S T U D Y :

BURIAL OF A COLD PIPE IN WET PERMAFROST

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INTRODUCTION

This report has been prepared in response to questions concerning the problems of burying a cold pipe in the permafrost of Alaska.

Basically, it outlines the preliminary investigations conducted by K.J. Anderson and Associates with respect to the Trans-Alaska oil pipeline and, later, to a proposed natural gas pipeline parallel to the Alyeska line.

Concerning the study of the cold pipe, it will be clear that a detailed, in-depth analysis was not possible because 1) no precise information was available on pipe characteristics beyond the simplest parameters, 2) little was known as to how far the El Paso pipeline study had progressed along these lines of research, and 3) neither time nor facilities were available to carry out a complex project.

The report, then, is intended to document the background and engineering concepts upon which our statements concerning a cold pipe were based.

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8. SOME ESTIMATES OF THE THERMAL EFFECTS OF A HEATED PIPELINE IN PERMAFROST, Arthur H. Lachenbruch; Geological Survey Circular 632 (1970)

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GENERAL

The Anderson System concept grew out of an awareness that Arctic Alaska presented numerous construction problems, most of them stemming from the unique characteristics of permafrost. Real knowledge about permafrost was, and still is, scarce. To date most permafrost research has been carried out in the U.S.S.R.; only a handful of experts are to be found in this country.

The references used were primarily authored by one geophysicist in the U.S. Geological Survey; however, they reflect not only his own prodigious efforts in Alaska, but those of his fellow scientists around the world. Our conclusions were heavily influenced by these scientific studies and we believe our report would be incomplete without the direct inclusion of significant portions of the references.

PERMAFROST

"Roughly speaking, frozen ground may be divided naturally into two classes: that which thaws annually, "seasonal frost," and that which does not, "permafrost." ...In regions where permafrost exists, the surficial layer that thaws each summer is called the "active layer."...Permafrost is defined as naturally occuring earth material whose temperature is below 0^{o} C, winter and summer..." (Ref. 2)

A further division is based upon moisture content. Dry permafrost is defined as ground which is either well drained, coarse-grained material or rock, and thus relatively ice-free. Wet permafrost is defined as ground which is composed of fine-grained deposits and has a high moisture content. The seasonal fluctuations of temperature are able to penetrate deeper and more rapidly as the moisture content is reduced. See Table 1.

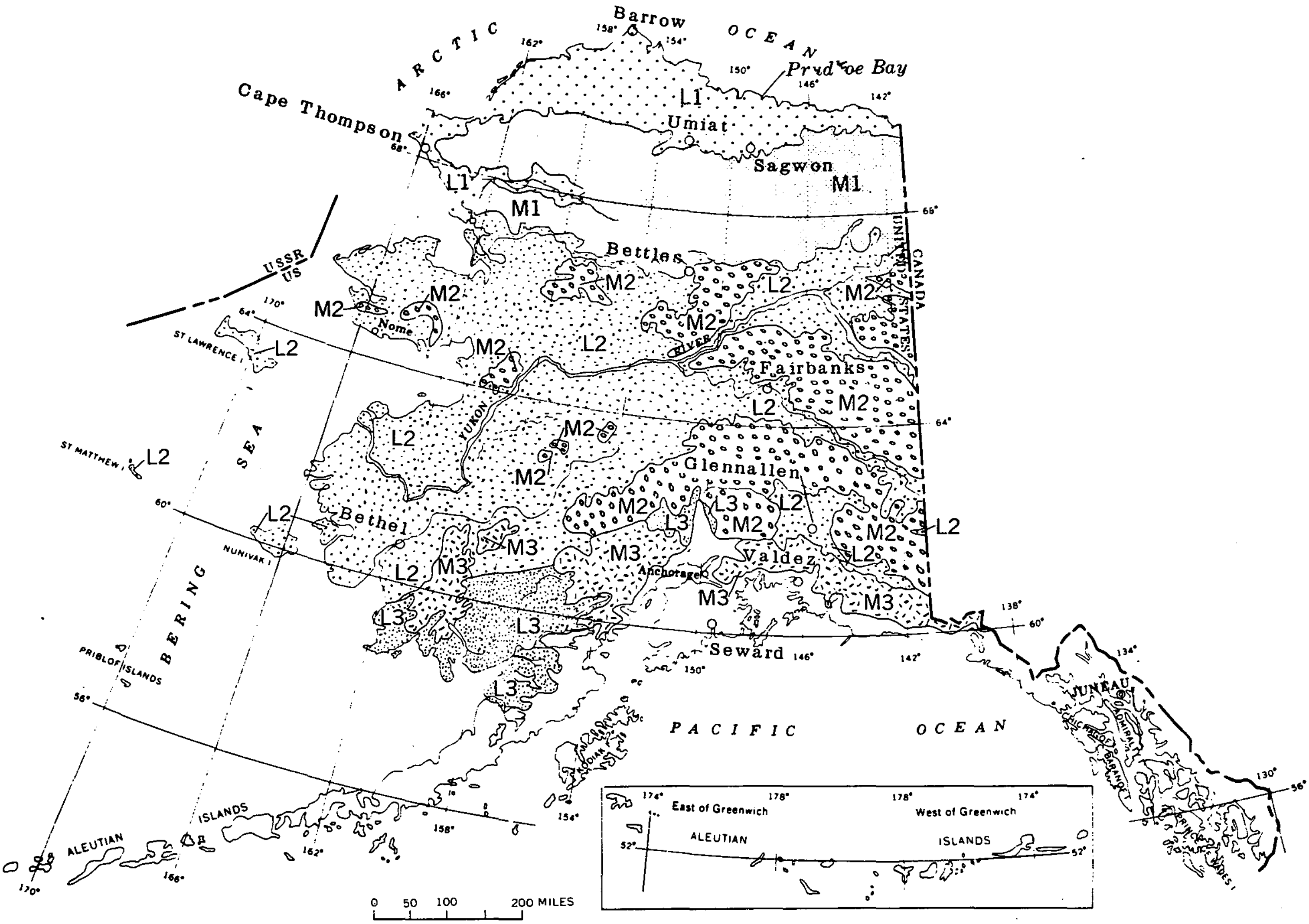
Table 1.—*Parameters used in the thermal calculations*

[Parameters: Thermal conductivity, volumetric specific heat, moisture content, and wet density are independently chosen parameters; the others are derived]

Parameter	Silt (17 1/2 percent)		Clay (65 percent)		Water/ice	
	Frozen	Thawed	Frozen	Thawed	Frozen	Thawed
Thermal conductivity (mcal per cm sec °C)-----	5.0	3.4	4.0	2.5	5.4	1.2
Volumetric specific heat (cal per cm³ °C)---------	.42	.57	.52	.83	.45	1.00
Thermal diffusivity (cm² per sec)------------	.012	.006	.008	.003	.012	.0012
Latent heat per unit volume (cal per cm³)-----	21.6		50.4		72	
Moisture content (percent wet weight)--------------	15		39.5		100	
Moisture content (percent dry weight)--------------	17.5		65		∞	
Moisture content (percent by volume)---------------	28.5		63		100	
Wet density (gm per cm³)---	1.8	1.8	1.6	1.6	.9	1.0
Wet density (lb per cu ft)----------------------	112	112	100	100	56.2	62.4

(Ref. 8)

"In many respects, the natural temperature regime of permafrost differs little from that of other earth materials, and if no water or ice were present, the only significant difference would be the position on the temperature scale. Owing to generally poor drainage and low evaporation, however, water is usually abundant in permafrost areas, and the superfreezing summer surface temperatures introduce large quantities of latent heat of fusion into the thermal budget of the terrain. This process results in some of the peculiarities of permafrost temperatures..." (Ref. 3)



EXPLANATION

AREAS WITHIN PERMAFROST REGION

Mountainous areas, generally underlain by bedrock at or near the surface

M1 — Underlain by continuous permafrost

M2 — Underlain by discontinuous permafrost

M3 — Underlain by isolated masses of permafrost

Lowland areas, generally underlain by thick unconsolidated deposits

L1 — Underlain by thick permafrost in areas of either fine-grained or coarse-grained deposits

L2 — Underlain by moderately thick to thin permafrost in areas of fine-grained deposits, and by discontinuous or isolated masses of permafrost in areas of coarse-grained deposits

L3 — Underlain by isolated masses of permafrost in areas of fine-grained deposits, and generally free of permafrost in areas of coarse-grained deposits

AREAS OUTSIDE OF PERMAFROST REGION

Generally free of permafrost, but a few small isolated masses of permafrost occur at high altitudes, and in lowland areas where ground insulation is high and ground insolation is low, especially near the border of the permafrost region

FIGURE 2.—Distribution of permafrost in Alaska. Modified after Ferrians (1965). (Ref. 1)

"In Alaska (Fig. 1), the two broad permafrost zones can be subdivided into: (1) mountainous areas where bedrock generally is at or near the surface, and (2) lowland areas commonly underlain by thick unconsolidated deposits. The thickness, distribution, and temperature of permafrost are extremely variable in the mountainous areas; in the lowland areas these characteristics are more uniform.

"From north to south, the mountainous areas can be further subdivided into areas underlain by continuous permafrost, areas underlain by discontinuous permafrost, and areas underlain by isolated masses of permafrost.

"The lowland portion can also be subdivided into (a) a northern area (largely north of the Brooks Range) which is underlain by thick permafrost; (b) a central area (between the Brooks and Alaska Ranges but including the Copper River Basin), which is underlain by moderately thick to thin permafrost in areas of fine-grained deposits and by discontinuous or isolated masses of permafrost in areas of coarse-grained deposits; and (c) a southern area (including the Bristol Bay area and the eastern and western margin of the Susitna Lowland north of Anchorage), which is underlain by numerous isolated masses of permafrost in areas of fine-grained deposits, and which generally is free of permafrost in areas of coarse-grained deposits." (Ref. 1)

The subdivisions of the lowland portion may also be characterized by their mean annual temperatures, i.e. the temperatures of the permafrost as dependant upon the mean annual surface temperatures. See Table 2.

Table 2.-Mean annual temperature data from representative stations in Alaska

(Data from U.S. Weather Bureau records)

Station	Mean annual temperature (° F.)
	Continuous permafrost zone
Barrow	10
Umiat	10
	Discontinuous permafrost zone
Bettles	22
Nome	26
Fairbanks	26
Glennallen (Gulkana)	27
Bethel	30
	No permafrost
Anchorage	35
Valdez	36
Seward	40
Juneau	41

(Ref. 1)

In the northern (a) or Arctic zone, the mean annual permafrost temperature is -8.9° C (average); in the central (b) or Interior zone, the mean annual permafrost temperature is -0.8° C; in the southern (c) zone, the mean annual permafrost temperature is very near 0° C.

"An active climatic change that has been in progress throughout the past century has increased the mean annual ground-surface temperature on the order of 2° C." (Ref. 4)

Figure 2 illustrates the results of this warming trend.

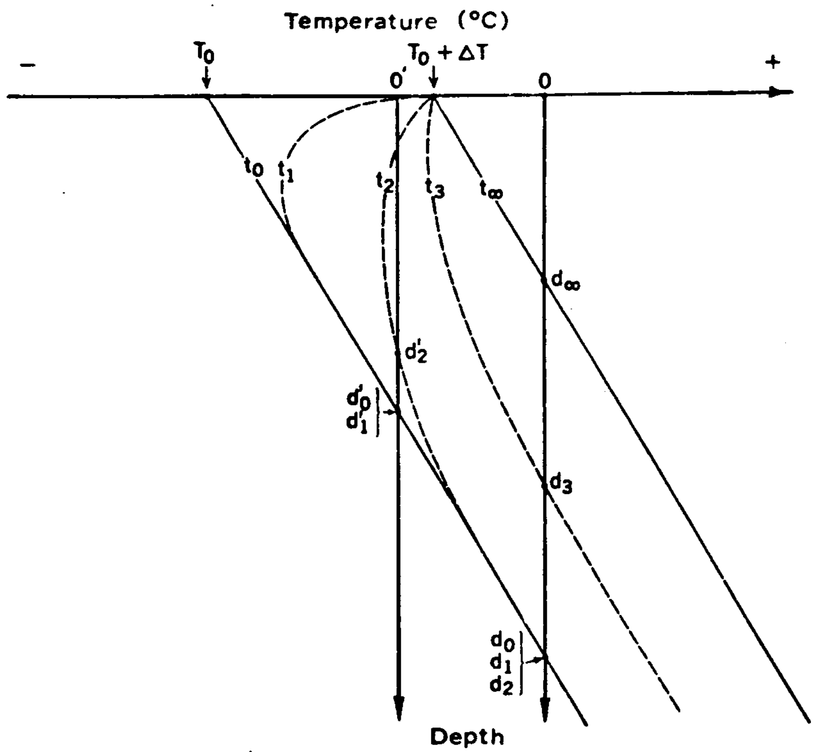


FIG. 2. Ground temperature at successive times ($t_0, t_1 \ldots t_\infty$) after an increase in mean ground surface temperature from T_0 to $T_0+\Delta T$. If the final temperature is below 0°C (the case in which 0°C lies at point O), the base of permafrost rises successively from d_0 to d_∞. If the final temperature is above 0°C (i.e., 0°C lies at point O′) the permafrost degrades first from the top (curve t_1) then from both top and bottom (curve t_2) and finally vanishes (curves t_3 and t_∞).

(Ref. 2)

"Present conditions are like those illustrated by curve t_2 with 0° C at point O. Similarly, near its southern boundary, permafrost sometimes extends to 200 or 300 feet beneath surfaces whose mean temperature today is very close to 0° C. Such permafrost is a relic, and the geothermal gradient within it is practically zero (curve t_2 with 0° C at point O'). Permafrost may be absent nearby where the material has a lower moisture content and hence responds more rapidly to changing surface temperature (curve t_3 with 0^{o} C at point 0')." (Ref. 2)

"Construction and maintenance of structures underlain by permafrost pose a wide range of problems. Engineers, designers, and construction and maintenance personnel are continuously plagued by severe frost heaving of structures, subsidence due to melting ground ice, soil creep or solifluction, landslides, and icings related to the presence of permafrost.

"The construction of pipelines in an arctic environment is, at best, a major undertaking. If the pipeline is placed underground, the vegetation cover overlying the permafrost is destroyed, disrupting the thermal regime. This disruption can cause differential settlement of the pipeline, and since it is underground, the settlement may not be noticed until the pipeline has been ruptured." (Ref. 1)

ICE-WEDGE POLYGONS

Consideration of problems associated with building and maintaining a gravel pipeline road in Alaska was strongly influenced by information published on the phenomena known as ice-wedge polygons.

"Thermal contraction of ice-cemented permafrost in winter often generates tensile stresses that exceed the strength of the material. The resulting tension cracks divide the surface into roughly equidimensional blocks, on the order of 30-300 feet across, that resemble the smaller patterns seen in drying mud. Summer meltwater draining into the cracks freezes to form veins of ice. The repetition of this annual cycle over centuries results in the growth of wedge-shaped masses of ice, sometimes tens of feet deep, and many feet wide at the top. The resulting ice-wedge polygons form striking patterns over thousands of square miles of polar terrain, and their growth and deterioration have far-reaching geomorphic and ecologic effects." (Ref. 2)

The speed of propagation of the tension cracks may be qualitatively deduced from a discussion of the stability of propagation: "It is known from the sounds and earth tremors associated with ice-wedge cracks that they propagate unstably." (Ref. 5)

Ice-wedge polygons occur both in the Arctic and the Interior zones of Alaska. See Figures 3, 4, and 5.

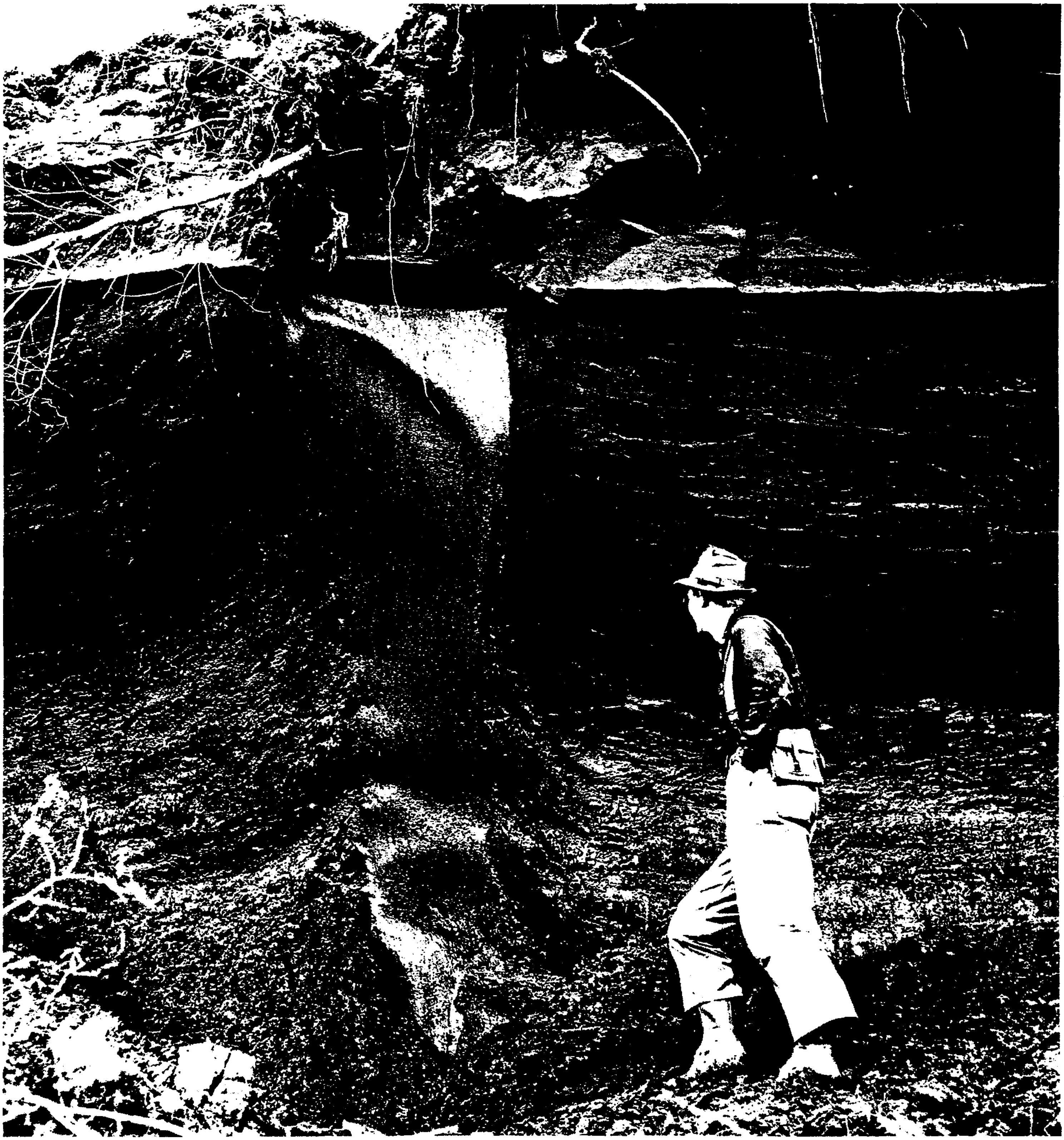


FIGURE 3.—Ice wedge (ground ice) in permafrost exposed by placer mining near Livengood about 50 miles northwest of Fairbanks. Photograph by T. L. Péwé, September 1949. (Ref. 1)

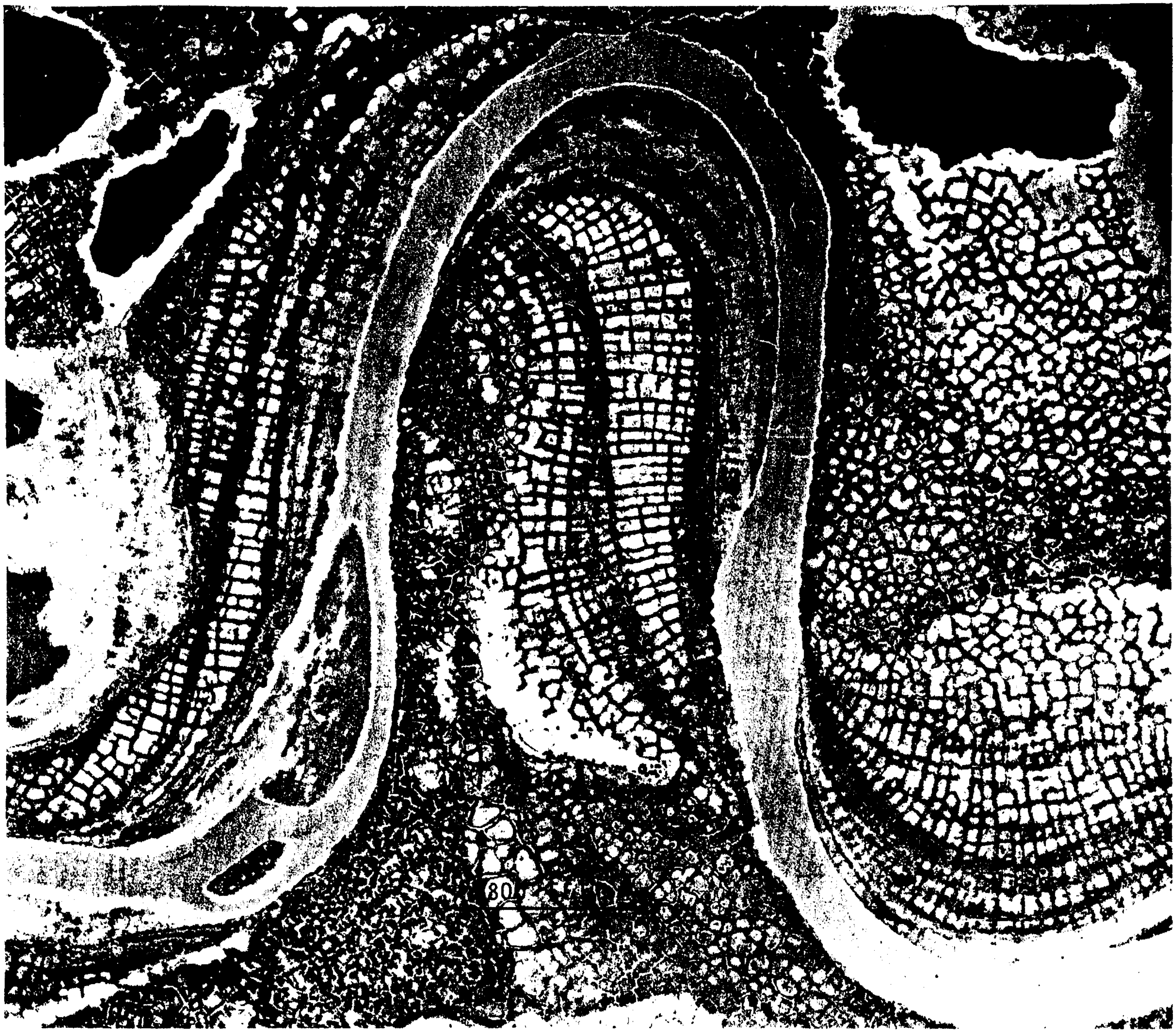


FIGURE 4.—Polygonal markings on ground surface (caused by ice-wedge polygons) in the vicinity of Meade River, about 35 miles southeast of Barrow, in northern Alaska. Photograph by U.S. Navy, July 1949. (Ref. 1)

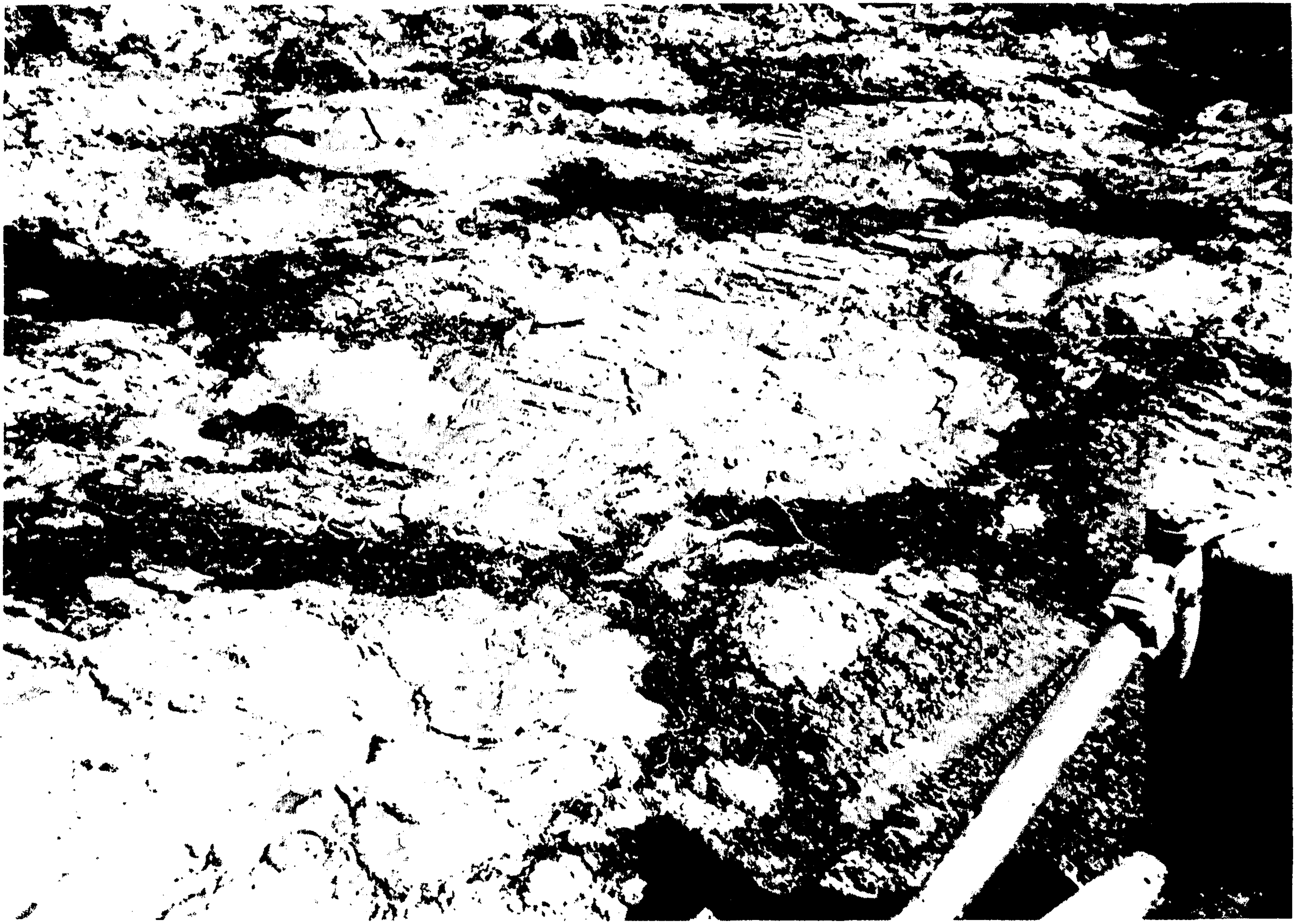


FIGURE 5.—Initial location of part of the Denali Highway near the Susitna River, interior Alaska. Construction crew is removing the insulating vegetation to expose polygonal ground in permafrost. Sediments are windblown sand and silt overlying silty glacial till. The dark areas outlining the polygons overlie ice wedges as much as 12 inches wide. Photograph taken in July 1953.

To examine the potential problems of a pipeline buried in a zone of active ice-wedges, certain assumptions were necessary.

(1) The pipe was considered to be 42" in diameter with a wall thickness of 1", made of steel with a tensile strength of 60,000 PSI;

(2) The pipe was assumed to cross an ice-wedge at right angles;

(3) The ice-wedge was considered to be 10 to 20 feet deep into the permafrost with a horizontal length of 30-200 feet;

(4) It was assumed that the pipe would become frozen into the ground sediments surrounding it. This assumes an adfreeze of moisture laden soil to the pipe surface. If the pipe were bare, i.e. without a surface coating, this adfreeze should produce a shear strength in the order of $.43 \times 10^6$ PSI; however, pipe coating could reduce this shear strength by some order or magnitude depending upon its characteristics, an unknown factor. In no case, however, would it be lower than the tensile strength of the sediment which the pipe displaces, and this conservative figure was assumed.

The tensile strengths of ice, frozen peats and mineral soils range from 75 to 300 PSI, with strengths as high as 470 PSI reported. (Ref. 6) The pipe cross section is 1385 square inches; therefore,

$$1385 \times 75 \text{ PSI} = 103{,}875 \text{ pounds} \quad \text{up to}$$
$$1385 \times 300 \text{ PSI} = 415{,}500 \text{ pounds.}$$

The 42" diameter, 1" thick pipe has an area of 129 square inches of steel and a tensile strength of 60,000 PSI; therefore, $129 \times 60{,}000 \text{ PSI} = 7.7 \times 10^6$ pounds.

It would appear from these figures that the pipe is capable of withstanding the tension stresses which produced the recurrent crack in the existing ice-wedge; however, there are several negative modifying factors which were not introduced into these calculations, either because no data was available or because the order of complexity was too great.

(1) Rate of stress application;
(2) Lowered temperature of the steel (embrittlement);
(3) Corrosion fatigue;
(4) Stresses other than tension.

Since no quantitative data was available to indicate the significance of these factors, no definitive conclusions could be drawn for a 90° crossing of an ice-wedge.

In some areas, the number of ice-wedges range from 17 to 176 per mile. It seemed reasonable to assume that more often than not a pipe would have to cross wedges at angles other than 90°.

Assuming the same parameters as before, except

(1) an angle of crossing of 45°, and
(2) a crack width of .25 inches, which is well within the crack width limits of .1 to .4 inches (A.H. Lachenbruch, Personal Comm. 1973);

a shear force will develop on the pipe proportional to the compressive strength of the sediment on each side of the crack and the displacement caused by the crack. See Figure 6.

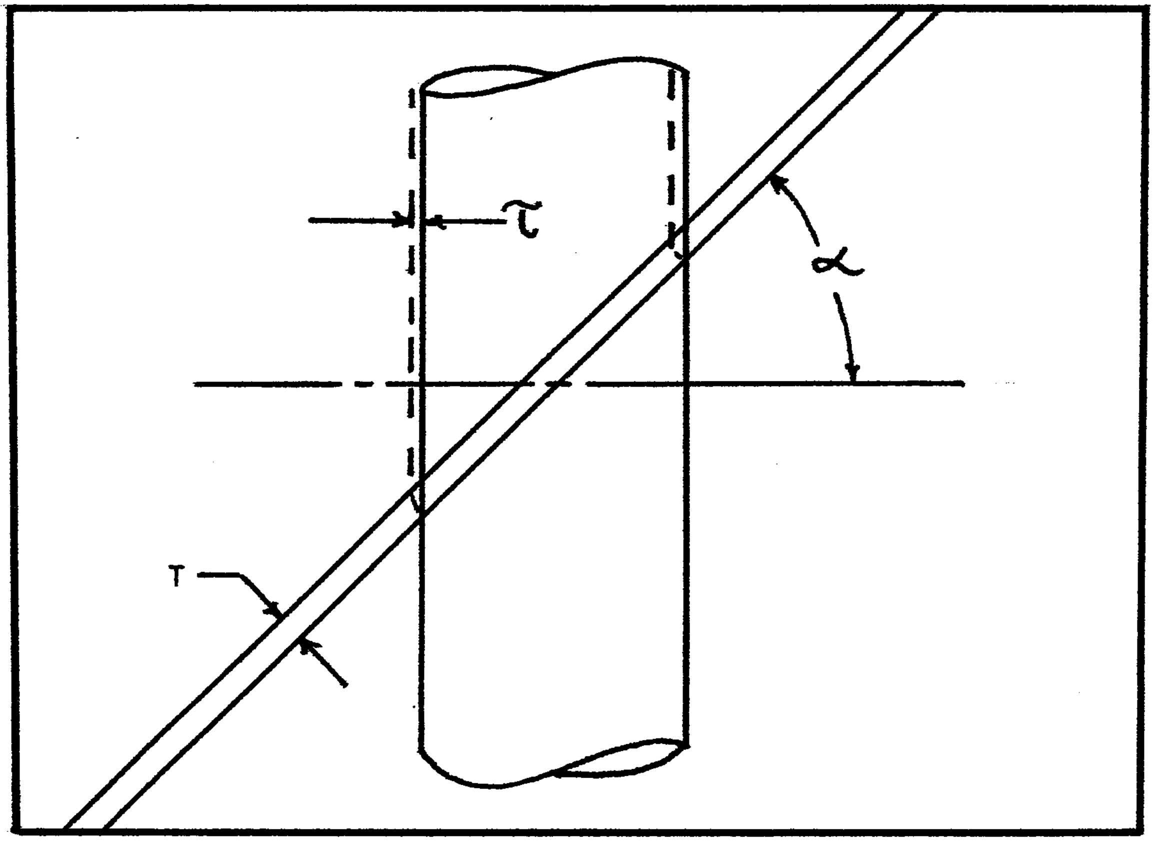


Figure 6. (No scale)

Assuming the shear force applied against half the circumference of the pipe for a distance of 1 foot beyond the crack, or 792 square inches, and given the compressive strength of ice (ice laden sediment) of 1.5×10^6 (Handbook of Fluid Mechanics), then

$$792 \times (1.5 \times 10^6) = 1.2 \times 10^9 \text{ pounds}$$

Given a shear modulus of 1.2×10^7 for high grade steel and a cross sectional area of 182 square inches (at 45^o), then

$$182 \times (1.2 \times 10^7) = 2.2 \times 10^9 \text{ pounds}$$

Displacement being a simple function of crack width and angle : $\tau = T \sin \alpha$, then

$$.25 \times .707 = .18 \text{ inches.}$$

Since the shear forces are in the same order of magnitude as the shear strength of the pipe, while the displacement is only .18 inches, we concluded that the pipe might not break, but would certainly deform. These forces, repeated annually, would eventually produce progressive failure.

The same modifying factors discussed for the 90^{o} case could in this instance reduce the number of cycles needed to fail the pipe or cause failure at the first occurence.

Again, no quantitative data was available, but the results of these calculations indicated the conservative limits of a potentially severe problem.

PIPE FREEZE-IN

The foregoing problems were recognized at the time work was being done on the oil pipeline and later appeared to be as directly applicable to an operational gas pipeline as to a pre-operational oil line. We did not know to what degree, if any, these problems forced Alyeska above ground, since the 80° C temperature of their line was such an overriding consideration; therefore, we examined the construction phase of a cold line in more detail. As a result we realized that a problem of considerable magnitude existed.

Burial of pipe in dry permafrost in mountainous areas presents relatively few major construction problems beyond those encountered in temperate zones; therefore this report does not deal with them.

Construction in areas of wet permafrost (Arctic and Interior zones) will have to be performed in winter to prevent damage to the unsupported tundra. A trench will be dug through the frozen active layer into the permafrost, the pipe laid on a bed of gravel and the trench filled with earth and gravel.

Trench fill will generally be of coarser-grained material than the permafrost surrounding the trench and therefore have a lower moisture content. This fill can be considered as almost dry permafrost.

When the active layer thaws the following summer, water will migrate through the active layer and drain into the pipe trench. This will occur for two reasons: (1) the coarse-grained fill material is relatively dry and the voids will readily accept the flowing water where the adjacent permafrost will not; (2) the lower moisture content of the fill will permit more rapid thawing to a greater depth than the adjacent saturated permafrost and ice particles present in the fill will melt, producing more voids throughout the sediment.

The amount of water present in the active layer, the surrounding air, ground and permafrost temperatures, topography, etc. will produce variable results within the pipe trench. We could not begin to research all of these combinations of results; however, it was possible to examine one such combination in light of the data we had, i.e. a heavy flow of water through the active layer and/or a low point in the surrounding topography will permit saturation of the trench fill.

The effects of periodic freezing and thawing in the active layer is illustrated somewhat schematically for a typical wet active layer in Figure 7. The action of this annual temperature wave is described by Dr. Lachenbruch, et al, as follows:

"When spring temperatures rise to the freezing point (Fig. 7 at time $t = t_1$), thawing of the active layer commences. Thawing has generally proceeded to the top of permafrost by the time t_3 when autumn temperatures drop below freezing at the surface. Between the time t_3 and t_5, the active layer is freezing largely from the surface downward, and the surface temperature drops sharply from 0° C to some low value θ' , characteristic of early winter. The heat

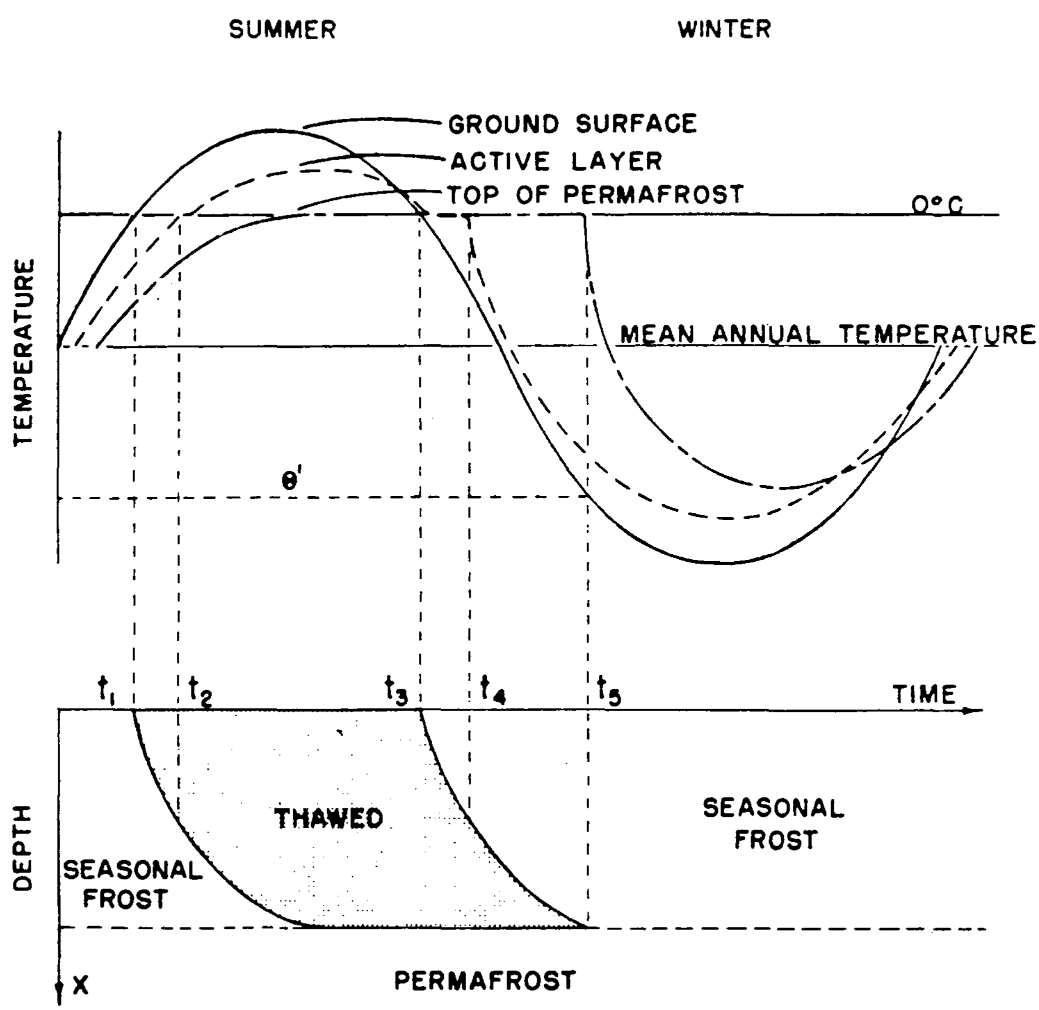


Fig. 7.-Passage of the annual temperature wave through a wet active layer. (Ref. 3)

being removed from the ground during this period is supplied largely by the latent heat of freezing moisture in the active layer. The top of permafrost is in contact with the unfrozen base of the active layer, and hence remains at the freezing point until the time t_5 when the last bit of active layer is frozen. At this time a steep thermal gradient exists across the active layer, which is 0° C at its base and θ' at the surface. The supply of latent heat which formerly maintained this large gradient is depleted, and the permafrost is in thermal contact with the seasonal frost. Sensible heat is rapidly drawn from the top of permafrost under the large gradient to produce the rapid cooling illustrated, ($t > t_5$).

"Temperatures at the middle of the active layer also are illustrated in Figure 7. There, and throughout the unfrozen active layer, temperatures drop to the freezing point shortly after freezing commences in the fall ($t = t_3$), for between times t_3 and t_5, the unfrozen active layer is a thin slab bounded above and below by isothermal surfaces at 0^{o} C, and thermal gradients cannot persist long. The result is the "zero curtain" a period (t_3 to t_4) during which temperatures at a given depth in the active layer remain at the freezing point. It is terminated when the seasonal frost penetrates to the depth in question and rapid cooling ensues. Little or no zero curtain occurs when spring temperatures rise past the freezing point ($t \doteq t_2$), for at that time only one surface is held at the freezing point and large thermal gradients can exist both above and below it. The time required to freeze the lower half of the active layer is seen to be $t_5 - t_4$." (Ref. 3)

We have already defined the pipe as a 42" diameter pipe having a wall thickness of 1" and made of steel with a strength in the order of 60,000 PSI. Collapse pressure can be computed from these data.

The first method uses a common graphical solution given by Edgerton and yields a value of 700 PSI collapse pressure.

The second method uses a simple formula from Marks Engineering Handbook (1968) where collapse pressure is defined as

$$KE\ (\frac{T}{D})^3\ PSI$$

where K = a constant between 90 and 2.2 dependant on the length to diameter ratio. 2.2 is the minimum value for a long pipe and is the value used here.

D = Outside diameter
E = Young's Modulus in PSI
T = Wall thickness

Given: D = 42"
T = 1"
E = 3.2×10^7 PSI approx.
K = 2.2

$$\text{Collapse pressure} = KE\ (\frac{T}{D})^3\ PSI$$

$$= (2.2)\ (3.2 \times 10^7)\ (12.1 \times 10^{-6})$$

$$= 84.8 \times 10^1 \text{ or } 848\ PSI$$

which is in good agreement with the 700 PSI from the Edgerton graph.

Using the larger value (848 PSI) and further assuming that the pipe will be pressurized during the construction period of the pipeline to 800 PSI, a collapse pressure of 1648 PSI is obtained.

Having defined the water conditions and the resultant saturation of the trench fill during the summer thaw, we examined winter freeze conditions at an Arctic zone site in which the defined water conditions are known to be prevalent. (Ref. 1) Figure 8 represents annual variations of air and ground temperatures at Barrow, Alaska.

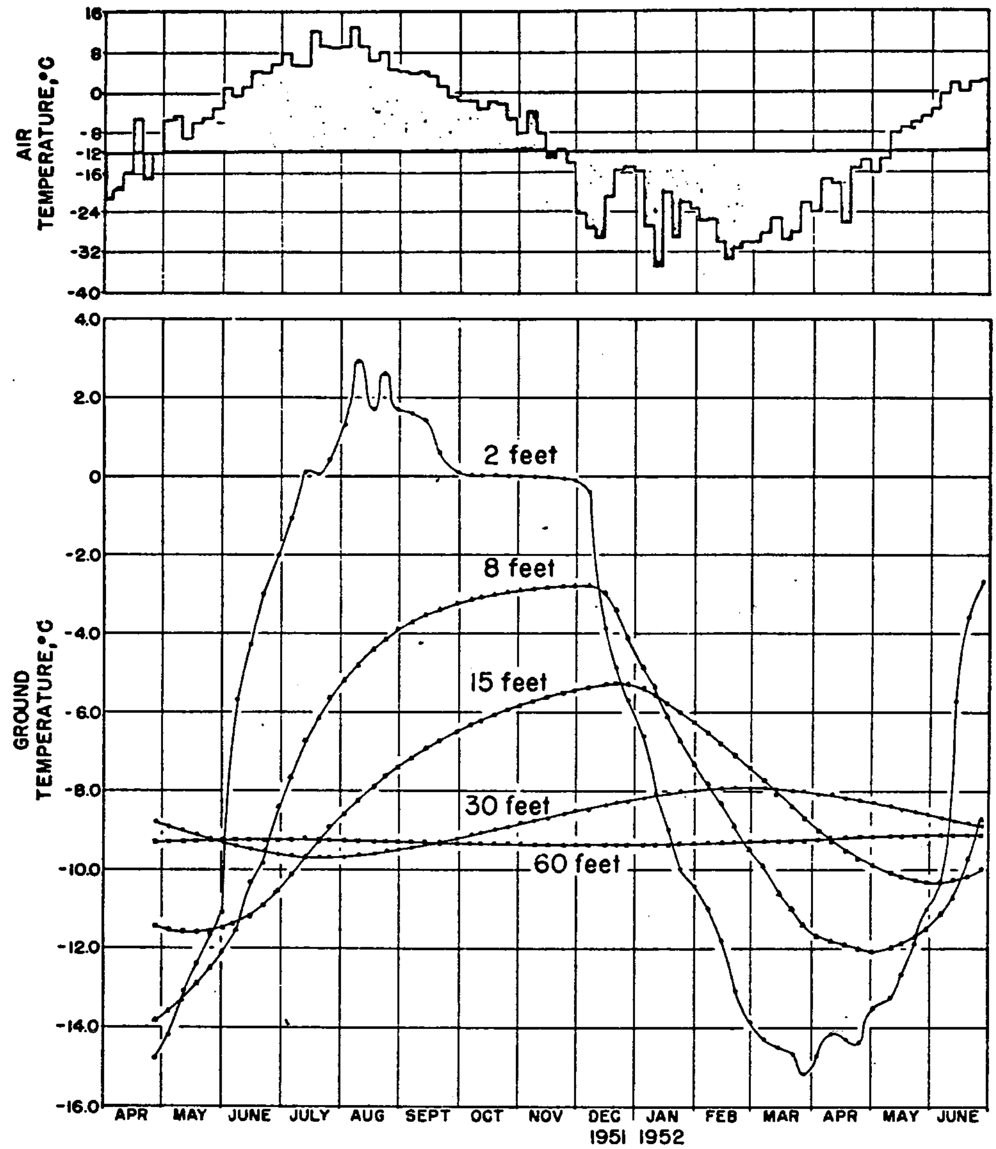


FIG. 6. Typical temperatures in the zone of annual temperature variation at high latitudes (Barrow, Alaska). Air temperatures averaged over 5-day intervals are shown for comparison.

(Ref. 3)

At approximately October 1, air temperature drops below 0° C and ground temperature at 2 feet (in the active layer) drops to 0° C. The ground temperature at 8 feet in the underlying permafrost is at nearly -3° C and rising.

Over the two month period (October through November) the temperature at the 2 foot level remains at 0° C. while the corresponding air temperature shows a drop to -24° C. As noted by Lachenbruch, et al, freezing of the active layer is progressing downward during these two months, but the zero curtain is preventing heat loss from the underlying permafrost, as is evident from the graph which shows the temperature at the 8 foot level still rising slightly during this period. At the first week in December, the last portion of the active layer becomes solidly frozen.

Within the trench itself, the drier fill material (approximately 10-25% moisture content at saturation) will freeze downward from the surface more rapidly than the wetter active layer; hoever, even disregarding this phenomenon, it can be seen that because the temperature at the 8 foot depth has up to now continued to rise, heat loss from the lower portion of the pipe trench to the adjacent permafrost has been less than the heat loss to the surface. Freezing within the trench has therefore been primarily downward, and when the active layer completes its freezing and makes thermal contact with the top of the permafrost, an ice cap will have been formed over the pipe trench.

At this point, the temperature at both the 2 foot and the 8 foot levels drop sharply, presenting a dramatically increased ΔT between the still unfrozen fill material in the trench and the surrounding material on all sides. This steep thermal gradient will produce rapid freezing of the remaining trench fill.

The increase in the volume of water upon freezing is approximately 10% and the pressure generated by this expansion in a confined area is acknowledged to be of enormous magnitude.

With the rapid freezing of the trench fill beneath a 2 foot ice cap, the pressure of the expanding ice will have to be relieved. The strength of the ice cap must therefore be calculated.

The tensile strength of ice rich soils varies widely, depending upon its temperature, rate of stress, etc., but as noted before it is generally between 75 and 300 PSI. The shear strength of ice is in the order of .43 X 10^6 PSI for rapid stress and is several orders of magnitude greater than the tensile strength; therefore, we used the weaker tensile strength for these calculations.

As a general rule, when pressures are exerted on a flat surface (such as the ice cap), the structure will fail by parting on either one side or both depending on the rate of stress. A common break is at 45^o. See Figure 9, below.

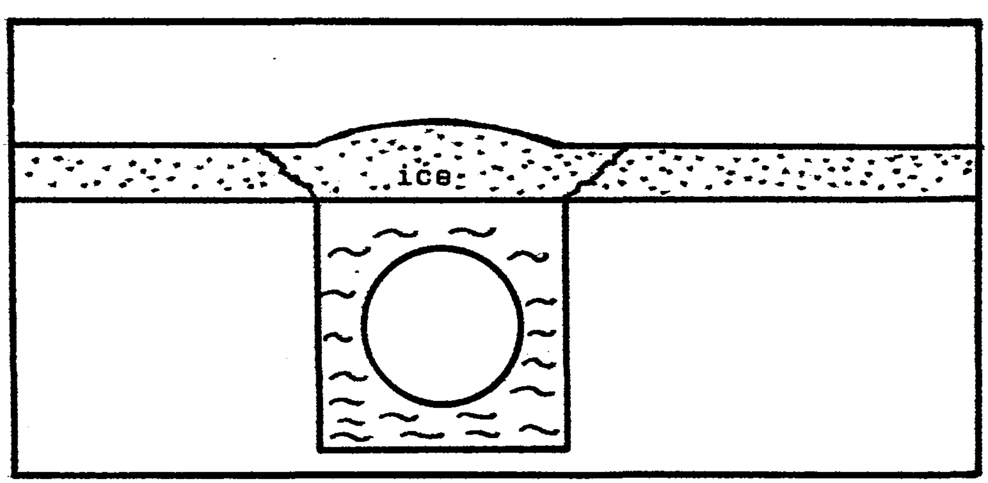


Figure 9. No scale

Therefore, given the tensile strength of the weakest sediment = 75 PSI, a 2 foot thick ice cap, and a 45° break, the length of the broken surface is

$$L = \frac{h}{\sin} = \frac{2'}{.7} = 2.8 \times 75 \text{ PSI} = 2520 \text{ PSI}$$

We concluded that in this site example or in any area where the active layer is 2 feet or greater and is in thermal contact with the top of the underlying permafrost, the pressure generated by freezing of the water in the trench fill will be relieved through deformation of the pipe.

It appeared that this result might be obviated by wrapping the pipe in a layer of crushable material of an appropriate thickness. In the Arctic zone where ground temperatures are low, the frozen saturated trench fill may not thaw to the depth of the pipe in the summer, despite the relatively greater conductivity of heat through the drier (although saturated) fill; however, in the Interior zone, where the mean average ground temperatures are near 0° C, the probability that the trench fill will thaw in the summer is relatively high. Water will then be able to drain from the active layer into the void left by the crushed portion of the protective material. Depending upon the amount of this material used, either the next freeze cycle or subsequent freeze-thaw cycles will deplete its crush volume and the resulting condition will be the same as for an unprotected pipe in the first winter following construction.

In considering a gas pipeline, we assumed that the pipe would be cold in operation, i.e. at or below 0° C at all times. Subsequent discussions indicated that, although the gas is normally cooled before entering the pipe, it is not as a rule refrigerated. In the Alaskan winter, cooling the gas with ambient air will readily maintain a below freezing temperature in the pipe. In summer, however, gas cooled by any means other than refrigeration will enter the pipe above 0° C, while the permafrost in which the pipe is buried will be below 0° C.

Even a 2° C increment of heat above the surrounding permafrost will have an effect on the thermal regime. Since Dr. Lachenbruch's discussion of a heated pipe (Ref. 8) dealt primarily with an 80° C pipe, it was not possible to evaluate quantitatively the exact dimensions of this effect; however, from the foregoing analysis of the freeze-thaw cycle in heavily moisture laden permafrost it can be seen that one undeniable effect of this heating will be to assist the rethawing of the trench fill in summer. This can only increase the probability of pipe deformation or crushing from ice expansion forces.

Burial of the pipe in the southern zone will in many places present a different problem. In areas of relic permafrost, the seasonal frost layer may extend quite deep and frost heaving can be experienced to a depth of from 6 to 8 feet, depending on the moisture content (A.H. Lachenbruch, Personal Comm., 1973). A pipe buried in such areas would be subjected to phenomena discussed under general problems.

SUMMARY

The original and primary purpose of the study formalized by this report was to determine whether a buried natural gas pipeline could survive the environmental stresses of wet permafrost in Alaska. Qualitative analysis of our prior investigations indicated some general problems, but specific quantitative data was needed.

It was obvious that only a simplified study of a very complex set of problems could be attempted. Therefore, prarmeters were selected on a highly conservative basis: i.e. site conditions which we knew to be prevalent along the pipeline route, the weakest natural stresses acting upon the pipe, and above all the assumption of a perfect pipe - without welds, flaws, or quality control problems. Factors requiring a high level of complex mathematical computation were discarded when preliminary investigation showed them to be negative modifiers which could only magnify the problems.

Two major problems were identified. In the case of the ice-wedge polygons, calculations on the 45° crossing showed the simple stresses to be in the same order of magnitude as the strength of the pipe. In the case of pipe freeze-in, calculations showed the pipe strength to be less than the natural stresses acting upon it.

This level of study precluded any statistical prediction that a cold pipe would be damaged or broken 5 or 50 times, once every 5 miles or 5 times a mile.

It did serve to convince us that, given the widely variable, highly inconsistent nature of permafrost and its associated phenomena, the actual problems would turn out to be of even greater magnitude than our calculations indicated.

We concluded that an above ground pipeline, despite its drawbacks, would have a better chance for survival and be more reliable than an underground pipeline in areas of wet permafrost.

A D D E N D A

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A D D E N D A

Introduction

On February 27, 1973, K. J. Anderson and Associates met in Juneau with Dr. Max Brewer, formerly Director of the U.S. Navy Arctic Research Laboratory at Pt. Barrow, Alaska, and presently Commissioner of Environmental Conservation for the state of Alaska. Dr. Brewer is one of the few acknowledged experts in this country on arctic geology and permafrost. (See Ref. 3)

Our purpose was primarily to submit our report to him for evaluation of our findings. In a four-hour interview, Dr. Brewer confirmed our conclusions, as had Dr. Arthur H. Lachenbruch of the U.S. Geological Survey at Menlo Park. Both of these scientists agreed that our report was conservative and that the problems discussed would be of greater magnitude in fact than had been shown in theory.

Dr. Brewer was further able to add valuable information to that we had already used. This addenda is intended to present some of this information insofar as it bears on this report.

I Pipe Freeze-in: Additional Information

On page 19, paragraph 2, our report states:

> "The amount of water present in the active layer, the surrounding air, ground, and permafrost temperatures, topography, etc. will produce variable results within the pipe trench. We could not begin to research all of these combinations of results..."

We were aware that numerous test installations had been made in Alaska for pipeline research, but neither test conditions nor test results were available for inclusion in our report.

Dr. Brewer commented on one such installation. The location was Point Barrow and the test terrain, like almost all of these arctic test installations, was completely flat. Actual amounts of water and actual temperatures were not known, but Dr. Brewer confirmed an earlier report that Alyeska's test pipe had, in fact, been "crimped" by ice action during this test.

II Cold Pipe Buried in Relatively Dry Permafrost: A New Consideration

As mentioned, almost all test installations were made in flat terrain, but none in hilly areas of relatively dry or well drained permafrost. It has always been assumed - and we accepted this assumption (p. 18, para. 2) - that dry or relatively dry permafrost offered adequately stable soil conditions to support burial of a pipe (even a hot oil pipe) and therefore presented no major problems.

Dr. Brewer, however, defined a problem relating to these hilly areas as follows:

The pipe is installed in a gravel-filled trench in a hilly, relatively dry area of permafrost. During the first summer after pipe installation, snow melt and rainwater will flow into and along the trench. The amounts of water involved in this condition are much smaller than those discussed in the case of wet permafrost.

With the following winter freeze, a cap will be frozen over the trench on the top of each hill and down into the interjacent depression or gully. Because the active layer at the top of the hill is drier than at the bottom, the entire trench will freeze first on the hill tops. This total trench freeze will progress down both slopes toward the increasingly wetter trench soil (and permafrost) in the gully.

The force of this freeze will drive the free water in the trench downhill <u>under</u> the already formed ice cap, causing an increasing hydrostatic pressure in the unfrozen trench toward the bottom of the gully.

One of two final results will occur:

a) The pipe at the bottom of the gully will be crushed for the distance required both to relieve the built-up hydrostatic pressure and to accomodate the expansion, from freezing, of the water collected in the low point of the trench; OR

b) The frozen trench cap will break, forming a man-made pingo in the gully which will upthrust the water, the trench fill and the pipe.

Dr. Brewer stated that he had brought this problem to Alyeska's attention, but that to his knowledge no studies or tests have been performed to define the problem quantitatively.

Dr. Brewer was not concerned with environmental impact since the damage will occur before the oil pipeline becomes operational and will have to be repaired before any oil can flow. He believed the major impact to be economic.

This is primarily a construction problem. Once an oil line is operational the heat of the oil will preclude its recurrence. In the case of a gas line, recurrence during operation will depend upon gas temperatures. If the pipeline carries ambient gas, the problem will be repeated annually because of the depth of thaw in the relatively dry permafrost. If the gas is refrigerated to below 0° C, the problem would not recur.