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GROUND TEMPERATURE INVESTIGATIONS IN CANADA

by
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Ground Temperature Investigations in Canada

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National Research Council, Canada, Division of Building Research

Presented to the Engineering Institute of Canada, Montreal Branch, December 1955

This paper describes the program of work undertaken by the Division of Building Research, of N.R.C., to determine ground temperature variations in Canada. Some of the practical results and theoretical problems are discussed.

THE VARIATION OF temperature in the ground, with time, and with increasing depth from the surface, is a natural phenomenon with which civil engineers come into contact in many special branches of work. Determination of the depth at which service pipes should be installed, the design of road and airport pavements, calculation of heat losses from structures in contact with the ground, the design and operation of heat pumps — these and similar projects can be carried out efficiently only if the appropriate ground temperature regime is known with reasonable accuracy.

At some depth below the surface, the temperature of the ground ceases to be affected by daily and monthly changes in the surface temperature. In many parts of Canada this depth is of the order of 20 feet. Below this depth ground temperatures usually increase slowly with increasing depth. This phase of the phenomenon is related to the problem of high temperatures in deep mines. Much has been written about the practical aspects of this problem and with corresponding scientific deductions from deep ground-temperature observations.

Between the critical depth noted and the ground surface, the effect of changing surface temperature will be evident to a steadily increasing degree as the ground surface is approached. The increase is not linear; major variations in temperature are greatly reduced within the first two or three feet from the surface. Following the basic laws of heat transfer, there should be a steadily increasing time lag for maximum and minimum temperature conditions. Observations show that in Canada the lag is six months, as the critical depth of approximately steady temperature is approached. These basic features of the over-all phenomenon are shown in graphs accompanying this paper which will be discussed later.

This outline of the pattern of ground temperature variation indicates that the problem of theoretically computing the ground temperature, at any particular depth, in any particular location, at any specified time, is a complex one — so complex that it can be said to be insoluble except on the basis of a number of simplifying assumptions. Variations in soil type, variations in groundwater level, variations in surface vegetation and even in the colour of this vegetation, variation in snow cover, variation in rainfall — these are but some of the factors which will affect the ground temperature regime for any selected locality. Although generalized solutions can be obtained theoretically for ideal conditions, the study of ground temperature variation is one which must be based, at the start, upon field observations. This is reflected in the literature of the subject which is extensive despite the restricted and special nature of the problem. It has been critically analysed by Crawford (1952)[3]. An early paper of unusual interest records observations made in Edinburgh as early as 1837, by Professor Forbes[5], who used glass bulb thermometers with stems 25 feet long.

Early Measurements in Canada

The first known ground temperature measurements in Canada were made at McGill University by Prof. H. L. Callendar, beginning in October 1894. Electrical resistance bulbs were installed in the side of a trench from the surface to a depth of 9 feet and readings were made for several years (Callendar 1897)[2].

During the years 1921 to 1923 ground temperatures were observed at depths of 1 to 8 feet at 1-foot intervals on the campus of the University of Saskatchewan in Saskatoon. Electrical resistance thermometers were used and temperatures were recorded continuously (Harrington 1928)[7]. From 1929 to 1934 ground temperatures were measured at the University of Manitoba in Winnipeg at various depths from the surface to a depth of 15 feet. Frost penetration was computed from these measurements (Thomson 1934)[15].

During the period 1924 to 1939 ground temperatures were measured in Toronto with electrical resistance thermometers at the surface and at intervals to a depth of 15 feet in sandy soil at the Canadian Meteorological Office. From 1945 until 1952 further readings were obtained at the same site at depths of 4, 6, and 8 feet using a recording mercury bulb instrument supplied by the University of Toronto.

Records of shallow ground temperatures have been obtained for many years and in many locations by the Experimental Farms Service of the Department of Agriculture. Most of these observations have been made in connection with problems of crop culture and the results are not directly applicable to engineering problems. At present a general study of ground temperatures is being carried out at the experimental farms at Ottawa and Fort Vermilion.

Some earth temperature measurements have been made at great depths to study vertical temperature gradients and heat flow (Misener, Thompson and Uffen 1951)[11]; similar work has been done in some of the deeper Canadian mines.

Studies by the Division of Building Research

Shortly after the formation of the Division of Building Research a project was started to determine ground temperature variations in Canada. This project was prompted by a request to the Division to install an experimental heat pump and by an urgent problem relating to frost penetration in the City of Ottawa. Early Divisional work in the north of Canada showed that an accurate knowledge of ground temperature variations was essential in permafrost research. These and other demands for practical information were linked with an increasing appreciation of the necessity for study of the over-all theoretical problem, arising from earlier work of the senior author and from the clear necessity for a long-term study of frost action in soils.

Accordingly, the Division of Building Research has developed a steadily increasing number of field observing stations for ground temperature variations jointly with other organizations. The records so far obtained are already proving to be of much practical value. At the same time they indicate that little is to be gained by a much wider extension of such field observations. The time seems ripe, therefore, for the presentation of a review of the work that has been done in this field, not only to tell the engineering profession in Canada of the information that is available for public use, should it be needed, but also to place on record in convenient form a summary of this extensive field program against which more detailed and theoretical studies can be assessed. This paper is a statement of the field research work into this problem which the Division has carried out, in association with other research agencies noted in the descriptions of the individual installations. The locations of ground temperature installations are shown in Fig. 1.

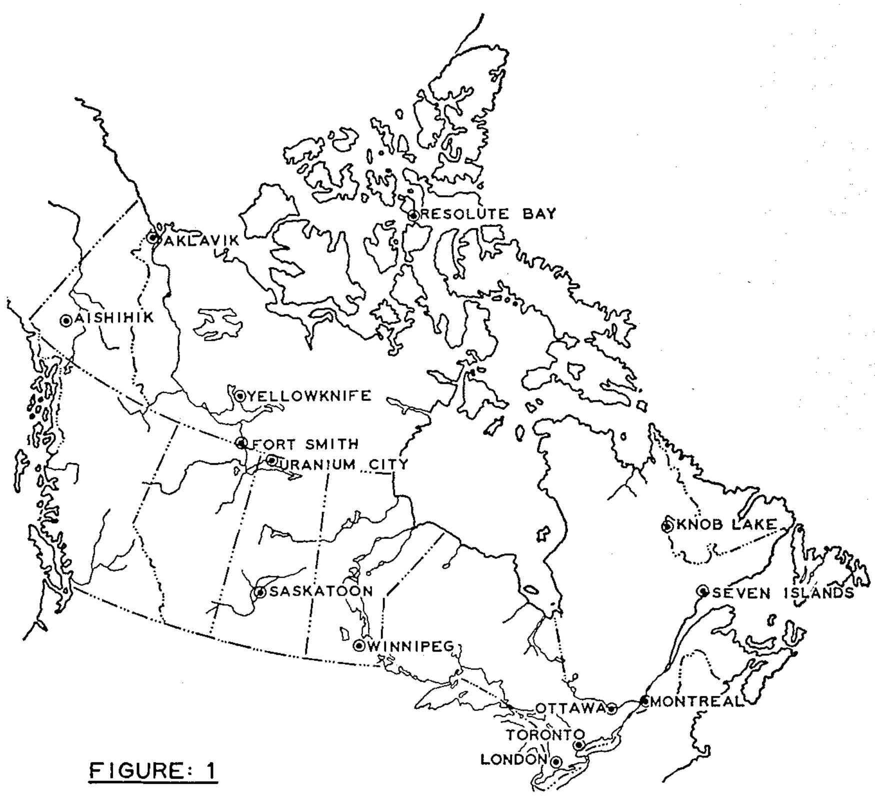


FIGURE: 1

LOCATION OF SOIL TEMPERATURE INSTALLATIONS

Current Temperature Measurements

Ottawa, Ontario

Following the severe winter of 1947-48 during which the City of Ottawa had many difficulties with frozen water lines, the Division began co-operatively with the City, a study of ground temperatures under city streets. In the fall of 1948, recording thermometer bulbs were placed under two streets; one in a sandy area and one in a clay area. Readings were taken for two and three years respectively.

In 1949 thermocouples were placed in a vertical profile at 1-foot intervals to a depth of 15 feet in undisturbed clay and to a depth of 8 feet in test pits (Fig. 2) in both sand and clay. These installations were designed to evaluate the effect of air temperatures, soil type, soil density and snow cover on ground temperatures. This work was extended in 1952 with the installation of thermocouples under a snow-cleared roadway and under adjacent grass cover near the Building Research Centre at Ottawa. Readings have been made weekly at these sites.

During the winter of 1954-55 temperatures at 2-inch intervals through natural snow cover were measured to evaluate the thermal properties of snow and its effect on ground temperatures. This study will soon include the measurement of heat flow in the snow.

Aishihik, Y.T.

As part of an international study of temperatures in permanently frozen ground (permafrost), arrangements were made with the U.S. Corps of Engineers and the Dominion Meteorological Service to provide and maintain a ground temperature installation at the air field at Aishihik in the Yukon Territory. In October 1952, thermocouples were placed at three locations: from the surface to a depth of 10 feet at 1-foot intervals in a wooded area and in a brush area; from the surface to 10 feet at 1-foot intervals; and from 10 to 20 feet at 2-foot intervals in a grassed area. Weekly temperature readings have been made.

Aklavik, N.W.T.

During the summer of 1953 the Permafrost Section of the Division installed a number of thermocouples for measuring ground temperatures at Aklavik. One string of thermocouples was placed in natural ground under grass cover at intervals of 1-foot from the surface to a depth of 10 feet and at 12.5, 15 and 20 feet. Temperature readings and snow cover measurements have been made every week since August 1954. At the same time twelve additional thermocouple strings were installed on the sites of two proposed buildings: a ten-room school and a teacherage (Pihlainen and Johnston 1954)[13]. These installations were established to study the effects of buildings on permafrost but due to the subsequent decision to relocate the town of Aklavik, the buildings have not been constructed and no temperature readings have been made. It is expected, however, that some of these thermocouples will be read beginning in 1956.

During 1953 thermocouples were also located on the perimeters of four wooden piles immediately after they had been steam-jetted into permafrost. Observations on these thermocouples have given information on the refreezing of such steam-jetted piles in permafrost.

Yellowknife, N.W.T.

In 1951 seven temperature measuring installations were made at Yellowknife by the Department of National Health and Welfare in co-operation with the Division of Building Research. One three-point mercury-bulb recording thermometer was used; thermocouples were used in the remaining installations.

In addition to the general collection of ground temperature information in this area, these installations were planned to give data necessary for the engineering design of municipal services in northern regions where heat input to the system is required. Analysis of the data revealed that for a satisfactory solution of the design problem more precise ground temperature measurements are necessary as well as measurements of water temperatures, flow rates, heat input and a complete understanding of thermal properties of the soil. The complexity of this problem may delay its solution for many years. Meanwhile some guidance for design can be obtained by reference to the data which have been obtained. This information is now being processed for publication.

The Yellowknife installations include two reference stations: one beneath a roadway and one under natural cover. Other installations have been made around water and sewer pipes with temperature measurements recorded above, below, and in and around the pipes (Fig. 3). Temperature measurements have been made since 1951 although, owing to various difficulties, these were not continuous during the first two years of operation. The data confirm that the installation of service pipes has a significant effect on ground temperatures. The topography of Yellowknife is shown with the instrument huts in Fig. 4.

Fort Smith, N.W.T.

One three-point mercury-bulb recording thermometer has been in continuous operation at Fort Smith since May 1952 to provide information for the control of heating of the municipal water supply. This instrument was installed and is maintained by the Department of Northern Affairs and National Resources in co-operation with the Division of Building Research.

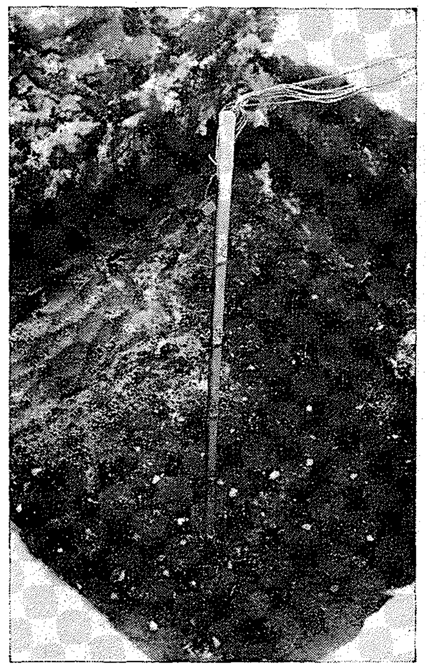
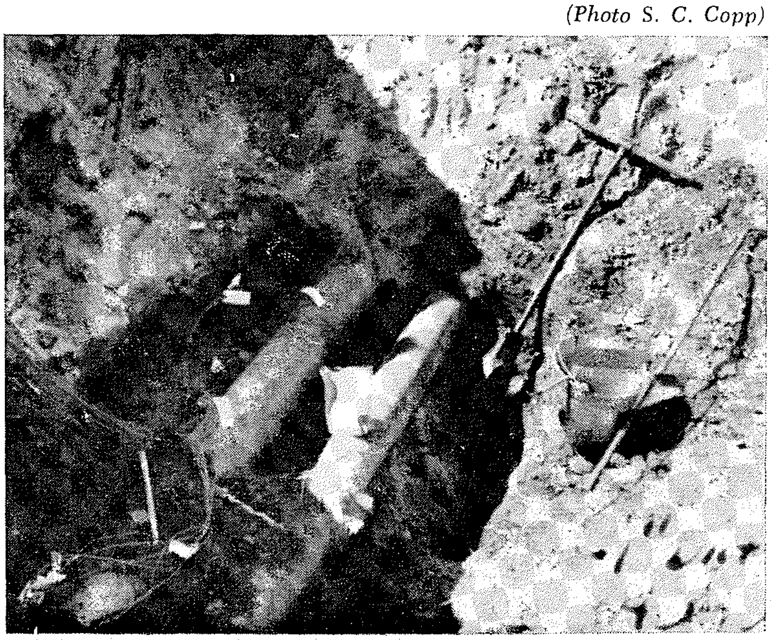


Fig. 2. Thermocouples located in test pit in clay; Ottawa, Ont.

Fig. 3. Thermocouples around water main, Yellowknife, N.W.T.
(Photo S. C. Copp)



Resolute Bay, N.W.T.

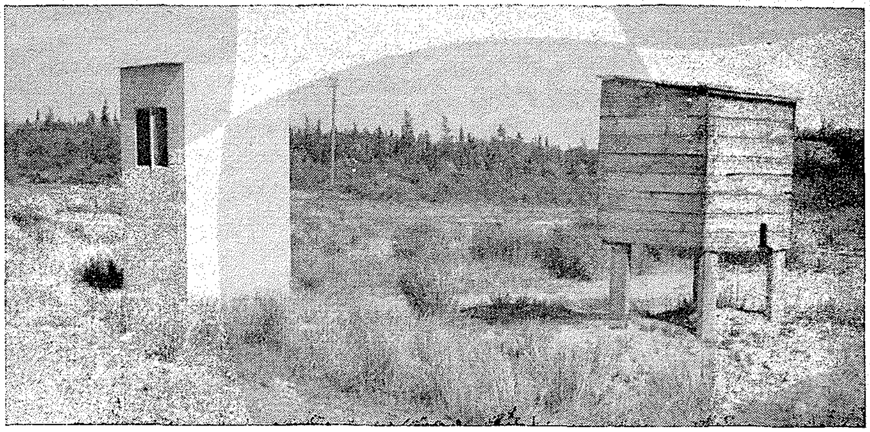
In 1948 thermistors (electrical resistance type thermometers) were established at shallow depths in the ground at the weather station at Resolute Bay which is situated just south of the 75th parallel and is operated jointly by the Meteorological Division of the Department of Transport and the U.S. Weather Bureau. Later the Dominion Observatory and the National Research Council of Canada joined with the Meteorological Division and the U.S. Geological Survey to establish deep ground temperature observations as a means of estimating the depth of permanently frozen ground and to record long-term changes in permafrost temperatures. Owing to the many practical difficulties of boring through frozen rock this program required four seasons to complete the main deep hole to 650 feet deep.

Temperature measurements have now been made in shallow holes at various depths down to 5 feet since 1948. Since September 1950 readings have been obtained at 5-foot intervals to a depth of 98 feet and this was extended in May 1952 to points at 300 feet and 450 feet. In August 1953 readings began at 50-foot intervals to a depth of 650 feet.

Data from these installations show that the ground temperature at a depth of 20 feet varies annually from about +5° F. to +13° F. At 50 feet the variation is about 1° F. and averages about +8° F. during the year. This temperature remains fairly constant to a depth of about 150 feet where it begins to increase at a rate of about 2° F. per 100-foot depth. Preliminary estimates place the depth of permafrost at between 1,000 and 1,500 feet.

Uranium City, Saskatchewan.

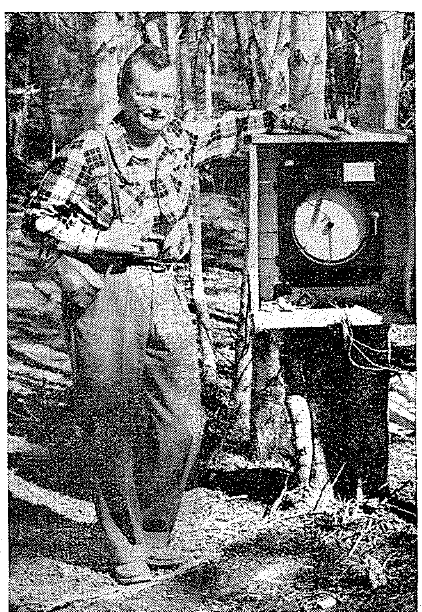
At the request of the Provincial Government of Saskatchewan, the Division of Building Research loaned two three-point mercury-bulb recording thermometers to the Provincial Department of Natural Resources for installation at Uranium City. These instruments were located to obtain design information in advance of the proposed installation of municipal services and to study an unusual permafrost condition which caused problems in road construction at this new townsite. In 1951 both instruments were installed at the Uranium City townsite. During the summer of 1952 one instrument was relocated in the townsite and the other was moved to a location known as "Ice Hill" on the main road near the town to obtain information on an unusual occurrence of permafrost. A typical installation is shown in Fig. 5.



(Photo S. C. Copp)

Fig. 4. Typical topography and instrument huts, Yellowknife, N.W.T.

Fig. 5. Typical mercury-bulb recording thermometers, Uranium City, Sask.



During September 1954 the instrument at the townsite was replaced with a thermocouple installation measuring temperatures under a snow-cleared driveway and under natural snow cover. Because of instrument difficulties satisfactory readings of the thermocouples were not obtained until the summer of 1955.

Saskatoon, Saskatchewan

The Prairie Regional Laboratory of the Division of Building Research made several thermocouple installations on the University Campus at Saskatoon in 1949 to study the effect of a heated building on ground temperatures. Unfortunately the leads from the neutral reference station, extending to a depth of 35 feet, were destroyed shortly after installation. There remain a number of thermocouple strings under and around the building. One string with points at the surface, 1, 2, 4, 6, 8, and 10 feet in depth and located 20 feet from the building will approximate natural ground temperatures. Readings have been made weekly since March 1950.

Winnipeg, Manitoba

In the fall of 1952 many thermocouples were installed in the ground in connection with an experimental basementless house which was constructed on the University of Manitoba Campus by the Division as a joint research project. Temperatures are measured at various depths under and around the slab and at a considerable distance from the slab to a depth of 15 feet. The data from these installations allow study of the effect of the slab on thermal conditions in the ground.

London, Ontario

Dr. A. D. Misener, working at London, Ontario, in co-operation with the Division of Building Research, has installed thermocouples in a grid under the floors of two school buildings to study the effect of floor panel heating on ground temperatures. Additional thermocouples were placed in the ground outside the influence of the buildings. *In situ* field tests for thermal properties of the soil were made.

Labrador

In co-operation with the Iron Ore Company of Canada and the Quebec North Shore and Labrador Railway, several installations for the measurement of ground temperatures were made in 1953 to obtain information for construction and operations. At mile 266 on the railway non-recording remote-reading mercury-bulb thermometers were placed to a depth of 13 feet in a typical granular fill, to a depth of 6 feet in a typical silty cut and at depths of 1.5 and 3.75 feet in muskeg. Weekly temperature readings were made during the first winter but due to inaccessibility further readings are not anticipated. It is hoped that these instruments can be moved to a position in the roadbed near a permanent camp.

At Knob Lake, site of the Iron Ore Company town, recording mercury-bulb thermometers were located under a snow-cleared road to a depth of 9 feet and to a depth of 5 feet under natural cover. This installation was relocated in the fall of 1954 owing to the unexpected extreme penetration of frost in the dry granular soil, and bulbs were placed to a depth of 15 feet under a roadway and to 12 feet under natural cover. Thermocouples were installed with the mercury-bulbs to allow periodic checking of the instruments. Continuous ground temperature readings have been obtained at Knob Lake since 1953.

Results of Field Observations

This paper does not record detailed results or even average results of all the temperature installations described; these will be published in individual papers. Some general results, however, are shown in Figs. 6 to 9. Figure 6 shows monthly average ground temperature profiles with depth under natural grass and snow cover in undisturbed clay at Ottawa during one year. These curves illustrate the decreasing mean annual temperature amplitude with depth (43° F. at the surface, 4° F. at a depth of 15 feet).

Temperature lag with depth is also illustrated (coolest in July, warmest in December at 15 feet). Figure 7 shows similar monthly averages in disturbed clay soil with the snow cover removed. Removal of the snow cover causes an increase in temperature amplitude and a decrease in the mean ground temperature. Figure 8 illustrates temperature profiles at Knob Lake in Labrador in a coarse granular soil under a snow-cleared roadway. More severe climatic conditions cause much greater temperature amplitudes (more than 10° F. at 15 feet).

Figure 9, which summarizes Figs. 6, 7, and 8, shows that the mean annual temperature under natural conditions (based on weekly observations) to a depth of 15 feet at Ottawa is approximately constant at 48° F., and increases to 48.4° F. in the upper 3 feet (curve A). The effect of snow cover is illustrated by the decrease in mean annual temperature under snow-cleared ground in the upper 6 or 8 feet (curve B). The depth to which this effect extends will depend on the boundaries of snow clearance, in this case a radius of about 6 feet. The mean annual ground temperature under a snow-cleared road at Knob Lake decreases from 33.5° F. at a depth of 15 feet to about 30.3° F. at the surface (curve C). Boundary conditions for this curve are similar to those for curve B. Mean annual ground temperatures at Knob Lake suggest that this is a region not far removed from permafrost; in the iron ore mining operations some permafrost has been observed.

The most significant feature of these curves of mean annual ground temperatures is the wide variation, even without snow cover, between mean surface temperatures and air temperatures. This variation will be discussed in some detail later. It may be appropriate to consider first the main results of the field studies.

Discussion of Results

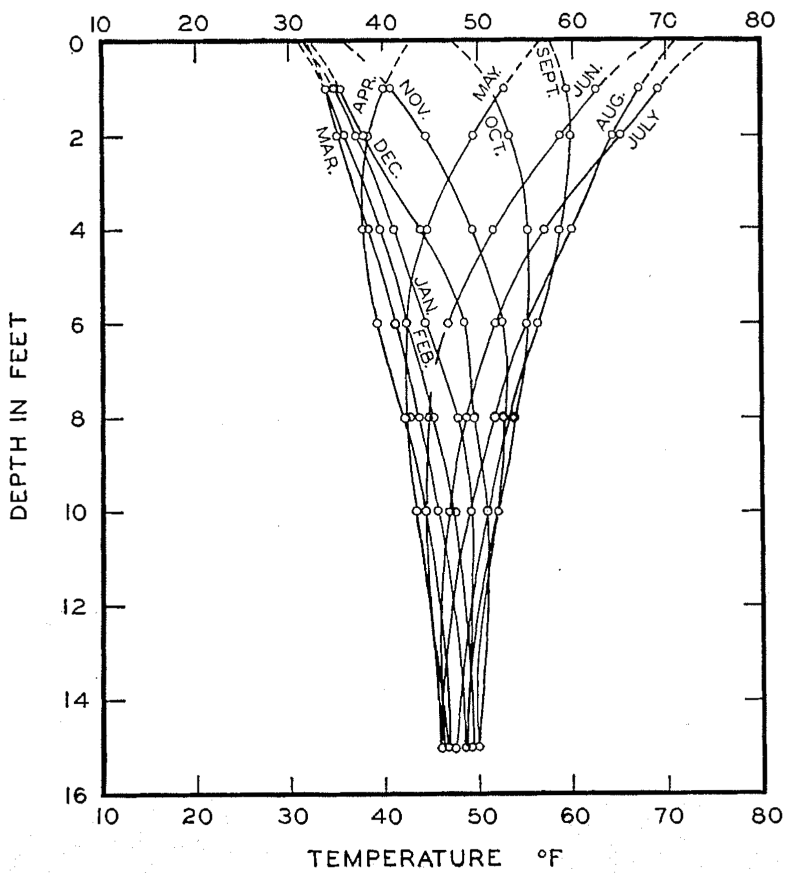
Much valuable information related to ground temperatures has been published within the last 100 years: information on the thermal properties of soil, the effect of surface cover, precipitation, soil type, water content, organic content and various weather elements notably air temperature. For the most part this information is qualitative or applies to specific cases and is therefore difficult to apply to engineering operations. Probably the greatest single development, for engineering, is the simple empirical relationship between air temperature and frost penetration, first suggested by Casagrande (1931)[1] and later developed by the U.S. Corps of Engineers (1947)[14]. It is recognized that this relationship is an oversimplification with limiting conditions of a complex phenomena but it can be used to estimate frost penetration. A "freezing index" map of Canada (Wilkens and Dujay 1954)[16] can be used with the empirical curve to make a first approximation of frost penetration (Crawford 1955)[4]. The field measurements outlined in this paper have generally confirmed the accuracy of the empirical relationship but it is also important to note that in one case (Knob Lake) the frost penetration was twice as great as the estimate. Many field observations will be required to improve the accuracy of this method.

The field studies have added to our knowledge of the effect of soil type on ground temperatures and have illustrated the great effect of snow cover in preventing the penetration of frost (Legget and Crawford 1952)[9]. More is being learned about the general effect of basementless houses on ground temperatures and heat loss from the slab. It is apparent that the various service pipes greatly affect subsurface temperatures. Perhaps the most important result of field observations is an appreciation of the complexity of the thermal regime in the ground. This leads to consideration of a combined empirical and theoretical approach to the problem.

Evaluation

When one considers the influence which the thermal properties of the

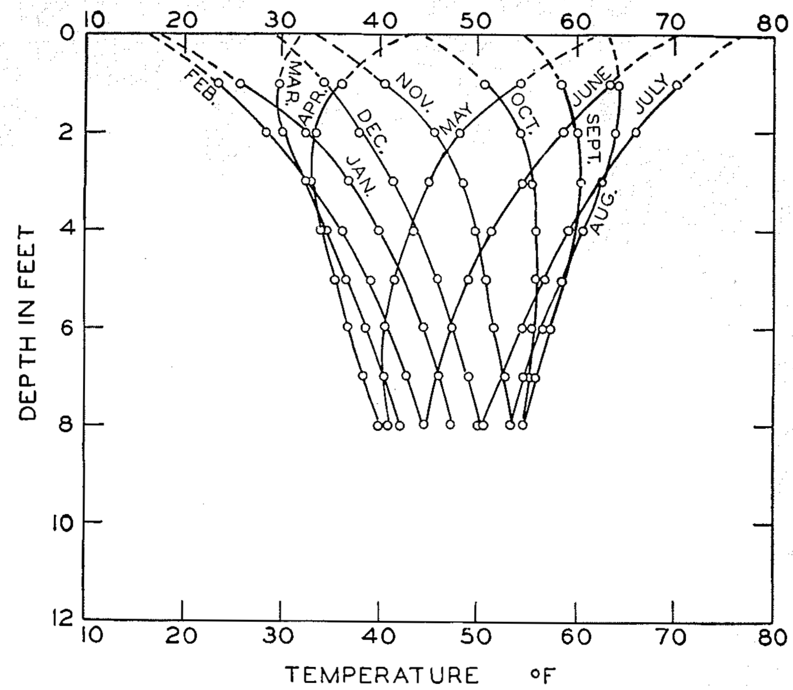
Fig. 6. Monthly average ground temperature in clay soil at Ottawa, Ont., from May 1954 to April 1955 (under natural surface cover).



soil must have upon ground temperature variations, it becomes evident that the final understanding of this phenomenon must be guided by the theories of heat transfer. Theoretical solutions are complicated because the problem involves transient heat flow in a material with constantly changing thermal properties. On the other hand, field measurements alone will not suffice because it would be necessary to obtain results to cover every possible combination of climate and soil in sufficient numbers for statistical analysis.

In the first approach to the problem by the Division of Building Research, it was planned that study should include theory, laboratory experiments, and field observations. Field observations were begun immediately since a year of measurement is required for one complete weather cycle and because these measurements could provide interim answers to practical problems. During 1955 equipment has been developed and constructed at the Building Research Centre, Ottawa, in which small samples of soil can be subjected to various controlled temperature, density, and moisture conditions. Experiments to study the effects of freezing on various soils are continuing (Penner 1956)[12]. Work and laboratory heat transfer studies is also being planned.

In empirical approaches to ground temperature studies, it has been customary to simplify the problem by neglecting most of the variables which are known to affect temperatures to arrive at workable relationships such as the simple relationship of frost penetration to degree-days of freezing air temperature. This neglects important variables such as thermal properties of the soil (which depend greatly on water content), water movement (with its tremendous potential as a heat transfer mechanism), nature of the ground surface and all of the weather elements except air temperature. To obtain engineering design data the problem must be simplified in this way but it appears to be equally necessary to consider all the variables to achieve a satisfactory understanding of the problem.



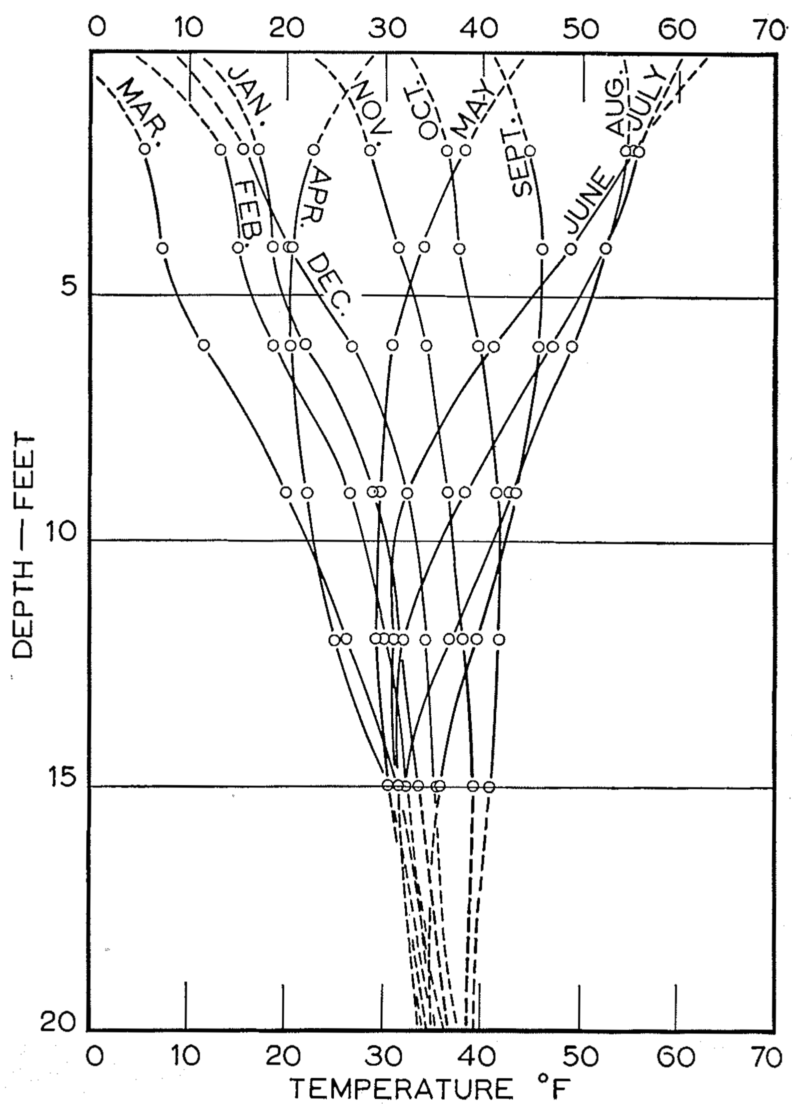


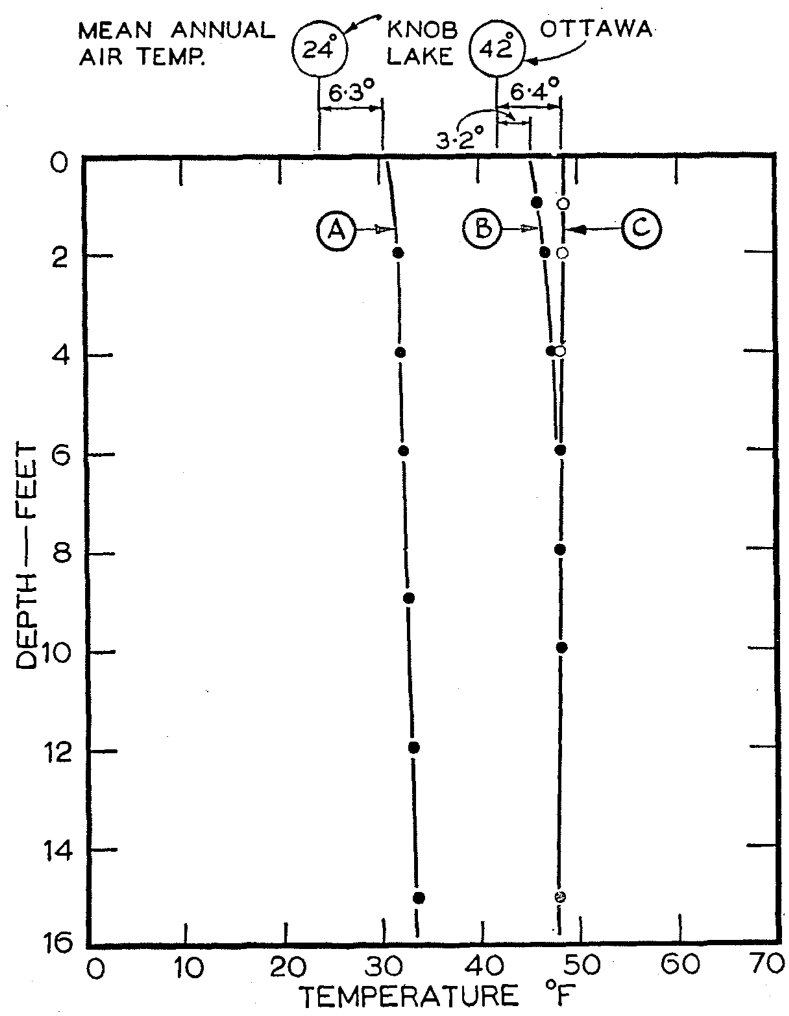
Fig. 7. Monthly average ground temperature in clay soil at Ottawa, Ont., from May 1954 to April 1955 (under snow cleared surface).

Fig. 8. Monthly average ground temperature at Knob Lake from October 1954 to September 1955 (under snow cleared road).

From Fig. 9 it can be seen that the mean annual temperature of the upper 15 feet of the earth at Ottawa is more than 6° F. warmer than the mean annual air temperature. Even under conditions of no snow cover the difference is more than 3° F. at Ottawa and more than 6° F. at Knob Lake. These curves clearly indicate the influence of snow cover, the effect of climate between Ottawa and Knob Lake, and the fact that there does not exist a simple direct relationship between air and ground temperatures as has generally been supposed to exist.

Further consideration of air temperature as a variable is therefore warranted. Air temperature is chosen as representing the effect of climate on ground temperatures because it is a simple variable, easily understood, and a weather element of long-term record. Further study, however, shows that ground temperature is not wholly a function of air temperature. If mass air movements are neglected the air temperature may equally well be regarded as the result of heat exchange with the earth rather than the reverse. This is caused by the fact that practically all of the heat reaching the surface of the earth results from short wave (high temperature) radiation by the sun, of which only a small amount is absorbed by the atmosphere (Geiger 1950)[6]. About 40 per cent of the radiant energy from the sun is lost to space by reflection from clouds and by diffuse scattering. The remainder, except for the small amount absorbed by the atmosphere arrives at the earth's surface by direct solar radiation and by sky radiation, having had almost no effect on atmospheric temperature. The intensity of this radiation depends on altitude, slope and orientation of the receiving ground surface, inclination of the sun and on various atmospheric conditions. At Winnipeg during 1952, for example, the average cloudless day insolation ranged from about 500 B.t.u. per square foot per day in winter to nearly 3,000 B.t.u. per square foot per day in mid-summer (Mateer, 1955)[10].

Fig. 9. **Relationship between mean annual air temperature and mean annual ground temperature.**



Examination of the heat exchange at the earth's surface shows that only part of the radiation that reaches the ground results in a net heat gain to the ground. Part of it is reflected directly; the amount of reflection may be largely dependent on the colour of the ground surface. Some is re-radiated as long wave (low temperature) radiation which is absorbed much more readily by the atmosphere than is the incoming radiation and therefore greatly affects the air temperature. Some radiation is used in the evaporation of moisture; this can have a marked effect on both air and ground temperatures. In the net heat exchange, condensation may balance the effect of evaporation. Minor losses to the net heat gain by radiation include convection losses to the atmosphere. During the day there is a net heat gain to the earth and at night there is a net heat loss, the balance between the two depending greatly on the season and on atmospheric conditions. Radiation from the ground surface is particularly important during the long, clear, winter nights. For practical purposes, smudge-pots are often placed in orchards to provide an artificial haze to trap this heat loss.

It is evident from the above, and supported by the curves of Fig. 9, that simple heat conduction theory does not apply at the air-to-surface interface although it may be correct within the ground, except for the complications of heat transfer by moisture movements. Field work by the Corps of Engineers and at the University of Minnesota (Kersten and Johnson 1955)[8] indicated a discrepancy in using air temperature to compute frost penetration and this has resulted in an air-surface correction factor to obtain a "pavement freezing index". This may prove to be the most practical engineering approach for estimating frost penetration. For research studies designed to understand the ground temperature regime, however, it will be essential to consider all the basic climate factors.

Research on ground temperatures has not yet answered the question of when to make field measurements and when to attempt theoretical analysis. Field measurements give a quick answer without requiring a basic understanding of the problem, but not without a significant margin of error; this should be reduced as more data become available. The success of theoretical study, directed toward a basic understanding of the problem, will depend on the development of ability to measure correctly the thermal properties of the ground, to deal with the complications of moisture flow, and to assess properly all the relevant climatic influences. It is in this direction that the studies of the Division of Building Research are now proceeding.

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