# Thawing of permafrost by passive solar means

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By pre-thawing and consolidating the upper layers of the permafrost, a thinner stable roadway embankment may be constructed, provided the thickness of the embankment plus that of the pre-thawed layers are adequate to contain the full seasonal thaw zone.

Six test plots were established near Fairbanks, Alaska, in April 1980, to determine how surface modifications may be used to accelerate thawing of permafrost by increasing the solar heat gain. The various modifications examined included clearing and stripping the surface, construction of a thin gravel pad, darkening of the gravel pad surface with asphalt, and the use of clear polyethylene film to create a "greenhouse effect" on both gravel pad and stripped sections. Each section simulated a full roadway width with adjacent uncleared vegetation. Instrumentation used to monitor performance included heat flow meters, windspeed and radiation sensors, and thermocouples for subsurface temperature observations. Thaw depths and surface settlements were recorded monthly at nine points on each section, and monthly measurements of surface albedo were also made for each treatment.

Differences between thaw depths achieved with the different treatments have been as much as 40 per cent. Results of this study are used in analyses of probable benefits of roadways and airfields constructed after pre-thawing for one season.

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En dégelant et en consolidant les couches supérieures du pergélisol, on peut construire une assiette de route stable de faible épaisseur, pouvu que la couche formée de l'assiette et des couches dégelées englobe toute l'épaisseur de la zone de dégel saisonnier.

On a étudié six sites près de Fairbanks, Alaska, en avril 1980 dans le but de déterminer quelles modifications de la surface permettent d'accélérer le dégel du pergélisol en accroissant le gain thermique solaire. Les différentes modifications de la surface examinées sont: nettoyage et mise à nu de la surface, pose d'une mince couche de gravier, noircissement de cette couche de gravier à l'asphalte et utilisation d'un film de polyéthylène transparent pour créer un "effet de serre" tant sur la couche de gravier que sur les sections mises à nu. Chaque section simule une pleine assiette de route bordée de végétation. Les instruments de contrôle de l'expérience sont: appareils de mesure des flux thermiques, capteurs anémométriques et de rayonnement, et thermocouples pour l'observation des températures sous la surface. On a enregistré, chaque mois, la profondeur de dégel et le tassement de la surface en neuf points de chaque section; on a aussi mesuré, chaque mois, l'albédo des surfaces modifiées.

On note entre les profondeurs de dégel atteintes au moyen des différentes modifications des écarts allant jusqu'à 40 pour cent. Les résultats de cette étude servent à analyser les avantages possibles de la construction de routes et d'aérodromes après un premier dégel provoqué.

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## Introduction

Roadways having unstable foundations require major annual maintenance efforts by the Alaska Department of Transportation and Public Facilities. Previous field studies of insulated and uninsulated paved roadways and airfields over areas of permafrost in Alaska have demonstrated that, in most instances, a state of thermal equilibrium is eventually reached beneath these surfaces, in which the summer thawing is balanced by full annual refreezing (Esch 1973). This state results in a stable surface, however, only if seasonal thawing is confined to soils which are thaw stable. In areas with permafrost soils having excess ice, roadway and airfield stability can be assured only by preventing thaw of the permafrost soils beneath the roadway. This can be accomplished through use of very thick gravel embankments, as much as 4.5 to 6 m for the Fairbanks area, or by a properly designed insulated roadway embankment.

By pre-thawing and consolidating the upper layers of the permafrost before construction, a thinner roadway embankment could be used, with the thickness of the embankment plus that of the pre-thawed layer designed to be thermally adequate to contain the full seasonal thaw zone.

Thermally stable embankment thicknesses required for climatic regions similar to Fairbanks on both peat and silt subgrade soils have been calculated (Figure 1). The thickness necessary in the Fairbanks area could be reduced from 6 m with no thawed foundation soils, to 1.5 m of gravel with 1.7 m of pre-thawed silt beneath the embankment. The pre-thawing method therefore appears to be an economical means of constructing stable roadways over permafrost. These analyses were one-dimensional only, and are based on surfaces maintained free of snow to assure annual refreezing. Problems of thaw and instability associated with embankment side slopes not maintained free of snow are outside the scope of this study.

The use of a single thawing season to increase the active layer depth is examined in this report.

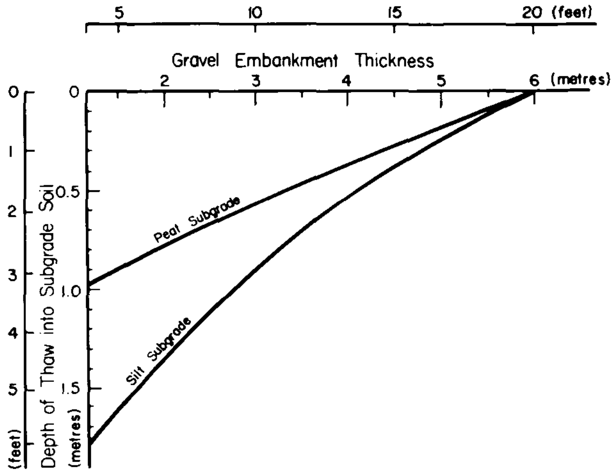

FIGURE 1. Gravel embankment thicknesses required over silt and peat subgrades.

## Alternative Design Modes

The author's intent in this study was to evaluate the benefits of various simple modifications to the surface in optimizing passive solar heating to maximize the seasonal thaw depth during one and two thawing seasons. It should be feasible to require at least one summer of thaw-acceleration as the first stage of a roadway construction project, particularly if this treatment is confined to short sections with alternative access available. The surface modifications considered were those directed at improving the surface heat gains by reducing shading and reflectance, and reducing surface cooling by evaporation, transpiration, natural convection, and wind effects. Specific modifications considered in this study included the following modes:

### *Mode 1 — Stripping of Vegetation*

The benefits of vegetation removal in accelerating thaw are believed to result primarily from elimination of the shading and insulation effects of vegetation, exposure of the soil surface to direct absorption of incoming radiation, and the elimination of heat losses by transpiration. Adverse effects of vegetation removal include an increase in evaporative cooling and in forced convective cooling by winds. The effects of stripping on thaw acceleration in permafrost have been documented by several researchers (Brown and Grave 1979; Linnel 1973; Nicholson 1978).

### *Mode 2 — Polyethylene Film Surface Covering*

Clear polyethylene films have been used for many years in the agricultural community to increase average soil temperatures in northern regions. Dinkel (1966) has reported that at Palmer, Alaska, a covering of clear polyethylene film increased average daily soil temperatures at a depth of 25 mm by as much as 17°C over uncovered soil surfaces. Black and smoke-coloured polyethylene, conversely, did not significantly increase soil temperatures in similar studies (Dinkel 1967). The benefits of clear polyethylene in increasing surface temperatures in a tundra environment, both with and without stripping, have also been reported by Nicholson (1978). Clear polyethylene operates through the "greenhouse effect," transmitting incoming short-wave radiation to the soil, while retarding the predominately long-wave radiation given off by the soil surface. The heat thus trapped is not readily dissipated by wind or by the evaporation of soil moisture, and becomes available to accelerate thawing of underlying permafrost.

### *Mode 3 — Thin Gravel Pad (0.3 m)*

This case was included primarily to analyze the merits of a thin granular soil layer which could carry light construction traffic during the thawing period. The pad also serves the additional functions of providing a consolidation loading and preventing erosion of the thawing soil layers. The thermal benefits of the pad in reducing evaporative cooling of the soil surface and consolidating the thawed layers, is offset to some extent by the thermal insulating effect of the gravel layer and the higher albedo of the light-coloured gravel surface.

### *Mode 4 — Darkened Gravel Surface*

To lower the albedo of the gravel and thereby increase the average surface temperature through increased solar radiation absorption, the gravel surface was darkened by a spray application of RC 800 cutback asphalt. The application rate found necessary for reasonable coating of the coarse gravel, which ranged up to 200 mm in maximum size, was approximately two litres per square metre.

### *Mode 5 — Hand-Cleared Vegetation*

This procedure was included to represent the clearing process normally specified by the Alaska Department of Transportation for ice-rich permafrost areas, in which trees and brush are hand cut without disturbing the surface layer of mosses and grasses. This layer has been shown to have some significant long-term insulation value beneath a roadway embankment (Esch 1973), and also serves as a filter layer to prevent erosion. Simple removal of trees and brush will have only a minor effect on accelerating thaw (Linnel 1973), unless compressed by some measure such as gravel pad construction (*see* mode 2).

## Site Description

To examine the effects of these ways of accelerating thaw, a site was selected on undisturbed forested permafrost within the USA-CRREL Alaska Field Station, located near Farmers Loop Road, approximately 4 km north of Fairbanks, Alaska. The site selected (Figure 2) was located roughly 150 metres north-west of the long-term thaw study site reported on by Linnel (1973). The soil and permafrost conditions at both sites are similar. The terrain slopes gently to the south and west, with soils primarily being deep colluvial deposits of slightly organic silts, Unified Class ML, with occasional wood fragments and peat layers. A change in the silt colour from brown to gray was generally noted near the two-metre depth. Ice occurred primarily in the form of thin lenses (1 to 3 mm), which were more frequent within 1 m of the surface. Moisture contents and organic contents for samples obtained in this study are shown in Figures 3 and 4. The organic contents were determined from the weight loss on heating the soil to 900°C for three hours. Permafrost at this location is estimated to exceed 30 m in depth, with a mean annual soil temperature at a depth of 10 m of approximately −1°C. Vegetation at the selected location was dominated by a very dense growth of white and black spruce ranging from 3 to 10 m in height, with occasional white birch. The ground surface was covered by a layer of moss and roots 0.15 to 0.25 m thick, with scattered low-bush cranberry, blueberry, and Labrador tea. Resistivity surveys were made of

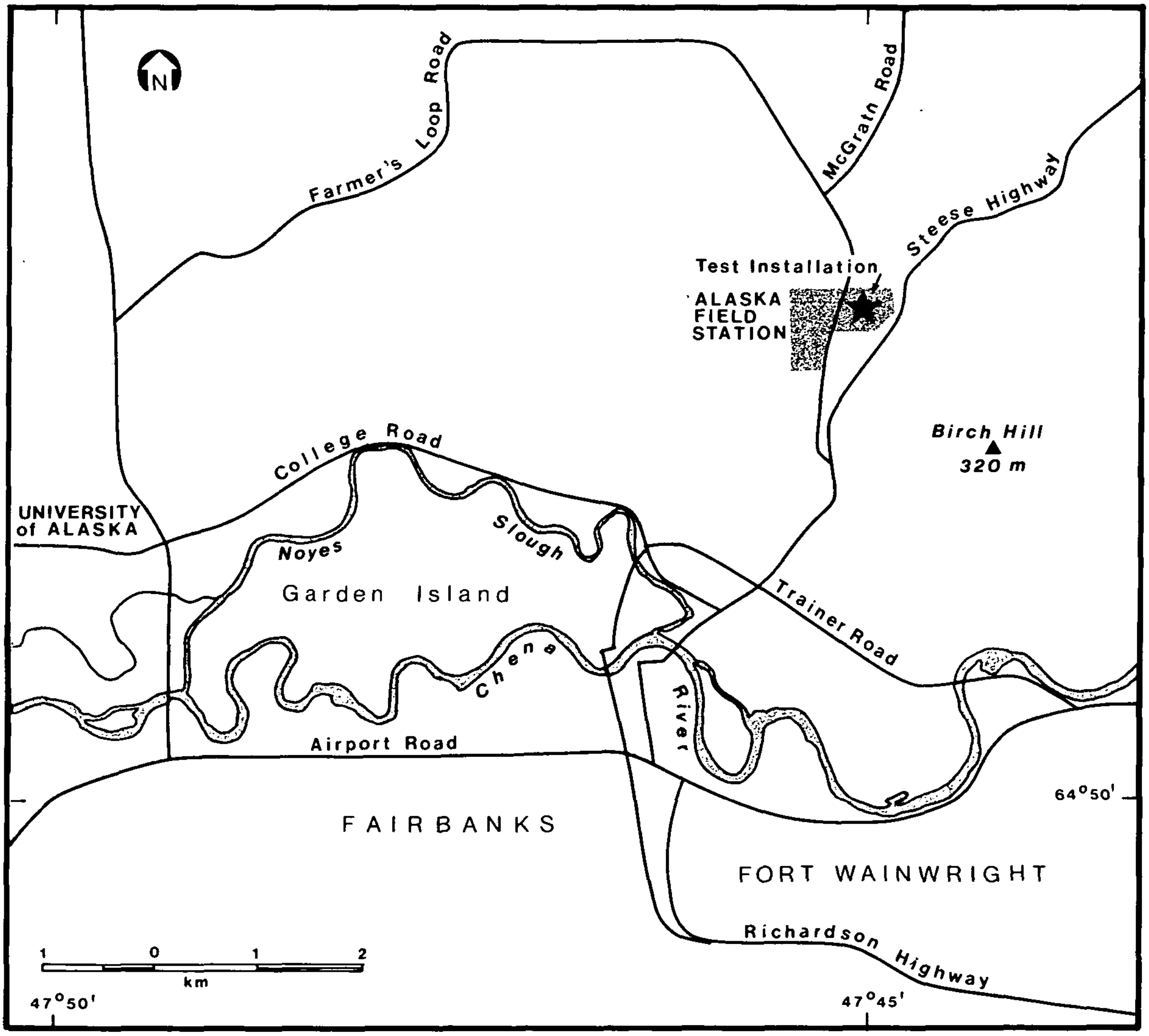

FIGURE 2. Location map.

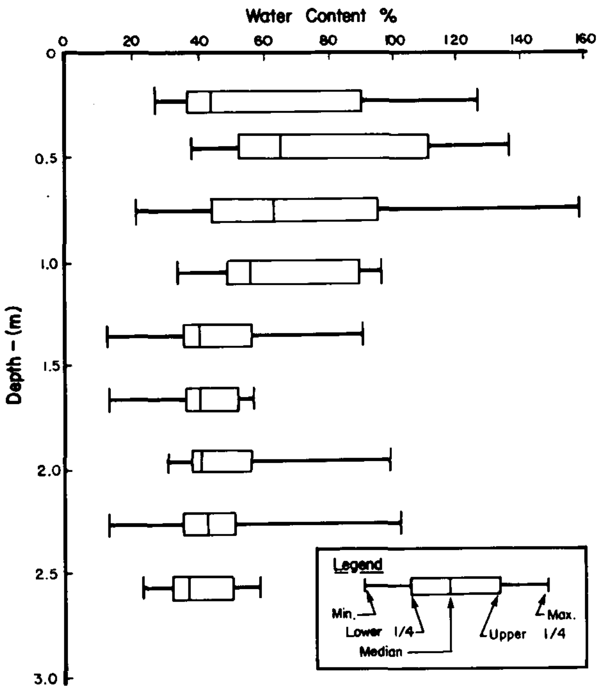

FIGURE 3. Water content ranges of soils *versus* depth.

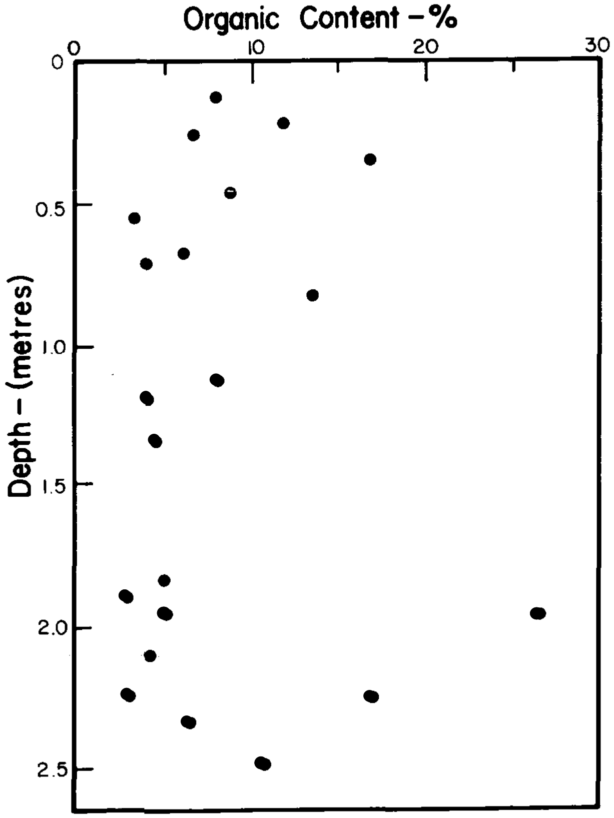

FIGURE 4. Organic contents of soils *versus* depth.

the selected site with an EM-31 non-contact conductivity meter, and indicated the site to be free of anomalous resistivity readings and presumably free of massive segregated ice.

Climatic conditions at the site are similar to those at Fairbanks International Airport, the closest long-term U.S. Weather Service station. This station has a mean annual temperature of −3.44°C, with extremes of +34 and −54°C. Freezing and thawing indices have averaged −3200 and +1844 degree Celsius days, respectively. Precipitation averages 0.29 m, including the average water equivalent of 1.54 m of snowfall.

## Site Construction

To maximize the thaw depth in a single thawing season, it was considered essential to remove the layers of snow and vegetation from the surface just prior to the start of the thawing season, which normally commences in early to mid-April in the Fairbanks area. Six different pre-thaw plots were used to evaluate different thawing mode combinations. Each test plot was approximately 18 m wide by 23 m long, with the width selected to represent a normal roadway. The test plots were grouped in pairs and separated by narrow undisturbed forest areas, to keep all sections close together for instrumentation purposes while permitting the duplication of normal roadway sites (Figure 5). A description of the thawing treat-

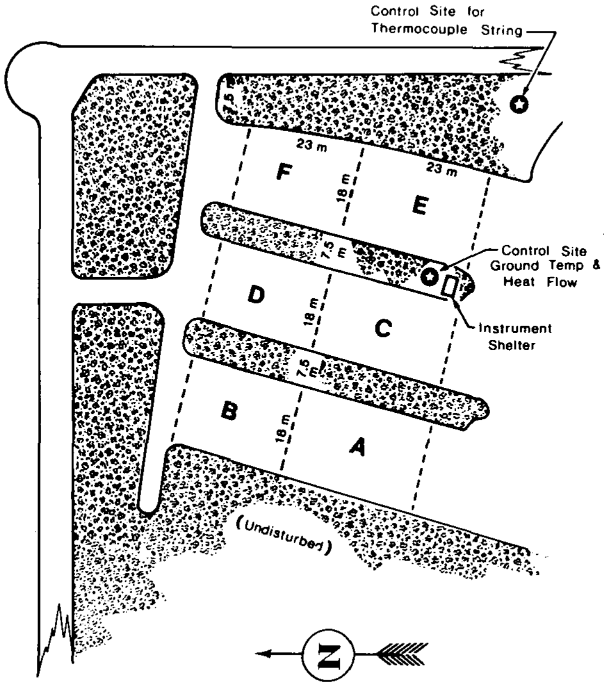

FIGURE 5. Site plan and test plot layout.

TABLE 1. Test plot descriptions and thawing modes

| Plot | Description | Thawing modes |
|---|---|---|
| A | Machine stripped | 1 |
| B | Stripped, with poly film | 1 + 2 |
| C | Stripped, with gravel, asphalt, and poly | 1 + 2 + 3 + 4 |
| D | Stripped, with gravel and asphalt | 1 + 3 + 4 |
| E | Hand cleared, with gravel and poly film | 2 + 3 + 5 |
| F | Stripped, with gravel pad | 1 + 3 |

ments used in each plot is included in Table 1. Removal of trees from all plots, and the vegetation stripping operation on all plots except hand-cleared Plot E, were completed in early April, 1980. The vegetation was stripped with a small bulldozer by pushing the blade across the top of the solidly frozen mineral soil, leaving only the thinnest possible layer of moss and embedded tree roots. This operation worked very well, and is similar to land-clearing operations commonly used in the Fairbanks area to minimize the volume of stripped material. The vegetation was totally removed from the area with trucks and a loader, to create a clean site. In actual practice, the vegetation would normally be burned on-site or pushed aside and later placed in the toe-of-slope areas.

Gravel hauling and placement on selected plots was completed by April 8, and was followed by light compaction with a track-mounted drill rig in early May.

The work of extensively sampling the underlying soils and fully instrumenting the various plots delayed the subsequent completion of operations such as placing the asphalt surface coating and the polyethylene until early in June, which resulted in some loss of the potential full-year benefit of these treatments. The cumulative air thawing index prior to June 1, 1980, was 395 degree Celsius days, or 21 per cent of the seasonal total.

For purposes of comparison, an undisturbed forest site was selected adjacent to the test plots, and was sampled and instrumented to a depth of 9.14 m. The construction sequence for the various plots is summarized in Table 2.

## Instrumentation

Monitoring equipment installed to measure the relative thermal performance of the six different prethaw plots included six heat flow meters, seven top of mineral soil temperature sensors, one air temperature sensor, a pyranometer-solarimeter, and a cup anemometer; all of which were recorded hourly on magnetic tape by a Fluke Model 2240B Datalogger. Subsurface temperatures were measured from vertical strings of 12 thermocouples installed in borings made at the centre of each plot, located at depths ranging from 0.30 to 4.57 m. Thermocouples were read on a monthly basis and provided indications of thaw depths.

Thaw depths and surface elevation changes were determined monthly at nine grid points established within each test plot. A settlement plate was installed at the original ground surface at each grid point. Each plate consisted of a horizontal plywood base 0.3 m square with a vertical $^3/_4$-inch iron pipe extension attached to the centre of the base with a threaded pipe flange. Hand probing was done through the centre of each settlement plate with a steel rod 12.7 mm ($^1/_2$ in.) in diameter. The probed thaw depths were referenced to the top of the pipe extensions, and the elevations of the pipes were determined by monthly surveys from fixed bench-marks. These settlement plates therefore provided information on both surface and permafrost table elevations, permitting accurate calculations of settlements and thaw depths.

Observations of net radiation were made periodically at the middle of each plot with a hand-held net radiometer (Weather Measure Corp. Model R422). This radiometer provided an indication of the net (incoming minus outgoing) radiation in the wavelength range from 0.3 to 80 microns. This information was used primarily to evaluate the relative solar energy retained by the various plots.

## Performance Observations

### *Net Radiation*

Intermittent net radiometer readings were obtained under clear, and overcast sky conditions, with the hand-held net radiometer positioned at a height of 1 metre above the centre of each plot. The readings obtained represent the difference between the incoming direct solar, diffuse solar and long-wave sky

TABLE 2. Construction schedule for prethaw plots, 1980

| Dates | Construction operation | Plots |
|---|---|---|
| April 1-3 | Cleared and stripped vegetation | A - D |
| April 3 | Hand-cleared trees and brush | E |
| April 3-8 | Hauled and spread gravel pad | C - F |
| May 7-12 | Drilled and sampled test borings | A - F |
| May 7-12 | Gravel compaction w/drill carrier | C - F |
| May 7-12 | Temperature sensor installations in borings | A - F |
| May 13 | Installed and surveyed settlement plates | A - F |
| May 28-30 | Installed heat flow meters and surface temperature sensors | A - F |
| May 30 | Installed polyethylene film | B |
| June 2 | Applied asphalt coating | C & D |
| June 9 | Installed polyethylene film | C & E |
| June 16 | Monitoring system completed | A - F |
| October 14 | Data logger removed for winter | |

radiation, and the outgoing reflected solar and terrestrial radiation (ERDA 1976). These data provide a means of comparing the surface heating energy available from different treatments. For purposes of direct comparison, data from all other plots and from the forested control site have been calculated as percentages of the net radiation at Plot A, which represents the stripped surface condition (Table 3).

Because of the small number of observations, exacting conclusions on relative radiation balances for the various treatments are not possible. However, certain relationships are apparent.

1) The polyethylene-covered plots B, C, and E captured 20 to 40 per cent less of the available incoming radiant energy as compared to the bare soil plot. This is believed to be primarily due to reflection from the polyethylene surface and from the layer of water condensate commonly present on the underside of the polyethylene.

2) The asphalt-covered gravel surface had roughly the same radiation balance as the stripped soil plot, indicating similar albedos.

3) The light-coloured gravel surface of Plot F absorbed significantly more radiant energy than the polyethylene-covered plots on both sunny and cloudy days.

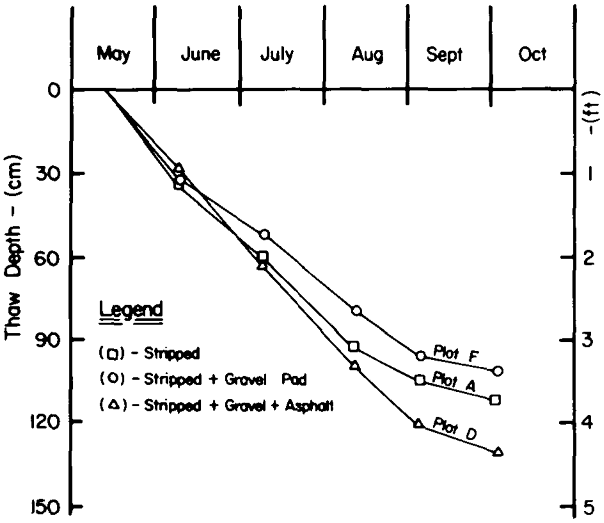

FIGURE 6. Thaw depths at plots without polyethylene covering.

*Thaw Depths and Settlements*

Results of monthly thaw depth probings are expressed as the average of nine measurements on each plot. For the three plots without polyethylene film (Figure 6) it can be seen that the thin gravel pad as in Plot F reduced the total thaw depth by 10 per cent from that obtained by simple stripping of the vegetation. By comparison, the application of a black asphalt surface to a gravel pad as in Plot D increased the thaw depth by 28 per cent over that for the bare gravel, and resulted in thawing 15 per cent deeper than beneath a stripped surface.

For the two polyethylene-covered gravel pad plots (Figure 7), the absence of a dark surface and the presence of the surface moss and vegetation beneath the gravel as in Plot E, resulted in a decrease in thaw depth of 23 per cent from that at Plot C. Compari-

TABLE 3. Observations of net radiation absorbed by various test plots

| Date | Time | Condition | Cloud cover | Radiation @ Plot A | Net radiation as percentage of Plot A | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | A | B | C | D | E | F | Control |
| | | | (%) | (w/m$^2$) | (%) | (%) | (%) | (%) | (%) | (%) | (%) |
| 6-16-80 | 12:30 PM | Sunny | 50 | 627 | 100 | 76 | 81 | 103 | 58 | 75 | 1 |
| 6-30-80 | 10:10 AM | Lt. Rain | 100 | 106 | 100 | 100 | 90 | 130 | 120 | 150 | 80 |
| 7-8-80 | 9:00 AM | Lt. Rain | 100 | 32 | 100 | 67 | 67 | 67 | 33 | 100 | 67 |
| 7-18-80 | 10:30 AM | Sunny | 5 | 510 | 100 | 71 | 83 | 100 | 71 | 88 | 2 |
| 7-22-80 | 3:30 PM | Rain | 95 | 43 | 100 | 25 | 100 | 150 | 125 | 200 | 125 |
| 8-11-80 | 2:10 PM | Sunny | 10 | 457 | 100 | 63 | 72 | 91 | 58 | 79 | 2 |
| 9-18-80 | 4:15 PM | Sunny | 0 | 234 | 100 | 86 | 77 | 109 | 68 | 95 | 5 |
| Average Values | | Sunny Days | | 457 | 100 | 74 | 78 | 101 | 64 | 84 | 2 |
| | | Overcast | | 60 | 100 | 64 | 86 | 116 | 93 | 150 | 91 |
| Surface condition mode* | | | | | 1 | 2 | 2 | 4 | 2 | 3 | — |

*Mode 1 = Stripped soil surface
Mode 2 = Polyethylene film
Mode 3 = Gravel surface
Mode 4 = Gravel sprayed with asphalt

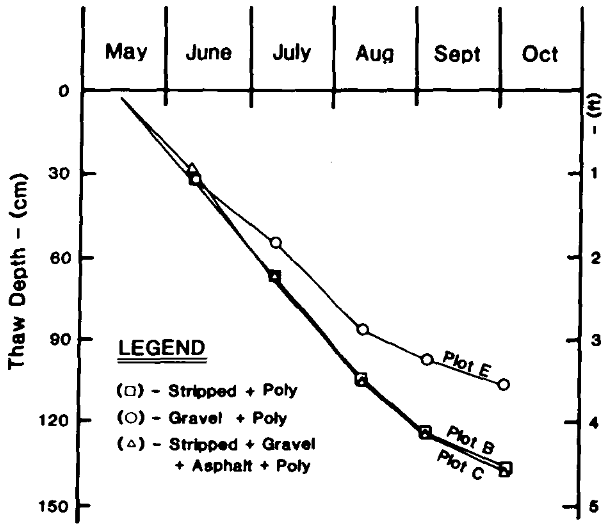

FIGURE 7. Thaw depths at plots with polyethylene covering.

sons between similar plots with and without the polyethylene film, show that the application of the polyethylene increased the thaw depth by 21 per cent for a stripped site, and by 8 per cent when applied over a blackened gravel surface. Although no frost probing was done at the undisturbed forest site, thermocouple temperatures indicated the maximum thaw depth at that location to be approximately 35 cm below the top of the mineral soil.

Measured settlements at the end of the first thawing season are listed in Table 4. For stripped Plots A and B, which had no gravel pad, settlements averaged approximately 18 per cent of the thickness of the thawed layer. The four gravel pad plots had settlements which averaged 28 per cent of the thickness thawed. This major difference in settlement magnitudes was the direct result of the added pressure of the gravel layer, estimated at 6.2 kPa (0.9 psi). This added consolidation of the thawing soil layers by the gravel pad certainly increased the strength and load capacity of the thawed layer, and would also be expected to decrease frost heaving and increase the rate of thawing of this layer during the second thawing season as a result of the increase in thermal conductivity and the decrease in latent heat of the consolidated soils.

### *Air and Surface Temperatures and Heat Flow Measurements*

Data from the Fairbanks Airport Weather Station, located 11 km south-west of this site, indicated the total thawing index for 1980 to be 1893 degree Celsius days. Total rainfall during this period was 146 mm while the average wind velocity at the airport location was 3.5 m/s.

Although the surface temperature and heat flow measurement data recorded from the different test plots are not complete due to the late start-up and equipment malfunctions, continuous data were obtained from June 17 to July 21 of 1980. During that period, the air temperature on-site averaged 15.2°C as compared to 15.6°C at the Fairbanks Airport. Wind velocities and incoming global radiation at the site averaged 1.1 m/s and 188 W/m$^2$, respectively, during that period.

Soil temperatures and heat flow measurements for the same period, taken at a depth of approximately 25 mm, were recorded hourly and averaged over this full 35-day period of recording (Table 5).

These data generally confirm the trends and relationships between the different modes and plots which were previously discussed. Site E was not included in this monitoring program due to equipment limitations. Data are also provided on heat flow entering the ground, expressed as percentages of the average incoming global radiation during this period, changes in average thaw depth at each test plot, and

TABLE 4. Thaw depth and settlement changes from 5/13/80 to 10/3/80

| Plot | Thaw | Settlement | Thaw rates: 5/13 to 8/11 | Surface modifications |
|---|---|---|---|---|
| | (m) | (m) | (m/mo) | |
| A | 1.14 | .23 | .313 | Stripped |
| B | 1.38 | .24 | .330 | Stripped + poly |
| C | 1.41 | .36 | .353 | Stripped + gravel + asphalt + poly |
| D | 1.31 | .31 | .335 | Stripped + gravel + asphalt |
| E | 1.08 | .34 | .286 | Gravel + poly |
| F | 1.02 | .29 | .271 | Stripped + gravel |

TABLE 5. Average soil temperatures and heat flows for period 6/17 to 7/21/80 (840 hrs)

| Plot | Temp. soil surface | Measured heat flow | Percentage of global solar radiation | Change in thaw depth | Thaw energy reqd.* |
|---|---|---|---|---|---|
| | (°C) | (W/m²) | (%) | (m) | (W/m²) |
| A | 15.2 | 25.9 | 13.8 | .31 | 19.2 |
| B | 20.5 | 23.3 | 12.4 | .40 | 24.8 |
| C | 16.6 | 33.4 | 17.8 | .44 | 27.3 |
| D | 12.5 | 24.9 | 13.3 | .38 | 23.6 |
| F | 10.8 | 17.7 | 9.4 | .24 | 14.8 |
| Forest | 1.0 | 0.6 | 0.3 | -0- | |

*Based on saturated soil at $w = 60\%$ average frozen moisture content and Sp.Gr. = 2.6

calculated energy requirements to achieve these increases in thaw depth.

The most significant observation which can be made for all thawing modes is that the percentages of the average incoming solar energy which actually entered the ground and were available to perform the work of thawing were very low, less than 18 per cent, even for the best performing of the test plots. Obviously there is still much more free energy to be gained by further developments in this area.

Heat flow measurements at Plot B appear somewhat anomalous in view of the average temperature and the thaw depth observed for this plot, and may be the result of convective heat flow from ponded water at the sensor location.

### Discussion of Relative Performance

As would be expected, superior performance was demonstrated by the test plot which had received the full combination of methods selected to maximize the rate of thawing, including vegetation removal, an asphalt-darkened surface, and a covering of polyethylene film. The benefit of darkening a light-coloured gravel surface with a layer of asphalt was most significant, and indicated that greater thawing and greater surface settlements can be achieved by this method than by merely stripping the vegetation. Comments on the performance aspects of the various thawing modes follow.

*Mode 1 — Stripping of Vegetation*

After mechanically stripping away the surface vegetation from a permafrost site, the maximum depth of first-year thaw achieved was approximately 1.1 m in an organic silt with an average moisture content of 63 per cent. This was roughly three times the thaw depth at an adjacent undisturbed site. Problems with such a stripped site would be the impossibility of summer travel across the site by vehicle due to soft saturated soils, and the shading effects of the vegetation regrowth from seeds and roots following the stripping operation.

*Mode 2 — Polyethylene Film Surface Covering*

The benefits of a clear polyethylene film layer were more apparent above the stripped plot than on plots with gravel surfaces, perhaps because of greater evaporation retardation. Net radiation measurements periodically taken above the test plots indicated that the polyethylene surface reflects away a significant percentage of the incoming solar energy. The benefit of the polyethylene therefore must result from its barrier effect in retarding evaporative and convective heat losses. As traffic could quickly destroy the film, this must be considered a "closed road" procedure. To maximize the transparency to radiation, the thinnest polyethylene film having adequate durability should be used. Vegetation regrowth was significantly retarded by the polyethylene, but application of herbicides to eliminate vegetation would also be hindered.

*Mode 3 — Thin Gravel Pad*

When applied to a stripped area prior to thawing, a gravel pad will provide three significant advantages. The pad can carry light traffic, it prevents erosion of the exposed native soils, and it provides a surcharge loading to consolidate and strengthen the thawing soils. Because of the light surface colour of the gravel used in this study and its added thermal resistance, thawing was reduced by roughly 10 per cent as compared to a stripped soil surface.

*Mode 4 — Darkened Gravel Surface*

The application of asphalt to darken a gravel surface resulted in major increases in absorption of surface heat and in depth of thaw. The performance of the asphalt-treated gravel surface was improved slightly by covering the surface with polyethylene. Durability of asphalt-covered gravel surfaces under traffic remains in question, as only the top surface of the exposed particles were coated at the asphalt application rate used. After two weeks of exposure, the surface of the asphalt became sufficiently dried and oxidized as to pose no problem to foot travel.

## Economic Considerations

The normal practice of roadway design in Alaska is to specify "hand clearing" before construction over thaw-unstable permafrost areas. The change to machine clearing and stripping in these areas would result in an average savings of \$500 to \$1000 per acre (4048 $m^2$), based on current bid averages. The placement of a gravel pad is not considered an extra item of cost, as the gravel will remain as a part of the normal embankment structure. Polyethylene film and asphalt both involve obvious non-recoverable extra costs. Polyethylene film is commonly available in thicknesses of 0.05, 0.10, and 0.15 mm (2,4, and 6 mils). The cost of this product is almost directly related to the cost of polyethylene. As a result, the cost of material of 0.15 mm thickness is three times that of the 0.05 mm material. Placement of the polyethylene involves unrolling and spreading the material from rolls containing 30-m (100-ft) lengths and variable widths up to 12 m (40 ft). This operation is followed by the placement of rocks, wood, or soil along the edges and at interior points as necessary to secure the film against wind. Asphalt placement would be done by a spraybar from a distributor truck or by a hand-held spray wand for small applications.

Estimated added construction costs for the various treatments which are in excess of normal construction costs are presented (Table 6), based on an average treatment width of 18 m.

TABLE 6. Net installed costs of prethaw modes

| Mode | In-place cost | | Estimates | |
|---|---|---|---|---|
| | (\$/$m^2$) | (\$/$yd^2$) | (\$/km) | (\$/mi) |
| Polyethylene film (.1 mm) | 0.35 | 0.29 | 6,300 | 10,200 |
| Polyethylene film (.15 mm) | 0.47 | 0.39 | 8,500 | 13,700 |
| Asphalt emulsion on gravel (2 litres/$m^2$) | 0.96 | 0.80 | 17,500 | 28,200 |
| Machine stripped | 0.49 | 0.41 | 8,900 | 14,400 |
| Hand cleared | 0.62 | 0.52 | 11,400 | 18,300 |

The economic benefits to be obtained from increased thawing and consolidation of the subgrade soils can be calculated directly from the reduced embankment material quantities required for a thermally stable embankment. As the thickness of an embankment is increased, the base width must be increased to maintain the same side slopes. Using standard 3:1 side slopes, the base width must be increased by six times the increase in thickness, making material quantities escalate rapidly (Figure 8).

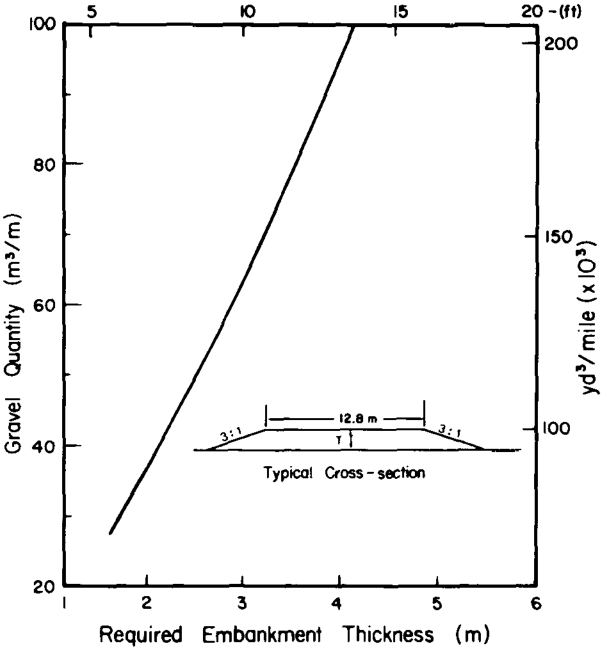

FIGURE 8. Gravel quantities required *versus* embankment thickness.

Current (1980) construction cost information for highways in the Interior Region of Alaska indicates that embankment material excavated from other areas along the roadway averaged \$4.06/$m^3$ (\$3.11/$yd^3$), while embankments constructed from remote "borrow pit" sites averaged \$8.72/$m^3$ (\$6.67/$yd^3$). For analysis purposes, the average of these costs (\$6.39/$m^3$) was used. From Figures 1 and 8, the thicknesses and quantities of embankment materials required for the various depths of thaw attained at the test plots were determined and compared to those required for construction over undisturbed permafrost terrain with a normal active layer of 0.5 m (1.7 ft). Results of this analysis (Table 7) indicate excellent benefit-to-cost ratios for the various prethaw modes discussed here. Results of this type of benefit/cost analysis must be considered relative, as they will vary with local material costs, climatic factors, and soil types. Road embankments in the Interior Regions of Alaska are not presently designed for thermal stability, due to the great material thicknesses required. The economic aspects of distress and increased maintenance resulting from these thermally unstable designs have not yet been evaluated.

## Summary

Based on results of full-scale field trials involving combinations of passive design modes intended to intensify solar thawing of permafrost, it is apparent that thermally stable embankments could be constructed much more economically by maximizing the thaw depth during a single summer prior to construc-

TABLE 7. Benefits of prethaw modes in reduced costs for thermally stable embankments

| Prethaw mode | Required embankment thickness | | Material saved over undisburbed | Net savings @$6.39/m | Approx. net cost | Relative benefit/cost ratio |
|---|---|---|---|---|---|---|
| | (m) | (ft) | (m$^3$/km) | ($/km) | ($/km) | |
| Hand cleared | 4.1 | 13.5 | -0- | -0- | 11,400 | — |
| Stripped & gravel | 2.8 | 9.2 | 43,200 | 276,000 | 8,900 | 31.0 |
| Stripped only | 2.5 | 8.2 | 51,800 | 331,300 | 8,900 | 37.2 |
| Stripped + gravel + asphalt | 2.1 | 7.0 | 60,600 | 387,200 | 26,400 | 14.7 |
| Stripped + gravel + asphalt + poly | 2.0 | 6.6 | 64,300 | 410,900 | 34,900 | 11.86 |

tion. Measures evaluated in this study included hand clearing and machine stripping of vegetation, thin gravel pad construction, the use of asphalt for surface darkening, and clear polyethylene film as a surface covering to create a "greenhouse" effect. Significant increases in thaw depths resulted from machine stripping, asphalt surface darkening, and polyethylene surface coverings. The benefit of gravel pad installation was primarily that of increasing the consolidation of the thawed soils, preventing erosion, and increasing trafficability.

In general, the benefits of any mode of intensifying preconstruction thaw in thaw-unstable permafrost appear to greatly exceed the costs involved during the actual construction. It should be noted that the conclusions of this study are somewhat site-specific, and the relative performance of the different thawing modes may be different in areas exposed to greater wind velocities, different moisture, temperature, and drainage conditions, and different levels of incoming solar energy. Further studies of these test plots are scheduled for 1982, to evaluate the effects of a wintertime of refreezing and a second thawing season on the maximum depths of thaw.

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