**EVALUATION OF GARDNER CREEK AIR DUCTS**

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**ABSTRACT (Maximum 200 words)**

The use of ventilated air ducts under the sideslope of roadways over permafrost offer potential reductions in thaw under the sideslope. Airducts use a long horizontal corrugated metal pipe with a vertical stack. The stack provides a chimney effect which cools and stabilizes the sideslopes.

Air ducts were constructed on the Alaskan Highway near the Canadian border to test the design procedure developed by Zarling et. al. The air ducts proved successful. The roadway over the air ducts performed significantly better than the control areas. However, future installations should be placed high enough in the fill to eliminate flooding. This installation was plagued with icing from water flowing through the embankment.

**SUBJECT TERMS**

Permafrost, air Ducts, Convection Cooling heat transfer, Thaw settlement

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EVALUATION OF GARDNER CREEK AIR DUCTS

FINAL REPORT

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*FRONT COVER:* Research Technician Rick Briggs inspecting an air duct shortly after installation.
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INTRODUCTION

Roadways over ice rich permafrost continue to challenge Alaskan engineers. Road construction generally results in warning of underlying frozen soils. Some or all of these soils may thaw over a period of many years. Engineers use many techniques to minimize the effects of thawing permafrost. Many highway projects employ thick gravel fills and insulation to thermally protect the underlying frozen ground. These techniques reduce differential settlement which leads to costly annual maintenance.

Another common type of road embankment failure in warm permafrost areas is embankment rotation due to thaw settlement at the shoulder. The thickness of the embankment helps insulate subsoils under roadways from summer heat, while the soils beneath the thinner sideslopes experience deeper thawing. This results in lateral cracking of the embankment, as shown in Figure 1. Removal of insulating snow from the roadway and its deposition further aggravates the situation by promoting refreezing under the road and retarding it under the sideslopes. Previous research has shown that the annual road surface temperatures in interior Alaska are about 32°F while the sideslope surface temperatures are between 35°F and 40°F.

A study completed by Zarling et al. in 1984 developed a design procedure for cooling soils under sideslopes using ventilated air ducts (ref), which are placed in a soil berm at the toe of the sideslopes, as shown in Figure 2. The ducts use corrugated metal pipe with short sloping or vertical inlets leading to a long horizontal section. The vertical outlet or stack provides a "chimney effect." Cold air flows into the duct, is heated by the surrounding ground and exits through the stack. The chimney effect results from the less dense warm air in the outlet stack being buoyed upward by the surrounding cold air. Air flow occurs whenever the ground temperature exceeds the ambient air temperature. This passive device provides cooling during the winter months and becomes dormant during the summer. However, because summer winds can create a problem by causing air to flow through the ducts and warm the ground, caps are placed over the inlet during the summer.

As a result of Zarling’s study, air ducts were designed and used on a project near the Canadian border. The ducts were instrumented and monitored to determine whether the design procedures predicted the desired cooling of the surrounding ground and whether longitudinal cracking was reduced.
Typical roadway distress from thaw beneath side slopes.
INSTALLATION

During the spring of 1983, ten air ducts were installed at milepost 1240 on the Alaska Highway as part of the Gardner Creek (Project S-062-1(16)) reconstruction project. The roadway which the ducts protect traverses a bog area underlaid by frozen gray sand. Figure 3 shows a plan view of the embankment indicating the air duct positions. Two of these ducts were instrumented for analysis. A cross section of the roadway embankment shown in Figure 4 provides the location of the instrumented air duct on the northern side of the road. Figure 5 shows a pictorial view of the corrugated metal pipe (CMP) duct and the location of instrumentation for monitoring.

The two foot diameter duct consists of a 32 foot inlet, a 116 foot main section paralleling the roadway and a 12 foot vertical exhaust section. Holes drilled into the bottom of the 45° elbow allow accumulated water to drain. The horizontal section slopes at a 0.5% angle to this drain. A trash grate on both the inlet and the outlet protect against injury. The damper installed on the inlet eliminates airflow during the summer months. A rain shield on the top of the vertical section minimizes rain and snow entry. The other nine ducts used the same design.

INSTRUMENTATION AND DATA COLLECTION

Thermistor strings for ground temperature monitoring were placed radially about the duct at 90° angles with thermistors positioned at 1 ft., 2 ft. and 4 ft. from the duct surface at Stations "B"-"D" (Figure 5). Thermistors were also placed on the surface of the duct at these stations. The inlet and outlet air temperatures were measured using thermistors extending several inches into the duct at Stations "B" and "E". Thermistors were similarly configured about the instrumented duct located on the southern side of the road.
Figure 5

NORTHSIDE

GARDNER CREEK AIR DUST
NEAR NORKWAY
Temperature data were collected monthly, commencing in the fall of 1983. In the fall of 1986, onsite data collection equipment was installed. This equipment consisted of a data logger, two multiplexers, and a RAM data storage module. The installation of this equipment allowed for more detailed monitoring of ground and duct temperatures and the collection of additional meteorological data at the site. The collection of solar radiation data, ambient air temperature, relative humidity, and wind speed began at this time. A hot-wire anemometer was installed at Station "B" in the duct and a relative humidity sensor installed at Station "A".

After several months of operation, the data logger was removed due to condensation problems. The system was reinstalled in May of 1987 with the addition of a telephone modem. The modem allowed data to be transferred directly from the site to a computer in the office and also allowed monitoring of equipment at the site without frequent visits. This system was used to collect data for 10 months. The instrumentation was removed when an ice-plugged culvert caused flooding of the instrumentation shelter.

**DATA ANALYSIS**

Air velocities measured in the duct were quite erratic and were often small in relation to the accuracy of the hot-wire anemometer. Consequently no strong correlation was found between duct air velocity and the temperature difference between the duct wall and ambient air. It seems likely that other factors also significantly affect duct air velocity. Outside wind speed may be one of these, but attempts to correlate wind speeds with duct air velocities also met with little success. Outside wind direction (relative to duct openings) may be important, but was not measured for the study.

Because there were not 12 consecutive months of uninterrupted data collected using the data logger, it was decided to use the data collected at monthly intervals for analysis of the ducts' performance. Figures 6 and 7 show the measured ground temperatures 1 ft. and 4 ft. below the bottom of the duct. Inlet temperatures were measured at Station "D", as indicated in Figure 4, while outlet temperatures were measured at Station "B". Figures 6 and 7 show a progressive cooling of the ground around the ducts at a gradient of approximately 70°/year. To better quantify the ducts' actual performance, analytical approaches are used below.

In order to ensure that the measured air temperatures at the ducts' inlets were characteristic of the mean monthly temperatures at the site, these data were compared to data recorded about 15 miles away at the Northway FAA site (1985-1987). It was determined that the inlet air freeze index for the air duct located on the north side of the roadway was nearly identical to the Northway freeze index for the winter of 1985-86. The air freeze index for the 1986-87 winter differed by 30% for this duct compared to Northway.
Freeze indices for the inlet air on the southside air duct differed by 800% and 300% for the 1985-86 and 1986-87 winters, respectively. This was due to ice plugging and stopping the air flow in this duct. Based on these comparisons, only the data recorded from the northside air duct during the 1985-86 winter were used in this analysis.

From the monthly air and pipe wall temperature data, freeze and thaw indices were calculated and are presented in Table 1. Northway air freeze and thaw indices obtained from the National Weather Service are also given.

<table>
<thead>
<tr>
<th>Freeze Indices (°F Days)</th>
<th>Thaw Indices (°F Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Air</td>
<td>Outlet Air</td>
</tr>
<tr>
<td>6,217</td>
<td>2,961</td>
</tr>
</tbody>
</table>

Northway Weather Service
Freeze Index = 6,294
Thaw Index = 2,581

The mean annual temperatures at the site, inlet and outlet of the pipe and pipe surface can be estimated by Equation 1:

\[
T_m = 32 + \frac{TI - FI}{365}
\]  

(1)

where

- \(T_m\) = mean annual temperature, °F
- \(TI\) = Thaw index, °F days
- \(FI\) = Freeze index, °F days

Using this equation, the following mean annual temperatures have been calculated based on the 1985-86 recorded data.

Mean annual site air temperature:

\[
T_m = 32 + \frac{2,581 - 6,294}{365} = 21.8°F
\]
North Side Instrumented Duct
Temperatures at 1' Below Duct

Figure 6

TEMPERATURE °C


OUTLET  INLET
North Side Instrumented Duct
Temperatures at 4’ Below Duct

**Figure 7**

![Graph showing temperatures over time for North Side Instrumented Duct](image)

- **OUTLET**
- **INLET**

Temperature °C

Years:
- 1983
- 1984
- 1985
- 1986
- 1987
Mean annual duct inlet air temperature:

\[ T_m = 32 + \frac{797 - 6.217}{365} = 17.1^\circ F \]

Mean annual duct outlet air temperature:

\[ T_m = 32 + \frac{405 - 2.961}{365} = 25.0^\circ F \]

Mean annual average duct wall temperature:

\[ T_m = 32 + \frac{475 - 2.896}{365} = 25.4^\circ F \]

Assuming the site air temperature at Gardner Creek varies sinusoidally, a first estimate for the amplitude of the annual temperature variation, \( A_o \), is 37°F from Hartman and Johnson (1978).

Using this amplitude and the site mean annual air temperature, 21.8°F, the beginning, \( t_1 \), and end, \( t_2 \), of the thaw season can be calculated as follows:

\[ t_1 = \frac{365}{2\pi} \left[ \cos^{-1} \left( \frac{T_m - 32}{A_o} \right) \right] \]

\[ = \frac{365}{2\pi} \left[ \cos^{-1} \left( \frac{21.8 - 32}{37} \right) \right] = 107 \text{ days} \]

\[ t_2 = \frac{365}{2\pi} \left[ 2\pi - \cos^{-1} \left( \frac{T_m - 32}{A_o} \right) \right] \]

\[ = \frac{365}{2\pi} \left[ 2\pi - \cos^{-1} \left( \frac{21.8 - 32}{37} \right) \right] = 257 \text{ days} \]

The length of thaw season, \( t_1 \), is equal to \( t_2 - t_1 \) or 150 days. The length of the freeze season is therefore

\[ t_1 = 365 - (t_2 - t_1) = 365 - 150 = 215 \text{ days} \]
An improved estimate of the amplitude of the annual air temperature variation, $A_o$, can be calculated by the equation given in Zarling and Braley (1988):

$$A_o = \frac{2\pi}{365} \left[ \frac{AFI - (32 - T_m) (t_f)}{\sin \left( \frac{2\pi t_1}{365} \right) - \sin \left( \frac{2\pi t_2}{365} \right)} \right]$$

$$A_o = \frac{2\pi}{365} \left[ \frac{6,294 - (32 - 21.8)(215)}{\sin \left( \frac{2\pi (107)}{365} \right) - \sin \left( \frac{2\pi (257)}{365} \right)} \right] = 36.7^\circ$$

Reiteration of $t_1$, $t_2$, $t_f$, and $A_o$ does not change these values. The mean air inlet and outlet and duct wall temperatures for the freeze season can now be estimated.

The mean duct inlet air temperature during the freeze season was

$$T_{mf} = 32 - \frac{FI}{t_f} = 32 - \frac{6,217}{215} = 3.1^\circ F$$

The mean duct outlet air temperature during the freeze season was

$$T_{mf} = 32 - \frac{FI}{t_f} = 32 - \frac{2,961}{215} = 18.2^\circ F$$

The mean duct wall surface temperature during the freeze season was

$$T_{mf} = 32 - \frac{FI}{t_f} = 32 - \frac{2,896}{215} = 18.5^\circ F$$

**FLOW ANALYSIS**

Heat transfer to the duct air from the warm soil surrounding the duct results in thermal expansion of the air. This less dense air flows upward through the vertical outlet duct to be replaced by cold dense air to continue the process. The flow rate is based on equilibrium condition. A detailed derivation is given in Zarling et al., (1984).

The total length of straight pipe from Figure 2 is:

$$L_t = L_1 + L_2 + L_3 = 116 + 32 + 12 = 160 \text{ feet}$$
The equivalent length of the fittings is based on the friction factor, $f$, for CMP and minor loss coefficients $K$, or

$$L_e = \frac{D\sum K}{f}$$

The minor losses in the duct are due to two-piece mitered elbows, on 45° elbow, one sharped edge entrance and two trash grates. The loss coefficients for these components based on ASHRAE (1985) are

$$\sum K = 2(1.5) + .43 + 1.0 + 2(1.0) = 6.4$$

Assuming an initial Reynolds number of 30,000, then from Figure 4 of Zarling et al. (1984), $f = .07$ and the equivalent length of the fittings is:

$$L_e = \frac{D(6.4)}{f} = 183$$

The total equivalent length of duct becomes:

$$L = L_t + L_e = 160 + 183 = 343$$

The average air speed in the duct during the freeze season is then estimated using equation 5 from Zarling et al. (1984).

$$V = \sqrt{\frac{4gh}{\left(1 + fL\right) \left[\frac{(T_o-T_i)}{(T_o+T_i)}\right]}}$$

where $T_o$ and $T_i$ are absolute temperatures in degrees Rankine of the outlet and inlet air.

$$V = \sqrt{\frac{4(32.2)(12)}{\left(1 + .07\left[\frac{343}{2}\right]\left[\frac{(478.2-463.1)}{(478.2+463.1)}\right]\right)}}$$
which yields

\[ V = \frac{1.38 \text{ feet}}{\text{sec}} \]

The stack efficiency is assumed to be 90\%, therefore \( V' = 1.24 \text{ feet per second} \).

Recalculation of Reynolds number gives

\[ Re = \frac{V'D}{v} = \frac{(1.24)(2)}{13.5 \times 10^{-5}} = 18,400 \]

where the kinematic viscosity, \( v \), was taken at 15\(^\circ\)F. Reiteration leads to \( V' = 1.14 \text{ feet per second} \) and \( Re = 17,000 \).

**HEAT TRANSFER ANALYSIS**

There are three approaches that can be used to estimate the embankment cooling that occurred due to the presence of the air duct. These approaches include an energy balance on the air flow, the convective heat transfer from the duct to the air, and conductive of heat through the soil to the duct. Each of these approaches is applied in the following analysis.

The total heat flow for the freeze season can be calculated using the First Law of Thermodynamics or energy balance on air flow yielding

\[ Q_t = M c_p \Delta T_f = A \rho V' c_p \Delta T_f \]

\[ Q_t = \frac{\pi D^2}{4} \cdot 0.084 \cdot 1.14 \cdot 0.24 \cdot (18.2 - 3.1) \cdot (215) \cdot (3600) \cdot (24) \]

\[ Q_t = 20.3 \times 10^6 \text{ BTU} \]

where

- \( M \) = mass flow rate of air
- \( c_p \) = specific heat of air
- \( V' \) = air speed
- \( T_f \) = length of freeze season
- \( \rho \) = air density
- \( A \) = cross-sectional area of duct
Using a convective heat transfer analysis, a second estimate can be made on the total heat flow during the freeze season. Applying Newton’s Law of Cooling leads to

\[ Qt = h_e A \Delta T_f = h_e (\pi DL) (T_w - T_{AVE}) t_f \]

\[ Qt = (1.11)(\pi)(120) \left( 18.5 - \frac{18.2 + 3.1}{2} \right)(215)(24) \]

\[ Qt = 33.9 \times 10^6 \text{ BTU} \]

where \( h_e \) = convective heat transfer coefficient
\( A \) = effective surface area of duct
\( L \) = effective heat transfer length of duct
\( T_w \) = mean duct wall temperature during freeze season
\( T_{AVE} \) = mean duct air temperature during freeze season

\( h_e \) was determined from Zarling et al. (1984) at a Reynolds number of 17,000.

The third approach to evaluating the heat transfer occurring between the ground and the air duct is to calculate the conduction rate through the ground. The ground temperatures were recorded at a distance of two, three and five feet from the duct centerline (one, two and four feet from the duct wall) at monthly intervals along vertical and horizontal planes. At each radius four temperature measurements were made: above, below and to either side of the duct. Temperatures presented in Table 2 are the average of the four recorded values.

Fourier’s Law of Heat Conduction, expressed in radial coordinates can be used to estimate the heat flow, i.e.:

\[ Q = \frac{\Delta T}{\ln \left( \frac{R_2}{R_1} \right) 2\pi K_s L} \]

where \( R \) = radial distance from duct centerline
\( K_s \) = thermal conductivity of soil
\( L \) = effective length of duct
\( \Delta T \) = temperature difference

This equation was used with the soil temperature data and estimated thermal conductivity to arrive at estimates of monthly heat flows. Table 2 gives the temperatures and heat flows based on the monthly data for the 1985-86 freezing season using a soil thermal conductivity of \( K_s = .9 \text{ BTU/HR-FT-}^\circ \text{F} \) (Frozen sand with \( D = 115 \text{ LB/FT}^3 \) and \( W = 5\% \)).
The size (radius) of toe of slope thawed zone (TALIK) that can be frozen by the northside air duct can also be estimated. The lowest value of the estimated total heat flow will be used and a silt with a dry density of 90 lb/ft³ and a 15% moisture content will be assumed.

Latent heat of soil surrounding air ducts is:

\[ \gamma = 144w = 144(0.15)(0) = 1, \ 44 \ T / t \]

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Northside air duct</th>
<th>Average temperatures around and along duct and calculated heat flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁</td>
<td>T₂</td>
<td>T₄</td>
</tr>
<tr>
<td>04/24/85</td>
<td>05/24/85</td>
<td>27.34</td>
</tr>
<tr>
<td>05/24/85</td>
<td>06/29/85</td>
<td>32.33</td>
</tr>
<tr>
<td>06/29/85</td>
<td>07/26/85</td>
<td>34.71</td>
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<td>07/26/85</td>
<td>08/30/85</td>
<td>35.71</td>
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<td>08/30/85</td>
<td>09/26/85</td>
<td>34.60</td>
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<td>10/31/85</td>
<td>32.43</td>
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<td>10/31/85</td>
<td>12/05/85</td>
<td>24.05</td>
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<td>01/16/86</td>
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<td>02/13/86</td>
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<td>02/13/86</td>
<td>03/11/86</td>
<td>17.22</td>
</tr>
<tr>
<td>03/11/86</td>
<td>04/10/86</td>
<td>15.97</td>
</tr>
<tr>
<td>TOTAL</td>
<td>BTU / YEAR</td>
<td>-20.52</td>
</tr>
</tbody>
</table>

The sensible heat of the frozen soil surrounding the air ducts is:

\[ C_r = D(.18 + .005_w) = 22.9 \text{ BTU/ft}^3 - F^° \]
The Stefan Number for the freezing season is:

\[
Ste = \frac{C_f(32 - T_mfD)}{L} = \frac{22.9(32 - 18.5)}{1,944} = .16
\]

The radius of soil frozen is:

\[
R = \sqrt{R_o + \frac{Q_t}{\pi LD}} = \sqrt{1 + \frac{20.3 \times 10^6}{\pi (1,944)(120)}} = 5.3 \text{ft}
\]

To correct R for sensible heat effect:

\[
R' = \frac{R}{\sqrt{1 - \frac{Ste}{8}}} = \frac{5.3}{\sqrt{1 - \frac{0.16}{8}}} = 5.2 \text{ft}
\]

**DISCUSSION**

The three approaches used to estimate the annual amount of heat removed by the air duct system yielded the following values:

- Air flow energy balance \( Q_t = 20.3 \times 10^6 \) BTU
- Convective heat transfer \( Q_t = 33.9 \times 10^6 \) BTU
- Conductive heat transfer \( Q_t = 20.4 \times 10^6 \) BTU

It is the opinion of the author that the best estimate of the annual heat flow is provided by the first and third approach. The problem with the second approach is that is difficult to obtain an accurate value for the convective heat transfer coefficient. The first and third approach are independent of one another, which supports the validity of these values. Results, as presented above, are nearly identical for the two methods. Based on the limited data from the Gardner Creek northside air duct and the calculations presented here, the design approach presented by Zarling et al. (1984) appears valid. Additional experiments should be carried out on the convective heat transfer coefficient for air flow in CMP. The effects of helix angle, corrugation height, and Reynolds number should be studied.
SETTLEMENT DATA

An elevation survey of the road surface and embankment side slopes was completed in June 1984. Additional surveys were made in September 1984 and annually thereafter to monitor the effects of the air ducts on the roadway prism. The surveyed section was initially 1000 feet long, including the entire air duct section (approximately 600 feet) and about 400 feet of untreated control area (mostly to the east of the ducts). PK nails were placed in the asphalt concrete to allow monitoring of settlements in the pavement surface. In addition, settlement plates were installed across three embankment cross sections. One of the cross sections is near the center of the air duct section (and also near a culvert), another is near the ducts’ eastern end, and the last one is beyond them in the control area.

By 1986 cracking, differential settlement, and shoulder sloughing in the control area east of the ducts necessitated extensive patching of the pavement (after leveling with gravel). The patch extended about 100 feet into the air duct area except along the northern edge of the pavement. In both of the following years (1987 and 1988) new patches were needed; these extended only about 75 feet into the air duct area. Early road distress also occurred in the unsurveyed area west of the air duct section; patching was needed there by 1985. In 1989 virtually the entire road surface in the vicinity was leveled with gravel and received a new chip seal. This included the entire air duct section, most of which had not previously been patched.

Vertical movements measured at the cross sections are shown in Figures 8, 9, and 10 (Note: this requires renumbering all successive figures; old numbers were 8 & 9). Note that in the first two figures the data shown at centerline and the left pavement edge (marked with question marks) are interpolated, not measured. Measured data were not available since the original pavement was lost beneath the patches at these points.

The figures show that the south side of the embankment settled approximately twice as much as the north side. This may be due to greater exposure to solar insolation on the south side, which would induce greater thawing. Alternatively (or additionally), the old roadbed lies just north of the new alignment, so the ground there may have been more stable when the new embankment was built.

The air ducts, as expected, seem to have had little effect on settlement near the road centerline. The greatest measured settlement is in the middle of the air duct area (Figure 10). 0.10 feet of settlement were measured at the right (north) pavement edge there. None was measured at the other two cross sections at the right pavement edge. At centerline the measured settlement in the middle of the air duct area (Figure 10) was 0.28 feet by September 1988. This is much more than the interpolated centerline values in Figures 9 and 10 (0.10 feet and zero, respectively).
SETTLEMENT PLATES
CROSS SECTION #1

SEC #1 LOCATED AT
STA 1+85
CONTROL SEC.
NO AIR DUCTS

HORIZONTAL DISTANCE FROM C.L.

--- SEPT, 86      ----- SEPT, 88

Figure 8
SETTLEMENT PLATES
CROSS SECTION #2

SEC #2 LOCATED
AT STA 4+00
EAST END OF
AIR DUCTS.

BASE YR. 1984

HORIZONTAL DISTANCE FROM C.L.

SEPT, 86       SEPT, 88

Figure 9
SETTLEMENT PLATES
CROSS SECTION #3

SEC #3 LOCATED
AT STA 6+50
CENTER OF AIR DUCTS.

BASE YR. 1984

HORIZONTAL DISTANCE FROM C.L.

--- SEPT, 86 ---+--- SEPT, 88

Figure 10
Surface settlement in the road shoulder areas was quite different. At a distance of 30 to 60 feet from centerline the measured settlements were significantly smaller in the air duct area than in the control area. Moreover the differential settlement across the embankment was much smaller in the air duct area (which was precisely the intent of the design). This is clearly illustrated in Figure 11, which shows differential settlements as of September 1988. Settlements in the duct area are 83 to 88 percent less than in the control area on the north side of the road, and 84 to 98 percent less on the south side.

Figures 12, 13, and 14 show the measured settlement of the pavement surface. The roadway elevations in the patched areas were not comparable from year to year since the thickness of the patches is unknown. In these areas the settlements could not be computed, and thus there is a considerable amount of missing data in the control area. Like the cross section measurements just discussed, these figures show greater settlement south of centerline than north of it.

The most notable feature of the data, however, is the large settlement (five to eight inches) in the vicinity of the culvert. Ground subsidence near culverts is even more of a problem in permafrost areas than elsewhere. Surface water flowing through a culvert can transfer large amounts of heat into the ground, causing thaw settlement. Moreover, as in any location, the area around the culvert may have been inadequately compacted during construction.

The air ducts did not prevent this settlement (although it is possible that they reduced it somewhat). It is significant that even at the culvert location, where substantial settlement was observed, no patching was required until 1989. As noted before, patching was required almost every year beyond the ends of the air duct area.

This supports the thesis that differential settlement between the road centerline and the embankment toe causes more pavement distress than settlement per se. It also indicates that the air ducts have resulted in improved roadway performance in this thaw-unstable area, at least in the first years after construction. This is true despite the fact that the ducts did not always operate as designed due to icing problems, which are discussed in the next section.
DIFFERENTIAL SETTLEMENT
Between Pavement and Duct Area

Figure 11

Differential Settlement (feet)

North Side

South Side

- Mid Ducts (Sec. 3)
- End Ducts (Sec. 2)
- Control (Sec. 1)
VERTICAL MOVEMENT
10' Rt (North) of CENTER LINE

VERTICAL MOVEMENT (FEET)

STATIONING

--- SEP'T, 84 --- SEP'T, 86 --- SEP'T, 88
VERTICAL MOVEMENT
AT CENTER LINE

VERTICAL MOVEMENT (FEET)

STATIONING

— SEPT, 84    — SEPT, 86    — SEPT, 88
VERTICAL MOVEMENT
10' Lt (South) of CENTER LINE

Figure 14

VERTICAL MOVEMENT (FEET)

0.00
0.10
0.20

-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70

0
200
400
600
800
1000

STATIONING

□ □ □ SEPT, 84
○ ○ ○ SEPT, 86
△ △ △ SEPT, 88

PATCHED AREA
CULVERT
AIR DUCT LOCATIONS

CROSS SEC. #1
CROSS SEC. #2
SEC. #3
ICING

It was determined early in the project that icing within several of the air ducts was blocking or inhibiting airflow. Each air duct was checked visually for ice buildup during the monthly visits to the site by looking into the inlet and outlet of each duct. This method was later found to be unreliable when icing was discovered in the central portion of some ducts by observers crawling through the ducts. For the remainder of the study, the procedure to determine if the ducts were obstructed involved simply yelling through one end of the duct. If the sound traveled freely, the duct was open. If no sound was heard at the other end, the duct was plugged.

In 1986, five 2" well pipes were installed to serve as piezometers in the embankment side slopes near the ducts. Water table readings were recorded monthly for one year. The source of the water entering the ducts was determined to be a high water table during the spring and infiltration from the surface of embankment soils. Ironically, the ducts which worked well and did in fact lower the nearby soil temperature below the freezing point, also became plugged with ice. Those ducts which did not lower the soil temperature sufficiently to cause freeze back allowed excess water to drain freely, leaving the duct open to airflow.

Frost buildup within the portion of the outlet stack extending above the embankment surface caused varying degrees of airflow disturbances. The quantity of frost formed in this area depended on the airflow rate, temperature, and quantity of moisture within the pipe. As cold, dry air is drawn through the duct and warmed by the surrounding soil, moisture is absorbed by the heated air. As this air exits the pipe, rapid cooling in the aboveground portion of the outlet stack causes the moisture to condensate on the pipe walls in the form of frost. This problem could be rectified by using insulated pipe or by berming embankment materials around the outlet portion of the pipe. The duct caps used to prevent rain and snow from entering the outlet would also have to be redesigned.
CONCLUSIONS

1. Differential settlement between the centerline and shoulders of the road was much less in the area where air cooling ducts were located than in the adjacent control area during the first five years after construction, although it is not conclusive that the ducts were entirely responsible for this.

2. Roadway performance has been significantly better in the air duct area than in the adjacent portions of the road, and maintenance requirements have been much less. The air duct area was resurfaced five years after construction while the adjacent control area was resurfaced four times during the same period.

3. The design approach developed in Zarling et al. (1984) appears generally valid based on the performance of the air ducts examined for this study.

4. Additional work is needed to accurately predict the Reynolds number and thus the convective heat transfer coefficient for corrugated metal pipe such as was used on the air ducts studied.

5. Some of the air ducts became plugged with ice for extended periods, stopping air flow. How much this icing affected the ducts’ performance was not determined. The possibility of such icing should be addressed in future designs through consideration of local hydrology and placement of the ducts well above original ground level.

6. Air velocities measured in the ducts were erratic and appear to be influenced by factors other than just the chimney effect created by air temperature and density differences. The procedures of Zarling et al. (1984), based on the "chimney effect", may adequately approximate long-term average duct air velocity, however, and thus be suitable for design purposes. Further study is needed to confirm this.
IMPLEMENTATION

Convective cooling ducts are effective when properly designed and installed. The design procedures developed by Zarling et. al. should be used to size the ducts and determine the duct spacing. However, the ducts should be placed high enough to ensure water does not enter the duct. Further, the slope of the horizontal section should be such that water drains. This will also allow for some differential settlement without altering the performance of the duct.

Air ducts should be considered in areas where taliks form under the shoulders causing severe longitudinal cracking in the traveled way. They may be used in conjunction with other techniques such as insulation.
REFERENCES