

# Two Dimensional Finite Element Heat Transfer Analysis of a Buried Refined Bitumen Pipeline during Initial Start-up, Shutdown Following Initial Start-Up, and Normal Operation

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**Abstract:** This body of work uses the two dimensional finite element heat transfer capabilities of the conduction application mode within COMSOL V.3.5a to examine the temperature distribution in the fluid, pipe wall, insulation, and surrounding soil of a prototypical bitumen pipeline operating in a cold weather environment during the following modes of operation: initial start-up, shutdown following initial start-up, and normal steady state operation. Additionally, an insulation thickness sensitivity is performed to assess the impact of increased insulation on the temperature distribution during each mode of operation. The practical objective of this type of analysis and one explored in this body of work is the determination of the maximum amount of time the pipeline can be shutdown before a restart must be commenced using existing pumping facilities or alternative the amount time before an intervention operation must be performed in order to successfully restart the pipeline.

**Keywords:** FEA, Heat Transfer, Pipeline, Bitumen, Oil

## 1. Introduction

Refined bitumen is a highly viscous petroleum product that results from the fractional distillation of heavy crude such as that found in oil sands of Canada. Due to the high viscosity of refined bitumen, transportation of the fluid via pipeline networks is difficult and often requires large intermediate pumping stations. The shutdown of such a pipeline in a cold weather environment can result in elevated pumping requirements upon restart, operational interventions such as the displacement of the fluid with a less viscous fluid, costly active

thermal intervention methods such as temporary or permanent heat tracing, and in extreme circumstances pipeline abandonment.

To circumvent the need for the laborious and costly active operational interventions described in the preceding paragraph, passive thermal management methods are typically evaluated during the early phases of engineering design. The most common forms of passive thermal management are insulation and pipeline burial. Pipeline insulation systems, while less cost effective than pipeline burial, typically offer higher levels of thermal protection, an increased form of protection against impacts during installation and construction, protection against external corrosion, and protection for the environment in the case of cold weather or environmentally sensitive areas.

The current paradigm in midstream pipeline design is to use a quasi two dimensional lumped capacitance approach for heat transfer. When the design or operation of this system is not driven by thermal management concerns this is a sufficient and time effective means for evaluating thermal performance and selecting an appropriate insulation if necessary. The operation and design of a refined bitumen pipeline, however, calls for an extra level of granularity in its thermal design and hence a finite element analysis approach needs to be adopted.

The following three modes of operation typically drive the thermal design of a refined bitumen pipeline: initial start-up, shutdown following an initial start-up, and normal steady state operation.

During the initial start-up phase of operation, the soil immediately surrounding the pipeline is at ambient temperature and thus the whole body of soil acts as a large heat sink. During this mode

of operation the heat losses from the pipeline to the ambient surroundings is largest thereby causing the fluid transported in the pipeline to cool the quickest. This rapid cooling of the fluid increases its viscosity and may in fact help to drive the pump selection for the temporary or early production facilities due to the pressure required during this transient flowing condition as well as pipeline inlet heating requirements.

Shutdowns following initial start-up are common and pose an extremely challenging issue for pipeline designers. The cool down time (i.e. maximum amount of time before the pipeline can be restarted with operational intervention) is at a minimum during this time due to the rationale described above for the initial start-up period. Initial cool down time consideration may force the pipeline design to include provisions for intervention operations such as flanges for temporary pumps and tanks to aid in the displacement of the a volume of the pipeline with less viscous fluid or to consider continuously injecting a diluent to decrease the viscosity of the flowing fluid and provide a longer or infinite cool down time.

During normal (steady state) operation, the environment surrounding the pipeline has reached thermal equilibrium. In contrast to initial start-up and shutdown following initial start-up, environmental concerns can take center stage during this mode of operation. Designers may be faced with the questions such as what is radius of thermal impact, what is the maximum temperature encountered in the near pipeline region, and what effect this temperature will have on the local ecosystem.

The questions and design consideration raised in the preceding paragraphs will be explored in the remainder of this body of work through the use of a simplified two dimensional finite element heat transfer analysis of a prototypical refined bitumen pipeline in a cold weather environment.

## 2. Theory

### 2.1 Constitutive Equations

Heat transfer by conduction is governed by the well known heat equation:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$$

Where  $T$  is the temperature,  $\rho$  is the density,  $C_p$  is the heat capacity,  $k$  is the thermal conductivity tensor, and  $Q$  is a heat source or sink. Note that if the thermal conductivity can be assumed to be isotropic, it can be treated as a scalar rather than a tensor.

At steady state (i.e. when the time derivative of the temperature can be taken to be zero), the heat equation is reduced to Fourier's Law of Heat Conduction:

$$\mathbf{q} = k \nabla T$$

Where  $\mathbf{q}$  represents the heat flux vector.

### 2.1 Boundary Condition Formulations

In this body of work only constant temperature and internal continuity boundary conditions have been implemented.

For a constant temperature condition a boundary's temperature is assumed to remained constant for all time or stated mathematically  $T=T_0$ .

For an internal continuity boundary condition, the heat flux across the normal of two boundaries must be continuous or equal.

$$-\mathbf{n}_1 \cdot (\mathbf{q}_1 - \mathbf{q}_2) = 0$$

The obvious implication of the internal continuity boundary condition is that temperature on either side of the boundary must be equal ( $T_1=T_2$ ).

## 3. Methodology

### 3.1 Model Description

A diagrammatic representation of the buried bitumen pipeline system is shown below in Figure 1.

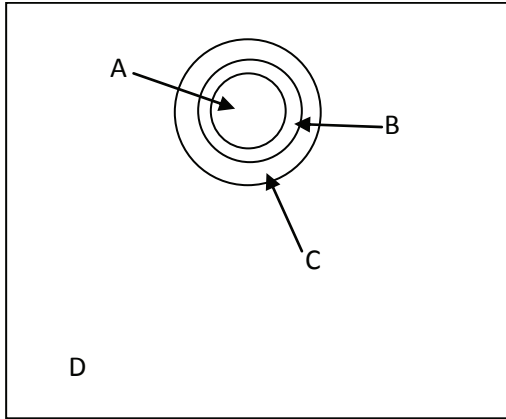


Figure 1. Model representation of the Buried Pipeline System (not drawn to scale)

The pipeline has been assumed to be buried a distance of 2 meters from the top of the soil layer, represented as region D in Figure 1, to the top of the insulation layer, represented as region B in Figure 1. Region D is a 7 m by 7 m block of soil. The dimensions of the soil block were selected based on past modeling experience as the maximum distance that is thermally penetrated by an uninsulated buried pipe.

Table 1 displays a description of the material and geometry of regions A through D in Figure 1, while Table 2 displays the physical properties of those same regions.

Table 1: Description and Geometrical Details of Regions in Figure 1

Region	Description	Outer Radius (m)
A	Refined Bitumen	0.679
B	Steel	0.709
C	Polyurethane Foam Insulation	0.787 (Case 1) 0.944 (Case 2)
D	Soil	7 x 7 square

Table 2: Physical Properties of Regions in Figure 1

Region	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/(m*K))	Heat Capacity (J/(kg*K))
A	949	0.16	1,670
B	7,850	44.50	475
C	220	0.03	1,590
D	2,200	1.30	880

### 3.2 Boundary Conditions

The boundary conditions used to simulate each mode of operation are shown below in Table 3. Note that the boundary conditions shown in this table were applied to the outermost wall of the region and held constant throughout the simulation.

Table 3: Boundary Conditions

Region	Normal Operation	Initial Start-Up	Shutdown
A	110°C	110°C	Continuity
B	Continuity	Continuity	Continuity
C	Continuity	Continuity	Continuity
D	5°C	5°C	5°C

### 3.3 Initial Conditions – Initial Start-Up

All parts of the pipeline system except the transported fluid (i.e. region A), were assumed to have an initial temperature of 5°C,

### 3.4 Initial Conditions – Shutdown

The results from day 14 of the initial start-up simulations were used as the initial conditions for the shutdown simulations.

### 3.5 COMSOL Application Mode

For this analysis, the convection contribution from the flow of the fluid in the pipeline was ignored thereby allowing the conduction application to be used to analyze all three modes of operation.

### 3.5 Mesh

A free triangular mesh was generated for the system using the default parameters in the free meshing tool.

Based on the results of preliminary simulations, a refinement of this mesh was then made and used for all other simulations. The final mesh consisted of 28,800 elements.

### 3.6 Solver

The UMFPACK direct solver was used for all simulations. For the transient simulations, the time integration was performed using the backward differentiation formula (BDF).

## 4. Results and Discussion

### 4.1 Normal Operation

Surface contour plots of the temperature for the two different insulation thicknesses are shown below in Figure 2 and Figure 3. As expected, the 0.944 m insulation system limits the heat flow from the fluid to the environment thus limiting its ultimate thermal penetration to the soil layer immediately surrounding the pipe.

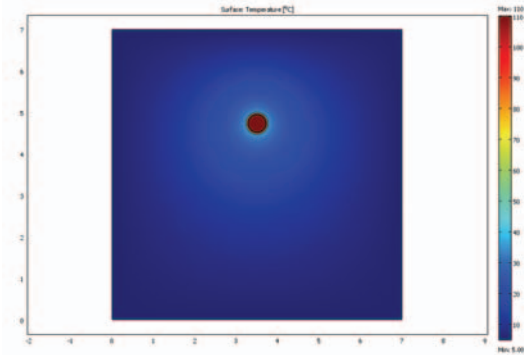


Figure 2. Temperature during Normal Operation with 0.787 m of Insulation

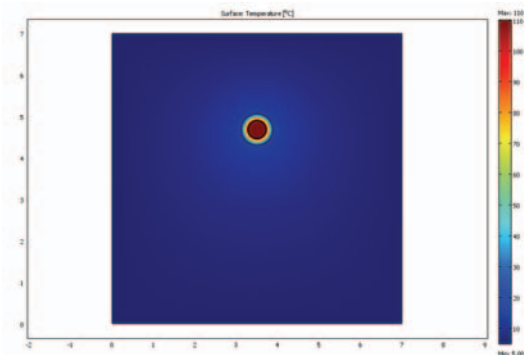


Figure 3. Temperature during Normal Operation with 0.944 m of Insulation

### 4.2 Initial Start-Up

Surface contour plots of the temperature 4.5 days and 14 days following the start-up of the pipeline are shown below in Figure 4 through Figure 7. The decrease in heat flux to the environment due to the increase in insulation thickness results in a substantial increase in the amount of time required to heat the soil in the immediate vicinity

of the pipeline.

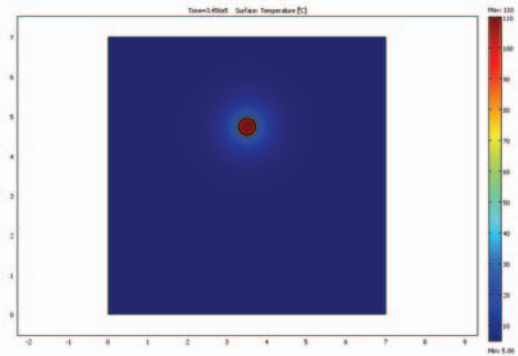


Figure 4. Temperature after 4.5 days of operation with 0.787 m of Insulation

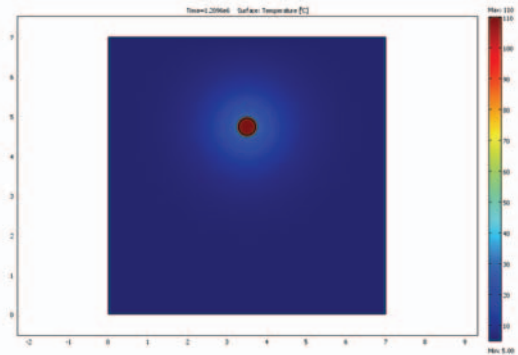


Figure 5. Temperature after 14 days of operation with 0.787 m of Insulation

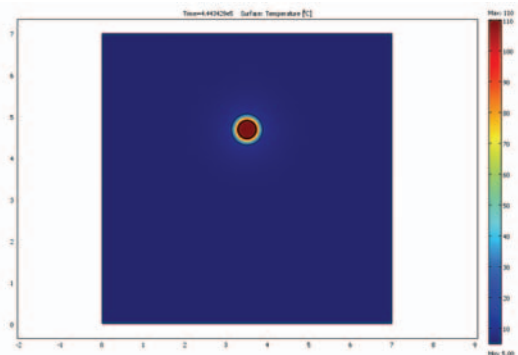
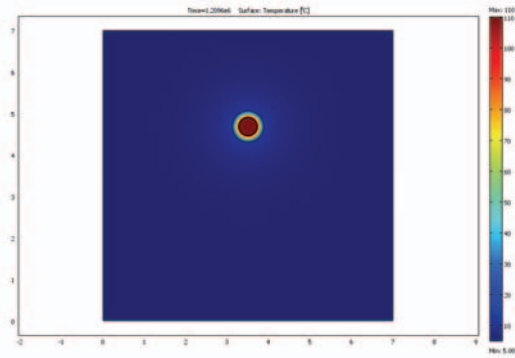


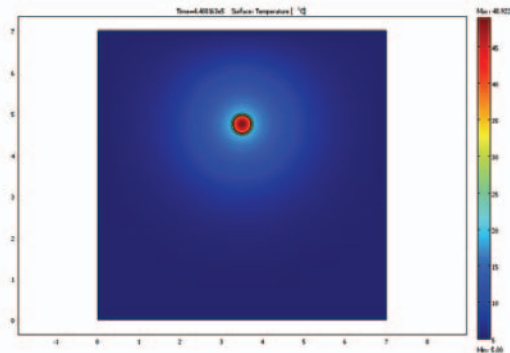
Figure 6. Temperature after 4.5 days of operation with 0.944 m of Insulation



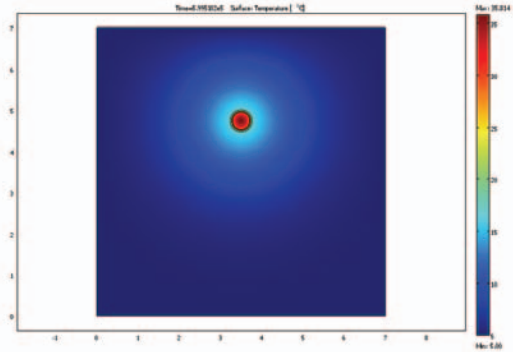
**Figure 7. Temperature after 14 days of operation with 0.944 m of Insulation**

#### 4.3 Shutdown following Initial Start-Up

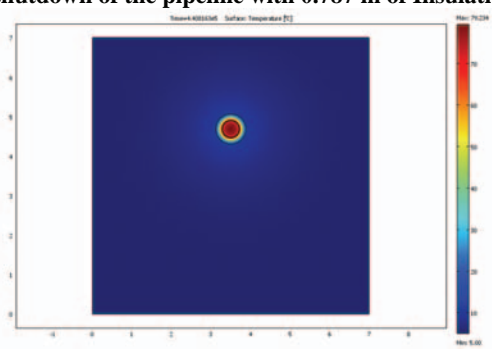
Surface contour plots of the temperature during 5 day and 7 day shut-in durations are shown below in Figure 8 through Figure 11. The decrease in heat flux to the environment and increase in overall thermal diffusivity of the pipeline system due to the increase in insulation thickness results in a substantial increase in the time required the time to decrease the fluid temperature.



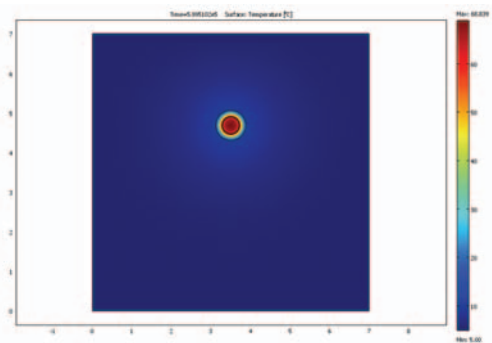
**Figure 8. Temperature 5 days following the shutdown of the pipeline with 0.787 m of Insulation**



**Figure 9. Temperature 7 days following the shutdown of the pipeline with 0.787 m of Insulation**



**Figure 10. Temperature 5 days following the shutdown of the pipeline with 0.944 m of Insulation**



**Figure 11. Temperature 7 days following the shutdown of the pipeline with 0.944 m of Insulation**

## 5. Conclusions and Future Work

COMSOL was successfully used to model a two dimensional cross section of a refined bitumen pipeline in a cold weather environment during normal and transient modes of operation. The results from a study such as this can be used to aid in the selection of pipeline insulation system, environmental impact assessment, and development of operating strategies

Future modeling efforts will include a three dimensional multiphysics approach that will include the effects of convection from internal pipe flow on heat transfer as well as a stress analyses.

## **6. References**

1. COMSOL, COMSOL V3.5a Multiphysics Modeling Guide, pages 167 – 178, November 2008.
2. Plawsky, J., Transport Phenomena Fundamentals, pages 164 – 168, November 2001.