APPENDIX G

THERMAL ANALYSIS OF THE ITC LAKE ERIE CONNECTOR HVDC PROJECT

Thermal Sciences Practice

Thermal Analysis of the ITC Lake Erie Connector HVDC Project

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Limitations

At the request of K&L Gates LLP on behalf of its client, ITC Lake Erie Connector LLC (ITC Lake Erie), Exponent calculated temperature profiles created by a proposed 320-kV direct current (DC) transmission line in Lake Erie that will transmit approximately 1,000 Megawatts of electricity. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on information provided to Exponent by ITC Lake Erie and ITC Lake Erie's engineering and technical consultants as to operating parameters and configurations of the transmission line. The findings presented herein are made to a reasonable degree of engineering certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this analysis may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented here independent of the proposed project are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied

Introduction

Exponent was retained to analyze the thermal gradients in the vicinity of a proposed ITC Lake Erie Connector direct current (DC) underwater transmission project (the LEC Project), to be installed under the bed of Lake Erie. Calculations of heat transfer into the soil surrounding the cables and water above the soil were performed for cable configurations and environmental conditions provided by ITC Lake Erie's engineering and environmental consultants—HDR and Black & Veatch.

Methodology

Modes of Heat Transfer

Heat released from the pair of electric transmission cables is transferred via two modes: conduction and convection. Given that the cables are buried in the lakebed, the initial stage of heat transfer consists of conduction from the cables into the ground beneath the lakebed, as well as conduction within the soil toward the water/soil interface at the surface of the lakebed. Once heat reaches this interface, it is both conducted through water and transported away by water via convection.

Cable Configurations

The cables are proposed to be buried in the lakebed at a minimum depth of 0.5 meters (m) measured from the top of the cables. Two burial configurations were evaluated:[1]

1. Trench Configuration: the cables are buried in a trench in the bedrock and covered with fill material as seen in Figure 1.
2. Jet Plow Configuration: the cables are buried in the soft soil by a jet plow as seen in Figure 2.

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[1] The proposed LEC Project will also involve placement of a short section of the cables within borings through bedrock installed by horizontal directional drilling. Because of the greater depths involved in this segment, HDR and Black & Veatch have deemed preparation of a separate thermal estimate for this segment unnecessary since the values at the soil/water interface will be lower than those calculated for adjacent cables.

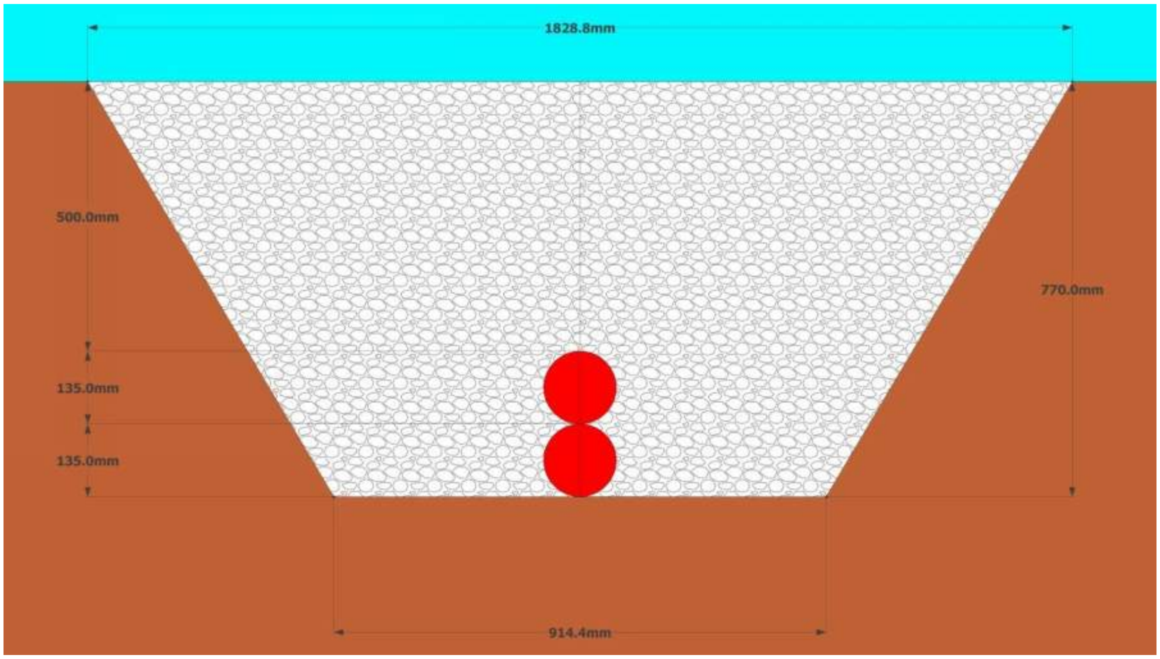

Figure 1. Configuration of cables installed in a trench.

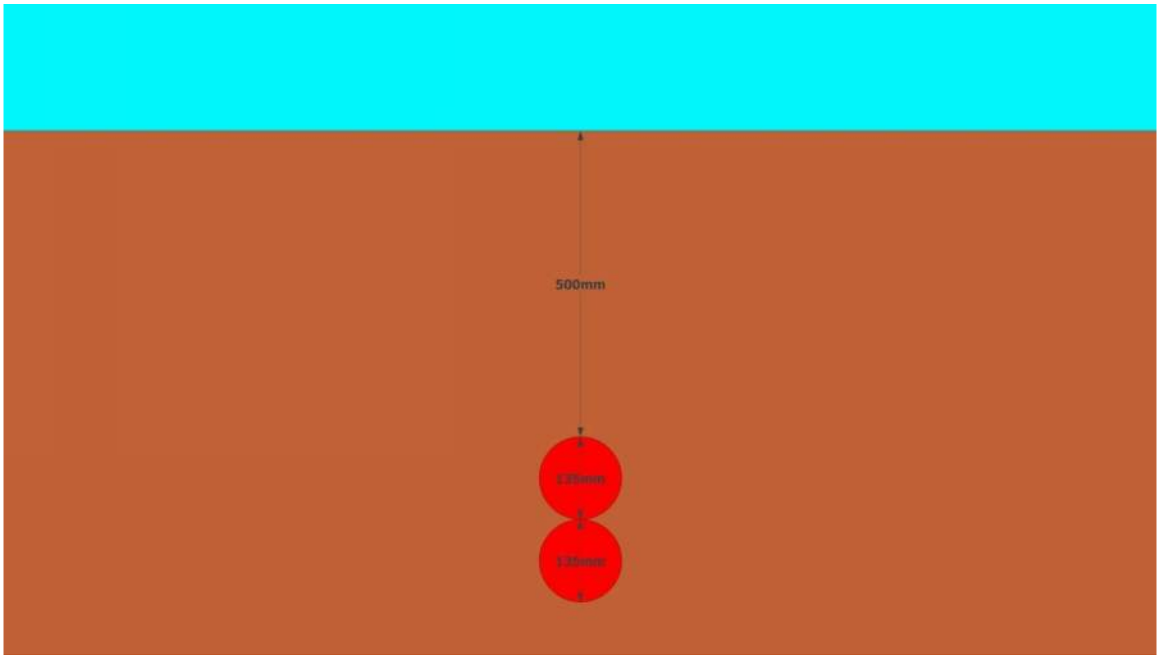

Figure 2. Configuration of cables installed by a jet plow.

Variables Affecting Heat Transfer

The temperature increase in the environment surrounding the cables is a function of multiple variables including:

- Cable orientation and proximity;
- Cable burial depth;
- Soil type and thermal conductivities;
- Heat load; and
- Water velocity and direction.

Thermal modeling could be performed for each and every possible combination of these variables; however, the analysis was narrowed to a conservative set of variables that maximized the potential increase in water temperature around the cables.

Conservative Assumptions

Cable Orientation and Proximity

In the Trench Configuration and Jet Plow Configuration scenarios, the cables are buried either side-by-side or stacked one on top of the other. A side-by-side configuration will spread heat over a wide horizontal area, while a stacked configuration concentrates heat in a narrower column above the cables, resulting in higher maximum temperature values above the cables. To be conservative, only the stacked configuration with the cables in contact with one another is presented for both the Trench and Jet Plow Configurations.

Cable Burial Depth

The burial depth is anticipated to be between 0.5-1 m for the Trench Configuration and 0.5-3 m for the Jet Plow Configuration. As a conservative modeling assumption, a burial depth of 0.5 m was used for both cases.

Soil Type and Conductivities

Soil type directly affects the conductive heat transfer coefficient (i.e., thermal conductivity). Black & Veatch provided Exponent with the data in Table 1. It is important to note that the maximum temperature increase observed at the soil/water interface will be sensitive to the accuracy of these provided values.

Table 1. Soil material conductivities

Material	**Conductivity (W/m-K)**
Limestone	1.2 to 1.4
Shale, Marcellus	1.5 to 2.0
Clay, hard	1.5 to 2.0
Sand/Silt mixture	0.8 to 2.0
Backfill, Engineered	1.4 to 2.0

According to data provided by Black & Veatch:

- In the Trench Configuration:
  - The soil is either shale or limestone; and,
  - The trench fill material is an engineered gravel mix.
- In the Jet Plow Configuration:
  - The soil is a mixture of silt, clay, sand, cobbles, and boulders.

Consolidating the above information, we determined the range of conductivities for each configuration, which is summarized in Table 2.

Table 2. Consolidated conductivities range for the Trench and Jet Plow Configurations

Trench Configuration Conductivities (W/m-K)				**Jet Plow Configuration Conductivities (W/m-K)**	
Soil		Fill material		Mixture of silt, clay, sand, cobbles, and boulders	
Min	Max	Min	Max	Min	Max
1.2	2	1.4	2	0.8	2.0

The choice of a conservative set of conductivity values needs careful examination. For example, with respect to selection of an appropriate soil conductivity value, on one hand, a high value leads to a faster heat transfer from the cables to the water/soil interface, but on the other hand, it contributes to faster heat dissipation deep into the ground and away from the water. In the next sections, we will elaborate on the choice of conductivity values that maximize the potential increase in water temperature.

Heat Load

According to Black & Veatch, the range of heat loads is 5-8 Watts per foot (W/ft) per cable. Exponent selected the largest value of 8 W/ft per cable (i.e., 26.25 Watts per meter per cable) for modeling.

Water Depth

- In the Trench Configuration, the water depth is 5-10 m;
- In the Jet Plow Configuration, the water depth is 5-60 m;
- Exponent assumed the shallowest water depth value of 5 m.

Water Velocity and Direction

The Lake Erie environment is extremely dynamic in terms of water velocity and direction. These parameters vary as a function of topography, wind velocity, seasons, and other factors. The water velocity is understood to range from a few centimeters per second (cm/s) to tens of cm/s. At each location along the transmission line’s route, the water velocity vector can be divided into two components in the horizontal plane: one parallel to the cables’ centerline and one perpendicular to their centerline. A water velocity perpendicular to the cables’ centerline is most effective in transporting heat away from the cables, whereas water velocity along the cable would not effectively transport heat away from the cables.

Exponent took an extremely conservative approach to the convective heat transfer analysis in that a very low water velocity value of only 1 millimeter per second (mm/s) was assumed to carry heat away from the cables in the perpendicular direction. Moreover, this velocity was used in conjunction with a boundary layer velocity profile where 1 mm/s corresponds to the average water velocity in the 5-m deep water column. This means that the layers of water near the bottom of the lake move at significantly lower velocities. We will elaborate on the details of the velocity boundary layer below.

Thermal Simulation Model

Simulation Software Package

The heat transfer and fluid dynamics of the cable environment were modeled using the multi-physics simulation software package STAR-CCM+, Version 9. We did not consider the effect of buoyant gravity forces to yield conservative calculations of the maximum water temperature increase near the water/soil interface.

Velocity Boundary Layer

Prior to running heat transfer simulations, Exponent ran a STAR-CCM+ simulation in the Reynolds-Averaged Navier-Stokes mode using the k-ε turbulence model to determine the fully developed boundary layer profile for a 5-m deep water column (Figure 3), with the following results.

- The average velocity is 1 mm/s
- From a height of approximately 0.5 m to 5 m, the velocities are slightly above 1 mm/s (approximately 1.04 mm/s).
- From the lakebed to approximately 0.5 m above the lakebed, the velocities are below 1 mm/s. For example, at a height of 0.1 m, the velocity is only 0.275 mm/s.

This velocity profile was subsequently used as an input into the heat transfer simulations to ensure a fully-developed boundary layer prior to and after traversing the cables' burial location.

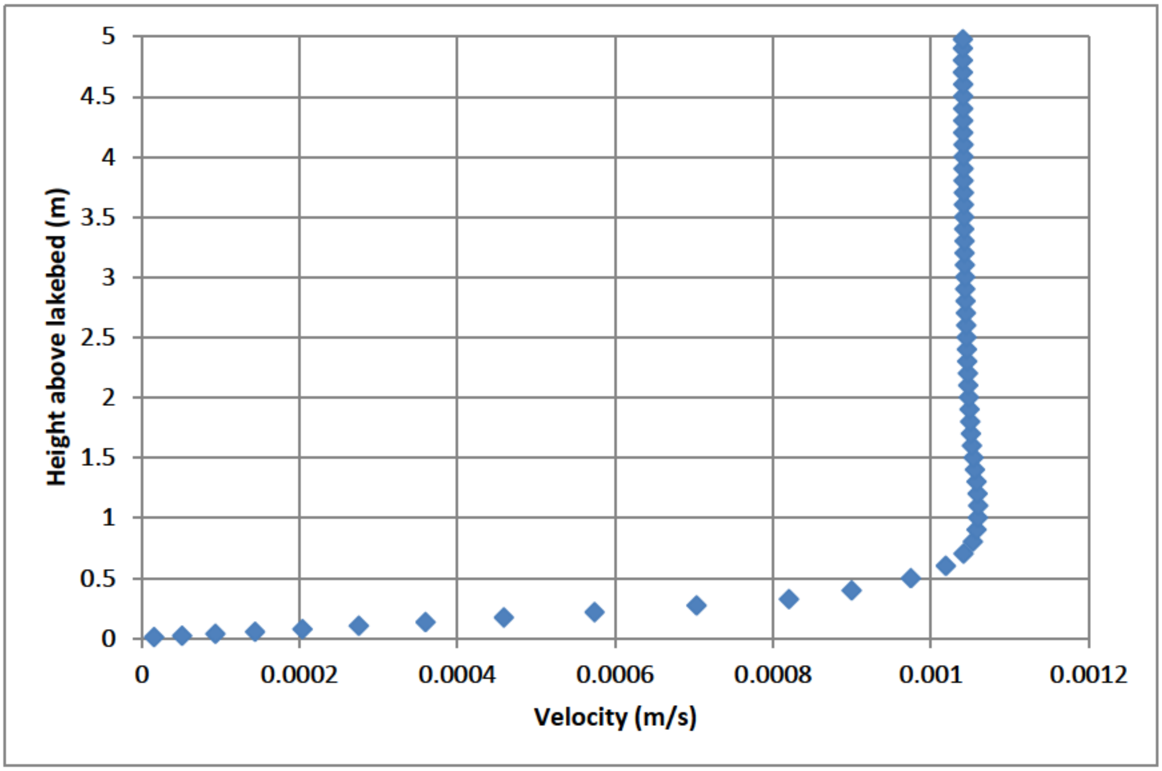

Figure 3. Boundary layer velocity profile for an average velocity of 1 mm/s.

Computational Domain

The cables were assumed to have a nominal diameter of 0.135 m each. For the heat transfer simulations, we chose a computational domain with sufficient far-field boundary extensions: 15 m upstream (the fluid domain at the left of the centerline prior to traversing the cables), 15 m downstream (the fluid domain at the right of the centerline after traversing the cables), 15 m deep into the ground, and 5 m of water height. Figure 4 shows the extent of the computational domain as well as the fully-developed boundary layer mentioned earlier.

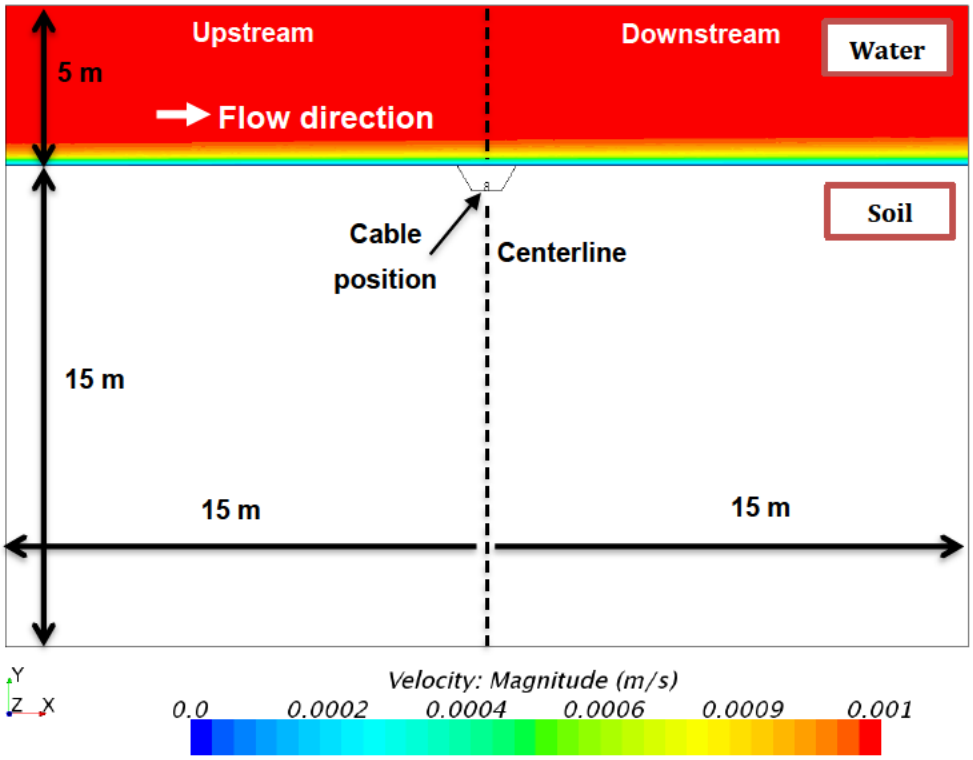

Figure 4. Computational domain and fully developed boundary layer showing flow direction and water velocity.

Mesh

The computational mesh is shown in Figure 5 (entire domain) and Figure 6 (zoom-in view in the vicinity of the cables).

The computational mesh uses polyhedral meshing throughout the domain except in the boundary layer where it uses prism layer cells to capture the velocity and temperature profiles properly. The mesh resolution is increased in the vicinity of the cables to capture the curved surfaces and other geometric features.

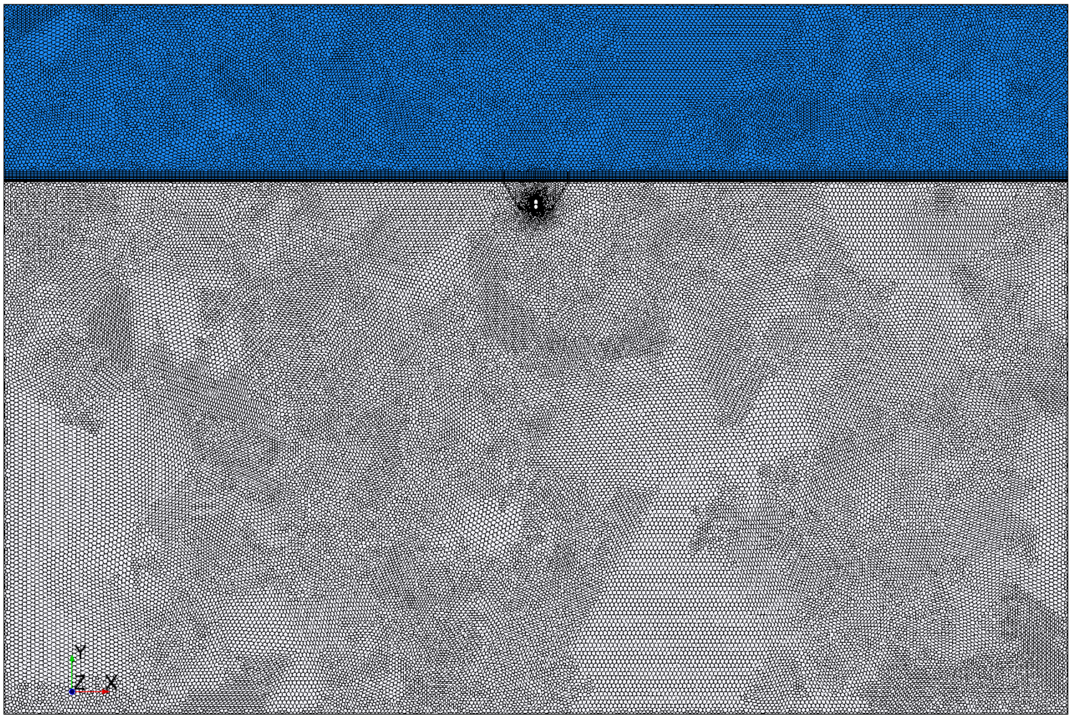

Figure 5. The entire domain of the computational mesh incorporated into the thermal model.

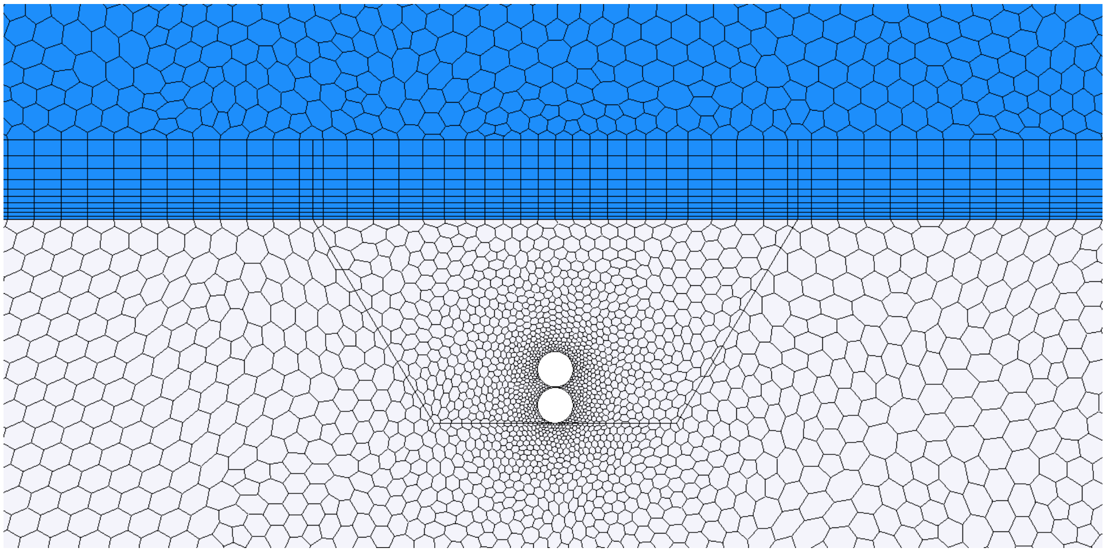

Figure 6. Zoom-in of the computational mesh in the vicinity of the cables.

Results: Water Temperature Increase

Exponent evaluated four permutations of the Trench Configuration and two permutations of the Jet Plow Configuration utilizing the range of soil and fill material conductivity values summarized in Table 2. The results are shown in Table 3.

Table 3. Summary of temperature increases calculated for different thermal conductivities of soil, fill, and cable configurations

Simulation #	K soil (W/m-K)	K fill (W/m-K)	Configuration	Max Water ΔT (°C)
1	1.2	1.4	Trench	2.3
2	2.0	2.0	Trench	2.1
3	1.2	2.0	Trench	2.4
4	2.0	1.4	Trench	2.0
5	0.8	0.8	Jet Plow	2.3
6	2.0	2.0	Jet Plow	2.1

- The highest temperature increase (Simulation #3) is 2.4 degrees Celsius (°C) and occurs for the Trench Configuration. The combination of conductivities that produces the highest temperature increase requires:
    - Minimum soil conductivity; and,
    - Maximum fill material conductivity.
- For the Jet Plow Configuration, the highest temperature increase (Simulation #5) is 2.3°C and occurs for minimum soil conductivity.

Figure 7 shows the temperature increase profile for Simulation #3. It reveals that the temperature increase is imperceptible in most of the water domain except for a thin layer of water near the soil/water interface. Zooming into the vicinity of the cables and the trench, Figure 8 shows the shape of this warm zone. The point of highest temperature increase is found approximately 23 cm downstream of the cables' centerline. The warm zone is also limited vertically such that that if one were to move a distance of only 10 cm from the point of highest temperature increase on the lakebed, the temperature increase drops to just 0.1°C.

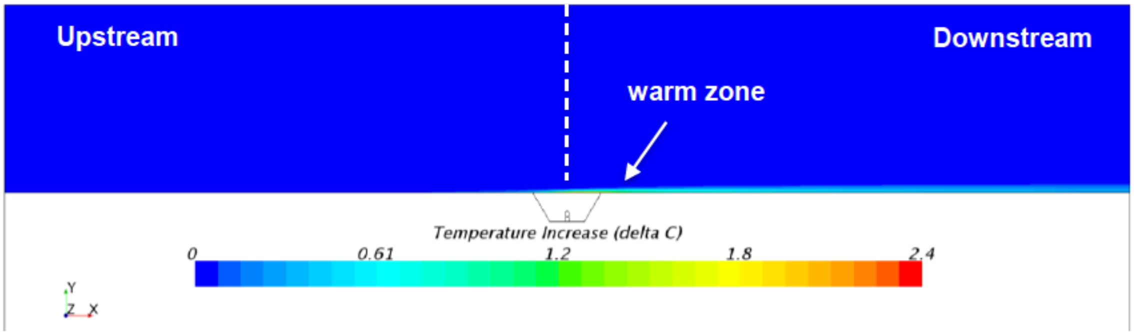

Figure 7. Temperature increase profile for Simulation #3 (Trench Configuration).

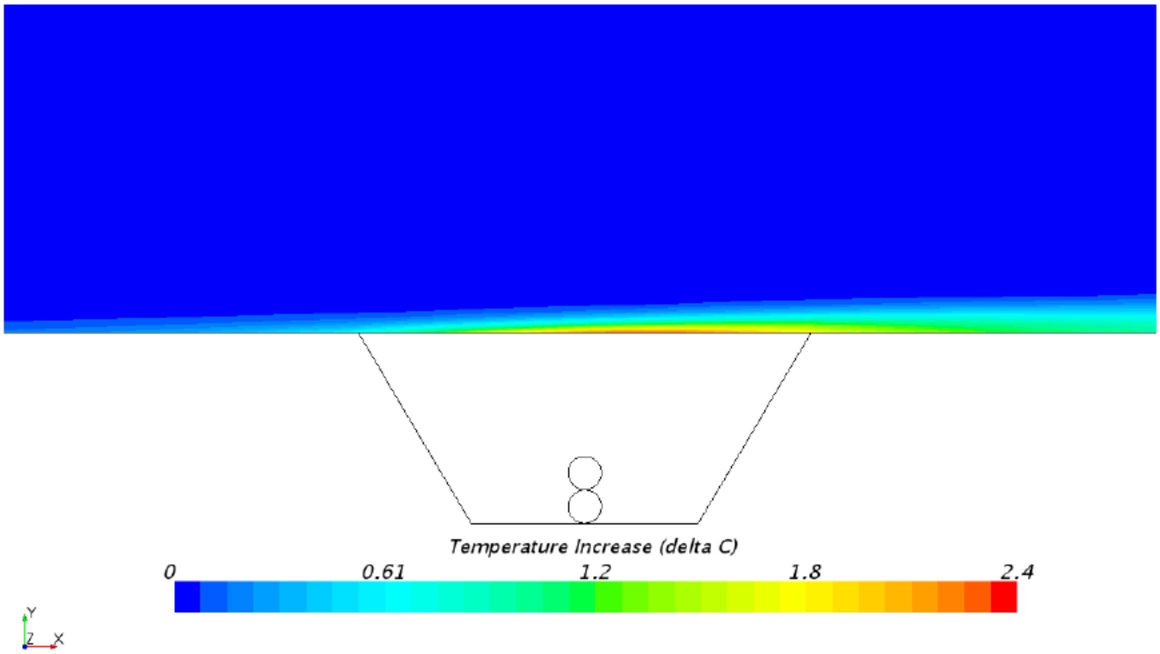

Figure 8. Zoom-in of temperature increase profile for Simulation #3 (Trench Configuration).

Conclusions

The temperature increase in the water and soil surrounding the proposed ITC Lake Erie DC transmission cable was estimated using the STAR-CCM+ multiphysics simulation package. Two different cable configurations were used, a Trench Configuration and a Jet Plow Configuration. Conservative estimates of the fluid flow rate across the cable region and the thermal conductivities of the surrounding trench and soil materials were used. The maximum increase in the water temperatures calculated for the Trench and Jet Plow Configurations were 2.4°C and 2.3°C, respectively. The increase in water temperatures was limited to a small region at the soil/water interface slightly downstream of the cable installation. The temperature increase drops to 0.1°C at a 10 cm vertical distance above the lakebed.