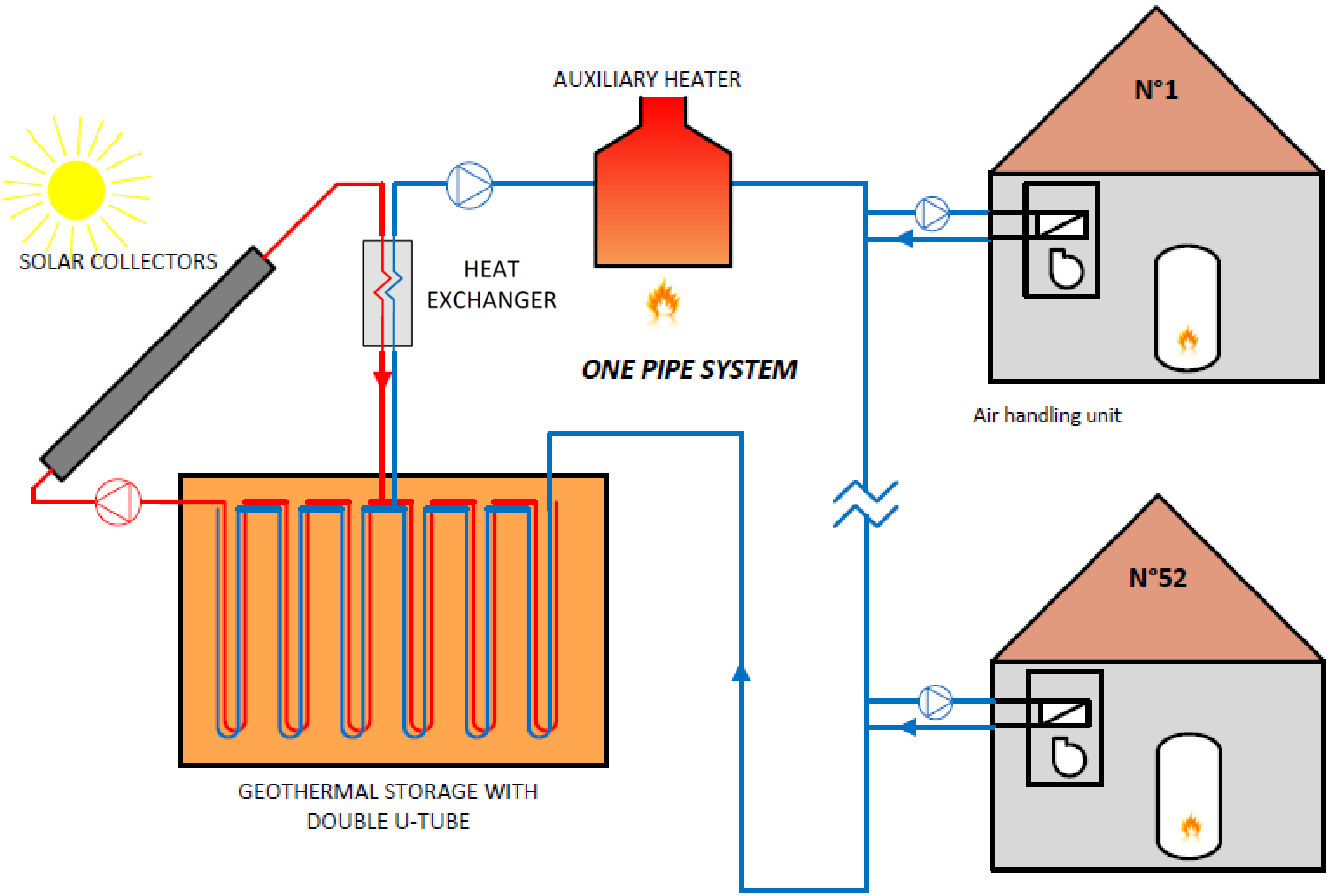


DLSC – CURRENT SYSTEM



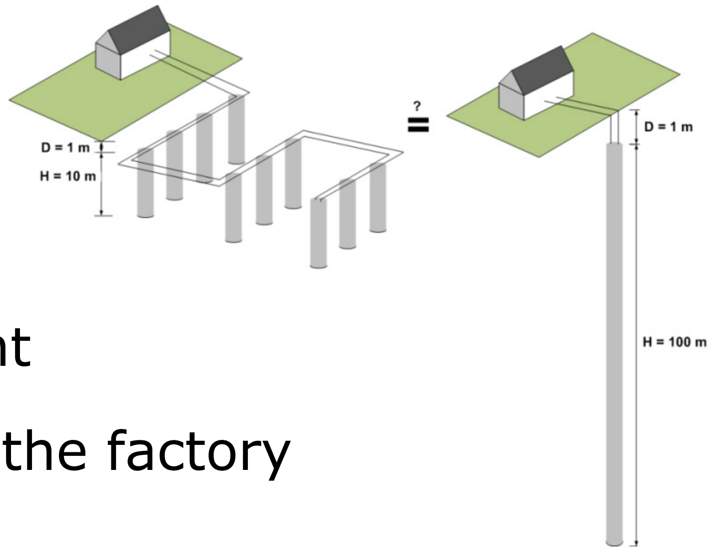
Solar fraction of 95% in year 5

PROPOSAL : SIMULTANEOUS CHARGE/DISCHARGE



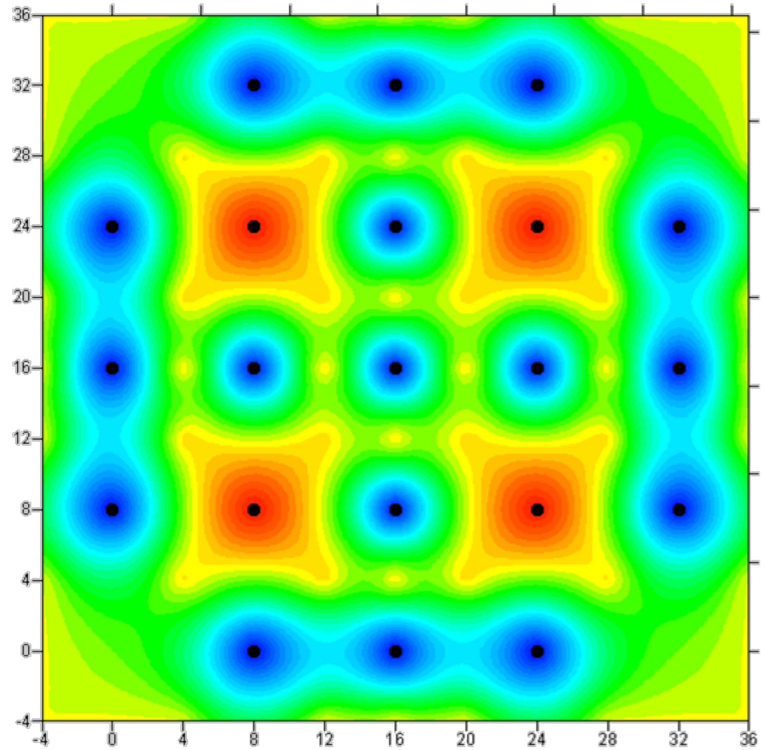
RESEARCH NEEDS

- Short boreholes
  - Surface effects become important
  - Need to model borehole is series
  - Horizontal piping becomes important
  - Can we produce these boreholes in the factory (like sausages !)



RESEARCH NEEDS

- Modeling of borehole fields with arbitrary geometry including boreholes in series has to go mainstream in general simulation program (TRNSYS, EnergyPlus …)



RESEARCH NEEDS

- Good experimental data over a number of years to validate long-term modelling
- Thermal capacity effects of the fluid in the borehole and in the building loop have to be properly accounted in energy simulations and in sizing.

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