



Dawson City Front Street

Thaw Depth Model



# Front Street Thermal Modeling

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## Introduction

### Executive Summary

Dawson City is located on an alluvial floodplain in a region of discontinuous, warm permafrost. Sediments beneath the town are ice-rich, with potential for thaw settlement and infrastructure damage in the event of permafrost degradation. The upper regions of permafrost beneath the town site are less than 0.5°C below freezing. A proposed project by Yukon Highways and Transportation Engineering involves paving Front Street with either black asphalt pavement, coated White Channel Gravel quartz chips pressed into asphalt, or chipseal aggregate surfacing.

Changing the surface color affects the amount of solar radiation absorbed by the ground surface, which is converted into heat. This heat propagates downwards, affecting the soil temperature at depth. A finite element thermal modeling program was used to predict potential increases in seasonal thaw depths as a result of different paving materials. Kryotek used MUT1D, a geothermal modeling program developed by the Alaska Department of Transportation, to predict the thaw depths for up to twenty years after paving. Potential climatic warming change was then introduced into the model to provide an indication of natural thaw progression.

Drilling in December of 2008 determined that permafrost was absent beneath Front Street from the Klondike Highway at Crocus Bluffs to Church Street, then present from Church Street to Duke Street. Permafrost was present in ice rich silts containing moisture contents of 33% to 205%. This permafrost is extremely thaw-sensitive, especially in the section of Front Street



between Princess and York Streets where buildings and infrastructure such as buried sewer and water mains adjoin the street.

Modeling projected a steady thaw depth under a gravel (0 m thaw depth increase by 2019, 0 m by 2029) or white concrete (0.1 m thaw depth increase by 2019, 0.1 m by 2029) surface, and slightly increased depths of thaw under a chipseal (0.3 m thaw depth increase by 2019, 0.6 m by 2029) surface in the absence of climatic warming. Coated chip (0.3 m-1.4 m thaw depth increase by 2019, 0.6 m-2.4 m by 2029) surfacing and black asphalt (1.4 m-2.1 m thaw depth increase by 2019, 2.4 m-3.5 m 2029) surfacing were modeled to greatly increase depths of thaw. Modeling using projected rates of climatic warming indicated that significant natural thaw (0.2 m thaw depth increase by 2019, 0.9 m 2029) may occur in the absence of road surface changes. Permafrost with high ice contents may experience rates of surface subsidence of up to 50% of thaw depth increases.

From Crocus Bluffs to Church Street, Front Street is underlain by unfrozen sands and gravels. Paving this section of Front Street should not impact permafrost.

### **General Site Conditions**

Dawson City is built on a floodplain below the confluence of the Yukon and Klondike Rivers. Alluvial gravel overlain by a thick layer of silt is found beneath most of the townsite. There is often a sharp contact between the layer of silt and gravel or cobbles beneath which extend to bedrock (Table 1). The silt, with an average thickness of 3 m is ice-rich, with 20% sand and 10% clay. Streets in Dawson are silty gravel fill dumped over surface organic soils to a depth of approximately 0.6 m-1.0 m. Front Street has been built up using fill to approximately 2.0 m-3.5 m above the surrounding flood plain to serve as a dyke during spring floods (EBA, 1983).

Valley-bottom sediments comprise five general units (Bond, 2008):

- 1) Alluvial sediments, which are unfrozen close to present river courses (EBA, 1977).
- 2) Colluvial materials, both organic and mineral sediments, which often contain aggrading ice (Fraser & Burn, 1997).
- 3) Gravel, which often acts as a conduit for groundwater and is unfrozen.
- 4) Loess, mostly perennially frozen, containing ice wedges 1 m or more in cross-section and up to 5 m tall (Fraser & Burn, 1997).
- 5) Organic Horizons, containing ice masses in horizontal beds and ice wedges distinct from, and smaller than, similar features in the loess (Naldrett, 1982). The narrow widths of many large ice wedges in the loess suggest that they formed syngenetically with deposition. In lower portions of the loess, tabular bodies of ground ice occur, which may have been preserved by burial or grown later (French & Pollard, Bond, 2008).



Table 1. Dawson City General Subsurface Conditions

Strata	Depth	Composition	Ice Content
Fill	0.6 m-1.0 m	Debris, Silty Gravel	Seasonally Thawed
Silts	1.0 m-4.0 m	Silt, Clay 10%, Sand 20%	10-50%
Gravels	5.0 m-12.0 m	Gravel, Cobbles, Sand	Massive Ice
Bedrock	>12.0 m	Klondike Schist	n/a

### Current Climatic Conditions

Dawson City has a historical (1970-2000) mean air temperature of  $-4.4^{\circ}\text{C}$  (Environment Canada 2009). A thermistor mounted in a solar shield at standard air temperature height in the yard of Robert Service School recorded a mean annual air temperature of  $-3.16^{\circ}\text{C}$  in 2007-2008 (Table 2). Climatic warming projections by Natural Resources Canada predict a  $3.0^{\circ}\text{C}$ - $4.0^{\circ}\text{C}$  warming over the next 30 -70 years in the central Yukon (NRCAN, 2008). A warming rate of  $0.10^{\circ}\text{C}/\text{year}$  was used in the climate change model. These are conservative estimates as actual rates of warming may vary and heat transfer to the surface is affected by many variables such as differing cloud cover, insolation, precipitation amounts and temperatures and wind speeds.

Table 2. Temperatures as Recorded at Robert Service School Oct 2007-Oct 2008 (Permafrost Outreach Program, University of Alaska Fairbanks. Courtesy of Panya Lipovsky, Yukon Geological Survey).

Mean Annual Air Temperature	$-3.16^{\circ}\text{C}$
Mean Annual Surface Temperature	$2.72^{\circ}\text{C}$
Temperature at Top of Permafrost (2.0 m)	$-0.17^{\circ}\text{C}$
Air Freezing Degree Days	-3030.90
Air Thawing Degree Days	1881.57
Ground Freezing Degree Days	-751.54
Ground Thawing Degree days	1739.88
n-Factor Freezing	0.25
n-Factor Thawing	0.92



## Methodology

### Data Collection

#### December 2008 Drilling

Nine boreholes were drilled to 4.5 m-6.0 m during December 3-4, 2008 along Front Street using a truck-mounted CME 150 drill and 150 mm solid and hollow-stem auger. At all boreholes grab samples were collected from auger flights at 1.0 m intervals, material composition was recorded and samples were placed in sealed double 5 mil poly bags then frozen to preserve moisture contents. Seasonal frost and permafrost depths were recorded.

Core samples were taken at BH06 with a CRREL permafrost coring barrel to provide undisturbed samples. Coring was only done at BH06 as cold temperatures caused the core to immediately freeze to the inside of the core barrel, slowing drilling considerably. The cores and grab samples were examined and logged for micro-cryostructure, then shipped to the Yukon Transportation Engineering lab for geotechnical parameters. This data was used in the thermal modeling process.

Soil and permafrost conditions encountered are summarized in Table 3. In general, no permafrost was encountered in BH01-BH03. Permafrost was encountered at depths ranging from 2.5 m to 4.1 m in BH04-BH09. Sand and gravel fill 1.0 m-2.0 m deep overlay sandy silt which extended down to alluvial sands and gravels. Woody debris was encountered in several boreholes in the silt layer. No massive visible ice was encountered, although individual ice crystals less than 10 mm in diameter were present in several samples. Core taken at BH06 revealed laminated ice lenses 1 mm-2 mm thick and separated by 3 mm-5 mm throughout the silt.

Table 3. Borehole Geotechnical Conditions

Borehole	Frost Depth	Permafrost Depth	Gravel Fill Depth	Silt Depth	Sand and Gravel Depth	Borehole Depth
BH01	1.7 m		1.0 m		1.0 m-5.0 m	5.0 m
BH02	1.9 m		1.9 m		1.9 m-6.0 m	6.0 m
BH03	2.0 m		4.0 m	4.2 m-6.0 m		6.0 m
BH04	3.0 m	3.6 m	2.8 m	2.8 m-5.6 m	5.6 m	6.0 m
BH05	1.7 m	3.2 m	1.7 m	1.7 m-6.0 m		6.0 m
BH06	2.5 m	3.0 m	2.5 m	2.5 m-4.7 m		4.7 m
BH07	1.8 m	2.5 m	1.8 m	1.8 m-5.0 m	5.0 m-6.0 m	6.0 m
BH08	1.7 m	2.8 m	1.8 m	3.5 m-6.0 m		6.0 m
BH09	3.0 m	4.8 m	1.0 m	4.8 m-6.0 m	1.0 m-4.8 m	6.0 m



### Permafrost Conditions

Permafrost exists in the north end of the townsite at depths below 1.5 m. Soil ice volumes may exceed 50%, and areas of massive ice such as ice wedges and segregated ice lenses have been observed in excavations (EBA, 1983). Permafrost was found to exist beneath Front Street from Church Street north. There was considerable variation in the depth to the top of the permafrost table, but active layer depths were generally the shallowest on the east side of the street adjoining buildings near the intersection of Front and Queen Streets. This, coupled with high ice contents (up to 205%) makes the permafrost highly susceptible to disturbance and thaw (Table 4).

Table 4. Active Layer and Permafrost Moisture Contents.

	Mean % 0-2 m	Mean % 2-6 m	Minimum %	Maximum %
BH01	6.1%	3.7%	2.8%	9.3%
BH02	19.8%	18.3%	4.0%	35.7%
BH03	1.8%	16.4%	1.6%	39.1%
BH04	3.6%	43.2%	2.7%	60.1%
BH05	6.1%	34.8%	4.7%	114.6%
BH06	3.0%	55.9%	2.9%	78.8%
BH07	15.2%	90.3%	12.3%	205.0%
BH08	15.2%	45.2%	10.1%	61.8%
BH09	4.3%	26.0%	3.1%	45.2%

The permafrost beneath Front Street has been adjusting to surface disturbance since the creation of the street in the late 1890s. Since that time sand and silty gravel fill have been dumped over the sandy silts that underly much of Dawson and the surface chip-sealed. For several years the street was paved with asphalt. The current maximum depths of thaw likely represent the thermal equilibrium reached after the fill was added.

The mean depth of thaw as of early December 2008 was 3.1 m, minimum was 2.5 m and maximum was 4.8 m. Thaw depth was related to the depth of granular fill over silt. Fill has a higher thermal conductivity, and thus freezes and thaws deeper than silt due to its lower water content. The Front Street borehole data indicated that depth of thaw was generally 135% of the depth of gravel fill. Those areas which had greater depths of fill also had deeper active layers. As of December 2008, seasonal frost had penetrated to the base of the gravel layer in all boreholes, but had not frozen into the silt beneath at any of the sites. The highly variable permafrost table depths encountered are likely due to variable thermal conditions over the road



surface due to color differences in chipseal or gravel surfacing, shading by buildings, historical thaw patterns and winter snow depths.

### **Geothermal Modeling**

Geothermal modeling was conducted using the MUT1D finite element model developed by the Alaska State Department of Transportation. Multi-layer User-Friendly Thermal Model in 1 Dimension (MUT1D) uses 1D implicit finite difference techniques to determine the thermal regime in layered material systems (Andersland & Ladanyi, 2003). The MUT1D program is available from the State of Alaska, Department of Transportation and Public Facilities Statewide Research, 2301 Peger Road, Fairbanks, Alaska.

Thaw depth values produced by MUT1D were checked against an algorithm-based program using Microsoft Excel used by Kryotek Arctic Innovation for the prediction of climate change impacts on permafrost. These programs utilize the Stefan and Modified Breggen solutions, which have been used for decades in the prediction of thaw and freezing depths. The results were then compared with thaw and frost depth data gathered during the December 2008 drilling as well as thermal data from several instrumented Dawson boreholes. Final modeled results of thaw depths were compared with similar climatic and surface conditions found in scholarly journal articles (eg. Ya-ling et al., 2008, Jin-ping, Yu, 2007).

The analysis was designed to determine the maximum depths of thaw under the current Front Street surfacing of light-colored gravel, a black asphalt surface and an asphalt surface with light colored rock chips pressed into the surface. In addition, the model considered light-colored asphalt or concrete pavement and the effects of atmospheric climatic warming.

The model took into account air temperature, ground surface temperature, thermal conductivities of various soil materials, current initial thermal profiles, thermal effects of climate change and latent heats of fusion within the soils.

#### **Model Testing**

Grid convergence by double node testing was used to compare the final files and had less than 2% divergence. A range of potential input temperature profiles gathered from eight previously drilled and instrumented Dawson boreholes was used to test the sensitivity of the modeling to initial temperature conditions, and found less than 5% divergence. An accuracy of  $\pm 0.5^{\circ}\text{C}$  in initial conditions as well as projected mean annual surface temperature increases was used.

#### **Model Parameters**

Soil materials were input as an upper layer consisting of 2.0 m sand and gravel with moisture contents 9-12%. A lower layer consisted of 4.0 m silt with ~40% moisture content. Finite element nodes were evenly distributed every 0.125 m throughout each layer. Mean annual surface temperature (MAST) amplitude and an initial midwinter ground temperature profile (Table 5) was estimated at  $15^{\circ}\text{C}$  based on borehole thermal data from eight instrumented Dawson City boreholes. The simulation was started on the January 1, 2008, and ran until January 1, 2029, outputting temperatures at selected nodes and  $0^{\circ}\text{C}$  isotherms every 10 days. Using this data,



maximum depths of thaw for each year were graphed through to 2029.

Table 5. Midwinter Temperature Envelope Profiles, Dawson City. Data from eight previously drilled boreholes in Dawson City.

	Maximum	Minimum	Average
0.5 m	-0.5°C	-9.5°C	-5.2°C
1.0 m	0.1°C	-7.4°C	-3.3°C
1.5 m	-0.1°C	-2.4°C	-1.5°C
2.0 m	-0.1°C	-0.9°C	-0.5°C
2.5 m	-0.1°C	-0.4°C	-0.3°C
3.0 m	-0.2°C	-0.7°C	-0.3°C
3.5 m	-0.1°C	-0.9°C	-0.4°C
4.0 m	-0.1°C	-1.0°C	-0.4°C
5.0 m	-0.2°C	-1.0°C	-0.5°C

#### Mean Annual Surface Temperature

Mean annual surface temperature (MAST) was the variable chosen to best represent changes to the thermal regime caused by different road surfacing materials. The MAST increases associated with each surfacing type were added to a baseline current MAST for Front Street.

No data is available for current MAST in the roadbed of Front Street. At Robert Service School, a thermistor at the ground surface recorded a MAST of 2.7°C during the 2007-2008 season. This warm temperature is likely due to the winter insulation provided by the snowpack, and is only the representation of a single year of data. Front Street is cleared of snow, and will have a correspondingly colder MAST. At a site 100 km south of Dawson City, the natural ground surface had MAST of -0.5°C to -2°C in the 2005-2006 season. At adjacent sites that had been burned by a forest fire which had blackened the soil surface, the MAST were an average of 2.6°C higher, ranging from -0.2°C to 1.8°C (Coates, 2008). Modeling using the depths of permafrost and soil materials encountered during the drilling indicated that current surface temperatures beneath Front Street are likely in the -1.0°C to +1.0°C range.

In order to obtain a MAST for modeling purposes, back-calculations were performed using the geotechnical data gathered during the December 2008 drilling. The geotechnical conditions encountered were entered into the model and various MAST were tried until the modeled depths of seasonal surface freezing and permafrost table depth matched the model. At the BH07 location, MAST was calculated to be between -1.0°C and 0°C. The modeling used 0°C as the baseline MAST.



MAST likely varies by up to 3.0°C within the Dawson townsite, depending on aspect, shading, surface material and color, vegetation, and snow depth. MAST also likely varies by 1.0°C-2.0°C across Front Street due to changes in insolation, surfacing color, surface water drainage, groundwater movement, groundwater vapor movement, ect. This model assumed that the street would be plowed, with a bare or packed snow surface during the winter. The other boreholes, particularly those in locations with chipseal surfacing, likely have mean annual surface temperatures from 0°C to 1.0°C.

The data from BH07 was chosen as the most representative of subsurface conditions likely to be encountered along the east side of Front Street. The east side has the most potential for infrastructure damage caused by permafrost thaw as buildings and buried utilities immediately adjoin the street. This site had the shallowest active layer as well as the most ice-rich permafrost. The borehole itself was located in front of the Gold City Tours office. A hypothetical initial thaw depth of 2.5 m-2.8 m was used, although most thaw depths along Front Street were greater and fluctuated considerably. This depth of thaw represents the most vulnerable permafrost that would be the first to thaw and cause the most surface subsidence and infrastructure damage if it did thaw.

Using a baseline MAST of 0°C in 2008, MUT1D calculated ground temperatures and 0°C isotherms for 20 years to 2029. Initial ground thermal profiles were developed by interpolating data from eight other instrumented boreholes in Dawson City. There is currently no paving at this site, and so temperatures were increased according to the albedo differences discussed in the next section. While wind speed is a factor there was a lack of good data from the immediate area, and it was not included in the model.

#### **Albedo and Temperature Change**

The main effect of paving is that of changing the surface albedo. This directly and immediately affects the MAST and the quantity of heat transferred to deeper soil strata. Albedo is a measure of the reflectance of a surface. The lower the number, the more solar energy the surface will absorb. An increase in albedo by 0.1 produces a change in pavement surface temperature of about  $-4.0 \pm 1.0^\circ\text{C}$  for an insolation of about  $1000 \text{ W/m}^2$  (Pomerantz et al. 2000). The literature reports values of asphalt pavement albedos from 0.05 to 0.15 (Bolz et al. 1973). The albedo of new asphalt pavements is about 0.04. Pavements that are about 5 years old have albedo of about  $0.12 \pm 0.02$ . The albedo of a chip seal will be about 67% of the albedo of the aggregate from which it is composed. A aggregate with an albedo of 0.5 will produce a chipseal with an albedo of 0.35, which is approximately the same as fresh concrete cement. (Pomerantz et al. 2000). The use of coated chips on asphalt will result in a slightly lower albedo than chipseal due to the exposed asphalt around the individual chips. Using the White Channel Gravel, which is mostly quartz and has an albedo of between 0.25 and 0.35, a coated chip surface may have an albedo of 0.23 (Naldrett, 1982, Lamb, 1972). Table 6 indicates the increase in MAST from the natural surface that may be expected from each of these paving techniques.



Table 6: Albedos and Corresponding MAST Increases from Gravel Surface used in Model (Santamouris & Asimakopoulos, 2001).

Material	Albedo	MAST Increase (10 years)
Asphalt Pavement	0.05	3.0°C
Coated Chips	0.23-0.25	2.0-3.0°C
Chipseal	0.35	1.0-2.0°C
Concrete	0.5	1.0°C
Gravel	0.6	0.0°C

Engineering studies conducted in a region of China with similar mean air and surface temperatures to Dawson City (MAAT -3.5°C), and a rate of climatic warming of 0.15°C/year were examined in order to compare results (Table 7). Surface temperature sine wave amplitude was approximately 15°C in Dawson, similar to values in China. In this case, the asphalt pavement was four degrees warmer than the natural surface, and 2.8°C warmer than a gravel surface (Jin-ping, Yu, 2007). Thaw depth increases of 1.0 m to 3.0 m over 20 years were modeled, however these calculations assumed that an embankment would be used.

Modeling by Ya-ling et al. (2008) showed that after 20 years, the maximum depth of thaw beneath an asphalt roadbed would be 4.5 m, with an initial depth at paving of 1.7 m. For the same road with a gravelly surface, the maximum depth of thaw would increase from roughly 1.0 m to 1.2 m during the same time span. These results compare favorably with the results from the Dawson Front Street MUT1D modeling.

Table 7. Mean Annual Temperatures of Various Paving Materials (Ya-ling et al., 2008) (Jin-ping, Yu, 2007)

Material	Mean Annual Temperature	T Amplitude
Air	-3.82°C	11.5°C
Natural Surface	-1.32°C (-1.0°C)	12°C (11.89°C)
Gravelly Surface	0.38°C (0.2°C)	14.5°C (14.82°C)
Asphalt Pavement	2.88°C (3.0°C)	15°C (15.15°C)
Cement Pavement	1.0°C	14.55°C

#### Atmospheric Warming Model

Atmospheric warming effects upon thaw depths were modeled using the Natural Resources Canada projection of a 3.0°C-4.0°C increase in air temperatures over the central Yukon Territory



over the next 30-70 years. Values for this model were as conservative as possible, using low temperature increases and initial temperatures. The model used a year-over-year MAST increase of 0.1°C with a gravel road surface. For the purposes of this model and due to a lack of surface temperature data, MAST increases were considered to mirror mean annual air temperatures (MAAT).

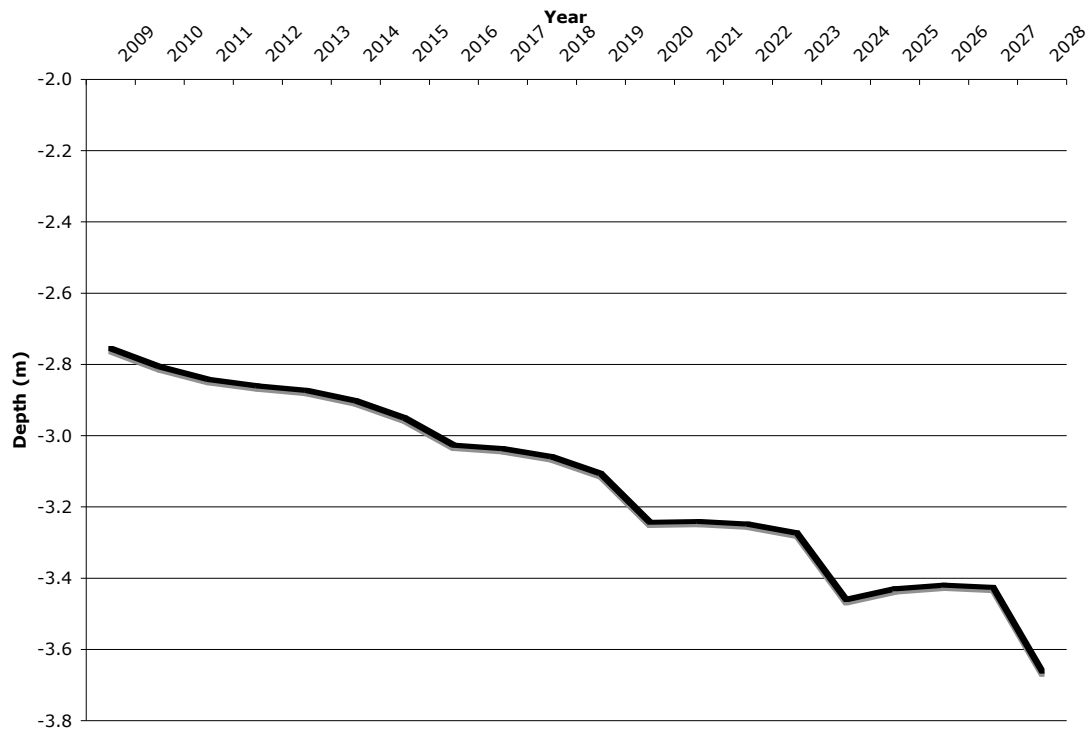
In this model, 5-year increments were used to smooth the temperature and depth curves and account for inevitable inter-annual climatic variations. The model was initiated using an assumption of steady-state permafrost conditions (ie. permafrost that is neither refreezing or thawing) with a mean annual surface temperature of -1.0°C. Each five-year modeling batch used the final geothermal conditions from the model before as its starting condition. This model was run for twenty years using the geotechnical conditions encountered at BH07. This model does not take into account unpredictable changes in summer precipitation, wind, insolation or snow depth.

## **Modeling Results**

Maximum annual thaw depths were projected for several surfacing materials for 20 years, starting in 2009. Natural thaw due to climate change was projected for the same time period. Modeling of a combination of natural and artificially induced thaw was not attempted due to complexities which were beyond the scope of this project. Figure 1 summarizes thaw that may be expected due to climatic warming in the next 20 years. This could produce thaw depth increases of up to 0.2 m deeper than present in 2019 and 0.9 m deeper than present in 2029. Results are displayed with a three-year moving average. Artifacts in the model create certain fluctuations in the thaw depth progression towards the end of the time span.



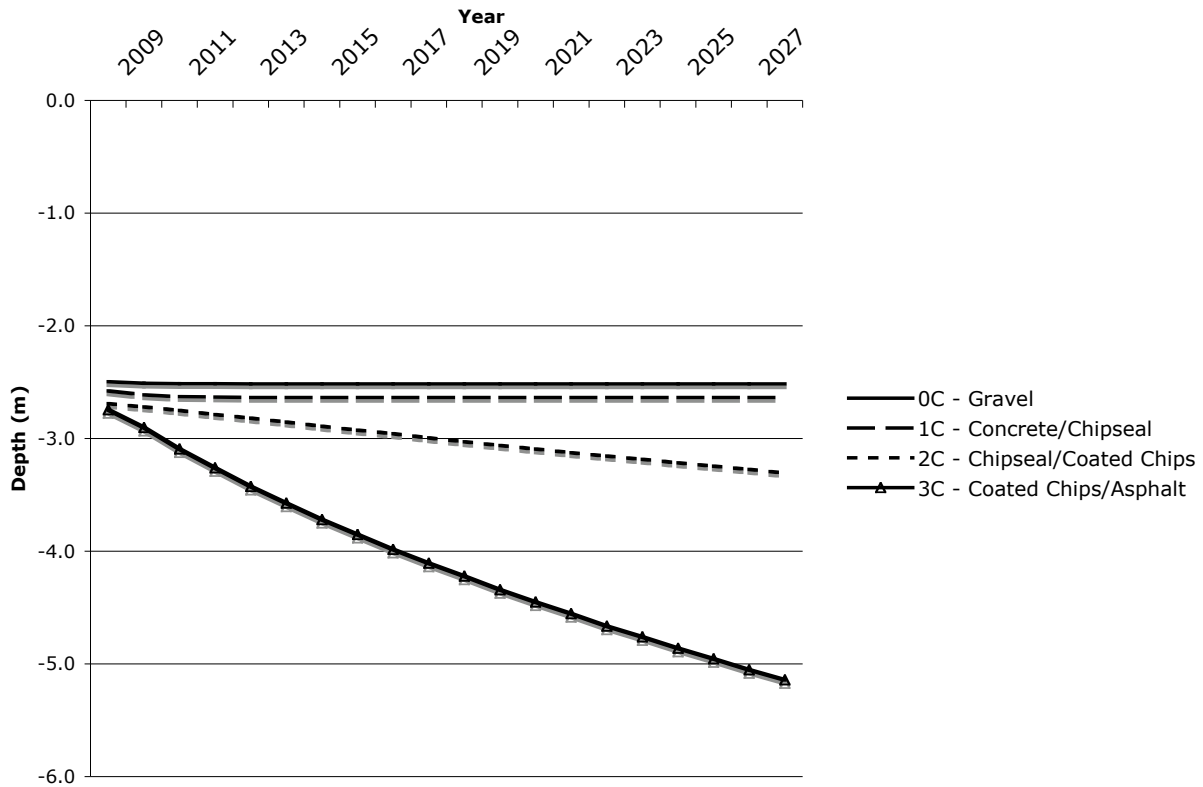
Figure 1. Modeled Thaw Depth Increases as a Result of Climatic Warming (+0.1°C/year).



Differential thaw depth increases over the next 20 years which may occur as a result of different surfacing techniques are displayed in Figure 2. While these results show a steady progression of thaw, a single anomalously hot summer may cause a significant increase in the depth of thaw. These results are presented in absence of the atmospheric warming displayed in Figure 1. Mean annual surface temperatures of 0°C and 1°C resulting from gravel, concrete and possibly light-colored chipseal surfacing produce a stable permafrost table with negligible additional thaw. If dark-colored chipseal or light-colored coated chip surfacing is used, MAST may increase to 2°C, leading to a slow increase in depth of thaw. If black asphalt pavement or dark coated chips are used, an immediate and dramatic increase in depth of thaw occurs. The crucial threshold before a significant thaw of permafrost occurs appears to be between 2.0°C and 3°C.



Figure 2. Projected Maximum Annual Thaw Depths, 2009-2019, of Different Road Surfacing Materials.



Asphalt pavement is likely to increase thaw depths 1.4 m-2.1 m by the year 2019 and 2.4 m to 3.5 m by 2029 (Table 8). This is a 50% and 88% increase in thaw depth, and may result in 0.7 m and 1.4 m of surface subsidence. Coated chip asphalt pavement is likely to increase thaw depths by 0.3 m-1.4 m by 2019 and 0.6 m to 2.4 m by 2029. This is a 11% and 33% increase in thaw depth, and is may result in 0.15 m and 0.3 m surface subsidence. The permafrost beneath an asphalt or dark coated chip surface will likely be out of thermal equilibrium within 10-12 years and continue to thaw indefinitely.

Chipseal surfacing is likely to increase thaw depths by 0.1 m-0.3 m by 2019 and 0.6 m by 2029, and may regain thermal equilibrium in the absence of climatic warming. Gravel, light-colored asphalt or white concrete pavement is not likely to increase thaw depths. Front Street is likely already in a equilibrium state, but any climatic increases in temperature will result in increasing depths of thaw.



Table 8. Projected Thaw Depth Increases.

	Gravel	Concrete/ Chipseal	Chipseal/ Coated Chips	Asphalt/Coated Chips	Climatic Warming
MAST Increase	0°C	1°C	2°C	3°C	0.1°C/Year
Thaw Depth 2009	2.5 m	2.5 m	2.7m	2.7 m	2.5 m
Thaw Depth 2019	2.5 m	2.6 m	3.0 m	4.2 m	3.1 m
Thaw Depth 2029	2.5 m	2.6 m	3.3 m	5.1 m	3.6 m
% Thaw 2019	0.8%	2.3%	11.3%	49.6%	08.1%
% Thaw 2029	0.8%	2.3%	22.9%	87.3%	32.9%
Thaw 2019	0.0 m	0.1 m	0.3 m	1.4 m	0.6 m
Thaw 2029	0.0 m	0.1 m	0.6 m	2.4 m	1.1 m
Surface Subsidence 2019	0.0 m	0.05 m	0.15 m	0.7 m	0.3 m
Surface Subsidence 2029	0.0 m	0.05 m	0.3 m	1.2 m	0.55 m

## Discussion

The drill program results indicate that Front Street is underlain by permafrost from Church to at least Duke Street and seasonally unfrozen ground south of Church Street. High ice contents and warm permafrost temperatures make this permafrost thaw sensitive. Thaw would result in surface subsidence. Surface subsidence would likely result in damage to buildings and buried utilities adjoining Front Street.

The results of computer finite element modeling indicate the maximum annual depths of thaw beneath Front Street from 2009 to 2029. These results display the 0°C isotherm, which confirms thaw. However, various combinations of unfrozen pore water content and salinity may depress the freezing point to several tenths of a degree below 0°C. Modeled temperatures were very close to 0°C near the top of permafrost, and deeper thaw values may be possible.

The current projections for atmospheric warming in the central Yukon indicate that increased natural depths of thaw may be expected beneath Front Street in the upcoming two decades. The modeled projections indicate that up to 1.1 m of additional thaw due to climate change could lead to 0.6 m in surface subsidence by 2029.

According to the model, the critical mean annual surface temperature threshold before rapid, significant lowering of the permafrost table will occur is approximately 2.0°C-3.0°C. At these



temperatures, a talik (unfrozen region within permafrost) forms in 10-12 years whereby winter surface freezing does not reach the top of the permafrost table (French, 1996). Once this happens, the permafrost table may continue to lower indefinitely and will likely not stabilize under the current climatic regime. Asphalt paving of the road surface would almost certainly raise the mean annual surface temperature to the point where a significant lowering of the permafrost table may occur.

A surface temperature below 1°C should maintain a stable permafrost table. As the mean surface temperature of Dawson City is currently between -1.0°C and 1.0°C, white concrete or gravel surfacing will likely maintain current depths of thaw in the absence of climatic warming. Chipseal may maintain a marginally stable permafrost table, but slight increase in MAST could precipitate increased depths of thaw.

Thaw beneath Front Street would not be uniform, with increased thaw depths occurring at some places to a greater or lesser extent than other locations. Consideration should be given to techniques to limit the depth of thaw and consequent damage to the roadbed itself and adjoining infrastructure.

## Conclusions

1. Climatic warming may cause up to 1.1 m of natural thaw beneath the roadbed by 2029. Up to 0.6 m of surface subsidence may occur. This subsidence is in addition to that caused by road surface changes.
2. Asphalt surfacing may cause up to 1.4 m of additional thaw beneath the roadbed by 2019 and 2.4 m or greater of by 2029. Up to 0.7 m of surface subsidence may occur by 2019 and 1.2 m by 2029.
3. Chipseal surfacing may cause up to 0.1 m-0.3 m of additional thaw beneath the roadbed by 2019 and 0.1 m-0.6 m by 2029. Up to 0.05 m-0.15 m of subsidence may occur by 2019 and 0.05 m-0.3 m by 2029.
4. Coated chip surfacing is may cause up to 0.3 m-1.4 m of additional thaw by 2019 and 0.6 m-2.4 m by 2029. Up to 0.15 m-0.7 m of surface subsidence may occur by 2019 and 0.3 m-1.2 m by 2019.
5. Light colored pavement, concrete pavement or gravel surfacing is likely to maintain a stable permafrost table over the next 20 years, excluding the afore-mentioned effects of climatic warming.
6. The critical mean annual surface temperature threshold before significant thaw occurs is between 2°C-3°C.



## Recommendations

1. Black asphalt paving is not recommended along Front Street north of Church Street.
2. Coated chip surfacing is not recommended along Front Street north of Church Street.
3. Chipseal paving along Front Street north of Church Street is marginal, but is likely to maintain a stable permafrost table in exclusion of climate change impacts.
4. Light-colored pavement or concrete pavement along Front Street north of Church Street is likely to maintain a stable permafrost table.
5. Permafrost was not encountered between Crocus Bluffs on the Klondike Highway and Church Street, therefore a change in the paving surface should have little effect.
6. Efforts should be made to mitigate natural thaw due to climatic warming along Front Street.
7. Thermal monitoring should be conducted under Front Street.



We trust that the above information is suitable for your purposes. If there are any further questions or concerns, please do not hesitate to contact us.

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Kryotek Arctic Innovation  
January 15, 2009

### **Terms and Conditions of Use**

The data presented in this report is the product of computer modeling. Modeled results may not resemble actual future conditions. The data and results are not to be used for construction. The author (James Coates operating as Kryotek Arctic Innovation) assumes no risk, responsibility or liability whatsoever for the use of data, materials and information contained in this report by all and any authorized or unauthorized parties. This report is intended for informative and planning purposes only and is not to be used for design or construction.

Geotechnical conditions may vary from those encountered by boreholes. Projected future climatic conditions may not resemble those used in the modeling. Ground ice conditions will vary throughout the study area. Regions of massive ground ice such as ice lenses or ice wedges are known to exist in the Dawson area and could result in more rapid thaw and subsidence. While none of these were encountered during the drilling, they may be present beneath the road and surrounding area. Modeling is in one dimension only, while heat flow beneath Front Street and the adjacent buildings is three-dimensional. This may create unpredictable subsurface condi-



tions which are impossible to model.

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