National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594

PLD23LR002

MATERIALS LABORATORY

Specialist's Study Report 23-086

October 11, 2023

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A. ACCIDENT INFORMATION

Location: West Reading, Pennsylvania
Date: March 24, 2023
Vehicle: West Reading, Pennsylvania
Investigator: Kim West, RPH-20

B. STUDY TOPIC

Ground temperature profile around a buried intact steel pipe conveying steam.

C. STUDY PARTICIPANTS

Specialist Donald Kramer, Ph.D.
National Transportation Safety Board
Washington, DC

D. DETAILS OF THE STUDY

1.0 Background and assumptions

An Aldyl A service tee, originally installed in 1982 on 1-1/4-inch Aldyl A pipe and providing gas service to 17 S. 2nd Ave in West Reading, PA, was retired from service in 2021. The tee was subsequently found at the accident site with a longitudinal fracture in the tower shell and a transverse fracture through the insert. A nearby steam pipe (see below for horizontal and vertical separation) was found with a breach on its east side. See Materials Laboraotry Factual Report 23-072 for additional details.

A 2-dimensional finite element simulation was conducted of a buried intact steel pipe conveying steam at 10 psig and 115 °C to estimate the ground temperature field around the pipe. The simulation studies the temperature field prior to any breach in the steam pipe. Details of the pipe are presented in table 1.

Table 1. Attributes of the buried steel steam pipe.

Attribute	Value
Nominal pipe size	3-1/2
Outer diameter	4.000 inch (0.1016 m)
Inner diameter	3.548 inch (0.09012 m)
Buried depth	19.4 inch (0.493 m)
Thermal conductivity	54 W/m-K[1]

[1] The Engineering ToolBox (2005). Metals, Metallic Elements and Alloys - Thermal Conductivities. [online] Accessed at: https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html on 10/5/2023.

The 2-dimensional model encompassed an area of ground 20-meters wide by 10-meters deep, with the pipe centered horizontally in the volume, as shown in figures 1a and 1b. Baseline thermal conductivity for the ground, k, was estimated based on external data sources for soil moisture content and variations in thermal conductivity with moisture content and soil type. The moisture content was estimated using weather station data collected by the USDA Natural Resources Conservation Service.[2] Soil moisture content for the closest station at 40.76° North, 76.67° West is shown in figure 2. Based on the station data, a moisture content of 25% was assumed. An associated baseline soil thermal conductivity of k = 1.644 W/m-K (0.95 BTU/hr-ft-F) was assumed for the simulation based on the moisture content of 25%. The value of thermal conductivity lies between the upper and lower bounds for sand and clay soil types at that moisture content, as shown in figure 3.[3] Sand and other filler materials can have thermal conductivities that differ from soil, therefore simulations were also run at half and twice the baseline value. As shown below, the ground temperature at the location of interest was not strongly dependent on the choice of soil thermal conductivity.

Other simulation attributes:

- Standard (implicit) solver, uncoupled simulation (no thermal stress effects), steady state solution (time independent).
- Boundary conditions: 4.44°C (40.0 °F) or 15.6 °C (60.0 °F) at bottom and side boundaries with 4.44 °C or 15.6 °C air temperatures, respectively.[2,3]
- Assumed convective heat transfer coefficient, h_c, of 20.0 W/m^2-K at ground/air interface.[4]
- Forced convective heat transfer coefficient at steam/pipe interface: 20.0 W/m^2-K (low velocity, lower bound) or 200 W/m^2-K (high velocity, upper bound).
- The pipe outer diameter surface is tied to the ground in the simulation to allow heat to flow between the two media, with no insulation or thermal barrier in between that would frustrate heat transfer.
- A volume of calcium carbonate that was found around the steam pipe at the accident site is assumed to have similar conductivity as the soil.
- A 1-1/4 NPS Aldyl gas main passes underneath and perpendicular to the steam pipe. The effect of this heat sink is not considered.

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[2] U.S. Department of Agriculture Natural Resources Conservation Service. Accessed at https://wcc.sc.egov.usda.gov/nwcc/rgrpt?report=daily_scan_cy on 8/10/2023.

[3] National Bureau of Standards. "NBSIR 81-2378: Heat Transfer Analysis of Underground Heat and Chilled-Water Distribution Systems," U.S. Department of Commerce, 1981.

[4] Dassault Systems, "Thermal Analysis," downloaded from https://www.solidworks.com/sw/docs/thermal_2010_eng_final.pdf on 10/6/2023.

- Two conduits carrying heat tape-wrapped chocolate lines are located below the steam line. The chocolate lines operate at 37.8 °C (100 °F) and are air-gapped. The heat from these lines is not considered.
- Pipe mesh seed: 0.001 m. Meshed with 8-node quadratic heat transfer quadrilaterals.
- Ground mesh seed: 0.002 m at pipe interface; 0.1 m at ground/air interface; 0.25 m at bottom and side edges. Meshed with 8-node quadratic heat transfer quadrilaterals.

2.0 Simulation results

Temperatures were extracted at two specific nodes: 1) a node on the outer diameter surface at the bottom of the steam pipe and 2) a node at a 0.589 m horizontal offset and 0.389 m vertical offset below the center of the pipe. The latter node was the approximate relative location of an Aldyl A service tee, formerly providing gas service to 17 S. 2nd Ave and retired from service in 2021. According to survey data, the top of the tee was offset approximately 0.594 m (23.4 inch) horizontally and 0.394 m (15.5 inch) vertically below the center of the pipe. The selected node was closest to this location. The temperature fields for two conditions are shown in figures 4a and 4b, with the approximate location of the tee indicated in figure 4a. The top image shows the temperature field assuming a 4.44 °C ground temperature and a 20.0 W/m^2-K convective heat transfer coefficient at the steam/pipe interface. The lower image shows the temperature field assuming a 15.6 °C ground temperature and 200 W/m^2-K convective heat transfer coefficient. Data from the various simulation conditions are listed in table 2.

Table 2. Simulation inputs and temperature results.

Ground temp, °C	h_c (steam to pipe ID), W/m^2-K	k (ground), W/m-K	Steam pipe OD temp, °C	Ground temp at service tee, °C
4.44	20.0	1.644	74.5	23.2
4.44	200	1.644	109.0	32.4
15.6	20.0	1.644	78.5	32.4
15.6	200	1.644	109.6	40.8
4.44	20.0	0.822	89.7	26.5
4.44	20.0	3.288	56.8	19.3

3.0 Analytical solution

The expression for steady-state heat conduction from a buried pipe in a homogeneous medium is:[3]

$$Q = \frac{2\pi k_s (T_P - T_G)}{\ln\left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right)}$$

where Q = heat loss from unit length of pipe
k_s = average thermal conductivity of ground surrounding the pipe
d = depth of the pipe from the ground surface to the center of the pipe
r = outer radius of the pipe
T_P = is the temperature of the pipe outer diameter surface
T_G = average ground temperature

The ground temperature, T, at a point (x,y), where x is the horizontal distance from the pipe and y is the depth below the surface is given by:[3]

$$T = \frac{Q}{4\pi k_s} \ln\left[\frac{(x-a)^2 + (y-d)^2}{(x-a)^2 + (y+d)^2}\right] + T_G$$

Substituting the first equation into the second, the temperature can be calculated as:

$$T = \frac{(T_P - T_G)}{2\ln\left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right)} \ln\left[\frac{(x-a)^2 + (y-d)^2}{(x-a)^2 + (y+d)^2}\right] + T_G$$

Table 3 shows the results of this equation applied to the system analyzed above, namely the 4-inch diameter steam pipe at a = 0 inch and a buried depth, d = 19.4 inch. The temperature is calculated at a location x = 23.4 inch horizontal and y = -34.9 inch (15.5 inch below the steam pipe centerline).

Table 3. Ground temperature at x = 23.4 inch and y = -34.9 inch for two different ground temperatures and a range of pipe outer diameter surface temperatures.

Average ground temperature, °C	Pipe OD surface temperature, °C	Temperature at retired tee, °C
4.44	70.0	20.9
4.44	80.0	23.4
4.44	90.0	26.0
4.44	100.0	28.5
4.44	110.0	31.0
15.6	70.0	29.3
15.6	80.0	31.8
15.6	90.0	34.3
15.6	100.0	36.8
15.6	110.0	39.3

E. DISCUSSION

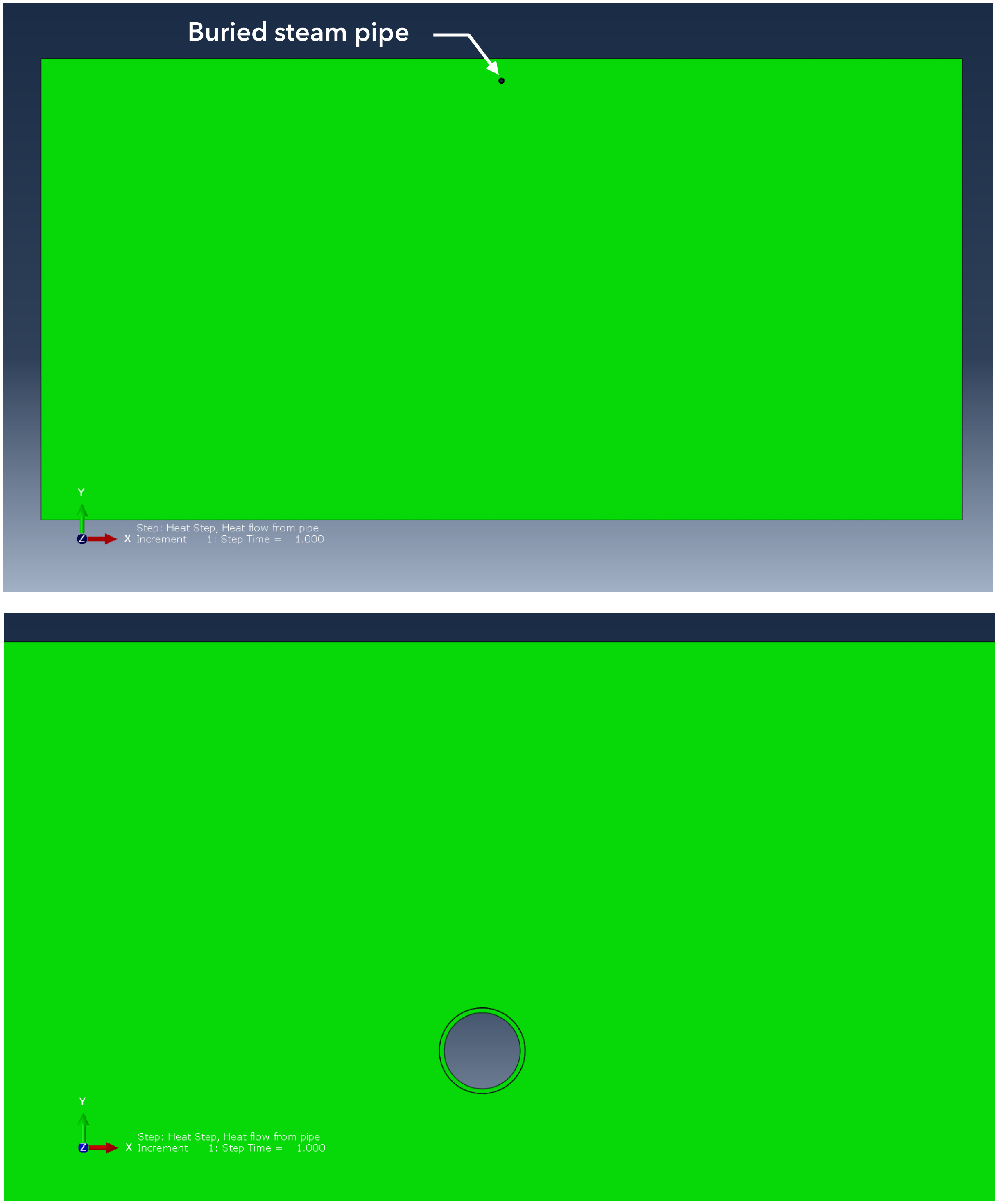
For the low convective heat transfer condition at the steam/pipe interface, two parameters of the model were varied, each one at a time: 1) ground temperature at fixed ground thermal conductivity and 2) ground thermal conductivity at fixed ground temperature. For the first case, the temperature on the outside of the steam pipe ranged between 74.5 °C and 78.5 °C and the temperature at the node closest to the location of the retired service tee ranged between 23.2 °C (73.8 °F) and 32.4 °C (90.3 °F). For the second case, at a ground temperature of 4.44 °C, lowering the ground thermal conductivity by half raised the outside temperature of the pipe to 89.7 °C and doubling it lowered the temperature to 56.8°C. The ground temperature at the nominal location of the retired service tee increased by 3.3 °C and decreased by 3.9 °C, respectively. For the above four conditions combined, the temperature at the location of the retired service tee ranged from 19.3 °C (66.7 °F) to 32.4 °C (90.3 °F).

For the high convective heat transfer condition, the temperature on the outside of the pipe increased to 109.0 °C and 109.6 °C for the low and high ground temperature conditions, respectively. The temperature at the location of the retired tee increased by 9.2 °C and 8.4 °C, respectively, compared to the low convective heat transfer condition.

The results from the analytical solution were similar to but slightly lower than the results from the finite element simulation. For the finite element simulation, the lowest computed temperature at the location of the retired tee was 19.3 °C (see table 2) and the corresponding temperature of the steam pipe OD surface was 56.8 °C. The result for the analytical solution using the same ground temperature and steam pipe surface temperature was 17.6 °C, for a difference of -1.7 °C. At the opposite end of the studied conditions, the highest computed temperature at the location of the retired tee for the finite element simulation was 40.8 °C and the corresponding temperature of the steam pipe OD surface was 109.6 °C. The result for the analytical solution using the same ground temperature and steam pipe surface temperature was 39.2 °C, for a difference of -1.6 C.

Submitted by:

Donald Kramer, Ph.D.
Senior Materials Engineer



a) b)

Figure 1. Overview of model used to calculate the steady-state temperature distribution around the buried pipe: a) low mag and b) high mag.

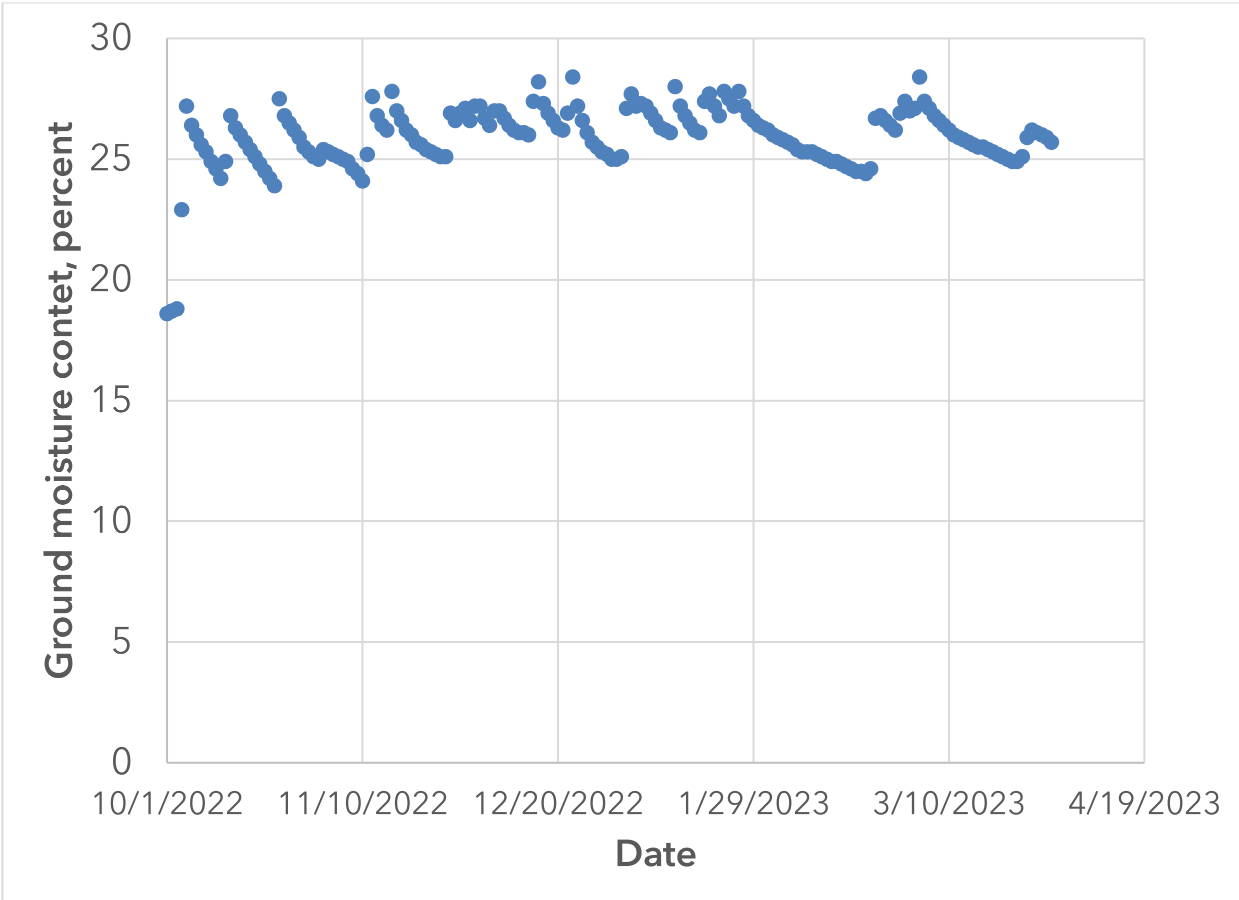


Figure 2. Ground moisture content for weather station in eastern Pennsylvania located at 40.76° North, 76.67° West.

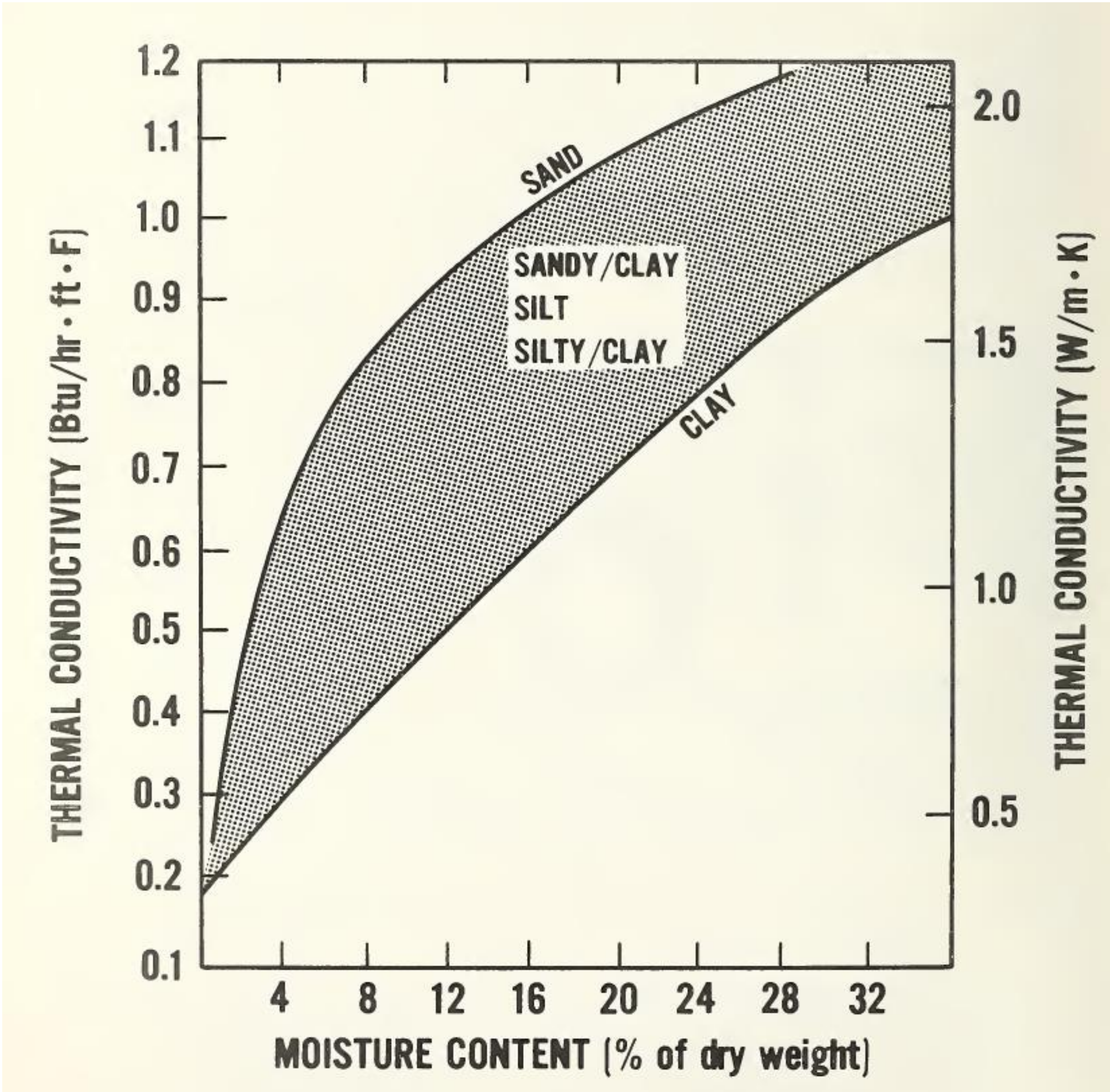


Figure 3. Variation of ground thermal conductivity with soil moisture content. Reference: National Bureau of Standards. "NBSIR 81-23-78: Heat Transfer Analysis of Underground Heat and Chilled-Water Distribution Systems," U.S. Department of Commerce, 1981.

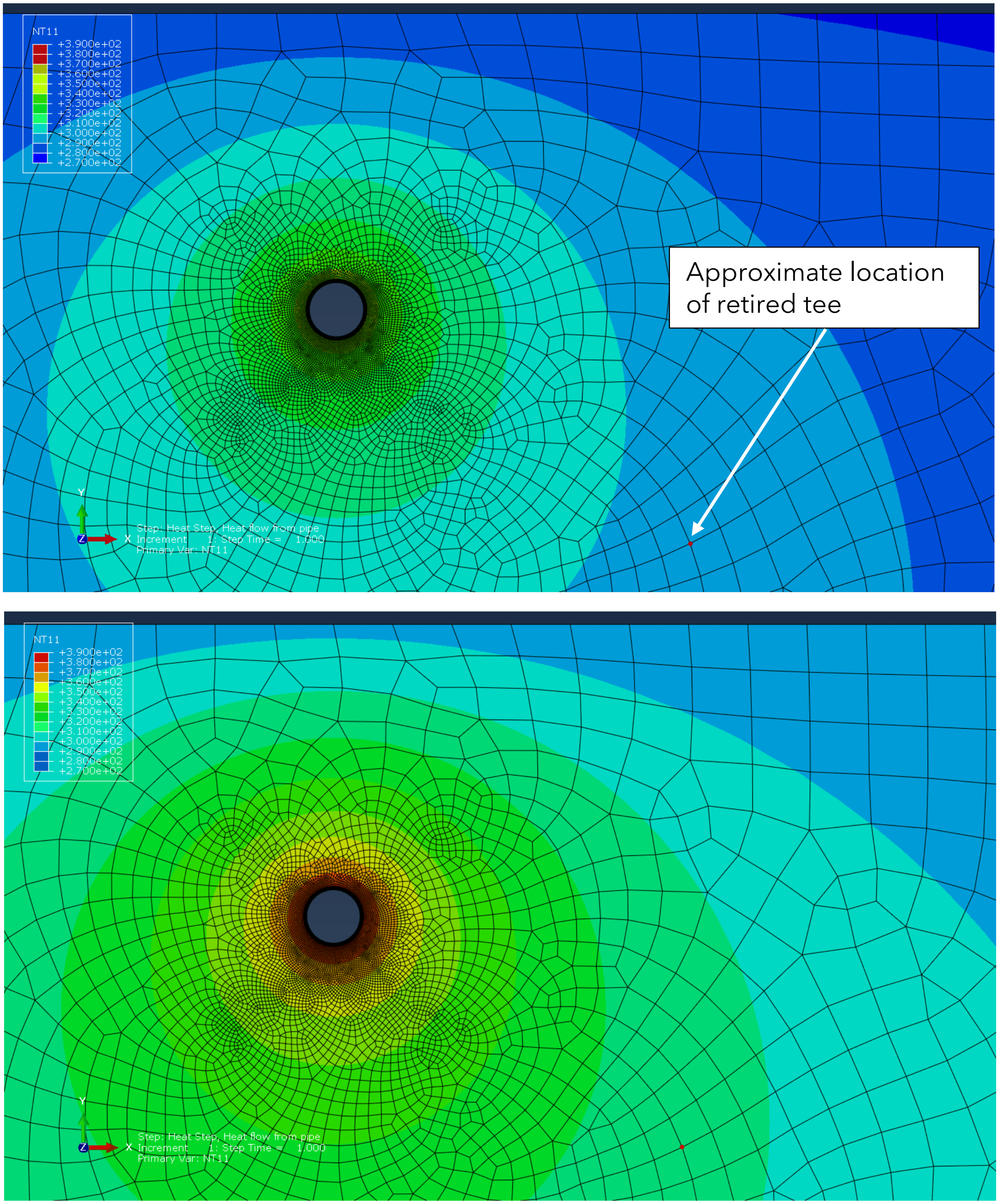


Figure 4. Steady state temperature fields around the buried steam pipe. Temperature values in the legend are given in Kelvin: a) 4.44 °C (40.0 °F) ground and air temperature, h_c = 20.0 W/m^2-K and b) 15.6 °C (60.0 °F) ground and air temperature, h_c = 200 W/m^2-K.