Verification of the Numerical Simulation of Permafrost Using COMSOL Multiphysics® Software

Elias Dagher
Environmental Program Officer

Directorate of Environmental and
Radiation Protection and Assessment Canadian Nuclear
Safety Commission

COMSOL Conference 2014 Boston
Boston, MA
October 8 – 10, 2014

COMSOL CONFERENCE
2014 BOSTON

CNSC CCSN

e-Doc: 4516632

nuclearsafety.gc.ca

Presentation Outline

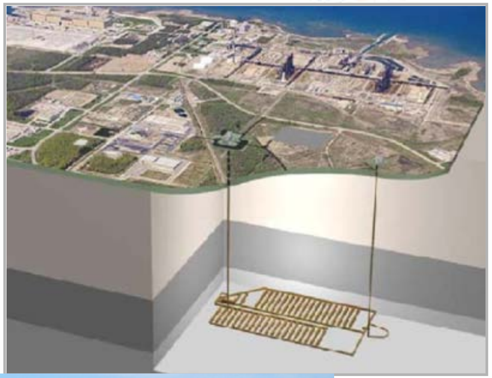
- Canadian Nuclear Safety Commission Overview
- Introduction
- Objectives of the Study
- Governing Equations
- Model Description
- Results and Discussion
- Conclusions

Canadian Nuclear Safety Commission

Regulates the use of nuclear energy and materials to protect the health, safety and security of Canadians and the environment and to implement Canada’s international commitments on the peaceful use of nuclear energy; and to disseminate objective scientific, technical and regulatory information to the public

The CNSC Regulates All Nuclear-Related Facilities and Activities

- Uranium mines and mills
- Uranium fuel fabricators and processing
- Nuclear power plants
- Waste management facilities
- Nuclear substance processing
- Industrial and medical applications
- Nuclear research and educational
- Export/import control



… from cradle to grave

Introduction

- Thaw potential of warm uranium tailings disposed of in an in-pit tailings management facility (TMF) and constructed in continuous permafrost could influence long-term contaminant migration resulting in potential future environmental effects

- Understanding of coupled processes of heat transfer with phase change and groundwater flow is needed to assess the changing thermal regime of TMF and surrounding geological formations, as well as potential thaw effects that could lead to permafrost degradation and talik development

Introduction

- Permafrost:
  - ground that has remained at temperatures at or below freezing (0˚ C) for at least two consecutive years
  - acts as natural barrier for contaminant migration through groundwater
- Talik:
  - layer or body of unfrozen ground within the permafrost
  - forms under water bodies which do not completely freeze through during the year
  - water body provides heat source for frozen ground underneath
  - temperature gradient drives permafrost degradation and talik formation
- Potential for talik development under a TMF due to warm tailings

Study Objectives

- In order to assess whether COMSOL Multiphysics® could adequately model the coupled multiphysics problem in the application to uranium tailings disposal, verification of a simple model in COMSOL was performed

- FEM model based on that of Ling and Zhang (2003) for the numerical simulation of the long-term influence of shallow thaw lakes on the permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan arctic coastal plain

- Two-dimensional heat transfer model with phase change under cylindrical coordinate system

Governing Equations

- Overall Heat Transfer Equation

$$(\rho c_m)_{eq}\frac{\partial T}{\partial t}+\rho_L c_{m,L}\mathbf{u}\cdot\nabla T=\nabla\cdot\left(k_{eq}\nabla T\right)+\mathrm{Q}$$

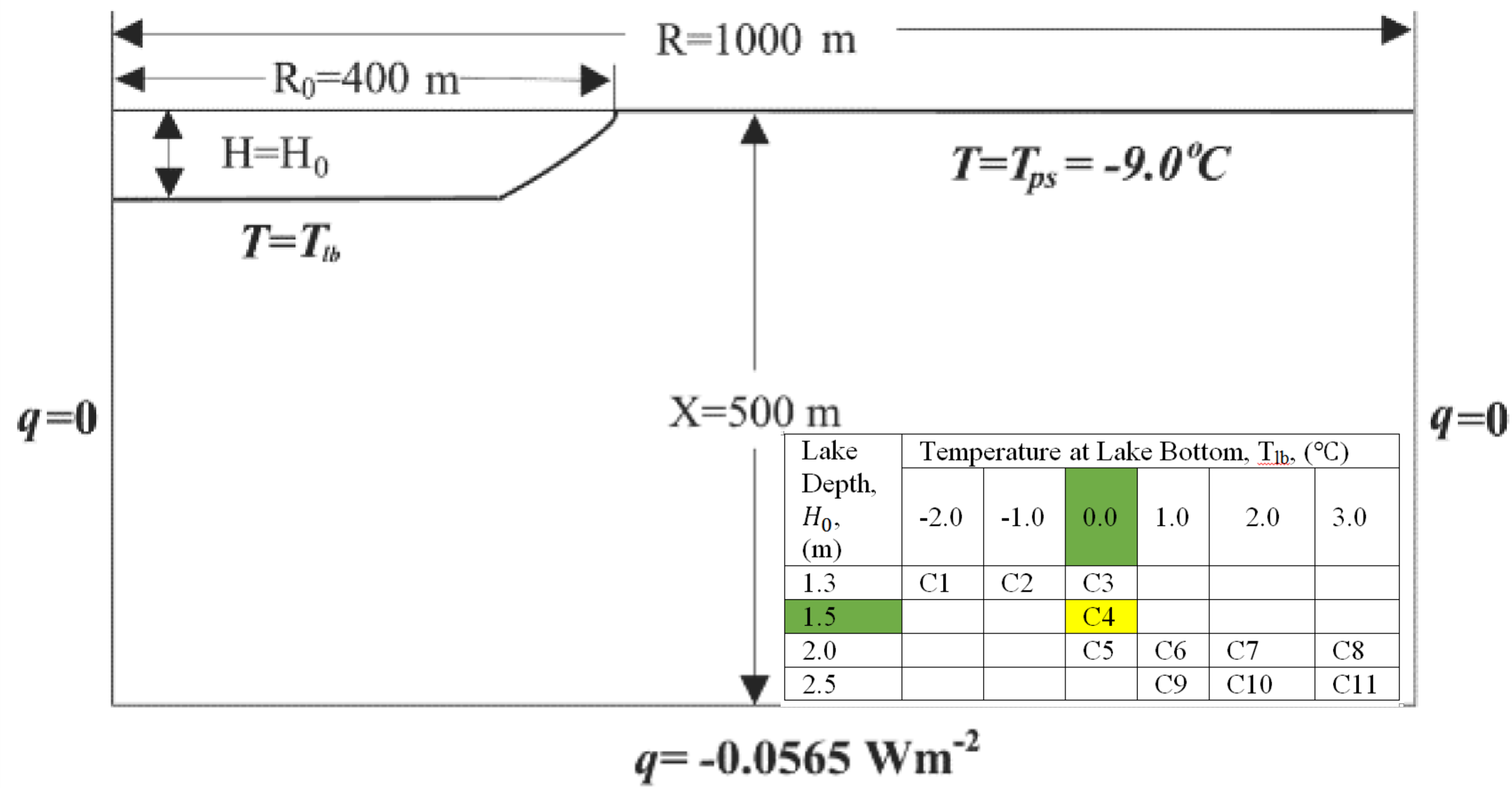
- Modified - heat transfer by conduction w phase change
  - Unfrozen Zone

$$C_u\frac{\partial T_u}{\partial t}=\frac{\partial}{\partial \mathrm{r}}\left(\mathrm{k_u}\frac{\partial T_u}{\partial r}\right)+\frac{\mathrm{k_u}}{r}\frac{\partial T_u}{\partial r}+\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{k_u}\frac{\partial T_u}{\partial x}\right)\quad (0<t<t_{TS},(x,r)\in\Omega_u$$

  - Frozen Zone

$$C_u\frac{\partial T_u}{\partial t}=\frac{\partial}{\partial \mathrm{r}}\left(\mathrm{k_f}\frac{\partial T_f}{\partial r}\right)+\frac{\mathrm{k_f}}{r}\frac{\partial T_f}{\partial r}+\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{k_f}\frac{\partial T_f}{\partial x}\right)\quad (0<t<t_{TS},(x,r)\in\Omega_f$$

Model Description: Analysis Domain and Boundary Conditions



Lake Depth, H_0, (m)	Temperature at Lake Bottom, T_{lb}, (°C)					
	-2.0	-1.0	0.0	1.0	2.0	3.0
1.3	C1	C2	C3			
1.5			C4			
2.0			C5	C6	C7	C8
2.5				C9	C10	C11

Figure adopted from Ling, F., and Zhang, T. 2003. Numerical simulation of permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan Arctic Coastal Plain. *Journal of Geophysical Research*, 108(D16), 4511

Model Description (cont'd): Soil and Material Properties

- Soil Properties:

Depth (m)	Soil Type	Dry Density ρ_d, (kg m^{-3})	Percent Water Content by Mass, w (kg kg^{-1})	Unfrozen Water Content by Mass, w_u (kg kg^{-1})
0.5-5	silt	1100	56	4.8
5-50	silt and clay	1200	32	4.8
50-400	gravel and sand	1450	25	3.8
400-500	gravel	1580	22	3.8

- Model Parameters and Material Properties

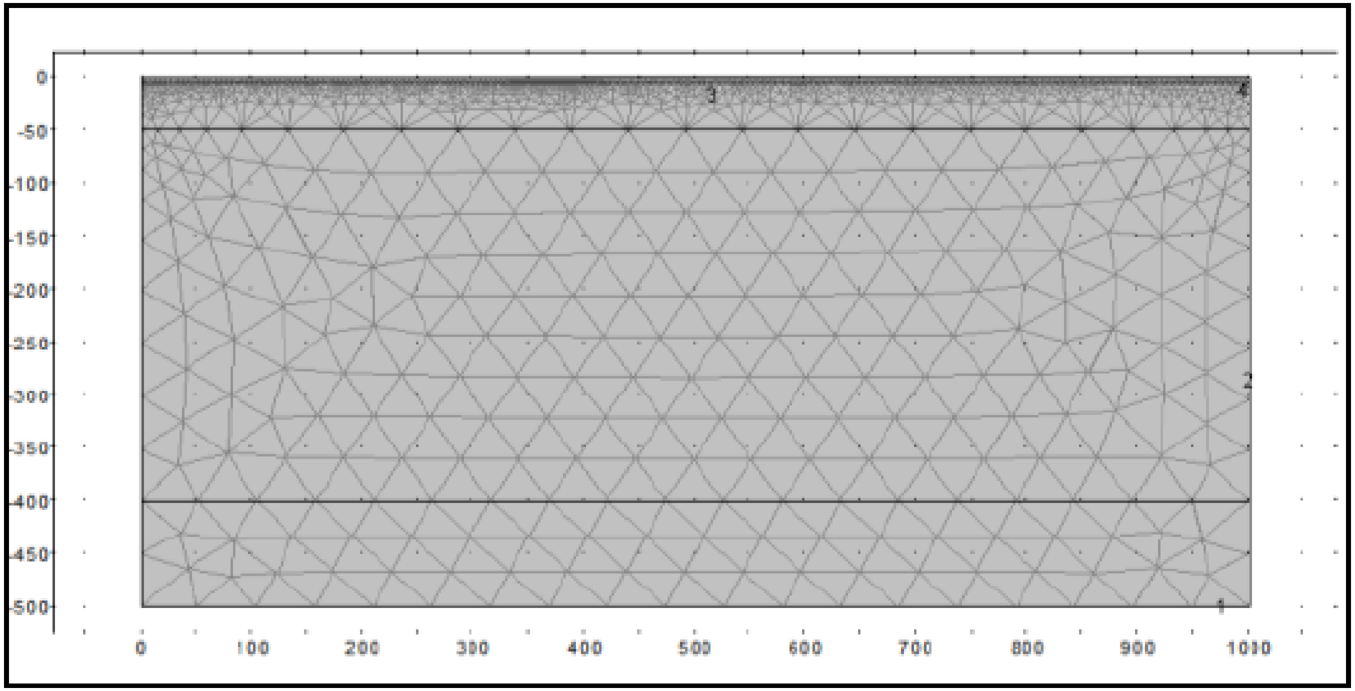
Parameter	Value	Description
H_0	1.5 m	Lake depth
H_{pal}	0.5 m	Depth of permafrost active layer
R_0	400 m	Lake radius
T_e	0°C	Permafrost freezing temperature
ΔT	1°C	Width of the phase change interval
t_{TS}	3000 years	Total simulation time
L_w	333.7 kJ kg^{-1}	Mass specific latent heat of fusion of water
ρ_w	1000 kg m^3	Density of water
c_{vw}	4.187 MJ m^{-3} °C	Volumetric heat capacity of water at constant pressure

Model Description (cont'd): Thermal Boundary Conditions

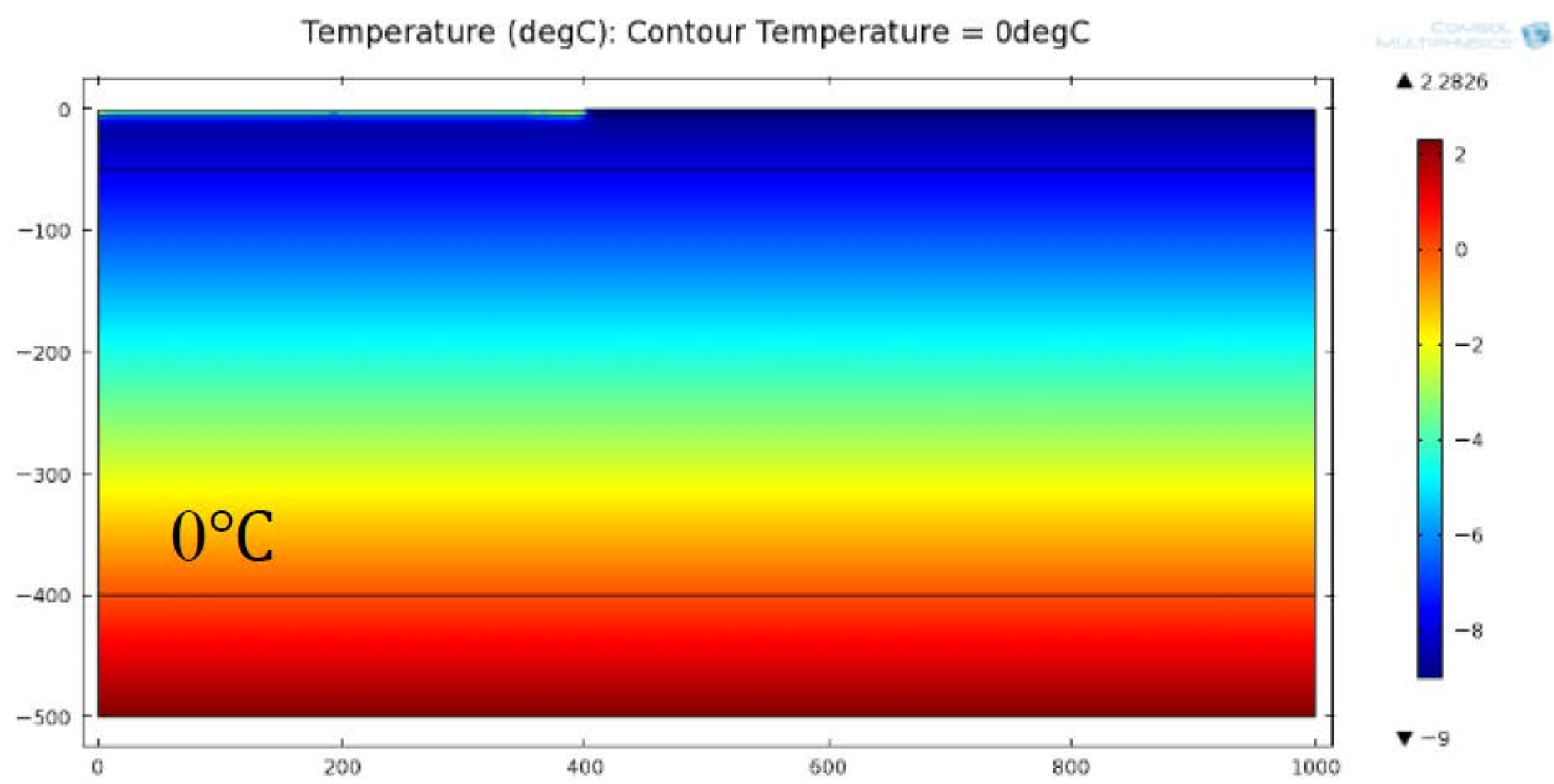
- Upper Boundary - Dirichlet BCs
  - fixed lake bottom temperature: T_{lb} = 0 ºC
  - fixed average annual surface temperature: T_{ps} = -9 ºC
- Lower Boundary - Neumann BC
  - constant inward heat flux q = 0.0565 W m-2
- Lateral Boundaries
  - q = 0 W m-2 (zero heat flux BC)

Model Description (cont'd): Geometry and Mesh

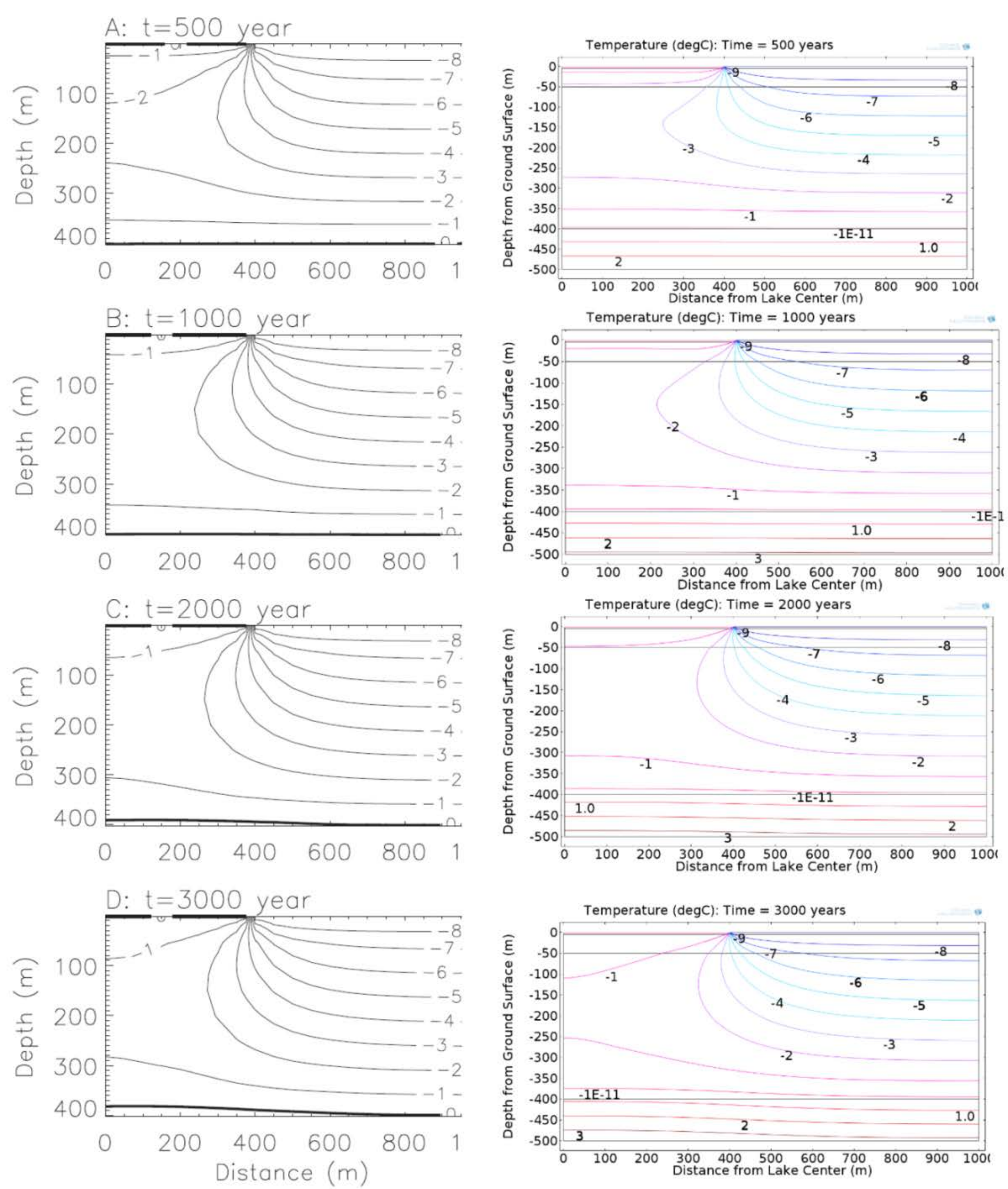
- Due to simplification of geometry and co-ordinate system assuming symmetry at the center of the lake, an extra fine mesh was applied to achieve accurate results that were computationally achievable



Model Description (cont'd): Initial Conditions (t = 0s)



Results and Discussion: Verification



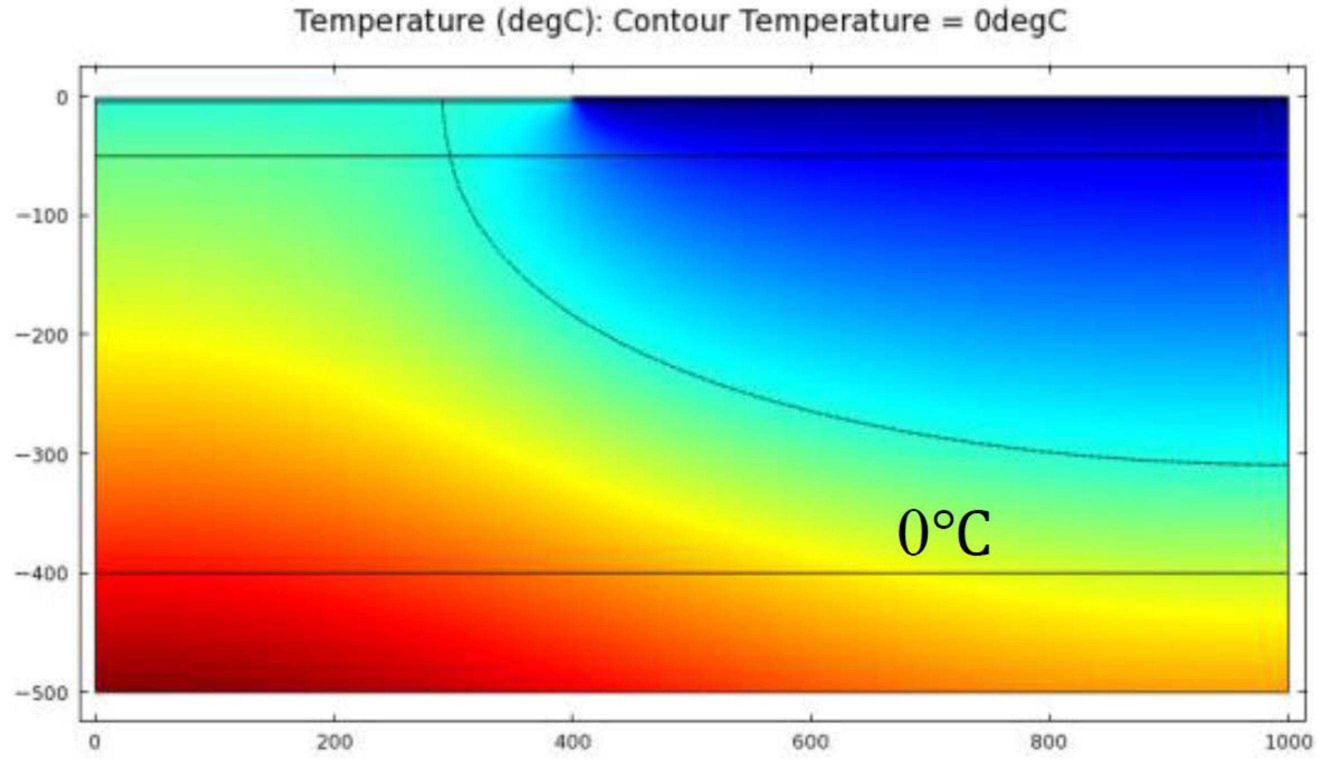
Case C4 Results (Ling and Zhang, 2003)

Verification Results in COMSOL

- Results from COMSOL are very close to those published by Ling and Zhang (2003)
- Explanation of differences
  - Ling and Zhang model modified from highway thermal stability analysis in permafrost regions
  - sophistication of COMSOL

Results and Discussion: Steady State Solution

- In order to verify the extent of the thaw bulb and degree of talik development and permafrost degradation, the model was run under steady-state conditions



Conclusions

- Graphical comparison of the simulation results show that they are in agreement with those published by Ling and Zhang (2003)
- COMSOL can be used to adequately model the time-dependent conductive heat transfer with phase change and assess the thaw effects due to a shallow thaw lake over continuous permafrost
- COMSOL code can be applied to more complex multiphysics problems, including modelling of coupled heat transfer (conduction and convection with phase change) and groundwater flow in order to determine the thaw effects surrounding a uranium in-pit TMF in continuous permafrost

Thank you!

nuclearsafety.gc.ca