1 Study Parameters

- S varies from $2''$–$15''$, with at least 4 increments ($X \geq 4$).
- $L = 150'$.
- Barely turbulent flow (water).
- Annular grout ($0.5''$ thick around) Hex tube.
- Typical soils in Arizona or Minnesota.

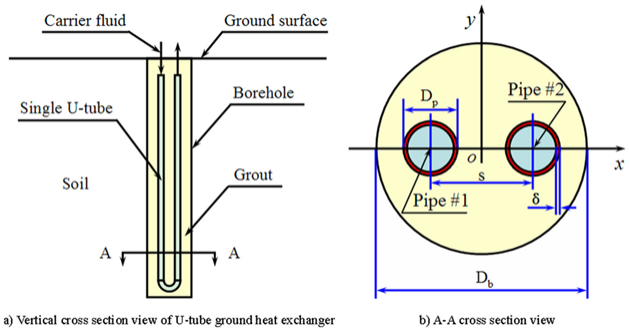

Figure 1: Caption for the PNG image.

2 Pipe Specifications

2.1 200 PSI SDR 11

- 200 PSI refers to the pressure rating of the pipe.
- SDR 11 (Standard Dimension Ratio) means

$$\frac{\text{Outer Diameter (O.D.)}}{\text{Wall Thickness (Wall)}} = 11.$$

- The table lists three different pipe sizes: $3/4''$, $1''$, and $1\frac{1}{4}''$, along with:
  - O.D. (Outer Diameter)
  - I.D. (Inner Diameter)
  - Wall thickness
  - Weight per foot (Wt/ft)

2.1.1 Highlighted Section (1″ Pipe Size)

- O.D. (Outer Diameter) = 1.315″
- I.D. (Inner Diameter) = 1.077″
- Wall thickness = 0.120″
- Weight per foot (Wt/ft) = 0.191 lbs/ft

2.2 Spacing Variable ($S = 1.935''$)

- S represents the tube spacing in a geothermal ground loop system.
- According to IGSHPA (International Ground Source Heat Pump Association), these pipes meet geothermal system standards.
- The study varies tube spacing, so S is the distance between adjacent tubes in a loop system.

3 Typical Soil Types in Arizona and Minnesota

3.1 Arizona

- **Aridisols**: Dominant in Arizona's arid climate, characterized by limited organic matter and often sandy or gravelly.
- **Entisols**: Found in areas with little soil development, such as recent river deposits.

3.2 Minnesota

- **Alfisols**: Common in central and eastern regions, typically formed under deciduous forests.
- **Mollisols**: Predominant in western parts; rich, dark soils formed under prairie vegetation.

4 Annular Grout: Definition and Purpose

Annular grout is the sealing material placed in the annular space between a borehole wall and an installed conduit (e.g., a geothermal heat exchanger). Its primary purposes include:

- **Enhancing Heat Transfer**: Facilitates efficient thermal exchange between the conduit and surrounding soil.
- **Preventing Contamination**: Acts as a barrier to protect groundwater from potential contaminants.
- **Structural Support**: Stabilizes the borehole and installed components.

5 Soil Thermal Properties

- **Thermal Conductivity**: Varies based on soil type, moisture content, and density.
- **Sandy Soils**: Generally have lower thermal conductivities, especially when dry.
- **Clay Soils**: Thermal conductivity increases with moisture content but can vary widely.

6 Grout Thermal Properties

- **Thermal Conductivity**: A key factor influencing heat transfer in geothermal systems.
- **Conventional Bentonite Grout**: Typically 0.38–0.45 W/m·K.
- **Thermally Enhanced Grouts**: Can reach up to 1.60 W/m·K or higher, depending on additives (e.g., silica sand or graphite).

7 Questions Comments

- **Question 1:** Where a 200–1500 m depth range is suitable for the middle-shallow BGHE. Is the material of the U-tube polyethylene?
- **Question 2:** Unit Confirmation.
- **Comment 1:** In previous calculations for shallow U-tube BGHEs, the analytical method that ignored the geothermal gradient was frequently used. The analytical solution employed mathematical analysis, and some methods such as the Green function method, the Laplace transform, and other corresponding mathematical formulas were utilized to solve the heat transfer problem. The finite line heat source method was adopted to obtain the temperature response based on the analytic theory, and the temperature responses are shown in Equation ...
- **Governing Equations Assumptions:** To establish the governing equations of energy conservation for both the circulating fluid and the underground rock-soil, some preconditions are made or assumed to ensure accurate calculations. The simplified assumptions must be made for the U-tube to speed up the calculation while ensuring accuracy. The detailed information is as follows:
  - In the process of analysis, the circulating fluid of the U-tube is generally in a turbulent state to improve the heat transfer performance of the BGHE. The heat transfer mode of the circulating fluid is mainly carried out by heat convection, and thus the axial heat transfer of the BGHE is neglected, which means that a one-dimensional unsteady heat transfer is suitable for the circulating fluid.

– The temperature difference between the inlet and outlet temperatures of the circulating fluid is generally less than 10 °C, and it is assumed that the physical property parameters such as the density, the specific heat, or other parameters do not change with time or temperature.
– The rock-soil around the U-tube BGHE is assumed to be a uniform medium, and the thermophysical properties of the medium do not change with the rock-soil's temperature.
– The heat transfer outside the BGHE is regarded as a two-dimensional unsteady heat conduction process, which only generates heat transfer in the radial and axial directions.
– The influence of groundwater seepage can be ignored because the seepage velocity is low.
– The terrestrial heat flow, that is, the product of the geothermal gradient and the underground rock-soil's thermal conductivity, moves from the Earth's interior to the surface, and the value is deemed to be constant during the heat transfer of the BGHE.