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GROUND SURFACE ENERGY EXCHANGE STUDIES AT NORMAN WELLS, N.W.T.

by

R. J. E. Brown

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PREFACE

Information on permafrost in Canada is being gathered continuously from a variety of sources including technical literature, reports from others operating in permafrost areas, circulation of a questionnaire to appropriate groups in the North, and from direct field observations. Accompanying the collection of permafrost information by these means is the continuing study of the basic factors affecting its distribution and continued existence in order to improve the ability to predict its occurrence. Such work involves investigations of the basic climatic and terrain components of the energy exchange at the earth's surface that affect the occurrence of permafrost.

This report records the results of field studies of some of the components conducted by the author at the Division's Northern Research Station at Norman Wells, N.W.T. during the summers of 1959 and 1960. Difficulties were encountered in instrumentation and some of the results are inconclusive. Nevertheless, the Division hopes that the information obtained will contribute to a better understanding of some aspects of the energy exchange regime in permafrost regions.

The author is a research officer in the Northern Research Group of the Division of Building Research, National Research Council where he is doing research on the distribution of permafrost in Canada.

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GROUND SURFACE ENERGY EXCHANGE STUDIES AT NORMAN WELLS, N.W.T.

by

R. J. E. Brown

For the past few years, investigations have been conducted by the DBR Northern Research Group (formerly the Northern Building Section) on the occurrence and distribution of permafrost in Canada. Information has been gathered from a variety of sources including technical literature, reports from others operating in permafrost areas, and from direct field observations. Emphasis has been placed on the determination of the southern limit of permafrost but observations from the entire permafrost region are being recorded also. This collection of information is continuing, facilitated by a permafrost questionnaire, which was prepared by the Division of Building Research and circulated to appropriate groups throughout northern Canada.

Obtaining a picture of permafrost distribution solely by such means is inevitably a long-term project but the need was recognized for studying the basic factors affecting its distribution and continued existence to improve the ability to predict its occurrence. In the fall of 1958, the Division initiated studies of the basic climatic and terrain components of the energy exchange at the earth's surface affecting the occurrence of permafrost. During the summers of 1959 and 1960, field observations were carried out at the Division's Northern Research Station at Norman Wells, N.W.T. Norman Wells is located on the right bank of the Mackenzie River, 90 miles south of the Arctic Circle and about 300 miles north of the southern limit of permafrost (Figure 1). The depth to permafrost at Norman Wells varies from a few inches to several feet depending on the surface cover and disturbance by construction. Permafrost occurs everywhere under the ground surface and is about 200 ft thick.

The objectives of the field studies at Norman Wells were twofold: to develop instrumentation techniques and to obtain quantitative values of some of the energy components at the ground surface. Potential evapotranspiration, latent evaporation, and net radiation of various types of vegetative cover and incoming short-wave radiation were measured. Ground temperatures were measured in both the seasonally thawed and perennially frozen ground under these vegetative types. The locations of the sites in the Norman Wells area at which these observations were made are shown in Figure 1.

The object of this report is to describe the instrumentation techniques used in the 1959 and 1960 summer field studies and to present the results of these studies.

APPARATUS AND OBSERVATION METHODS

1. Potential Evapotranspiration and Evaporation

The transfer of water, in the form of vapour, from the soil to the air by evaporation, and from vegetation to the air by transpiration, is a significant process in the energy exchange regime operating at the ground surface. For every cubic centimetre of liquid water in the ground that is transferred to the atmosphere, 540 cal of heat are consumed to change this liquid to vapour. This represents a significant proportion of the total heat budget and affects the thermal level of the ground in which the perennially frozen condition exists. It is suspected that considerable heat transfer may be involved also in the condensation of water vapour as evidenced by the presence of a supersaturated layer at the bottom of lichen even when its surface is completely desiccated (3).

The objectives of the Norman Wells potential evapotranspiration and evaporation studies were threefold (1). The first one was to continue observations of potential evapotranspiration at the clipped grass (Kentucky bluegrass) plot installed by the Ontario Research Foundation in 1949 (9). The original purpose of this installation was to test the validity of the Thornthwaite world climatic classification system, which is based on potential evapotranspiration, for northern areas that have long days during the vegetative growing season. Accompanying this was the attempt to determine quantitative differences in potential evapotranspiration from different vegetation types (i.e. sedge, moss, lichen) beneath which permafrost exists, and to compare these with measurements obtained from the Thornthwaite site. The second objective was to measure the latent evaporability of the air. The third one was to measure evaporation from an open water surface. The last two measurements have been compared with the potential evapotranspiration.

(a) Potential evapotranspiration at Thornthwaite site

In 1949, a Thornthwaite type evapotranspirometer (5-ft sq pans) for measuring potential evapotranspiration was installed by the Ontario Research Foundation beside the airstrip, 1 1/2 miles east of Norman Wells (9). Daily measurements were taken each summer until 1953 when the installation was moved to an exposed site in the town at the top of the bank of the Mackenzie River, about 250 yd west of the Northern Research Station (Figures 2, 3). Personnel of DBR/NRC took daily potential evapotranspiration measurements for the Ontario Research Foundation each summer from 1955 to 1960 inclusive.

During the summers of 1959 and 1960, Pan "A" was replenished by a constant water supply system. Pan "B" was supplied daily with water. After the overflow had been recorded, a measured quantity of water in excess of the anticipated potential evapotranspiration was sprinkled uniformly over the surface. The grass was cut weekly and fertilizer sprinkled on the grass several times during the summer. Air temperature and rainfall were measured daily. Dew point and wind speeds were obtained from the D.O.T. Meteorological Station at Norman Wells.

(b) Potential evapotranspiration at other vegetation sites

During the summers of 1959 and 1960, daily potential evapotranspiration measurements were extended to sedge, moss and lichen, which are native to the permafrost regions, using various sizes of evapotranspirometers (5,6). Several were installed at the Thornthwaite site to compare potential evapotranspiration rates with those obtained from the large pans. Other similar devices were installed in sedge, moss and lichen areas to compare potential evapotranspiration rates through these vegetation cover types.

The largest evapotranspirometers consisted of half a 45-gal oil drum about 56 cm in diameter. On the bottom of each drum was welded a threaded outlet from which a pipe led to an overflow container about 3 ft away (Figure 4). The smallest evapotranspirometers consisted of fruit juice cans of 15 and 10 cm in diameter respectively. Overflow was held in the bottom of these containers until released for measurement by removing a stopper.

Evapotranspirometers were installed at five locations (designated as Sites One to Five respectively (Figure 5)). Site One was the Thornthwaite site where one oil drum, three large and three small fruit juice cans were installed in 1959. In 1960, no readings were taken on two of the large and two of the small cans, but readings were taken throughout the summer on the others installed in 1959 (Figure 2).

Site Two was a treeless area with no moss or lichen, where sedge grew to a height of about 1 ft with scattered dwarf willow and ground birch (Figure 6). One oil drum, three large and three small fruit juice can evapotranspirometers were installed here in 1959. In 1960, these were replaced by three oil drums.

Site Three was a moss-covered area with scattered spruce and tamarack up to 6 ft high, dwarf willow and birch 2 ft high with a ground cover of Labrador tea and moss. One oil drum, three large and three small fruit juice can evapotranspirometers were installed here in 1959. This site was replaced in 1960 by a sphagnum moss-covered area 1/4 mile west of D.O.T. Lake, about 4 miles east of Norman Wells where three oil drums were installed.

Site Four was a densely forested moss-covered area with spruce and tamarack up to 20 ft high, willow and alder undergrowth up to 4 ft high and ground cover of Labrador tea and moss (Figures 4, 7). In 1959, six large and six small fruit juice cans were installed. From a close examination of the ground, it appeared that three distinct species of moss covered the area in a mosaic. (Samples of the three types were brought to Ottawa for examination at the National Herbarium and were identified as Thuidium abietinum, Thuidium abietinum and Pleurozium sp. in association, and Sphagnum sp.) In an attempt to detect possible differences of potential evapotranspiration through these different moss species, two large and two small fruit juice cans were installed in each of the three types of moss. Three oil drums were added in 1960.

Site Five was covered with lichen (Cladonia alpestris, Cetraria nivalis and Cetraria cucullata in close association) together with scattered spruce, tamarack and birch up to 10 ft high and Labrador tea. This site is 1/4 mile west of D.O.T. Lake and about 4 miles east of Norman Wells (Figure 8). Three large and three small fruit juice cans were installed at this site in 1959. These were replaced by three oil drums in 1960.

Measurements were taken every morning on each evapotranspirometer from the date of installation until the first autumn frost. After the overflow had been recorded, a measured quantity of water in excess of the anticipated potential evapotranspiration was sprinkled uniformly over the surface.

In 1959, the period of observation was very short. The drum and cans at the Thornthwaite site were installed between 5 and 10 August and readings were completed about 10 September. The remaining evapotranspirometers were not installed until the last week in August and readings on these were also completed about 10 September.

In 1960, readings began in June and were completed on 17 September. Air temperatures and rainfall were measured daily at each site. At Sites Two to Five, some perennially frozen soil had to be excavated to accommodate the oil drums and overflow apparatus but the low soil temperatures did not appear to interfere with the evapotranspiration or overflow.

(c) Latent evaporability of the air

An Alumdum disc atmometer was borrowed from the Federal Department of Agriculture to measure the latent evaporability of the air at Norman Wells, as part of a country-wide program of evaporation measurements being conducted by the Meteorological Branch, Department of Transport (Figure 9 (8)). This atmometer was installed in the southwest corner of the Thornthwaite potential evapotranspiration site. In 1959, daily readings were taken from the beginning of August until early September. In 1960, daily readings were taken from 11 June until 17 September. The results of both summers were compared with observations from the Thornthwaite site.

(d) Evaporation from open water surface

In 1960, a Class "A" Evaporation Pan was supplied by the Meteorological Branch, Department of Transport to measure the evaporation from the surface of water in an open pan, as part of a country-wide program of evaporation measurements (Figure 10). This installation was located 15 ft west of the Thornthwaite site. Daily readings were taken from 11 June to 17 September and the results compared with the observations from the Thornthwaite site.

2. Radiation

The main source of energy contributing to the energy exchange at the ground surface and to the ground thermal regime is the sun. Some of the incoming radiation is absorbed in the atmosphere, some is reflected at the ground surface back into the atmosphere, and the remainder enters the ground. Two instruments were used to measure the radiation component of the energy exchange at Norman Wells: a Gunn-Bellani radiation integrator and an economic net radiometer.

(a) Incoming short-wave radiation

The Gunn-Bellani radiation integrator (2) gives a measure of the total incoming short-wave solar and sky radiation reaching a blackened copper sphere containing alcohol (Figure 11). The integrated radiation received by the copper sphere vapourizes the alcohol within it which condenses in the graduated glass receiver.

Three of these instruments were obtained for use at Norman Wells. Prior to this, they had been installed in the DBR Test Area in Ottawa and readings compared with the Eppley pyrheliometer there to obtain calibration constants. In 1959, two of these instruments were installed about 4 ft apart in the northwest corner of the Thornthwaite site and daily readings were taken from 8 August to 12 September (Figure 12). In 1960, two of these instruments were installed again in the northwest corner of the Thornthwaite site. On 23 June, the third instrument was installed at Site Five (lichen area) at D.O.T. Lake. Daily readings were taken on the three instruments until 17 September.

(b) Net radiation

The net radiation normal to the earth's surface is the difference between the total upward radiation flux and the total downward radiation flux. Net radiation is important to many meteorological problems because it is a measure of the energy available at the earth-atmosphere interface; it is significant in permafrost areas as it indicates the amount of energy put into the ground in which permafrost exists.

An economic net radiometer (10) was used at Norman Wells in 1959 to measure the net radiation of the various vegetative surfaces at which potential evapotranspiration measurements were being made (Figures 13, 14). Weekly readings were taken at each of these sites when the depth of thaw and ground temperature measurements were taken.

A record of the sunshine duration for each hour was obtained from the meteorological station at Norman Wells. Unfortunately, no radiation measurements were taken at Norman Wells by the Department of Transport so that there were no observations with which the results of the economic net radiometer could be compared. This instrument was not used in 1960.

3. Ground Thermal Regime

Observations were made at the potential evapotranspiration sites to compare the ground thermal regime under different types of vegetative cover. These consisted of depth of thaw measurements and ground temperature observations on thermocouples in the seasonally thawed and perennially frozen ground.

(a) Depth of thaw

In 1957 and 1958, depth of thaw measurements were taken at five sites of which some were used as potential evapotranspiration sites in 1959 and 1960. In 1959 only four of these sites were kept under observation. The purpose of these measurements was to determine quantitative variations in the depth of thaw under different types of vegetative cover and to assess the relative importance of the individual components comprising the vegetative cover, i.e. trees, undergrowth, sedge, moss, and lichen.

Weekly observations were made with a Hoffer probe when the depth of thaw was less than 3 ft, and with a 1 1/2-in. diameter soil auger when the depth of thaw exceeded 3 ft. Three or four measurements were made weekly at each site and an average value was taken. These observations were not carried out in 1960 because it was thought that 3 years of observations was sufficient to indicate significant depth of thaw variations.

(b) Ground temperatures in thawed layer

In 1959, 20-gauge copper-constantan thermocouples were installed at the potential evapotranspiration sites at the following depths:

Thornthwaite site on 11 August at depths of 0, 3, 6, 9, 12, 36 and 60 in. On 9 September, a thermocouple was installed at the 70-in. depth.

Sedge area (Site Two) on 13 August at depths of 0, 3, 6, 9, 12, 18, 24, 30, 36 and 60 in.

Sparsely treed moss area (Site Three) on 13 August, at depths of 0, 3, 6, 9, 12 and 18 in. On 25 September, a thermocouple was installed at the 22-in. depth.

Wooded area (Site Four) on 13 August, at depths of 0, 3, 6, 9 and 12 in. On 22 September, a thermocouple was installed at the 14-in. depth.

Besides the above installations, thermocouples were installed at depths of 0, 3, 6, 9, 12, 18 and 24 in. on 13 August in a moss-covered sedge area in which depth of thaw measurements were taken. It had been intended to install evapotranspirometers here, but waterlogged conditions prevented this.

Two special sets of thermocouple strings were fabricated to obtain a detailed temperature gradient through moss and lichen. In each case, 13 thermocouples were spaced at 1-in. intervals from the ground surface to the 1-ft depth and read with a 20-point selector switch. These were installed on 24 August 1959, one in the wooded area (Site Four) where the sphagnum moss exceeds 12 in. in thickness, and the other in the lichen (Site Five) which is about 2 in. thick at D.O.T. Lake.

The seven sets of thermocouples were read weekly when the depth of thaw observations were taken. In addition, 27 consecutive hourly readings from 9.00 a.m. 14 August to 11.00 a.m. 15 August were taken at the Thornthwaite site.

The observation program of ground temperature readings was continued in 1960 with a few changes. Weekly readings were taken beginning on 9 June and ending on 23 September. At the Thornthwaite site, readings were taken on the thermocouples installed in 1959. In addition, thermocouples were installed at depths of 24 and 48 in. on 5 July. Thermocouples were also installed in Pan B at depths of 6, 12 and 26 in. on 11 June to compare ground temperatures inside the pans with those outside.

In the sedge area (Site Two), readings on the thermocouples installed in 1959 were not taken in 1960. New thermocouples were installed at depths of 6, 12 and 18 in. on 15 June, at a depth of 48 in. on 12 July and at 60 in. on 10 August. The last two thermocouples were installed shortly after the soil had thawed to the depths indicated.

In the wooded area (Site Four), readings were taken on the thermocouples installed in 1959. In addition, thermocouples were installed beside the oil drums at depths of 6 and 12 in. on 5 July.

Readings were not taken in 1960 on the thermocouples installed in 1959 in the moss-covered sedge area, which was too wet for the installation of evapotranspirometers.

The two special thermocouple strings with selector switches were installed in thick moss and lichen respectively at the potential evapotranspiration sites at D.O.T. Lake.

(c) Ground temperatures in permafrost

Variations in mean annual ground temperatures in permafrost are of particular interest in energy exchange studies. The temperature of the permafrost marks the thermal level of the ground and is the sum total of the heat gains and heat losses contributed by the various factors comprising the environment in which permafrost exists. Vegetation is one of these factors, and in 1960, a device was developed and installed to measure variations in mean ground temperatures in permafrost caused by different types of cover. The device consisted of a maximum-minimum recording dial thermometer 3 in. in diameter with a 2 1/2-in. stem. This was housed in a 10-ft plastic pipe in a drill hole in the ground (Figure 5).

Ten dial thermometers were installed at Norman Wells in 1960. The plastic pipes were installed in August to allow them to freeze solidly in the drill holes in the permafrost by September. Three were located in the sedge area (Site Two). Three were located in a moss-covered area (similar to Site Four) beside the road to the airport, and four were located in the lichen area (Site Five). At the end of September the thermometers were placed in the pipes. The intention was to retrieve them a year later, in September 1961, and record the maximum and minimum temperatures. It was assumed that the average of the maximum and minimum temperatures would be a close approximation of the mean ground temperature. The thermometers were read in May and September 1961.

To check on the temperatures recorded on the dial thermometers, thermocouple cables were installed at the sites with thermocouples at the following depths:

Sedge area - 1/2, 1 1/2, 2 1/2, 3 1/2, 4 1/2, 9 1/2, 14 1/2 and 19 1/2 ft.

Moss area - 1/2, 1 1/2, 2 1/2, 3 1/2, 8 1/2, 13 1/2 and 18 1/2 ft.

Lichen area - 1, 2, 3, 4, 5, 10 and 11 1/2 ft (Figure 8).

Weekly readings were taken on these until late September. Arrangements were made to have monthly readings taken on these cables throughout the winter by local personnel, but unforeseen circumstances prevented this.

(d) Soil moisture content

In 1959, moisture content samples were taken in late August and late September at the sites, at the depths where thermocouples were located in the thawed layer. These samples were taken immediately after measuring the ground temperatures to discover what effects the differences in moisture content might have on ground temperatures.

RESULTS OF OBSERVATIONS

1. Potential Evapotranspiration and Evaporation

(a) Potential evapotranspiration at Thornthwaite site

In 1959, the potential evapotranspiration (P.E.) of the large grass-covered pans at the Thornthwaite site was measured daily from 1 August to 7 September inclusive. The P.E. for Pan "B" for August was 5.44 cm. The P.E. for Pan A from 15-31 August was 3.19 cm and 3.28 cm for Pan B (Table I). It appears that the two pans had similar P.E. rates during the 1959 operating season.

In 1960, calculations of P.E. for the Thornthwaite site were made for the 80-day period of 30 June to 17 September inclusive (Table I). During this period, Pan A, equipped with the constant water supply system, gave a lower P.E. (16.73 cm) than Pan B (19.41 cm) because of occasional sticking of the float pan valve which reduced the supply of water from the reservoir tank. It is suggested that Pan B gave a more realistic measure of the P.E. than Pan A.

These observed P.E. rates were compared with four theoretical formulae used to compute P.E., and with the evaporation of water from the Class A Pan.

The first formula suggested by the Experimental Farm, Canada Department of Agriculture, derives P.E. from latent evaporation measurements obtained from the Alumdum disc atmometer (8). From 5 to 11 August 1959, this apparatus was not functioning because the porous plate was broken and a new one had to be ordered from Ottawa. Near freezing temperatures and snow in early September made the validity of the September observations questionable. Comparison was made, therefore, with the evaporation total of 15 to 31 August. The formula is:

$$L.E. \times 0.0034 \times 2.54 = P.E. \text{ (cm)(Ref. 6)} \quad ......(1)$$

where

L.E. is latent evaporation.

Applying this formula gives a P.E. of 4.19 cm compared with 3.19 and 3.28 cm measured in the Thornthwaite pans (Table I). In 1960, a good correlation was obtained between the P.E. measured from Pan B and the latent evaporation measured on the Alumdum disc atmometer for the period of 30 June to 17 September. The total P.E. for Pan B was 19.41 cm compared to 19.47 cm for the atmometer (Table I).

The second formula is Thornthwaite's (11) in which he derived P.E. by considering the length of day and a heat index related to the number of degrees that the mean daily temperature is above 32°F. The amount of precipitation is not considered because it is assumed that the amount of water evaporated and transpired is determined by temperature and length of day. Without going exhaustively into the derivation of Thornthwaite's factors, it is sufficient to say that the P.E. at Norman Wells using a heat index of 17.3 varies almost linearly from 0.02 cm at 33°F to 0.30 cm at 60°F. The applicable P.E., depending on the mean daily temperature, is multiplied by the duration of sunlight for that day in units of 12 hours. Using this formula, the computed P.E. for August 1959 was 7.91 cm. For 15 to 31 August 1959, it was 4.47 cm (Table I). In 1960, the Thornthwaite computed P.E. was also higher than the measured P.E. for the 80-day period being 24.75 cm (Table I).

The use of the Thornthwaite formula in high latitudes has been criticized because (1) the heat index has been computed only north to 50° and Norman Wells, for example, lies at 66°N; (2) the length of day factors used to compute P.E. at Norman Wells have also been computed for 50°N. Further north the days are longer during the evapotranspiration period but the amount of incoming solar radiation is less because of the lower angle of the sun and the low angle of incidence. It is not known, however, how well these factors balance out.

The third formula is Holdridge's which is (4):

$$P.E.(mm) = 58.93 \left(\frac{\text{Unit period of time}}{\text{Number of units of time in 1 year}}\right)\left(\begin{array}{l}\text{Comparative plant}\\ \text{growth mean}\\ \text{temperature, °C}\end{array}\right) \quad ...(2)$$

The solved values for the items in first bracket for periods of time normally used for determining P.E. are:

1 year	- 58.93	Leap Year	
1 month (31 days)	- 5.00	1 month (31 days)	- 4.99
1 month (30 days)	- 4.84	1 month (30 days)	- 4.83
1 month (28 days)	- 4.52	1 month (29 days)	- 4.67
1 day	- 0.16		

The comparative plant growth mean temperature equals

$$\left[\frac{\text{Sum of average positive temperatures in °C/unit of time}}{\text{Total number of the units of time in the period of the mean}}\right].$$

For the purposes of computing P.E., this formula can be simplified to a selecting of the pertinent factors for the length of time involved. For August 1959 (31-day month - not Leap Year) the factor is 5.00. This is multiplied by the mean monthly temperature in °C - 10.3°C. Therefore the computed P.E. using Holdridge's formula was

$$5.00 \times 10.3 = 51.50 \text{ mm} = 5.15 \text{ cm}.$$

For 15 to 31 August inclusive, the factor is

$$0.16 \times 17 \left(\begin{array}{l}\text{number of days}\\ \text{in the period}\end{array}\right) \times \left(\begin{array}{l}\text{mean temperature}\\ \text{for the period}\end{array}\right)$$

which works out to 2.98 cm (Table I). In 1960 the Leap Year factors were used to compute the Holdridge totals. For the 80-day period, the total was 16.07 cm which compares more favourably with the 16.73-cm total for Pan A than with the 19.41-cm total for Pan B (Table I).

Holdridge claims that the determination of P.E. from temperatures alone without using precipitation data or other climatic factors is possible because, first, the P.E. rate at a given temperature decreases proportionately along a gradient of increasing precipitation from dry to wet areas, so that the product of evaporation rate and mean annual precipitation is constant along the gradient. This is reflected in the regularity of the pattern of changes in physiognomy between the single climatic plant associations of each of the formations along the precipitation gradient. Second, local variations in edaphic and atmospheric factors sufficient to cause an appreciable change in either evaporation or transpiration, or in both, are counterbalanced by different physiognomies of the natural vegetation, developed in the past through evolutionary processes which bring the actual evapotranspiration into equilibrium with the P.E. rate and the moisture available. These variations are reflected in the diversity of aspect and lack of regularity of the pattern of changes of physiognomy of the (usually several) edaphic, atmospheric, and hydric associations of the same plant formations along the moisture gradient.

The fourth formula is Penman's mass transfer formula (7):

$$E_o = 0.35\ (e_o - e_d)\ (0.5 + \frac{U_2}{100}) \qquad \text{......(3)}$$

where

E_o = evaporation, cm

$e_o - e_d$ = vapour pressure difference between surface and air, mm of Hg

U_2 = mean wind speed, miles per day.

It was assumed that the mean temperature of a saturated surface is approximately equal to the mean air temperature. Wind velocity and air temperature records were obtained from the D.O.T. Meteorological Station at Norman Wells. The wind factor was adjusted to the 2-meter level by assuming that the wind velocity decreases with height according to the one-seventh power law. The Penman total for the period of 15 to 31 August 1959 was 4.51 cm which is considerably higher than the totals observed for the Thornthwaite pans (Table I). The Penman total for the 80-day period, 30 June to 17 September 1960, was 19.32 cm compared with 16.73 cm for Pan A and 19.41 cm for Pan B (Table I). A comparison was made between the calculated Penman formula and measured P.E. from Pan B for 10-day and monthly totals, resulting in good correlation (Figure 15).

Finally, the observed P.E. from Pans A and B were compared with the evaporation of water from the Class A Pan in 1960. It was noted that the latter was considerably higher - 25.63 cm (Table I).

The P.E. computed from the Holdridge formula more closely resembles the observed P.E. for 1959 than either the Thornthwaite or converted latent evaporation formulae. The P.E. computed by Thornthwaite's formula for previous summers' operation of the Thornthwaite site have shown it to be nearly twice as high as the observed P.E. For the period of 15 to 31 August 1959, the latent evaporation formula gave almost as high a P.E. as the Thornthwaite formula. This period of latent evaporation observations was really too short to draw any unqualified conclusions. In 1960, there was considerable variation among the various formulae and the observed P.E. during the first half of the 80-day period, but they were quite close to each other during the second half.

The main objection to the Thornthwaite, Holdridge and latent evaporation formulae seems to be their disregard for different plant types. This would perhaps be particularly true for northern areas where moss and lichen are so widespread. Moss is a vascular plant although of much simpler structure than higher plants such as sedge, shrubs and trees. In addition, the amount of transpiration surface per unit ground area may be of a different order of magnitude than the higher order plants. Lichen is not a vascular plant and does not transpire. The mechanism of water movement in moss and lichen is not clearly understood. One objective of the Norman Wells studies was to gain an understanding of the role played by moss and lichen in the over-all moisture transfer.

(b) Potential evapotranspiration at other vegetation sites

Comparisons were made between the P.E. from the grass-covered pans and the P.E. from the various natural vegetation cover types in the Norman Wells area. A number of difficulties were encountered in 1959. The summer was unusually cool and wet which reduced the evapotranspiration of all the vegetation making it more difficult than usual to detect differences between the various types when they are small. The evapotranspirometers (oil drums, large and small fruit juice cans) were installed throughout August. The first frost occurred in early September so that the total length of time when all installations were operating simultaneously was very short. Some oil drum readings were invalidated because of flooding of the overflow containers. This occurred at sites located in low-lying poorly drained areas. Periodically, some of the fruit cans became clogged in the bottom and prevented all of the excess water being collected as overflow. Although the observation period was very limited, examination of the results indicated that evapotranspiration rates were higher for the Thornthwaite site and sedge area (Site Two) than for the moss and lichen.

Better success was obtained in 1960 because of improvements in the installations, a longer operating season, and a warmer summer than in 1959. The installations were completed before the end of June and daily readings were taken until 17 September.

The results for 1960 are tabulated in Table I. At the Thornthwaite site, the oil drum and the 15-cm diameter can gave higher totals than the large pans. The drums at the other sites gave somewhat erratic results; results for the small cans at Site Four were particularly scattered. It is thought that the oil drums probably gave more realistic P.E. values than the smaller containers because of their larger surface area, greater depth and decreased rim effect. Sprinkling is undoubtedly a less reliable method of adding water than maintaining a constant water supply.

Mean daily air temperatures were recorded at four of the five sites but there was no apparent correlation with P.E. The Thornthwaite site had the highest P.E., but its mean temperature for the 80-day period of 54.6°F was higher than that of the wooded site (which was shaded) and the sedge site and lower than the moss and lichen sites near D.O.T. Lake. The higher degree of exposure to wind of the Thornthwaite site would contribute to its having a higher P.E., but the moss and lichen sites at D.O.T. Lake were also fairly exposed. These last two sites had P.E. values similar to the wooded area which was sheltered. It appears, therefore, that P.E. rates are significantly higher through Kentucky blue-grass (which is not native to permafrost regions) than through sedge, moss and lichen which are indigenous. The results of 1960 are probably more valid than those of 1959 because of the longer observation period. Over several months, day to day discrepancies can be ironed out and a longer term pattern emerges.

It has been stated that meteorological factors play a prominent role in evapotranspiration rates where soil moisture is not the limiting factor. Nevertheless, it is possible that the physiological characteristics and radiation and thermal properties of plant materials such as moss and lichen, which maintain a high permafrost table, are significant factors in determining the contribution of evapotranspiration to the energy exchange of permafrost. One discrepancy that arises is the fact that sedge does not maintain a high permafrost table, but has P.E. rates comparable to moss and lichen. This may be caused by its lower insulating qualities which permit a greater depth of thaw during the summer.

2. Radiation

(a) Incoming short-wave radiation

Incoming short-wave radiation was measured daily at the Thornthwaite site from 8 August to 12 September 1959 inclusive, using two Gunn-Bellani radiation integrators (designated as A and B) which were read at the same time each day.

In the spring of 1959, integrator A was installed in the D.B.R. Test Area in Ottawa and readings from it were compared with radiation measurements obtained from the Eppley pyrheliometer at the Division. In the spring of 1960, integrators A and B and a new one (designated as C) were installed in the D.B.R. Test Area for calibration. The calibration constant obtained for A in 1959 was 24.39 Langleys per millilitre of condensed alcohol. In 1960, the value obtained was 41.5 Langleys. The value obtained for B was 366 Langleys and for C it was 476 Langleys, which do not correspond with the manufacturer's constant of 18.8 Langleys for both instruments. Shipping the integrators back and forth between Norman Wells and Ottawa could have caused invisible but sufficient damage to prevent them from functioning properly. Despite this, the three integrators were used at Norman Wells during the summer of 1960. Integrators A and B were installed at the Thornthwaite site as in 1959 and instrument C was installed in the lichen area (Site 5).

The 10-day total of radiation values is tabulated in Table II. Millilitres of alcohol condensed in each integrator are shown followed by the conversion of these values into Langleys of radiation. In the last two columns are shown the 10-day totals of incoming solar radiation at Fort Simpson, N.W.T. and Aklavik, N.W.T. recorded by the Department of Transport on Eppley pyrheliometers. It appears that the integrators must have been faulty because all the radiation values from Norman Wells are lower than those from Fort Simpson and Aklavik whereas they should probably fall between the two. There is little consistency among the integrators in any given 10-day period. Because the instruments proved to be so unsatisfactory, the only way that any values of incoming short-wave solar radiation could be obtained was by taking a mean of the values from Fort Simpson and Aklavik, which are located about the same distance south and north of Norman Wells respectively.

(b) Net radiation

During the summer of 1959, weekly net radiation measurements of various vegetative cover types in the Norman Wells area were taken using an economic net radiometer. To obtain net radiation with approximately 3 to 5 per cent accuracy, the short expression for radiation in Langleys per minute was used:

$$Rn = 1.25\sigma\ (T_t^4 - T_b^4) + 0.0025\ (T_t - T_b) \qquad ......(4)$$

where

Rn is net radiation, Langleys per minute

σ is the Stefan-Bolz constant

T_t = temperature of top face, °C

T_b = temperature of bottom face, °C.

This expression considers incoming radiation positive and outgoing radiation negative.

The calculated net radiation results and air temperatures at the time of reading are tabulated in Table III. This table also includes the exact times at which observations were taken and the percentage of sunlight recorded during the hour in which each reading was made. As mentioned previously, no continuous measurements of incoming solar radiation were made with which the observed net radiation values could be compared. It was thus impossible to compare the differences of net radiation through different types of vegetative cover with the incoming solar radiation at the time of observation.

Despite the questionable validity of the observations, a general qualitative pattern is evident. For example, it was anticipated that the net radiation values for lichen would be the lowest because of this plant's light colour and consequent high reflective properties. This was true on clear days but not on partly cloudy or overcast days when differences in net radiation from one plant type to another were small. On the other hand, net radiation values for sedge, which is also a light-coloured plant, were much higher than for lichen on clear days and indeed higher than the darker-coloured plants such as grass and moss. Net radiation values at the Thornthwaite site were the highest on some days but not on others. Net radiation through moss was highest on clear days but not always on overcast days.

From these crude measurements, it appears that net radiation through moss is higher than through lichen. Nevertheless, these two plant types maintain the permafrost table at about the same level in a given area and near surface ground temperatures are similar under both plant types. Consequently, if lichen rejects a higher proportion of the radiative flux than moss, this may be compensated by the moss rejecting a higher proportion of some other component of the energy exchange than the lichen.

3. Ground Temperatures and Depth of Thaw

(a) Depth of thaw

Depth of thaw measurements in various types of vegetative cover were plotted against Fahrenheit degree days for the summers of 1957, 1958 and 1959. The use of degree days gives a more realistic comparison than calendar dates because of the variation in air temperature from one summer to another. For example, the depth of thaw in 1959 was considerably less than in the two previous summers because of the lower air temperatures. Nevertheless, a comparison of depth of thaw with degree days of thawing indicated a similar relationship existing for the three summers of observations. Average values of depth of thaw vs degree days of thawing were obtained for each vegetation cover type and plotted (Figure 16).

Difficulties are inherent in obtaining depth of thaw observations by probing because of small but significant variations in the depth of thaw over a horizontal distance of only a few feet at any site. In addition, probing in the same area week after week unavoidably disturbs the surface cover of the area to the extent of affecting the natural thaw penetration. Nevertheless, the trends in depth of thaw at the various sites could be detected after three summers and these observations were not continued in 1960. Figure 5 shows the vegetation and soil profiles at the sites in the Norman Wells area at which depth of thaw measurements were taken.

The greatest depth of thaw occurred in the sedge area (Site Two) where there was no moss cover. The next greatest depth of thaw was observed in the wooded area (Site Four), probed only in 1957 and 1958. This site had a moss cover 4 in. thick overlying 3 in. of peat. Actually the 1958 depth of thaw was much greater than in 1957 which may be explained by the inadvertent disturbance of the site in 1957 resulting in an unnaturally deep thaw the following year. The treeless sedge and moss area with a 3-in. moss cover overlying 6 in. of peat had less depth of thaw than the previously mentioned area. The most shallow depth of thaw was observed in the sparsely treed area that has a 5-in. moss cover overlying about 18 in. of peat (Site Three) and the wooded area with 4 to 12 in. of moss overlying several inches of peat (Site Four).

It appears therefore that the depth of thaw is primarily dependent on the thickness of moss and peat. It is not certain to what degree the depth of thaw is influenced by the shade of shrubs and trees. This is probably a relatively minor factor compared with the influence of moss and peat. This is supported by the air temperature observations obtained at the various sites during the summer of 1960. The mean daily air temperature at the treeless sedge area (Site Two) for the period of 30 June to 17 September 1960, which includes a major portion of the thawing period, was 53.2°F. The mean daily air temperature for the same period in the wooded area (Site Four) was 54.2°F although the depth of thaw was several feet less.

(b) Ground temperatures in thawed layer

Weekly ground temperatures taken during the summers of 1959 and 1960 showed that significant differences existed under different types of vegetation. The Thornthwaite site had the highest ground temperatures in the thawed layer followed by the sedge area (Site Two). The next highest was in the treeless sedge area with moss followed by the sparsely treed moss-covered area (Site Three - 1959). The 12-in. thick moss in the wooded area (Site Four) had the same temperature regime in the last three weeks of September prior to winter freezing. It is interesting to note that, in August, Site Three had lower temperatures than the wooded area and the lichen area had higher temperatures. There appeared to be a general decrease in temperature with increased moss cover and peat thickness. Although the depth of thaw did not appear to be significantly less in areas shaded by trees, these areas experienced slightly lower temperatures in the thawed layer than treeless areas.

An interesting feature was revealed when ground temperatures were compared with degree days of thawing. The cooler nature of the 1959 summer was confirmed by the fact that the cumulative total of degree days of thawing on 30 September totalled 2513 compared with 2954 on 23 September 1960. It was anticipated, however, that a plot of ground temperatures vs degree days of thawing would show similar patterns for the two summers. This was not the case, however, because for any given degree day total, the ground temperatures were much higher in the warmer summer of 1960. For example, in 1959, the temperature at the 12-in. depth at the Thornthwaite site on 28 August was 46.6°F at which time the cumulative total of degree days of thawing was 2232. Almost the same degree day total was reached on 5 August 1960 (2202), at which time the temperature at the 12-in. depth was 54.4°F.

In 1959 and 1960 weekly temperature readings were taken on the thermocouple strings installed in moss and lichen at D.O.T. Lake. Thermocouples were spaced at 1-in. intervals from the ground surface to the 12-in. depth. The purpose of this was to obtain a temperature gradient through the living plant cover itself to see if it was uniform throughout or if it varied with depth, and to see if there was any difference in the gradient between the moss and the lichen. These are the two most common ground cover plants in the permafrost region and both maintain a high permafrost table. In the summer, the air temperature frequently rises above 80°F but the temperature at the bottom of the moss and lichen remains close to 32°F. The moss cover exceeded 12 in. in thickness so that the whole thermocouple string was in the moss. In contrast, the lichen was only 2 in. thick so that the thermocouple string extended several inches below the lichen.

In 1959 the temperature gradients for the two strings were higher in the top 8 in., and lower in the bottom 4 in. This means that the gradient was uniform throughout the lichen and the top few inches of the underlying peat, in contrast to the moss where the gradient changed in the moss itself.

In 1960 the same large differences between surface temperatures and temperatures at the lower end of the thermocouple strings were evident. The chief difference between the two summers was that temperature profiles in 1960 showed changes in gradient at about the 4- or 5-in. depth in contrast to the 8-in. depth in 1959. In all cases, the temperature observed at the surface of the moss and lichen was several degrees higher than the screen air temperature observed at the time of the ground temperature readings.

In 1959, the temperatures observed at the 12-in. depth were the same in both the moss and lichen, but in 1960 the temperature at the bottom of the thermocouple string in the moss was consistently about 5°F higher than in the lichen. It is difficult to know whether temperatures at the 12-in. depth actually varied by this amount between the two plant types or whether one of the thermocouple strings was faulty. It is possible that the thermocouple string in the moss was defective because the 12-in. thermocouple gave unreliable readings and the 11-in. thermocouple was used instead. The readings on the lichen were probably closer to reality but even they were about 4°F higher than temperatures observed at the 12-in. depth in the wooded area.

Taking all the weekly readings from 28 August to 30 September 1959, which was the period when the depth of thaw reached its maximum and the differences caused by variations in vegetative cover were most pronounced, the average temperature at the 1-ft depth was calculated. It was noted in the hourly readings taken at the Thornthwaite site (mentioned below) that over a 24-hour period the temperature fluctuation at the 1-ft depth was 1.5°F. All the ground temperature readings at the various sites were taken between 9.00 a.m. and 4.00 p.m. during which period the temperature fluctuation at the 1-ft depth at the Thornthwaite site was 0.8°F. (This would probably be as large a variation as would ever occur because it was measured through a day which was clear with a large air temperature amplitude.) The mean air temperature for this period was 41.2°F. The mean ground temperatures were:

Thornthwaite site	40.0°F
sedge area (Site Two)	36.5°F
sedge area with moss	35.0°F
sparsely treed moss area (Site Three, 1959)	33.7°F
wooded area (Site Four)	32.8°F
thick moss (Site Three, 1960)	32.5°F
lichen area (Site Five)	32.6°F

It is interesting to note that the lichen and moss had approximately the same average temperature over this period although the lichen was only 2 in. thick in contrast to the 12 in. of moss, both overlying similar thicknesses of peat.

Means of the weekly temperatures at the various depths for different time periods were calculated for 1960. Mean ground temperatures and amplitudes for the period of 15 July to 16 September are plotted in Figure 17 showing them to be much higher in the Thornthwaite and sedge areas with no moss cover than in the moss-covered wooded area. Differences between the mean air and mean ground temperatures at the 12-in. depth at the various sites for the period of 28 August to 30 September 1959 were compared with the differences for the period of 15 July to 16 September 1960. The differences are:

Thornthwaite site	1.2°F (1959), 3.3°F (1960)
sedge area (Site Two)	4.7°F (1959), 5.6°F (1960)
wooded area (Site Four)	8.4°F (1959), 19.8°F (1960)
thick moss at D.O.T. Lake (Site Three - 1959)	8.7°F (1959), about 12°F (1960)
lichen area (Site Five)	8.6°F (1959), about 17°F (1960)

This appears to confirm the thermal resistance of the moss and lichen because the much higher air temperature means in 1960 did not cause ground temperatures that were much higher than those recorded in 1959.

In 1959, a series of 27 consecutive hourly observations of screen air temperature, ground surface temperature and temperatures at depths of 3, 6, 9, 12, 36 and 60 in. were taken at the Thornthwaite site from 9.00 a.m. 14 August to 11.00 a.m. 15 August. A plot of these observations showed that the temperature amplitudes were greatest in the air and at the grass surface, and decreased progressively with depth. The lag in maximum and minimum temperatures also increased with depth (Figure 18).

Mean ground temperatures for the 24-hour period from 9.00 a.m. 14 August to 9.00 a.m. 15 August were calculated for the 3-, 6-, 9-, 12-, 36- and 60-in. depths as well as for the grass surface and the screen air temperature (Figure 19). A plot of the means on a graph indicates a linear decrease with depth from the surface to the frost table at the 60-in. depth and a decrease of amplitude. The highest mean temperature for the period occurred at the grass surface (52.9°F) and the mean air temperature in the screen (51.7°F) was almost the same as the ground temperature at the 3-in. depth (51.5°F).

(c) Ground temperatures in permafrost

Readings on the dial thermometers in the plastic pipes embedded in permafrost were taken on 11 May 1961, 3 October 1961 and 25 September 1962 by two of the author's colleagues (Table IV).

In May 1961, it was possible to visit only the sedge area. The three pipes at this site had heaved about 5 ft upwards because of winter freezing in the ground and readings obtained there were considered unreliable. Temperature measurements at this site were abandoned because it was impossible to reset the pipes in the ground.

The maximum temperatures recorded on the thermometers in October 1961 were of no value because the maximum temperature at a depth of 10 ft in the permafrost was known to be below 32°F. The minimum temperatures show a degree of consistency at each site but are much lower at the moss site.

In September 1962, readings were taken on the three thermometers in the moss area. It was possible to obtain readings on only two of the four thermometers in the lichen area. One of the pipes could not be located; in the other the insulation could not be removed because it was frozen. The maximum and minimum temperatures showed a degree of consistency at each site. In the moss area, the temperatures were lower and the differences between the maximum and minimum temperatures were greater.

The large difference between the moss and lichen areas suggests, perhaps, the effect of other factors besides these two plant types on the ground thermal regime. Future readings will be taken when Northern Research Group personnel visit Norman Wells.

Weekly readings were begun on the three 20-ft long thermocouple strings at the end of July 1960 and continued until 23 September. Subsequent readings were taken on 18 and 19 October 1960 and 12 May 1961. The means and amplitudes of the seven weekly sets of ground temperature readings taken in August and September 1960 were plotted on a graph (Figure 20). The lower summer ground temperatures under the moss and lichen as compared with the sedge are immediately evident. In addition, the temperature amplitude in the top few feet is much greater under the sedge than under the moss or lichen.

(d) Soil moisture content

The moisture content of samples taken in the thawed layer at the various sites in 1959 is tabulated in Table V. The samples of 28 and 29 August were taken during a period of dry weather and those of 23 and 24 September were taken after a wet period. The two sedge areas (Site Two and the sedge area with moss) had much higher soil moisture contents in September. The sparsely treed moss area (Site Three - 1959), the wooded area (Site Four) and the lichen area (Site Five) had similar moisture contents both times, despite the different weather conditions. On the other hand, the thick sphagnum moss at D.O.T. Lake had a much higher moisture content during the dry period in August than during the wet period in September. The large differences in moisture content between this site and the lichen site did not appear to affect the temperature readings. One significant feature was the moisture content in the lichen cover. At the 1-in. depth on 29 August, the moisture content was 8 per cent and at the 2-in. depth it was 120 per cent. The same depths were sampled on 23 September and the differences in moisture content between the two depths were much less. In the first instance, the samples were taken during a period of dry weather when the lichen was very dry down to the basal layer at the 2-in. depth which was very wet. In the second instance, a period of wet weather had preceded the sampling and the upper part of the lichen was still moist although not as wet as the basal layer.

CONCLUSION

After two summers of study on the relationship between the energy exchange regime at the ground surface and the distribution and occurrence of permafrost, it is difficult to draw definite conclusions.

Obtaining a complete energy balance is difficult even in Ottawa where more complex instrumentation is available. At Norman Wells, simpler instruments designed for the field were used. The results obtained were variable and their validity is questionable. Two components of the total energy balance, evaporation and radiation, were measured but no observations were made of the conduction - convection component. As a result, a total energy balance could not be computed.

A comparison between the amount of energy involved in evaporation (i.e. evapotranspiration and evaporation) and net radiation was also not possible. The measurement of potential evapotranspiration by adding water to the surface of a small plot of vegetation and measuring the overflow has been criticized for several reasons. First, the daily addition of water actually changes the climate of the vegetation under test and the results do not give a true representation of the natural moisture regime. Second, the use of very small test plots such as oil drums or smaller containers has been criticized because the edge effect is so pronounced that it significantly changes evapotranspiration.

A comparison was made between the evapotranspiration rates of moss and lichen and those at the Thornthwaite site and in the sedge area (Site Two). There was speculation that the high permafrost table under moss and lichen may be caused in part by high evapotranspiration removing large quantities of heat from the ground. Observations in 1959 revealed, however, that the potential evapotranspiration from moss and lichen was similar but lower than that from grass and sedge. Observations in 1960, which are probably more reliable because of the longer season and warmer air temperatures, indicated that the potential evapotranspiration was similar in moss, lichen and sedge but these values were lower than for the Thornthwaite site.

Measurements of incoming solar radiation and net radiation gave inconclusive results. It is recognized that incoming solar radiation is influenced by latitude so that it is probable that the values for Norman Wells lie somewhere between those obtained by the Department of Transport at Fort Simpson, N.W.T. and Aklavik - Inuvik, N.W.T. From the crude net radiation measurements taken at Norman Wells, it appears that values are somewhat higher for moss than for lichen. Because the thermal regime of the ground under moss and lichen appears to be similar, as manifested by similar depth of thaw and ground temperature regime, differences between the two plant types must occur in some other component of the energy regime which was not studied.

Observations showed that the depth of thaw was less under moss and lichen than in areas where these plant types did not exist. Ground temperature observations in the thawed layer and in the perennially frozen ground showed that these were lower in areas covered by moss and lichen than in areas supporting other types of plant growth. There are not yet enough observations on the maximum-minimum dial thermometers to indicate existing differences in the mean annual ground temperature under different types of vegetation. It appears, however, that this method of obtaining mean annual temperature is not reliable and little hope is placed in future observations.

It appears that there is little to be gained in continuing the measurement of individual components of the energy exchange in an area such as Norman Wells where the installation and maintenance of the required more complex instrumentation is difficult. Some idea was obtained of possible differences in some of the components existing in the various types of vegetation growing in permafrost areas. From numerous discussions held in the Division of Building Research, it has been decided that the most fruitful avenue of investigation of the permafrost regime is the measurement of mean annual ground temperature under different types of vegetation. Development of reliable self-recording devices to measure this is in progress.

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TABLE I

POTENTIAL EVAPOTRANSPIRATION AND EVAPORATION AT NORMAN WELLS TEST SITES

	Thornthwaite Site (Site One) 1960	Sedge Area (Site Two) 1960	Moss Area (Site Three) 1960	Wooded Area (Site Four) 1960	Lichen Area (Site Five) 1960	D.O.T. Met. Station 1960
Elevation above sea level, ft	318	339	300 ft from Site Five at same elevation	344	348	340
Mean daily air temperature, °F	54.6	53.2	not measured	54.2	53.6	55.2
Mean daily max air temperature, °F	64.3	64.7	not measured	66.9	65.0	63.8
Mean daily min air temperature, °F	44.7	41.7	not measured	41.5	42.2	46.5
Rainfall, cm	17.89	18.63	19.30	18.89	19.10	19.06

P.E., cm	1959	1960	Sedge Area	Moss Area	Wooded Area	Lichen Area
Pan "A"	3.19	16.73				
Pan "B"	3.28	19.41				
Oil drum	-	22.90	12.51	14.01 17.36 12.72	11.76	10.75
15 cm can	-	20.32				
Class "A" pan	-	25.63				
Atmometer	4.19	19.47				
Thornthwaite	4.47	24.75				
Holdridge	2.98	16.07				
Penman	4.51	19.32				

N.B. 1959 period - 15 to 31 August.
1960 period - 30 June to 17 September.

TABLE II

TEN-DAY TOTALS OF INCOMING SOLAR RADIATION FOR GUNN-BELLANI RADIATION INTEGRATOR AT NORMAN WELLS N.W.T. AND EPPLEY PYRHELIOMETERS AT FORT SIMPSON N.W.T. AND AKLAVIK N.W.T. - 1960

Ten-day period	Millilitres of alcohol condensed in integrators			Langleys of radiation using calibration constants (given below)			Eppley pyrheliometer (D.O.T.)	
	A	B	C	A 41.5	B 366	C 476	Fort Simpson	Aklavik
30.6- 9.7	80.9	11.1	6.4	3590	4317	3415	4375	4792
10.7-19.7	103.5	9.7	4.1	4595	3772	2188	4675	5399
20.7-29.7	61.4	7.7	6.0	2726	2995	3202	4225	2980
30.7- 8.8	58.8	8.6	2.3	2611	3345	1228	4862	3562
9.8 18.8	28.4	5.3	2.3	1261	2061	1228	3440	2798
19.8-28.8	7.9	5.9	5.2	351	2295	2775	3373	2266
29.8- 7.9	3.9	4.4	3.2	173	1711	1708	2526	1793
8.9-17.9	2.9	1.6	2.3	129	622	1228	2680	moved to Inuvik

TABLE III

NET RADIATION VALUES OBTAINED AT VARIOUS TYPES OF VEGETATION AT NORMAN WELLS N.W.T. USING ECONOMIC NET RADIOMETER - 1959

Date	Site	Net radiation gm-cal/cm^2/min	Time P.S.T.	Air Temp. °F	Sky conditions
Aug. 28	Thornthwaite	0.34863	1155	57.3	Clear
"	Site Two - sedge	0.44000	1408	59.1	Clear
"	Site Three - moss	0.38050	1447	60.0	Clear
"	Site Four - wooded	0.55762	1522	60.0	Clear
"	Site Five - lichen	0.04525	1025	54.3	Cloudy bright
Sept. 7	Thornthwaite	0.12213	1343	38.4	Cloudy bright
"	Site Two - sedge	0.12525	1509	38.5	Overcast
"	Site Three - moss	0.11250	1415	38.3	Overcast
"	Site Four - wooded	0.24675	1059	37.3	Cloudy bright
"	Site Five - lichen	0.02288	0953	37.1	Cloudy bright
Sept. 11	Thornthwaite	0.27875	1351	42.9	Clear
"	Site Two - sedge	0.17400	1500	43.0	Clear
"	Site Three - moss	0.12400	1532	43.0	Clear
"	Site Four - wooded	0.06013	1603	43.0	Clear
Sept. 12	Site Five - lichen	0.09638	0913	37.4	Scattered cloud
Sept. 23	Thornthwaite	0.05988	1604	43.3	Cloudy bright
Sept. 24	Site Two - sedge	0.08763	0935	34.8	Cloudy bright
"	Site Three - moss	0.18175	1051	36.8	Cloudy bright
"	Site Four - wooded	0.18713	1413	40.1	Cloudy bright
Sept. 23	Site Five - lichen	0.16550	1022	43.6	Cloudy bright
Sept. 30	Thornthwaite	0.11425	0950	36.8	Overcast
"	Site Two - sedge	0.02275	1516	38.2	Overcast
"	Site Three - moss	0.03413	1540	38.0	Overcast
"	Site Four - wooded	0.00563	1631	38.0	Overcast
"	Site Five - lichen	0.02288	1049	38.3	Overcast

TABLE IV

MAXIMUM AND MINIMUM TEMPERATURES OBTAINED WITH DIAL THERMOMETERS AT 10-FT DEPTH IN PLASTIC PIPES IN PERMAFROST AT NORMAN WELLS N.W.T.

Site	Lichen				Moss			Lichen				Moss		
Date	3 October 1961							25 September 1962						
Pipe number	1	2	3	4	8	9	10	1	2	3	4	8	9	10
Temperature when removed from pipe, °F	29	29	29	26.5	27	27	26	29.5	29	Insulation frozen	Not located	26	26	27
Maximum temperature, °F	42.5	39.5	30.5	34.5	41	41	26	30.5	30			26	28	33
Minimum temperature, °F	27.5	28	29	26.5	19	18.5	19	28	28			17	18	18
Temperature when replaced in pipe, °F	28.5	28.5	29	27	31	27	27	29.5	28.5			26	26	27

TABLE V

SOIL MOISTURE CONTENTS IN SEASONALLY THAWED LAYER
AT NORMAN WELLS TEST SITES - 1959

Site	Depth (in.)	Soil type	Moisture content	
			28 and 29 Aug.	23 and 24 Sept.
Thornthwaite site	3	Black decomposed OM and silt	No samples taken	67
	6	↑		35
	9	Brown clayey silt with fine		25
	12	sand with streaks of brown		30
	36	and black decomposed OM		37
	60	Random stones and pebbles		19
	70	↓		20
Sedge area (Site Two)	3	Root zone	205	Site waterlogged
	6		411	
	9	↑	284	
	12	Organic silt	140	
	18	↓	41	
	24	Clayey sandy silt	23	
	30		23	
Sedge and moss	3	Sedge, moss and roots	1004	Site waterlogged
	6	Decomposed black OM	740	
	9	Organic sandy silt with clay	-	
Sparsely treed moss area (Site Three - 1959)	3	Moss and roots	238	330
	6		219	291
	9	↑	573	468
	12	Decomposed OM	327	410
	15	↓	415	494
Wooded area (Site Four)	3	Moss and roots	210 394 689	194 350 800
	6	Black decomposed OM	262 305 576	308 461 657
	9		25 388 442	275 487 570
	12	Brown clayey silt	418 363 533	446 340 367
Moss area (Site Three) 1960	1	↑	412	167
	2		750	194
	3		421	188
	4		427	67
	5		453	39
	6	Moss	482	25
	7		488	28
	8		455	23
	9		468	28
	10		963	25
	11		413	30
	12	↓	769	32
Lichen area (Site Five)	1	Lichen	8	92
	2		120	193
	3	Roots and black OM	178	402
	4	↑	554	265
	5		600	385
	6		620	912
	7	Brown decomposed OM	882	1214
	8		882	1143
	9		750	1273
	10		728	715
	11		1120	1100
	12	↓	-	2048

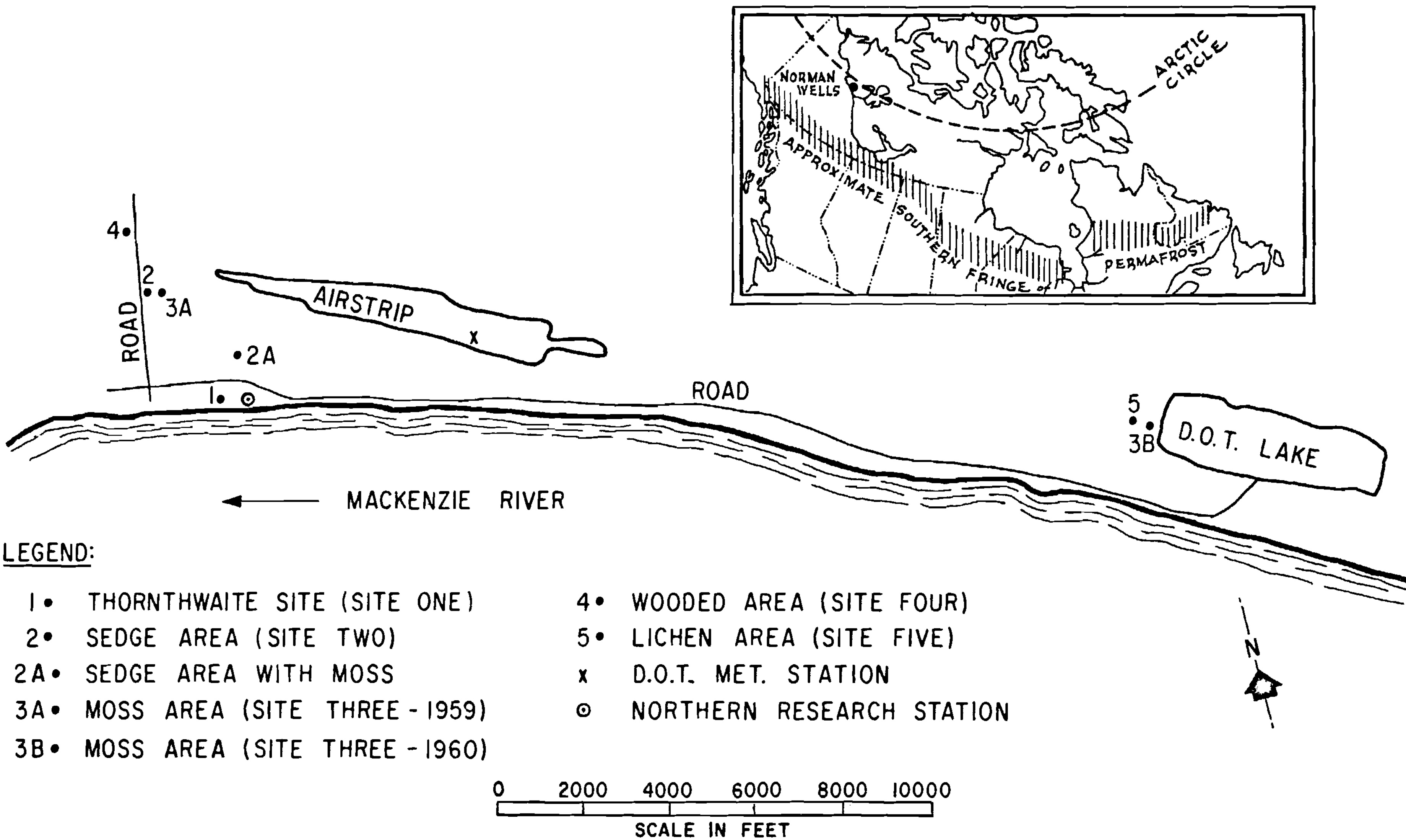

FIGURE 1

LOCATION OF TEST SITES AT NORMAN WELLS, N.W.T.

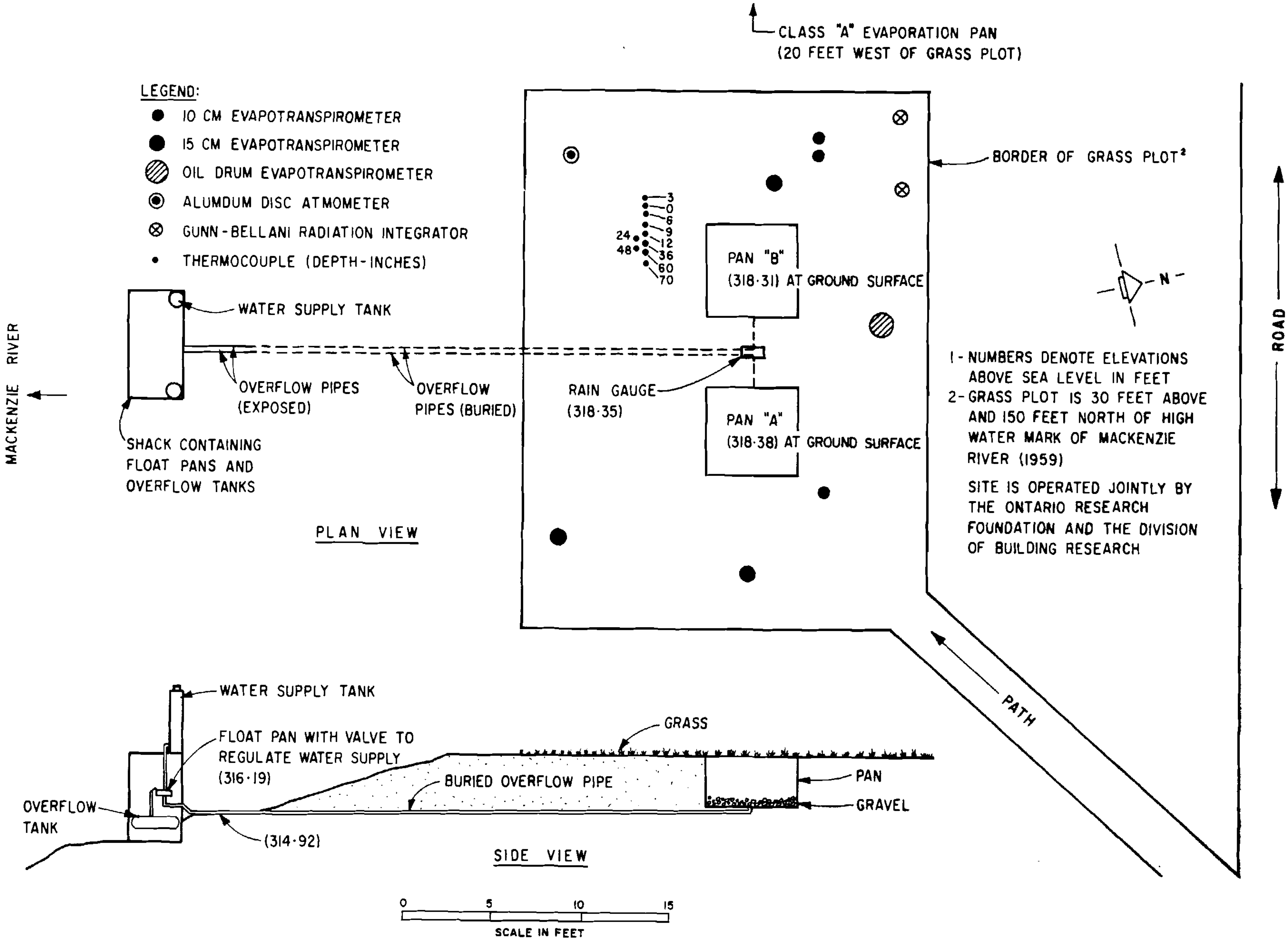

FIGURE 2
THORNTHWAITE SITE INSTALLATIONS - 1959 - 60

BR. 2781-2

Figure 3 Thornthwaite site at Norman Wells, N.W.T. Grass-covered pans with tensiometers in foreground. Supply tanks and overflow housing in background. (Tensiometers not used in 1959 and 1960.) August 1956.

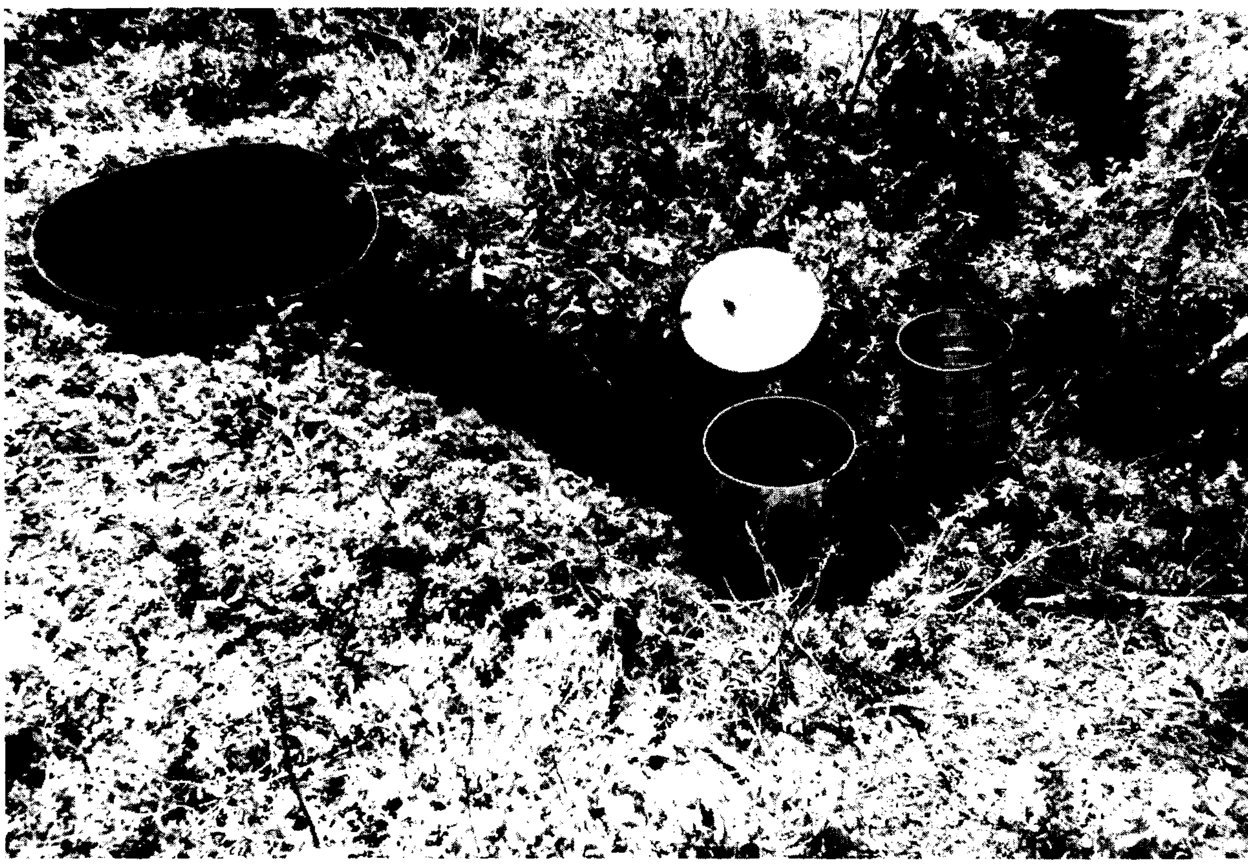

Figure 4 Ground cover of moss and Labrador tea in wooded area (Site Four) showing installation of oil drum evapotranspirometer. 27 June 1960.

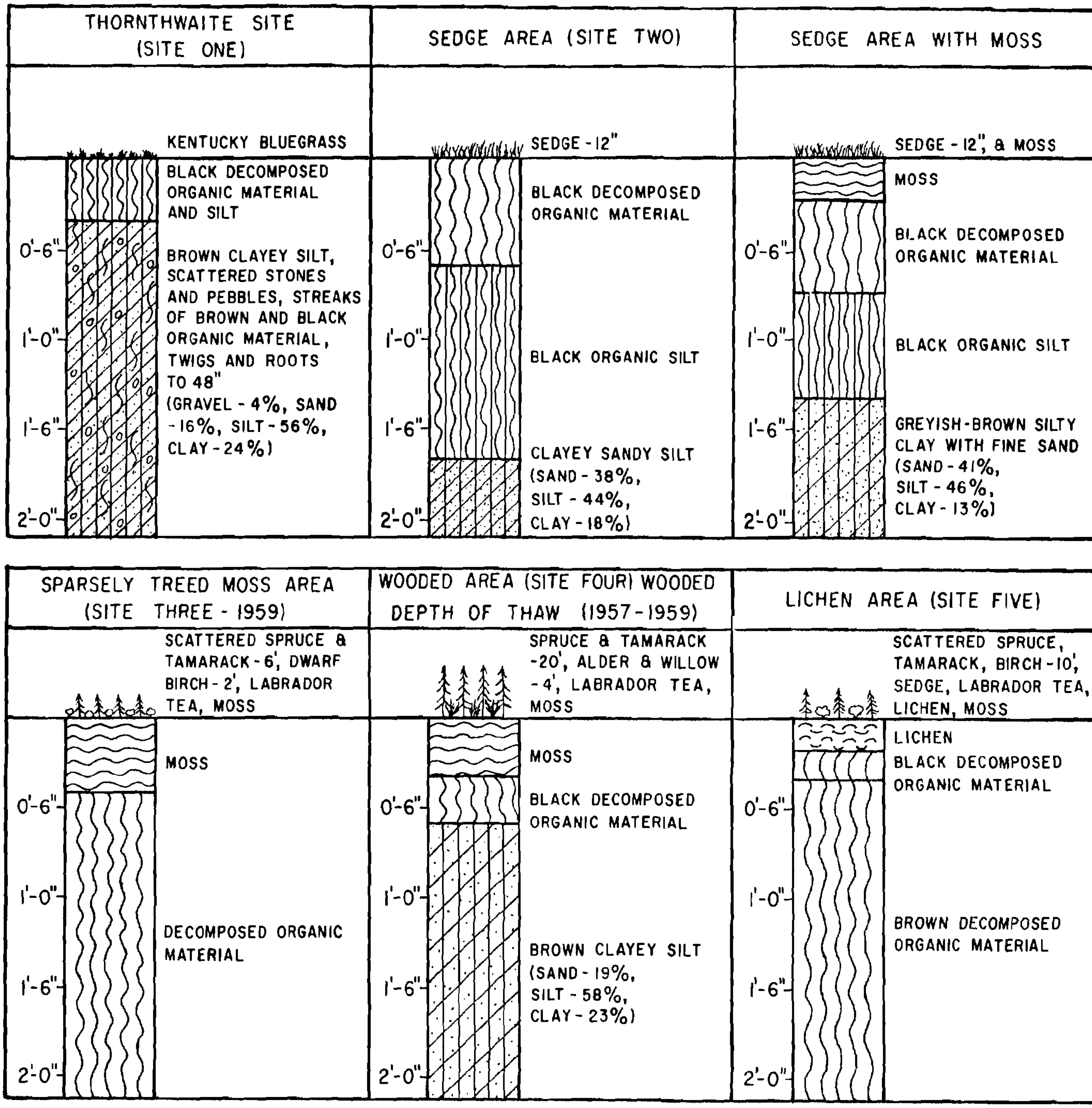

FIGURE 5

VEGETATION AND SOILS AT NORMAN WELLS TEST SITES

BR. 2781-5

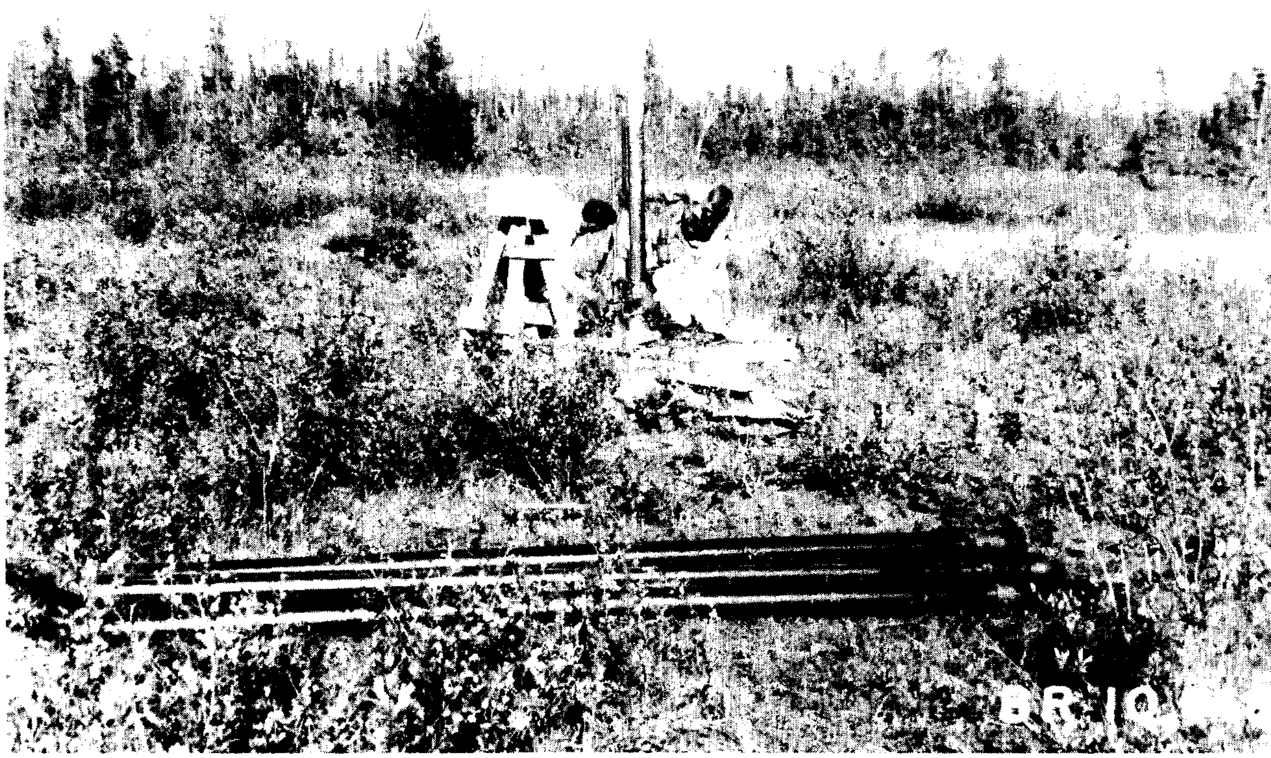

Figure 6 Sedge area (Site Two) showing installation of plastic pipes for mean annual ground temperature measurements in permafrost using maximum-minimum dial thermometers. August 1960.

Figure 7 Tree vegetation - spruce, tamarack, willow and alder - in wooded area (Site Four). 29 August 1959.

Figure 8 Lichen area (Site Five) showing installation of thermocouple cable in permafrost. September 1960.

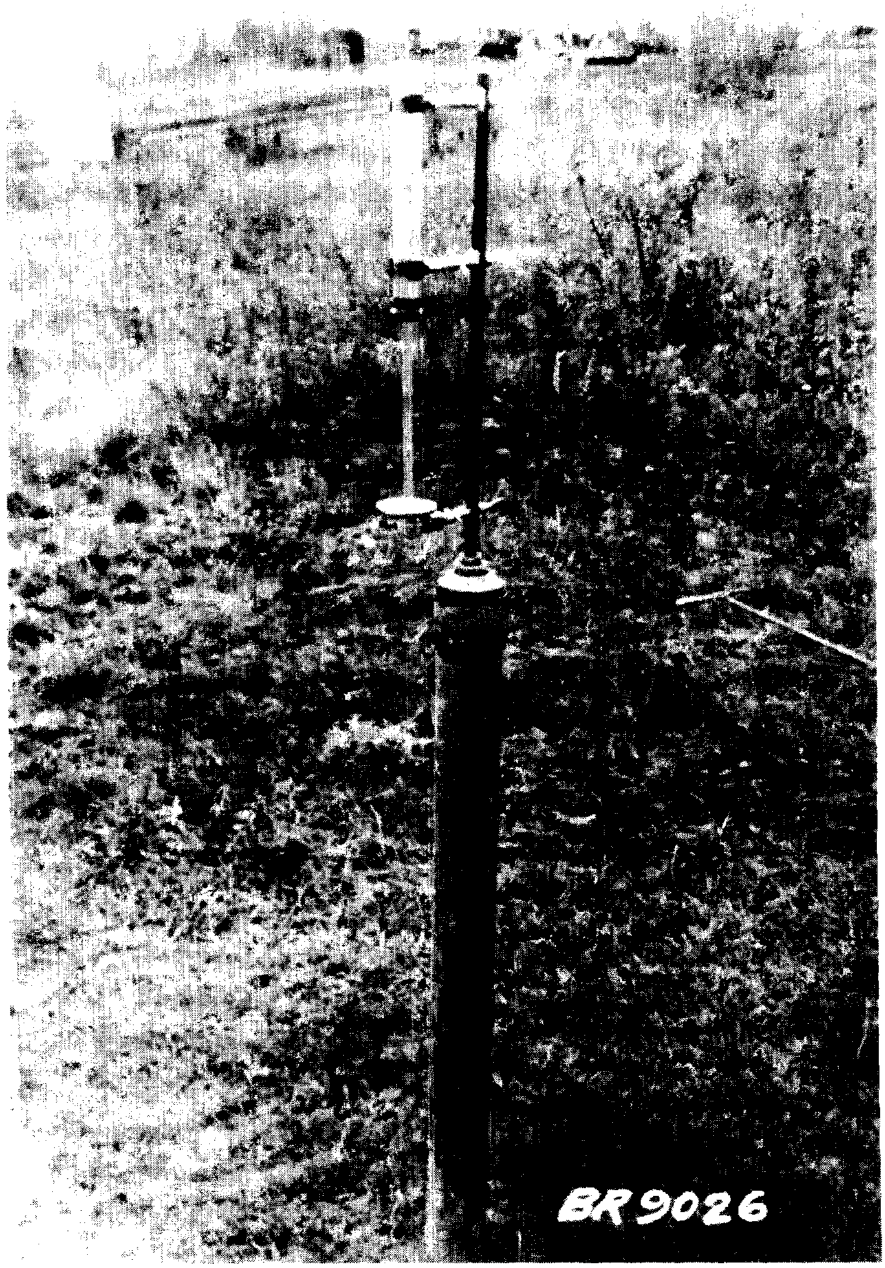

Figure 9 Alumdum disc atmometer at Thornthwaite site. Bottom clamp holds cup containing black porous plate. Top two clamps hold water reservoir. Porous plate is 4 ft above ground. 8 September 1959.

Figure 10 Class "A" evaporation pan at Thornthwaite site. Pan is 4 ft in diameter. 27 June 1960.

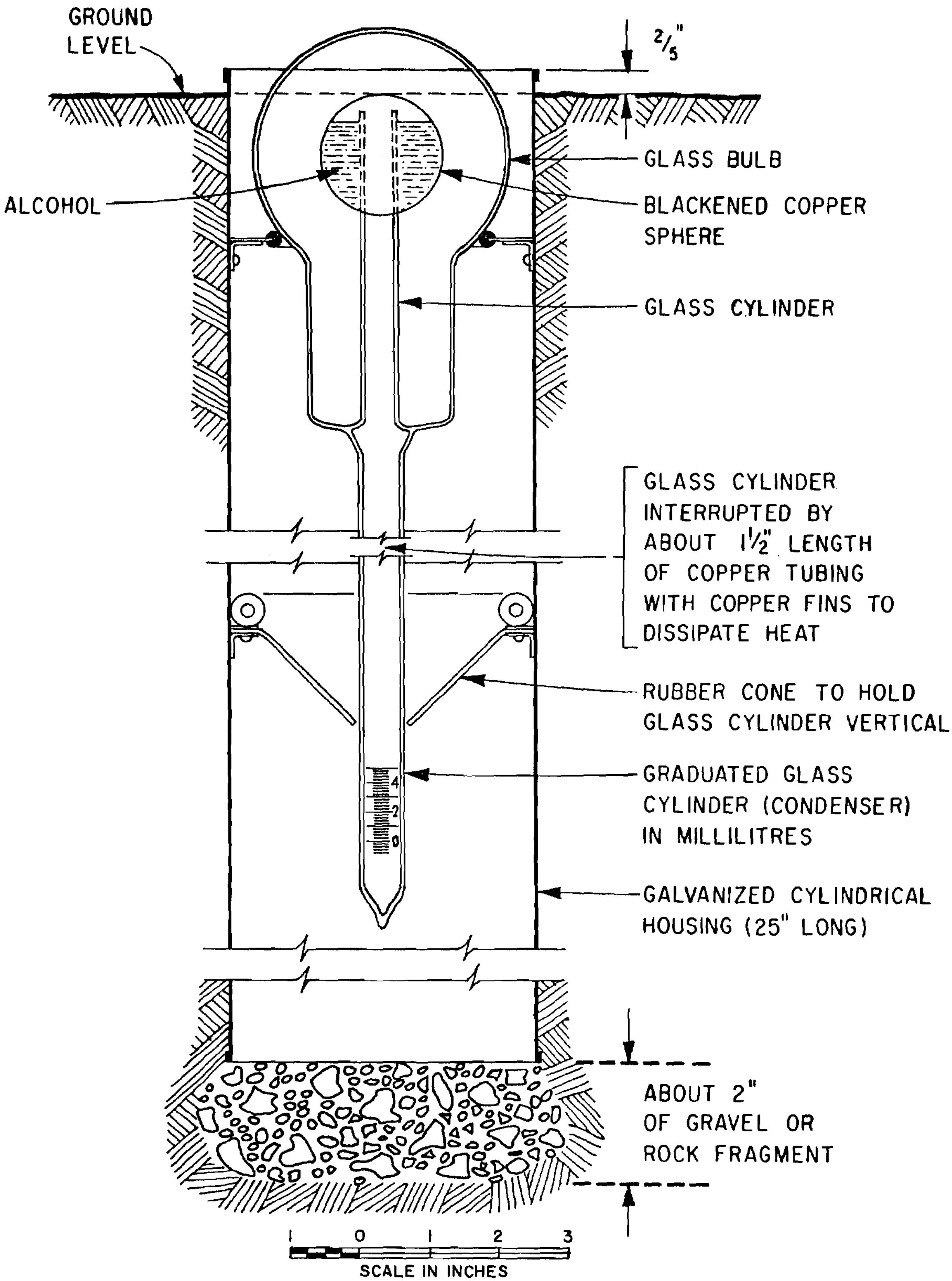

FIGURE 11

GUNN-BELLANI RADIATION INTEGRATOR

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Figure 12 Gunn-Bellani radiation integrators installed at Thornthwaite site. 8 September 1959.

Figure 13 Economic net radiometer on standard 4 ft above ground. July 1959.

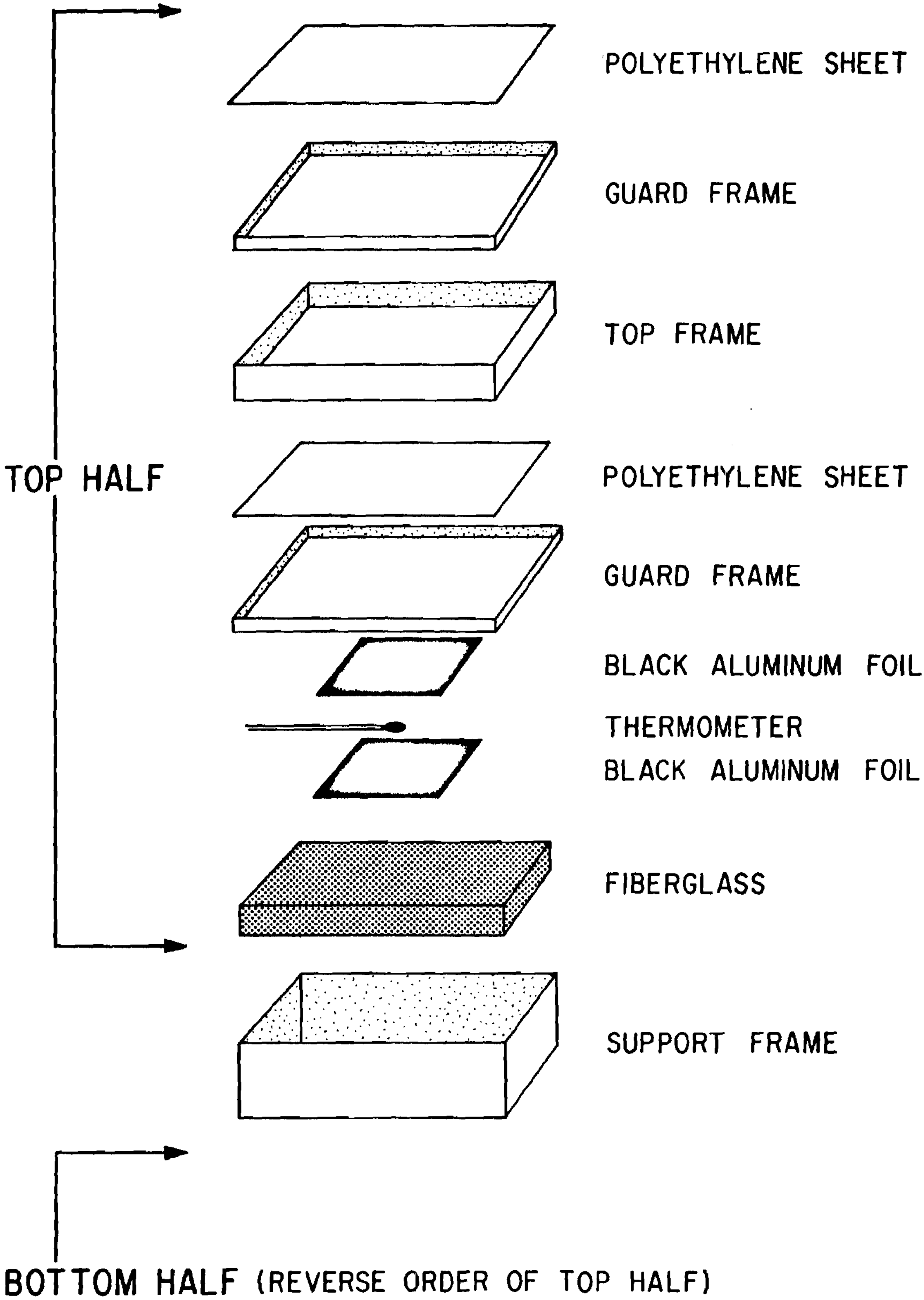

FIGURE 14

EXPLODED VIEW OF ECONOMIC NET RADIOMETER

BR. 2781-5

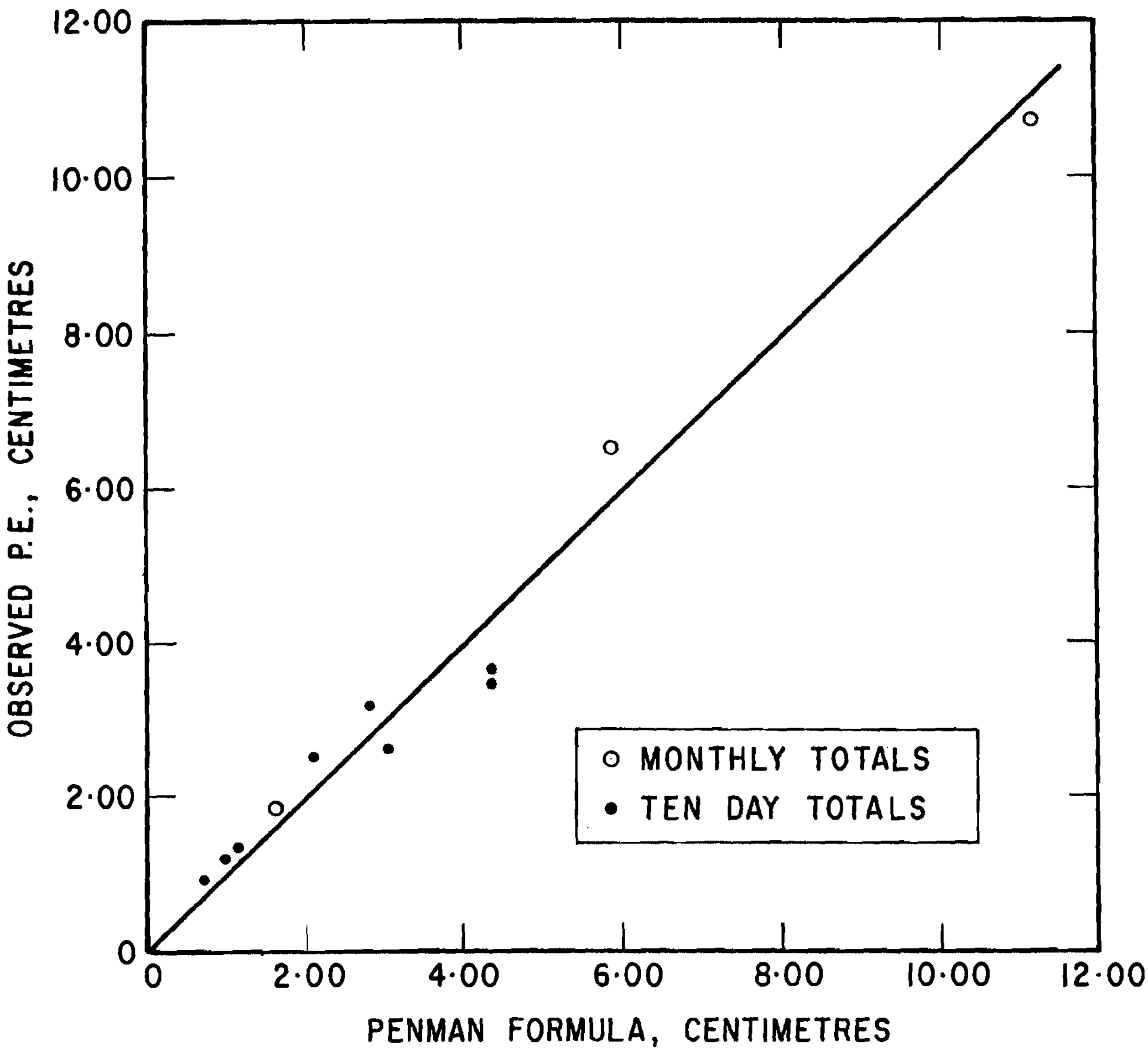

FIGURE 15
COMPARISON OF OBSERVED POTENTIAL EVAPOTRANSPIRATION (PAN "B") FROM KENTUCKY BLUEGRASS AT THORNTHWAITE SITE WITH PENMAN EVAPORATION FORMULA FOR SUMMER 1960

BR. 2781-6

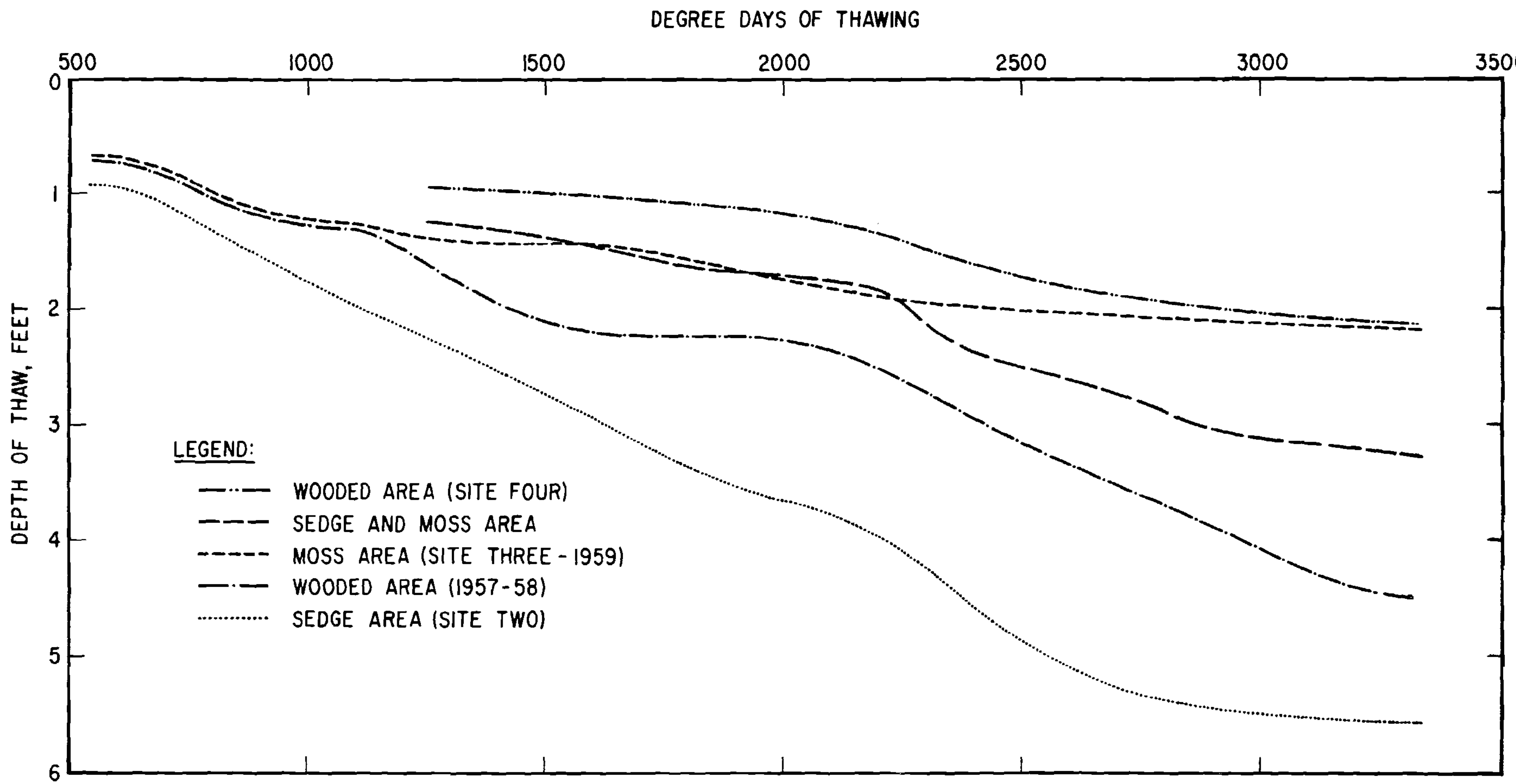

FIGURE 16
DEPTH OF THAW VS CUMULATIVE DEGREE DAYS OF THAWING AT NORMAN WELLS, N.W.T. 1957, 1958, 1959

BR. 2781-7

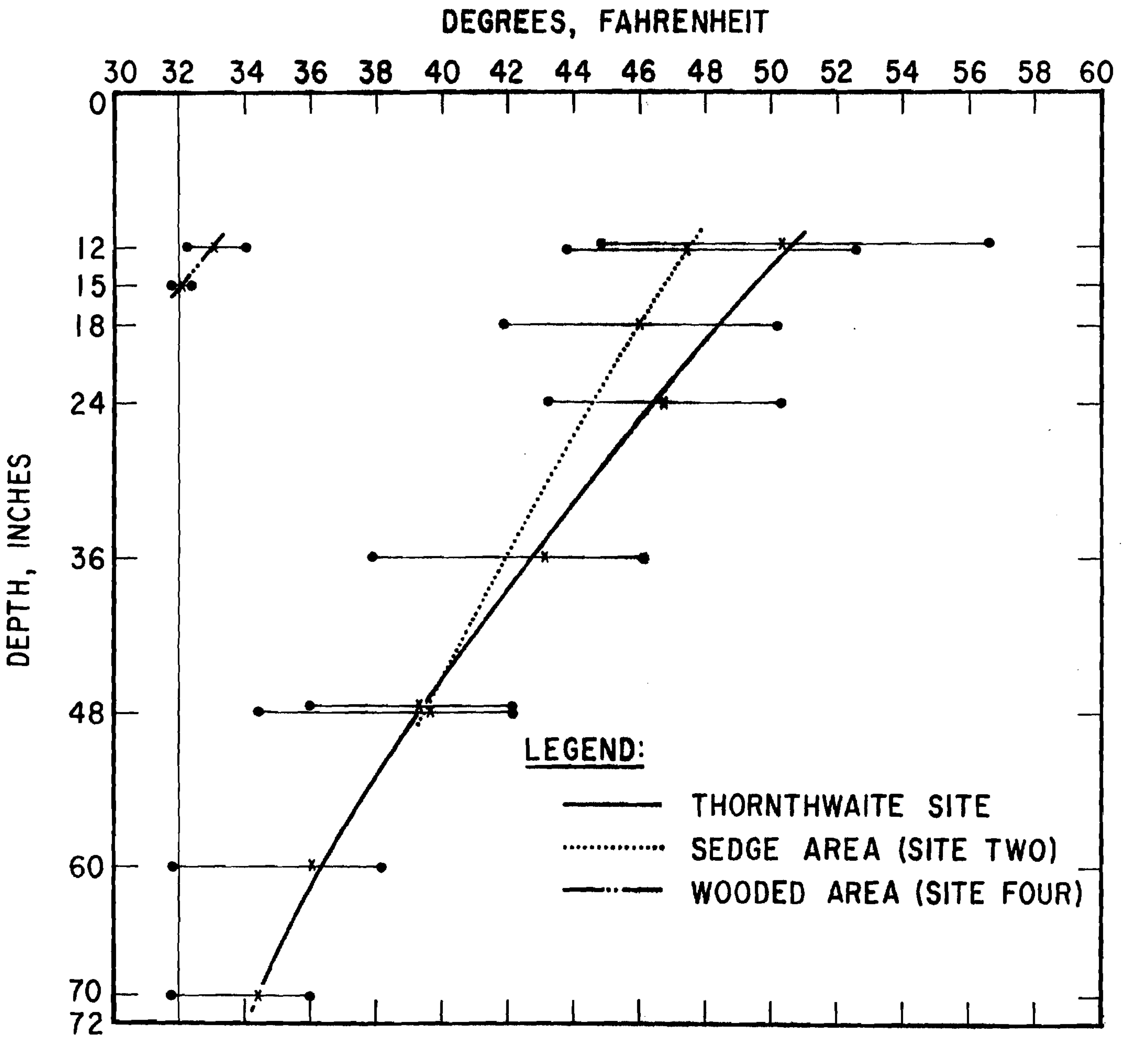

FIGURE 17

MEAN GROUND TEMPERATURES (x) AND AMPLITUDES (•——•)

(JULY 15 TO SEPTEMBER 16, 1960)

BR. 2781-8

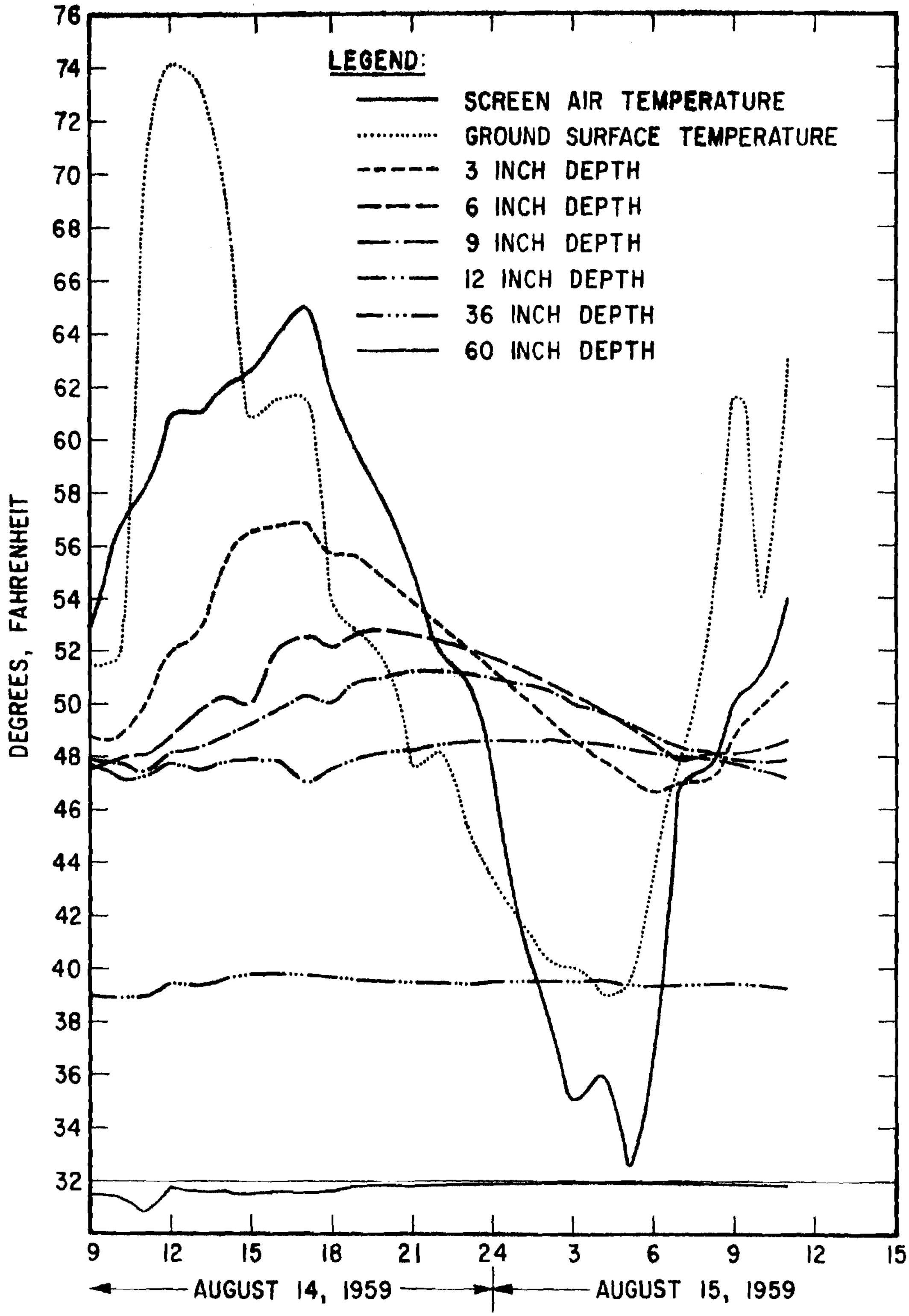

FIGURE 18

GROUND TEMPERATURES AT THORNTHWAITE SITE

(HOURLY READINGS FROM 0900 ON AUGUST 14, 1959 TO 1100 ON AUGUST 15, 1959)

BR 2781-9

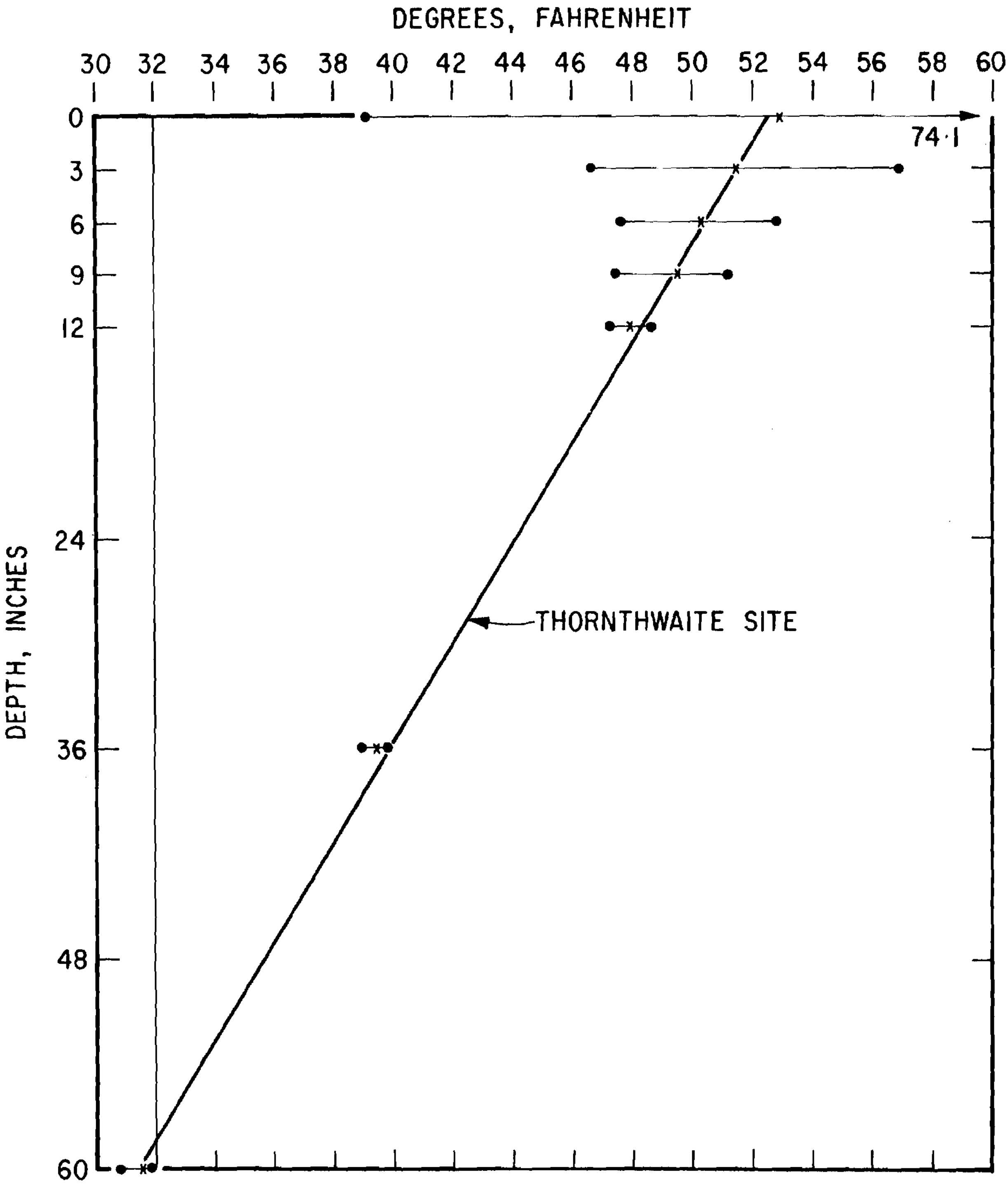

FIGURE 19

MEAN TEMPERATURE OF 24 HOUR PERIOD VS DEPTH AT THORNTHWAITE SITE

(HOURLY READINGS 0900-AUGUST 14, 1959 TO 0900-AUGUST 15, 1959)

MEAN AIR TEMPERATURE FOR THIS PERIOD - 51·7 °F WITH FLUCUATIONS FROM 65·0 °F TO 32·5 °F

BR. 2781-10

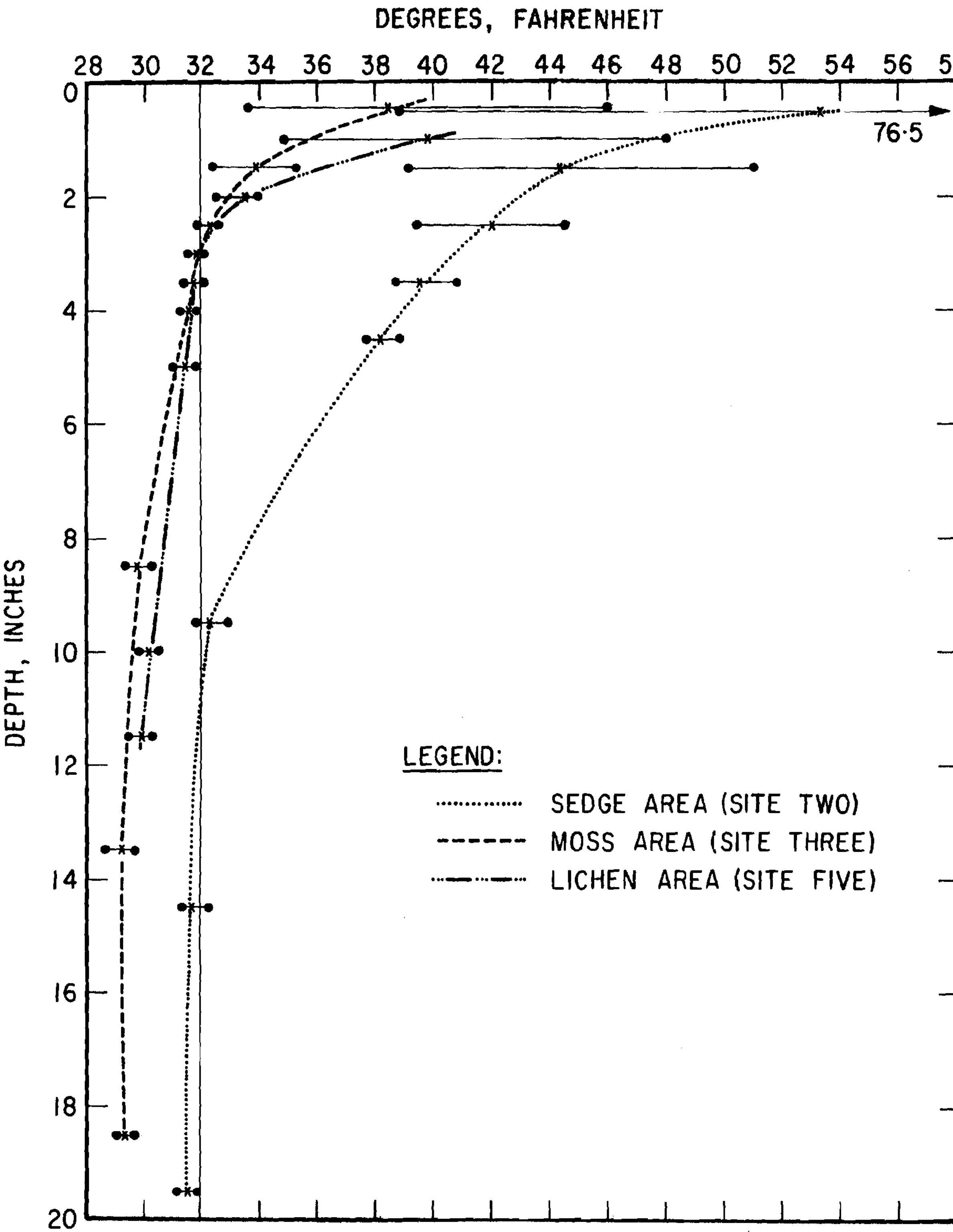

FIGURE 20

MEAN GROUND TEMPERATURES (x) AND AMPLITUDES (•—•)

(AUGUST 12 TO SEPTEMBER 23, 1960)

BR. 2781-11