GEOLOGICAL SURVEY CIRCULAR 632

Some Estimates of the Thermal Effects of a Heated Pipeline in Permafrost

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By Arthur H. Lachenbruch

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FOREWORD

One of the greatest mineral resource discoveries in the history of man is a colossal petroleum resource near Prudhoe Bay on the Arctic Slope of Alaska. Today, industry and government are engaged in an important dialogue as to how this resource may be developed and transported to market, and in what time frame, in the best interests of the Nation. The petroleum industry, by its own initiative, determined that a 800-mile pipeline, four feet in diameter, should be constructed reaching from Prudhoe Bay across all of Alaska to the ice-free south coast port of Valdez.

Since the early years of this century, geologists and geophysicists of the U.S. Geological Survey have been investigating permafrost in Alaska. During the past six months, a concentrated effort has been made by our scientific and technical personnel to evaluate conditions of the terrain, in response to industry's request for a permit for a right-of-way and permit to construct the pipeline across Federal domain.

A year or so ago the concept of the pipeline was being considered in terms of cold oil being transported. Subsequently, however, the Trans Alaska Pipeline System (TAPS) announced that a throughput of oil at a maximum capacity in the order of two million barrels per day, requiring several pumping stations, would result in maintaining a high temperature of the oil from the point of entry on the North Slope to its delivery point at Valdez. Estimates of the temperature of the flowing oil range between 150°F. to 180°F.

To bury a hot pipeline in hard rock or in coarse rocky terrain does not cause concern because the foundation is firm enough to support the pipeline without danger of disturbing it. But to bury a hot pipeline in permafrost ground composed of unconsolidated sediments with relatively high ice content could give us grave concern, not because of the melting by itself, but because of the consequences of the melting if safeguards were not designed into the engineering system.

We have made detailed studies over the past few months in critical areas and have evaluated the possible effects through utilization of a computer program. We believe that rapid thawing of the permafrost in critical areas could have most significant effects on the local environment and upon the security of the pipeline itself. It is important, therefore, that these effects be anticipated and predicted as accurately as possible so that the problems can be accommodated by proper engineering design above or below ground or by selection of alternative routes.

It is with these concerns in mind that the results of our preliminary studies are being made available at this time. This report presents an evaluation of the potential problems and effects of a buried hot oil pipeline in critical soil areas of the arctic and sub-arctic environment.

W. T. Pecora

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Director, U.S. Geological Survey

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Abstract

As one means of transporting crude oil from oil fields on the Alaskan Arctic coast to a year-round ice-free port, a large pipeline traversing most of the state of Alaska from north to south has been proposed. Plans call for a pipe 4 feet in diameter, which will be buried along most of the route in permafrost. According to preliminary estimates. the initial heat in the oil plus frictional heating in the pipe are expected to maintain oil temperatures in the neighborhood of 70° to 80°C (158° to 176°F) along the route when full production is achieved. Such an installation would thaw the surrounding permafrost. Where the ice content of permafrost is not high, and other conditions are favorable, thawing by the buried pipe might cause no special problems. Under adverse local conditions, however, this thawing could have significant effects on the environment, and possibly upon the security of the pipeline. It is important that any potential problem be identified prior to its occurrence so that it can be accommodated by proper pipeline design. Identifying a problem in advance depends upon an understanding of the conditions under which the problem will occur. For that reason much of this report is concerned with problems. If the pipeline system is properly designed, and if it is constructed and maintained in compliance with the design, they will not occur. Perhaps "proper design" in some areas will involve abandoning plans for burial or changing the route; in others it might involve burying the pipe and invoking special engineering designs or monitoring procedures. These are matters to be determined by much additional study and an intensive program of field and laboratory measurements of conditions along the route.

In this report a few basic principles are applied to simplified models of permafrost regimes to identify some effects of a heated pipe, the conditions that control them, and the approximate ranges of physical properties for which these effects are likely to result in problems. The computations are approximate, and the problems discussed are only illustrative examples. Comprehensive discussions of these and related effects, taking account of physical and theoretical refinements, are beyond the scope of the report. Refined studies will probably be needed, however, to form an adequate basis for engineering design.

It is difficult to summarize these effects briefly, but a few will be mentioned. The reader is urged to consult the full text for a more complete statement of the conditions under which they are likely to occur. It should be emphasized that whether or not such conditions exist is a matter yet to be determined by measurements on permafrost materials along the pipeline route. Such measurements are essential for predictions of the interaction between the pipeline and its environment.

A 4-foot pipeline buried 6 feet in permafrost and heated to 80°C (176°F) will thaw a cylindrical region 20 to 30 feet in diameter in a few years in typical permafrost materials. At the end of the second decade of operation, typical thawing depths would be 40 to 50 feet near the southern limit of permafrost and 35 to 40 feet in northern Alaska where permafrost is colder. Except for special materials near the northern end, equilibrium conditions will not be reached and thawing will continue throughout the life of the pipeline, but at a progressively decreasing rate. If the thawed material or the water within it flows, these amounts of thawing can be increased several fold. If the pipeline temperature were only 30°C (instead of 80°C), the depth of thawing would probably be reduced by only 30 or 40 percent. The principal effect of insulating the pipe would be to increase oil temperatures rather than to decrease thawing.

If permafrost sediments have excess ice and a very low permeability when thawed, melting below the pipe could generate free water faster than it could filter to the surface. As a result the material in the thawed cylinder could persist as a semiliquid slurry. Where

permeabilities are very low and excess ice contents are moderate, thawing rates could be sufficient to maintain this state for decades.

If the strength of these slurries is less than 1 pound per square foot, they will flow with substantial velocities on such imperceptible slopes as are characteristic of "flat" basins. The entire thawed cylinder would tend to flow like a viscous river and seek a level. As an extreme example, if these slurries occured over distances of several miles on almost imperceptible slopes, the uphill end of the pipe could, in a few years, be lying at the bottom of a slumping trench tens of feet deep, while at the downhill end, millions of cubic feet of mud (containing the pipe) could be extruded out over the surface. Where the pipe settled to the bottom of the trench, it would accelerate thawing and flow, and the process could be self-perpetuating. The pipeline could be jeopardized by loss of support in the trench and by displacement in the mudflow, and the disruption to the landscape could be substantial. Where such extreme conditions might occur, these problems could normally be anticipated by observations prior to or during construction. Less extreme conditions leading to partial liquefaction might be more difficult to identify in advance.

Where the pipe passed from strong material into a liquefied region, it would tend to float or sink, depending on the density of the slurry. It could be severly stressed by the resulting forces.

Almost imperceptible systematic movements of the thawed material can accelerate the thawing process locally by as much as a thousand times. Hence if flow occurs the ultimate amount of thawing can be very great and difficult to predict.

Seismic vibrations can cause loosely packed saturated sands and silts to liquefy. Hence where such material occupied the thawed zone around the pipe, the flow, buoyancy, and convective effects just discussed could also be caused by an earthquake. The southern part of the pipeline route lies in an active seismic zone.

Differential settlement causing shearing stresses in a pipe can result from a variety of processes—the most conspicuous of which is probably the thawing of ice wedges. These massive vertical veins of ice form tight polygonal networks, commonly invisible from the surface and difficult to delineate with borings. They are widely distributed in northern Alaska. A pipeline crossing ice-wedge networks at random angles would thaw the wedges quickly and could thereby lose support over considerable spans. A statistical calculation suggests that in typical ice-wedge terrain, conditions which might exceed the design stress of the pipeline could occur on the average of once every mile. Most of these conditions could be anticipated by observations made during trenching.

Settlement of the pipe due to thawing is a cumulative effect of all of the thawed material beneath it. Only a negligibly small fraction of this material will be directly observed in separated bore holes. Rather small and subtle changes in porosities, moisture content, and other properties occurring over lateral distances of tens of feet could cause differential settlement resulting in excessive stress on the pipe. Such changes may be difficult or impossible to detect in advance by trenching and boring, even if holes were drilled every 1,000 feet along the route.

Where the sediments are saturated or oversaturated, a trench one or more feet deep and tens of feet wide will probably develop over the pipeline in a few years; it will deepen and widen somewhat as time progresses. Where the trench is discontinuous it could create a series of ponds which could enlarge by thermal processes under certain conditions. Indiscriminate drainage of these ponds could create excessive stress on the pipe by removing buoyant forces that might be partially supporting it in these differentially settled zones.

Where the trench above the pipeline is continuous, it could become a stream channel, altering drainage patterns and creating erosion problems along the pipeline.

Heat conducted from the pipe to the surface will have a significant effect on surface temperatures and plant-root temperatures over a band not more than about 60 feet wide. Directly over the pipe snow will probably remain on the ground only after the heavier storms.

The inflow of water into the depression likely to develop over the pipe will probably more than supply the heat requirements for excess evaporation, and in general conditions will probably remain wet. However, if the material overlying the pipe should be very permeable, thermal convection of water in the sediments could probably increase heat loss from the pipe to the surface one-hundred fold. Under these conditions evaporation would probably exceed the rate of local water supply and the region above the pipe could eventually become desiccated. Heat and moisture transfer above the pipe could have a significant effect on the formation of local ground fog.

This study was not exhaustive. Potential problems certainly exist that have not been considered, and some that have been considered may be shown not to exist by further studies. The report represents one perspective on an overall problem that transcends many disciplines and requires the perspectives of many for an optimal solution. It is hoped that the report will provide one reference point for objective discussion between the people of many backgrounds who must communicate effectively on this issue.

INTRODUCTION

As one means of transporting crude oil from oil fields on the Alaskan Arctic coast to a year-round ice-free port, a large pipeline traversing most of the state of Alaska from north to south has been proposed. Plans call for a pipe 4 feet in diameter, which will be buried along most of the route in permafrost. According to preliminary estimates the initial heat in the oil plus frictional heating in the pipe are expected to maintain oil temperatures in the neighborhood of 70° to 80°C (158° to 176°F) along the route when full production is achieved. Such an installation would thaw the surrounding permafrost. Under adverse local conditions this thawing could have significant effects on the environments, and possibly upon the security of the pipeline. Although adverse conditions may be present along only limited parts of the pipeline route, this report focuses on them and the problems they could create. It is important that these problems be anticipated as accurately as possible so that they may be avoided by appropriate engineering procedures or by the selection of alternative routes.

The logical starting point for the study of thermal effects of a hot pipeline buried in permafrost is an estimate of the amount of thawing that will take place at various times after installation for the range of climatic conditions, permafrost properties, and pipeline temperatures that might be anticipated along the route. At the time of this writing no such study had been made, and hence no scientifically valid estimates of the thawing were available. Therefore as a starting point for the present study the theory of heat conduction has been applied in an attempt to provide such estimates; the results are described in the section that follows. Of the various quantities required for this analysis, the climatic conditions are reasonably well known and the range of possible permafrost properties can be assigned within rather specific limits from previous scientific studies. However, it was necessary to use a preliminary estimate of the temperature of the oil in the pipeline. This temperature is not yet known accurately, as it depends upon factors relating to production and transmission which are still under study.

Once the thawing has been estimated, it is possible to apply a few basic principles to simplified models of permafrost regimes and thereby to identify some potential problems, the conditions that control them, and the approximate ranges of the physical properties for which the problems are likely to occur. In the section "Some subsurface manifestations of thawing" this procedure is used to discuss some conditions under which thawing might result in large stresses in the pipe or in mudflows on gentle slopes. The computations are approximate ones designed only to identify the order of magnitude of pertinent quantities. The specific problems discussed are only illustrative examples. Comprehensive discussions of these and related problems, taking account of stratification of the sediments and other important physical and theoretical refinements, are far beyond the scope of this report. Such studies will probably be needed, however, to form an adequate basis for engineering design.

Where the ice content of permafrost is not high, and other conditions are favorable, thawing by a buried pipe might cause no special problems, and this could very well be the common case. However, it is important that any potential problem be identified prior to its occurrence so that it can be accommodated by proper pipeline design. (Because our knowledge may never be so complete as to achieve this ideal, it is desirable to develop monitoring procedures to detect a developing problem in time for remedial action.) Identifying a problem in advance depends upon an understanding of the conditions under which the problem will occur. For that reason much of this report is concerned with problems. If the pipeline system is properly designed, and if it is constructed and maintained in compliance with the design, they will not occur. Perhaps "proper design" in some areas will involve abandoning plans for burial or changing the route; in others it might involve burying the pipe and supporting it by buried piling or exercising other engineering precautions. These are matters to be determined by much additional study and an intensive program of detailed field and laboratory measurements of conditions along the route.

Basic engineering problems relating to the security of the pipeline are of concern to ecologists to the extent that if they are not properly solved, they might result in mudflows, oil spills, erosion, and so on. Apart from these major considerations there are other physical perturbations of the environment that cannot be evaluated by ecologists until estimates of their magnitude are provided. These relate to such questions as "What will be the disturbance to the temperatures at the surface and at plant-root level? Over how wide a band will it be appreciable? Will there be a winter snow cover over the pipeline? Will the ground over the pipe be saturated or desiccated?" An attempt is made to provide approximate answers to some of these questions in the section "Some surface effects."

To be useful it is necessary that this report be quantitative; it is based upon analyses and computations of many kinds. However, in order to keep it readable by nontechnical people with an interest in this general subject, no mathematical expressions are used in the text. Pertinent theoretical results are summarized in numerical tables or described verbally. The mathematical foundation for the thermal calculations is presented in appendixes.

The writer gratefully acknowledges the assistance of his colleagues, Patrick C. Doherty, who programmed the numerical solution for the heat conduction equation, and Reuben Kachadoorian, who helped gather geologic and engineering information essential for this study. The writer is also grateful to them and to many other colleagues in the Geological Survey, in universities, and in industry for valuable discussions and for constructive comments on the draft manuscript.

TEMPERATURE EFFECTS

The purpose of this section is to obtain rough estimates of the amount and rate of thawing and of the configuration of the thawing surface for the complete range of climatic conditions and sediment properties expected along the pipeline route. Figure 1 illustrates the notation used for the discussion. The pipe temperature (T_p) will be taken as 80°C, and the depth of burial of the pipe's axis (D) will be taken as 8 feet unless otherwise stated. Most of the results presented were obtained by the numerical solution of the differential equation of head conduction described in appendix A. The problem was programmed by Patrick C. Doherty, and it is documented in detail in a separate report.[1] The numerical results were checked with analytical approximations, and separate analytical results were obtained for the equilibrium case (appendix B).

and these values serve amply to bracket the possibilities. Vertical temperature profiles through the centerline of the pipe are illustrated for the arctic case in figure 3. In the solution leading to these results, provision has been made for the annual thawing and refreezing of near-surface materials with the passage of the seasons (appendix A). The solid curves (fig. 2) denote conditions in the month of April and represent a more or less average annual condition. The dashed curves marked "(September)" represent conditions in the fall of the year at the time of maximum annual thawing. They illustrate how the frozen cap can be expected to roll back each year to provide continuity

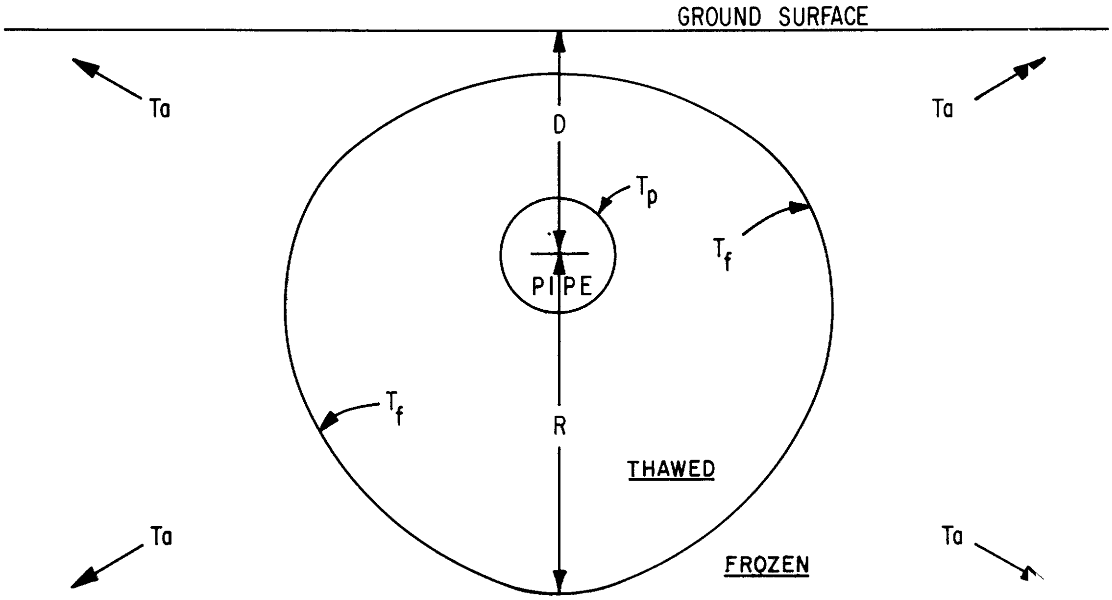

Figure 1.—Notation. T_a is the average annual temperature of the ground surface and of the undisturbed permafrost. T_p is the pipe temperature and T_f is the freezing temperature (0°C). D is the depth of burial of the pipe axis and R is the distance of the thawing surface beneath the pipe axis.

THAWING IN THE FIRST TWO DECADES

Figure 2 illustrates the approximate positions of the thawing surface for various times after emplacement of an 80°C pipe in a typical permafrost medium. The curves on the right-hand side of the figure represent conditions near the southern limit of permafrost; for example, in the Copper River Basin, where the mean annual ground temperature (T_a, fig. 1) is taken as -0.8°C. This condition will be termed the "interior case." The curves on the left denote conditions near the Arctic coast where the mean annual ground temperature is taken as -8.9°C. This will be referred to as the "arctic case." The true range of ground temperatures is well known from many previous studies,

between the naturally thawed material in the active layer and the artifically thawed cylinder around the pipe. September curves are shown in figure 2 only for the 1- and 20-year cases, but the analogous curves for the other times are easily visualized, as the depth of the shoulder is about the same for each. The curves in figure 2 marked "t=∞ (April)" represent the equilibrium configuration approached after a very long time (appendix B). They are discussed further under "Thawing after very long times—equilibrium results."

Figure 2 indicates the effect of the extreme range of climate on the thawing induced in a single material. It is necessary to perform similar analyses on other materials to understand how the thawing might be influenced by variations in physical properties of the permafrost along the route. The parameters tabulated in table 1 represent the materials chosen for this purpose. The material designated "silt (17½ percent)" is the one represented in figures 2 and 3. In table 1, only four quantities are chosen independently; the

[1]That report is released in open file as a Geological Survey Computer Contribution under the title "Hot Pipe" by Patrick C. Doherty and is available upon request from the Computer Center Division, U.S. Geological Survey Washington, D. C. 20242.

others are derived from them. The four independently chosen parameters are actually severely constrained, as they must represent a combination that occurs typically in nature. Their selection was based upon extensive measurements made over several years in the vicinities of Barrow, Umiat, Fairbanks, and Glenallen, Alaska. For convenience the hypothetical materials used in the examples are designated by a sediment name, "clay," or "silt," with the percent moisture by dry weight in parentheses. Actual materials with these designations would typically have properties like the ones chosen, but other sediments can, of

Approximate analytical formulations of the thawing problem suggest that moisture content by volume is the parameter of overriding importance in determining rate of thawing. This is confirmed by the numerical results presented in figure 4 for the depth of thaw beneath the pipe axis (R) as a function of time. The curves labeled "dry (0 percent)" represent a short computer run on material with the properties of silt (17½ percent) with the moisture removed. Typical dry sediments tend to have high thermal diffusivities subject to rather little variation, and they are uninteresting insofar as thawing permafrost is concerned.

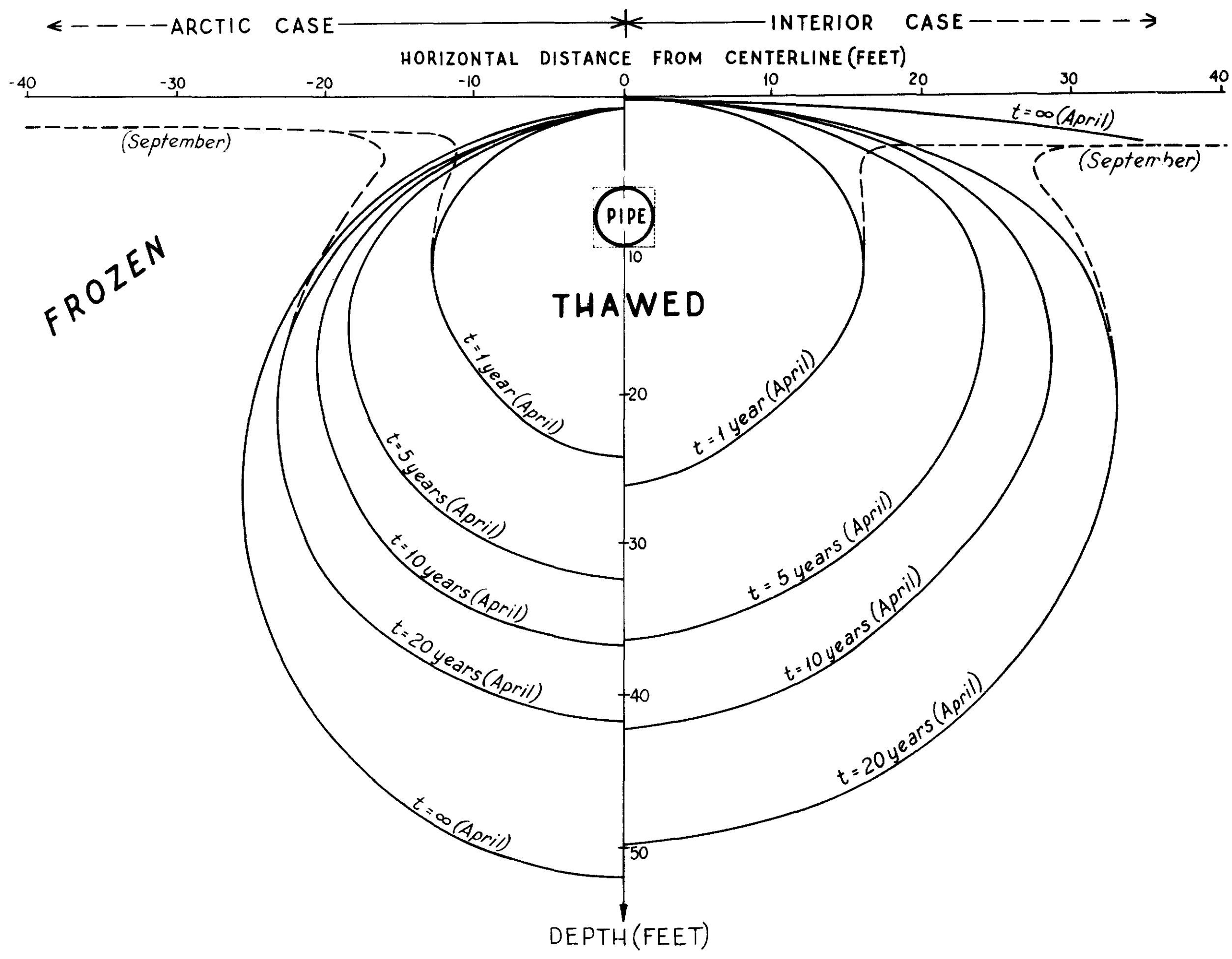

Figure 2.—Growth of the thawed cylinder around a 4-foot-diameter pipe with its axis 8 feet beneath the surface and its temperature maintained at 80°C. Curves on the left represent conditions near the Arctic coast; those on the right represent conditions near the southern limit of permafrost. Dashed curves represent conditions at the conclusion of summer thawing (September) for 1 year and 20 years. Calculations were made by the method of appendix A for the medium "Silt (17½ percent)" in table 1.

course, have similar thermal properties. The material designated "water/ice" has properties almost identical to saturated peat, and insofar as thawing is concerned, similar to some very high ice content inorganic materials incorporated into permafrost in special ways.

The reasons for including these curves are to present an upper limit and to illustrate the great retarding effect of moderate amounts of moisture on thawing. There are two reasons for this effect, the most obvious being the great amount of heat required to change

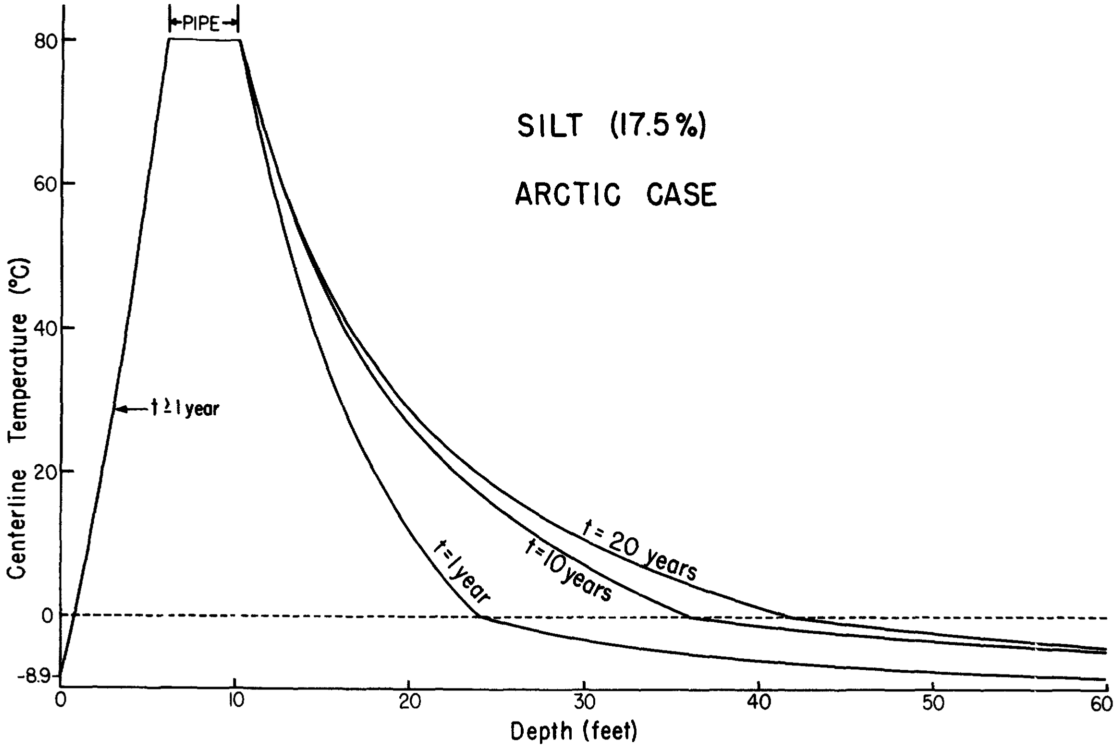

Figure 3.—Vertical temperature profiles through the axis of the pipeline (April).

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) Frozen	Silt (17 1/2 percent) Thawed	Clay (65 percent) Frozen	Clay (65 percent) Thawed	Water/ice Frozen	Water/ice 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

ice into water. Also important, however, is the anomalously high volumetric specific heat of water which demands large amounts of heat to raise the temperature of wet sediments after they are thawed. Both of these quantities, the latent heat and the volumetric specific heat, are best indicated by the moisture content by volume (see table 1). Moisture content by dry weight is used to designate the materials, however, as this parameter is more familiar to those concerned with the description of soils.

Figure 4 taken with figure 2 yields a rather complete description of the range of effects of climate and properties on thawing for the first two decades

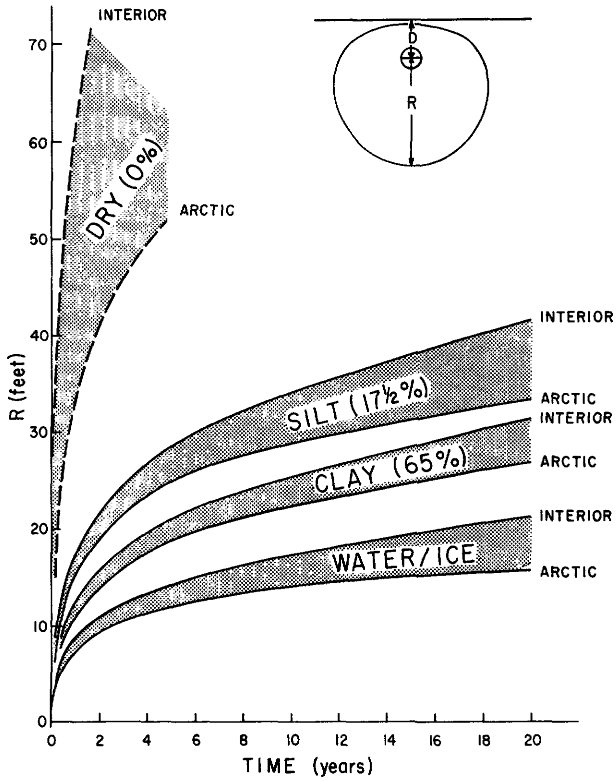

Figure 4.—Depth of thawing beneath pipe axis (R) for media described in table 1. D=8 feet.

of operation of the pipeline. The case of water/ice gives a confident lower limit; most materials of interest will lie in the range for the silt and clay cases. Each of the curves for water/ice yield thawing distances (R) of about 50 percent of the corresponding values for silt, and those for clay are about 75 percent of the values for silt. A rough indication of the complete configuration of the thawing surfaces for these materials can be obtained by applying scale reductions of those amounts to figure 2. (It should be mentioned that all of these numerical results may be subject to systematic adjustments (downward) on the order of 10 percent as a result of a geometric simplification in the numerical solution (see appendix A). Such discrepancies are unimportant in the context of the present discussion.)

One useful additional result can be derived from the calculations presented. The total amount of water thawed from permafrost after a given length of time is relatively independent of the moisture content of the material as long as at least moderate amounts of moisture are present. The more ice-rich sediments thaw more slowly, but in these, a little thawing produces more water. This point will be elaborated in a later section.

THAWING AFTER VERY LONG TIMES—EQUILIBRIUM RESULTS

If the pipe is maintained at a uniform temperature for a very long time, heat will eventually leave the earth's surface as fast as it is being supplied by the pipe and the ground temperatures will remain steady. This equilibrium condition, which is easily described mathematically, has been the basis for previous discussions regarding thawing by the pipeline. The solution is based on the assumptions that the ground surface temperature is uniform, that the pipe temperature eventually reaches a constant value, and that the materials are homogeneous. The solution proves that as long as these assumptions are satisfied, the final position of the thawing surface is a circle whose size and position is completely independent of the properties of the material; it depends only on the initial temperature conditions.

A refinement of this solution (equations B–11 and B–12, appendix B) takes account of the change in conductivity on thawing, but even that result depends only upon a ratio of conductivities and not upon the absolute value of any property of the medium. The solution says nothing about the time required to approach this equilibrium configuration, and this time *does* depend upon properties, including in a very sensitive way the moisture content. It also depends upon the distance the heat has to travel to achieve equilibrium. Figure 3 shows that immediately over the pipe, equilibrium is achieved in the first year. However, beneath the pipe, it will require on the order of a half century to approach equilibrium in typical materials in the arctic (except for the case of water/ice), and thousands of years to approach it in the interior (appendix B). It would appear that during the life of the pipeline equilibrium conditions generally will not be reached, and conductive thawing will continue, though at a progressively decreasing rate in typical materials.

The curves labeled "t=∞ (April)" in figure 2 were computed from the refined solution in appendix B. The much greater equilibrium thawing for the interior case is typical, generally about 10 times as great as for the arctic case (appendix B). It is seen from figure 4, however, that during the first two decades results for the arctic and interior cases differ by only 10 or 20 percent. For longer times the arctic and interior curves will diverge, and typically this divergence will occur earlier in the drier materials. (The case water/ice is anomalous, as there the strong contrast in conductivity leads to an early conductive equilibrium state in the arctic.)

Thus considerations of the equilibrium results alone can be very misleading. They suggest that thawing is very insensitive to material properties and that the quantity of overriding importance is climate, which causes variations in thaw by an order of magnitude along the pipeline route. Results for times of practical importance (fig. 4) indicate just the opposite; thawing is rather insensitive to climate, but sediment properties, particularly moisture content, are of overriding importance.

EFFECTS OF CHANGES IN PIPELINE TEMPERATURE

In addition to the sediment properties and permafrost temperature, the pipeline temperature is, of course, an important parameter in the thermal problem. It is worth considering the effects of lower pipe temperatures for two reasons: (1) The estimated value of 80°C may be subject to revision when detailed engineering studies are completed of heat balance along the pipeline, and (2) it is worth considering whether sufficient advantage might accrue from lower pipe temperatures to justify deliberate procedures to achieve them.

The assumption that the pipe temperature will be 80°C from the time the flow starts is unrealistic. The temperature will probably start out much lower and rise over a period of years as production increases and as heat loss to the warming permafrost decreases. For most purposes, however, quite satisfactory upper and lower limits to thawing under this condition can be obtained by adjusting the time origin in figure 4. For example, if the pipeline temperature built up gradually to 80°C over a period of 4 years, then the thawing depths after 10 years would lie somewhere between the values given in figure 4 for 6 and 10 years.

It can be shown from an approximate analytical formulation of the thawing problem, that if the steady pipeline temperature were reduced from 80° to 30°C (that is, by 50°C), the thawing depths indicated in figure 4 would probably be reduced by only 30 or 40 percent in general. Hence substantial amounts of thawing can be expected promptly even for pipeline temperatures much lower than that assumed.

Variation in the depth of burial of the pipe axis, say from 8 to 5 feet, is not expected to have a very large effect on the thaw depth (R of fig. 4). In general, however, deeper burial will result in somewhat greater thawing.

If conventional insulation were placed around the pipe, its principal overall effect would be to increase oil temperatures rather than to decrease thawing.

SOME SUBSURFACE MANIFESTATIONS OF THAWING

LIQUEFACTION

The most important difference between permafrost sediments and familiar unfrozen sediments stems from the fact that water generally has considerable strength when it is frozen (ice), and when it is thawed, it does not. In familiar stable sediments, gravity tends to pull the sediment grains together until they contact, and hence the volume of water generally cannot exceed the volume of the voids left between contacting grains. No such rule applies to permafrost, as it is perfectly stable even when it contains large masses of pure water as ice. Excess ice (that volume, which after melting, cannot fit in the soil voids) can be incorporated into permafrost in various ways during its initial formation, and subsequently by the growth of ice wedges. When such permafrost thaws, it is no longer stable, and the mineral grains tend to settle and to exclude the excess water. Where this settling is occurring the medium tends to behave as a dense fluid and has (virtually) no strength. Whether the liquid state persists long enough to have adverse mechanical effects depends upon the rate of this settling out, or equivalently, the balance between the rate at which excess water is supplied by thawing and the rate at which water can get out of the thawed sediment. This, in turn, depends upon the properties of the sediment and the configuration of the impermeable boundary with the surrounding frozen material.

Imagine the pipe to be embedded in sediments containing excess ice. As the thawed cylinder (illustrated in fig. 2) grows, excess water will be generated at the advancing interface. If it can migrate to the ground surface as fast as it is generated, the grains can settle down to contact one another, and the thawed sediment will gain increasing strength by consolidation (excluding additional water). If the rate of migration cannot keep pace with the rate of generation, excess water will persist in the thawed cylinder, part or all of which will tend to behave as a fluid. Predicting which type of behavior will occur is a very complex problem requiring careful study of the particular materials involved by an experienced soils engineer. However, the simple model described in the following paragraph yields order-of-magnitude results of some interest.

The excess water can migrate to the surface either by homogeneous flow through the material above it, or by channeled flow through or circumferentially around it. If the flow is not channeled and the material is homogeneous, a critical condition occurs when the vertical gradient of excess pore pressure is numerically equal to the buoyant unit weight of the sediment (typically 0.5 to 1.0 cgs (centimeter-gram-second)). Under this condition upward flow exerts sufficient force to support the weight of the sediment grains throughout the column, and the sediment can derive no strength from intergranular friction. This state will be referred to as the condition for potential liquefaction. Whether the sediment behaves more like a liquid or a plastic medium in this state depends upon the magnitude of any residual cohesive forces. If the flow is one-dimensional, the thawing rates required to maintain this critical condition can be calculated simply for any permeability and ice content if it is assumed that Darcy's law and the conventional permeability concept apply for the process (table 2).

Table 2.—*Conditions for potential liquefaction*

Permeability (cm per sec)	Velocity of flow (ft per yr)	Excess water (percent by volume)				
		2 1/2	5	10	20	50
		Minimum thawing rate for liquefaction (ft per yr)				
10^{-8}	0.005–0.01	0.2–0.4	0.1–0.2	0.05–0.01	0.025–0.05	0.01–0.02
10^{-7}	.05–.1	2–4	1–2	.5–1	.25–.5	.1–.2
10^{-6}	.5–1	20–40	10–20	5–10	2.5–5	1–2
10^{-5}	5–10	200–400	100–400	50–100	25–50	1C–20

The actual process by which excess water would exit from a deepening thaw zone is, of course, vastly more complicated than this idealized model and dependent upon small- and large-scale inhomogeneities in properties and their variation with time. If the excess ice were abundant and distributed homogeneously, after thawing the mineral grains would tend to be widely dispersed and the aggregate would be highly "permeable." In this case the exiting of water is most conveniently viewed in terms of settling velocities of the particles. As the grains settled closer together a more conventional view of permeability would apply, and this permeability would generally decrease as the mineral aggregate condensed. If the permeability decreased to the critical values given in table 2 before the sediment gained appreciable strength, further condensation would be arrested by flow forces and the fluid condition would persist (if homogeneous flow is assumed). Thus the permeabilities in table 2 refer to conditions of very low strength, perhaps at or above the liquid limit. If the excess ice were distributed in small discontinuous segregated masses, complex local processes would occur relating to absorption by overconsolidated clays or disaggregation of intervening soil masses. Typically these processes would have short time constants, and unless some form of chanelized flow developed, a gross condition similar to the model could evolve. (In many materials, however, cohesive forces might remain intact, locally at least.) If the medium were composed of strata with contrasting permeabilities, conditions for potential liquefaction of the individual layers would be slightly more complicated, but the same principles would apply. A medium consisting of alternating strata of contrasting ice contents could be subject to transient liquefaction in ice-rich layers for a time depending upon the thickness of the strata, the consolidation coefficient (or permeability) and initial pore pressure of the overlying stratum, and other factors. Although these and many other complications may have to be pursued in connection with particular designs, they are clearly beyond the scope of the present discussion. The simple model is adequate to provide some insight into conditions under which a potential for liquefaction exists. In the interest of brevity the qualifications relating to its applicability will not be repeated in the discussions that follow.

Table 3 gives the approximate thawing rate as a function of time for the materials described in table 1. For both arctic and interior cases, the thawing rates for all of them lie within about ±50 percent of the values tabulated. Thus if the permeability were 10^{-6} cm/sec and the excess ice 10 percent by volume, thawing at the rate of 5 to 10 feet per year would supply water as fast as it could filter to the surface (table 2) if the flow were homogeneous (not channeled). Consolidation could not occur and the material would tend to persist as a dense fluid with little or no strength. It is seen (table 3) that thawing at the rate of 5 to 10 feet per year would not be expected after the first year, and liquefaction due to thawing for that material should not be a problem thereafter.

Table 3.—*Rate of thawing beneath pipe as a function of time*

Time interval (years)	Computed thawing rate (fig. 4) (ft per yr ±50 percent)
0–1	10
1–5	2
5–10	1
10–20	.5

Looking more systematically at tables 2 and 3, we see that for permeabilities greater than 10^{-5} the formation of a liquid slurry poses no particular problem except possibly in the first year for materials that are more than half free water (ice). These materials, of course, would be more than half water even after the mineral grains had settled, and they pose a different problem to discussed later.

For permeabilities of 10^{-6}, liquefaction can be a problem during the first year for moderate amounts of excess moisture, and during the first few years for large amounts. Serious potential problems occur where the permeability is 10^{-7}, as liquefaction could persist for decades with only moderate amounts of excess water, and for several years for small amounts. For permeabilities less than 10^{-7} cm/sec the thawed materials could remain in a fluid state for the life of the pipeline even in sediments with very small amounts of excess moisture.

A material with a permeability of 10^{-7} is very impermeable, but clays typically have permeabilities that are lower still. In addition to clays, materials referred to as loess, sandy silts, silty sands, silts, and sandy clays have been reported with permeabilities in the range from 10^{-9} to 10^{-7} (although typically such sediments have permeabilities that are much higher). Materials designated by the same descriptive words occur frequently along the pipeline route. It is important to measure their permeabilities and ice contents as an aid in anticipating their behavior.

It has been pointed out that the calculations leading to the thawing rates in table 3 were based on the assumption that the pipe temperature was 80°C from the start of the operation of the pipeline. In reality the pipe temperature will, of course, be lower at first and increase (presumably to that value) over a period of years as the production increases to capacity and the surrounding permafrost warms. If the pipe temperature increases to 80°C over a period of say 5 years, the very high (and potentially most dangerous) initial thawing rates (~ 10 ft per yr) might be avoided, but the values for subsequent times will generally be increased somewhat. It is important, therefore, that a slow increase of pipe temperature will not avoid problems relating to persistent liquefaction.

It is seen that whether or not potential conditions for general liquefaction of the thawed cylinder occur depends upon the the presence of materials with very low permeability at or above the liquid limit (that is, in a condition of very small strength). However, in general as the water content of a sediment increases, its permeability increases and its strength decreases. The relationship greatly diminishes the probability of encountering such materials. Whether these conditions are possible along the pipeline route depends upon properties of materials yet to be determined in detail. However, if they occurred, substantial problems could result.

The case of general liquefaction was considered as an example because it is the simplest to discuss. Innumerable examples involving partial liquefaction of the thawed cylinder can be imagined, and similar principles apply. For example important problems relating to liquefaction can arise in a section that contains no excess ice on the average, if an isolated ice-rich layer is overlain by an impermeable one. The writer has not worked out the conditions for transient liquefaction for this case, but the problem is straightforward, and its solution should yield useful quantitative insight into conditions that are likely to occur. The liquefaction of an ice-rich layer beneath an impermeable relatively strong overburden would result in mechanical instability, and the slurry might migrate to the surface by channeled flow through or circumferentially around the denser consolidated core. In this case the core containing the hot pipe could settle downward and maintain undiminished thawing rates, and possibly perpetuate the process. If the trench were backfilled with gravel to provide a strong bed for the pipe in material subject to liquefaction, the entire gravel plug could settle in a similar manner if its effective density exceeded that of the slurry. In general, however, if some form of vertical channeled flow develops, the effective permeability of the overburden will be greatly increased and the danger of liquefaction greatly diminished.

Local liquefaction could also develop if the growing thaw zone intercepted an artesian aquifer confined by impermeable permafrost. The presence of such aquifers is sometimes indicated by the occurrence of pingoes.

Flow

Recognizing that general liquefaction of the thawed cylinder could occur only under a limited set of conditions that may or may not occur, we shall investigate some of its consequences, as the purpose of this report is to identify potential problems. If measurements indicate that the conditions set forth in the previous subsection are not approached, they can be taken as presumptive evidence that these problems will not occur, although further studies may be necessary. In general a potential for general liquefaction should be relatively easy to identify with appropriate measurements.

The most obvious question concerning a thawed tube of liquefied sediments relates to the conditions under which it would flow on sloping surfaces. This can be investigated by applying the theory of laminar flow of viscous and visco-plastic fluids. Table 4 gives velocities of flow in an inclined tube of viscous material. The assumed viscosity of 10^3 poises is a value sometimes quoted for solifluction materials and probably represents a reasonable upper limit. Judging from a variety of experimental results, the visosity could probably range downward to less than 1 poise.

Table 4.—*Flow of a viscous cylinder (viscosity=10^3 poise)*

Radius (ft)	Slope (ft per mile)			
	1	5	25	50
	Average velocity (miles per day)			
1 --------	0.02	0.08	0.4	0.8
5 --------	.4	2	10	20
25 --------	10	50	(Turbulent?)	

It is seen that the flow velocity increases sharply with the radius of the tube (table 4). But even for very thin cylinders and almost imperceptible gradients, material can be moved the total length of any naturally occurring continuous slopes in times on the order of a few days to a year. For example, the minimum slope over any few-mile section of the "flat" Copper River

Basin is about 5 feet per mile. Viscous mud could flow on such slopes at a rate that would cross the entire basin in one month if the thawed cylinder had a radius of only 5 feet. (The conditions represented by the lower right-hand corner in table 4 probably correspond to a state of turbulent flow. Most of the entries in the table would represent turbulent conditions if the viscosity were 1 poise.) Hence if the material is truly liquefied, viscosity is not likely to be a limiting factor in the flow.

As the grains of a slurry settle down and begin to interact, the properties of the material pass from those of a liquid to those of a plastic medium. In this transition the material acquires a small strength, that is, a shearing stress which it can sustain without flowing. Even slurries which appear very much as liquids might have strengths from 0.01 to 1 psf (pound per square foot). Remoulded clays at the liquid limit can have strengths from 10 to 100 psf. (Such strengths are determined from short-term laboratory tests, and the possibility must be considered that substantially smaller strengths might be applicable for stresses sustained over a period of years.) Such small strengths can keep the material stationary on gentle slopes. However, as the radius of the thawed cylinder grows, the shearing stresses within it may eventually exceed the strength, and the material can become unstable and flow. Table 5 shows the radius of the cylinder required to produce flow for various slopes and shear strengths. On a slope of 5 feet per mile material with a strength of 0.1 psf will flow when the radius exceeds 2 feet. It can be shown that in a visco-plastic medium if the thawed radius is substantially greater than this mimimum, the flow velocity will approach the value for the corresponding viscous case (table 4). Thus in this case, if the radius grew to 5 feet the plastic material would flow at a rate approaching 2 miles per day (table 4) for a high viscosity, and for the lower viscosities it could be turbulent. From the section on temperature effects we know that radii on the order of 25 feet can be expected. Hence material with long-term strengths up to 1 psf can be expected to flow on slopes as small as 5 feet per mile. For material with strengths up to 10 psf flow could occur on slopes of only 1 percent. Thus it would appear that flow could occur practically any place that such slurries occur, as imperceptible slopes such as these are almost omnipresent. For slopes greater than 10 percent (500 ft per mile), thawed cylinders composed of material as strong as 100 psf will probably flow.

Table 5.—*Instability of a visco-plastic cylinder*

Shear strength (psf)	Slope (ft per mile)				
	1	5	25	50	500
	Radius required for flow (ft)				
.01 ----------	1	0.2	0.04	0.02	0.002
.1 ----------	10	2	.4	.2	.02
1.0 ----------	100	20	4	2	.2
10 ----------		200	40	20	2
100 ----------				200	20

After an initial flow of the thawed cylinder, further flowage along the bottom of a trench would be approximated better by the case of an inclined layer with a free surface. The thickness required for flow of a plastic layer is half as great as the radius of the corresponding cylinder with the same slope, and the velocity of the layer in viscous flow is greater than that of the corresponding cylinder by a factor of 2 or 3. The pipe would, of course, have a retarding effect on these flows, but this effect can be shown to be unimportant.

From figures 2 and 4 it is seen that a cylinder 20 to 30 feet in diameter might be thawed in a few years. It is clear from tables 4 and 5 that if the cylinder contained a liquid slurry it would not reside where it was formed over such a period unless it were confined by frequent dams of stronger material along the route. The material can be expected to "seek a level" within a matter of days to months, depending on the distance over which the liquid slurry extends and its viscosity. As an extreme example, if there were a 5-mile stretch of liquefied material with a gradient of 25 feet per mile, the pipe could soon be lying at the bottom of a 50-foot slumping trench at one end, while some 10 million cubic feet of mud (containing the pipe) could have been extruded over the surface near the other end. On the uphill end the downward-settling pipe could continue to thaw to great depth. This would favor liquefaction (tables 2 and 3) and further flow (tables 4 and 5), and process could be self-perpetuating. It may be extremely difficult to stop slumping of large volumes from the walls into the widening trench. The slumped material would flow promptly to the downhill end where it would augment the mud flowing onto the surface. The pipe could be jeopardized by loss of support in the trench and displacement in the mudflow, and the disruption to the landscape could be substantial.

Because of the great radial distances to which the thawing extends (figs. 2 and 4), it may be difficult to anchor structures to retard the flow. Sheet piling that was installed at regular intervals to dam the flow would have to be anchored in material not subject to liquefaction. If it were not, it might serve only to transfer the hydrostatic flow forces to the pipe. The cumulative effect of such structures over an elevation drop on the order of 100 feet might stress the pipe in an amount approaching its tensile strength.

As in the previous discussion, the simplest and most adverse case, general liquefaction, was taken as an illustrative example. A variety of less extreme and perhaps more probable cases can be imagined. Under static conditions, gravitational shearing stresses are greatest at the bottom of the thawed cylinder on a sloping surface. A liquefied layer there might flow laterally if it could exit through a channel to the surface downslope (perhaps at a thawed ice wedge or a river terrace). Although a very weak bonding of the overburden materials to the frozen wall would keep them from participating in this flow, loss of support could cause settlement which could break this bond and trigger more massive movement.

This discussion has emphasized conditions relating to extremely small strengths because the forces that cause flow on gentle slopes are very small. On steeper slopes it will, of course, be necessary to analyze the stability of stronger materials.

Buoyancy and related problems

If the material surrounding the pipe were liquefied, the pipe would tend to sink or float depending upon whether its effective specific gravity were greater or less than that of the surrounding medium. The specific gravity of the oil-filled pipe will probably be from about 1.15 to 1.2 while that of the surrounding medium might vary from about 1.0 for highly ice-rich organic material to about 2.0 for some inorganic slurries. To avoid vertical displacement of the pipe by positive or negative buoyant forces, it would be necessary either to support it with structures anchored in material with permanent strength, or to weight it in such a way that it were neutral. If it were weighted, a mismatch in the specific gravities of 0.1 would result in vertical forces along the pipe of about 80 pounds per running foot. If it were not weighted or supported, net forces on the pipe could range from about 150 pounds per foot of pipe downward in pure water with or without organic material to about 600 pounds per running foot upward in inorganic slurries. To achieve neutrality in inorganic slurries by weighting with concrete, it would be necessary to use a volume of ballast comparable to the volume of the pipe. A further problem with weighting the pipe to match the specific gravity of the thawed medium is the uncertainty in the density of the sediment and the possibility that this density would change with time. Residual forces on the order of 100 pounds per running foot might be very difficult to avoid. Displacement by such forces would probably be suppressed by strengths on the order of 10 psf in the surrounding materials.

Where the pipe emerged from strong material into liquid at a depth of say 6 feet beneath the surface, these buoyant or sinking forces would have to be balanced by shearing stresses in the pipe out to that distance (probably on the order of 100 ft., at least) where it floated to the surface (for upward forces) or settled to the bottom (for downward forces). In such configurations the pipe would be subjected to severe bending moments which should be evaluated and compared to failure criteria. Upward forces might be released by tearing the pipe upward through the overburden at the point of support, but downward forces could not. However, the conditions for net sinking forces would probably be limited to materials of restricted thickness and extent. (The thermal effects of downward settlement of a hot pipe are obvious.)

CONVECTIVE THAWING

The thermal calculations of the first section are based on the assumption that heat transfer would be only by conduction, the most inefficient of heat transfer mechanisms. Although this is virtually the only mechanism possible in frozen materials, heat can be transferred much more efficiently in thawed materials if they are mobilized or if their interstitial water is. In such cases the curves of figures 2 and 4 may have no resemblance to the actual amount of thawing; their main importance is that they indicate that substantial amounts of thaw can be expected promptly even in immobile media. From figure 3 it is seen that substantial gradients occur in the thawed cylinder. When the thawed material moves, warm material is generally brought closer to the thawing surface and greatly accelerates thawing, while colder material is brought closer to the pipe and greatly accelerates heat extraction from it. Hence once the thawed material is mobilized, the thawing can be greatly accelerated and some of the effects described previously can be self-perpetuating. These convective effects have been estimated by applying the theory of heat conduction in a moving medium. Results presented in table 6 show the order of magnitude of the heat-flow enhancement by material flow between isothermal surfaces (for example, the pipe and the thawing interface). For distances of separation of several feet it is unimportant

Table 6.—*Enhancement of heat flow by movement in direction of thermal gradient between surfaces separated by a distance, with a temperature difference of 80°C*

Velocity		Convection+conduction / Conduction — Distance (feet)	
ft per yr	ft per day	8	16
1	0.003	1.05	1.1
5	.015	1.3	1.6
10	.03	1.6	3.2
20	.06	2.3	4.6
50	.15	5.0	10
100	.3	10	20
1,000	3	100	200
10,000	30	1,000	2,000

for velocities less than a few feet per year. However, for velocities of a few tenths of a foot per day, local thawing could be increased by an order of magnitude, and for 30 feet per day, by a factor of 1,000. A velocity of 30 feet per day is almost imperceptible; about the same as the speed of the end of the minute hand on a kitchen clock.

The values shown in table 6 for movement of sediments plus their contained water are about the same as those for filtration of the water alone, provided the velocity is considered as the volume of water passing through a unit area in unit time and not as the particle velocity. This is the sense in which velocity was used in table 3; hence, it is seen from tables 2, 3, and 6 that heat transfer by excess water filtering from the thawing surface would be unimportant except for rare materials during the first year. However, the processes discussed in the section on flow could cause substantial convective thawing.

SEISMIC LIQUEFACTION

In the foregoing sections we have considered conditions under which the sediments had little or no strength because, after thawing, they were settling downward through water, or water was moving upward through them, and their grains were not firmly in contact. A similar situation can occur when a saturated granular sediment is subjected to vibrations which tend to compact it. While the grains are tumbling down into denser packing configurations, they lose contact and the aggregate liquefies. The water excluded from the diminishing pore space moves upward from the liquefied zones and can cause the process to spread. Loosely packed sands and silts in the thawed cylinder could be liquefied by an earthquake with consequences relating to flow, buoyancy, and convective thawing similar to those discussed in the preceding paragraphs. The southern part of the pipeline route lies in an active earthquake zone.

DIFFERENTIAL SETTLEMENT

Some engineering considerations

It is well known from experience in the construction of roads, railroads, buildings, and other structures on permafrost that thawing can cause undulations of the surface resulting from differential settlement. For the most part this settlement results from reduction in volume of ice when it turns to water, or from loss by the sediments of water formerly contained in segregated ice masses or in the pore space of underconsolidated sediments. Such differential settlement can produce stresses in a pipeline just as it can in any other rigid structure the permafrost might have been supporting. Although analysis of these stresses is a matter for engineers, it is necessary to introduce some quantitative standard for pipe deformation to evaluate the possible impact of settlement on the pipeline.

An unsupported span of pipe will sag in the middle as a result of stresses created by the pipe's weight; the larger the span, the greater the stress and the sag. According to my understanding, the maximum stress for which the Alaskan pipeline is being designed (the "design stress") would be approached under operational conditions when such a free span is about 60 feet long, and under these conditions the sag at the center of the oil-filled pipe would be about 3 inches. If the pipe were laid on the surface and a 60-foot section of the ground settled more than 3 inches, conditions would be rather similar. From dimensional considerations it can be estimated that if the load on the pipe were four times its weight (as it might be if the pipe also supported its overburden in a free span), similar stresses would develop in a 30-foot span and the sag would be about 1½ inches. If the pipe were partially supported so that the load were only 25 percent of the pipe weight, such stress would probably be approached in a 120-foot span with about ½-foot displacement in the center. (It should be pointed out that the design stress probably includes a substantial margin of safety insofar as failure is concerned.)

In this discussion it should be borne in mind that settlement at the surface depends upon volume reduction throughout the entire thawed cylinder. Typically less than 10 percent of the material involved will ever be observed directly by boring and trenching. Settlement of the pipe depends primarily upon behavior of thawed materials below pipe level, of which only a negligible fraction will probably be directly observed. Properties below pipe level will probably be estimated by interpolation of information obtained in separated bore holes.

Ice wedges

If the distribution of ice in permafrost and the details of the thermal disturbance are known in advance, settlement of the thawed materials can be predicted satisfactorily. The chief problem in determining the distribution of ice in advance (by borings) probably lies in detecting the presence of large masses of high ice-content material of limited lateral distribution such as ice wedges. The chief problem in predicting the thermal disturbance lies in accounting for convective thawing if these materials are mobilized. Very abrupt changes in ice content (and consequent severe differential settlement) might occur under a variety of conditions, but the most severe are probably those related to the thawing of ice wedges.

It is well known that during the cold northern winter, thermal contraction of the ground surface causes the sediments to crack in a quasi-polygonal pattern resembling desiccation cracks in mud. These cracks may extend to depths of tens of feet, and they are typically 30 to 100 feet apart. Spring melt water draining into the cracks and freezing seals them to form a network of vertical ice veins in permafrost. Because of their weakness these veins are the sites of renewed cracking in succeeding winters. With the passage of centuries the veins grow into a honeycomb of massive ice wedges, sometimes 10 or more feet wide at the top. Because of the interaction of these wedges with surface processes, their traces at the surface are sometimes delineated by a conspicuous pattern of troughs or ridges or vegetation contrasts. Such patterns are called ice-wedge polygons. Where ice-wedge polygons appear, the locations of many (though generally not all) ice wedges in an area can be determined by surface observations. Rather little is known of the distribution of ice wedges in permafrost areas where no surface polygons appear. However, judging from observations in random excavations in such areas and from the theory of ice-wedge formation, it is likely that they represent a rather general condition in permafrost sediment, becoming better developed northward. Their presence is revealed by surface markings only under special conditions favorable for it.

Typically ice wedges underlie only 5 or 10 percent of the surface area. Hence on the average their presence would be revealed by exploratory drilling in only 1 out of 10 or 20 borings. However, a pipeline crossing ice-wedge laden permafrost might encounter a wedge every 50 or 100 feet on the average. As the wedges form closed figures (polygons) they generally could not be avoided by very local rerouting.

Where the pipeline crosses an ice wedge, it is likely that much if not all of the wedge will be removed locally by thawing in a few years. Even if heat transfer were only by conduction, the thawing would be much faster than that indicated by the curves for water/ice (fig. 4) because the thermal regime of the surrounding material would dominate. However, with so much localized free water, convective heat transfer would probably dominate conduction from the outset.

When ice beneath the pipe turns to water, its volume will reduce progressively, and the weight of the pipe and overlying materials will no longer be fully supported. As thawing of the ice wedge proceeds, the pipe and(or) the overlying material must settle downward into the water in a special way, or else they must support the unbalanced load with their strength. Assume for the moment that the pipe and surrounding materials settle as a unit. Then the relative rates of downward movement of the pipe and the fluid level in the underlying ice-wedge trough determine the load on the pipe. This can be discussed in terms of a few simplified conditions.

In the first condition, which will be called condition A, the water table is maintained near the surface by inward flow of water from surrounding materials to compensate for the volume reduction. In this case the overburden materials (including the pipe) are partially supported by buoyant forces. However, an unbalanced load on the order of one to two times the weight of the pipe in a free span (depending upon depth of burial) will persist. Unless the surrounding sediments have appreciable long-term strength, strain will accumulate in the pipe which will ultimately bear this load.

In the second condition (condition B), a void develops in the ice-wedge trough beneath the pipe. This could result from volume reduction of the ice wedge not compensated by inflow of water, by drainage of the melt water into a seasonal contraction crack formed in the wedge, or by convective thawing of a drainage channel through the ice wedge in regions with local relief. Under this condition the unsupported load on the pipe would typically be three or four times the weight of the pipe in a free span.

A third condition (C) is possible where the pipe and overburden settle into the fluid in the trough and the surrounding materials are so impermeable that the unbalanced weight is supported by filtration forces. In this case the material surrounding the wedge would probably be in a general state of liquefaction.

Independently of the processes just discussed, material will slump into the trough from the walls, filling its bottom and widening its top (below the pipe). This process will not change the volume of water (condition A) or of the void (condition B) in the trough, but it will increase the length of the unsupported span of pipe crossing the trough.

If the pipe and surrounding overburden material do not behave as a unit, thawed material will slump around the pipe into the ice-wedge trough and leave a depression on the surface across which the pipe would be exposed if the wedge were large enough. If the depression were full of water, the pipe would be partially supported by buoyancy, but if it were not, the pipe would be in a free span. The latter case will be referred to as condition D and the former as condition E. A final condition (F) represents the case in which the wedge is so small that slumping of material around the pipe fills the trench without exposing the pipe.

In summary, in conditions A, B, and C the ground surface remains more or less intact. In A the pipe is underlain by a water pocket and unbalanced forces on the pipe approach one to two times its weight. In B the pipe is underlain by a void, and the unbalanced forces on it approach three or four times its weight. In C the pipe overlies a slurry and conditions would be like those discussed in the section on liquefaction. In concitions D, E, and F a depression develops on the surface. In D the pipe is immersed in a pond of water, and the forces on it are only a small fraction of its weight. In E the pipe is exposed across a pit in a free span with the forces on it equal to its weight. In F it is buried in the bottom of a pit with no residual forces acting on it except the stresses resulting from its displacement.

As a pipeline crosses a field of ice wedges, these six conditions might be expected with all possible intergradations depending upon the size of wedges, the properties of the materials, and details of local convective thawing and drainage processes. In many cases conditions A or B may precede conditions D, E, or F. Conditions A and B are potentially the most dangerous, not only because they result in the greatest loading of the pipe, but also because they may occur with little or no surface expression. The other conditions can be detected by surface observations and remedial action can then be taken.

In considering what happens when an ice wedge thaws from beneath the pipe, it is important to keep in mind that the wedges are randomly oriented, and the pipe may cross them at any angle. (It has been explained that where ice wedges are well developed, local rerouting to avoid individual wedges is not feasible.) The length of the unsupported pipe span over an ice-wedge trough increases as the width of the trough increases and as the angle of intersection between the pipe and the ice wedge decreases (that is, the intersection of wider troughs at smaller angles creates larger unsupported spans). A simple statistical calculation shows that where individual wedges are about 100 feet long and the width of the thawed and slumped region beneath the pipe is 5 feet, the pipe centerline will be unsupported for distances greater than 60 feet, about once in every 50 crossings, or about once every mile for a spacing of 100 feet. Under comparable conditions unsupported centerline spans greater than 30 feet could be expected once in every 13 crossings, or about four times per mile if these 5-foot wide slumped zones occur at intervals of 100 feet. If the slumped region were 10 feet wide, these frequencies would be approximately doubled. It is possible that the spans greater than 60 feet could exceed the design stress of the pipeline under conditions A, B, and E and that those greater than 30 feet could do so under condition B.

In some respects a worse threat is posed by ice wedges which pass close to the trench but are not exposed by it. As the thawed zone is typically more than 10 times as large as the trench, the thawing of unexposed wedges in ice-wedge terrains is probable. Their presence might not be recognized until after they had caused disruptive effects. Perhaps the greatest displacement of the pipe would be caused by wedges which run close to the trench and parallel with it and those that pass under the trench, but whose tops are below trenching depths. Massive extinct wedges with their tops many feet beneath the surface have been observed in several areas.

Settlement in more homogeneous materials

Although the most conspicuous differential settlement usually results from the thawing of ice wedges, substantial amounts can be caused by more subtle lateral changes in properties. To illustrate this we shall first consider some simplified relations between the water content and absolute amounts of settlement to be expected in homogeneous sediments.

It has been pointed out in an earlier section that for a given climatic regime (for example, arctic or interior) the rate and amount of water melted from permafrost is rather independent of moisture content of the materials (unless they should be anomalously dry); the wetter the material, the more slowly it thaws, but the more water a little thawing will produce. For the thermal models presented in the section on temperature effects, it can be shown that roughly 750 cu ft (cubic feet) of ice is melted per foot of pipeline for the interior cases in the first two decades, and about 450 cu ft for the arctic cases in the same period. Roughly one-third of these amounts would be melted by the end of the first 2 years and about two-thirds by the end of the first decade. If the sediments were sufficiently undersaturated (at least by 10 percent) and homogeneous that they did not expand appreciably on freezing, the melting of this ice would not result in appreciable settlement. If, however, the sediments were saturated when they were frozen, they must have expanded by at least 10 percent of the volume of water present during the process. They would, therefore, reduce in volume by that amount when they thawed and returned to their original state of consolidation. Thus for such sediments the thawed cylinder would undergo a volume reduction in two decades of about 75 cu ft (per foot of pipeline) in the interior, and 45 cu ft in the arctic. This volume reduction would have to be expressed by settlement of the surface, and this settlement could occur only over the distance between the frozen shoulders (see September curves, fig. 2). For "silt" (fig. 2) this distance is roughly 30 feet in the arctic and 50 feet in the interior. Hence for both cases the surface settlement is about the same, 1½ feet. The corresponding value for the clay cases is about 2 feet and for water/ice about 3 feet, because the width of the band of settlement for them is narrower. After 2 years the volume reduction is about one-third as great and the shoulders are closer together, but not proportionately so, because equilibrium is achieved faster near the surface than at depth. Hence the settlement after 2 years is roughly one-half as great as it is after 20 years. Thus for typical saturated sediments a widening trench can be expected to develop over the pipeline, deepening from about a foot after a few years to about twice that after two decades. If the sediments were oversaturated and 20 percent of the ice were excess, the values would be approximately tripled if the excess water could filter to the surface; 3 feet of settlement in a few years and 6 feet in two decades. (If the excess water could not filter to the surface, liquefaction would occur.) If the sediments were sufficiently undersaturated, settlement at the surface would be negligible. If the pipe temperature were increased gradually during the first few years, the settlement would develop more slowly during that period.

In this discussion we are interested in the settlement that might occur below the pipe. Inspection of figures 2 and 4 suggests that typically it will be well over 50 percent of the surface settlement in homogeneous materials. If we now imagine the pipeline to be passing over materials that are vertically homogeneous, but whose degree of saturation or moisture content changes along the route, it is seen that differential settlements on the order of 1 foot might not be uncommon, and that they could occur even in the absence of oversaturated sections. They could result from changes in moisture content of only a few percent (on the order of 10 percent of the water present) or they could occur with no lateral change in moisture content at all if the porosity changed by only a few percent. It is even possible for the greater settlement to occur over the dryer of two materials (where the dryer material has a lower porosity and greater degree of saturation). Where oversaturation (excess water) occurs locally, several feet of differential settlement are possible at pipe level.

The homogeneous case discussed above is the one that generally results in the least settlement. Where the sediments are not homogeneous vertically, they may contain several percent of segregated ice even though they may be undersaturated on the average. Reabsorption or exclusion of the water formed by melting of this ice might cause settlement of a foot or more in inhomogeneous undersaturated sections.

One would hope that these subtle changes would be so gradual as not to result in abrupt vertical displacements of the pipe, but there is no assurance that this will always be so. Nor is there any assurance that lateral changes which could cause significant differential settlement would be revealed, even after extensive exploratory drilling and the completion of trenching for the pipe. The most troublesome changes would occur over lateral distances of a few tens of feet, too small to be detected by most exploratory drilling. They would occur at depths below the pipe level; generally too deep to be detected in trenching. Perhaps the most obvious place where sharp lateral changes could occur would be where the pipeline passed from bedrock to saturated sediments. There the problems could be anticipated by surface observations and local drilling. Although lateral contrasts undetected by drilling or trenching might be rare, they might occur, for example, at the banks of ancient river meanders or lakes, now buried in the sedimentary section.

It is convenient to discuss these differential settlements in terms of conditions similar to A, B, and C used in the discussion of ice wedges. In the first (condition A') the material initially forming the bed for the pipe settles downward and loses contact with the pipe, but the water table is at the surface. In this case the load is equal to the buoyant weight of the pipe plus the overburden material (one or two times the weight of the pipe in a free span). In the second (B') the water has drained off, and a void exists beneath the pipe. Here the load may be three or four times the free weight of the pipe. In the third (C') the surrounding material flows or falls into the void beneath the pipe to give it partial or complete support. This is the most favorable case, and perhaps it would be the most common one. It is possible, however, that if the pipe were laid in a gravel bed, the development of the third case (C') could be inhibited.

It is seen that for differential settlement on the order of 1 foot over a 60-foot span, the design stress could be equaled or exceeded under condition A'. If the material at and above pipe level were well drained (condition B'), the design stress could be exceeded by 200 or 300 percent unless the metal yielded to relieve local stress concentrations. (Much more extreme examples involving longer spans and several feet of settlement in oversaturated sediments are easily imagined.) It is interesting to note that if a drainage trench were dug to remove excess water around the pipeline, conditions could change from A' to B'. The loss of buoyant support for the pipe and overlying sediments could double the unsupported load on the pipe. Hence decisions relating to field maintenance problems might have significant engineering consequences.

It is important to emphasize here as elsewhere that the discussion is based upon approximate calculations and simplified physical models. However, the orders of magnitude of the quantities derived suggest potential problems that deserve further attention, including a more refined treatment.

SOME SURFACE EFFECTS

Most of the processes discussed in the preceding section on subsurface effects, are mechanical manifestations of thawing around and beneath the pipe. Although they can have profound effects on the surface, their controlling mechanisms are generally processes at depth. Although the classification is somewhat arbitrary, there is another group of effects for which the controlling mechanism operates primarily at or near the ground surface, and some of these are the subject of this section. These effects depend more or less directly upon the amount of excess heat delivered to the surface from the buried pipe. There seems to be two main ways that this heat can be transferred to the surface: (1) by thermal conduction through the overlying sediments, and (2) by thermal convection of water driven through the sediments by heat extracted from the pipe. The subsection that follows considers the near-surface temperature effects resulting from thermal conduction. It is followed (in the subsection on hydrologic effects) by a discussion of heat transferred to the surface by both convection and conduction. It should be anticipated here that, under certain circumstances to be discussed, the convective process can dominate the surface thermal regime.

THERMAL GRADIENTS AND TEMPERATURES NEAR THE SURFACE

To investigate the temperature disturbance near the surface by conduction from the pipe, it is convenient to use the steady-state solution (appendix B) because it is applicable after the first year directly over the pipe. At lateral distances of a few tens of feet, the steady-state solution will overestimate the heat losses somewhat, but the discrepancy is unimportant for the present purposes.

The excess thermal gradients produced by the heated pipe at the ground surface are shown approximately as a function of distance from the centerline in figure 5 for a pipe with its axis 5 feet beneath the surface (D=5 ft) and one with its axis 8 feet beneath the surface (D=8 ft). These can be viewed as average annual excess values if the heat transfer is primarily by conduction, and the material is more or less homogeneous. The thermal gradient anomaly at the surface immediately over the deeper pipe is about 10°C per ft, while that for the shallow one is more than twice as great. However, the anomaly from the shallower pipe falls off sharply, and at distances from the centerline exceeding 10 feet, both cases produce about the same effect (fig. 5). Thus the average annual temperature of plant roots 1 foot beneath the surface at the centerline would be elevated above the surface temperature some 22°C by a pipe at a depth of 5 feet and 10°C by one at 8 feet. Ten feet from the centerline both cases would elevate plant-root temperatures at the 1-foot level by 3½° to 4°C, still an appreciable amount. At distances greater than 30 feet, the effect would amount to only a fraction of a degree; on the same order as natural random variations on a microenvironmental scale.

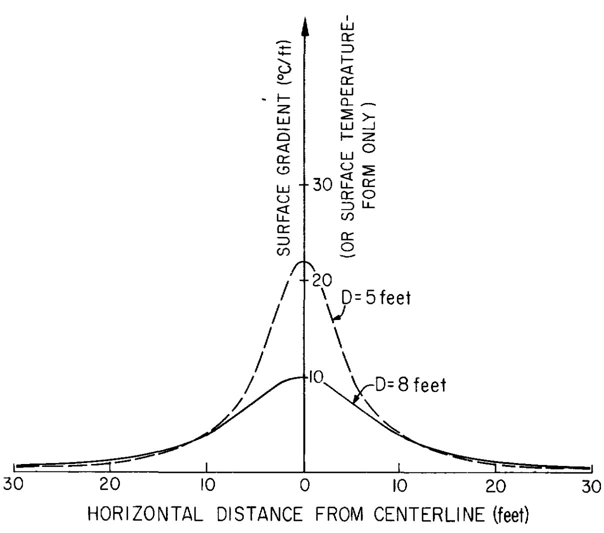

Figure 5.—Equilibrium temperature gradient at the surface for conductive transfer in homogeneous materials over a pipeline maintained at 80°C. D is depth of burial of pipe axis. Curves also give approximate form of surface temperature when local meteorological conditions are uniform.

Some interest is attached to the elevation of the surface temperature in the vicinity of the pipe. (For example, the total temperature anomaly at root level is the one caused by the anomalous gradient, just discussed, plus the temperature anomaly at the surface.) This problem has no simple solution, as the surface temperature is a consequence of complex processes of heat and mass transfer which are imperfectly known in detail. The temperature anomaly at the surface can be expected to be extremely variable with wind, moisture, and radiation conditions. However, when these conditions are uniform in the vicinity, the surface temperature will be approximately proportional to the temperature gradient at the solid surface (by Newton's low of cooling). Hence to a rough approximation the *form* of the temperature disturbance at the surface at any time would be given by the curves in figure 5; that is, we might view figure 5 as graphs of surface temperature versus distance from the centerline if we leave the scale on the ordinate axis (temperature) unspecified. At the centerline the surface temperature would probably be elevated about twice as much for the 5-foot burial as for the 8-foot burial, and in both cases the temperature elevation would probably be insignificant at distances greater than 30 feet. Combining results of the last two paragraphs, plant-root temperatures probably would not be affected significantly by conducted heat beyond a 60-foot swath centered over the pipeline.

SOME HYDROLOGIC CONSIDERATIONS

Heat plays a key role in hydrologic processes in cold climates, and the excess heat supplied to the environment near the pipeline can have some conspicuous effects. Table 7 indicates some possible thermal effects on surface water, ice, and snow for an assumed thermal conductivity (2×10^{-3} cal/cm sec °C) and a gradient of 10°C per ft. This represents conditions at the centerline for D=8 feet; conditions elsewhere can be scaled directly from figure 5. Variations in the conductivity could cause variations in the values in table 7 by a factor of 2, and heat transfer by moisture

Table 7.—*Potential hydrologic effects of heat conducted to the surface from a buried pipe*

[Values are for centerline over a pipe with its axis buried 8 ft; other values can be scaled from figure 5. Effective width of the layer is 25 ft for D=8 ft or 32 ft for D=5 ft]

Process	Layer thickness per year			Layer thickness per day	
	cm	in.	ft	cm	in.
Water at 0°C to vapor	35	14	1.1	0.1	0.04
Ice at 0°C to water at 0°C	260	100	8.5	.7	.3
Water at 0°C to water at 20°C	1,040	410	34	3.0	1.1
Snow (density=0.25 gm per cm^3) to water at 0°C	1,040	410	34	3.0	1.1

migration could change the values much more. These qualifications will not be repeated in the discussion that follows.

The total rate of heat loss at the surface per unit of pipe length for D=8 is about the same as if the centerline flux obtained over a band about 25 feet wide, and no loss occurred beyond that (equation B–6). Hence, for the purpose of computing volumes of materials involved, the processes of table 7 can be viewed as occurring over a 25-foot-wide strip. The comparable values for D=5 can be computed by imagining the D=8 centerline flux to be distributed over a 32-foot band.

Snowmelt

It is seen from table 7 that heat from the pipe is capable of melting 34 feet of partially compacted snow in a year, or over 1 inch per day (centerline, D=8). Indeed, whenever snow is on the ground, its insulating effect will cause rapid thawing (from below) of any crust that might have frozen in the ground, and thereafter all of the available heat will go in to melting the snow. At the centerline snow will lie on the ground for only a short while even after the heaviest snows. (Ten feet from the centerline it will remain about three times as long, while at the centerline for D=5 it will remain about half as long, fig. 5.) It is important that the snow cannot melt from below unless the ground upon which it rests is first thawed; hence, water from the melting snow will flow directly into the thawed cylinder around the pipe below, if material there is not already saturated. South of the Brooks Range on the order of one-fourth to one-half foot of water is precipitated annually as snow, and it is likely that significant additional amounts of water may be supplied by snow drifting onto the bare ground above the pipe. North of the Brooks Range the precipitation is much less, but drifting is much more important, and it is possible that more water would be supplied by snowmelt there than farther south.

Evaporation

Whereas the pipe can melt tens of feet of snow annually, all of the conducted heat delivered to the surface (centerline, D=8) could be consumed by the evaporation of only about 1 foot of water; that is, if excess evaporation over the pipe amounted to only 0.1 cm per day, the conducted heat would not even raise the surface temperature (table 7). Over much of the terrain traversed by the pipeline the natural evaporation rate is on the order of 1 foot per year. Doubling this value very locally is not likely to produce a gross disruptive effect—perhaps ground fogs will be frequent over the pipe, particularly after a snowfall.

Most of the heat conducted from the pipe will probably be consumed by evaporation if water is available. If it is not, surface temperatures will rise sharply.

Water from permafrost

If the sediments do not contain excess ice, in general no water will be delivered to the surface as a result of conductive thawing of permafrost. If 20 percent of the water were excess, it would appear at the rate of perhaps 20 or 30 cu ft per year (per foot of pipeline) in the first year. This would fall off rapidly in succeeding years to a few cubic feet per year. Hence, after the first year or two, water thawed from permafrost may be enough to provide an inch or so annually over a band a few tens of feet wide. This water probably will not play a significant role in the surface hydrologic regime or in hydraulic erosional processes; its cumulative contribution over 10 or 20 miles of pipeline would be equivalent to the output of one household water faucet.

If permafrost near the surface contained abundant excess ice, artificial disturbances could trigger self-perpetuating processes of thawing from solar radiation and convection. These could contribute significant amounts of surface water locally.

Surface drainage

In the section on temperature effects (fig. 2), it was shown that any frozen cap that might form over the thawed cylinder in winter would roll back in the spring to provide continuity with the naturally thawed active layer. In the section on differential settlement it was pointed out that this region above the pipe is likely to be the site of a depression. Typically, the surface has excess water in spring and early summer in permafrost regions, and it is likely that this water would tend to drain into the region around the pipe from the surrounding area. It is seen that an amount of water comparable to the excess annual evaporation (by conduction) could be supplied if an inch or so were drained from the surrounding terrain for distances on the order of 100 feet. If a depression occurred over the pipe and it were filled with permeable gravel, this drainage would not be impeded.

The depression, likely to occur over the pipeline in regions where the sediments are saturated, could have a profound effect on the surface drainage. If the depression were discontinuous, it could result in a series of ponds which can collect solar radiation and grow rapidly by thawing their banks in regions where the near-surface permafrost is ice rich. (It has been pointed out in the section on differential settlement that indiscriminate drainage of such ponds could result in severe stresses on the pipeline.)

If the depression over the pipe were relatively continuous, it could act as a focus for local surface drainage and intercept preexisting streams and create a drainage system where none existed before. This could affect the hydrologic regime over a substantial area, and it could cause problems of erosion along the pipeline.

Convective heat transfer and the hydrologic balance

It has been pointed out that conductive heat from the pipeline is not likely to have a major disruptive local effect on the hydrologic balance. It will result in excess annual evaporation equivalent to a layer of water on the order of 1 foot thick over a band effectively 25 or 30 feet wide. This is not different in order of magnitude from the natural annual evaporation over much of the route. It is likely that the deficiency will be more than compensated by the combined effects of local winter snowmelt that cannot run off, and by the influx of spring runoff into the depression likely to occur over much of the pipeline. If sediments in the thawed cylinder around the pipe are not saturated initially, it is likely that they will become saturated along much of it if the heat transfer to the surface is primarily by conduction.

We now consider the possible effects of heat transfer by convection arising from the potential instability of the water column heated from below in the sediments above the pipe. Density changes in the heated column will give rise to hydraulic gradients on the order of 2 percent. They must be balanced by dynamic forces arising from upward flow of warm interstitial water immediately above the pipe, and a downward counter flow of denser water at some distance from the pipe. The downward flow would normally represent a return of the upwelling water after it had given up its heat at the surface. The permeability of the materials determines the velocity of this flow, and the velocity and thermal gradient determine the amount of heat delivered to the surface by the convecting system. Thus, using Darcy's law for fluid flow and the heat-conduction equation, we can attempt an estimate of the vertical velocity of water movement and the convective heat flow for any permeability. A rigorous formulation of this convection problem is extremely complex and unwarranted by the objectives of the present study. It is possible that the numerical results presented in table 8 do not even represent the correct order of magnitude, but they are suggestive and of some interest. The fourth column (table 8) shows the enhancement of centerline heat flux resulting from convection. For permeabilities of 10^{-4} or less the convective contribution is unimportant. For permeabilities of 10^{-3} the contributions of convection and conduction at the centerline are comparable, and the effect on the surface regime becomes significant. However, the effective width of the convective contribution is about 4 feet, but that of the conduction is about 25 feet. Hence, total loss by conduction still tends to dominate loss by convection as is seen in column 5 (table 8). For permeabilities greater than

Table 8.—*Idealized relation between permeability and convective enhancement of surface heat loss (D=8 ft)*

Sediment permeability (cm per sec)	Vertical velocity (ft per yr)	Vertical velocity (ft per hr)	Convection+conduction / Conduction: Centerline flux enhancement	Convection+conduction / Conduction: Total heat loss enhancement	Vaporization rate for total heat loss (cu ft per yr per ft of pipe)
10^{-5} ---------	0.2	---	1.008	1.00	28
10^{-4} ---------	2.0	---	1.08	1.01	28
10^{-3} ---------	20	---	2.0	1.2	32
10^{-2} ---------	200	.023	16	3.4	94
10^{-1} ---------	2,000	.23	160	27	730
10^{-0} ---------	20,000	2.3	1,600	260	7070

10^{-3}, however, both centerline flux and total heat loss are dominated by convection; for permeable gravels ($\sim 10^{-0}$) the total heat loss is enhanced by two orders of magnitude (column 5, table 8).

Although the conductive centerline flux for D=5 is more than twice as great as that for D=8, the net convective heat loss is about the same in each case because it is insensitive to depth of burial.

The last column of table 8 shows the amount of water that would have to be vaporized annually to consume all of the heat that could be delivered to the surface from the convecting system. It is unlikely that the local hydrologic system would generally be able to supply the 7,000 cu ft or so of water per foot of pipe required annually by an 80°C pipe in permeable gravel (this is equivalent to about 1 ft of evaporation per day over a 20-ft band). Hence, conditions of desiccation would probably develop in most places where the pipe is embedded in very permeable materials. Until they did, however, the ground surface would remain unfrozen in winter, snow would melt almost as soon as it landed, and the pipeline might be shrouded in mist.

The remarkable variation of heat loss with permeability suggested by this calculation could offer an opportunity to control excess moisture or desiccation by controlling the permeability of the material above and adjacent to the pipe. To do this effectively it would not be enough to control permeability of backfill in the 4-foot-wide trench, as the convective system could not develop fully in such a restricted zone.

This convective effect might be utilized also to reduce the temperature of the oil in the pipeline and thereby reduce some of the adverse effects of thawing permafrost. If the entire pipe were laid in a trench whose width exceeded its depth and the trench were backfilled with permeable gravel, surely the oil could not maintain such high temperatures. If the pipe temperature were reduced from 80°C to 25°C, the hydraulic gradients would be reduced by a factor of 10 and thermal gradients by a factor of about 3. The convective heat loss would then be reduced by a factor of about 30. However, the total heat loss would still exceed, by an order of magnitude, the conductive loss from an 80°C pipeline, and further cooling might be expected. Even in this case, however, water supply may be a problem, as approximately 10 times the natural evaporation over a 25-foot band would be required. The ultimate amount of cooling possible by this process would depend upon heat generation by viscous forces in the oil. However, temperatures probably could not go below 15° to 20°C where the convective loss in permeable gravels would probably be of the same order as the conductive loss from an 80°C pipe. At such temperatures the water for cooling could probably be supplied by the natural regime. There are many problems with this scheme related to the availability of gravel and water, and the fact that significant permafrost thawing would occur even for greatly reduced pipe temperatures. The system is stable in the sense that as the pipe temperature tends to rise, the convective heat loss will rise sharply to counteract it. It is unstable in the sense that, if increasing heat loss outstrips the local supply of water, desiccation will commence, and pipe temperatures would rise sharply.

THE CONSTRUCTION DISTURBANCE

Among the most conspicuous surface effects relating to the pipeline could be the artificial modifications resulting from vehicular activity, excavation, grading, artificial drainage, and clearing of timber. These can have significant effects on the insulating and radiation-collecting properties of the surface and on heat-transfer processes relating to evaporation and movement of water. These, in turn, can have immediate and long-term effects on the thermal regime of the active layer and permafrost, and on the total environment. These effects are mentioned because some could be important. They are not elaborated because they are only indirectly related to the thermal effects of a pipeline, and further discussion is beyond the scope of this report.

CONCLUDING STATEMENT

This report has outlined some potential effects of a heated pipeline buried in permafrost. Effects selected for discussion were some that might be related to problems of disruption of the environment or to security of the pipeline. An attempt has been made to apply fundamental physical concepts to describe these effects in sufficient detail to identify the controlling parameters. These are the quantities that must be measured to ascertain whether the effects described might result in potential problems. An attempt has also been made to indicate the quantitative relation between these parameters and the effects they control, to serve as an aid in anticipating the problem after the measurements are made.

No attempt has been made to elaborate the many detailed environmental and engineering consequences that might arise from each of the effects and their various combinations. Those consequences discussed were generally in the nature of illustrative examples. To the extent that these effects exist, their detailed consequences are best considered by specialists: engineers, ecologists, hydrologists, geologists, and those concerned with matters of administration and control. No attempt has been made to suggest engineering solutions to the problems raised. Nor is there any intention to imply that these problems have not already been considered, or indeed solved, by engineers concerned with them.

This study was not exhaustive. Potential problems certainly exist that have not been considered, and some that have been considered may be shown not to exist by further studies. The report represents one perspective on an overall problem that transcends many disciplines and requires the perspectives of many for an optimal solution. It is hoped that the report will provide one reference point for objective discussion between the people of many backgrounds who must communicate effectively on this issue.

APPENDIX A—NUMERICAL SOLUTIONS

The numerical results presented in the temperature effects section were obtained on the U.S. Geological Survey IBM 360/65 computer. The program was written by Patrick C. Doherty at the U.S. Geological Survey Computation Center. It is documented in detail by him in a separate report. The purpose of this appendix is to describe what has been done.

The differential equation of heat conduction was solved numerically for the two-dimensional case of a pipe embedded in a semi-infinite homogeneous medium with a mean annual temperature T_a. From time t=0 onward the pipe temperature (T_p) is assumed to be 80°C, and the surface temperature fluctuates sinusoidally with a period of 1 year, an amplitude of 20°C, and a mean value of T_a. The initial temperature chosen for the medium is the quasi-steady-state periodic solution consistent with this surface temperature. Two different values of T_a were selected; -0.8°C termed the "interior case," and -8.9°C termed the "arctic case." The effects of latent heat absorption and liberation on thawing and freezing at the 0°C isotherm were accounted for. Also accounted for were the differences in thermal conductivity and volumetric specific heat between the frozen and thawed states. The geometric consequences of volume change of water on freezing were neglected as these are effects of higher order. The thermal behavior of the permafrost in the presence of the hot pipe was simulated over a 20-year period for three media described in the text (see table 1).

The principal geometric simplification of the problem resulted from representing the pipe as a prism with a square cross section 4 feet on a side. This permitted a substantial economy in the computations. It can be shown that this might result in an overestimate of the thawing distances by 10 percent or so, for early times. However, for longer times truncation errors in the time steps probably generated a small compensating error. For the purposes of the present study, discrepancies of this magnitude are not considered important; arbitrary decisions in the choice of thermal parameters could result in larger ones.

The problem solved is stated analytically below. The following notation is used (see also fig. 1):

T=temperature

t=time

α=thermal diffusivity

ρ=density

P=percent moisture by wet weight

K=thermal conductivity

x,y=cartesian coordinates

ω=angular velocity for a period of 1 year

A=amplitude of surface temperature variation

y^*=bottom of problem space

x^*=edge of problem space

X(t),Y(t)=coordinates of 0°C isotherm

L=latent heat of melting ice, per unit mass

The subscript "1" refers to the thawed state, and the subscript "2" refers to the frozen state.

Differential equations:

$$\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} = \frac{1}{\alpha_1}\frac{\partial T_1}{\partial t}, \quad y \geq 0, \quad (x, y) \text{ not in pipe}, \quad T > 0°C$$

$$\frac{\partial T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} = \frac{1}{\alpha_2}\frac{\partial T_2}{\partial t}, \quad y \geq 0, \quad (x, y) \text{ not in pipe}, \quad T < 0°C$$

Initial condition:

$$T=T_a + A\, e^{-y\sqrt{\frac{\omega}{2\alpha_2}}} \sin\left(\omega t - y\sqrt{\frac{\omega}{2\alpha_2}}\right), \quad t=0$$

fixed boundary conditions:

$$T=T_a + A \sin \omega t, \quad y=0$$

$$T=T_a, \quad y=y^*$$

$$\frac{\partial T}{\partial x}=0, \quad x-0,\ x^*$$

$$T=T_p, \quad (x, y) \text{ on pipe surface}$$

moving boundary conditions:

$$T_1=T_2=0, \quad x=X,\ y=Y$$

$$\left.\begin{aligned} K_1 \frac{\partial T_1}{\partial x} - K_2 \frac{\partial T_2}{\partial x} &= L\rho P \frac{\partial X}{\partial t} \\ K_1 \frac{\partial T_1}{\partial y} - K_2 \frac{\partial T_2}{\partial y} &= L_\rho P \frac{\partial Y}{\partial t} \end{aligned}\right\} \quad x=X,\ y=Y$$

APPENDIX B—STEADY-STATE RESULTS

The equilibrium solution for an isothermal pipe at temperature T_p embedded in a semi-infinite homogeneous medium with ambient and surface temperature T_a may be obtained directly from well-known results in potential theory. The problem may be stated formally as follows: (Notation is the same as in appendix A and fig. 1).

Differential equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \ , \ y > 0 \qquad \text{(B-1)}$$

Boundary condition:

$$T = T_a \ , \ y=0, \ (x, y) \rightarrow \infty \qquad \text{(B-2a)}$$

$$T = T_p \ , \ \text{on circle on radius } a \text{ with center at } x=0, \ y=D \qquad \text{(B-2b)}$$

The solution to this problem shows that the isotherms for any temperature (T) between T_p and T_a are circles with their centers on the axis of symmetry (y axis). Their depths beneath the surface (d) and radii (r) are given by

$$d = (D^2 - a^2)^{1/2} \coth \left[\frac{T - T_a}{T_p - T_a} \cosh^{-1} \frac{D}{a} \right] \qquad \text{(B-3)}$$

$$r = [D^2 - a^2]^{1/2} \left[\coth^2 \frac{T - T_a}{T_p - T_a} \cosh^{-1} \frac{D}{a} - 1 \right]^{1/2} \qquad \text{(B-4)}$$

The temperature T can be written as a function of d and r as follows

$$\frac{T - T_a}{T_p - T_a} = \frac{\cosh^{-1} \frac{d}{r}}{\cosh^{-1} \frac{D}{a}} \qquad \text{(B-5)}$$

An additional result, useful for computing the rate of heat loss from the pipe to the surface in equilibrium is

$$Q = \frac{2\pi K}{\cosh^{-1} \frac{D}{a}} (T_p - T_a) \qquad \text{(B-6)}$$

where Q is the total heat lost from the pipe per unit time per unit length.

Numerical results from (B-3) and (B-4) are presented in figure 6, for a pipe radius (a) of 2 feet and for burial depths (D) of 5 feet and 8 feet. We are interested in the parameters (d, r) for the freezing isotherm and, therefore, T is replaced by T_f (that is, 0°C). The quanity

$$\frac{T_f - T_a}{T_p - T_a}$$

will be referred to as the "temperature ratio." It is the ratio of the amount by which the freezing point exceeds the ambient temperature to the amount by which the pipe temperature exceeds the ambient temperature. For temperature ratios less than about 0.2 equations (B-3) and B-4) can be replaced by the approximations

$$d \simeq r \simeq 3.75 \frac{T_p - T_a}{T_f - T_a} \ , \ D=8 \qquad \text{(B-7)}$$

$$\simeq 2.92 \frac{T_p - T_a}{T_f - T_a} \ , \ D=5 \qquad \text{(B-8)}$$

where d and r are given in feet and the temperature is in °C. If the pipe temperature T_p is 80°C we have for the temperature ratio in the arctic case:

$$\frac{T_f - T_a}{T_p - T_a} = \frac{0 - (-8.9)}{80 - (-8.9)} = 0.1 \qquad \text{(B-9)}$$

and the interior case

$$\frac{T_f - T_a}{T_p - T_a} = \frac{0 - (-0.8)}{80 - (-0.8)} = 0.01 \qquad \text{(B-10)}$$

Combining the last four equations we see that for D=8, the equilibrium configuration of the freezing surface in the arctic case is a circle whose center is about 37.5 feet beneath the surface and whose radius is about 37.5 feet; that is, it is almost tangent to the surface and represents maximum thawing to a depth of about 75 feet. Correspondingly for the interior case (D=8) the radius is about 375 feet and maximum thawing is to about 750 feet.

In the idealized problem, d is always greater than r as long as $T_a < T_f$, but their difference, representing the thickness of a frozen surface crust, is generally very small, for example, 0.08 feet and 0.8 feet, respectively, for the interior and arctic cases (D = 8). Values for d and r can be read directly from the abscissa of figure 6 for any temperature ratio entered on the first ordinate scale (on the right). The second ordinate scale permits a direct reading of the parameters (d, r) for any mean annual temperature (T_a) under the condition that the pipe temperature is 80°C.

The third ordinate scale permits a direct determination of d and r for different pipe temperatures in the arctic case (T_a = -8.9°C), and the fourth ordinate scale yields the same information for the interior case (T_a = -0.8°C). Thus, if the pipe temperature is reduced from 80°C to 20°C, the total equilibrium thaw depth (d + r) will be about 190 feet in the interior but only about 25 feet in the arctic case for D = 8.

It is seen that as the temperature ratio approaches zero (that is, as the mean annual temperature approaches the freezing point) the equilibrium thawing depths approach infinity. Physically this means that eventually the heated pipe would remove all of the permafrost in this case; clearly this would take a long time. Actually for equilibrium values of d and r of a few hundred feet, thousands of years would be required to approach that condition at depth, and the solutions have little meaning in an engineering context. Above the pipe, however, equilibrium is approached rather quickly in all cases, and the solutions are useful for estimating conductive heat losses to the surface.

These solutions are adequate for order-of-magnitude steady-state calculations. They depart from reality chiefly by not accounting for the fact that the

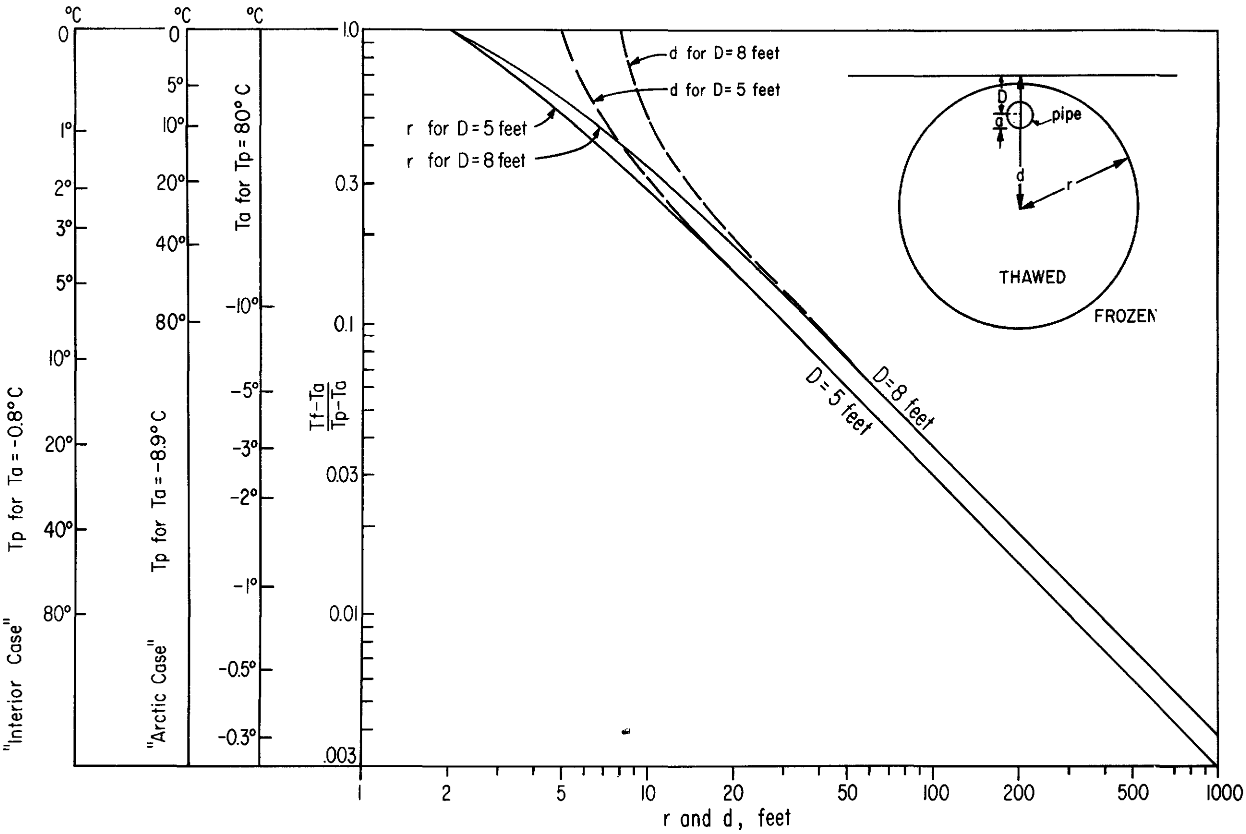

Figure 6.—Equilibrium position of the thawing interface for a 4-foot-diameter pipe with its axis at depth D (8 or 5 ft) in homogeneous materials. First ordinate scale on the right represents temperature ratio. Other ordinate scales are adjusted to give corresponding temperature ratios for fixed values of the pipe temperature (T_p) or ambient temperature (T_a). For refined calculations reduce T_p by the factor K_1/K_2 (see appendix B).

conductivity of the thawed material (K_1) is usually less than the conductivity of the frozen material (K_2). The effect of this contrast in conductivity can be accounted for by replacing T and T_p in foregoing equations by T' and T'_p defined by[2]

$$T' = \frac{K_1}{K_2}(T - T_f) + T_f \quad , \quad T > T_f \qquad \text{(B-11a)}$$

$$= T \qquad T \leq T_f \qquad \text{(B-11b)}$$

and

$$T'_p = \frac{K_1}{K_2}(T_p - T_f) + T_f \qquad \text{(B-12)}$$

[2]The writer is indebted to Mr. William Joyner for a suggestion leading to this solution.

For purposes of calculating d and r from figure 6 this is equivalent to reducing the pipe temperature in °C by the fraction K_1/K_2. If the true pipe temperature is 80°C, it is seen from table 1 that the effective pipe temperatures to be used in figure 6 for silt, clay, and water/ice are respectively 54.4°C, and 50.0°C, and 17.8°C. These lead to equilibrium thawing depths (d + r) in the arctic cases of 52 feet, 50 feet, and 24 feet, respectively (fig. 6). Corresponding values for the interior case are 520 feet for silt, 480 feet for clay, and 185 feet for water/ice. It can be estimated from figure 4 and scaling laws for heat conduction that in the arctic case equilibrium might be approached for water/ice in two decades, but for more typical materials it will take on the order of a half century. For the interior cases equilibrium would not be approached for tens of centuries.

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