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LES EFFETS THERMIQUES ET LE PERGÉLISOL

RESUME

Les auteurs étudient brièvement le rôle du climat et, en particulier, de la température de l'air dans la distribution géographique du pergélisol au Canada. Ils étudient en termes généraux les propriétés thermiques du pergélisol et les facteurs climatiques qui constituent le bilan thermique superficiel. Ils montrent l'importance des zones superficielles dans la détermination du régime thermique du sol au moyen de calculs théoriques qui se fondent sur un modèle de différences finies à une dimension. A l'aide d'un modèle simplifié de différences finies à deux dimensions, ils présentent des calculs théoriques du dégel autour d'un oléoduc "chaud" et du gel autour d'un gazoduc "froid", et font une étude qualitative des problèmes de tassement et de stabilité qui en résulteraient. Les auteurs mentionnent l'importance du drainage et l'effet des nappes d'eau sur le pergélisol. Enfin, ils passent brièvement en revue les méthodes de conception et de construction courantes qui visent à réduire au minimum les perturbations thermiques par suite des travaux de remblai et de fondation dans les régions de pergélisol.

NATIONAL RESEARCH COUNCIL OF CANADA
DIVISION OF BUILDING RESEARCH

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SUMMARY

The role of climate and, in particular, air temperature in determining the geographical distribution of permafrost is discussed briefly for Canadian conditions. The thermal properties of permafrost materials and the climatic factors that make up the surface heat balance are discussed in general terms. The importance of surface materials in determining the ground thermal regime is illustrated by a number of theoretical calculations based on a one-dimensional finite-difference model. Using a simplified two-dimensional finite-difference model, theoretical calculations of thawing round a hot oil pipeline and freezing around a cold gas pipeline are presented and the settlement and stability problems that would result are discussed qualitatively. The importance of drainage and the effect of water bodies on permafrost is commented on. Finally, a brief review is given of current design and construction practice to minimize thermal disturbance when placing fills and foundations in permafrost regions.

THERMAL EFFECTS IN PERMAFROST

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Permafrost is defined as the condition of the ground when the temperature is continuously below 0°C for more than one year. When the ground is in this condition, the water in it is usually frozen. If the ground surface is disturbed, a temperature change large enough to cause thawing may be induced. Thawing of ice-rich soils can create serious problems, particularly for construction and related activities. For many of these problems, solutions have not yet been developed either through experience or research. It is important, therefore, that those responsible for work in the North have an appreciation of the factors that affect the temperature of permafrost, the effects of engineering activities on these factors, and the design and construction practice that should be followed when thermal disturbance must be kept to a minimum. These topics are discussed in this paper.

GROUND THERMAL REGIME

The surface of the ground is the lower boundary of the earth's atmosphere. Driven by radiation from the sun, the atmosphere carries heat and moisture to and over it under the influence of the Coriolis force and topographical features. The earth's surface responds thermally not only to the direct effects of this radiation, but also to the heat and moisture brought to it or taken away by the moving atmosphere.

Thermal and moisture conditions at the earth's surface are continually changing. The temperature at which these changes occur undergoes cyclic variations due, primarily, to the periodicity in the intensity of the sun's radiation that reaches the surface. These cyclical variations have major periods of one year and one day, but superimposed on these are periods of variable length associated with weather and climatological changes.

Along a given longitude, the average annual temperature about which the cyclic changes take place, decreases northward. At some latitude the decrease is sufficient to produce the conditions required for the occurrence of permafrost. In Canada this can be expected north of the zone whose mean annual air temperature is about 30° F (-1° C). Climatological information[1] indicates that about one-half of Canada is underlain by permafrost.

Brown[2] has given considerable attention to the distribution of permafrost in Canada. In general, the permafrost region can be divided into two zones: the discontinuous in the south and the continuous in the north. At the southern edge of the discontinuous zone, permafrost is shallow, occurs in patches or islands and is confined to certain types of terrain, mainly peatlands. The islands of permafrost are surrounded by unfrozen material and have a temperature close to the melting point. They can be transient, forming and disappearing in response to fluctuations in climate or changes in surface conditions.

With increasing latitude the permafrost becomes thicker and more extensive. At the boundary between the discontinuous and continuous zones, where the average annual air temperature is about 17° F (-9° C), its thickness is about 200 ft (60 m) and continues to increase northward, exceeding 1500 ft (460 m) in the Arctic Archipelago.

Average annual air temperature is a good indicator of the possible presence of permafrost. The average annual temperature of the ground, however, may be more than 10° F (6° C) warmer than the average annual air temperature[3], the difference depending on the factors controlling the exchange of heat and moisture between the surface and the atmosphere and the thermal properties of the ground near and at the earth's surface.

Thermal Characteristics of Permafrost

The average annual temperature of the ground usually increases with depth, indicating conduction of heat from the interior of the earth to the surface. This increase, or geothermal gradient, is about 1° F per 100 ft (about 1° C per 50 m) and the heat flow associated with it about 2×10^{-2} Btu/ft^2 hr (6.3×10^{-2} w/m^2). Superimposed on the geothermal gradient near the surface is the daily and annual variation in temperature. The amplitude of these periodic temperature changes decreases exponentially with depth at a rate determined by the thermal conductivity, density and heat capacity of the soil and the frequency of the change[4,5]. A typical value for the depth of penetration of the annual wave is about 25 ft and for the daily wave about 1 ft. The depth dependence of ground temperature is illustrated in Figures 2, 3 and 4.

It can be seen from the figures that the ground in permafrost areas can be expected to thaw to some depth beneath the surface each summer. The material subject to annual thawing constitutes the active layer. Usually the depth of thaw defines the top of the permafrost (or permafrost table) but in some cases, particularly in marginal permafrost areas, there may be a stratum of unfrozen material between the bottom of the active layer and the top of the permafrost.

Soils do not usually obey the assumptions of simple heat conduction. They are porous and normally have a significant water content. The thermal properties, such as the diffusivity, conductivity and heat capacity, depend on soil type, density, water content and temperature. Transfer of heat can occur not only by normal conduction, but also by the movement of water and water vapour through the pores.

Freezing is also a complicating factor. Water can be drawn from the unfrozen soil by the forces set up by the freezing process, to form segregated ice. This ice is usually in the form of lenses and can cause significant heaving of the ground and uplift forces[6,7].

Studies of the freezing process in soils have shown that the temperature at which water begins to freeze depends on the size of the space in which it is contained and the degree to which it is bonded to a surface[6,7,8]. The freezing of the water is spread over a temperature range that depends on soil type and water content. For sands and coarse silts, most of the water will be frozen if the temperature is below 28° F (-2° C). For clays, there may still be significant unfrozen water at 20° F (-7° C). This behaviour has a significant effect on thermal properties.

Freezing and thawing requires the extraction or addition, respectively, of an amount of heat called the latent heat of fusion. For water, it has a value of 144 Btu/lb (3.35×10^5 J/kg), an amount large compared with the heat required to change the temperature of 1 lb of saturated soil by 1° F (i.e. about 0.3 Btu/lb). It can be appreciated, therefore, that the rate of advance of the region of freezing will depend on the type of soil, water content and the ability of water to move into it (i.e. the permeability of the soil).

The distribution of the ice in permafrost is determined by its genesis[9]. It can vary from a uniformly dispersed, non-segregated condition to monolithic masses. The distribution of the ice becomes particularly important when it is necessary to predict the behaviour of permafrost during and after thawing.

These factors must all be taken into consideration when accurate calculations are required concerning temperature changes in the ground. When consideration is also given to the variation in thermal properties associated with the normal layering of soil and rock, it is clear that for many locations it will not be possible to make such calculations using simple theory. For these situations it may be necessary to give careful thought to defining the "design condition," and to use numerical methods to determine the associated thermal response of the permafrost.

Surface Conditions

The earth's surface receives or loses heat by radiation, evaporation, convection or conduction in the ground. At all times the heat associated with these processes must be in balance. The temperature imposed on the surface is determined by this balance.

Radiation is received directly from the sun, the amount depending on the atmospheric conditions, time of day, time of year, latitude and orientation of the surface. A certain amount of this "short wave" radiation is absorbed and converted to heat; the remainder is reflected. The amount absorbed depends upon the characteristics of the surface and the angle of incidence of the radiation; a water surface may absorb more than 98 per cent, a soil surface between 80 and 90 per cent and a snow surface as little as 10 per cent.

Every surface emits "long wave" radiation, the rate of emission being determined by the temperature of the surface and its emissivity. The surface of the earth not only emits such radiation but receives it from the sky as well.

The relative importance of evaporation and convection with respect to the surface temperature, depends on the availability of water. If evaporation is restricted as, for example, on an airstrip or by some lichen covers, the average surface temperature will be higher than if the surface were saturated, because absorbed solar radiation must be dissipated by increased convection, long wave radiation and heat flow into the ground. A freely evaporating surface would probably have an average weekly temperature not very different from the average air temperature; a completely dry surface can have an average weekly temperature several degrees higher[10].

The ability of the ground to accept or give off heat depends upon the product of the thermal conductivity and the volumetric heat capacity. This quantity has been called the thermal contact coefficient[4]. The smaller its value the smaller is the effect that the heat received or lost at the surface has on the ground thermal regime.

Ground Temperature Calculations

Calculations were carried out with a one-dimensional finite-difference computer program to illustrate the effect of surface conditions on the ground thermal regime. The program was capable of handling time- and temperature-dependent thermal properties and latent heat effects; it was not able to take into account frost heaving or thaw settlement.

The depth dependence of the amplitude of the annual temperature wave and the mean annual temperature were determined for a clay deposit with and without snowcover; clay deposit overlain with 11.8 in. (0.3 m) of peat, with and without snowcover; and a clay deposit overlain with 59 in. (1.5 m) of gravel. The thermal properties assumed for the calculations are presented in Table 1 and Figure 1. A sinusoidally varying air temperature with an annual mean of 18°F (-7.7°C) and amplitude of 38.4°F (21.3°C) was assumed. The surface temperature was made equal to the air temperature, (i.e. the surface materials were considered to be saturated at all times).

Snow cover was assumed to begin 29 September, with the depth increasing linearly to a maximum of 15.7 in. (0.4 m) on 1 February and remaining constant thereafter until the onset of melt. Melt was assumed to begin when the air temperature exceeded 30°F (-1°C); the period of melting was estimated using a simple melt factor approach. During the short snow melt period, the snow-ground interface temperature was set at 0°C.

The foregoing climate, ground and snow data are representative of conditions at Inuvik, N.W.T. Calculated ground temperature distributions refer, in all cases, to the periodic steady state.

The results for clay are presented in Figure 2. Comparison of curve 2a with 2b illustrates the significant effect of snowcover which, in this case, is to increase the average annual ground temperature by about 11.6°F (6.5°C) and the depth of thaw by about 1.3 ft (0.4 m).

Figure 3 gives the results for the case of clay overlain by peat. The effect of the peat is to make the average annual ground temperature lower than the corresponding no-peat situation and to decrease the depth of thaw. Comparison of Figure 3 with Figure 2 indicates the possible consequences of removing or disturbing the peat layer. Snowcover is again seen to have a marked influence on the ground thermal regime.

In Figure 4 are shown the consequences of replacing the peat layer by a 59-in. (1.5 m) snow-free gravel fill. The average annual temperature is about the same as for the snow-free clay deposit (curve 2b), but the depth of penetration of the active layer into the clay is reduced by 2.6 ft (0.8 m).

Figure 5 illustrates the consequences of placing a 3.9-in. (0.1 m) layer of insulation at the gravel-clay interface. The average annual ground temperature is unchanged from the no-insulation situation but the clay remains frozen throughout the year.

Finally, Figure 6 shows the effect of position of the insulation layer. In both Figures 5 and 6 the depth of the active layer appears to be determined almost completely by the position of the layer of insulation.

EFFECTS OF CONSTRUCTION AND OPERATIONAL ACTIVITY

The foregoing discussion has been for situations where the horizontal extent of the uniform surface and subsurface conditions has been much greater than the depth of significant annual temperature change. Engineering activities affect temperatures primarily by introducing changes of finite size in the ground surface or subsurface conditions. It is important to know what the effect of such changes will be on the physical and mechanical properties of permafrost. In some cases thawing will occur which may result in settlement or loss of stability; in others aggradation of the permafrost may cause frost heave problems. Normally the approach in design is to use methods that will preserve the frozen condition of the ground, but there are situations for which thawing cannot be prevented and steps must be taken to control the rate and extent of degradation. Some examples of northern engineering activities and their influence on the ground thermal regime are discussed in the following sections. An appreciation of the one-dimensional behaviour considered in the previous section is useful when considering these examples.

Buried Pipelines

The construction and operation of a buried pipeline will cause a disturbance to the ground thermal regime. Temperatures will change during construction because of the alteration to the composition of the ground and the heat balance at the surface by clearing, ditching, pipe-laying and backfilling. When operating, the pipeline will act as a heat source or sink, depending on whether the operating temperature of the line is above 32° F (0°C) or below.

Hot Lines

It is not uncommon for permafrost to contain 20 to 70 per cent ice by volume. Thawing of this ice will cause settlement and a marked change in the strength of the originally frozen soil. The integrity of a pipeline depends on the differential settlement that may take place during thawing and on the support provided by the thawed material. Settlement also affects the topography with potentially serious consequences with respect to surface drainage and erosion. It is necessary, therefore, to know how each particular permafrost condition will be affected by a buried hot pipeline in order to establish whether construction is feasible and if so, how it should be carried out and the line operated and maintained so as not to cause unacceptable damage.

The strength of soil depends on the stress that exists at the points of contact between the soil particles. This stress, in turn, depends on the pore water pressure. It can be reduced to zero if the pore water pressure is sufficiently high, causing the soil to have very little or no resistance to shear deformation.

During thawing the pore water pressure depends on the rate at which the ice is melted and the resulting water is moved through the thawed zone. If the rate of thaw is small and the permeability large, only negligible excess pore pressures will develop and the soil will probably have significant strength. If the rate of thaw is large relative to the rate at which water can be moved from the thaw front, the pore pressures may become high enough to reduce the strength of the soil sufficiently to cause an unstable condition. The foregoing discussion indicates the need to establish for design purposes the probable ice content and its spatial variability, the in situ permeability of the thawed soil and the time dependence of the extent and rate of thaw.

Figure 7 shows predicted thaw fronts after 1, 5 and 10 years of operation of a hot line in permafrost. The predicted fronts were calculated with a computer program incorporating several simplifying assumptions. It was assumed that the temperature of the ground surface was periodic, varying sinusoidally about a mean annual temperature of 17° F (-8.8°C) with an amplitude of 36° F (20°C). The soil was assumed to be a uniform saturated fine-grain material with a water content of 30 per cent. Average values of thermal conductivity for the frozen and unfrozen soil were selected from Kersten[12]. It was assumed that all ice melted at 32° F. Geometric changes due to settlement as thawing progressed were ignored. Two pipe temperatures were considered: 65° F (18.3°C) and 175° F (79.4°C).

Figure 7 indicates the amount of material that can be affected by a warm or hot pipe. Some of the possible consequences of these effects have been discussed by Lachenbruch[13]. Even if, on thawing, the material retains sufficient strength to prevent a sudden failure, slow downslope movement might still occur which, if not controlled, could result in serious maintenance problems. Very little is known at this time about the conditions for thawing permafrost that would allow either sudden failure or slow sustained movement.

Cold Pipelines

In the unfrozen areas of the discontinuous permafrost zone or adjacent to large water bodies in the continuous zone, freezing due to a pipeline operated below 32° F may cause heaving due to ice segregation, particularly if the soil is fine grained. Although the consequence of such heaving must be taken into consideration, it may not pose a serious problem for the line except, for instance, at pumping stations, because the frozen soil and pipe may act as a composite beam with sufficient strength to withstand the forces imposed on it.

If the cooling equipment breaks down, thawing may be induced resulting in the problems associated with a hot line. Problems might also occur when the thawed annulus is refrozen after the pipe is brought back into service.

Figure 8 shows predicted freezing fronts for a cold pipe in an initially unfrozen soil. The difference between the temperature changes imposed by a refrigerated natural gas line at 20° F (-6.6°C) and a liquefied one at -165° F (-109.4°C) is clearly evident from the position of the respective freezing fronts for the same time.

The frozen zone created by a cold line will act as a barrier to water and thereby affect surface and subsurface drainage. This effect may have serious consequences for surrounding areas, particularly at locations where there is significant water movement beneath the surface. It is difficult to assess at this time all the possible effects of a frozen barrier but it is probable that ponding would occur in warm periods and icing in cold periods.

Drainage and Water Bodies

A large amount of heat can be stored in water as sensible and latent heat and transferred from one area to another by drainage or stream flow and by evaporation-condensation. Because of its heat storage capacity, surface and subsurface water exerts an important influence on the ground thermal regime. Standing or moving bodies of water can inhibit the formation of permafrost. Flooding or ponding of water in areas underlain by permafrost imposes a new (and usually much warmer) temperature on the ground surface. Thawing of the permafrost may occur as the ground thermal regime adjusts to the new condition.

In permafrost areas a thawed zone is always found under lakes and streams that contain unfrozen water throughout the year. Although such water bodies have the greatest thermal effect on permafrost, small ponds that freeze to the bottom each winter also influence and modify the ground thermal regime. The thermal effect of a water body can be felt not only below but also to some distance beyond the water-land interface. Where a thawed basin exists beneath a lake or stream the boundary between the unfrozen and frozen materials is usually found (within the relatively shallow depths below the surface which are of engineering interest) at or immediately adjacent to the edge of the water. Its location, however, depends upon a number of factors including the water depth, soil type, and thermal characteristics of the water and soil.

The thawing effect of water is of particular importance to the engineer in the design and performance of structures that impound water, such as dams and dykes. Examples of changes in the ground thermal regime under lakes and reservoirs in permafrost areas have been reported[14,15]. Deep thawing under water bodies and adjacent structures raises the same problems of stability and settlement of foundation materials as does the hot buried pipeline.

Interruption of the natural surface and subsurface movement of water may have serious consequences if drainage is not considered or inadequate drainage facilities are provided. The effects of even shallow ponds (that may or may not freeze to the bottom during the winter) or redirection of existing drainage channels due to impeding the natural drainage or disturbing the surface cover, must be recognized. The ground thermal regime can be significantly affected to the point where deep thawing and erosion may have serious consequences on structures and engineering facilities. Settlement and stability are major considerations but, in addition, the availability of moisture can introduce or increase the detrimental effects of frost action.

One must also be aware of the effects of draining bodies of water. In this case cooling of the ground can cause freezing of the saturated materials with subsequent frost heave and thermal contraction cracking. The formation of pingos is possible and even probable.

Minor disturbance of natural drainage (surface and subsurface) can cause the formation of extensive "icings" (i. e. deposits of ice on the ground surface) at undesirable locations, which may interfere with the operation of roads, bridges or other structures and be a recurring maintenance problem. Solifluction (i. e. slow downslope movement of materials in the active layer) may be induced or rates of movement increased on even slight slopes. In the extreme, mud flows and large-scale slope failures may be precipitated by accelerated thawing and increased moisture resulting from changed drainage conditions.

FILLS AND FOUNDATIONS

Foundations and engineering facilities in permafrost areas are usually designed to preserve the frozen condition of the ground in order to prevent thawing and potential settlement and stability problems and to utilize the relatively high strength of frozen material. Where thawing of the frozen ground cannot be prevented, the rate and extent of degradation are factors that must be taken into consideration in design. The thermal interplay between the atmosphere, structure and the ground are basic considerations in foundation design.

Preventing degradation and encouraging aggradation of permafrost is accomplished by insulating the ground surface, isolating the structure from the ground, or a combination of both methods. Fills or pads are widely used not only for foundations but also to protect the surface cover from disturbance due to construction operations. Simple fills of sufficient thickness to prevent thawing of the underlying frozen ground, sometimes constructed of layers of materials having different thermal properties, are generally used for roads, airstrips and railway embankments.

The new conditions imposed by a fill result in a drastic change in the heat exchange at the original surface and consequently in the ground thermal regime. Because the snow cover is usually removed by plow or wind, or its effect greatly reduced by compaction, the fill is generally cooler than the adjacent ground during the winter. Conversely, in the summer, because more radiation may be absorbed by the relatively dark exposed surface and the cooling effect of evaporation is absent or markedly reduced compared with vegetation-covered areas, the fill is usually warmer than the surrounding ground. The increased amplitude of the annual surface temperature usually results in a proportionally larger fluctuation in temperature below the surface. The depth to which this effect will have an influence is dependent on the physical and thermal characteristics of the fill material. Fine-grained materials with high moisture content attenuate temperature changes more rapidly with depth than granular materials with low moisture content.

The effect of stripping the organic cover (or disturbing it to the extent that it loses its insulating value) prior to or as a result of placing a gravel fill can be seen by referring to the curves in Figures 3 and 4. The conditions assumed resulted in a decrease in the average ground temperature and little or no change in the depth of thaw in the clay. Similar illustrative comparisons can be made for other situations, e. g. by comparing curves in Figures 2 and 4. It must be remembered, however, that the illustrated cases are for a semi-infinite surface and do not consider edge or other geometric effects. In addition the assumption that the surface temperature is the same as the air temperature is not necessarily valid, particularly for a gravel fill.

Lachenbruch[4] has shown that the ability of a fill to maintain the frozen condition in the foundation material depends on its diffusivity and thermal contact coefficient and the contact coefficients of all underlying layers which are sufficiently close to the surface to produce appreciable effects, i. e. the minimum thickness of gravel necessary to preserve permafrost depends on the thermal properties of the subgrade. Only under favourable conditions of soil and climate will it be practicable to use a single layer of gravel to prevent thawing.

At locations where the construction of a fill sufficiently thick to prevent thawing is not economical or feasible, consideration can be given to a layer of insulation within the fill or between the fill and subgrade. This layer may be of locally available materials (e.g. peat or logs) or a commercially manufactured insulation. The effect of placing an insulating layer and its position in the fill can be seen by comparing Figure 5 with Figure 6.

Most heated structures, e.g. buildings, oil storage tanks, are supported on piles or piers, well embedded in the permafrost, with an air space between the bottom of the structure (which may be insulated) and the ground surface, in order to allow heat losses to be dissipated by natural air movement. The thermal conditions imposed on the ground by such structures are markedly different from the conditions at adjacent undisturbed areas. For example, a structure shelters the underlying ground from solar radiation and snow. In addition, a protective mantle of gravel, carefully sloped to provide surface drainage, is usually placed over the building site and thus eliminates the cooling effect of evaporation from the living vegetation cover. The changes induced in the ground thermal regime by the new conditions can have a significant effect on the strength of the frozen soil. It is necessary to predict these effects when the strength of the ground (and, therefore, the maximum temperature that will occur) is a factor in the design of a foundation. Changes in the annual amplitude of the ground temperature are of particular interest. Conduction of heat to and from the ground along foundation members must also be considered.

For heated structures that are in direct contact with the ground surface, e.g. maintenance garages, aircraft hangars, and oil tanks, and which maintain the surface temperature always above 32°F (0°C) it is usually more economical to intercept and divert heat from the structure if the foundation material must be kept in a frozen condition. Ventilating systems consisting of ducts placed through the fill under the structure, are normally used[16]. Air movement through short ducts (<20 ft (6 m) long) may be by natural convection, but for longer systems it may be necessary to utilize "chimney or stack effect" or ventilating fans to ensure adequate air flow and heat removal.

It is not usually necessary (or possible) to divert the heat flow all of the time. Ventilating systems operate only during periods when ambient temperatures are below 32°F. During warm periods the ducts are closed off. By judicious design, the thickness of floor insulation and underlying fill can be selected so that the permafrost will not thaw.

For critical structures which can tolerate little or no movement, or at locations underlain by ice-rich materials which, if thawed, would result in large-scale settlement and deformations, artificial refrigeration systems may have to be installed to ensure that the temperature of the permafrost remains below 32°F (0°C).

CONCLUDING REMARKS

The principal characteristic of permafrost that must be fully appreciated from the engineering point of view is its potential to contain ice which, when thawed, can result in serious settlement and stability problems. This fact indicates the necessity of being able to establish the effects of engineering activity on the ground thermal regime. Ground temperature is dependent on the conditions imposed on the surface or near surface regions. Because of the possible effects that thawing the permafrost may have on the integrity of structures and stability of the terrain, it is imperative that engineers establish the capability of predicting the consequences of their activity on ground temperature and develop the design and construction techniques that will be acceptable for permafrost areas.

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TABLE 1

THERMAL PROPERTIES ASSUMED FOR COMPUTER CALCULATIONS OF THE GROUND THERMAL REGIME

Material	Dry Density		Water Content (% by mass)	Specific Heat of Dry Material	Unfrozen Water (content function)	Thermal Conductivity (see Fig. 1)
	lb/cu ft	kg/m^3				
Peat	15.6	250	150	0.46	$Unf=0.94e^{3.73\theta}+0.56$*	Theoretical model of de Vries (11)
Gravel	109	1750	10	0.18	All water freezes at 0°C	Kersten (12)
Clay	81.2	1300	30	0.18	$Unf=0.24e^{-1.16\sqrt{-\theta}}+0.06$	Theoretical model of de Vries (11)
Snow	15	240	-	0.50	-	Abel's formula $k=2.9\times10^{-6}\rho^2\ w.m^{-1}.°C^{-1}$
Insulation	1.0	16	-	0.27	-	$0.023\ Btu.hr^{-1}.ft^{-1}°F^{-1}$ $(0.04\ w.m^{-1}.°C^{-1}$

*θ is temperature in °C

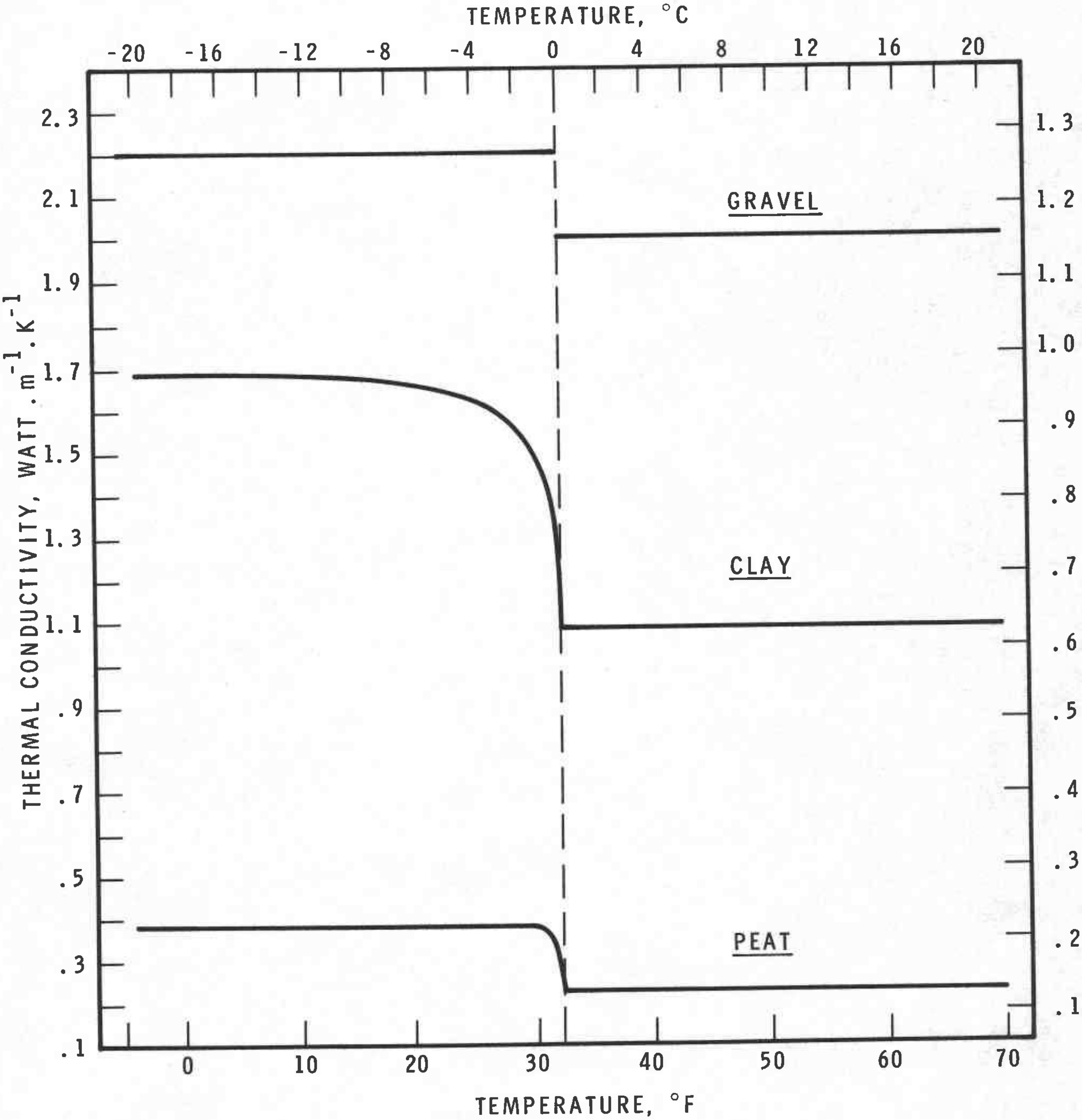

FIGURE 1

ASSUMED TEMPERATURE DEPENDENT THERMAL CONDUCTIVITY FOR GRAVEL, CLAY AND PEAT

BR 4855-1

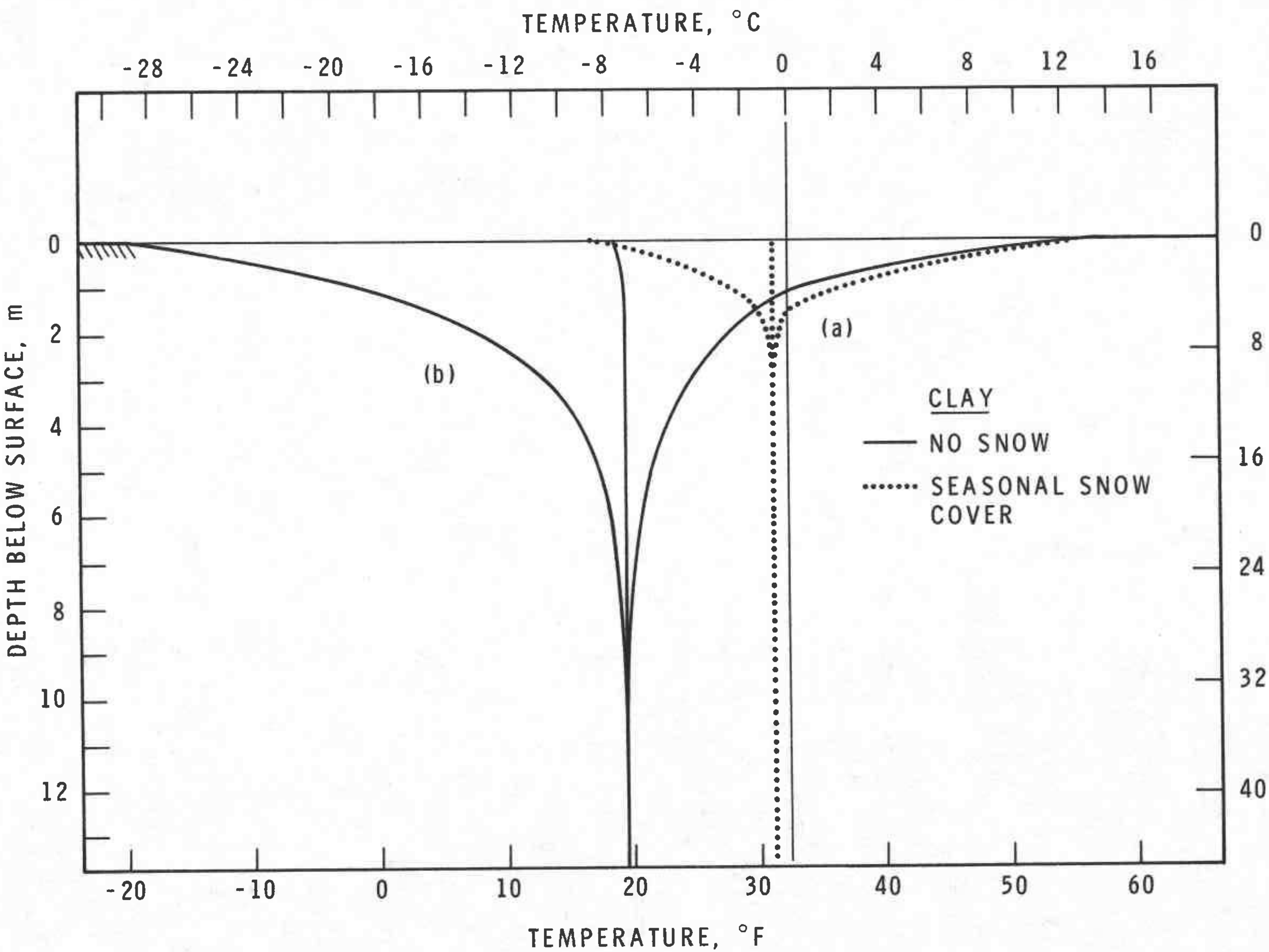

FIGURE 2

MEAN ANNUAL GROUND TEMPERATURE AND ENVELOPE OF ANNUAL TEMPERATURE CHANGE FOR CLAY; (a) 0.4 M SNOW COVER; (b) NO SNOW COVER

AR 4855-3

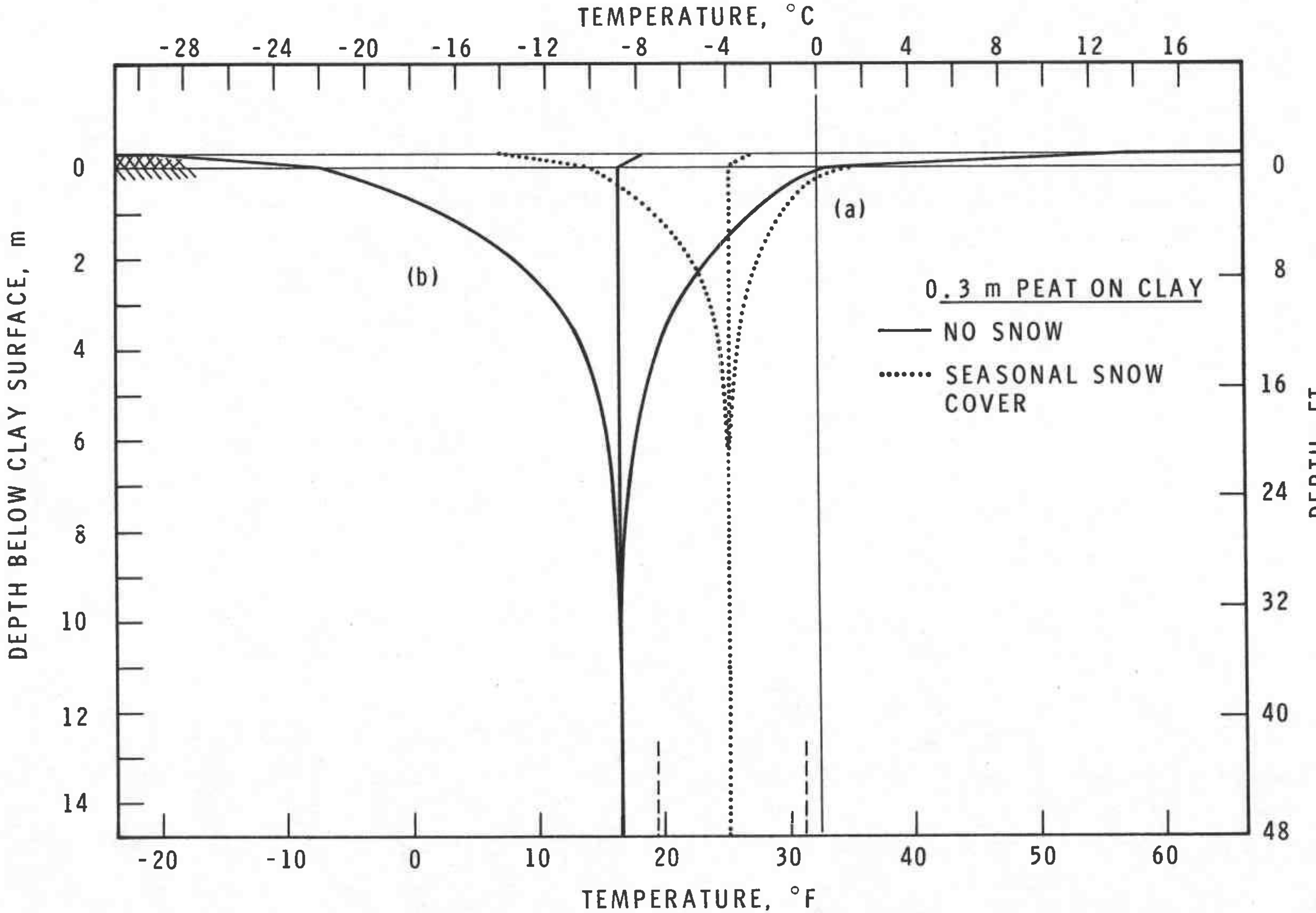

FIGURE 3

MEAN ANNUAL GROUND TEMPERATURE AND ENVELOPE OF ANNUAL TEMPERATURE CHANGE FOR CLAY OVERLAIN BY 0.3 M PEAT; (a) 0.4 M SNOW COVER; (b) NO SNOW COVER

AR 4855-2

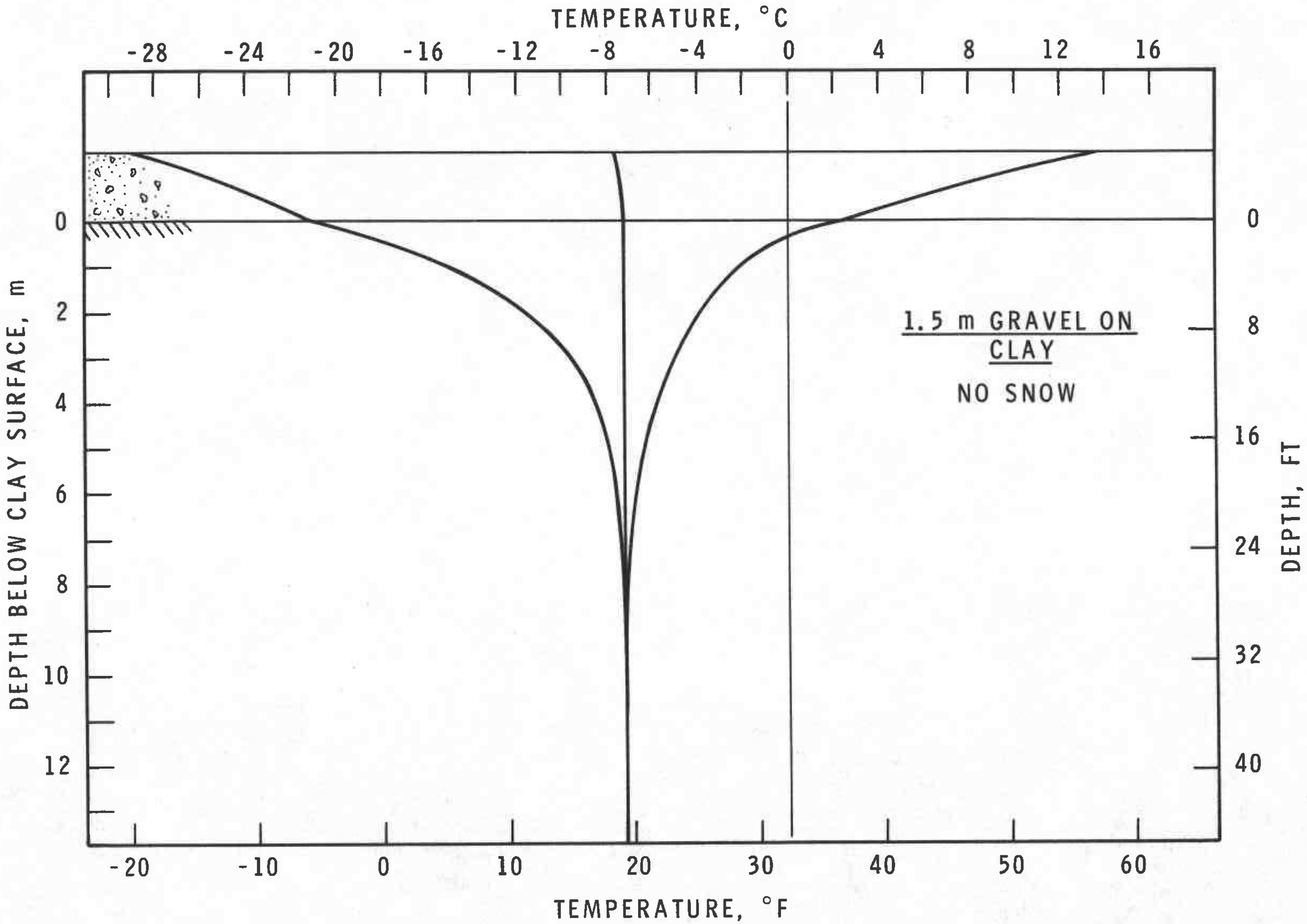

FIGURE 4

MEAN ANNUAL GROUND TEMPERATURE AND ENVELOPE OF ANNUAL TEMPERATURE CHANGE FOR CLAY OVERLAIN BY 1.5 M GRAVEL

AA 4855-4

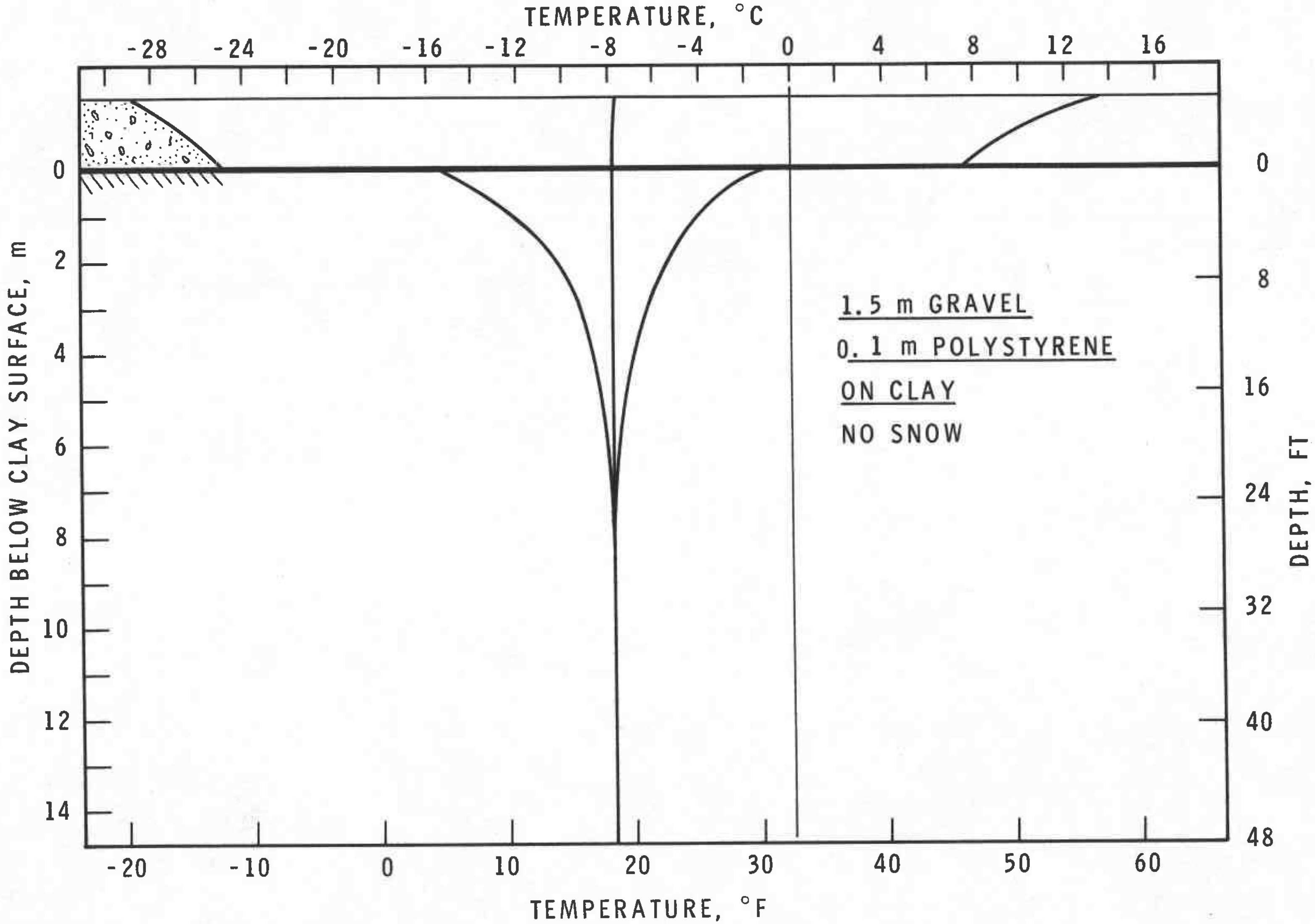

FIGURE 5

MEAN ANNUAL GROUND TEMPERATURE AND ENVELOPE OF ANNUAL TEMPERATURE CHANGE FOR 1.5 M GRAVEL AND 0.1 M POLYSTYRENE ON CLAY

AR4855-5

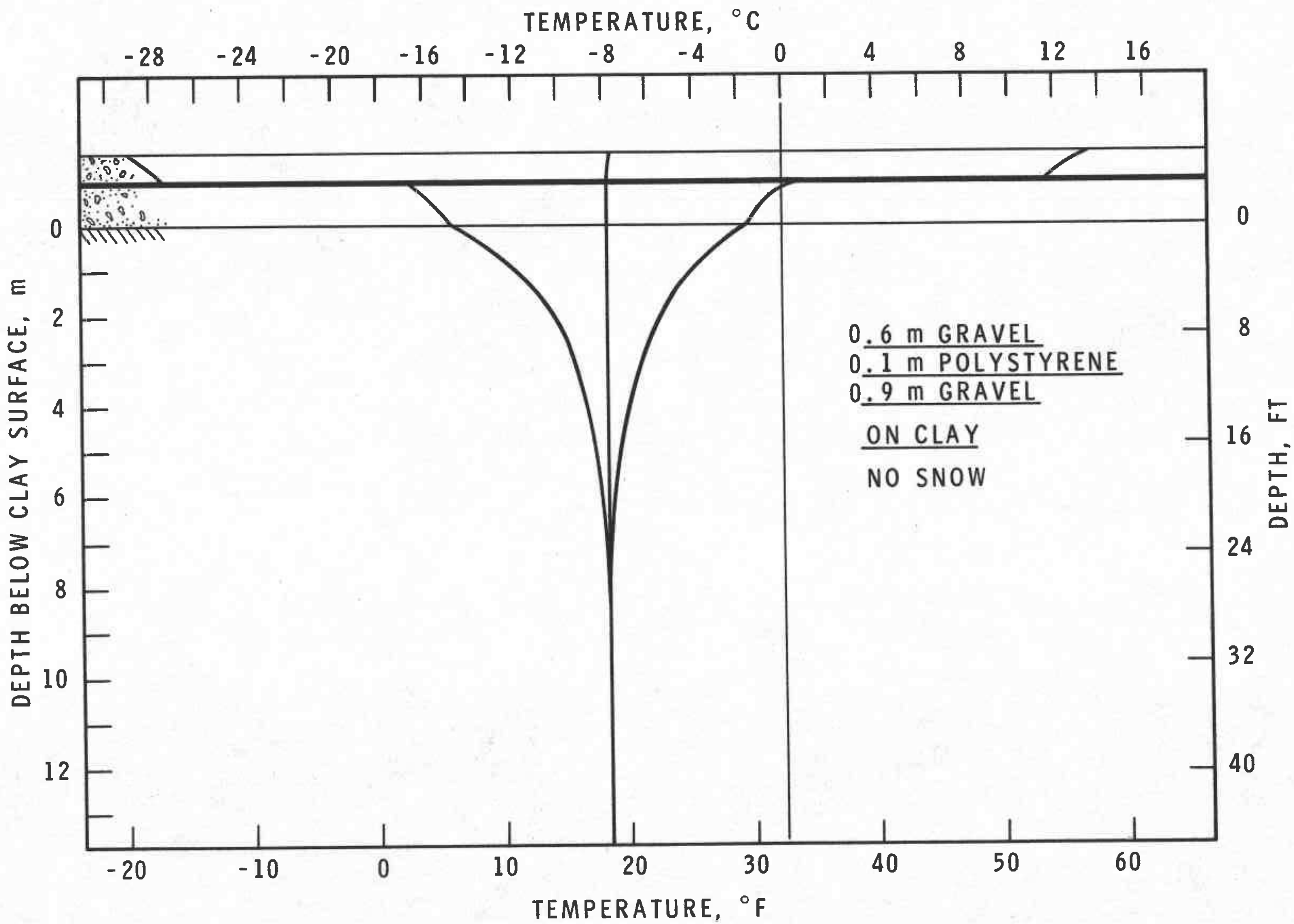

FIGURE 6

MEAN ANNUAL GROUND TEMPERATURE AND ENVELOPE OF ANNUAL TEMPERATURE CHANGE FOR 0.6 M GRAVEL, 0.1 M POLYSTYRENE AND 0.9 M GRAVEL ON CLAY

AR 4855-6

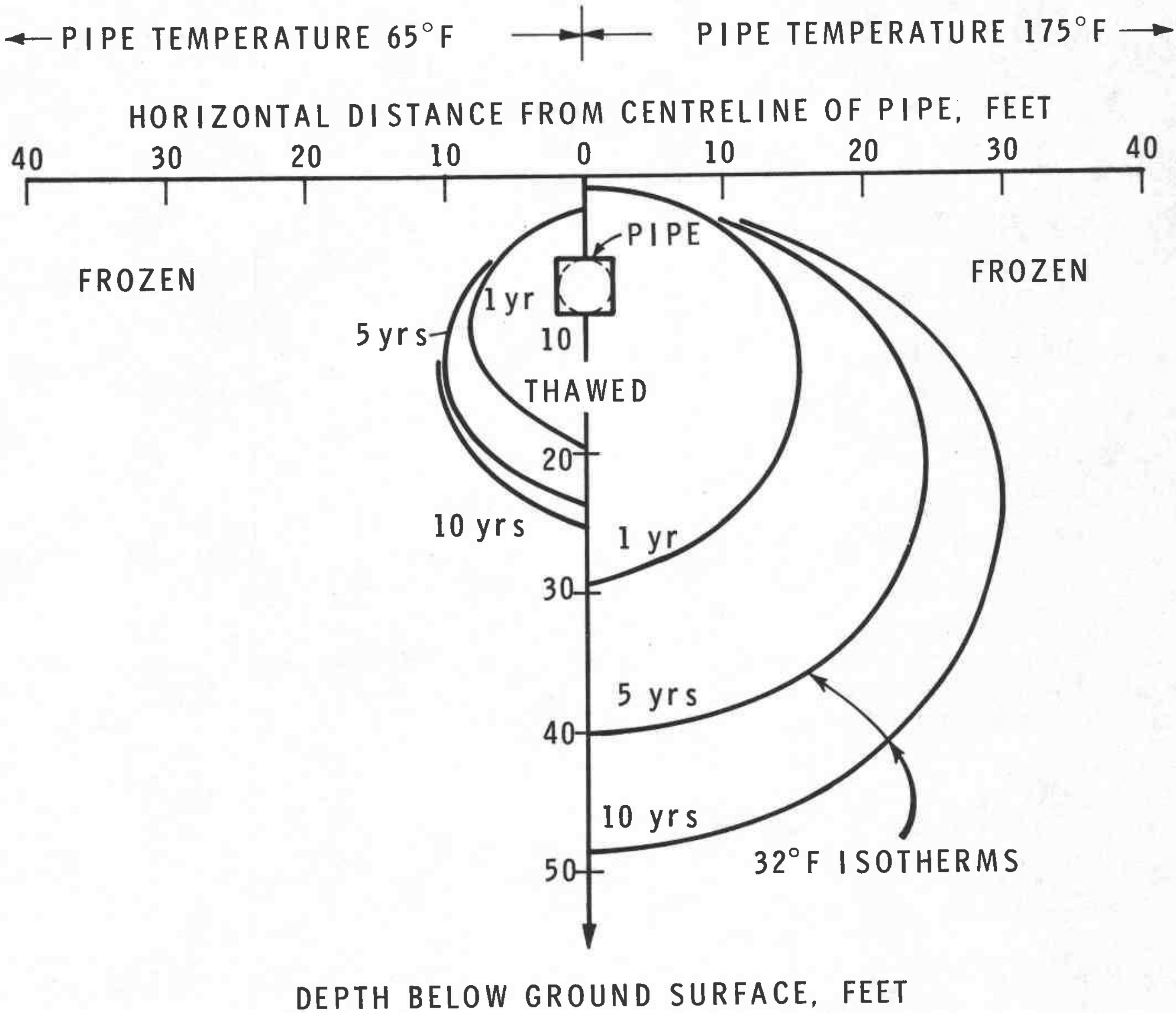

FIGURE 7

THAWING FRONTS AROUND HOT PIPELINES IN PERMAFROST IN SPRING

BR. 4830-2

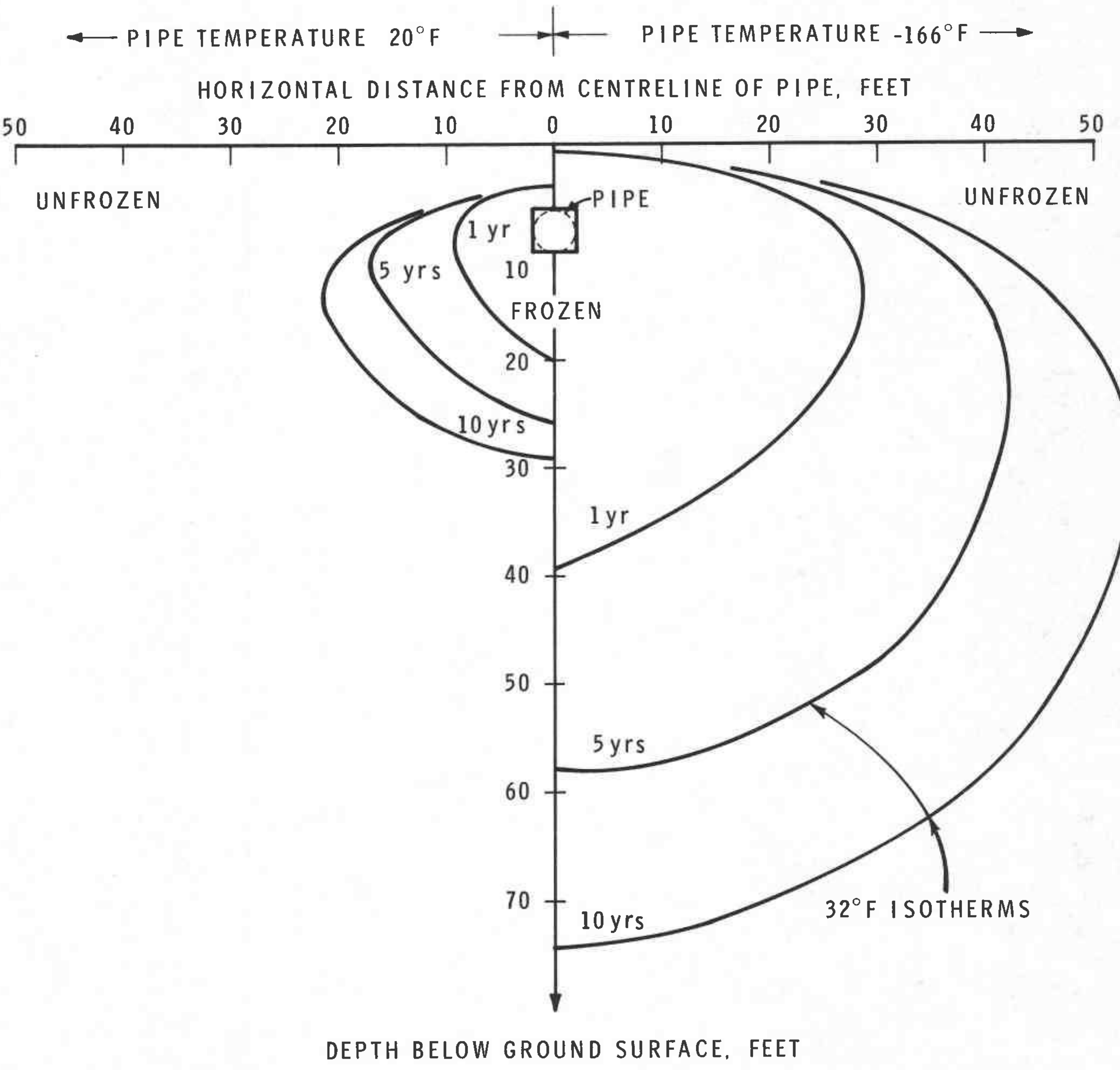

FIGURE 8

FREEZING FRONTS AROUND COLD PIPELINES IN DISCONTINUOUS PERMAFROST IN SUMMER

BR. 4830-1