Heat Transfer Model Estimating Energy Extraction from a Closed-Loop Geothermal System*

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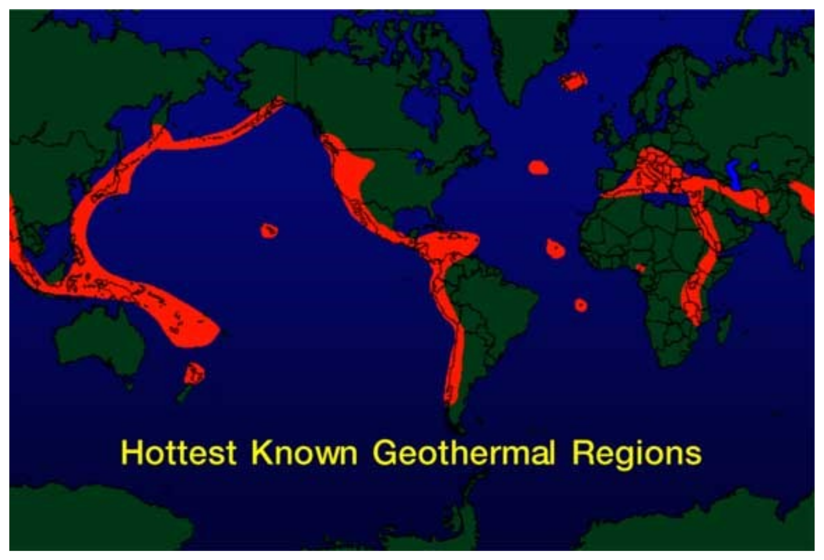
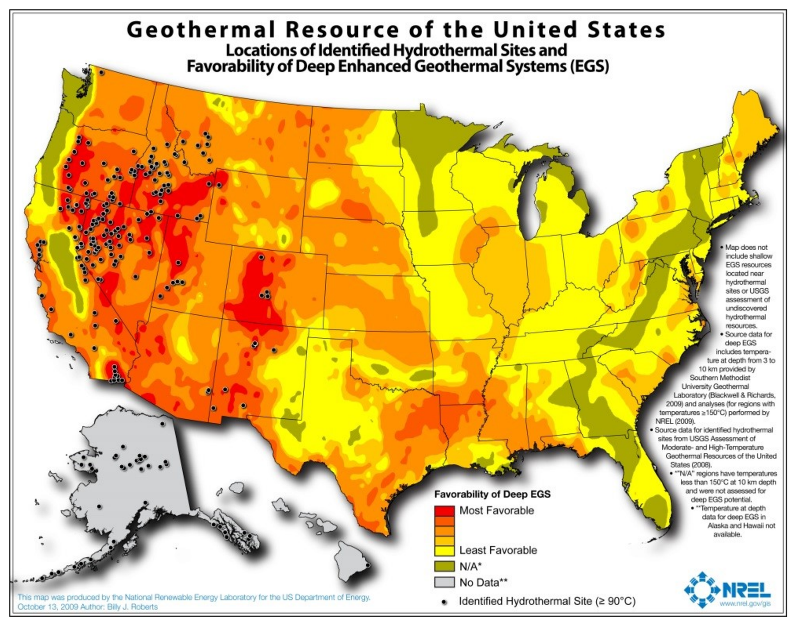


A heat transfer model is established for calculation of closed-loop geothermal systems. Of which the heat exchange sections have very large length-to-diameter (*L/d*) ratios. The model is used to estimate heat extraction from the system described in U.S. Patent 8,991,488. For quasi-steady-state heat transfer analysis, it shows that the soil-side thermal resistance is much larger than the liquid-side thermal resistance of the closed-loop system described in U.S. Patent 8,991,488. Conversely, the rate of energy extraction is limited by the soil-side heat transfer. For soil-side heat transfer, a simplified heat transfer model is established. The model is based on Kelvin's line-source model to account for large *L/d* ratios of the system, which exceeds 10,000, and to account for time-dependency of the energy extraction. The results show that for a pre-set outer-wall temperature of the heat exchange section, the total amount of energy extraction depends on the energy extraction rate. Higher energy extraction rates result in shorter periods of operation. For a fixed rate of energy extraction, higher surrounding temperatures result in longer periods of operation. The model also identifies a non-dimensional parameter that can be used as a scaling parameter for different diameters of the heat exchange section.



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Specific Objectives

- Develop mathematical model to estimate heat extraction from closed-loop geothermal systems that are characterized by
  - Large aspect ratios, i.e., large length-to-diameter ratios, presenting challenges to numerical calculation
  - Time scale of years
  - Complex physical properties

Case Study – InnerGeo, U.S. Patent 8,991,488 B2

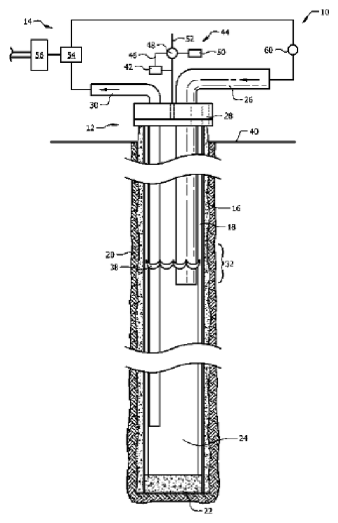


Table 1. Summary of Geometric and Operating Parameters

Geometry
- Well diameter: 17 in
- Injection tube: 8 in
- Production (heated water) tube: 3 in
- Heated tube section (horizontal): 5280 ft

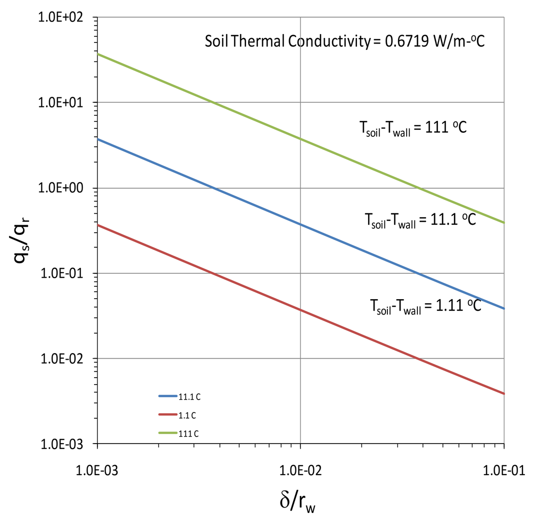
Operating condition
- Feed water: 200 F
- Production water: 350 F
- Flowrate: 1000 gallon/min

Quasi-Steady State Water-Side Heat Transfer

- Water-side heat transfer
  - Heat-load and overall heat transfer coefficient needed
    - ✓ $q_r = \rho Q(h_e - h_i)$ = 20.4 MW_{th}
    - ✓ $U_r = q_r/(A\Delta T_{lm})$ = 201.3 $W/m\text{-}^oC$
- Tube heat transfer coefficient – water properties
  - $Nu = 0.023 Re^{0.8} Pr^{0.4}$
  - U_r = 2,117 $W/m\text{-}^oC$ >> 201.3 $W/m\text{-}^oC$
- Water-side can deliver heat transfer needed

Quasi-Steady State Soil-Side Heat Transfer

- Soil-side
  - Heat transfer from soil to wall
    - ✓ $q_s = 2\pi L k_s (T_s - T_w)/\ln(r_p/r_w)$
  - Thermal penetration length
    - ✓ $delta = r_p - r_w$
  - Results showing that heat load can be met if
    - ✓ T_s-T_w = 11.1 or 111 °C and $delta/r_w$ < 0.4 or 0.04, respectively
    - ✓ T_s-T_w = 1.11 and $delta/r_w$ < 0.001



Line Source Analysis – Modified Kelvin's Theory

- T_s-$T_w = q_l/(4\pi k)\, E_1 (r^2/(4\alpha_{grd} t))$; $E_1 (r^2/(4\alpha_{grd} t)) = \ln(4\alpha t/r^2) - 0.5772$

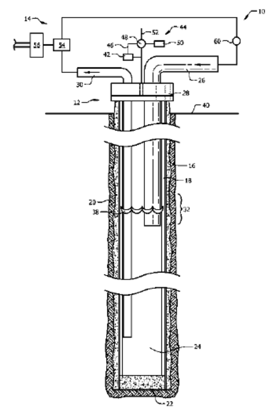
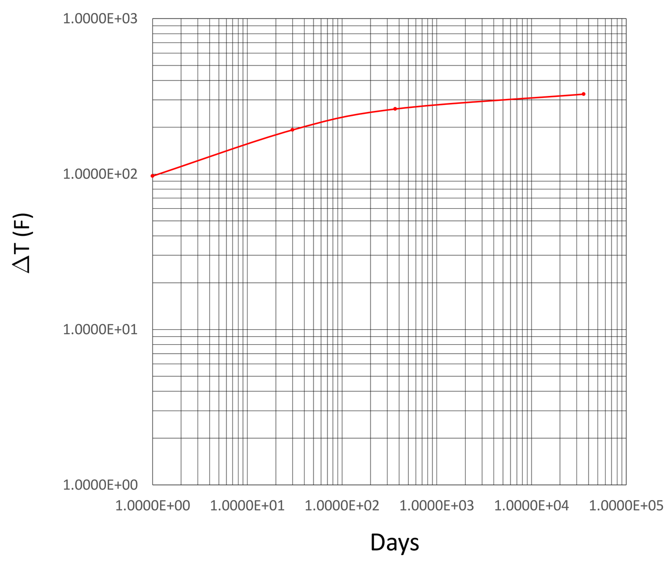


Table 2. Geometric and Operating Parameters – 408 kW_{th}

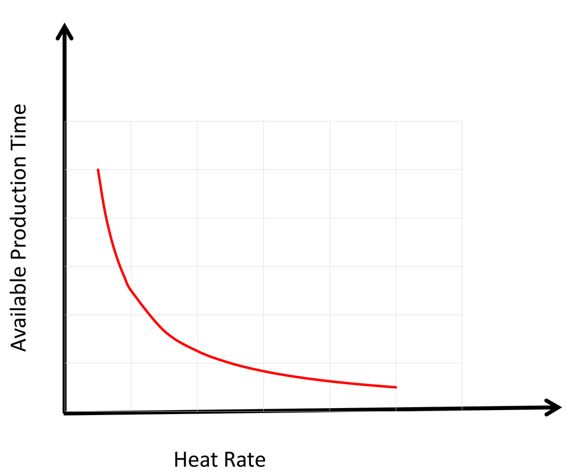
Geometry
- Well diameter: 7 in
- Injection tube: 3 in
- Production (heated water) tube: 2 in
- Heated tube section (horizontal): 5280 ft

Operating condition
- Feed water: 200 F
- Production water: 350 F
- Flowrate: 20 gallon/min

Soil Temperature Requirements



Heat Rate vs. "Available" Production Time



- "Available" production time decreases with increasing heat rate extraction
- Heat transfer analysis can assist setting the operating condition in design stage
- Heat transfer analysis can also assist revenue estimates and ROI

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