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Thermal Energy Storage in Borehole Heat Exchanger Arrays

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Acknowledgements

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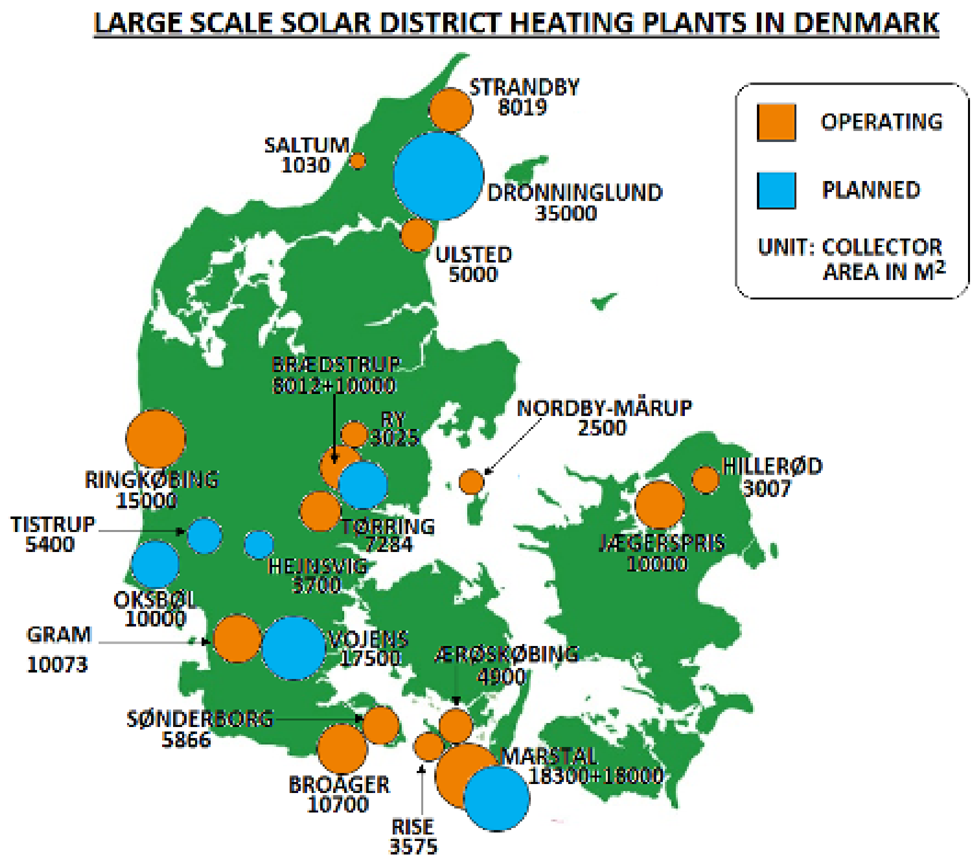
- Collaborators:
  - Ning Lu, Colorado School of Mines (geotech. eng.)
  - Shemin Ge, University of Colorado Boulder (hydrogeologist)
  - Kathleen Smits, Colorado School of Mines (env. science)
  - Adam Reed, University of Colorado Boulder (energy policy)
- Graduate Students:
  - Tugce Baser, UC San Diego
  - Nora Catolico, CU Boulder

Presentation Overview

- Overview of Soil-Borehole Thermal Energy Storage (SBTES) systems
- Simulation of Drake Landing Solar Community SBTES system using TOUGH2
- Design simulations of a small-scale SBTES in Golden, CO using COMSOL
- Field data from small-scale SBTES in Golden, CO
- Simulations of the scalability of SBTES systems
- Upcoming large-scale SBTES system in San Diego, CA

District Heating using Solar Thermal Energy



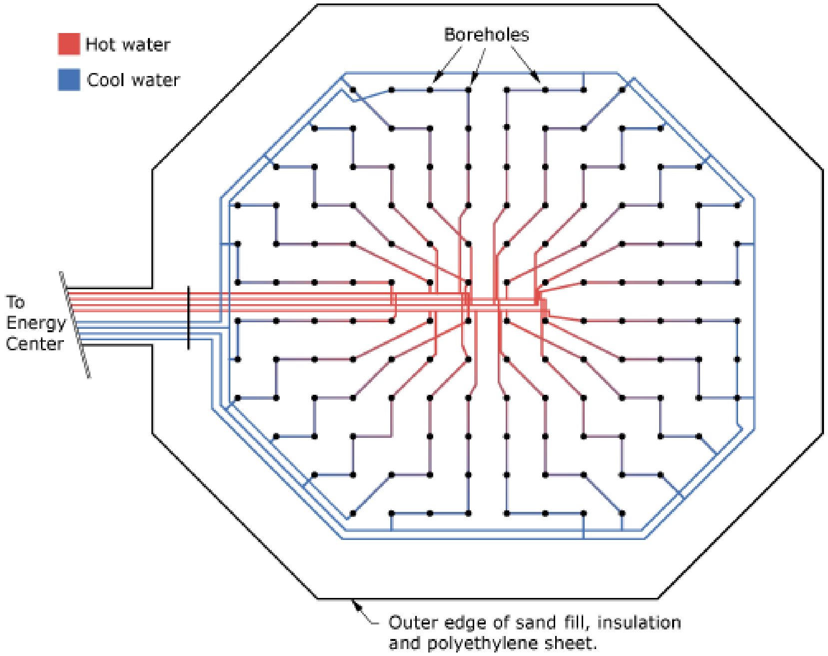
Challenge: Heat storage


Drake Landing, Canada


Braedstrup, Denmark

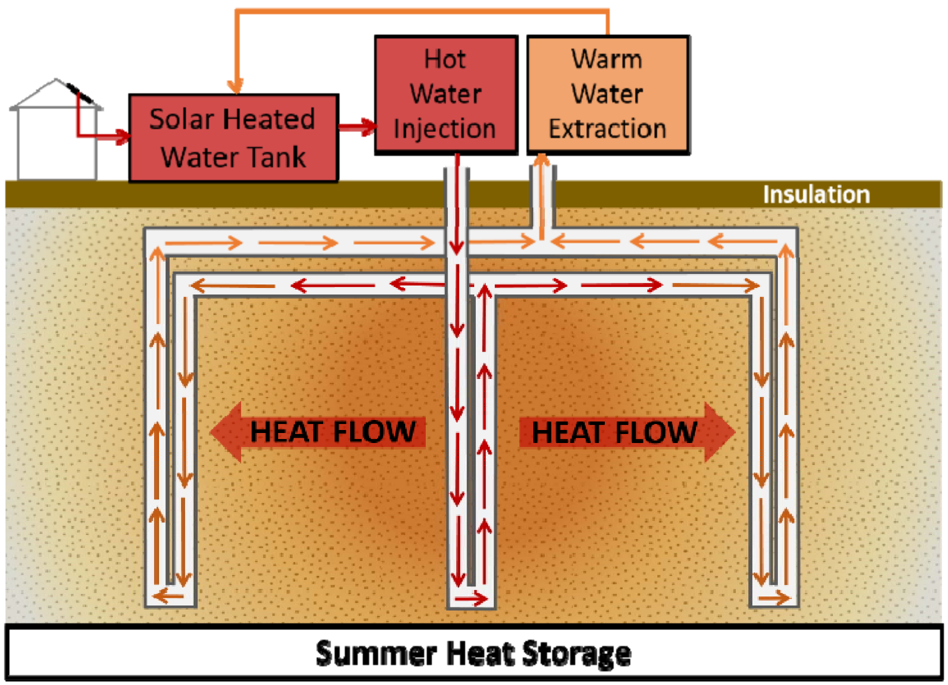
Heat Storage Option: Geothermal Boreholes

Sheffield, UK

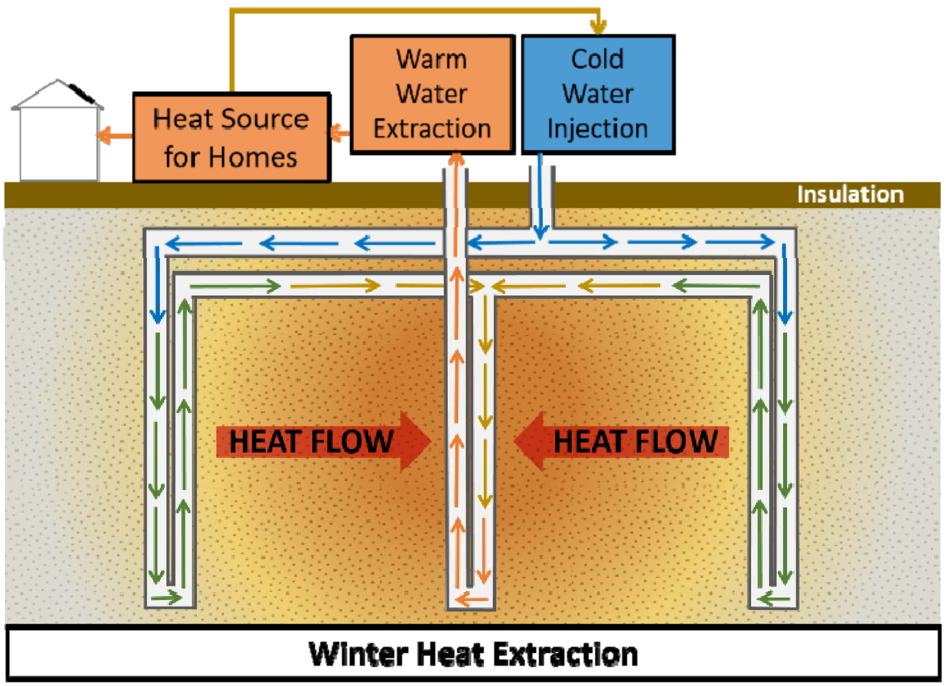


Drake Landing, Canada

SBTES System Operation



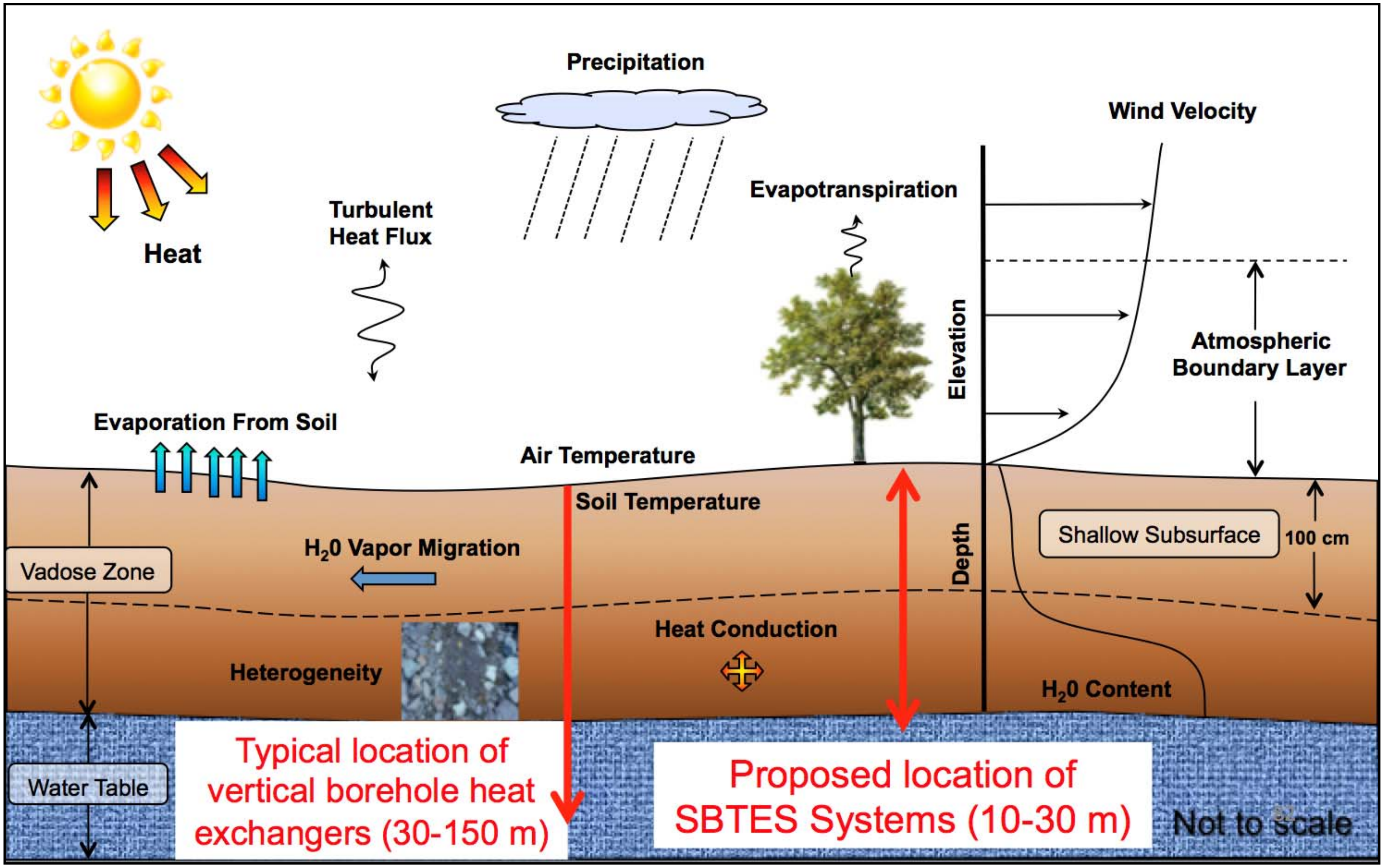
Heat Injection



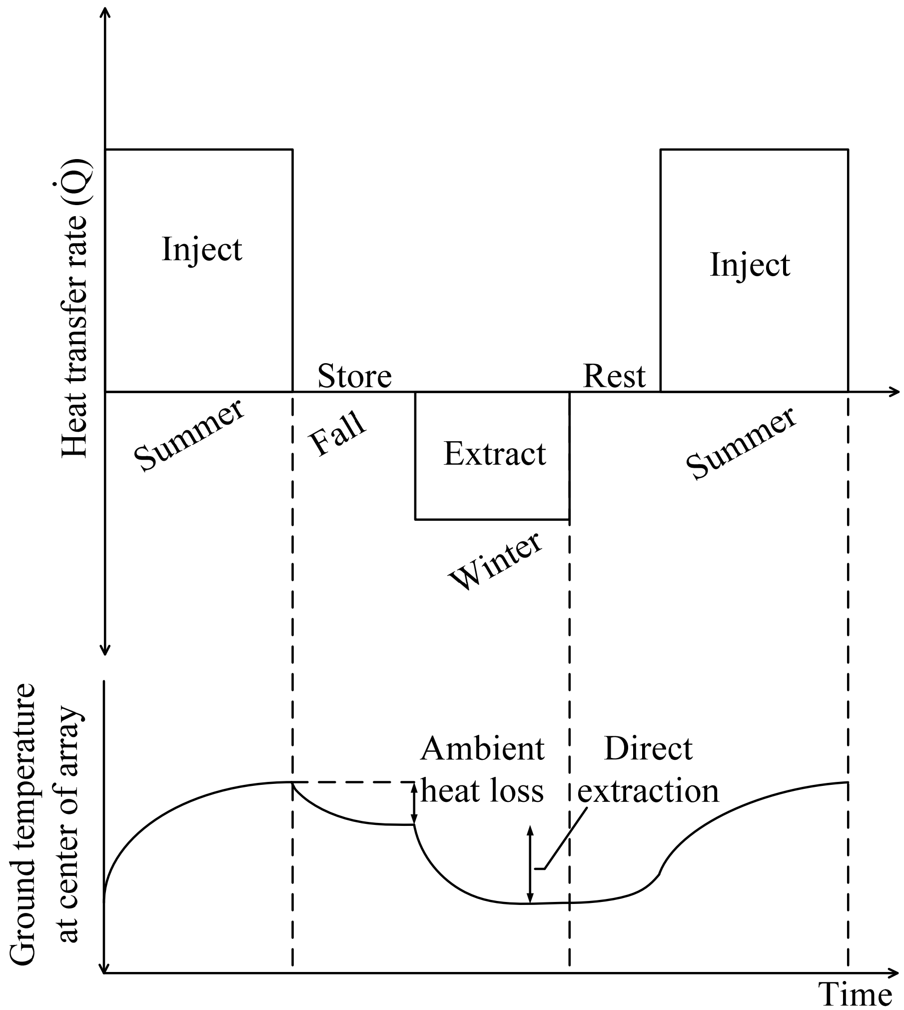
Heat Extraction

$$Efficiency = \frac{Heat\ Extraction}{Heat\ Injection}$$

SBTES Systems within the Vadose Zone



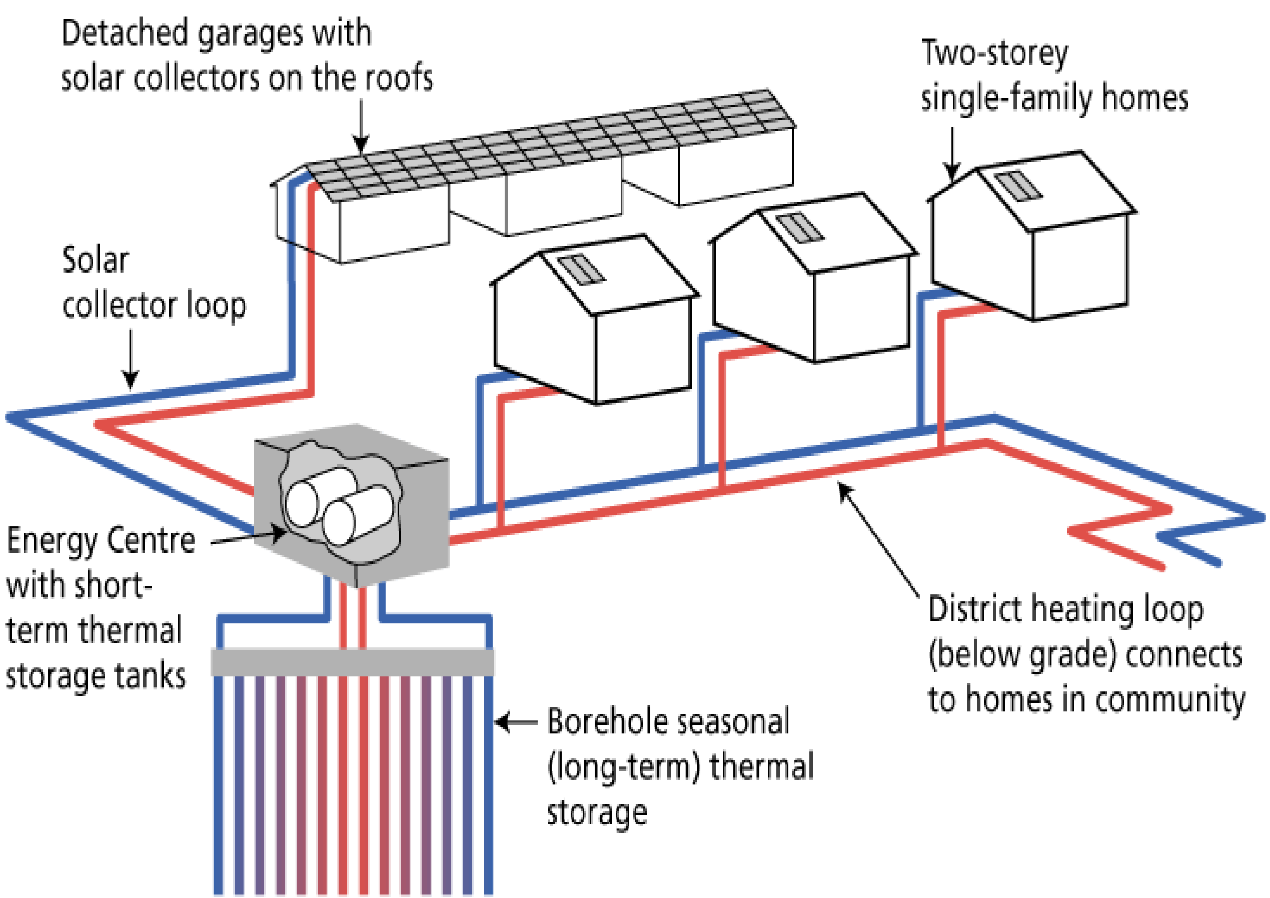
Operation of SBTES Systems



Overall study goals:

1. Understand the role of heat exchanger array geometry
2. Calibrate models using field-scale data from existing and new SBTES sites
3. Evaluate coupled heat transfer and water flow processes in the vadose zone
4. Understand scalability of SBTES arrays
5. Evaluate ways to improve the efficiency of heat extraction

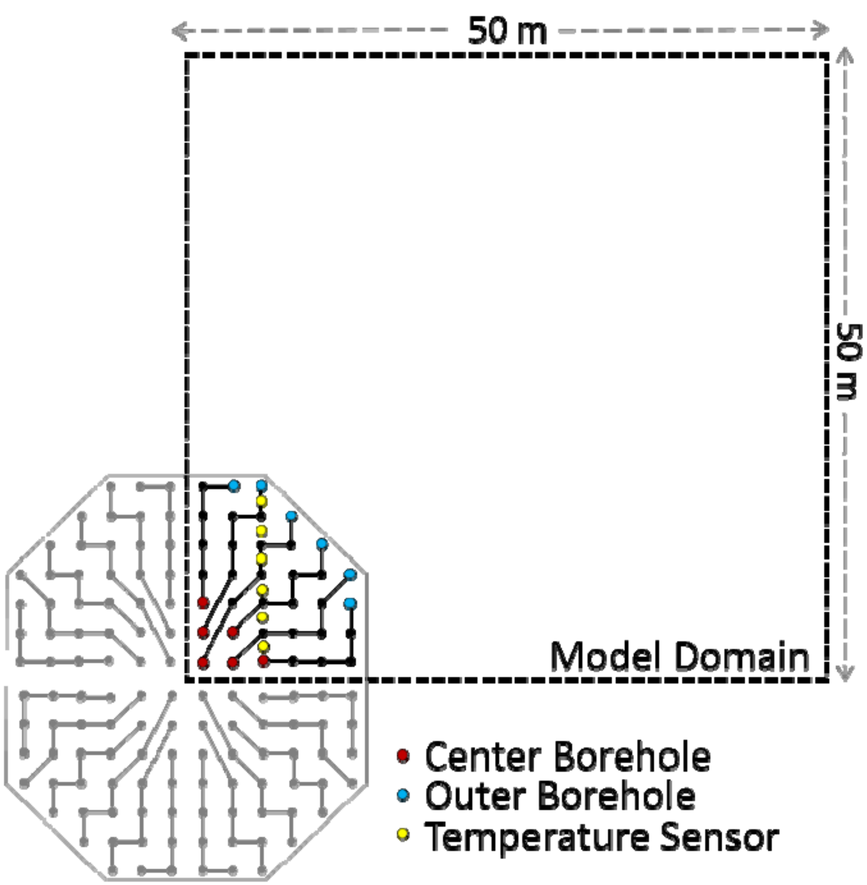
Drake Landing Solar Community (DLSC)

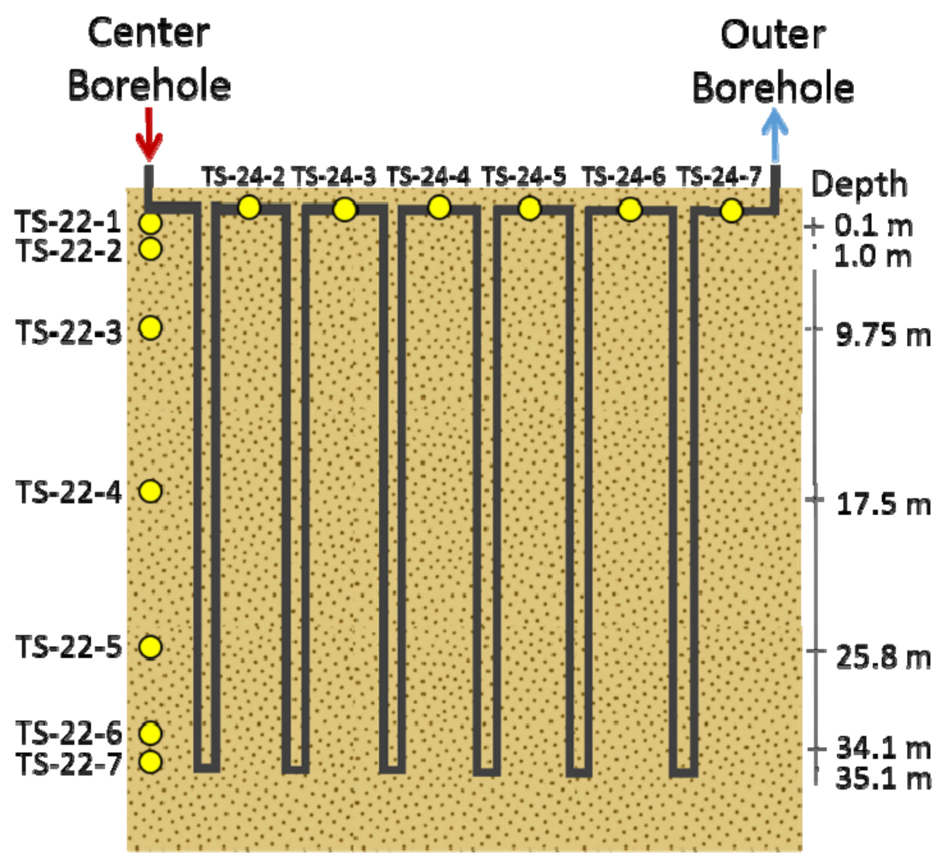


Drake Landing Solar Community (DLSC) Okotoks, Alberta, Canada

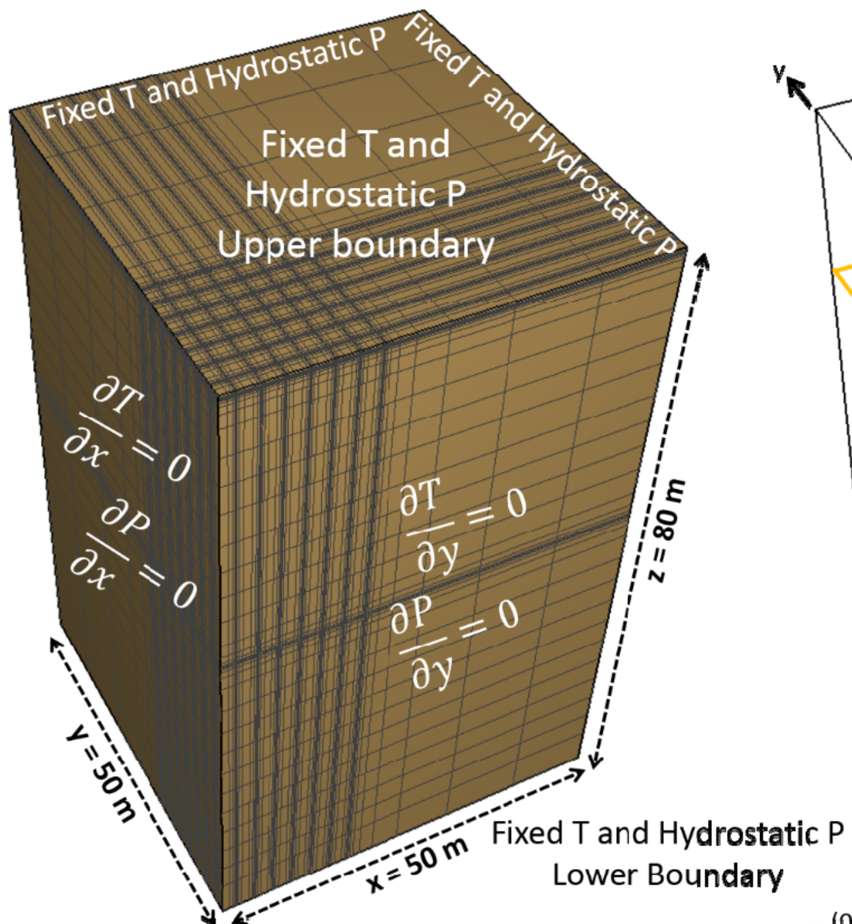
35mx35mx35m SBTES used to provide 95% of the heat to 52 homes

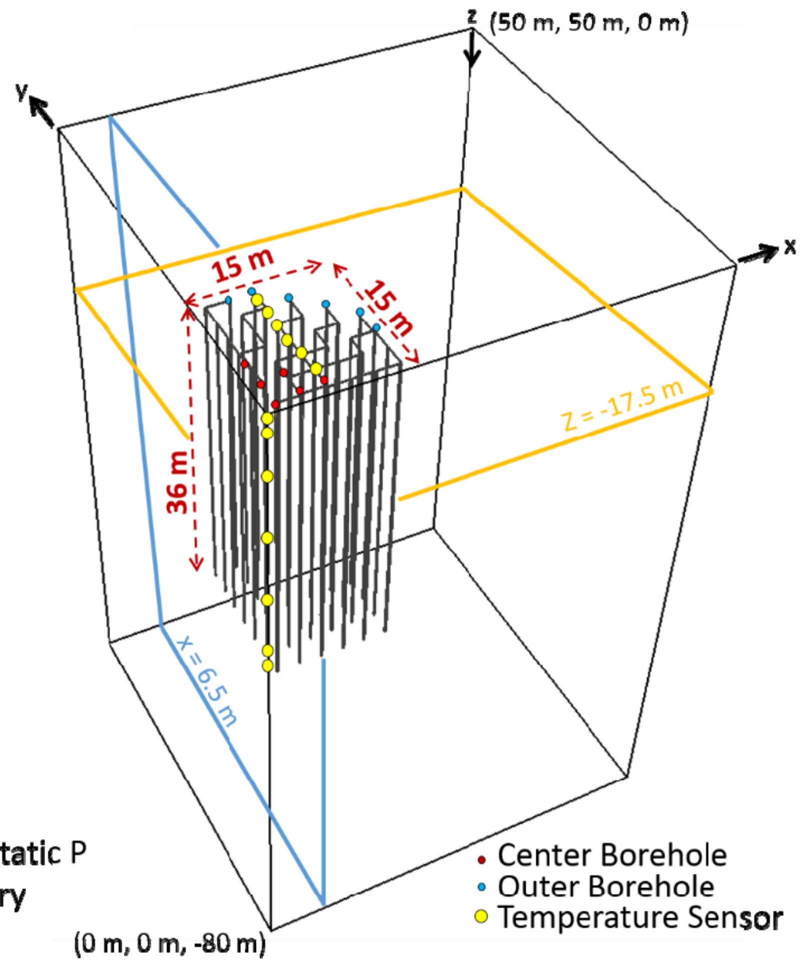
DLSC SBTES Numerical Model Domain



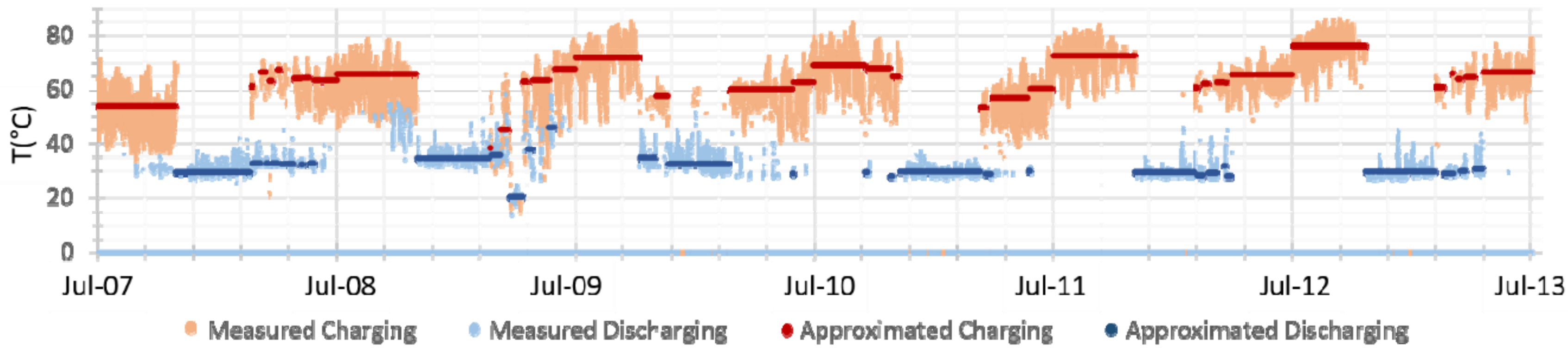


DLSC Numerical Model (TOUGH2)



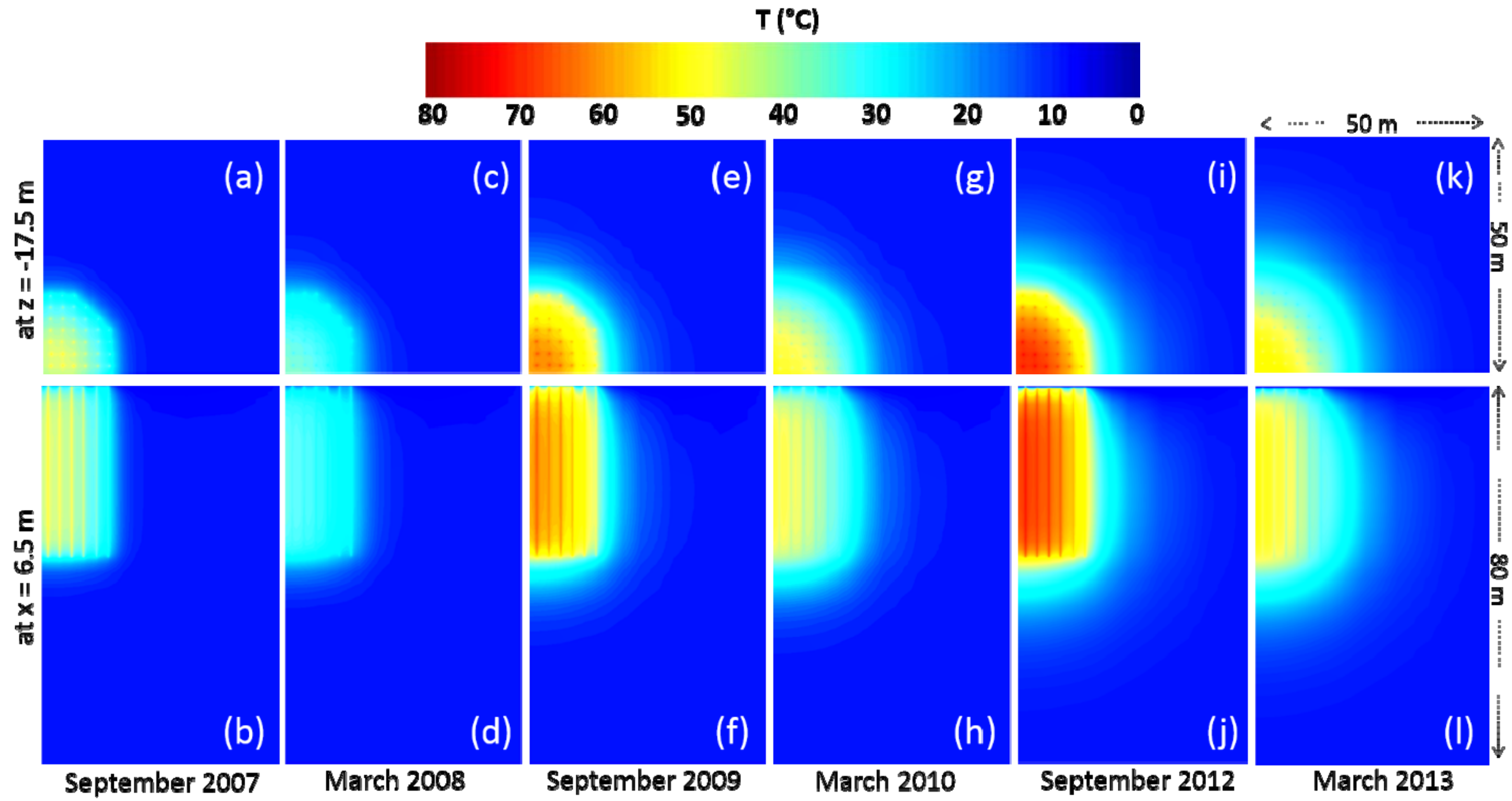


Boundary Conditions and Calibrated Parameters

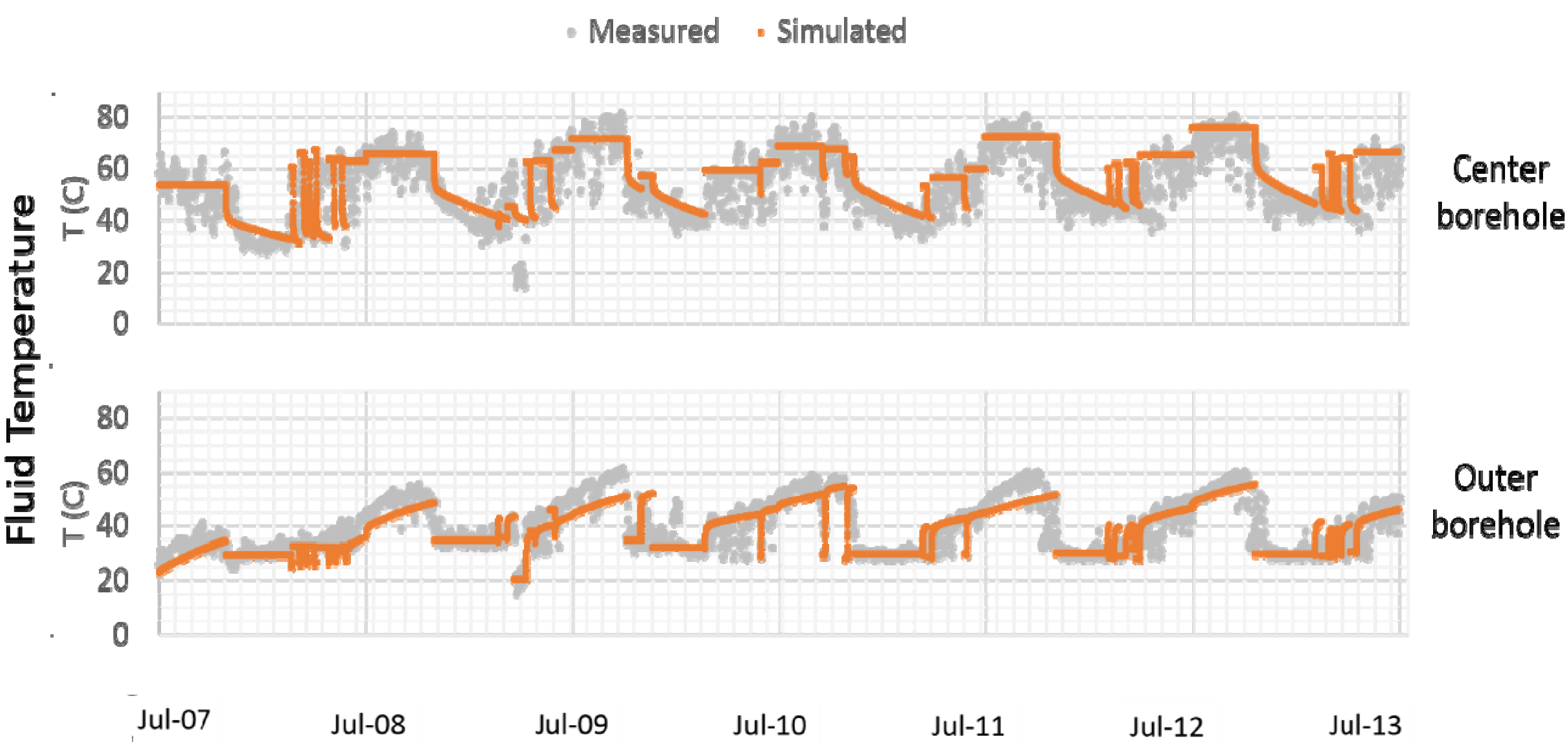


Parameter	Value	Unit
Soil Particle Density ǂ	2480	kg/m³
Soil Permeability	1.5×10^{-14}	m²
Soil Thermal Conductivity ǂ	2.03	w/m°C
Soil Porosity ǂ	0.50	m³/m³
Soil Heat Capacity ǂ	935.80	J/kg°C
Fluid Density	1000	kg/m³
Fluid Heat Capacity	4183	J/kg°C
U-tube Thermal Conductivity	0.51	w/m°C
Insulation Layer Thermal Conductivity ǂ	0.23	w/m°C
U-tube Radius	0.055	m
van Genuchten m	0.5	
van Genuchten a	0.01	kPa^{-1}

DLSC Simulated Seasonal Ground Temperatures



DLSC Simulation vs. Measured Values



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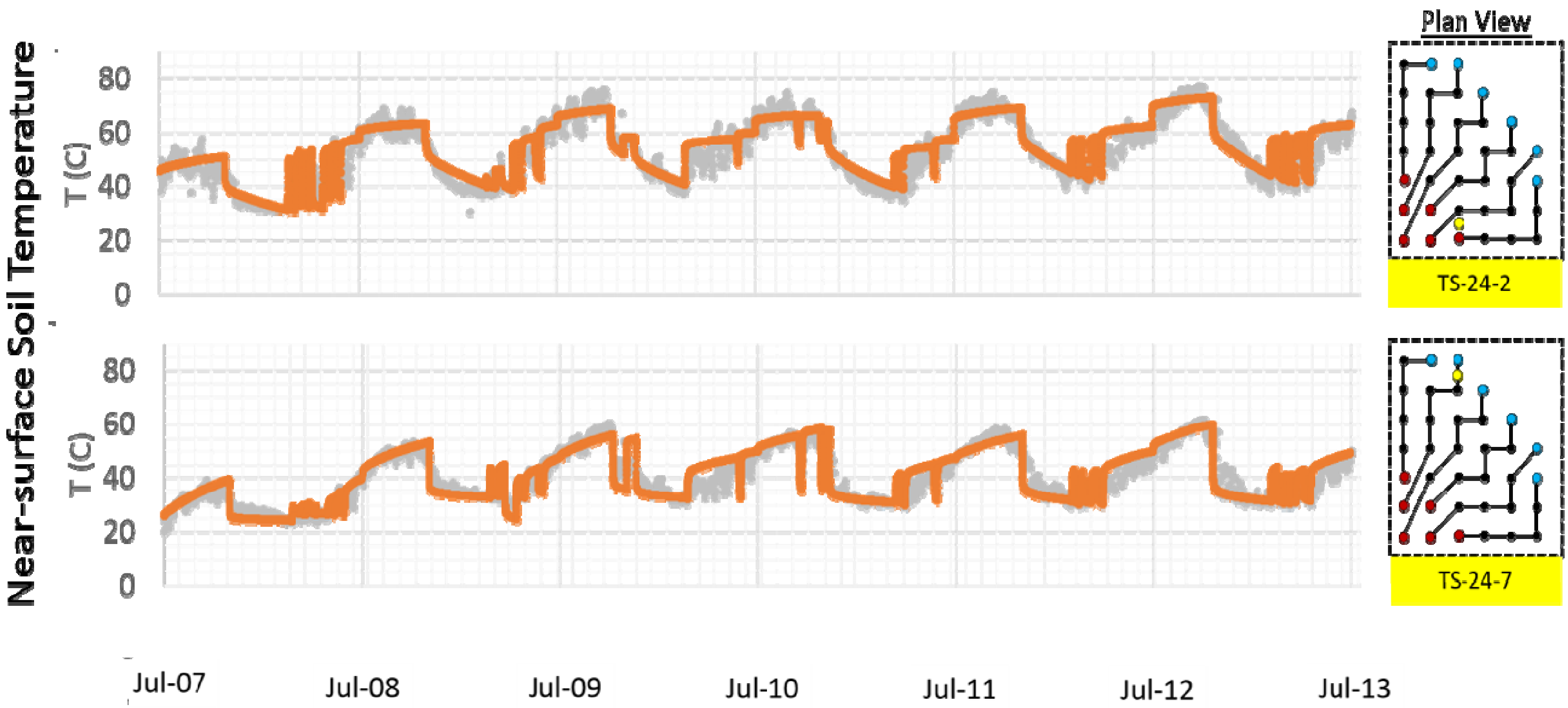

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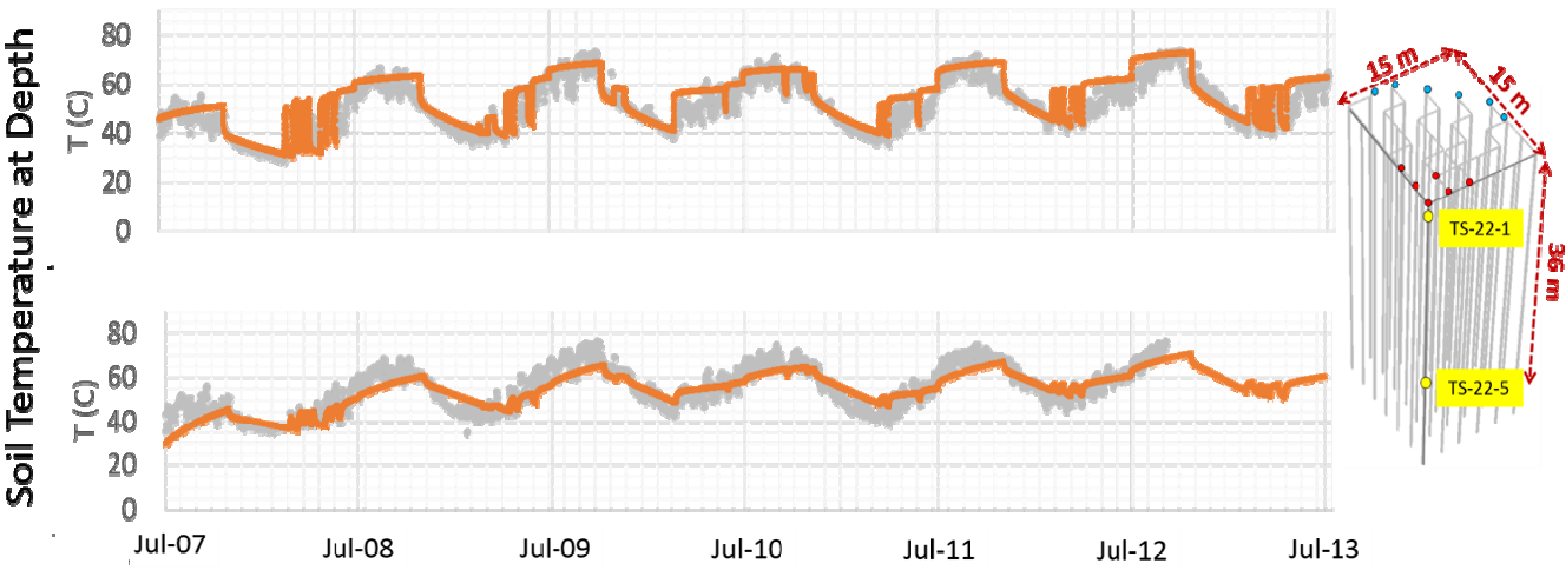
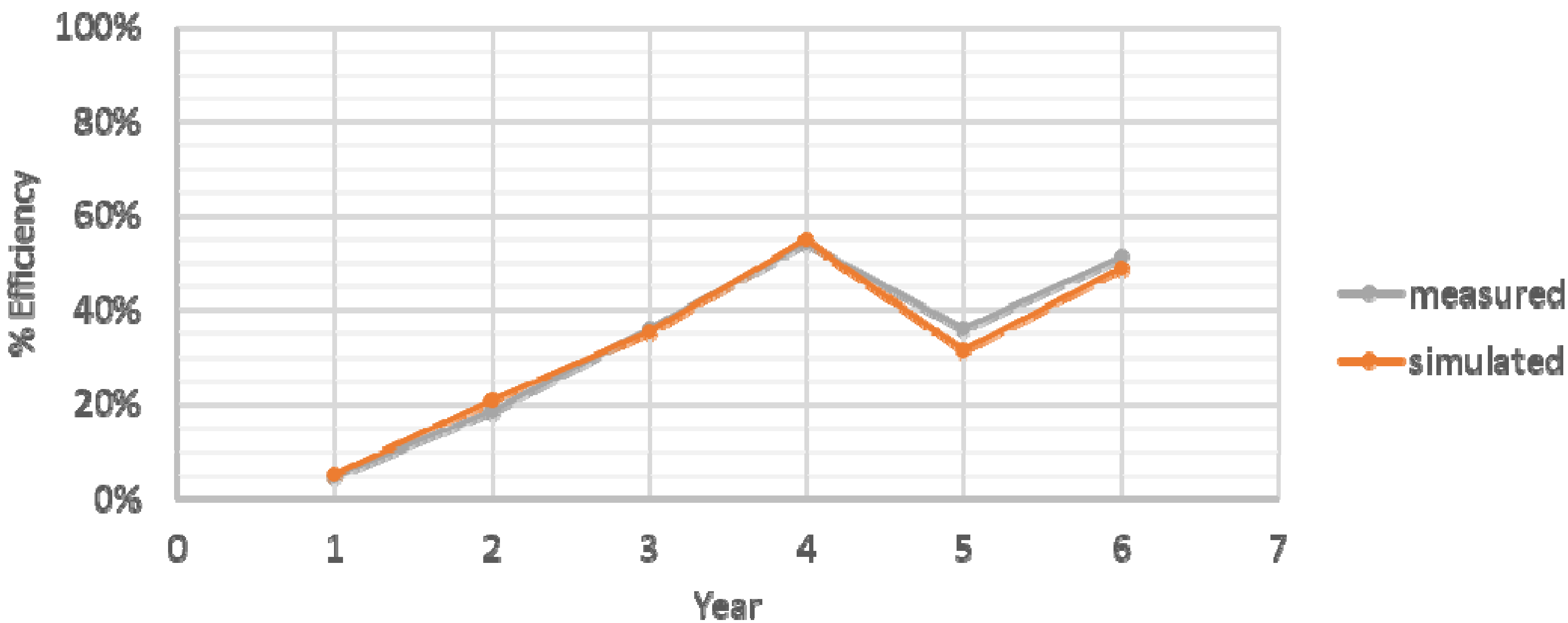
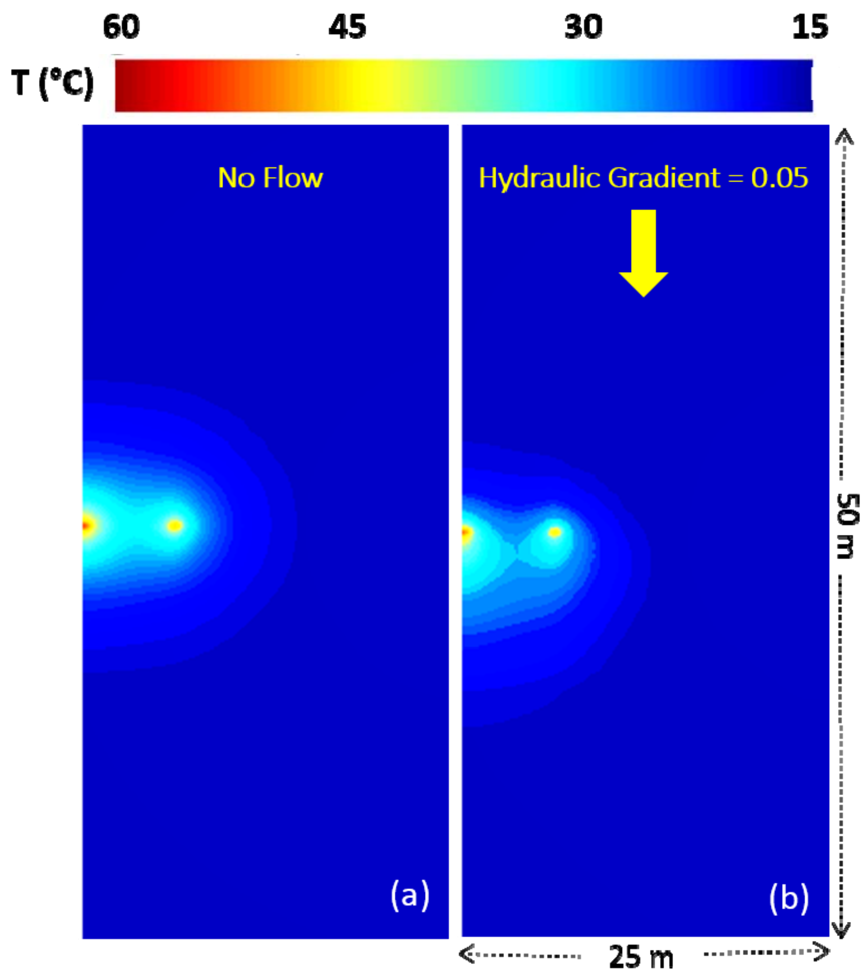


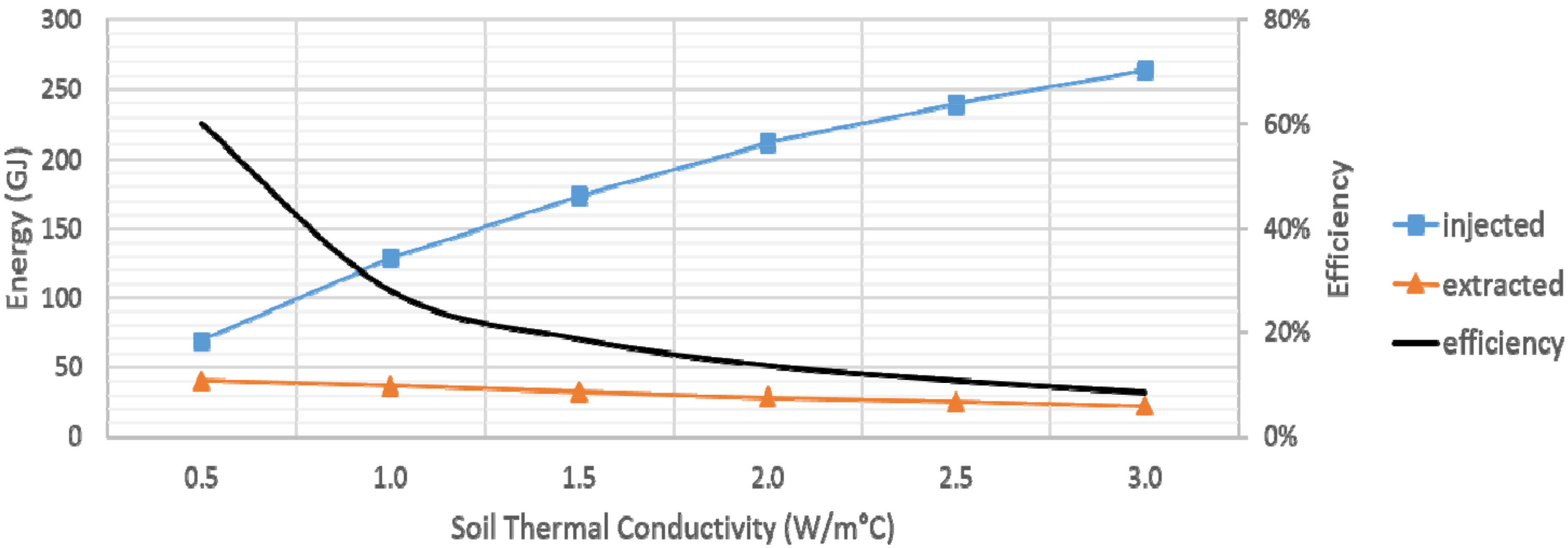
DLSC Efficiency of Heat Extraction



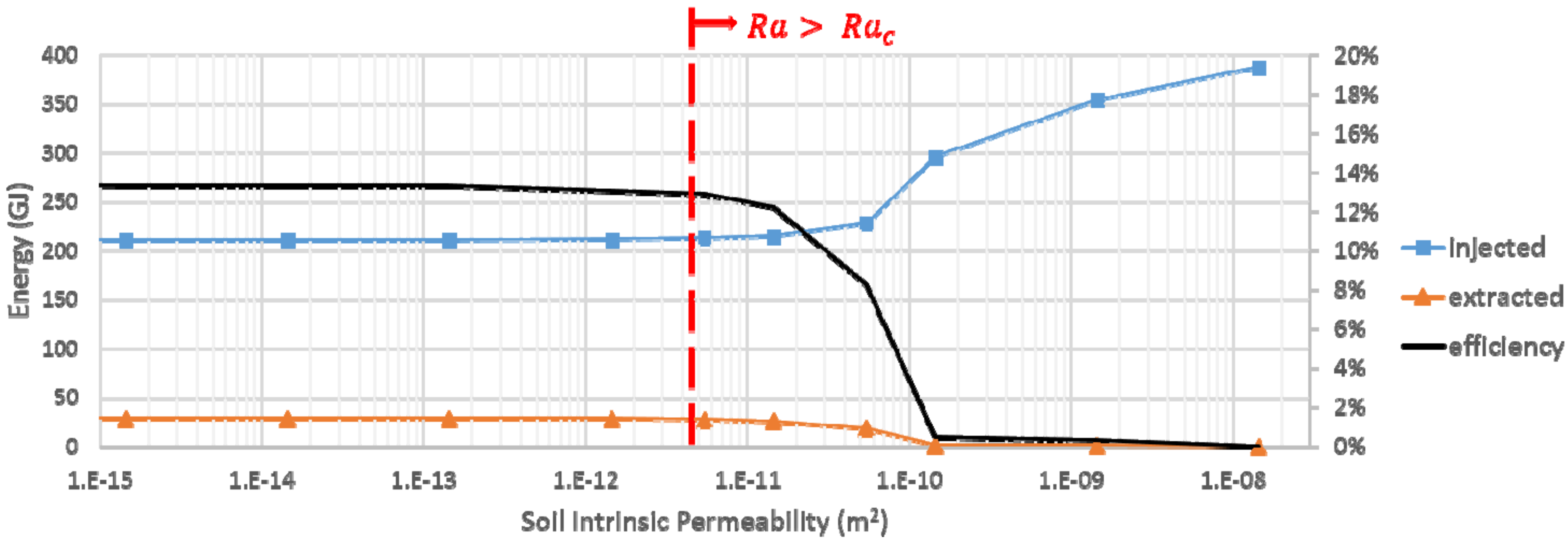
Groundwater Flow Effects on SBTES Systems



DLSC Parametric Evaluation (Perimeter Boreholes)

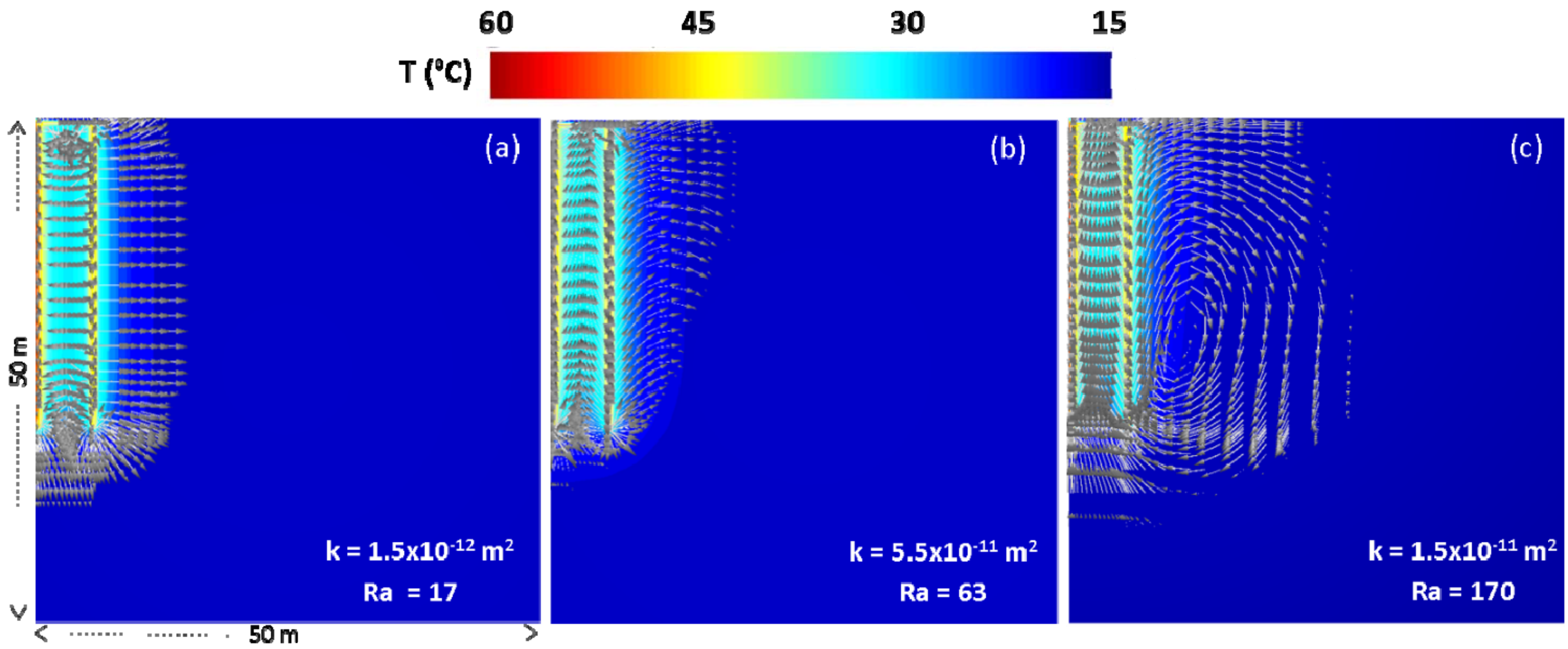


Convection Effects on SBTES Systems



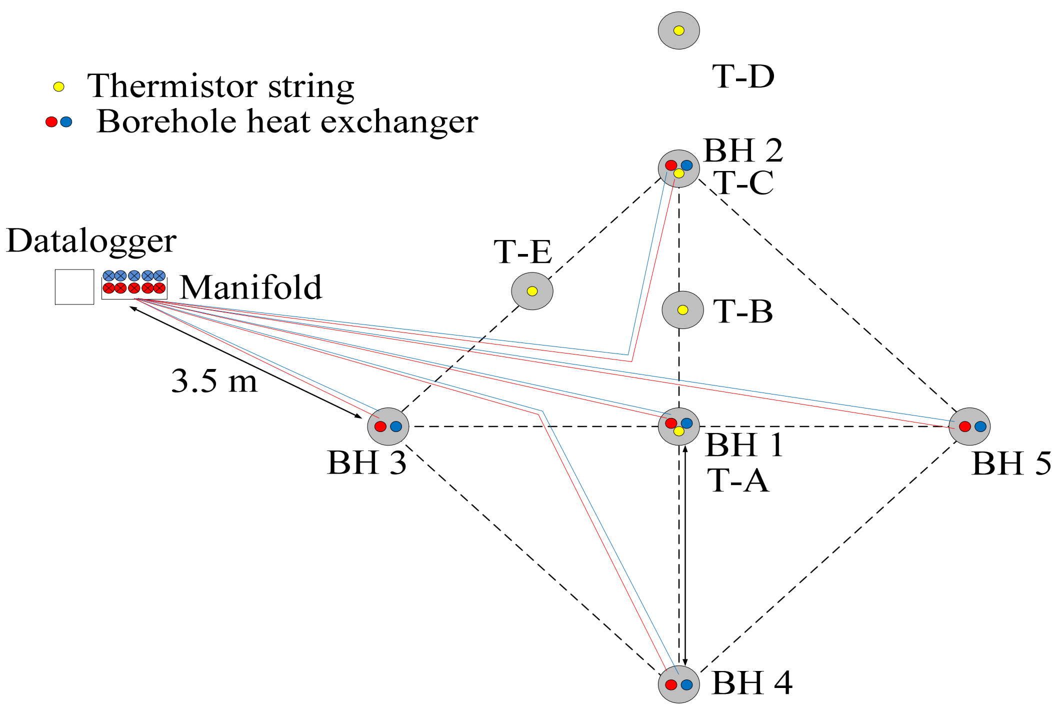
Saturated Soil Conditions with a Water Table at the Surface

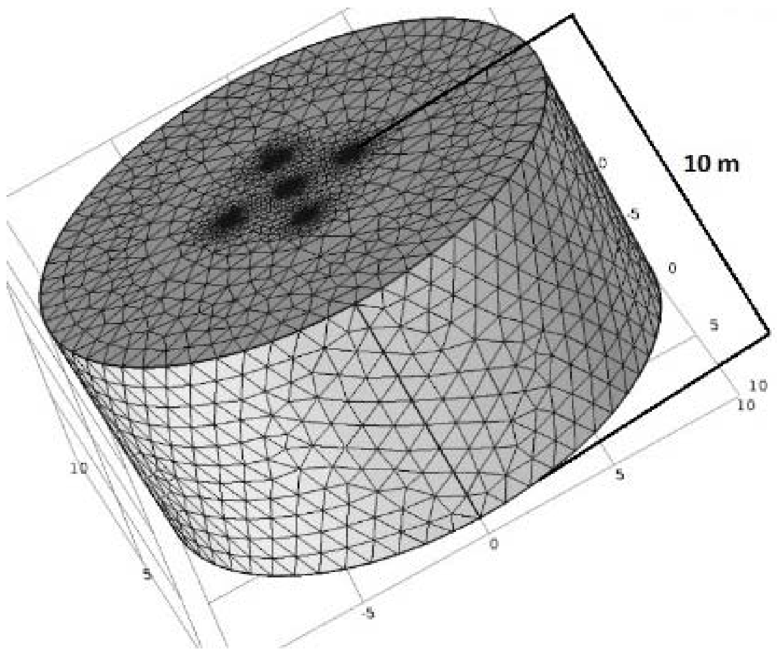
Convection Effects on SBTES Systems



Saturated Soil Conditions with a Water Table at the Surface

Pilot SBTES System at Colorado School of Mines





Simplified Numerical Analysis for Design

Assumptions

- Heat transfer is governed by conduction

$$\rho_t C_p \frac{\partial T}{\partial t} = \nabla(\lambda \cdot \nabla T)$$

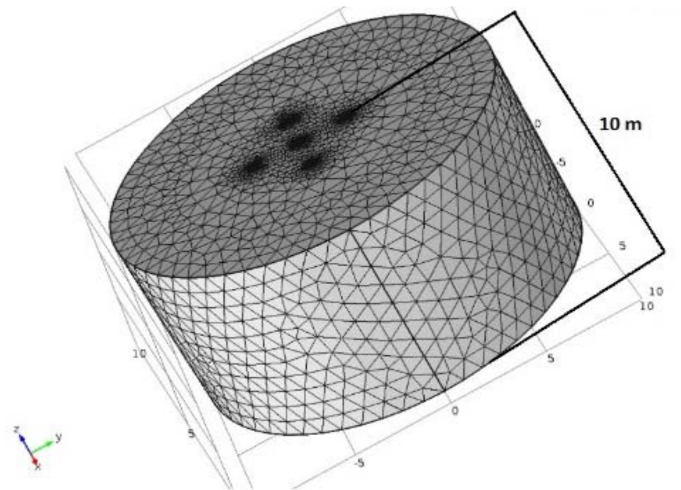
Boundary Conditions

- Constant heat flux applied to the boreholes
- Heat flux estimated as follows:

$$\dot{q} = \frac{\dot{V}\, C_p \Delta T}{2\pi r L}$$

- Thermally insulated layer at top
- Initial soil temperature of 10°C

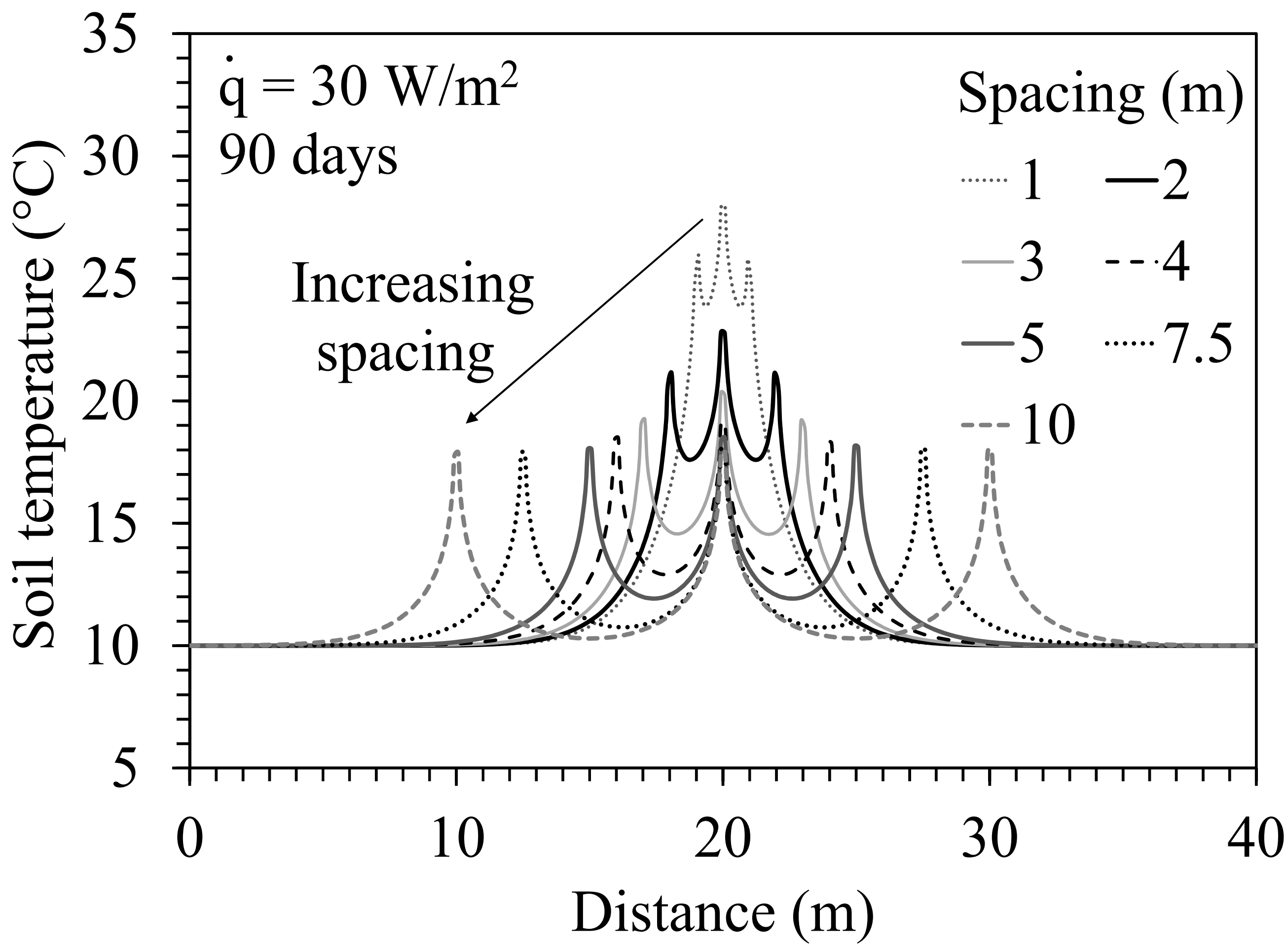
Model Geometry



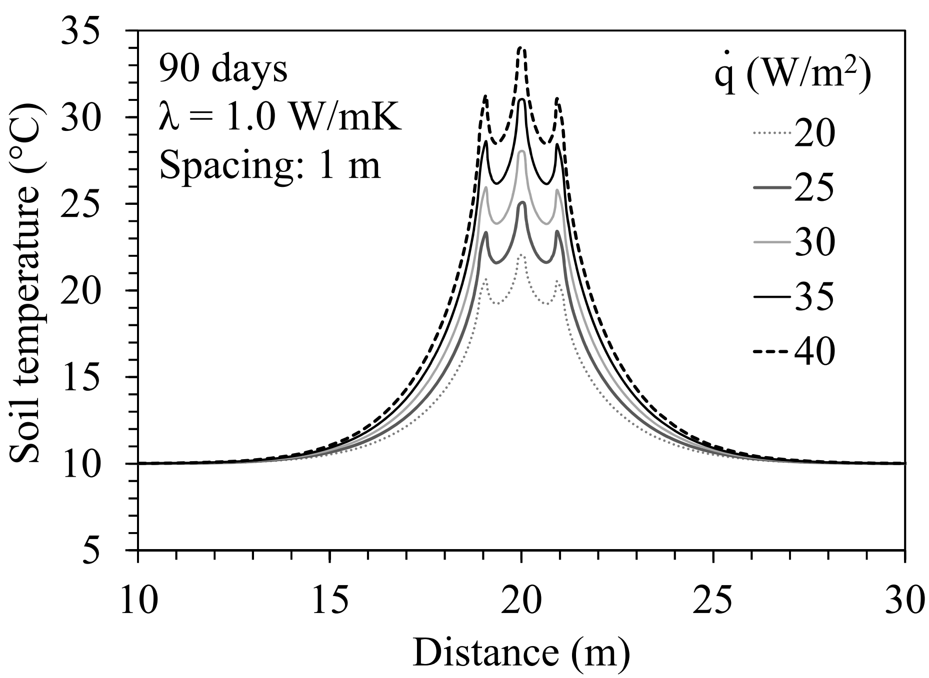
Baseline Model Inputs ($\dot{q}$ = 30 W/m)

Parameter	
Volumetric flow rate, $\dot{V}$	0.3 (m^3/s)
Temperature difference, ΔT	2 °C
Borehole length	10 m
Heat exchanger diameter	0.025 m

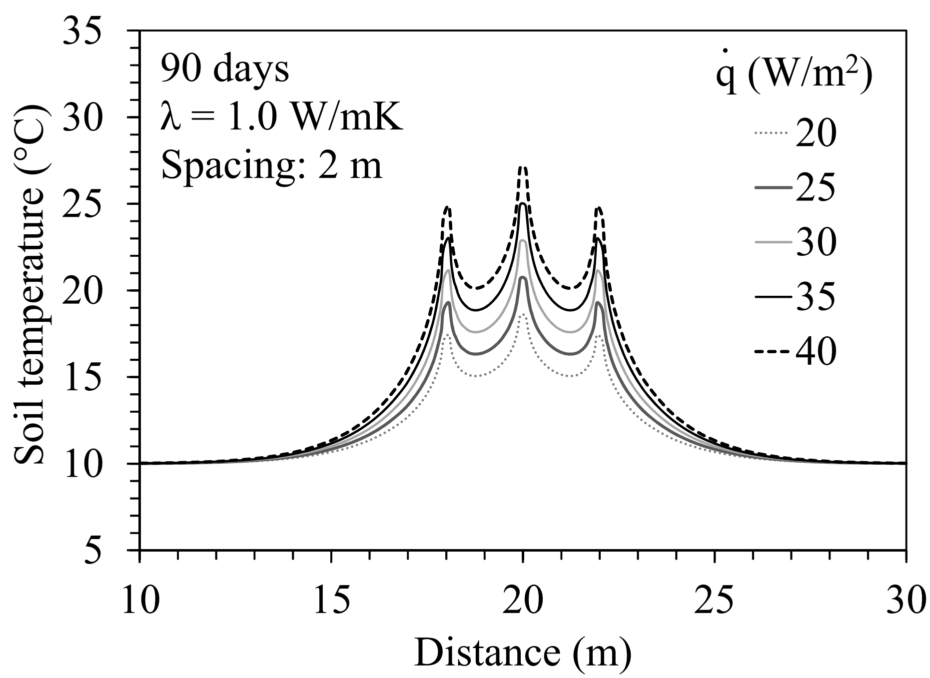
Results: Impact of Borehole Spacing



Results: Impact of Boundary Heat Flux

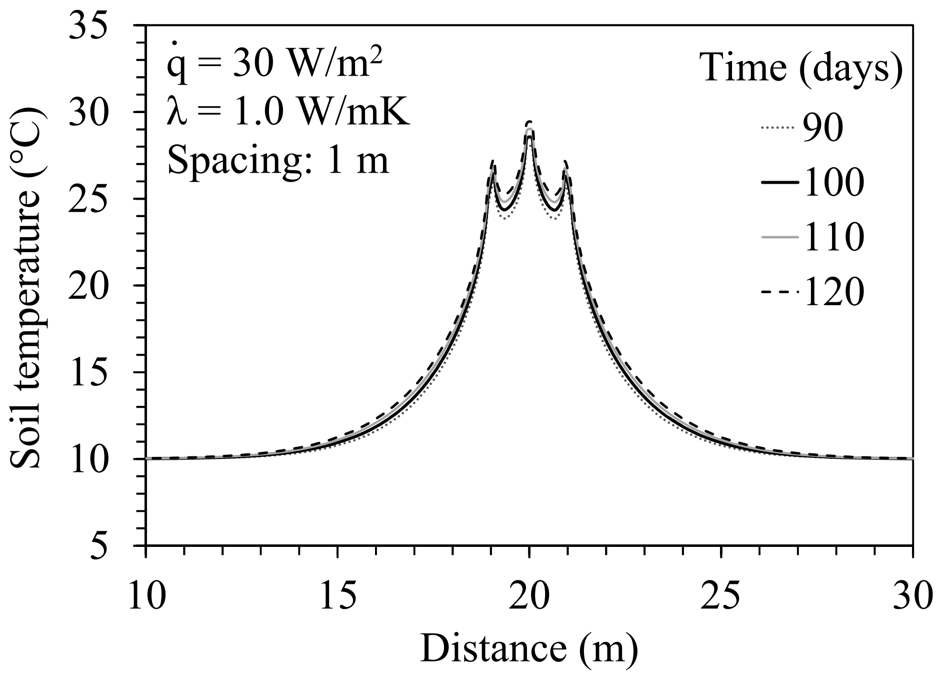


Spacing: 1.0 m

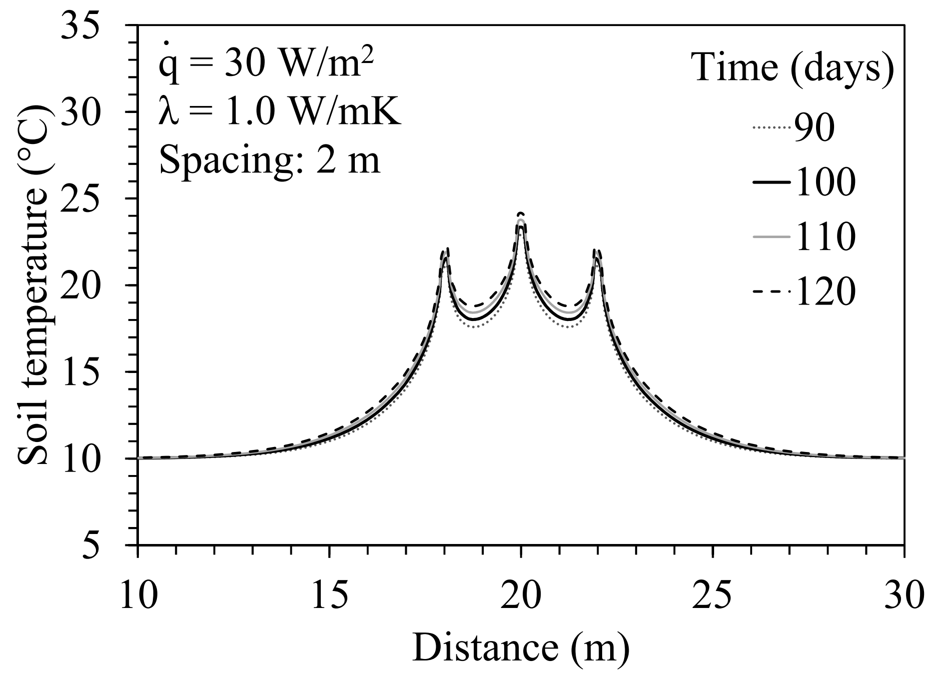


Spacing: 2.0 m

Results: Impact of Heating Duration

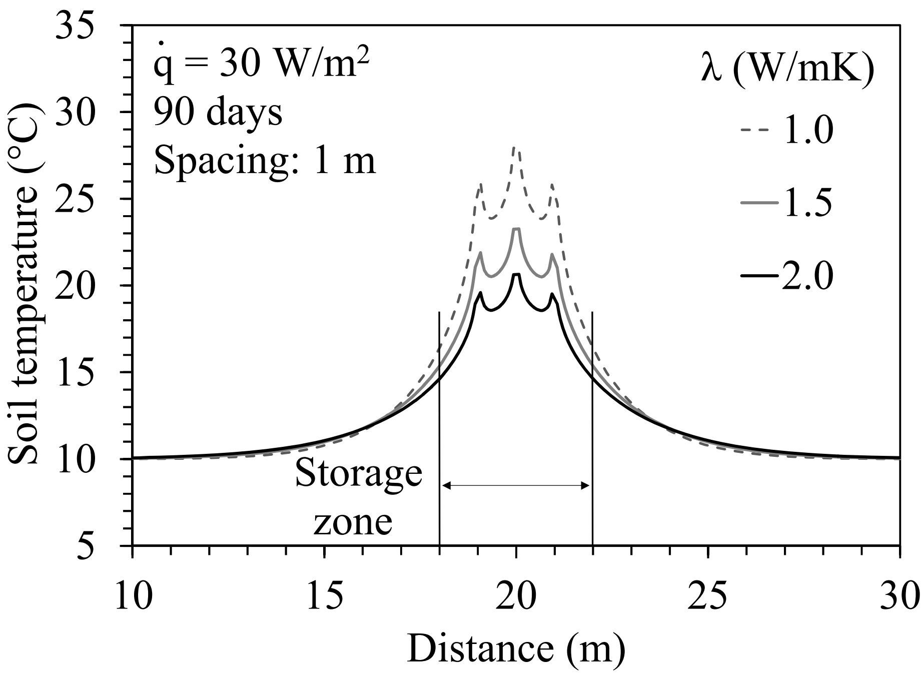


Spacing: 1.0 m

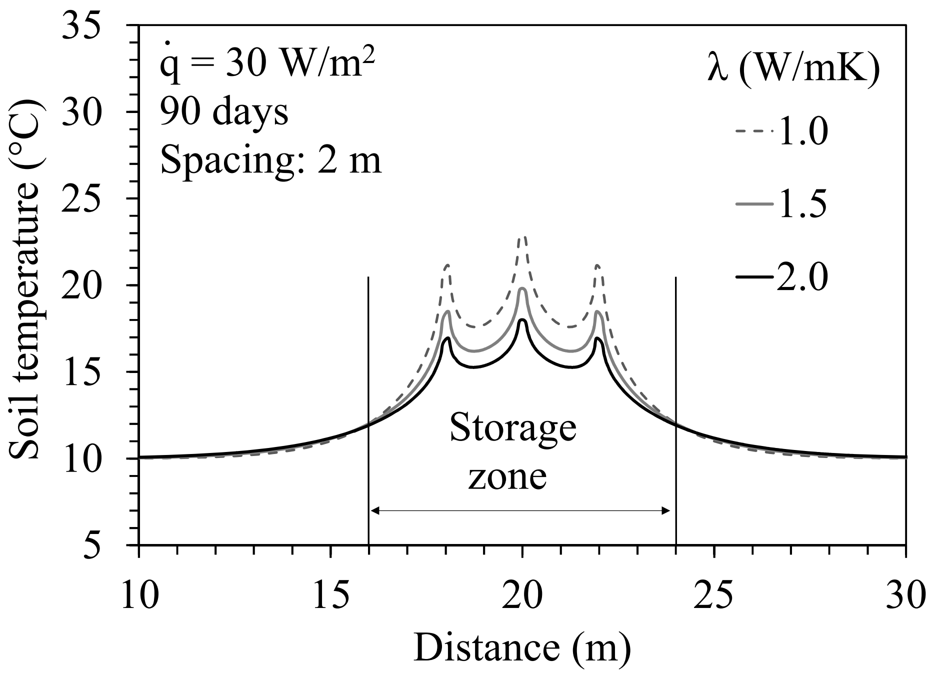


Spacing: 2.0 m

Results: Impact of Thermal Conductivity



Spacing: 1.0 m



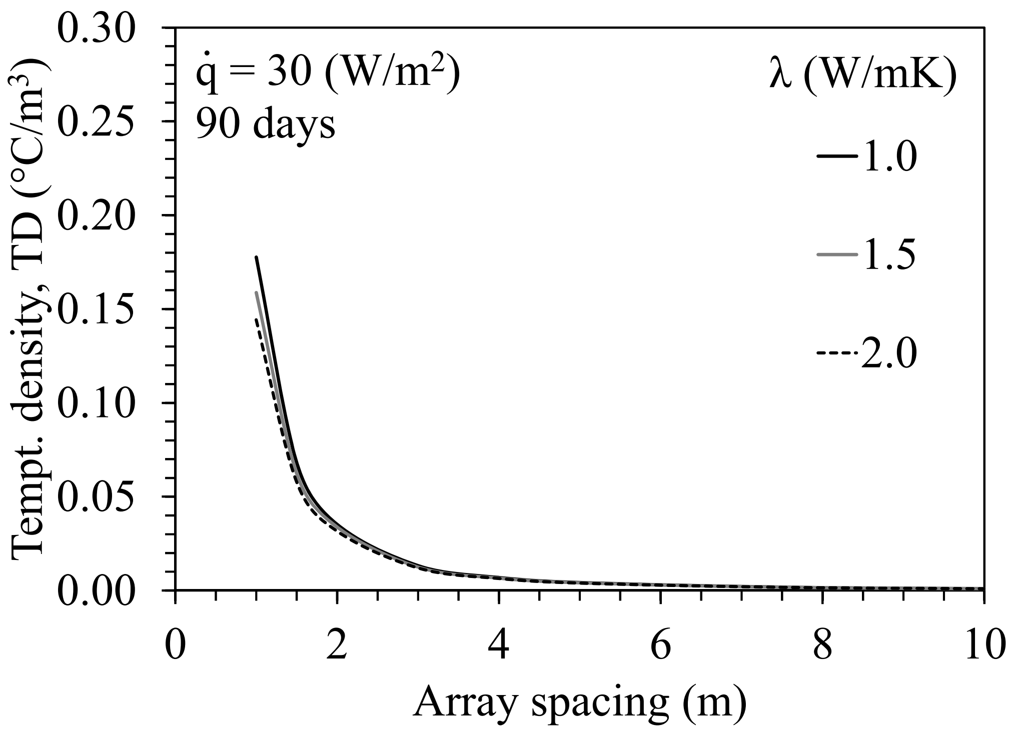
Spacing: 2.0 m

Performance Variables: Temperature Density

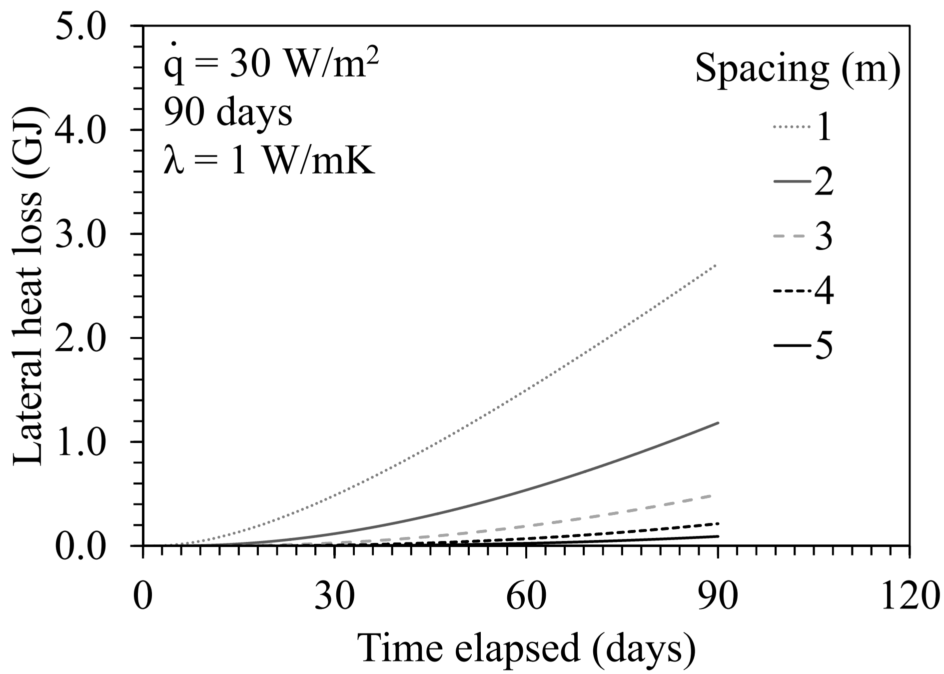
Temperature Density, TD (°C /m³) is defined as follows

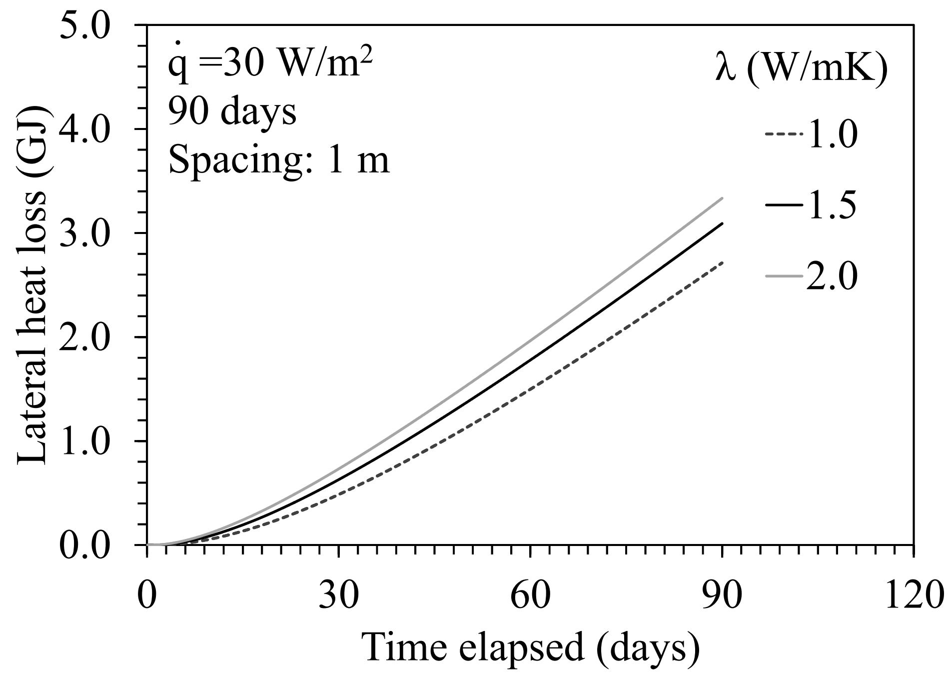
$$TD = \frac{T_{ave}}{V_{storage}}$$

T_{ave} is the average temperature of the soil (°C)
$V_{storage}$ (m³) is the heat storage volume



Performance Variables: Heat Loss



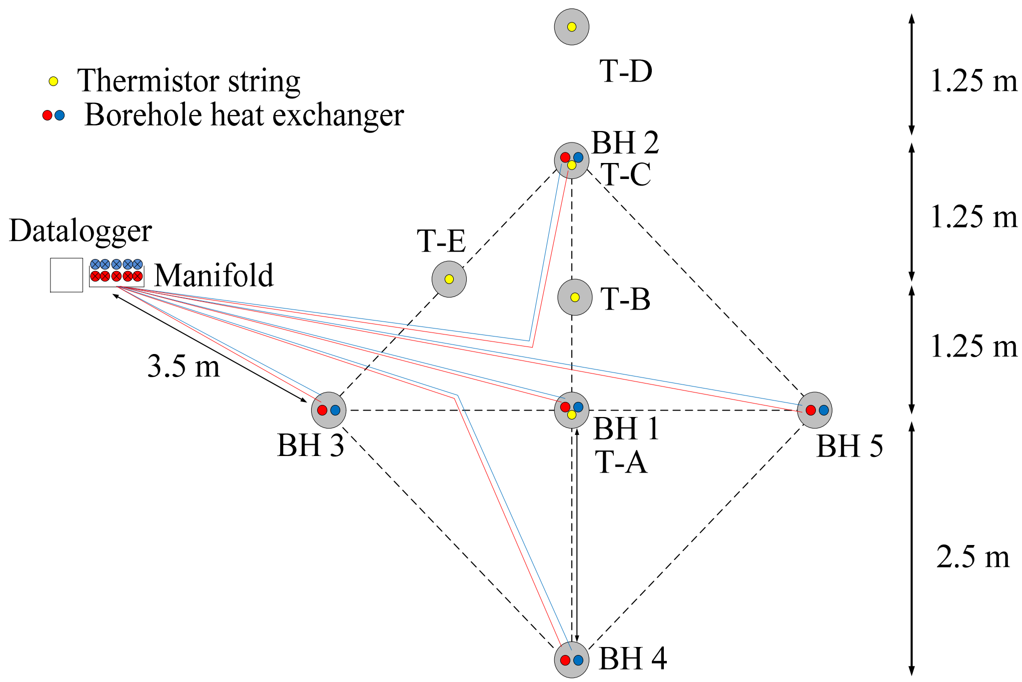


Lateral heat losses for:

Different array spacing (left)

Different soil thermal conductivity values (right)

Field Data from the CSM SBTES



Goals:

1. Perform a long-term thermal response test on the system (Summer 2014)
2. Monitor ambient cooling of system to evaluate losses (Fall 2014)

Construction Pictures

Geothermal boreholes

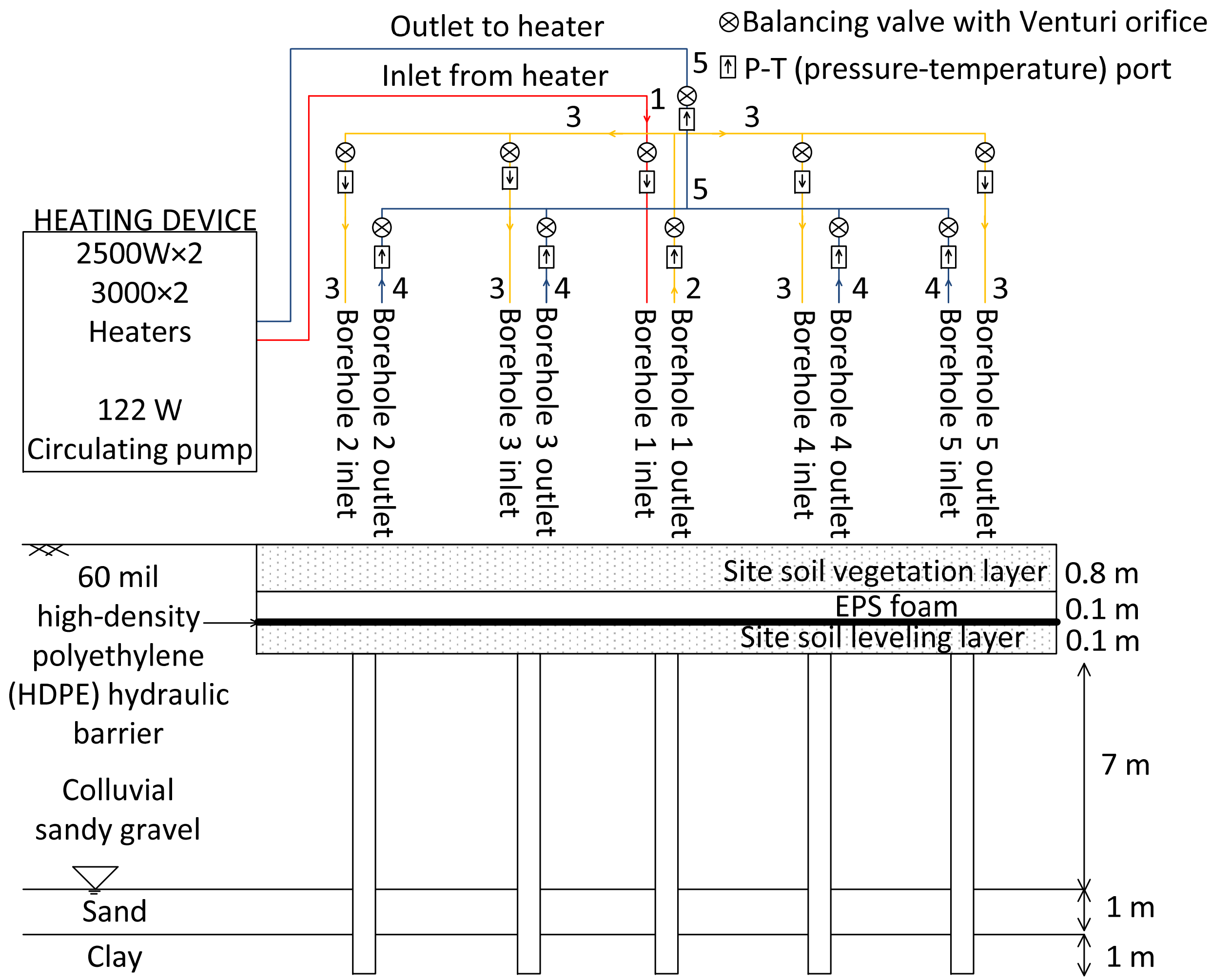
60 mil HDPE hydraulic barrier

Foam insulation

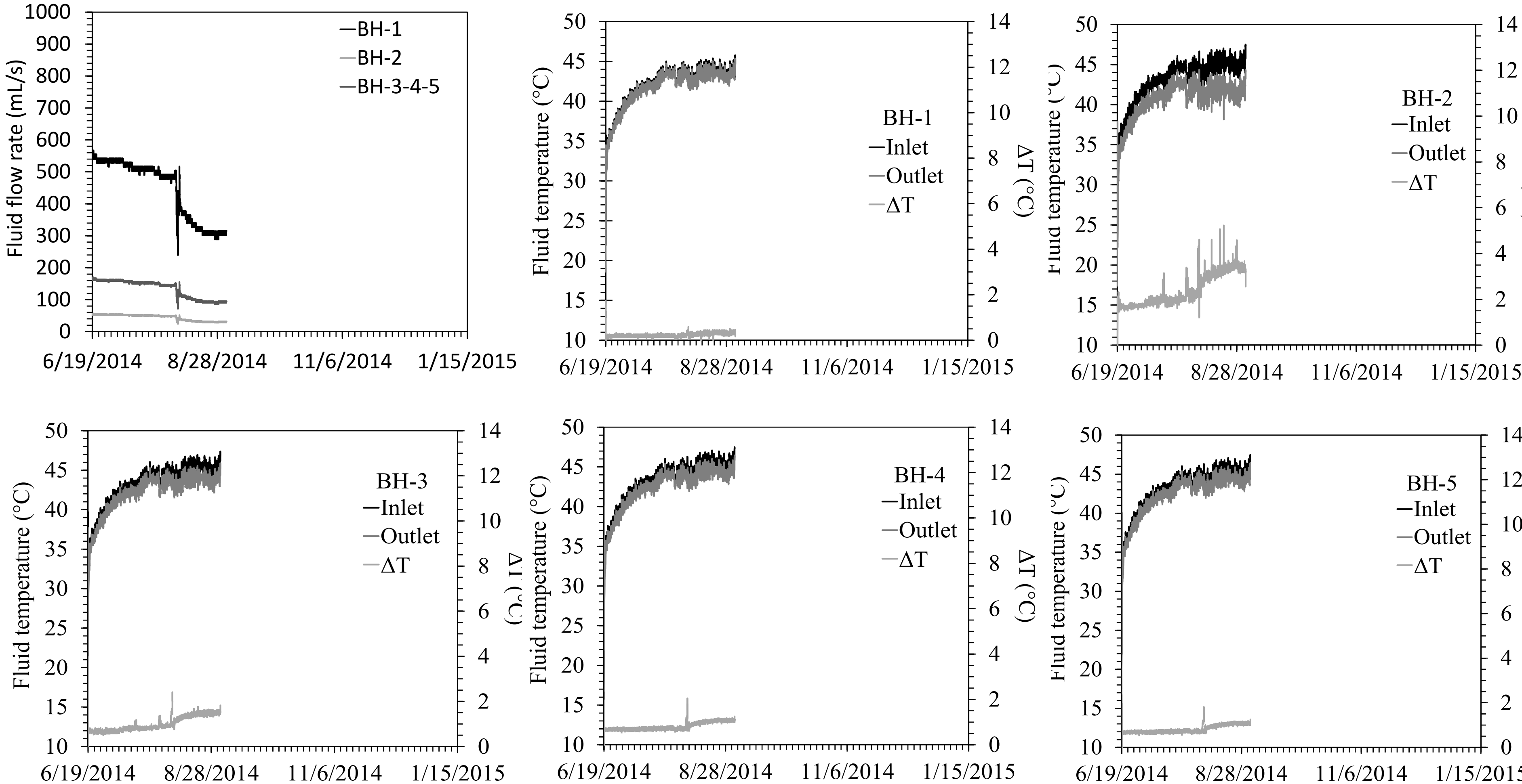
Manifold

Site soil

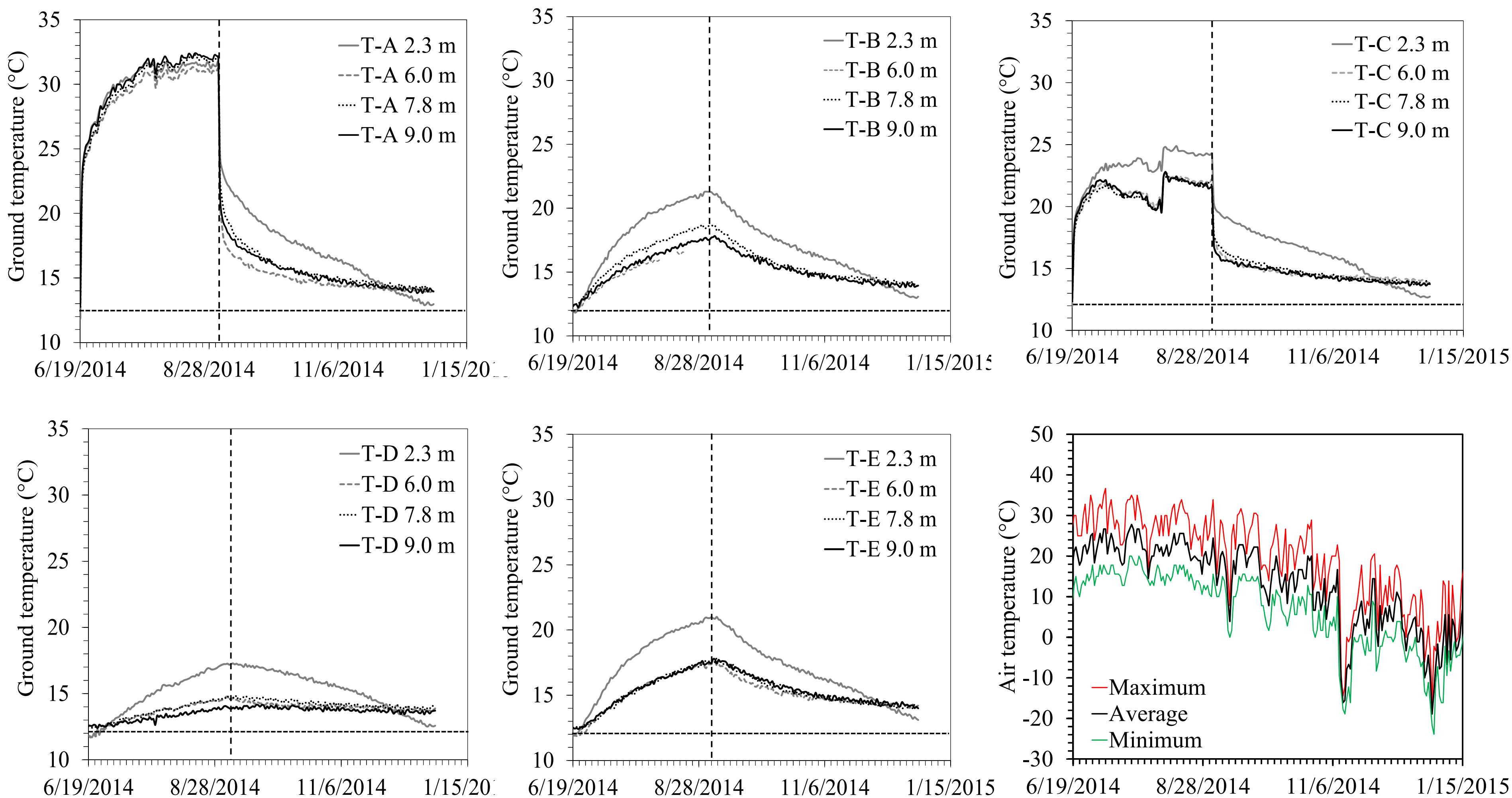
Heating Test Plan at Colorado School of Mines



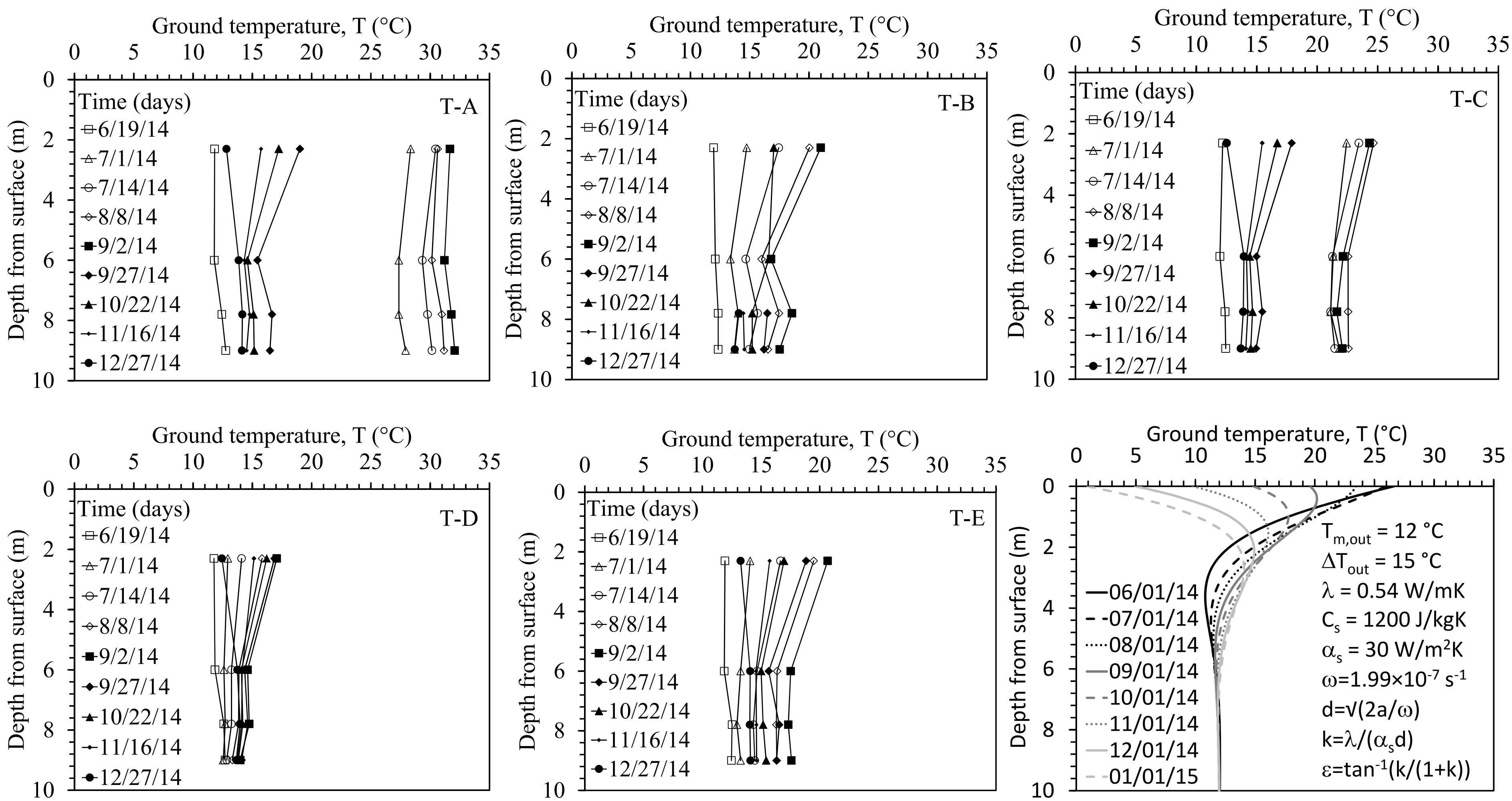
Results: Ambient and Fluid Temperatures



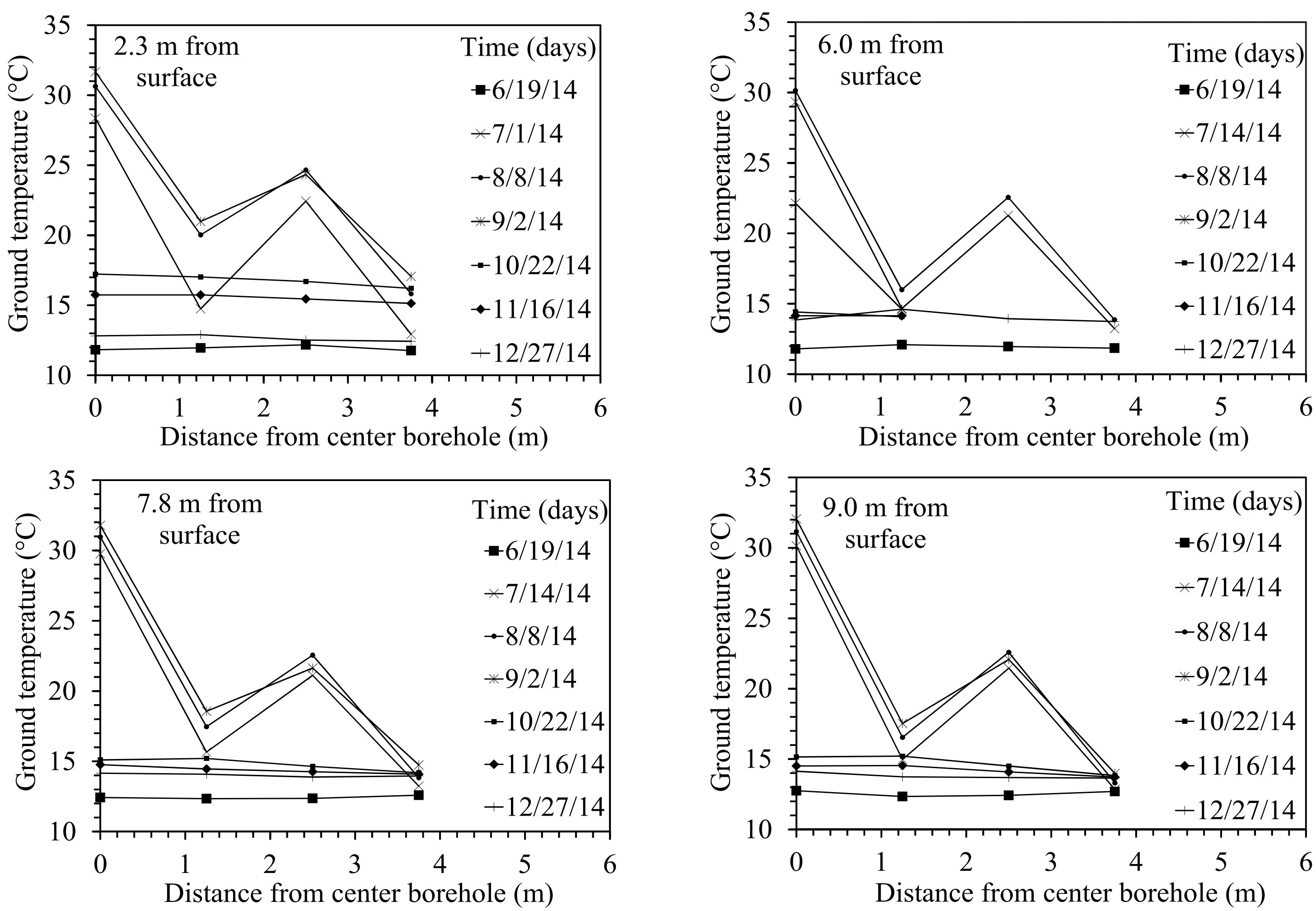
Results: Soil Temperatures



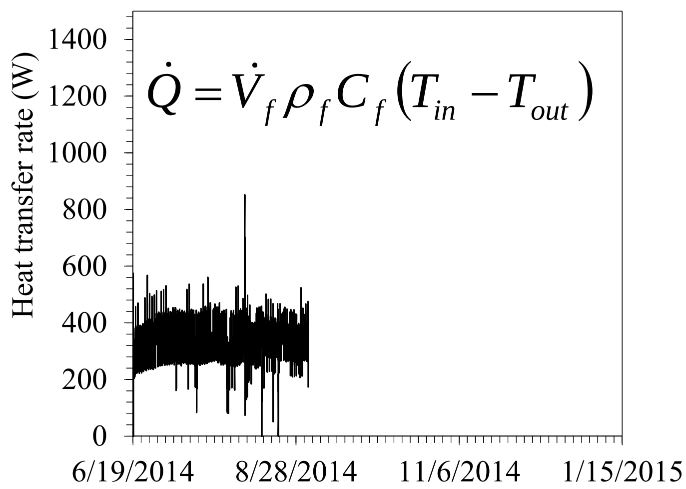
Results: Temperature Profiles

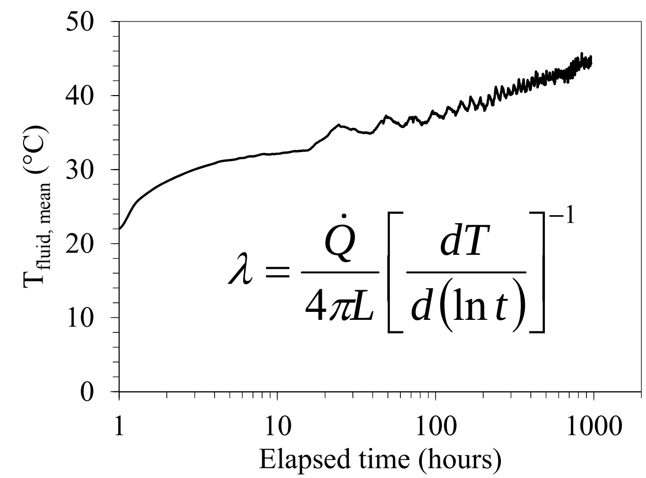


Results: Temperature Profiles with Radius



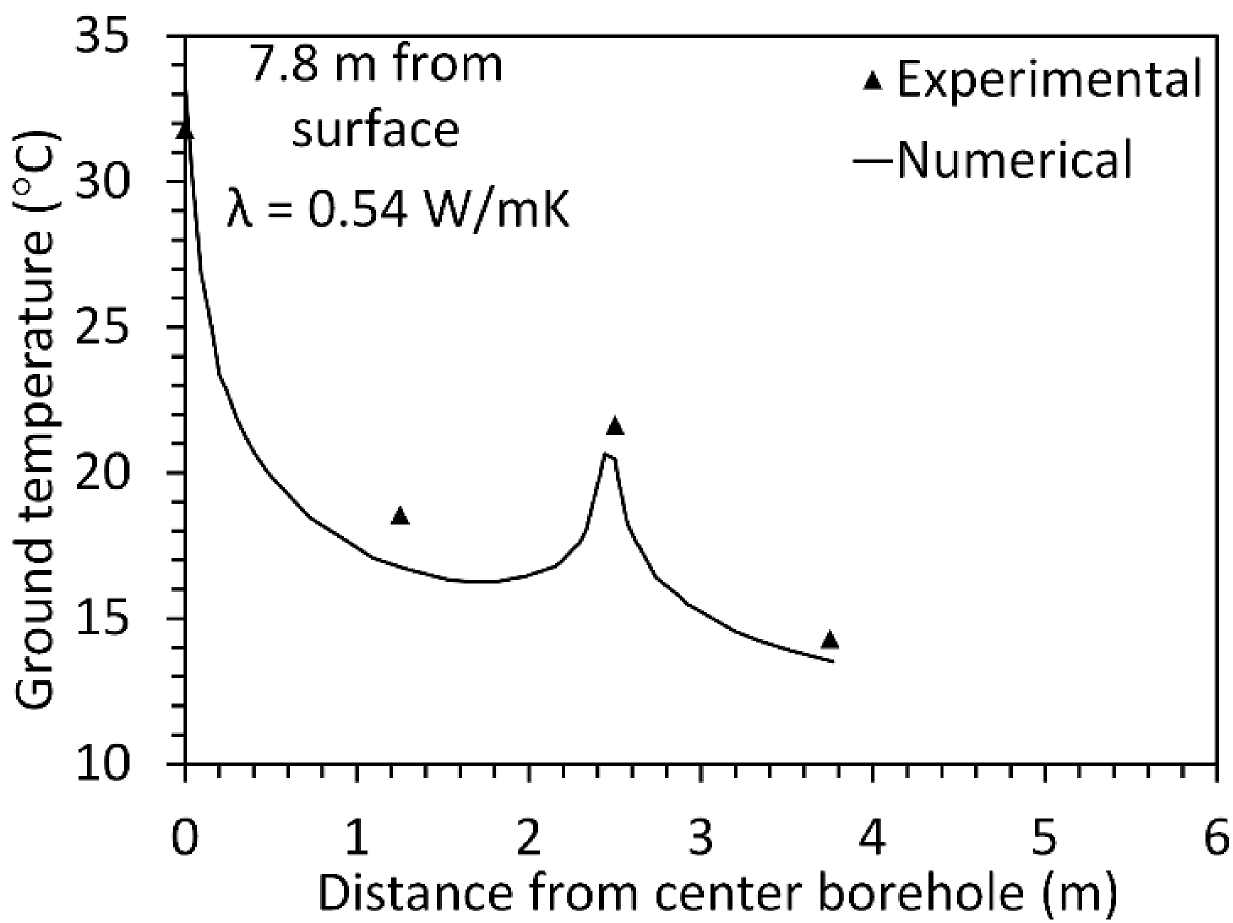
Heat Flux and Ground Properties





Borehole	Ave. flow rate (0 to 49 days)	Ave. flow rate (49 to 75 days)*	Average heat injection rate	Thermal Conductivity (1-4 days)	Thermal conductivity (12-17 days)	Thermal conductivity (49-75 days)
	(ml/s)	(ml/s)	(W/m)	(W/m K)	(W/m K)	(W/m K)
1	500	300	18.6	0.48	0.52	0.55
2	50	30	18.5	0.45	0.55	0.54
3	150	83	23.1	0.56	0.54	0.66
4	150	83	19.4	0.55	0.57	0.55
5	150	83	19.3	0.54	0.57	0.55

Analysis: Numerical vs Experimental



Analysis: Heat Balance

Conservation of Energy

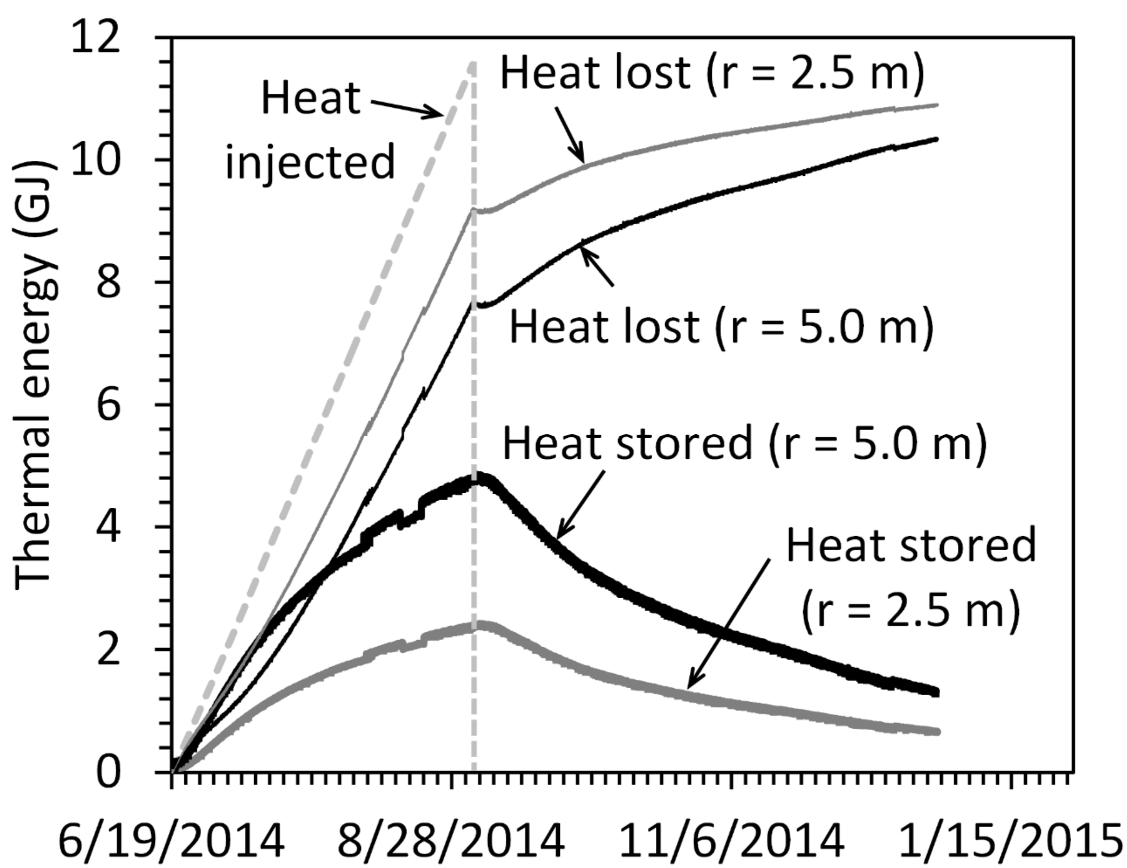
$$Q_{stored} = Q_{injected} - Q_{lost}$$

Injected Heat

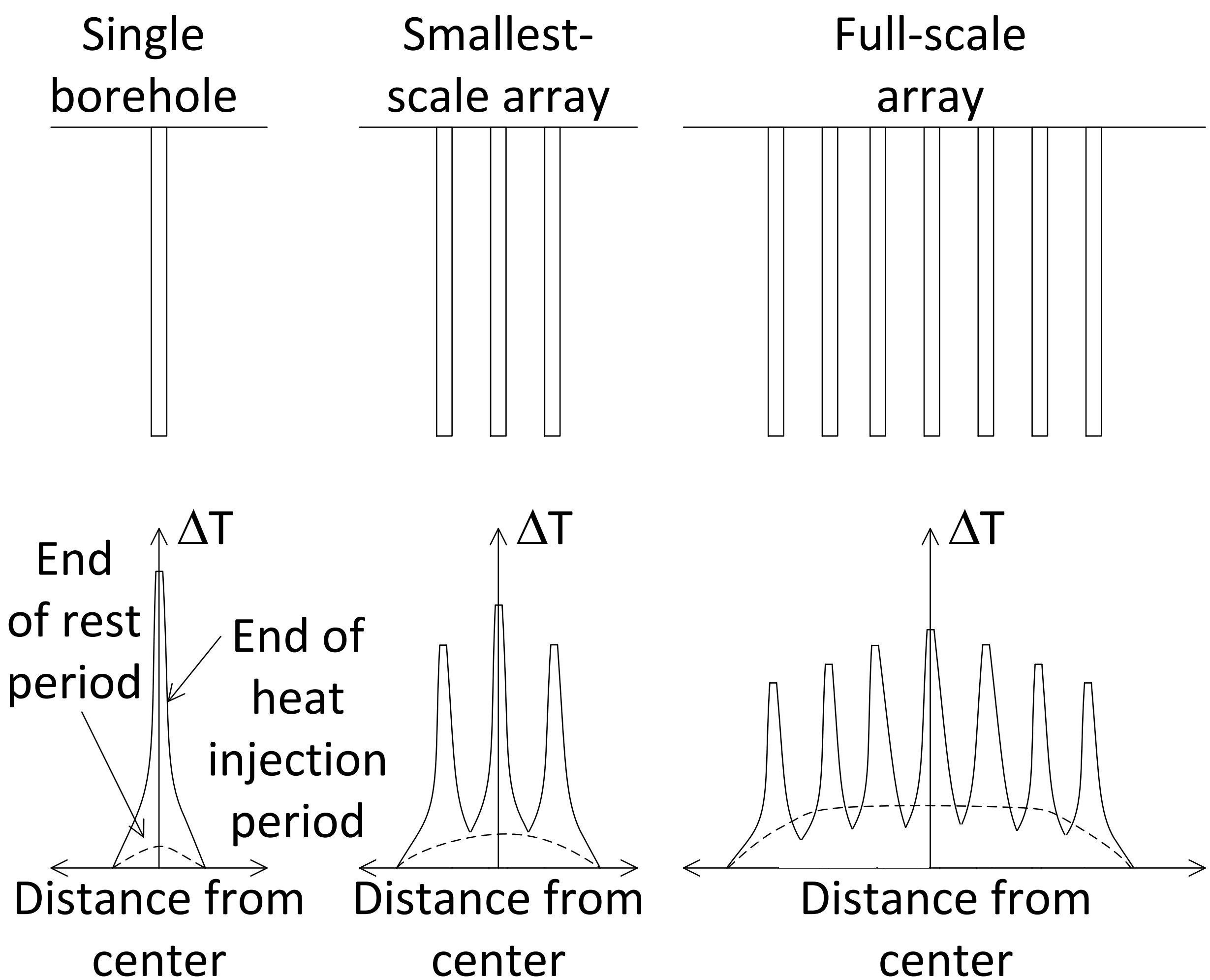
$$\dot{Q} = \dot{V}_f \rho_f C_f (T_{in} - T_{out})$$

Heat stored (Claesson and Hellstrom 1981)

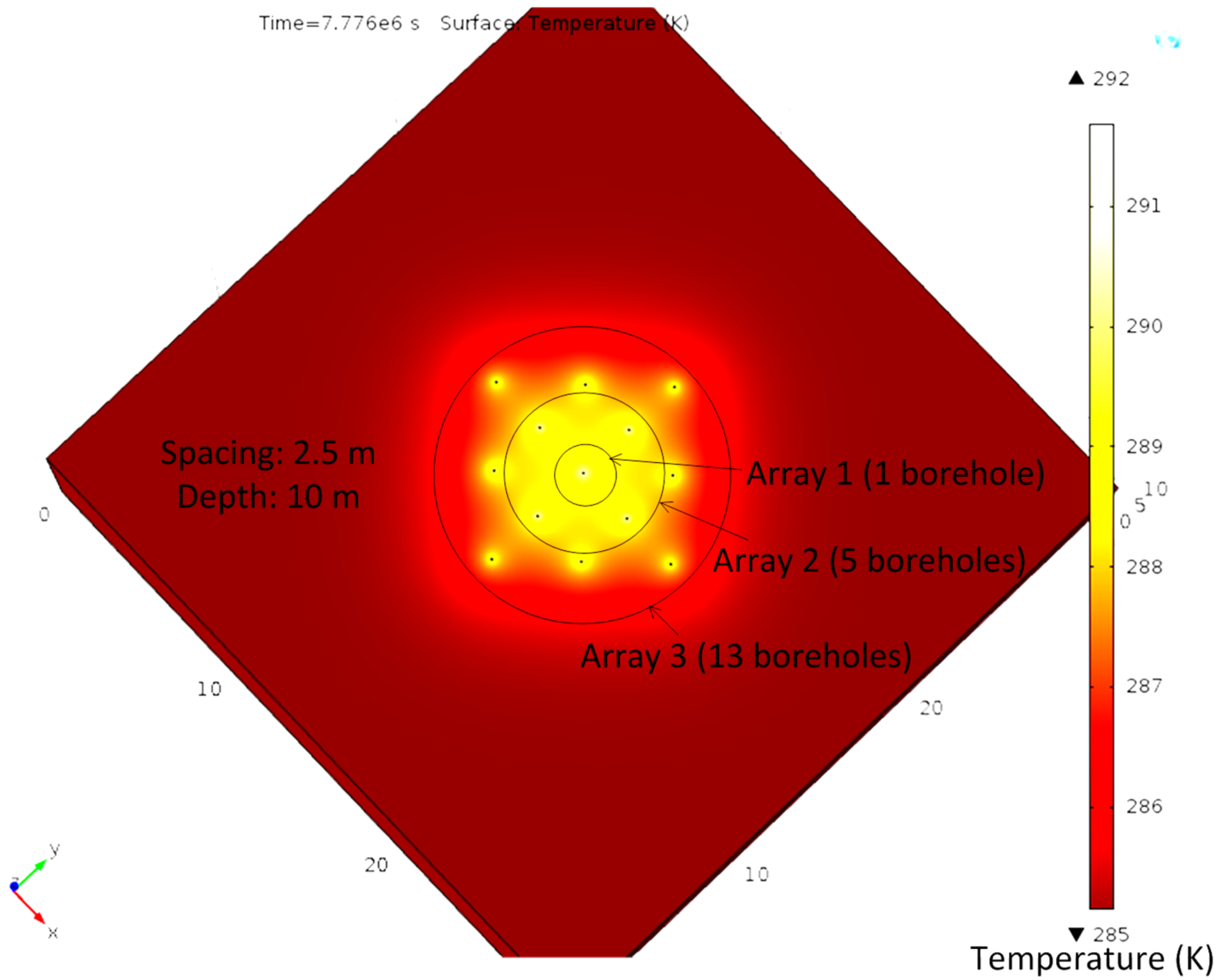
$$Q_{stored} = (T_s - T_a) C_p \pi r^2 H$$



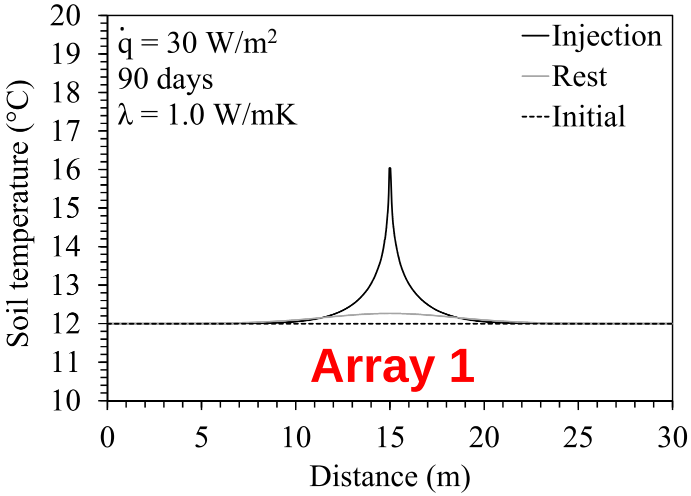
Scalability of SBTES Systems

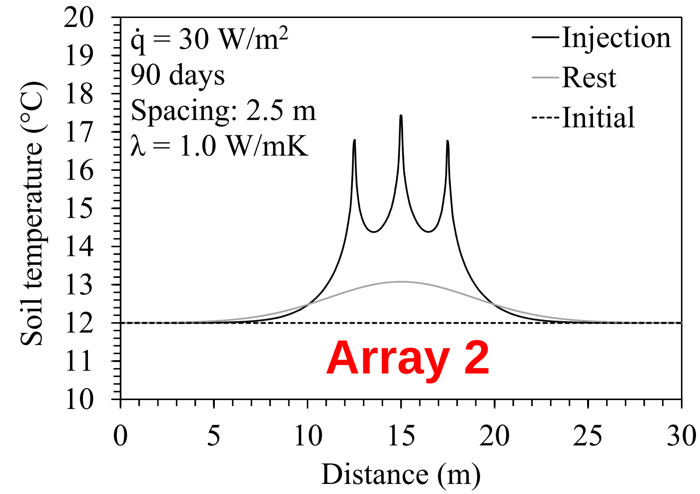


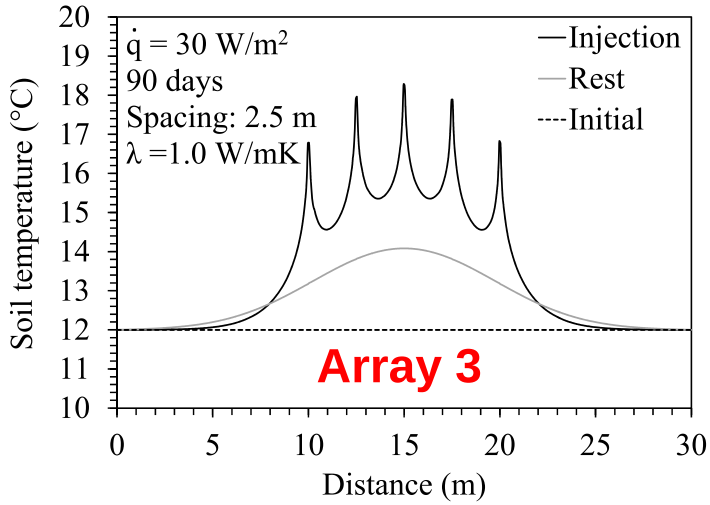
Scalability of SBTES Systems: Arrays Considered



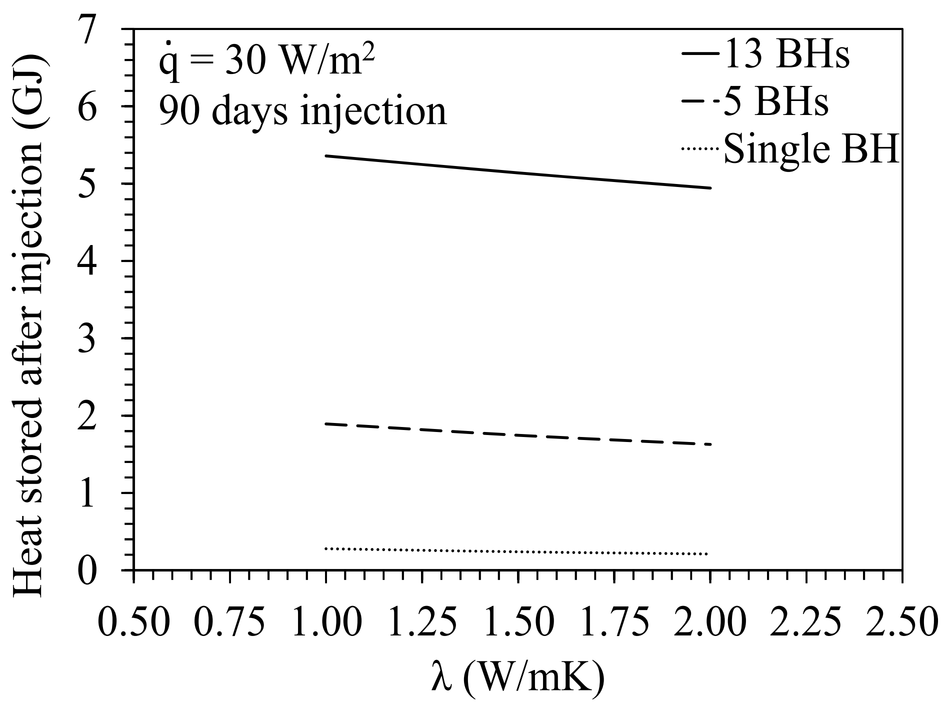
Scalability of SBTES Systems: Arrays Considered



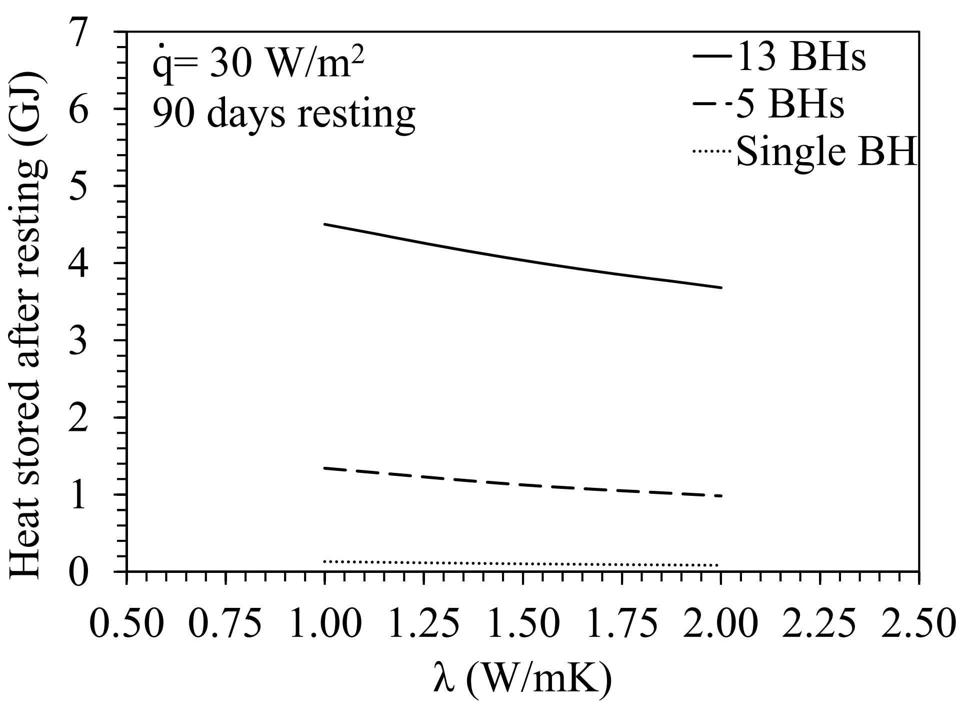




Scalability of SBTES Systems: Arrays Considered

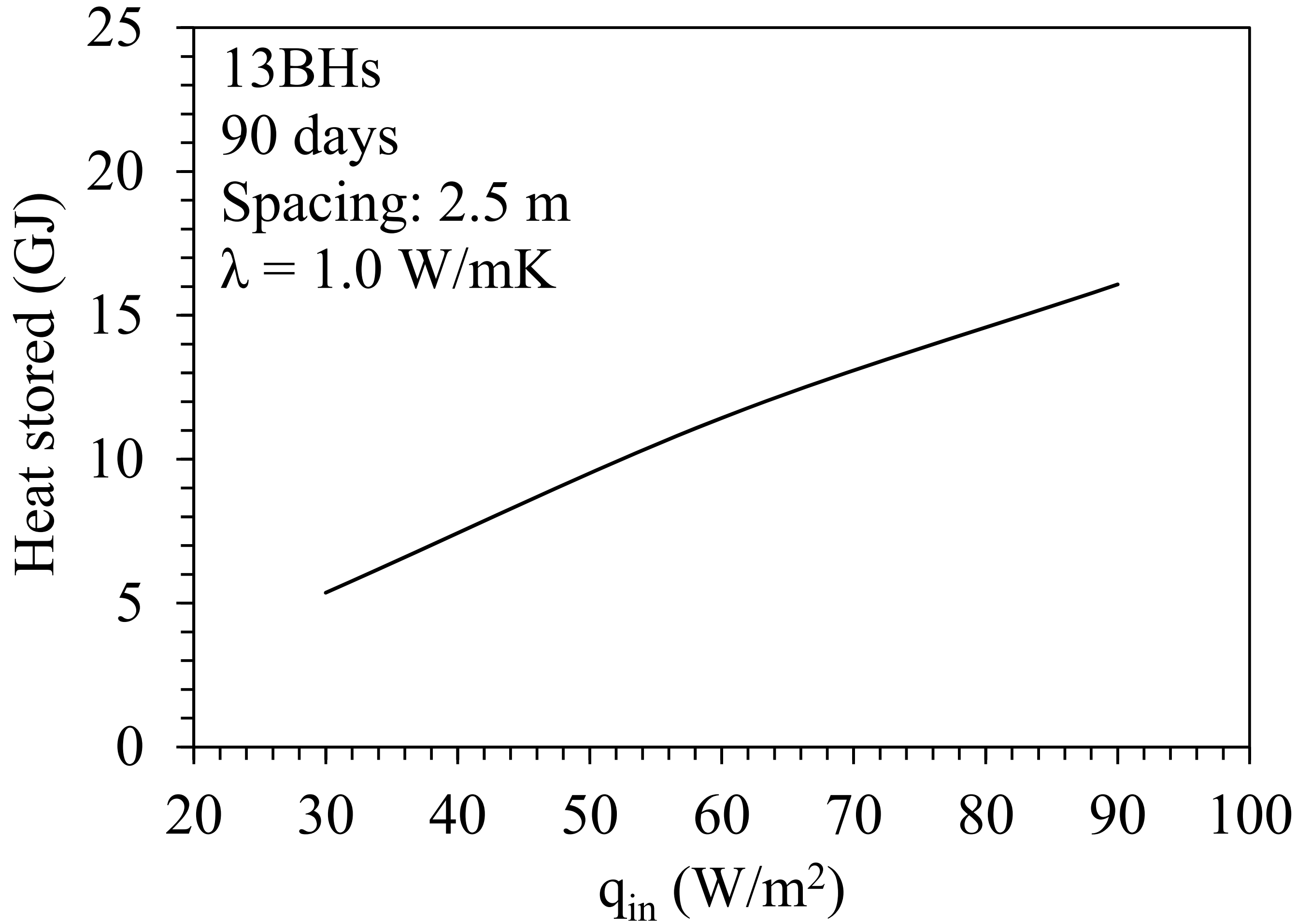


Storage After Heat Injection

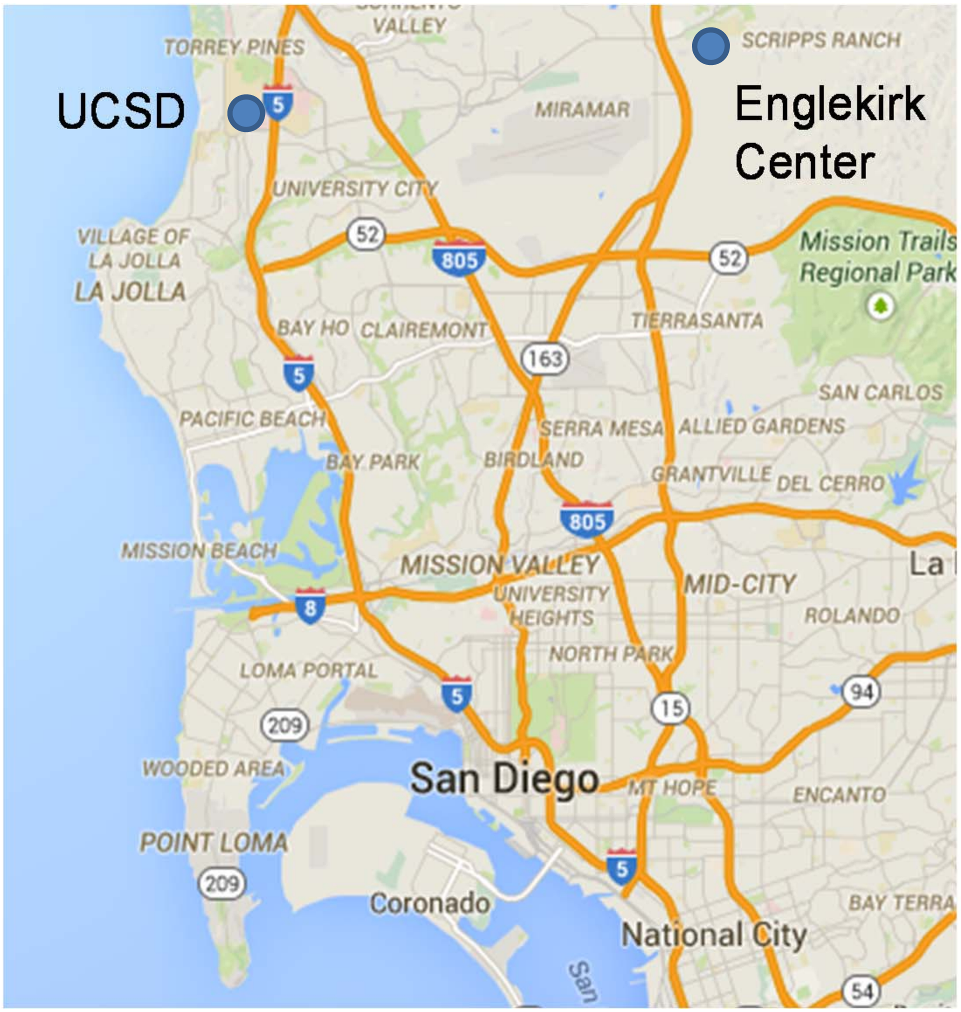


Storage After Resting Period

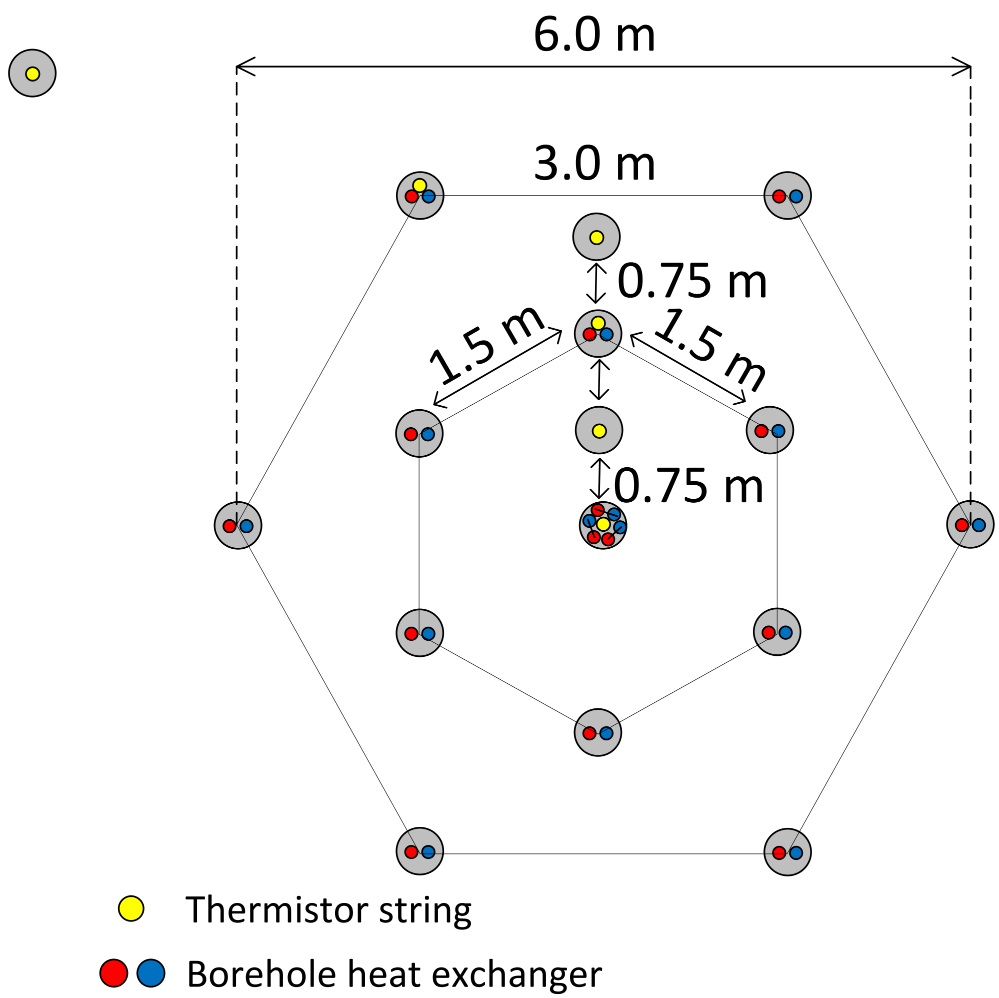
Scalability of SBTES Systems: Arrays Considered



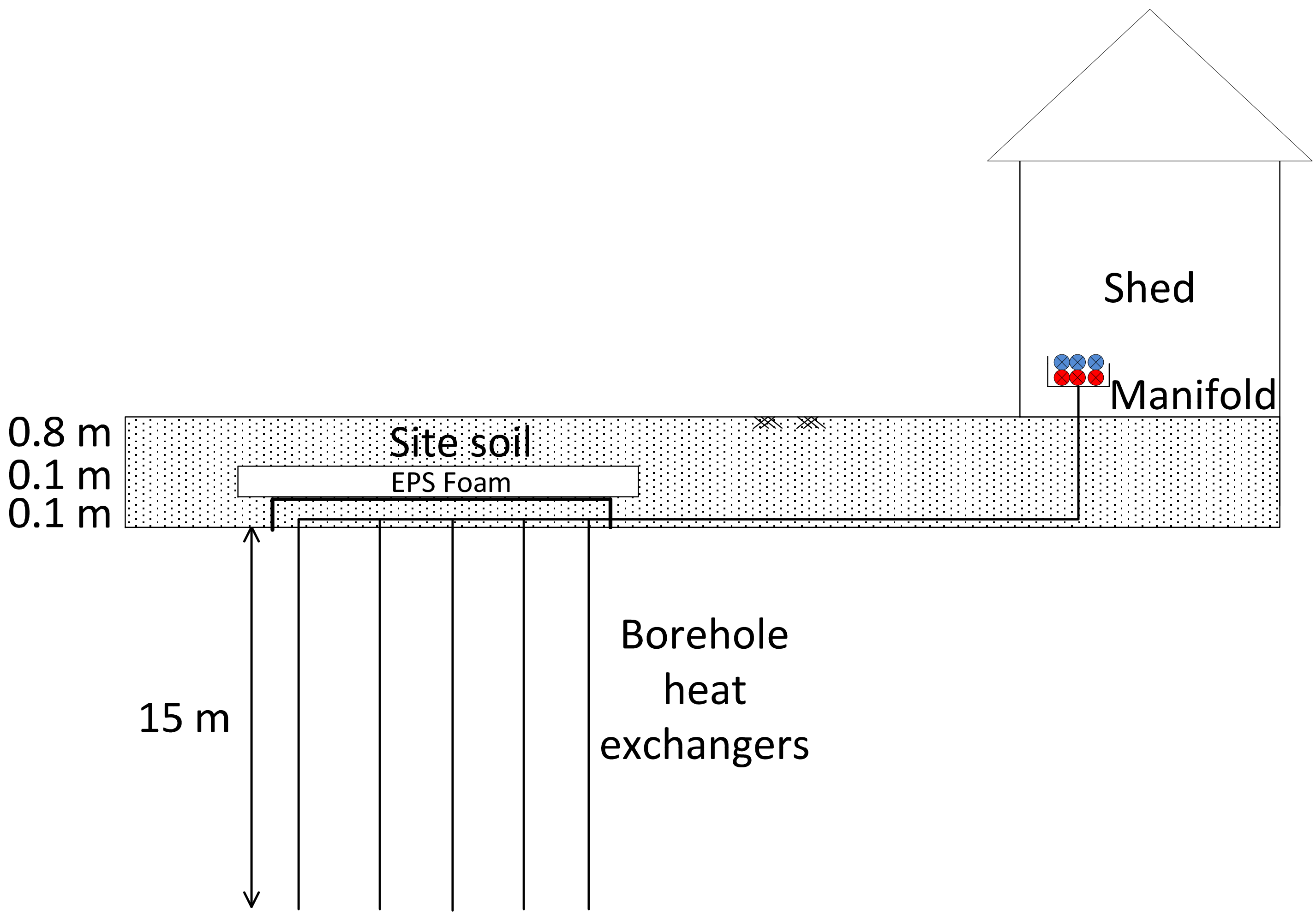
New SBTES Site at UCSD



Planned Borehole Array



Planned Borehole Array



Final Comments

- SBTES systems can effectively store heat in the subsurface
- Efficiency of heat extraction is low, but the heat source is renewable and nearly free
- Heat storage is best in soils with low thermal conductivity and with low permeability (low convection)
- Closer spacings (1-2 m) will result in the greatest concentration of heat
- Sufficient boreholes are required in an array to retain elevated ground temperatures after a resting period