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THERMAL PROPERTIES OF

FROZEN SALINE SOILS

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ABSTRACT

The thermal properties of three soils have been studied to ascertain the effects of saturating the soils with saline water. The frozen state is the primary area studied, although data during and after a phase change in the soils is also presented.

The thermal properties evaluated include the thermal conductivity and thermal diffusivity, measured by means of the transient thermal probe technique, in which a metal probe is inserted into a cylindrical soil sample. This technique allows the simultaneous determination of the two thermal properties by recording the temperature response at two locations in the sample to an ideal line heat source from the probe.

The experimental apparatus is described and the results are compared to several theoretical predictive methods of calculating the thermal conductivity of soils.

The data from the phase change region were determined to be inconclusive and the results of the unfrozen soil were too few to find representative results.

The results from frozen state show very little effect from the salinity of the porewater. Any effects seem to be less than the accuracy of the experiment itself. The predictions from the theoretical models support this conclusion. Finally, recommended values for the thermal properties of the frozen soils are given as independent of both the temperature and porewater salinity for the ranges considered in this work.

ACKNOWLEDGMENTS

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USEFUL CONVERSION FACTORS

The units used in this work are SI international heat transfer units. Some useful conversion factors to the traditional English heat transfer units are given below.

Quantity	to get	multiply	by
Thermal Conductivity k	BTU/hr ft °F	W/m °C	0.5778
Thermal Diffusivity α	ft^2/sec	cm^2/sec	1.0764×10^{-3}
Density or Specific Weight δ or γ	lb/ft^3	g/cm^3	62.4278
Line Heat Source Strength Q	BTU/hr ft	W/cm	104.0020

NOMENCLATURE

A, B, A_c, B_c	Coefficients used in the conductivity and diffusivity curve fit equations
a	Length of pore fluid layer in Mickley's Method
Ei(-x)	Exponential integral notation
F	Empirical constant in DeVries Method
g_a, g_b, g_c	Empirical shape factors in DeVries Method
k	Thermal Conductivity:
k_B	- of Ono's brine solution
k_f	- of pore fluid
k_I	- of pure ice
k_i	- of pore ice
k_o	- of other soil components (besides quartz)
k_q	- of quartz in the soil
$k_r = k_s/k_f$	- ratio used in Kunii - Smith Method
k_s	- of dry soil
k_{sat}	- of saturated (frozen or unfrozen) soil
k_{SI}	- of saline ice
k_w	- of pure water
MB	Mass of Ono's brine solution
MC	Moisture content of a soil sample
n	Porosity of soil
Q	Line heat source strength

q	Fractional quartz content of soil
r	Radius measured from the ideal line heat source
S	Salinity of porewater
SB	Salinity of Ono's brine solution
SP	Percent of full saturation of soil sample
T	Temperature or temperature rise
T_H	Theoretical temperature response
T_o	Initial or equilibrium temperature due to line heat source
t	time
t_c	Length of time that power to heating element supplied
V	Frozen volume of soil sample
V_a	Volume of air bubbles in saline solution
V_f	Volume of ice and water in soil sample
V_u	Unfrozen volume of soil sample
V_v	Volume of voids in soil sample
W_s	Weight of dry soil
W_u	Fractional unfrozen water content of soil sample
X_f	Volume fraction of fluid in saturated soil sample
X_s	Volume fraction of soil in saturated soil sample

GREEK SYMBOLS

α	Thermal diffusivity of the soil
$\bar{\alpha}$	Saline equilibrium constant
γ	Euler's constant = 0.5772156649
γ_i	Specific weight of pore ice
γ_s	Specific weight of dry soil
θ_1, θ_2	Shape factor dependent angles in the Kunii-Smith Method
δ	Dry density of soil sample
δ_B	Density of Ono's brine solution
δ_I	Density of pure ice
ϕ	Soil packing function in the Kunii-Smith Method
ϕ_1, ϕ_2	Extremes of ϕ, dependent on θ_1, θ_2

I. INTRODUCTION

With the continuing development of oil reserves in the Arctic regions of Alaska and Canada, a great deal of interest has developed concerning the properties of soils at or below the freezing point. In particular, offshore projects have been undertaken by building artificial islands in the shallow ocean coastal regions. These islands are made by depositing soil and gravel into the ocean to build up an island from the sea floor and then allowing the island to freeze through the winter. Consequently, the soils become frozen, not in fresh water, but in saline water. The salinity of the water in the frozen soils could significantly effect the properties of the soils, which could then have substantial consequences on the operations performed on these island structures.

In this work, the thermal properties, conductivity and diffusivity, have been investigated for three types of soils saturated and frozen with saline solutions of various concentrations. The soils studied included a sand, a gravel, and a silt and these were each frozen with water of three salinity levels.

The experimental technique used was the transient thermal probe method where the conductivity and diffusivity could be simultaneously determined. The application of the technique has been previously designed, developed, and refined by Inbody [4].

The results are given and compared with several theoretical models developed by various investigators to predict the thermal conductivity of soils. These models use the conductivities of the soil components as parameters in evaluating the overall soil thermal conductivity. The applicability of these predictive models have been studied by Farouki [1 and 2] and his recommendations followed.

Five of these predictive models recommended for use with frozen soils are discussed in the next section, along with a description of the computer program used in the predictive analysis. The compositions and test conditions of the three soils studied are detailed in Section III. A summary of the experimental theory and operation is given in Section IV while the results of the experiment and the comparison with the models is provided in Section V with a discussion of the results. Finally, the conclusions reached on the thermal properties of the frozen saline soils are detailed in the last section with recommendations for further study. Appendix A gives the listing of the predictive model program and Appendix B includes a detailed listing of the results of the 96 tests performed.

II. THEORETICAL METHODS

Theoretical models have been developed by several investigators to predict the thermal conductivity of soils as a function of the conductivity of the individual soil components and the way these components are arranged in the soil. The various models are applicable to a wide range of soil compositions and conditions, ranging from coarse gravels to fine clays in any state from dry to partially or fully saturated. For the wetted soils, both the unfrozen and frozen states have been studied. Omar Farouki, working with the United States Army Corps. of Engineers Cold Regions Research and Engineering Laboratory (henceforth referred to as CRREL) has performed an extensive evaluation of eleven of these theoretical models. In two reports, CRREL Monograph 81-1 [1] and CRREL Report 82-8 [2], the models are discussed and those most applicable to the various soil compositions and conditions are noted.

A. Description of the Models

This work is concerned with the determination of thermal properties of fully saturated, primarily frozen soils of three types - a coarse sand, a gravel, and a fine silt. The two CRREL reports recommend five of the eleven methods for use with the fully saturated frozen coarse soils. These are, in the order listed by Farouki, the methods of Johansen (1975), DeVries (1952 and 1963), Mickley (1951), the modified resistor method (from Woodside and Messmer, 1961), and

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the method of Kunii-Smith (1960). For saturated frozen fine soils (such as a silt), only the methods of Johansen and DeVries are recommended. All of these methods, in addition to others, are recommended for use with unfrozen soils, which are considered in this work, but only at a temperature just above the freezing point.

Each of the methods uses a single equation or set of equations, developed either empirically or theoretically with empirical modifications, to model the soil system. For saturated soils, components of the soil include the soil solids (differentiated between quartz and other soil solids) and the pore fluid, which could be ice, water or a combination of both. The primary parameters for these equations are the thermal conductivities of the soil components and the porosity of the soil. The nomenclature used is listed on pages xi through xiii.

A brief description of each of the five recommended methods is given below, with the input parameters and the equation or equations used. More details of each method, and others, can be found in the CRREL Monograph 81-1 pp. 102-116 [1].

1.   Method of Johansen

The method devised by Johansen is the most recent evaluated by Farouki and the most widely applicable method.

In its most general form, this method gives the conductivity of a soil as a logarithmic function of the fractional

degree of saturation, ranging between the extremes of the
dry state and full saturation. The conductivities at these
two extremes are found from relationships of the soil solid
particle conductivity (k_s) and the pore fluid (water, ice
or air) conductivity $(k_w, k_i$ or $k_a)$. The exponents are
functions of the porosity (n) and the fractional unfrozen
water content (w_u), if any.

Johansen's equation for the fully saturated state
(k_{sat}) is

$$k_{sat} = k_s^{(1-n)} \cdot k_i^{(n-wu)} \cdot k_w^{wu} \qquad (1)$$

Values used for the conductivity of ice and water are
readily available, but a value for the soil solid particle
conductivity is not so easily determined, since the soil
solids could be quite varied. Johansen developed an
equation to predict the soil solid particle conductivity
based on the fractional quartz content (q) of the soil. His
relationship is

$$k_s = k_q^{q} \cdot k_o^{(1-q)} \qquad (2)$$

where

k_q = conductivity of quartz

k_o = conductivity of other soil constituents (an
average value).

Farouki uses this equation to determine the soil solid
particle conductivity for all the models studied and it is

so used in this work. Johansen uses a constant value for the conductivity of quartz, 7.7 W/m·C, at any temperature. Farouki considers this to be in error, and he uses temperature dependent values from Touloukian's Thermophysical Properties of Matter [10]. These temperature dependent values are used here and will be described more below (see p. 11). A constant value is used by Johansen and Farouki for the conductivity of other soil components. This value is 2.0 W/m·C and Farouki noted that since the components of the other soil solids is uncertain, using this constant average value is appropriate. This value is used in this work.

More details on the use of the Johansen method for fully or partially saturated soils can be found either from the CRREL reports or from Johansen's work [5].

2. DeVries' Method

DeVries developed his method from the theory of electrical conductivity. The adaptation to thermal conductivity presented a model of soil particles in a continuous medium of air or water (ice). The equation he derived is

$$k_{sat} = \frac{x_f \cdot k_f + F \cdot x_s \cdot k_s}{x_f + F \cdot x_s} \tag{3}$$

where

k_f = conductivity of the pore fluid

k_s = soil solid particle conductivity

x_f = volume fraction of pore fluid

x_s = volume fraction of soil solid

F = empirical constant

DeVries intended the factor F to be a constant dependent on the shape factors of the soil solid particles, but it turned out to be more of an empirical constant. It is given by the relation

$$F = \frac{1}{3} \sum_{i=a,b,c} \left[1 + \left(\frac{k_s}{k_f} - 1\right)g_i\right]^{-1} \tag{4}$$

where

$\left.\begin{array}{c} g_a \\ g_b \\ g_c \end{array}\right\}$ DeVries intended shape factors.

Empirically, DeVries found that for saturated soils, the shape factor values that gave a good correlation are

$$g_a \approx 0.125$$
$$g_b \approx 0.125 \quad \text{note that} \quad g_a + g_b + g_c = 1.0. \tag{5}$$
$$g_c \approx 0.75$$

The volume fractions that DeVries uses are intended for use with partially saturated soils. When the soil is fully saturated, as in this work, the volume fraction of fluid (x_f) becomes identically the porosity since the fluid should completely fill the void spaces. Accordingly, the volume fraction of soil solid particles (x_s) reduces to

one minus the porosity. Thus the DeVries conductivity equation reduces to

$$k_{sat} = \frac{n \cdot k_f + F \cdot (1 - n) \cdot k_s}{n + F \cdot (1 - n)} \cdot \qquad (6)$$

3. Mickley's Method

Mickley envisioned a unit cube of soil and fluid that he subdivided into components through which heat flows. A simplified diagram of this division is shown in Figure 1 for a fully saturated soil.
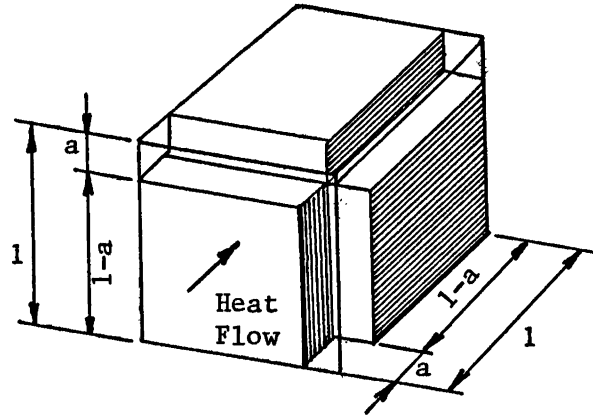
Figure 1. Theoretical Unit Soil Structure.

(from Farouki, 1981)

The length a is the length of the pore fluid layer surrounding the soil solid particle of length (1 - a). The simplified (for full saturation) equation of Mickley's model is

$$k_{sat} = k_f \cdot a^2 + k_s(1 - a)^2 + \frac{k_s \cdot k_f(2a - 2a^2)}{k_s a + k_w(1 - a)} \cdot \qquad (7)$$

For fully saturated soils, Mickley gives the following rela-
tion to determine the length a

$$3a^2 - 2a^3 = n. \tag{8}$$

This method becomes much more complex for three compo-
nents (air, water, and soil) and details are presented in
the CRREL report [1].

4.   Modified Resistor Method

This method, developed by Woodside and Messmer, is also
an adaptation from an electrical conductivity model. It
also uses flow lengths as in Mickley's Method, but the
lengths used have been determined empirically. The result-
ing equation for fully saturated soils is

$$k_{sat} = (n - 0.03) \cdot k_f + (1-n + 0.03)\left[\frac{1 - n}{1-n + 0.03}\left(\frac{1}{k_s}\right)\right.$$
$$\left.+ \frac{0.03}{1-n + 0.03}\left(\frac{1}{k_f}\right)\right]^{-1}. \tag{9}$$

Details on the derivation of the equation and the heat flow
lengths are given by Farouki.

5.   Method of Kunii-Smith

This method involves the application of a cumbersome
relationship between the contact of spherical soil particles
saturated with a fluid. Kunii and Smith found that the
conductivity is dependent on the contact between soil parti-
cles (assumed spherical) and thus on the soil packing. The

two extremes for packing are cubic and rhombohedral. The
actual packing of the soil is interpolated between these two
extremes and is a function of the porosity of the soil.

The conductivity equation developed by Kunii and Smith is

$$k_{sat} = k_f \cdot \left[n + \frac{(1 - n)}{\phi + (2k_f/3k_s)} \right] \tag{10}$$

where

ϕ = packing interpolation function

$$= \phi_2 + (n - 0.259) \cdot (\phi_1 - \phi_2)/0.217. \tag{11}$$

The angles ϕ_1 and ϕ_2 can be found from

$$\phi_i = \frac{1}{2} \frac{[(k_r-1)/k_r]^2 \sin^2\theta_i}{\ln[k_r-(k_r-1)\cos\theta_i] - [(k_r-1)/k_s](1-\cos\theta_i)} - \frac{2}{3}\frac{1}{k_r} \tag{12}$$

for $i = 1.2$

where

$k_r = k_s/k_f$

with θ_1 found using (for cubic packing)

$$\sin^2\theta_1 = 1/1.5 \tag{13a}$$

and θ_2 from (for rhombohedral packing)

$$\sin^2\theta_2 = 1/6.9. \tag{13b}$$

B.   The MODEL Program

A computer program has been developed to evaluate the
thermal conductivity using the five models described above

and compare the results with the experimentally determined
values. A listing of the program is given in Appendix A,
while a brief description of the program, the necessary
inputs and the equations used is given below.

1.   Input Parameters

The parameters used are either determined in the exper-
imental work and input to the program (i.e. soil type, pore
fluid salinity, dry density, and test temperatures) or found
by application of correlation equations in the program (i.e.
porosity, solid particle conductivity, and water or ice
conductivity). The experimentally determined conductivities
are entered for comparison and two user controlled variables
are also entered. First, the quartz content of the soil is
entered, and then an estimate for the unfrozen water content
at each temperature level is input. The format for the data
input is given with the program listing in Appendix A. All
the data for one type of soil is entered and run
simultaneously.

2.   Component Calculations

The soil component conductivities are determined using
the salinity and/or the temperature data as described above.

a.   Soil Solids Conductivity

The conductivity of quartz, as given by Touloukian [10],
varies about ten percent over the range of temperatures
considered (-20°C to +1°C). A linear regression curve fit

is used to describe the data. This curve fit equation is

$$k_q = 8.1639 - 0.03374 \, T \tag{14}$$

where k_q is in W/m°C and T is in degrees Celsius. The correlation coefficient for this curve fit to Touloukien's data is 0.99988, a very good fit. As noted above, a constant value of 2.0 W/m°C is used for the conductivity of other soil components, k_o. Equation (2) from Johansen's method is then used to determine the soil solids particle conductivity, k_s.

b. Saline Ice Conductivity

The conductivity of saline ice varies with both the the salinity and the temperature. Nobuo Ono [8] has developed a sea ice model from which he derives equations to predict the thermal conductivity and other properties. This model assumes that as the solution freezes, the salt is forced out of solution on a microscopic level and collects in layers until it reaches an equilibrium concentration. This brine solution, as Ono calls it, acts in series with the layers of pure ice and the overall conductivity of the saline ice is calculated from these components. Given a solution of temperature T (°C) and salinity S (in parts per thousand, or PPT) the mass of this brine solution (MB), per gram of total ice, below the freezing temperature is

$$MB = 0.001 \cdot S \cdot (1 - \bar{\alpha}/T) \tag{15}$$

where $\bar{\alpha}$ is the equilibrium constant for sea ice and is

equal to 54.11, as given by Ono. The salinity of the

concentrated brine solution (SB) is then

$$SB = S/MB \tag{16}$$

and the density (δ_B) is

$$\delta_B = 1 + 0.0008 \cdot SB \tag{17a}$$

Ono's equation for the density of pure ice (δ_I) is

$$\delta_I = 0.9168 - 0.00014 \cdot T \tag{17b}$$

and the conductivities of the components are

$$k_I = 0.00535 - 0.00002568 \cdot T \tag{18a}$$

$$k_B = 0.00125 + 0.00003 \cdot T + 0.00000014 \cdot T^2 \tag{18b}$$

where the dimensions of δ_I and δ_B are grams/cm^3 and the

dimensions of k_I and k_B are cal/cm s C. Finally, the

conductivity of the saline ice is given by

$$k_{SI} = k_I \cdot \frac{1 - (1 - \frac{\delta_I}{\delta_B} \frac{k_B}{k_I}) \cdot MB}{1 - (1 - \frac{\delta_I}{\delta_B}) \cdot MB} \cdot (1 - \frac{3}{2}V_a) \tag{19}$$

where V_a is the volume of air (bubbles) in the ice. Since

deaerated salt water solutions are used in the experimental

work (described below) V_a is taken as zero. The value for

k_{SI}, in cal/cm s C, is then converted to W/m·C by dividing by 0.00238846.

c. Saline Water Conductivity

The range of temperatures in which water, instead of ice, is the pore fluid is very small. The approximate relationship given by Ono for the melting temperature of saline water (WMT) is

$$WMT = -\bar{\alpha} \cdot S/1000. \qquad (20)$$

The melting temperatures calculated by this equation are -1.629°C for 30.1 PPT water and -0.812°C for 15.0 PPT water. These results are very close to the experimentally determined melting temperatures of -1.6°C and -0.8°C. The highest temperature used in the thermal property calculations is +1°C. Over this range, the conductivity of water (as long as it remains liquid) varies so little that a constant value could be used with little error. Additionally, the conductivity of sea water, as given by Horne [3], at 0°C is 0.563 W/m·C compared with 0.566 W/m·C for fresh water. The salinities used in this work are both less than the approximate salinity of sea water (35 PPT), so that the variation in the conductivity of less than one percent over the range of parameters is slight enough to ignore. The constant value that is used for both fresh and the saline waters above their melting points is 0.566 w/mC, that of fresh water at 0°C.

3. Program Calculations

Once all of the component conductivities have been calculated, the program evaluates the saturated soil conductivity for the various conditions and temperatures by using the five methods described above. The application of the equation or equations for each method is straight forward with the exception of calculating the length a from equation (8) in Mickley's method. This cubic polynomial is solved using software provided by Rice University's Institute for Computer Services and Applications, where the modeling computing work took place. The exact equation solved by the system is

$$2a^3 - 3a^2 + 0 \cdot a + n = 0 \tag{21}$$

where n is the porosity and a is the desired length. For porosity values in the range considered (0.2 to 0.4), the three roots of equation (21) are all real and, in fact, only one root lies in the feasible range for a of $0 \leq a \leq 1$ (recall Figure 1). The remaining two roots can easily be eliminated by the program so that the correct value for a is used.

The results of the calculations are printed out in a table allowing quick comparison among the methods and with the experimental values. These results are given and discussed below.

III. SOILS AND CONDITIONS OF TESTS

The three soils studied in this work include a homogeneous medium sand, a non-homogeneous gravel, and a fine silt. Each of these soils is saturated with porewater of three salinity levels (fresh water being one) and tested at temperatures ranging from $-20°C$ to $+1°C$. In that range, each of the nine soil samples experiences a phase change.

A. Ottawa Sand

The sand used in the experiments is 20-30 standard sand, ASTM designation C-190, obtained from the Ottawa Industrial Sand Company, Ottawa, Illinois. The properties of the sand are such that it makes a good soil with which to correlate the results.

The sand is composed entirely of grains of quartz between the sizes of 600 μm (a size 30 sieve) and 850 μm (a size 20 sieve), hence the 20-30 designation. The uniformity in size and the spherical nature of the particles make this sand ideal for investigation. The specific weight found to be 2.65 g/cm^3 corresponds to the values used by Kersten [6] and Johansen [5]. The quartz content is 100%. A sieve analysis was not performed on the sand because of the uniformity of the sand supplied.

B. Arctic Gravel

The second soil studied is an Arctic Gravel obtained for the use in this work by Exxon Production Research Company

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(EPR), Houston, Texas. The raw soil, as shipped from the North Slope of Alaska, is composed of fine clays and pebbles ranging from the smallest sizes to those larger than 3/4 of an inch in size. To standardize the soil for use in these and other tests, the soil is prepared as follows:

(1) the raw soil is oven dried at 100°C for 10-12 hours;

(2) gravel retained on a 3/4 inch sieve is removed and replaced on a weight basis with "medium gravel";

(3) medium gravel is obtained from the dried raw soil that passes through a 3/4 inch sieve and is retained on a No. 4 (4760 μm) sieve.

This prepared soil is then used in the tests. The results of a sieve analysis of this soil are shown in Figure 2. The specific weight is 2.60 g/cm^3 and the quartz content, as determined by EPR, is 81.3%.

C.   Fairbanks Silt

The final soil investigated is a clayey silt obtained by EPR from the area of Fairbanks, Alaska. This very fine soil is also dried before use but no particle replacement is necessary. Organic material is removed from the soil and the dried soil is pulverized before use. No sieve analysis has been performed. The specific weight of the silt is also 2.60 g/cm^3 and the quartz content is taken as an approximate average of 30%, as determined by EPR.
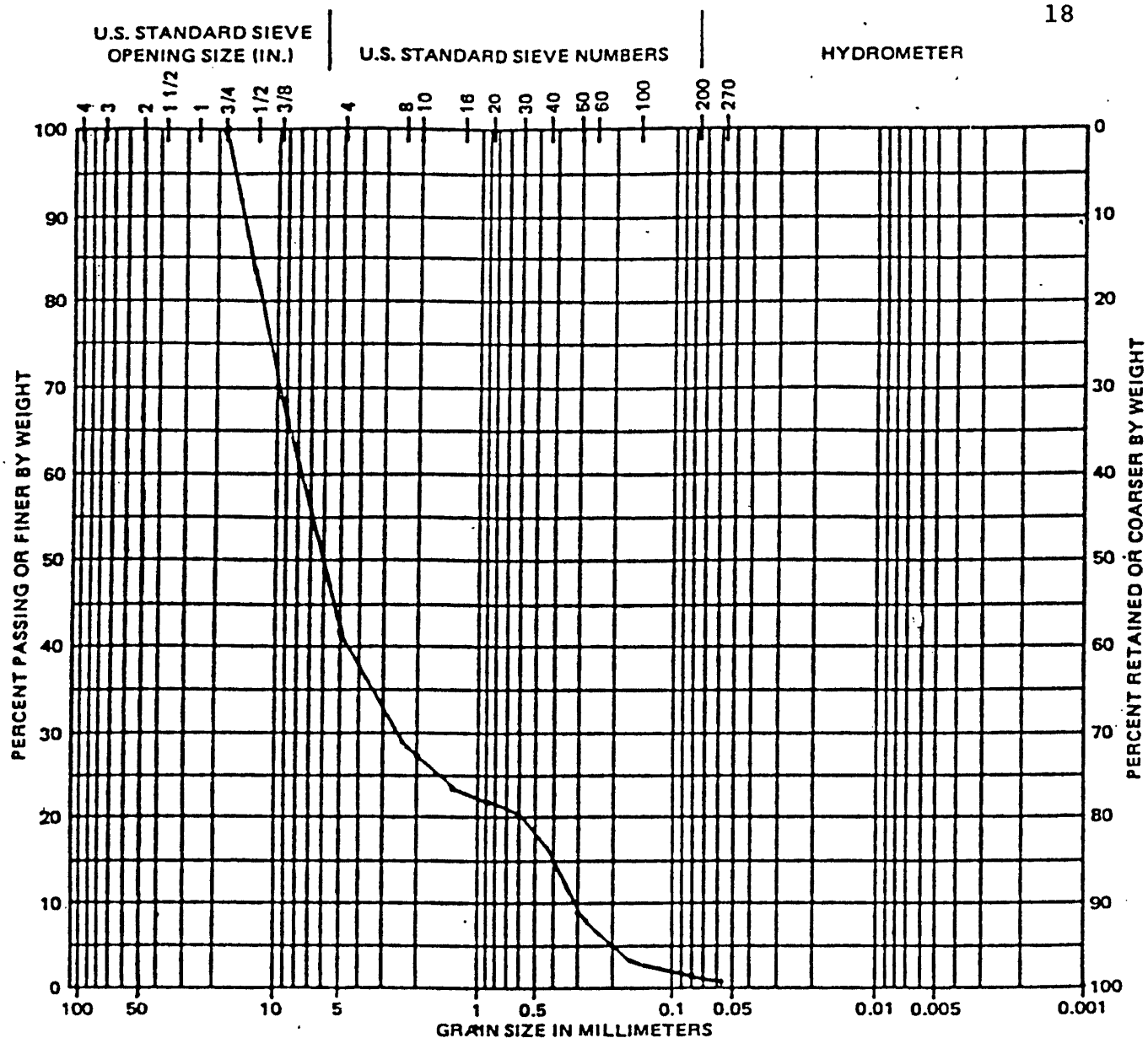
GRAIN SIZE DISTRIBUTION DIAGRAM

Figure 2.

SYMBOL	SAMPLE SOURCE	CLASSIFICATION
	Arctic soil - rocks larger than 3/4 inch replaced by soil less than 3/4 inch but retained on a U.S. Sieve No. 4	

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D.   Pore Fluid and Temperature Levels

Each of the soils is saturated with pore fluids of three levels of salinity, for a total of nine distinct samples. First, distilled water is used, pure, to obtain the thermal properties with which to compare to the saline soil conductivity. Then distilled water is used to make saline solutions of 15.0 and 30.1 parts per thousand (PPT) salt. A simulated sea salt from the Lake Products Company, Ballwin, Missouri is used. This salt contains the approximate chemical make-up of sea water and complies with the ASTM standard D-1141-52. The three waters are deaerated before saturating the soils. The melting points of these waters are 0°C for the pure water, -0.8°C and -1.6°C for the 15 PPT and 30.1 PPT saline waters, respectively.

The nominal test temperatures used for the experiments ranged from -20°C to +1°C. The first four samples tested had only the five temperature settings of -20°C, -10°C, -5°C, -2°C, and 0°C (the Ottawa Sand sample with 30.1 PPT porewater also was tested at -15°C). These levels had been selected so that one temperature (0°C) would be above the melting point, one at or near the melting point (-2°C) and the remaining levels below the melting point. Testing was begun at -20°C and proceeded upward. Upon evaluation of the data from these initial samples, it was determined that a different set of temperatures should be used. The last five samples had settings of -20°C, -15°C, -10°C, -5°C,

-2°C, and +1°C. The additional test temperature (-15°C) was used to provide more data to evaluate the trend. The higher final temperature of +1°C was used because it was observed that complete melting did not occur at the nominal temperature of 0°C in some of the early samples. The above test temperature levels were the nominal temperatures desired, as set on the test bath (described below). The equilibrium temperatures read from the thermocouples in the soil sample deviated slightly from the nominal values. As described in detail later, these deviations were due to the recording equipment and are listed in Appendix B.

E.   Soil Sample Preparation

The procedure used to make the soil samples from the dried dirt was similar for all three soils. The Arctic gravel and Fairbanks silt presented a few problems due to their clay content, but these problems were readily solved. The procedure used in the preparation is detailed in the following discussion, with the problems encountered and their solutions noted.

The problems encountered were due to the powdery nature of fine dried clays. In transferring the dried soils from the storage container to the sample mold, the dirt tended to diffuse into the air. A significant amount of the fine particles could be lost this way. Additionally, the dry soil did not have enough cohesion to compact easily into the sample mold. To alleviate both of these problems, the

gravel and silt, but not the Ottawa Sand, were prewetted with the particular pore water to be used for the sample. The amount of the water used to prewet the soil was 3% of the weight of the dry soil. This amount almost totally eliminated the diffusion of the particles into the air, and gave enough cohesion to the soil to allow compacting (as described below). The sand did not present these problems, and so it was not prewetted.

The soil was then ready to be placed into the sample mold. This mold, with the heating probe and thermocouples securely in place, was previously designed, built, and tested (see equipment description later). The appropriately prepared soil was filled in around the probe and thermocouples and hand packed with a metal rod. The packing was necessary for the gravel and silt to achieve the dry densities desired by EPR for the tests. The soil was packed at every 1-1/2 to 2 inches in depth in a 15 inch deep mold. The sand adequately filled the mold and did not require packing. Once filled, the lead wires from the probe and thermocouples were threaded through a top plug to seal the sample.

The air in the pore spaces of the soil sample was then evacuated by application of a vacuum at the top of the sample (see Figure 3). This was necessary to allow the pore water to completely fill the sample and to achieve full saturation. The vacuum was applied for 20-30 minutes with
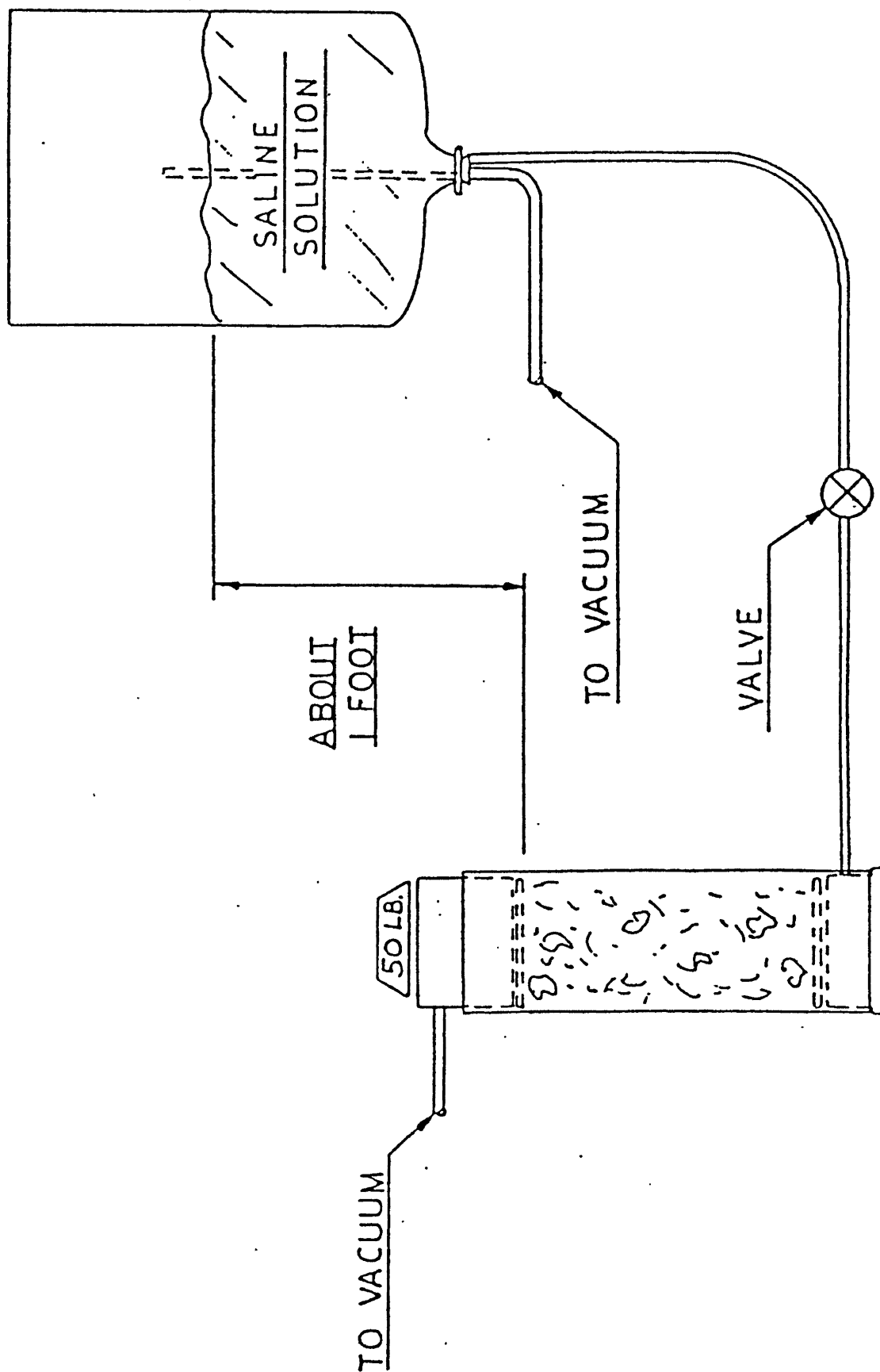
FIGURE 3. DEAERING SYSTEM

50 pounds of weight atop the sample mold in addition to atmospheric pressure. The vacuum was maintained during the saturation of the sample. The saturation was accomplished by allowing the desired pore water to enter the mold from the bottom, as shown in Figure 3. The pore water was itself deaerated, having been under a vacuum for at least 8-10 hours. In this way, water completely filled the pore space and thus full saturation could be achieved. The percentage of full saturation for the all samples was calculated and is shown below in Table 1.

Once full saturation was reached, the vacuum was gradually released and the entrance and exit levels of the water were allowed to equilibrate. Because of the fine nature of the Fairbanks silt samples, they were allowed to settle for two hours to accumulate any excess water at the top of the mold, where it could be squeezed out or duly recorded. Then the samples were ready to be frozen.

The freezing process took place in a cold room set at -26°C. However, the samples were not immediately exposed to this temperature because it was desired to simulate a natural freezing process. In nature, the ground freezes from the top surface downward and this process was desired for the soil samples prepared here. To accomplish this, the sample was placed in a wooden box, one foot by one foot by two feet tall. Zonolite brand Vermiculite insulation obtained from Vermiculite Products, Inc. Houston, Texas was

filled around the sample, leaving only the top plug exposed. Two steel weights, totaling seventy-seven pounds, were then applied to the top of the mold and the box was placed in the cold room. The weight was applied to minimize expansion of the soil sample as it froze.

The time allowed for the sample to freeze was a minimum of 24 hours. During a monitored freeze test, it was found that the sample did indeed freeze from the top downward. The top few inches of the sample froze within 3 hours of being placed in the deep freeze and the middle and bottom sections froze within 10 and 11 hours, respectively. Due to the heat transfer through the metal probe that was placed down the centerline of the sample, the soil surrounding the probe froze before the soil at the outer edge of the sample mold.

Even with the weight applied during freezing, expansion at the bottom of the sample was found. This expansion was never more than 3.75% of the soil volume. The expansion for each sample is listed in Table 1. After cleaning and measuring the expansion, the sample was removed to the test bath, which was set at the first test temperature of -20°C. The data collection was then ready to begin.

F. Soil Sample Conditions

The test conditions of the nine soil samples are given in Table 1. These values are determined from the

SOIL TEST CONDITIONS

SPECIFIC WEIGHT	OTTAWA SAND 2.65 G/CM3			ARCTIC GRAVEL 2.60 G/CM3			FAIRBANKS SILT 2.60 G/CM3		
POREWATER SALINITY	30.1	15.0	0.0	30.1	15.0	0.0	30.1	15.0	0.0
DRY DENSITY (G/CM^3)	1.60	1.61	1.62	1.78	1.87	1.98	1.55	1.57	1.61
SOIL POROSITY	0.395	0.394	0.389	0.315	0.281	0.239	0.405	0.396	0.380
MOISTURE CONTENT (PERCENT OF DRY WEIGHT)	25.19	22.36	22.73	17.60	15.41	12.05	27.36	27.22	24.13
PERCENTAGE OF FULL SATURATION	111.8	99.5	103.1	108.9	112.2	109.1	114.1	117.9	111.9
FREEZING VOLUME EXPANSION (PERCENT OF DRY VOLUME)	3.18	3.54	3.57	2.66	2.34	2.33	3.05	1.88	3.75

TABLE 1.

experimentally determined weights and volumes of the samples. The derivations of the values are given below.

The Ottawa Sand test conditions are quite consistent for each of the three tests. This is due to the fact that no hand packing of the sand became necessary. By adequately packing itself, similar conditions are present for all three samples, as shown in Table 1. Even the freezing volume expansions are remarkably close to each other. The largest deviations are found in the moisture content and saturation percent values, where the sensitivities are high, as explained below.

The Arctic Gravel samples do not show such similar results. Every effort was made to produce consistent samples, but differences in the force of packing led to varying results. The high and low dry densities differ by 10%, not as small a difference as the sand, but certainly within a reasonable limit. The porosities, calculated from the dry densities, differ by slightly more than 15%. The moisture content, which is dependent on the wet and dry weights of the soil, varies considerably, but in the manner expected. Higher dry densities yield less void space, which means less fluid in the soil, since the fluid fills only the void spaces. The freezing expansions are again quite close, and about 2/3 of the expansion of the sand. In fact, the proportion of the average gravel porosity (0.278 to 0.393, or 0.709) is virtually identical to the proportion of the

average gravel freezing expansion to the average sand freezing expansion (2.44% to 3.43% or 0.712). This shows that the expansion is due entirely to the expansion of the water as it freezes.

The Fairbanks Silt test conditions show very good similarity, much closer in range than the gravel, but not quite as good as the sand. The fine nature of the silt required hand packing, which could lead to variances in the conditions. But upon saturation of the sample, the silt settled to more or less consistent levels, thus giving fairly similar dry density and porosity values. However the fine particles hindered the saturation of the soil. The air did not prove to be as easily evacuated as the previous soils. The saturation process took up to an hour to complete, two to three times as long as with the previous soils. This did not lead to less consistent results, as the moisture content again behaved as expected, less water with a higher dry density. However freezing volume expansions were spread over a wider range. The low expansion of 1.88% is probably an anomaly, as the expected expansion should be roughly 3.5%, in line with the expansion of the sand samples since the average porosities of the silt and sand were roughly equal.

The values shown in Table 1 are derived from five measured soil sample properties, which are

    (1)   Soil specific weight γ_s, g/cm^3

    (2)   Dry soil weight W_s, grams

(3)   Wet soil weight W_w, grams

(4)   Sample volume, unfrozen V_u, cm^3

(5)   Sample volume, frozen   V,   cm^3

and from the standard specific weight of ice, γ_i, equal to 0.9163 g/cm^3 (57.2 pounds/ft^3). The frozen volume, referred to as simply the volume, is used to calculate all the properties. The unfrozen volume, V_u, is used only to find the freezing volume expansion.

The dry density, δ, in g/cm^3, is found by dividing the dry weight by the volume

$$\delta = W_s/V. \tag{22}$$

The porosity, n (dimensionless), is based on the dry density and the specific weight of the soil and it is

$$n = 1 - \delta/\gamma_s. \tag{23}$$

This equation is given by Lunardini for the investigation of frozen soils in Heat Transfer in Cold Climates [7].

The moisture content is the percentage of fluid in the sample. By convention, this percentage is based on the dry weight of the soil. Thus the moisture content, MC, is

$$MC = \frac{W_w - W_s}{W_s} \times 100\%. \tag{24}$$

The moisture content is highly sensitive to the dry weight (and thus the dry density). For instance, if the moisture

content is initially 25% and the dry weight is increased by 5% in a given volume, the weight of water is decreased by about 8.5%, since the soil is denser than water. Then the moisture content is reduced to 22%, a sizable decrease from a small increase in the dry weight. This effect is noticed in Table 1, where small differences in the densities (or dry weight) yield large changes in the moisture content.

The percentage of full saturation is based on the volume of the water and ice in the sample, which is found from the weight of the ice and water. This weight is the difference between the wet and dry weights of the sample. The volume of the fluid V_f, is

$$V_f = (W_w - W_s)/\gamma_i. \tag{25}$$

This volume, divided by the total volume of the voids, V_v, gives the percent of full saturation. The volume of the voids is

$$V_v = V - W_s/\gamma_s \tag{26a}$$

or, more simply

$$V_v = nV \tag{26b}$$

since the porosity is the fractional void volume of the total (frozen) volume. Then full (100%) saturation is achieved if the volume of the fluid is the same as the

volume of the voids. The percent of full saturation, SP, is

$$SP = V_f/V_v \cdot 100\%. \tag{27}$$

Most of the values listed in Table 1 for the saturation percent are greater than 100%, which can occur for several reasons. First, excess water could be present in the sample. This would be caused by a settling of the soil, leaving a layer of water. The silt samples did have a significant amount of settling, which is already taken into account in the calculations. Secondly, the saturation percent is highly sensitive to the data used in the calculation, just as the moisture content is sensitive to the dry weight. A volume change of the order of the freezing volume expansion (about 3%) reduces the percentage of saturation from 110% to about 103%, or very nearly full saturation. For the purposes of this work, each of the samples is considered to be fully saturated.

IV. EXPERIMENTAL APPARATUS AND OPERATION

The thermal probe technique has proven to be a fast and accurate method to determine the thermal properties of various materials. The method not only works well in the laboratory, but it is an effective method to use in field operations. The method, as used in this work, simultaneously determines the thermal conductivity and diffusivity of the frozen soils under consideration. The experimental setup and the data reduction programs have been previously designed and tested by Inbody [4]. A brief description of the application of the technique is provided below.

A. Theoretical Basis

The thermal probe technique involves the placement of a heating element and temperature measuring devices into a cylindrical soil sample. Generally, these two devices are built into one unit, the thermal probe, where a thermocouple is located in a metal shaft which is wrapped by the heating element. In this experiment, both internal and external (to the heating element) thermocouples are used. This allows for the simultaneous determination of the two thermal properties by measuring the temperature response at two locations in the sample.

Based on the assumption that the probe is an ideal line heat source at the center of the sample, the equation describing the unsteady heat conduction in one dimension, using cylindrical coordinates, is

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$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{28}$$

with the initial condition

$$T = T_O \quad \text{at} \quad t = 0 \tag{29}$$

and the boundary conditions

$$T = T_O \quad \text{as} \quad r \to \infty \tag{30}$$

$$Q = \lim_{r \to 0} 2\pi k r \frac{\partial T}{\partial r} \quad \text{for} \quad t > 0$$

where

r = radius at any point

t = time

T_O = initial temperature of sample

$T(r,t)$ = temperature at radius r and time t

Q = line heat source strength

k = thermal conductivity of soil

α = thermal diffusivity of soil

As Inbody found, the solution to this equation is

$$T(r,t) - T_O = \frac{Q}{4\pi k}\left[-Ei\left(\frac{-r^2}{4\alpha t}\right)\right] \tag{31}$$

where the term

$$-Ei(-x) = \int_x^\infty \frac{e^{-u}}{u}\,du \tag{32}$$

is the exponential integral. If the series representation
is used taking small values of the radius, the solution

becomes

$$T(r,t) - T_O = \frac{Q}{4\pi k}(- \gamma + \ell nt + \ln \frac{4\alpha}{r^2}) \qquad (33)$$

where

$$\gamma = \text{Euler's constant} = 0.5772156649$$

This equation can then be used, knowing the measured temperature response in the soil, to find the thermal conductivity and diffusivity for the heating period of the test, when the heat source is on.

Data taken after the heating source is turned off can also be used to determine the thermal properties. The system can be modeled as if an equal, but opposite, heat source had been turned on while maintaining the original heat source. The solution to equation (28) then becomes

$$T(r,t) - T_O = \frac{Q}{4\pi k}[-Ei(\frac{r^2}{4\alpha t}) - -Ei(\frac{r^2}{4\alpha(t-t_c)})] \qquad (34)$$

where t_c = time that original heat source is turned off or time that negative heat source is added.

This equation the further reduces to

$$T(r,t) - T_O = T_H - \frac{Q}{4\pi k} \ln(t - t_c) \qquad (35)$$

where

$$T_H = \frac{Q}{4\pi k} \; \ell n t$$

= theoretical temperature response had the

original heat source been maintained.

The constant terms involving Euler's constant and the diffu-
sivity have cancelled.

Inbody's original work also developed other methods
which have not been used in this work.

The advantages of the thermal probe technique over the
more traditional guarded hot plate method are the ease of
operation and the low temperature rises that must be imposed
on the sample. The method of operation, described below,
allows the investigator to make as many determinations as
desired on one sample. This assures comparability of the
data and the ability to establish a trend in the results.
Additionally, the experimental procedure is straightforward.

The temperature response needed depends on the record-
ing devices used, but temperature rises as low as 0.1 to
0.2°C are sometimes sufficient. The average maximum temper-
ature rises in this work were approximately 0.4 to 0.5°C or
less.

The drawbacks of this method are outweighed by the
advantages mentioned above when they are considered and
minimized. First the probe must be considered as an ideal
line heat source. How well this is obeyed could be criti-
cal. Small diameter probes (about 0.02 inches in diameter)

would be perfect to meet this requirement but they are very delicate and easily damaged, especially when the soils freeze. The larger diameter probe used in this work (0.204 inches in diameter) is significantly sturdier but is more likely to violate the ideal line heat source requirement. Inbody [4] discusses this in more detail.

Secondly, the size of the sample is important. In the field, imbedding the probe in the ground provides an infinite sample. However, in the laboratory, a finite size sample must be used. This limits the sample to a small section of the material and introduces a sample boundary at which the effects on the heat conduction may be altered.

A third complication arises from the contact that the probe has with the soil and the introduction of a holding device for the probe and auxiliary thermocouples. If poor contact is established, excess heat might be retained within the probe, giving an artificially high temperature response at the interior thermocouple and a corresponding low response at the exterior thermocouple. The holding device introduced into the sample would have thermal properties different than those of the soil, and thus affect the over-all properties.

B. Description of Experimental Equipment

As previously designed and developed, the equipment used in the experiment included first a sample mold container, which housed the soil sample, the thermal probe and

the auxiliary thermocouples, second a probe heater system, third a temperature measurement system, and last a constant temperature bath.

The sample mold container (see Figures 4 and 5) was an 18 inch long, 4 inch inner diameter PVC pipe. At both ends, 4 inch diameter aluminum plugs were used to seal the sample in the mold. Rubber O-rings were used to assure an adequate seal for an application of the vacuum and saturation as described previously. The bottom plug, 3 inches in height, had a 1/4 inch hole drilled for the inlet of the porewater. Between the bottom plug and the soil, a porous plate was inserted to spread the incoming flow of water evenly into the sample. A 1 to 2 inch layer of soil was placed on the plate, then a plexiglass probe jig was placed in the mold and the soil filled around it.

The probe jig consisted of two crosspieces (see Figure 4) connected by two rods and two tubes. The tubes contained the two exterior thermocouples (labeled Near and Far) with their sensing junctions exposed into the soil through holes drilled in the tubes and kept in place with a silicon seal-ant. The rods, used mainly for vertical support, were wrapped with additional thermocouples that were used to monitor the temperature rise at the boundary of the sample. The thermal probe was held in place at the center of the sample by the top and bottom crosspieces of the jig. The volume of the jig and probe (approximately 100 cm^3) was

SAMPLE MOLD–CONTAINER FOR EPR PROBE

ASSEMBLED CROSS-SECTION VIEW
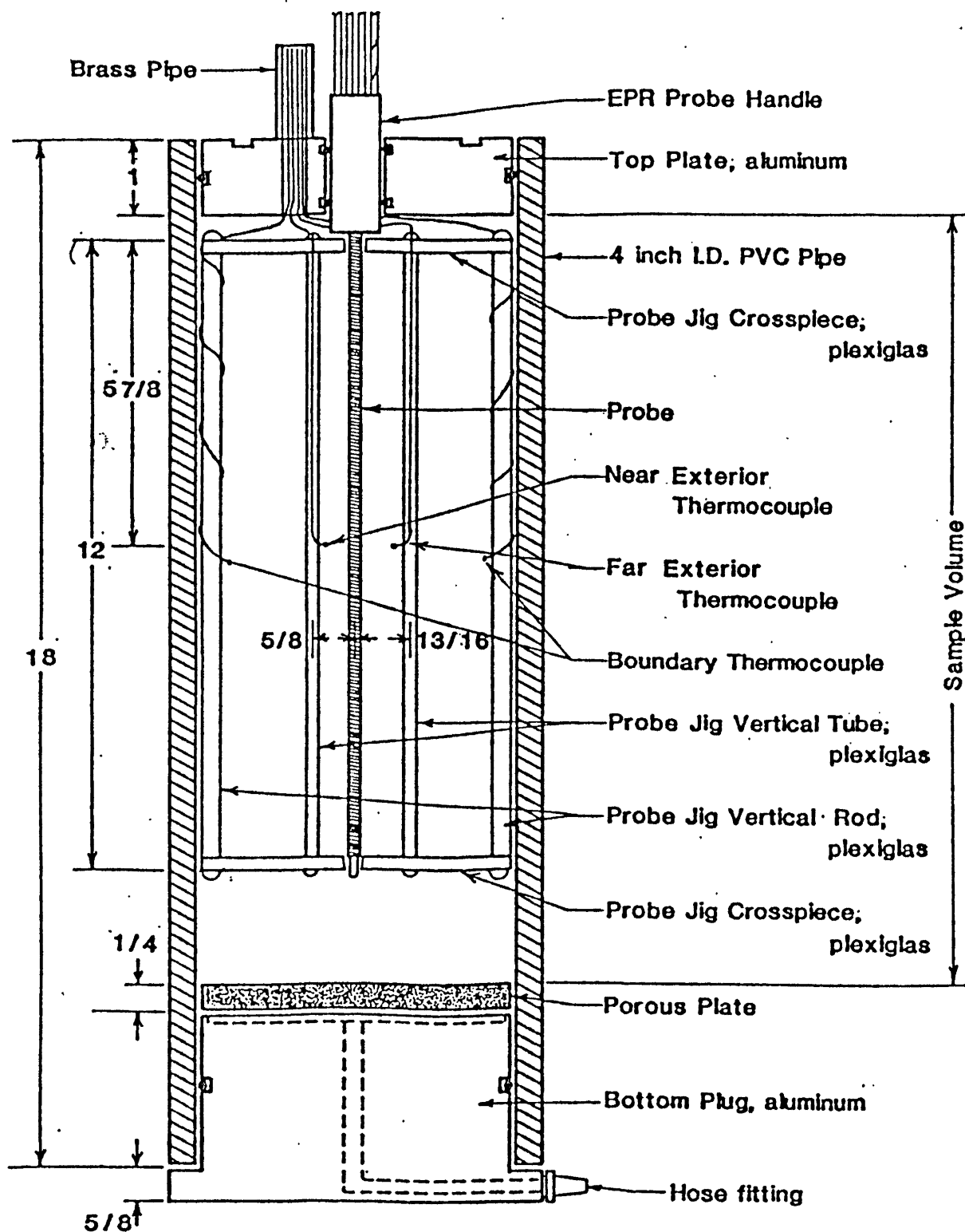
All dimensions are in inches

Figure 4.

accounted for in the calculations by subtracting it from the gross volume of the mold to obtain the soil sample volume.

Another layer of soil was laid between the top of the jig and the top plug. This plug, also sealed by a rubber O-ring, had two holes drilled in it. First, at the center, a 3/4 inch hole allowed the handle of the probe and the thermocouple lead wires to protrude (see Figure 5). Two small O-rings were used to seal this opening. A brass pipe was placed into a second hole to thread the exterior thermocouple wires out. For this pipe, a hose was connected from the vacuum apparatus, as shown previously in Figure 3. This allowed the vacuum to be applied to the sample and served as the top exit for the saturating porewater.

The probe itself was manufactured by the Instrumatics Corporation with the assistance of John Scattergood of Exxon Production Research Company. Hence it is referred to as the EPR probe. This probe contains three chromel-constantan thermocouples in a stainless steel shaft, 1/8 inch in diameter and 12-1/2 inches long (see Figure 6). The thermocouple at the center of the probe was used as the interior thermocouple. The heating element was a fourth thermocouple wire would around the shaft for a length of 12 inches. The lead wires were protected by the probe handle.

The exterior thermocouples used were 0.005 inch diameter chromel-constantan (Type E) insulated thermocouples

SAMPLE MOLD-CONTAINER FOR EPR PROBE

EXPLODED VIEW SHOWING SIDE AND TOP VIEWS

Cover Plate, aluminum

Brass Pipe for hose connection and wire conduit

O-Ring Grooves

3/4 inch dia. Hole for EPR Probe Handle

Slot for 2 7/8 inch O.D. Spacer Pipe

PVC Pipe
4 inch I.D., 4 1/2 inch O.D.

Slots cut in surface to spread water across bottom of sample

Porous Plate
4 inch dia.

Bottom Plug, aluminum

O-Ring Groove

1/4 inch O.D. Hole for water passage

Hose Fitting
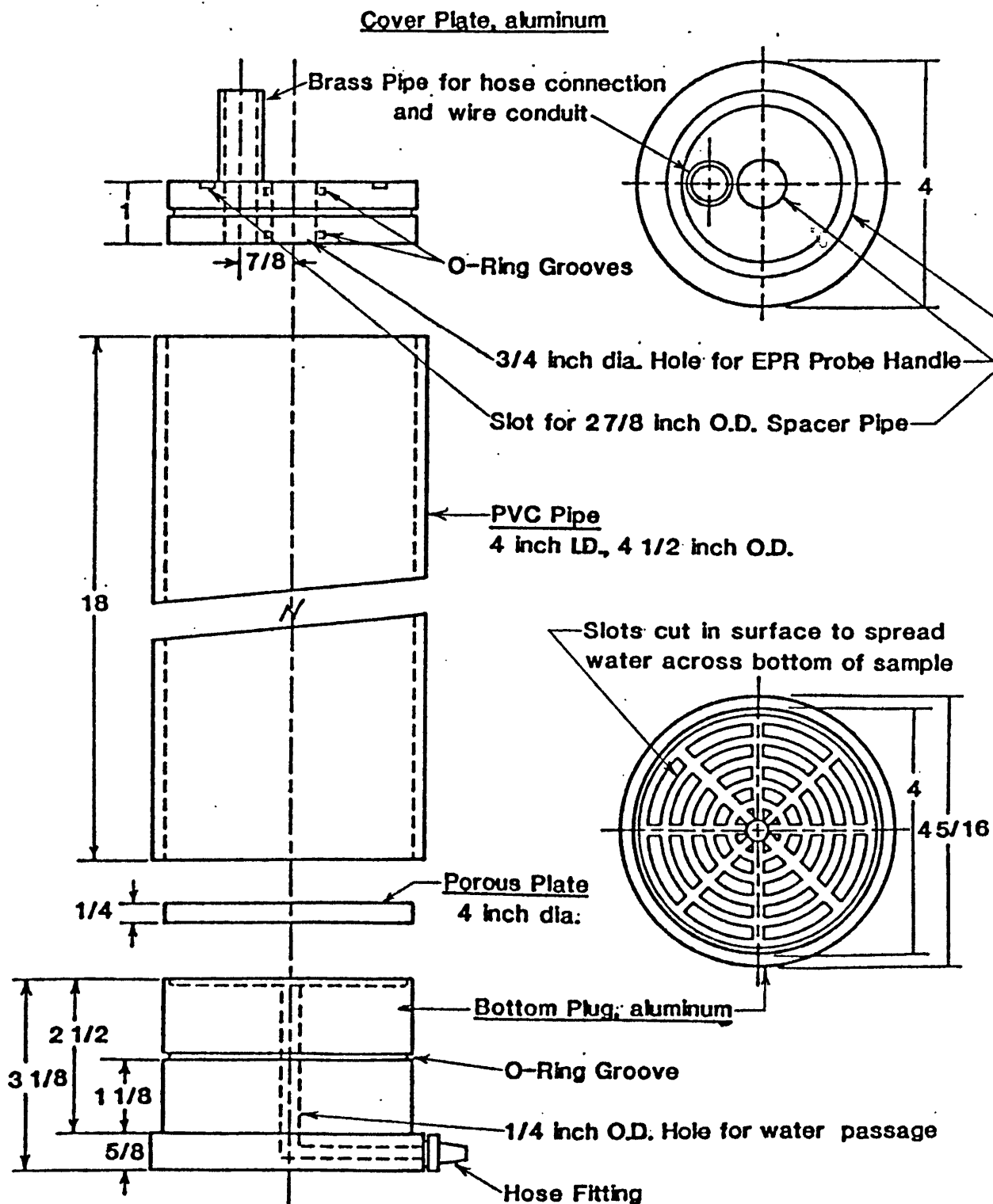
All dimensions are in inches
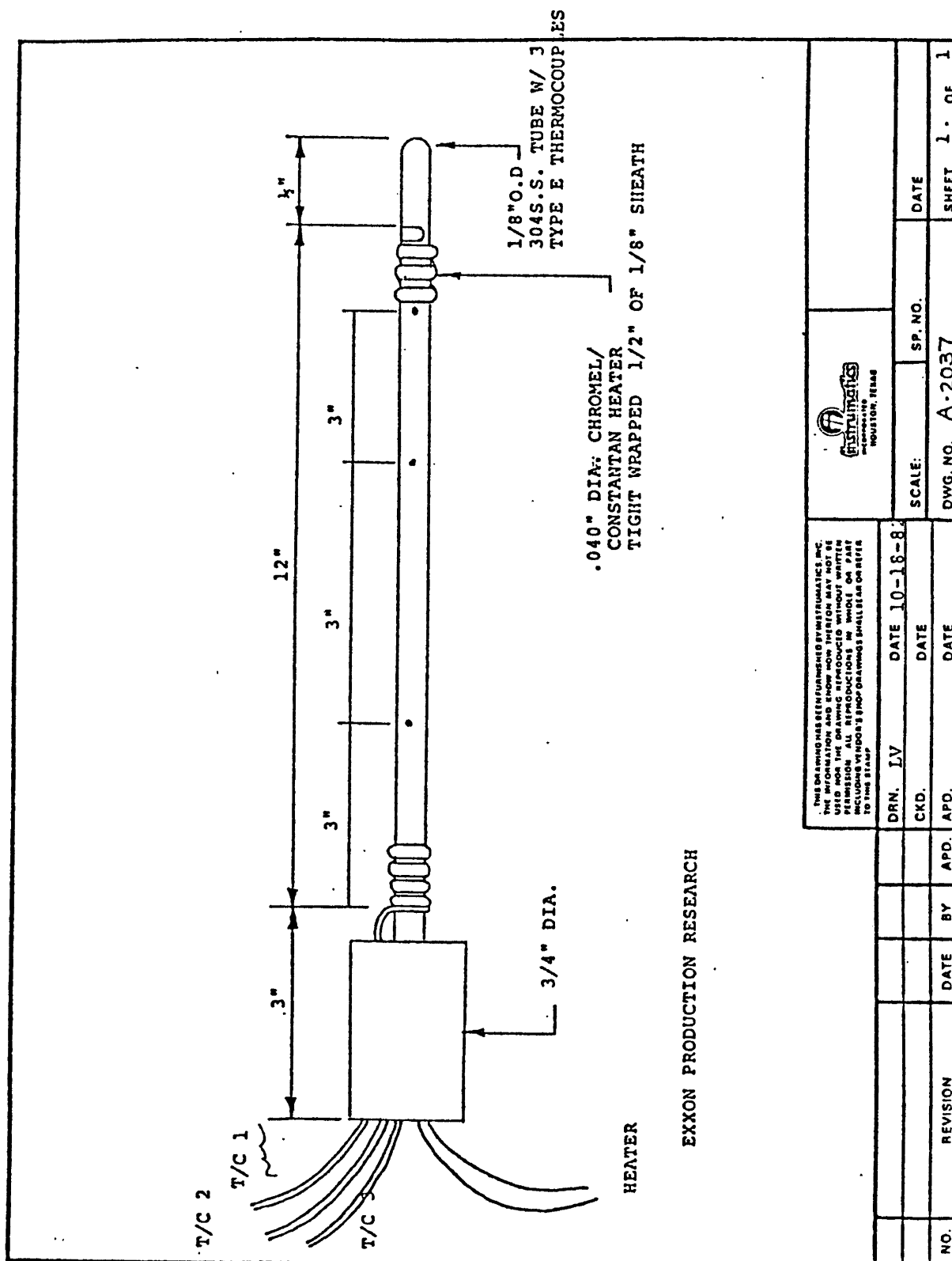
Figure 5.

Drawing of the EPR Probe, supplied by Instrumatics, Inc.
Figure 6.

obtained from Omega Engineering, Inc. They were placed, as previously mentioned, in the probe jig tubes, with their junctions exposed. The exact locations of the junctions were measured immediately before a sample was prepared and they ranged a distance of 1/4 of an inch to 15/32 inches away from the center of the probe.

To connect the power supply to the probe heating element, a switchbox was used which allowed for an instantaneous switch of power from a dummy resistance load to the heating element (see Figure 7). This dummy load, of approximate equal resistance as the heating element, allowed the power supply to stabilize before switching on the heat to the probe. This allowed an approximately constant line heat source strength. The power supply used was an HP 6237B Triple Output DC power supply. Data Precision 2480 R Digital Multimeters were used to monitor the voltage across the dummy load and the probe heating element.

The temperature measurement system involved various pieces of equipment. Due to the small temperature rises (on the order of 0.5°C), small voltage changes were produced by the thermocouples. To obtain a meaningful response for the data recording equipment, the signals had to be considerably amplified. This necessitated the system of equipment shown in Figure 8 and described in the following paragraphs.

During a test, no more than three thermocouples were monitored. The leads from the internal, one external, and a

PROBE HEATER SYSTEM

DC HEATING SYSTEM - EPR PROBE

Thermo-couple lead wires

EPR Thermal Conductivity Probe :
Heater is an 0.040 inch dia. chromel-constantan thermocouple connected with copper lead wires.

Heater lead wires

Adjustable Dummy Load (used during experiment set-up)

Dummy Load - Probe Selector Switch

All components inside the dashed lines are internal to the switchbox.

Figure 7.

Digital Voltmeter: Data Precision 2480R Digital Multimeter (measures voltage across Probe Heater)

18.88v

HP 6237B Triple Output DC Power Supply

18.88v

Digital Voltmeter: Data Precision 2480R Digital Multimeter (measures voltage across dummy load before test)

THERMOCOUPLE TEMPERATURE MEASUREMENT SYSTEM

EPR PROBES

EPR Thermal Conductivity Probe:
(3) chromel-constantan
thermocouples located
inside sheath

Heater
lead wires

Thermocouple
lead wires

(2) Omega TRP-E
Reference Probes

Exterior
Thermocouple:
Omega Teflon-insulated
chromel-constantan
thermocouple located
in sample by probe jig

Ice Point Reference:
Dewar flask containing
ice and water mixture

0 C

C = Omega Quick Disconnect
Thermocouple connectors

(2) Passive Low Pass
Filter and Integrated
Circuit Instrumentation
Amplifier
Gain = G

Gould Chart Recorder
2400
Dual Channel with
Medium Gain DC Amplifiers

Figure 8.

boundary thermocouple were connected to reference junctions inside an ice point cell. These reference junctions were chromel-constantan thermocouples enclosed in stainless steel sheaths. Thermocouple connectors were used to attach all the leads. The ice point cell consisted of ice and water in a Dewer flask. A constant temperature of 0°C was maintained in this cell for a period of several hours.

The voltage signals from the reference junctions were then amplified using an Analog Devices AD521JD integrated circuit precision amplifier. The amplification gain determined for the interior thermocouple was approximately 240 times. The lower temperature rise of the exterior thermocouple necessitated a gain of approximately 300 times. These values were determined in the design and development phase of the experiment, to produce adequate, measurable recordings.

These amplified signals were recorded on a dual Gould 2400 chart recorder. The most sensitive scale was used to give the largest responses possible. The responses from the interior and one exterior thermocouple were recorded, while the boundary thermocouple was visually monitored on an HP 3465 B digital multimeter, unamplified.

The constant temperature bath held the sample mold during the testing. The plastic tubing used for the saturation also protected the thermocouple lead wires from contacting the bath fluid. The bath was a Forma Scientific

Model 2925 refrigerated and heated bath and circulator. It was able to maintain the set temperature within $\pm 0.02°C$. The fluid was a mixture of approximately 65% ethylene glycol and 35% water. This mixture absorbed atmospheric moisture and hence changed with time.

C. Operation of Experiment

Once the soil sample had been saturated and frozen, it was placed in the bath which was set initially to $-20°C$. Since the sample had frozen to a colder temperature than this (the cold room was set $-26°C$) it was allowed to come to equilibrium at $-20°C$ before the testing was begun. At least 24 hours were allowed, although equilibrium was usually reached in less time. The temperature signals were monitored to ascertain that equilibrium had been reached.

To begin a test, the power supply was switched on to the heating element, having been stabilized with the dummy load resistor. The voltage supplied to the probe was monitored while the amplified signals from the thermocouples were recorded. After a specified length of time, the power supply was switched back to the dummy load. The thermocouple signals were recorded for an additional length of time equal to the time that the power had been supplied to the heating element. This length of time was generally 3 minutes, following the personal recommendations of Inbody. A few longer times were used, 5 to 8 minutes, but the same

problems that Inbody encountered with the data reduction minimized their use.

After the first test had been run, the effects of the heating were allowed to die out. As Inbody [4] noted, this took 15 times the length of time that the heat had been supplied. For a 3 minute heating period, a minimum of 45 minutes was needed. In practice, 1 to 1-1/2 hours were usually allowed. A second test was then run, identical in procedure to the first. If any problems were encountered with either of the first two tests, a third and possibly a fourth test were run after again allowing the heating effects to die out.

Finally, a voltage gain and offset test was run on the amplifiers. The offset of the amplifiers tended to drift with time, so the offset used was an average value of that found before and after the tests. This accounted for the variations in the measured temperatures from the nominal bath temperature.

The bath temperature was then raised to the next higher setting, either -15°C or -10°C. The circulating fluid increased the temperature increment within several hours, but the sample took longer to reach equilibrium. About 20 to 24 hours were allowed before the next set of tests were begun. As the sample was warmed in the bath, it would enter into a phase change during the course of the tests. Any localized effects of this phase change were unknown, as the mold

container was opaque. In several cases, only a partial phase change occurred in the 20-24 hours allowed. This was evident in the temperature responses recorded in the first test at the particular temperature setting. An additional 8-12 hours were allowed for the phase change to become complete and more tests were then run. No other difficulties were encountered because of the phase change in the operation of the experiment, but some became apparent only as the data was reduced. These problems will be discussed in more detail later.

When the last test had been run at either 0°C or +1°C, the sample was removed from the bath and the top plug was removed to examine the sample. In a few cases, the sample still had not experienced a complete phase change at 0°C. Therefore +1°C was thereafter used as the final temperature setting. The Fairbanks silt samples also showed a bit of settling, which was recorded to subtract out the excess water from the sample. The used soil was weighed wet, oven dried and reweighed to obtain the wet and dry weights used in the calculations.

D. Data Reduction Procedure

The charts of the voltage response from the thermocouples were read and the data was input into a set of computer programs developed to reduce the data. The hardware used was a Digital Equipment Corporation PDP11 VO3 system and the software was previously written and refined

by Inbody. This set of programs first reduced the amplified voltage signals to a temperature rise from the initial (equilibrium) temperature of the sample.

The temperature rise data was then used to find curve fit solutions to the equations developed above. For the interior thermocouple during the heating period, Equation (33) can be simplified to

$$T = A \, \ell nt + B \tag{36}$$

where

$$T = \text{temperature rise}$$

$$= T(r,t) - T_O$$

$$A = \frac{Q}{4\pi k}$$

$$B = \frac{Q}{4\pi k}[-\gamma + \ln \frac{4\alpha}{r^2}] .$$

A least squares curve fit procedure determined the coefficients A and B which best fit the data. Then, knowing the line heat source strength Q from the measured voltage across the heating element, the thermal conductivity can be found from the coefficient A as

$$k = \frac{Q}{4\pi A} . \tag{37}$$

For the cooling portion of the data, after the power had been turned off, Equation (35) can be stated as

$$T = T_H - A_c \ln(t - t_c) - B_c \tag{38}$$

where

$$T_H = A \ln t + B \quad \text{from Eqn. (36)}$$

$$A_c = \frac{Q}{4\pi k}$$

B_c = constant used in the curve fit

The conductivity from the cooling period is then found also by using equation (37).

Ideally, the conductivity from the heating and cooling period curve fits should be identical. In practice, the two values were never equal, but they did not vary, in most cases, by more than about 5%. A difference of 10% in the two conductivities was a reason to question the data from the test.

Statistical methods were used to evaluate the results of the curve fits. The programs calculated the standard deviation and correlation coefficient of each of the individual curve fits. This data is shown in detail in Appendix B.

The determination of the thermal diffusivity used curve fits of the data from the exterior thermocouples. Equation (31) can be written as

$$T = A\left[-Ei\left(\frac{-B}{t}\right)\right] \tag{39}$$

where

$$A = \frac{Q}{4\pi k}$$

$$B = \frac{r^2}{4\alpha}$$

and the data is fit to this equation to find the coefficients A and B. From the coefficient B, the thermal diffusivity is found as

$$\alpha = \frac{r^2}{4B} \qquad (40)$$

since the radius, r, of the thermocouple from the center of the probe had previously been measured. The coefficient A can also be used to find a value for the conductivity using Equation (37). This value could be compared with the value found from the interior thermocouple.

The results of the diffusivity measurements, along with the statistical results are given in Appendix B for each of the individual tests.

The programming details of the above methods and others developed by Inbody can be found in his work [4].

V. RESULTS AND DISCUSSION

A. Experimental Results

To determine the thermal properties of the three frozen saline soils, the data from 96 of the 110 tests performed were reduced as described above. The results for those 96 tests are presented in detail in Appendix B. The remaining tests are not listed, either because their data were not reduced or because the reduction procedure could not adequately find a solution. The data sets not reduced were those where problems were encountered in the operation of the test.

The thermal properties of the soils are presented below in Tables 2 through 4 and Figures 9 through 17. Generally, the results given are an average of the properties found from two tests at identical conditions. In some cases, as noted, only one test gave satisfactory results, so those properties are based on one value only.

The thermal conductivity values, in W/mC, are also an average of the determined heating and cooling period conductivities. The short test times of most of the trials (3 minutes of heating and 3 minutes of cooling) gave satisfactory results of the frozen soil thermal properties for both periods. The correlation coefficients, which measure the fit of the curve fit equations to the data points, 1.0 being a perfect fit, are consistently above 0.995 and the standard deviations, which measure the variance of the data points

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from the curves, are generally around 0.005, or about 1% of the typical temperature rise of 0.5°C. The standard deviations of the curve fits for the silt samples are somewhat higher, in the range of 0.010, but the correlation coefficients are still at or above about 0.995. The reason for the difference in the standard deviations is unknown.

The values for the thermal diffusivity are found using only the heating period results. The cooling period results were deemed less accurate because of the generally lower correlation coefficients and higher standard deviations found. Although some of the cooling period results are as good as or better than the heating period results, the overall less consistent curve fits, and a few examples of very poor or no curve fits at all, have caused the cooling period data not to be considered for any of the tests.

The results at the coldest temperatures studied show the best results. The correlation coefficients at -20°C, -15°C, and -10°C are among the highest, sometimes greater than 0.999, and the standard deviations are among the lowest. Furthermore, the most difficulties were encountered in the data reduction of the warmer temperatures, -5°C, -2°C, and 0°C or +1°C. In some cases, no adequate results could be found due to the small temperature rises of 0.1°C or less at the exterior thermocouples. In other cases, unacceptably low correlation coefficients of less than 0.90 were found. The majority of these problems occurred in the diffusivity

cooling period results, which were not considered, but nevertheless, these problems were evident mainly at the warmer temperatures. The cause for these problems is most likely the phase change that the sample experiences in this warmer region. This will be discussed after the results are presented.

The fact that the conductivity and diffusivity values are of the order of magnitude of the standard deviations of the curve fits is not a reason to suspect the data. The standard deviations listed measure the variance of the temperature rise data points from the curve fits. The conductivity and diffusivity values are derived from the coefficients of the curve fits, A and B in equations 36, 39, and 40. Thus the listed statistical results bear no relationship to, or denote the deviation of the conductivity or diffusivity values. They are concerned only with the accuracy of the curve fits to the data.

The mean thermal properties are given for each of the nine soil samples in the tables and figures which follow. A brief discussion is provided for each of the three soils.

1. Ottawa Sand Results

The results for the Ottawa Sand tests are listed in Table 2 and shown, individually for each of the three porewater salinities, in Figures 9, 10, and 11. The results of the 30.1 PPT tests (Figure 9) were found using only one test at each temperature. These early tests were performed, not

MEAN THERMAL PROPERTIES OTTAWA SAND		
POREWATER SALINITY AND TEST TEMPERATURES	THERMAL CONDUCTIVITY (W/M K)	THERMAL DIFFUSIVITY (CM^2/SEC)
30.1		
-20	4.75	0.0140
-15	4.72	0.0136
-10	4.99	0.0103
-5	5.28[+]	0.0050[+]
-2	6.45[+]	0.0028[+]
0	8.13[+]	0.0013[+]
15.0		
-20	4.85	0.0283
-10	4.79	0.0227
-5	4.94[+]	0.0125[+]
-2	6.41[+]	0.0049[+]
0	8.56[+]	0.0045[+]
0.0		
-20	5.25	0.0264
-10	4.84	0.0214
-5	4.76	0.0207
-2	4.89[+]	0.0216[+]
0	5.46[+]	0.0150[+]
[+]RESULTS IN PHASE CHANGE REGION ARE INCONCLUSIVE		
TABLE 2.		

MEAN THERMAL PROPERTIES
OTTAWA SAND
30.1 PPT WATER
DRY DENSITY = 1.60 G/CM³   MOISTURE CONTENT = 25.19 %
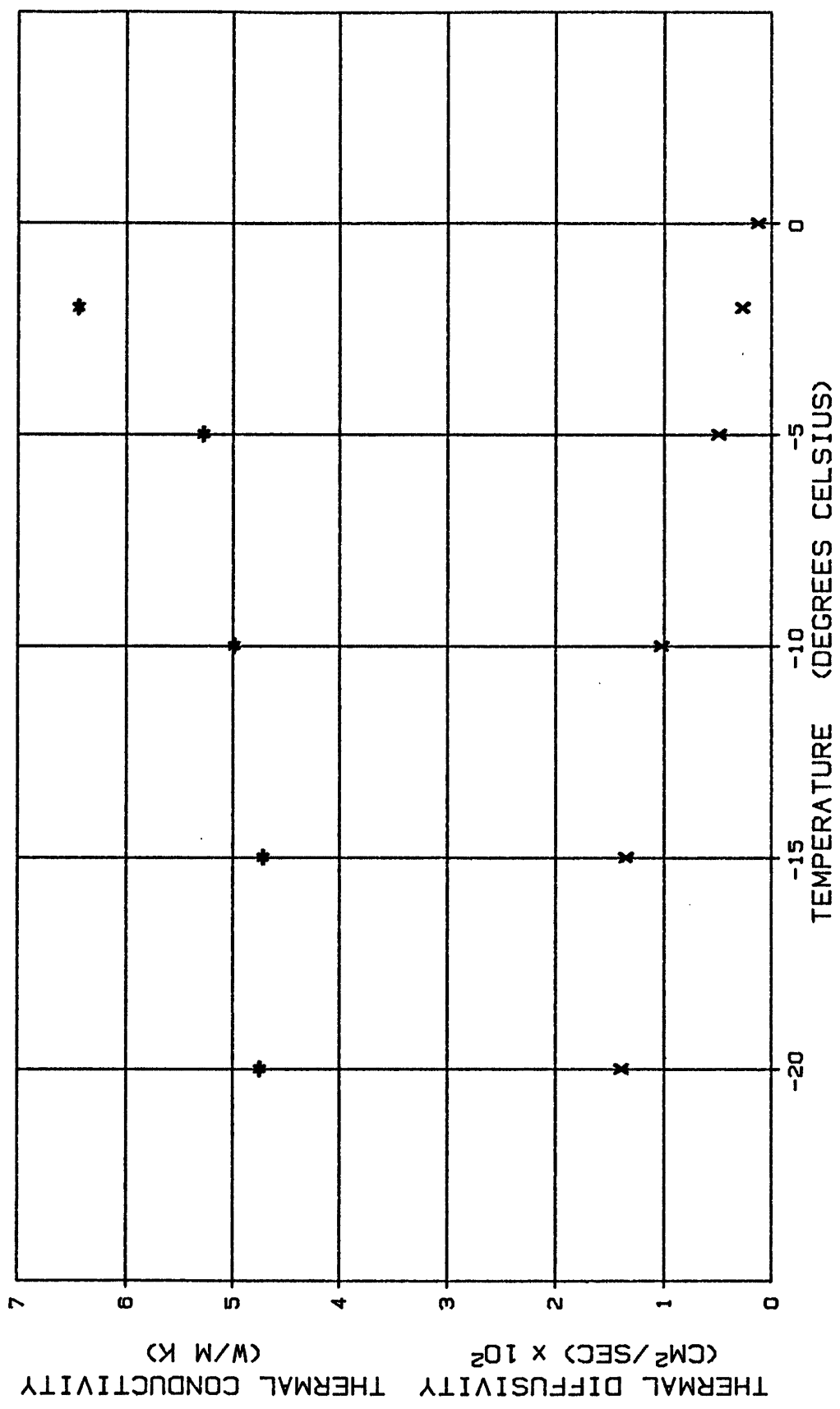
FIGURE 9

MEAN THERMAL PROPERTIES
OTTAWA SAND
15.0 PPT WATER
DRY DENSITY = 1.61 G/CM³
MOISTURE CONTENT = 22.36 %

TEMPERATURE (DEGREES CELSIUS)
FIGURE 10

THERMAL CONDUCTIVITY (W/M K)
THERMAL DIFFUSIVITY (CM²/SEC) X 10²
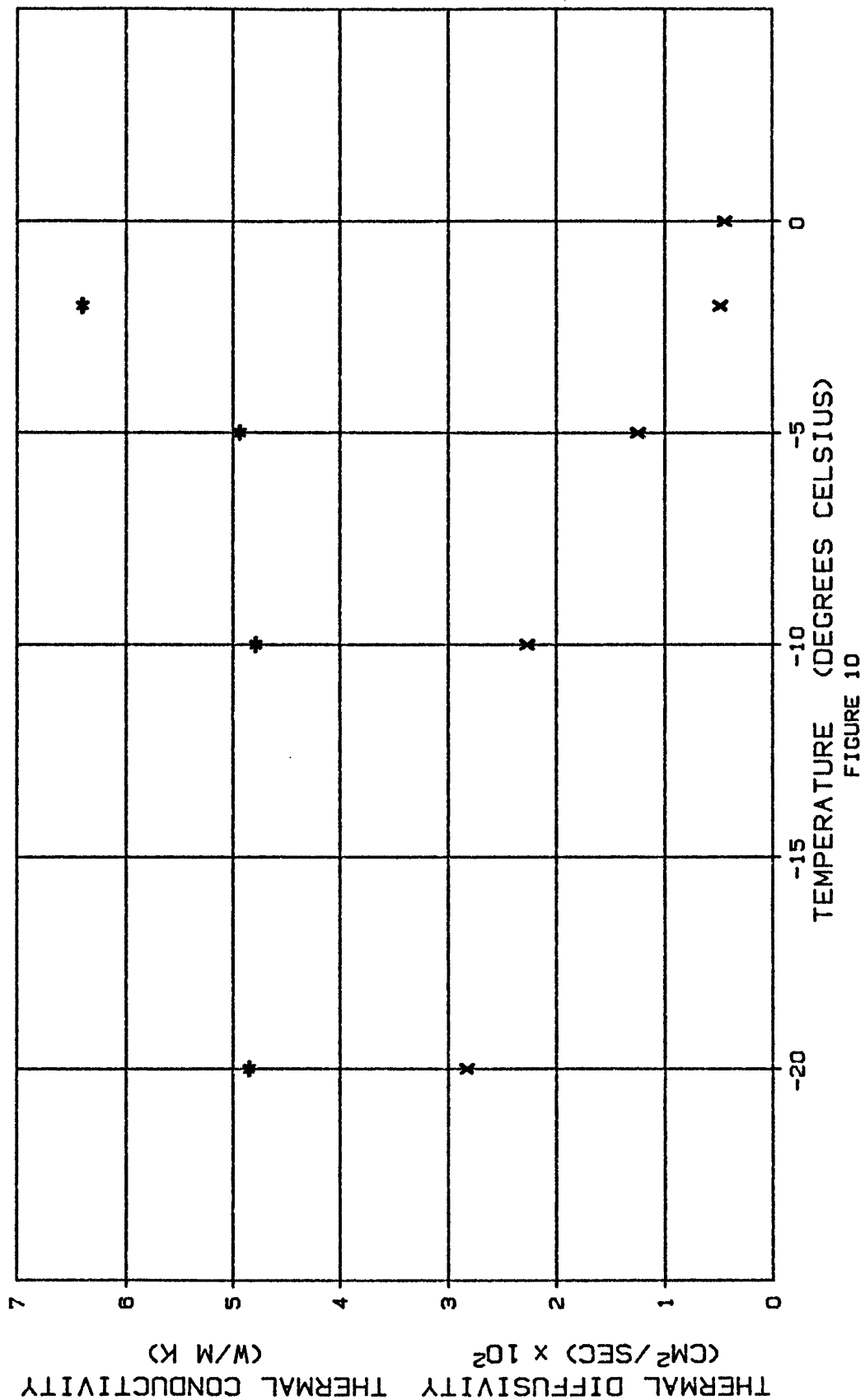
MEAN THERMAL PROPERTIES
OTTAWA SAND
0.0 PPT WATER
DRY DENSITY = 1.62 G/CM3   MOISTURE CONTENT = 22.73 %

TEMPERATURE (DEGREES CELSIUS)
FIGURE 11

THERMAL CONDUCTIVITY (W/M K)
THERMAL DIFFUSIVITY (CM²/SEC) X 10²
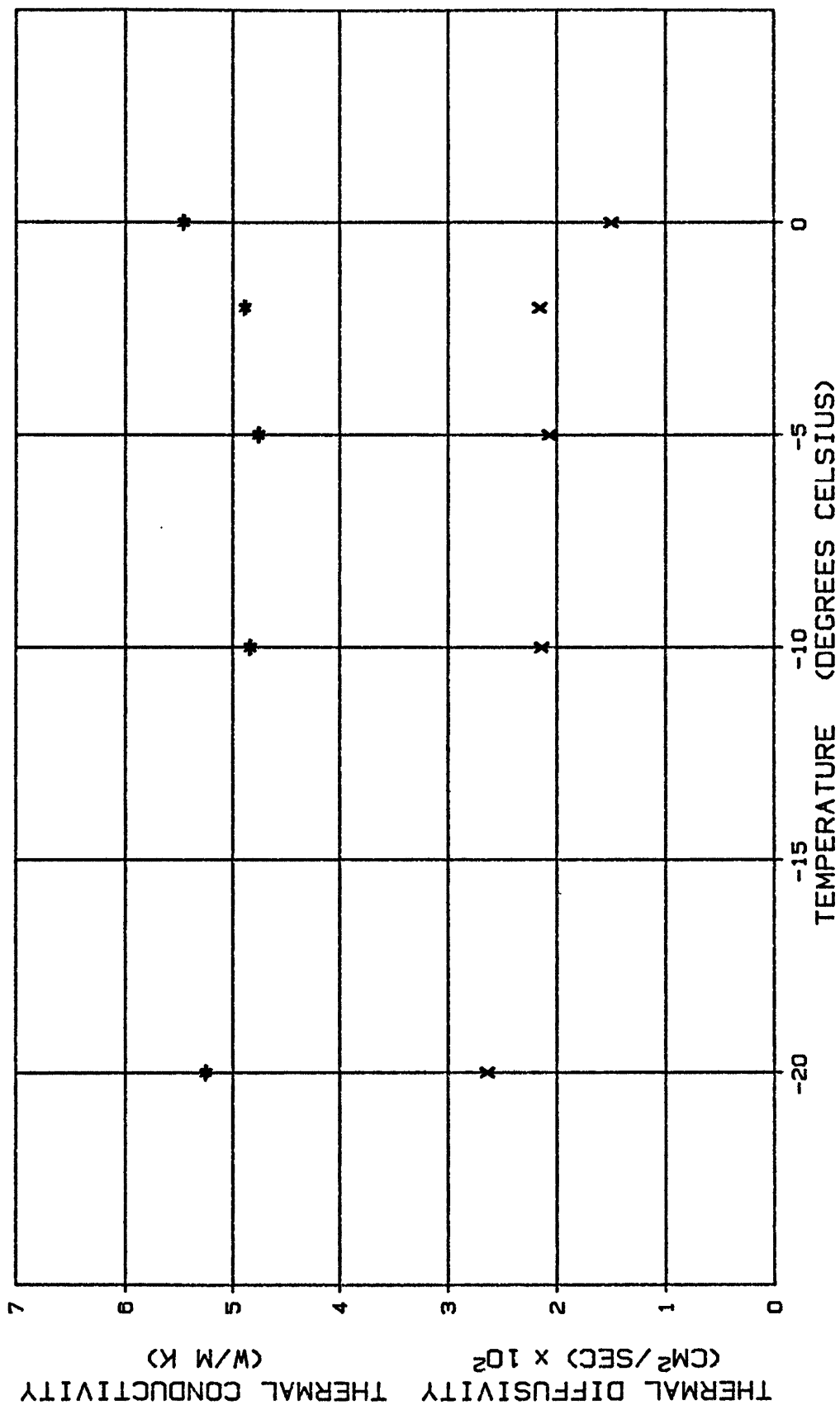
by using the two exterior thermocouples, but by using two lengths of time for the heating periods. A short test of 3 minutes of heating was run, then a longer 5, 6, or 8 minute test was performed. With the exception of one test, these long heating period results were not used due to the problems encountered with the data reduction.

The results of the 15.0 PPT and 0.0 PPT water tests are shown in Figures 10 and 11, respectively. Two tests, either of 3 or 5 minutes of heating, were averaged to find these property values. The only significant problems encountered with the data reduction were in the diffusivity calculations of the longer tests and at 0°C for the 15.0 PPT sample. No results could be found in these two tests.

The conductivity results at 0°C are not shown in either Figure 9 or 11 because they are greater than 7 W/mC. As will be discussed, these results were not considered representative.

2. Arctic Gravel Results

The mean thermal properties for the Arctic Gravel are listed in Table 3 and shown in Figures 12, 13, and 14. All of these results are based on the average of two tests.

Fewer data reduction problems were encountered as the application of the probe technique became more standardized. Most of the tests were short tests of 3 minutes in length. Both of the exterior thermocouples (labeled Near and Far in Figure 4) were used in the determinations. The reduction

MEAN THERMAL PROPERTIES ARCTIC GRAVEL		
POREWATER SALINITY AND TEST TEMPERATURES	THERMAL CONDUCTIVITY (W/M K)	THERMAL DIFFUSIVITY (CM^2/SEC)
30.1		
-20	4.24	0.0194
-10	4.13	0.0125
-5	4.41[+]	0.0071[+]
-2	5.31[+]	0.0032[+]
0	2.87	0.0098
15.0		
-20	3.93	0.0195
-15	3.89	0.0193
-10	3.88	0.0156
-5	4.01[+]	0.0129[+]
-2	4.71[+]	0.0051[+]
1	2.56	0.0100
0.0		
-20	4.29	0.0200
-15	4.29	0.0222
-10	4.12	0.0220
-5	3.94	0.0178
-2	4.09[+]	0.0185[+]
1	15.55[+]	[*]
[+]RESULTS IN PHASE CHANGE REGION ARE INCONCLUSIVE [*]NO RESULTS COULD BE DETERMINED		
TABLE 3.		

MEAN THERMAL PROPERTIES
ARCTIC GRAVEL
30.1 PPT WATER
DRY DENSITY = 1.78 G/CM³   MOISTURE CONTENT = 17.60 %

TEMPERATURE (DEGREES CELSIUS)
FIGURE 12

THERMAL DIFFUSIVITY (CM²/SEC) X 10²
THERMAL CONDUCTIVITY (W/M K)
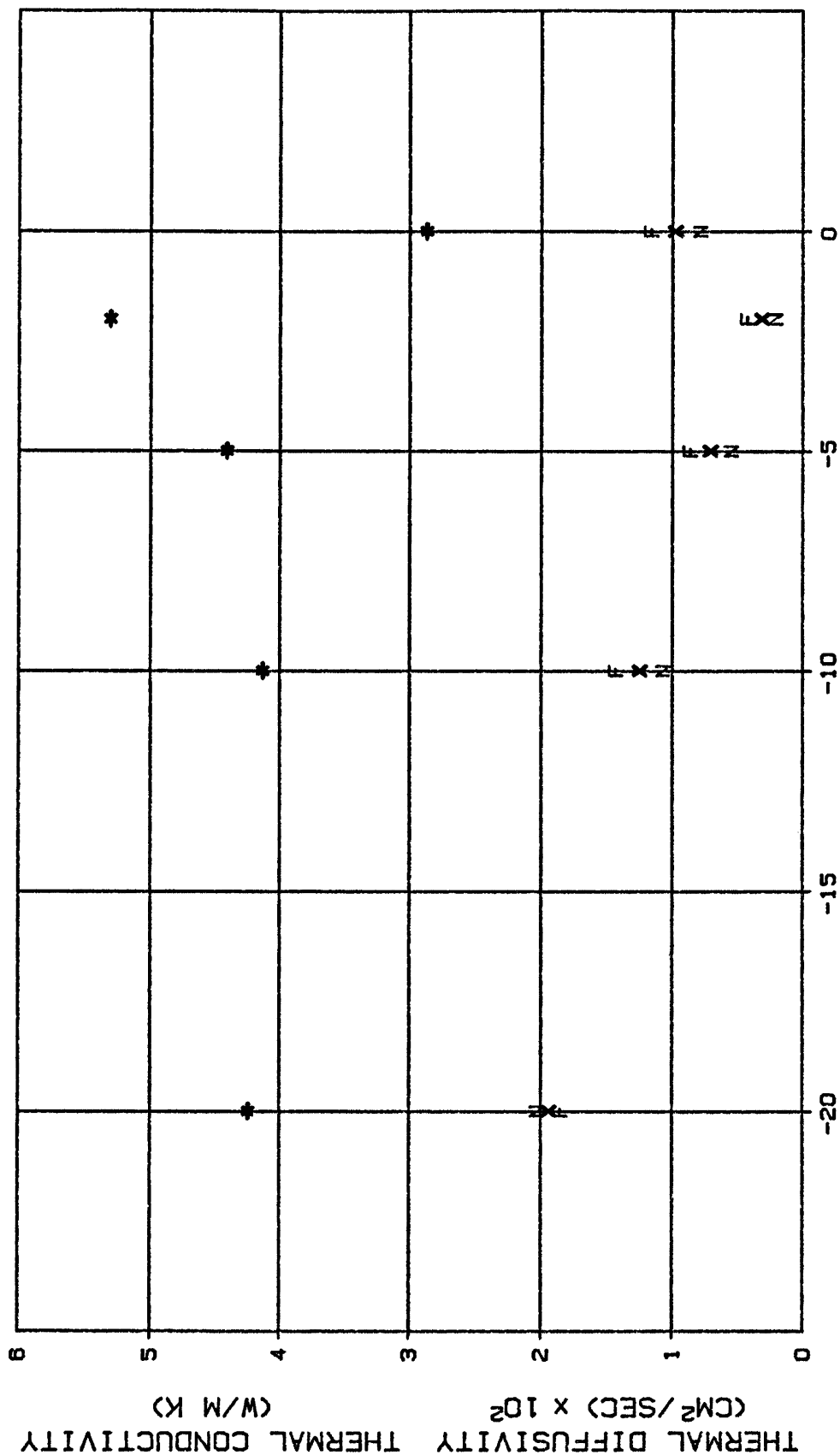
MEAN THERMAL PROPERTIES
ARCTIC GRAVEL
15.0 PPT WATER
DRY DENSITY = 1.87 G/CM³   MOISTURE CONTENT = 15.41 %
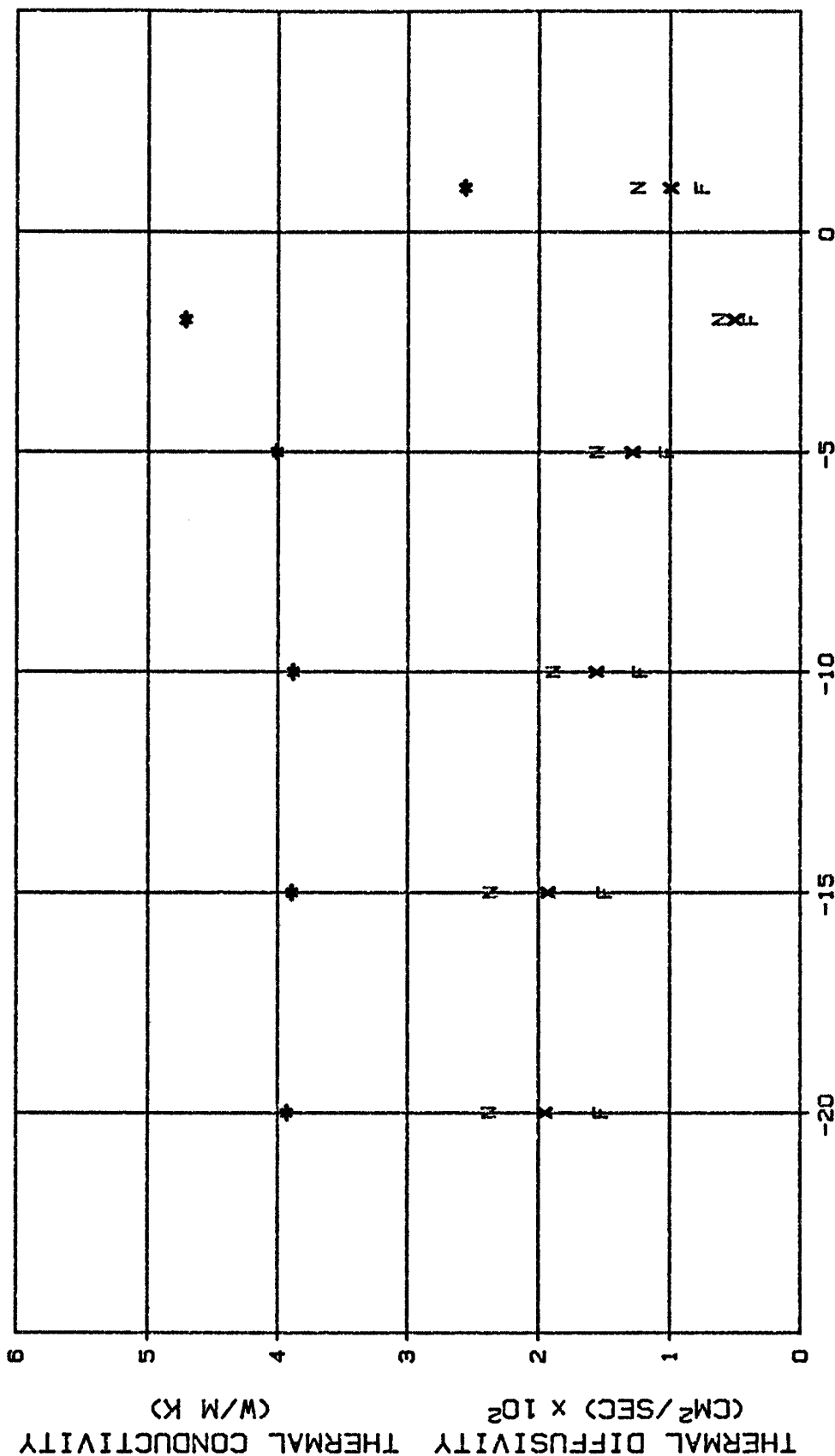
FIGURE 13

MEAN THERMAL PROPERTIES
ARCTIC GRAVEL
0.0 PPT WATER
DRY DENSITY = 1.98 G/CM³   MOISTURE CONTENT = 12.05 %

TEMPERATURE (DEGREES CELSIUS)

FIGURE 14

THERMAL DIFFUSIVITY   THERMAL CONDUCTIVITY
(CM²/SEC) x 10²   (W/M K)
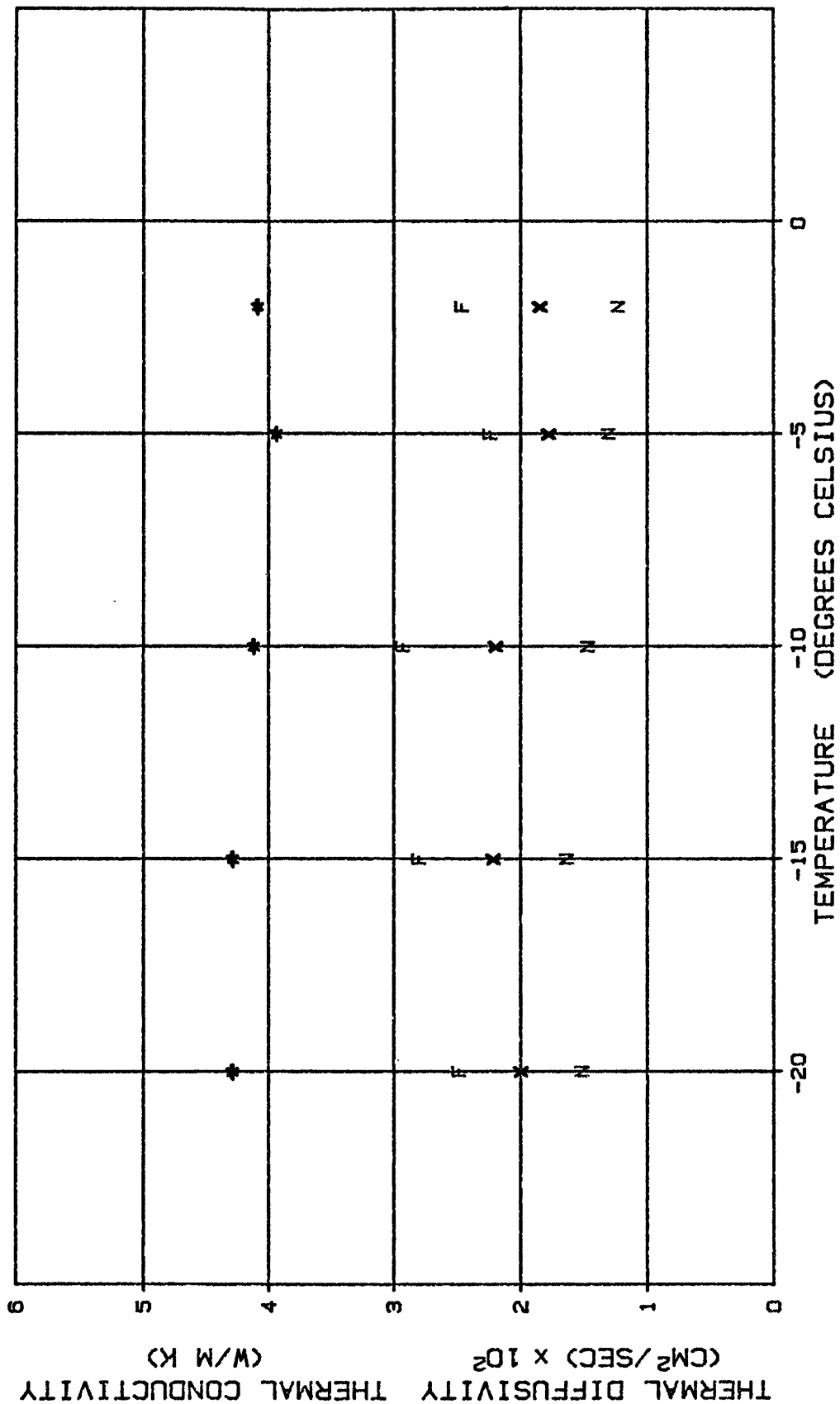
problems encountered were similar to those found with the sand - low correlation coefficients for some of the cooling diffusivity curve fits at the warmer temperatures.

However, a different, more significant, problem was encountered with the gravel tests. The results from the two exterior thermocouples did not closely correspond for two of the three samples. In Figures 12, 13, and 14, three diffusivity values are shown. First, denoted as a boldface **x**, are the average diffusivities. Above and below these, the results for the near and far exterior thermocouples are shown (labeled as N and F, respectively). The 30.1 PPT water sample shows very little deviation in the individual results. However the 15.0 and 0.0 PPT samples show a significant variance. Differences of 50% and greater are seen from the two thermocouples. The reason for these deviations, which were not found for the other soils, is discussed further below.

The value determined for the conductivity of the fresh water sample at 0°C is unrealistically high, and hence is not shown in Figure 17.

3. Fairbanks Silt Results

The thermal properties of the Fairbanks silt soil samples are listed in Table 4 and shown in Figures 15, 16, and 17. All of the tests were short tests, of 3 minutes in length, and both of the exterior thermocouples were used in the determinations. Six nominal temperature levels were

MEAN THERMAL PROPERTIES FAIRBANKS SILT		
POREWATER SALINITY AND TEST TEMPERATURES	THERMAL CONDUCTIVITY (W/M K)	THERMAL DIFFUSIVITY (CM^2/SEC)
30.1		
-20	2.70	0.0091
-15	2.71	0.0071
-10	2.87	0.0055
-5	3.30[+]	0.0022[+]
-2	4.47[+]	*
1	1.87	0.0042
15.0		
-20	2.53	0.0121
-15	2.55	0.0111
-10	2.64	0.0091
-5	3.00[+]	0.0054[+]
-2	3.90[+]	0.0019[+]
1	1.83	0.0052
0.0		
-20	2.60	0.0145
-15	2.63	0.0154
-10	2.60	0.0144
-5	2.69	0.0135
-2	3.14[+]	0.0113[+]
1	1.80	0.0089
[+]RESULTS IN PHASE CHANGE REGION ARE INCONCLUSIVE *NO RESULTS COULD BE DETERMINED		
TABLE 4.		

MEAN THERMAL PROPERTIES
FAIRBANKS SILT
30.1 PPT WATER
DRY DENSITY = 1.55 G/CM3
MOISTURE CONTENT = 27.38 %
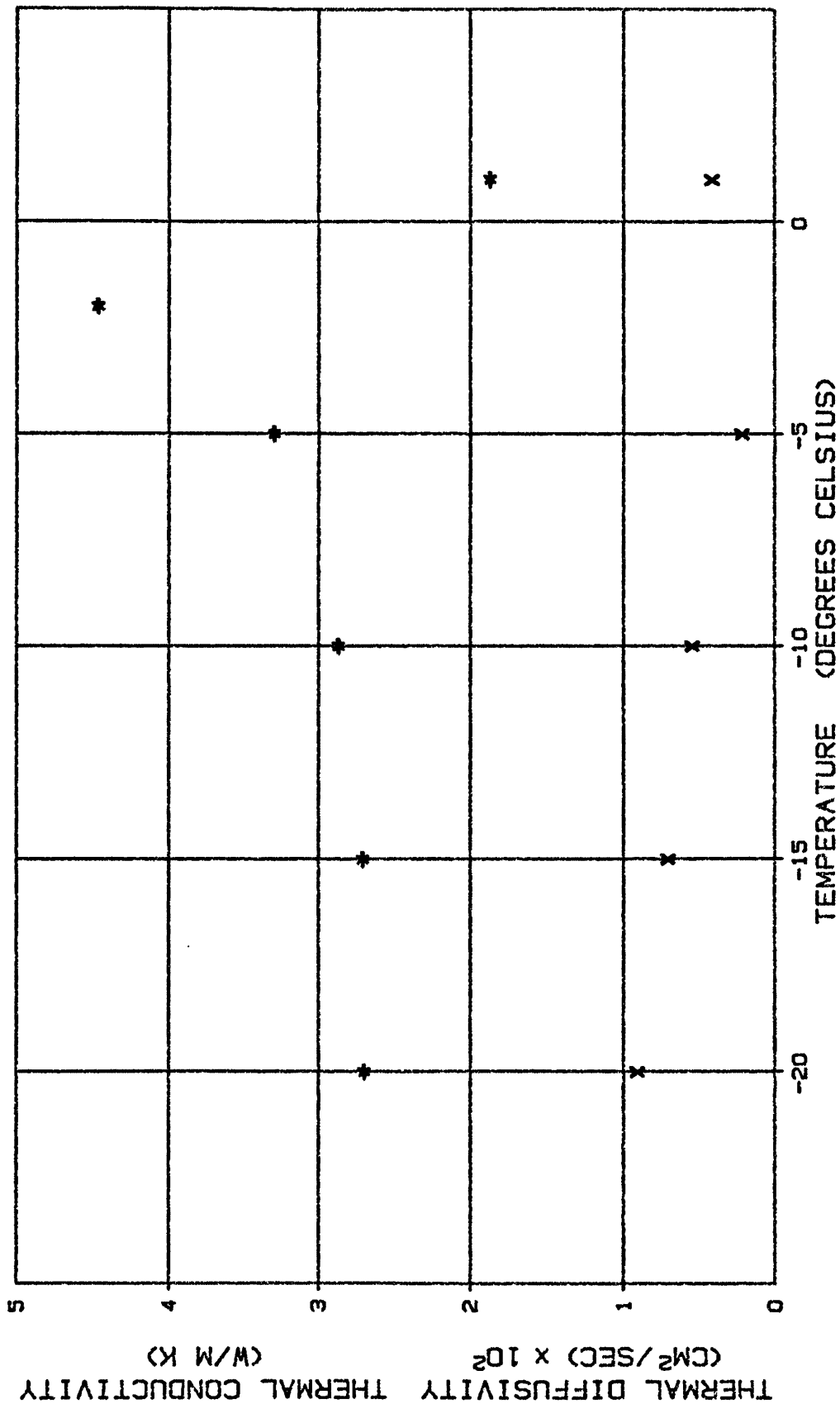
FIGURE 15

MEAN THERMAL PROPERTIES
FAIRBANKS SILT
15.0 PPT WATER
DRY DENSITY = 1.57 G/CM³   MOISTURE CONTENT = 27.22 %
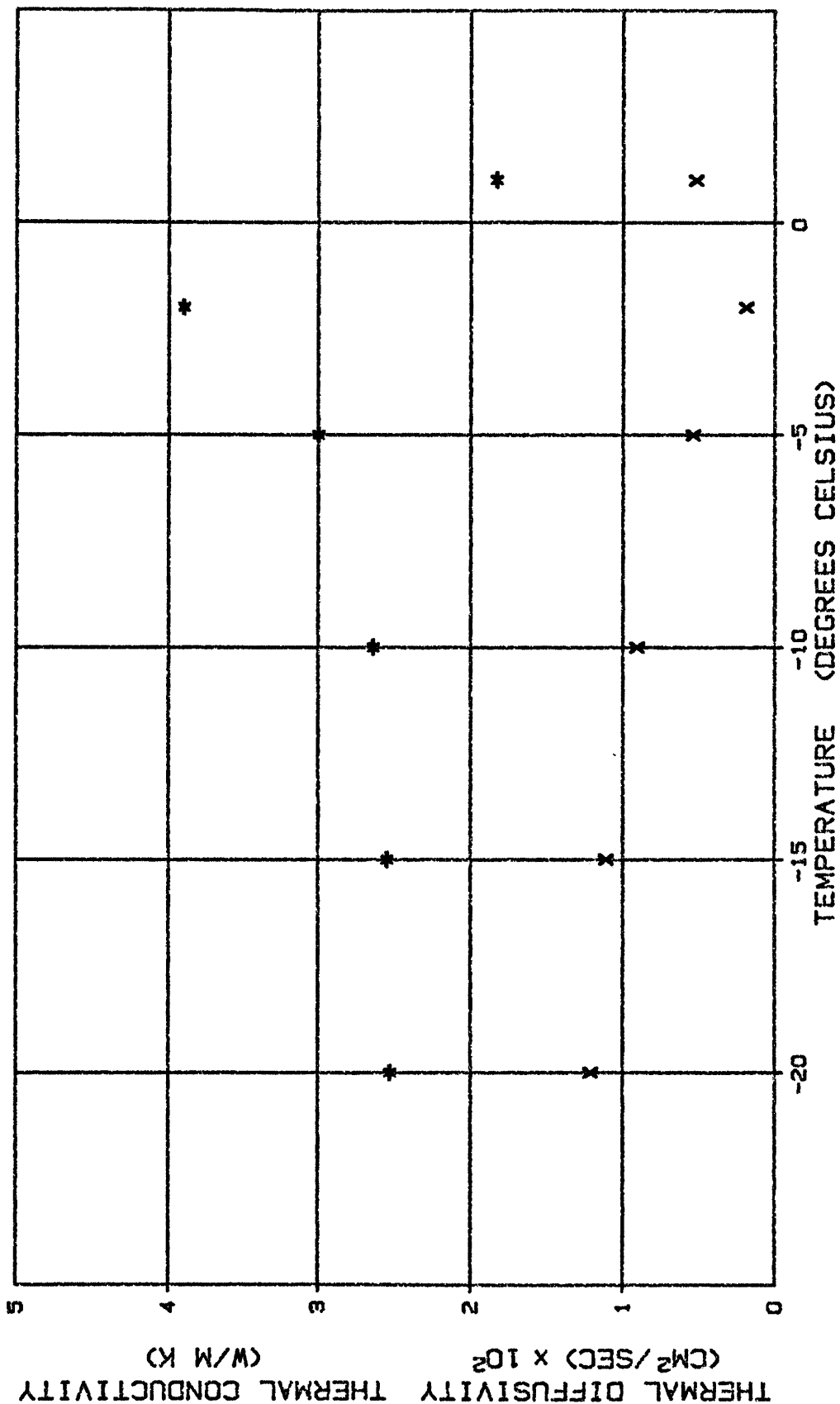
FIGURE 16

TEMPERATURE (DEGREES CELSIUS)

THERMAL CONDUCTIVITY (W/M K)

THERMAL DIFFUSIVITY (CM²/SEC) × 10⁵

MEAN THERMAL PROPERTIES
FAIRBANKS SILT
0.0 PPT WATER
DRY DENSITY = 1.61 G/CM³   MOISTURE CONTENT = 24.13 %

TEMPERATURE (DEGREES CELSIUS)
FIGURE 17

THERMAL CONDUCTIVITY (W/M K)
THERMAL DIFFUSIVITY (CM²/SEC) x 10²
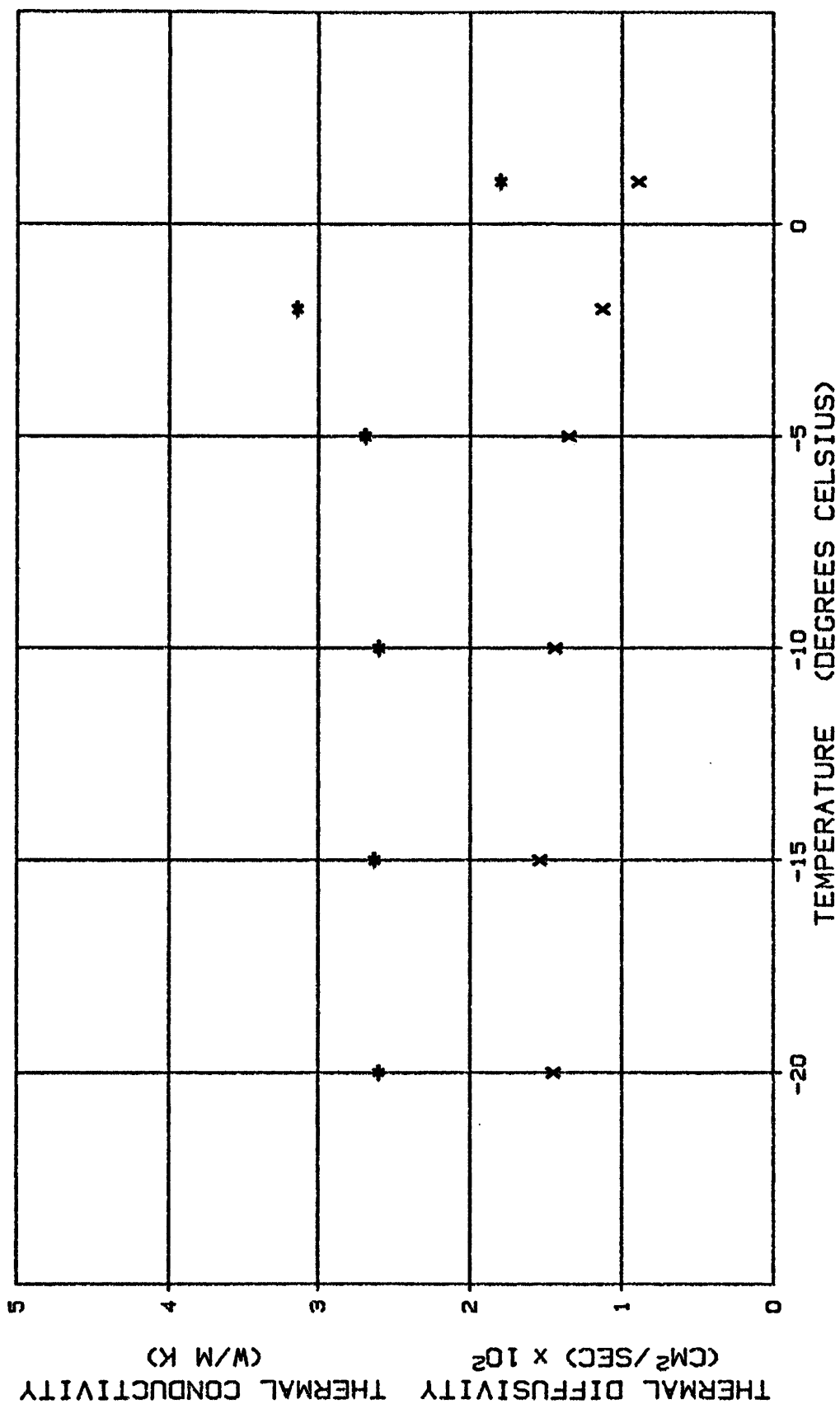
used for all three samples, as the data collection procedure had been finalized.

All but one of the values presented are based on the average of two tests. The first test run on the fresh water sample at +1°C did not produce satisfactory results. An incomplete phase change is the likely reason for this, as the second test gave adequate results.

Two problems were encountered with the saline water samples. First, no results could be found from the exterior thermocouple of the -2°C temperature level for the 30.1 PPT water sample because there was no measurable temperature rise. Then, for the 15.0 PPT water sample, no cooling diffusivity results were found at -2°C and the curve fits from the heating periods have low correlation coefficients. There was a very low temperature response for these tests, with maximum temperature rises of 0.066°C or less. These problems, for the saline water samples, were a result of the phase change of the sample.

B. Comparison of Results to the Predictive Methods

The five theoretical models described in Section II were used to predict the thermal conductivities of the three soils under the conditions tested. The results of these predictions are given below and compared to the experimentally determined values.

First, in Figure 18, a detailed example of the model results for one soil sample is given. This figure plots the

curves for the conductivity as calculated by each of the
five methods in relationship to the conductivities of the
soil constituents. This example is for Ottawa Sand (com-
posed of 100% quartz) saturated with 15.0 PPT water.

The five predictive methods give similar estimates for
the conductivities. In the frozen state, the difference
between the highest prediction (from DeVries Method) and the
lowest (from the method of Kunii-Smith) is only approxi-
mately 10% for the sand, and even less for the gravel and
silt. In the unfrozen state (above -0.8°C for the 15.0 PPT
water) the differences in the methods are greater, around
15%. The curves are nearly horizontal above the melting
point because neither the quartz nor water conductivities
vary significantly with temperature.

In the range between -5°C and the melting temperature,
the phase change region, a considerable change occurs in the
models. This is due to the melting of the soil, and the
considerable change in the conductivity of the pore fluid.
Significantly, this is the range where the most difficulties
were encountered with the experimental results.

Because the five methods give such close predictions
for the conductivities, an average of the five predictions
is used in the comparisons which follow. Farouki [1] con-
sidered the accuracy of the predictions to be within 25%, so
using an average of the methods does not result in any loss

RESULTS OF PREDICTIVE MODELS
DATA FOR OTTAWA SAND, 15.0 PPT WATER
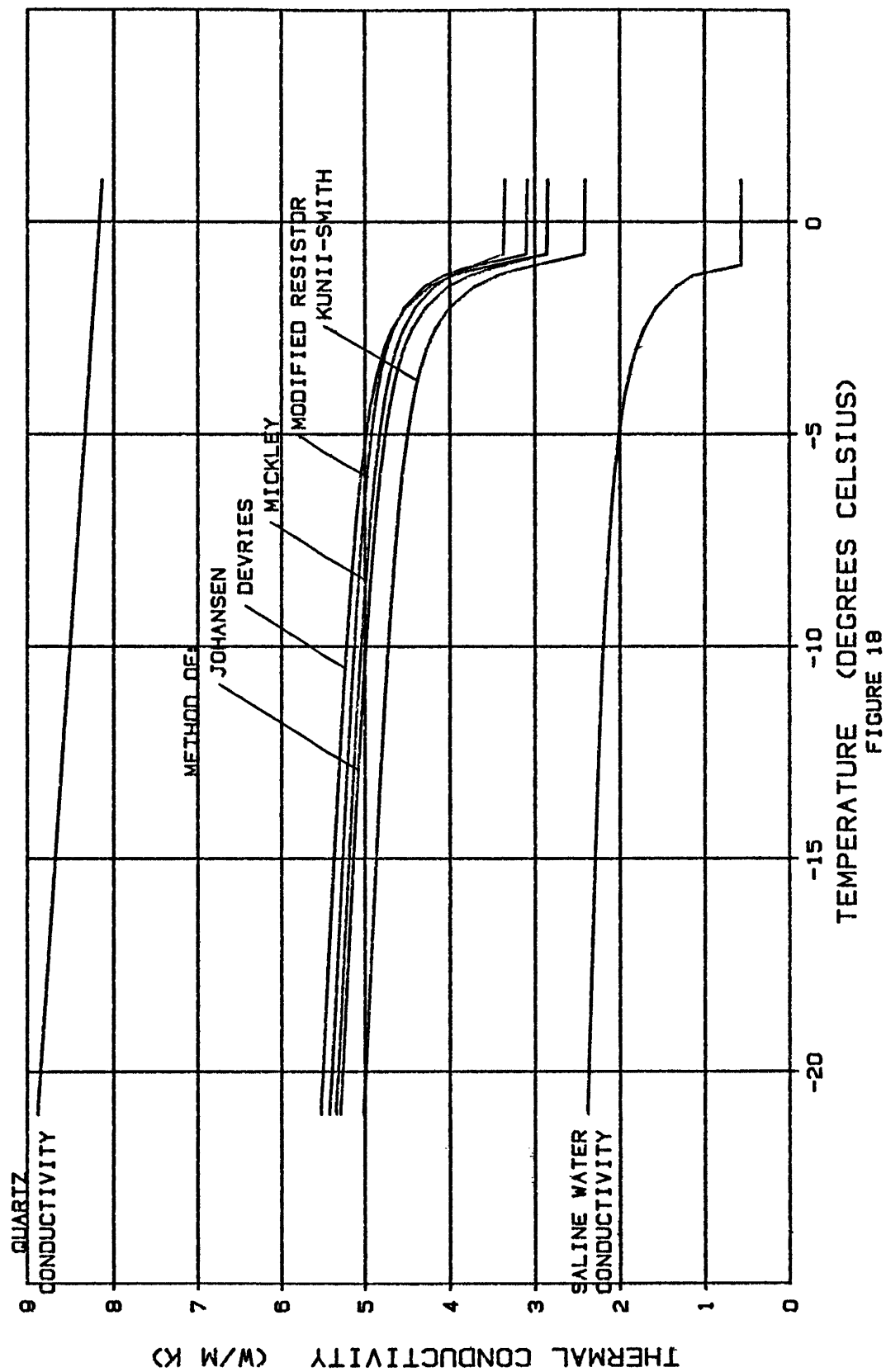
FIGURE 18

of generality, since the range of the predictions is less than their estimated accuracy.

The experimental results given previously are compared to the average of the predictive models for each of the soils in Figures 19, 20, and 21. The experimental values are listed with the predictions of the individual models at the test conditions, in Tables 5, 6, and 7.

In the coldest and warmest regions, -20°C to -10°C, and above the melting temperature, the difference shown in Figures 19, 20, and 21 for the conductivity as a function of salinity is small. For the sand and silt samples, the differences due to salinity are again less than the 25% margin of error allowed by Farouki for the predictive methods. For the gravel sample, the difference is larger, however this is due to other conditions, as noted below.

The phase change region again presents different values. The fresh water (0.0 PPT) curves are nearly linear in the entire range below the melting point of 0°C. This is due to the linear relationship between conductivity and temperature for ice. The drop occurs at 0°C because of the significant change in conductivity between ice and water. The saline soil conductivity curves decrease more slowly with temperature. This is most likely a result of the slow melting that occurs over a range of temperatures.

The experimental values shown in Figures 19, 20, and 21 for comparison with the models do not show the trends

EXPERIMENTAL DATA AND THEORETICAL PREDICTIONS
THERMAL CONDUCTIVITY DATA (W/M K)
OTTAWA SAND   QUARTZ CONTENT = 1.000

TEMPERATURE (DEG C)	UNFROZEN WATER	EXPERIMENTAL CONDUCTIVITY	METHOD OF: JOHANSEN	DEVRIES	MICKLEY	MODIFIED RESISTOR	KUNII-SMITH
SALINITY = 30.1 PPT		POROSITY = 0.395					
-20.0	0.0	4.750	5.168	5.403	5.228	5.312	4.893
-15.0	0.0	4.720	5.021	5.254	5.084	5.174	4.749
-10.0	0.0	4.990	4.831	5.063	4.902	5.003	4.561
-5.0	0.0	5.280	4.455	4.688	4.558	4.682	4.175
-2.0	0.0	6.450	3.282	3.399	3.638	3.593	2.894
0.0	0.0	8.130	2.848	2.844	3.355	3.089	2.401
SALINITY = 15.0 PPT		POROSITY = 0.394					
-20.0	0.0	4.850	5.256	5.486	5.309	5.380	4.986
-15.0	0.0	0.0	5.130	5.357	5.183	5.257	4.864
-10.0	0.0	4.790	4.984	5.209	5.040	5.120	4.721
-5.0	0.0	4.940	4.756	4.983	4.823	4.920	4.493
-2.0	0.0	6.410	4.283	4.514	4.403	4.530	4.001
0.0	0.0	8.560	2.852	2.848	3.359	3.092	2.406
SALINITY = 0.0 PPT		POROSITY = 0.389					
-20.0	0.0	5.250	5.368	5.592	5.412	5.469	5.112
-15.0	0.0	0.0	5.259	5.480	5.303	5.360	5.008
-10.0	0.0	4.840	5.151	5.368	5.194	5.251	4.904
-5.0	0.0	4.760	5.043	5.255	5.085	5.142	4.801
-2.0	0.0	4.890	4.977	5.188	5.020	5.077	4.738
0.0	0.0	5.460	2.888	2.879	3.390	3.121	2.448

IF EXPERIMENTAL CONDUCTIVITY = 0.0, NO DATA WAS FOUND

TABLE 5.

EXPERIMENTAL DATA AND THEORETICAL PREDICTIONS
THERMAL CONDUCTIVITY DATA (W/M K)
ARCTIC GRAVEL   QUARTZ CONTENT = 0.813

			METHOD OF:				
TEMPERATURE (DEG C)	UNFROZEN WATER	EXPERIMENTAL CONDUCTIVITY	JOHANSEN	DEVRIES	MICKLEY	MODIFIED RESISTOR	KUNII-SMITH
SALINITY = 30.1 PPT		POROSITY = 0.315					
-20.0	0.0	4.240	4.762	4.897	4.754	4.709	4.743
-15.0	0.0	0.0	4.647	4.783	4.640	4.605	4.631
-10.0	0.0	4.130	4.500	4.640	4.495	4.478	4.488
-5.0	0.0	4.410	4.212	4.364	4.215	4.243	4.210
-2.0	0.0	5.310	3.298	3.410	3.417	3.446	3.264
0.0	0.0	2.870	2.944	2.970	3.156	3.057	2.849
SALINITY = 15.0 PPT		POROSITY = 0.281					
-20.0	0.0	3.930	4.999	5.120	4.980	4.900	5.076
-15.0	0.0	3.890	4.899	5.020	4.880	4.807	4.978
-10.0	0.0	3.880	4.784	4.907	4.766	4.703	4.867
-5.0	0.0	4.010	4.613	4.742	4.595	4.557	4.707
-2.0	0.0	4.710	4.274	4.419	4.264	4.285	4.402
0.0	0.0	2.560	3.196	3.200	3.359	3.230	3.286
SALINITY = 0.0 PPT		POROSITY = 0.238					
-20.0	0.0	4.290	5.270	5.376	5.239	5.115	5.485
-15.0	0.0	4.290	5.180	5.285	5.150	5.030	5.394
-10.0	0.0	4.120	5.090	5.194	5.060	4.944	5.303
-5.0	0.0	3.940	4.999	5.102	4.969	4.857	5.212
-2.0	0.0	4.090	4.945	5.047	4.915	4.806	5.156
0.0	0.0	15.550	3.536	3.512	3.627	3.444	3.991

IF EXPERIMENTAL CONDUCTIVITY = 0.0, NO DATA WAS FOUND

TABLE 6.

EXPERIMENTAL DATA AND THEORETICAL PREDICTIONS
THERMAL CONDUCTIVITY DATA (W/M K)
FAIRBANKS SILT   QUARTZ CONTENT = 0.300

TEMPERATURE (DEG C)	UNFROZEN WATER	EXPERIMENTAL CONDUCTIVITY	METHOD OF: JOHANSEN	DEVRIES	MICKLEY	MODIFIED RESISTOR	KUNII-SMITH
SALINITY = 30.1 PPT		POROSITY = 0.405					
-20.0	0.0	2.700	2.744	2.754	2.743	2.588	2.685
-15.0	0.0	2.710	2.687	2.699	2.686	2.538	2.624
-10.0	0.0	2.870	2.605	2.622	2.605	2.467	2.537
-5.0	0.0	3.300	2.418	2.447	2.418	2.313	2.338
-2.0	0.0	4.470	1.777	1.858	1.798	1.826	1.674
0.0	0.0	1.870	1.542	1.628	1.592	1.639	1.427
SALINITY = 15.0 PPT		POROSITY = 0.396					
-20.0	0.0	2.530	2.797	2.805	2.797	2.635	2.745
-15.0	0.0	2.550	2.752	2.762	2.752	2.595	2.698
-10.0	0.0	2.640	2.696	2.708	2.696	2.545	2.638
-5.0	0.0	3.000	2.594	2.611	2.594	2.458	2.529
-2.0	0.0	3.900	2.348	2.383	2.347	2.258	2.268
0.0	0.0	1.830	1.566	1.651	1.613	1.661	1.459
SALINITY = 0.0 PPT		POROSITY = 0.380					
-20.0	0.0	2.600	2.851	2.857	2.850	2.684	2.808
-15.0	0.0	2.630	2.817	2.823	2.816	2.653	2.772
-10.0	0.0	2.600	2.782	2.790	2.782	2.621	2.736
-5.0	0.0	2.690	2.748	2.756	2.747	2.590	2.700
-2.0	0.0	3.140	2.727	2.736	2.726	2.571	2.678
0.0	0.0	1.800	1.609	1.693	1.652	1.699	1.517

IF EXPERIMENTAL CONDUCTIVITY = 0.0, NO DATA WAS FOUND

TABLE 7.

COMPARISON OF DATA TO PREDICTIVE MODELS
OTTAWA SAND

FIGURE 19

TEMPERATURE (DEGREES CELSIUS)

THERMAL CONDUCTIVITY (W/M K)

AVERAGE OF
PREDICTIVE MODELS
0.0
15.0
30.1

EXPERIMENTAL
CONDUCTIVITY
x 30.1 PPT
+ 15.0 PPT
o   0.0 PPT
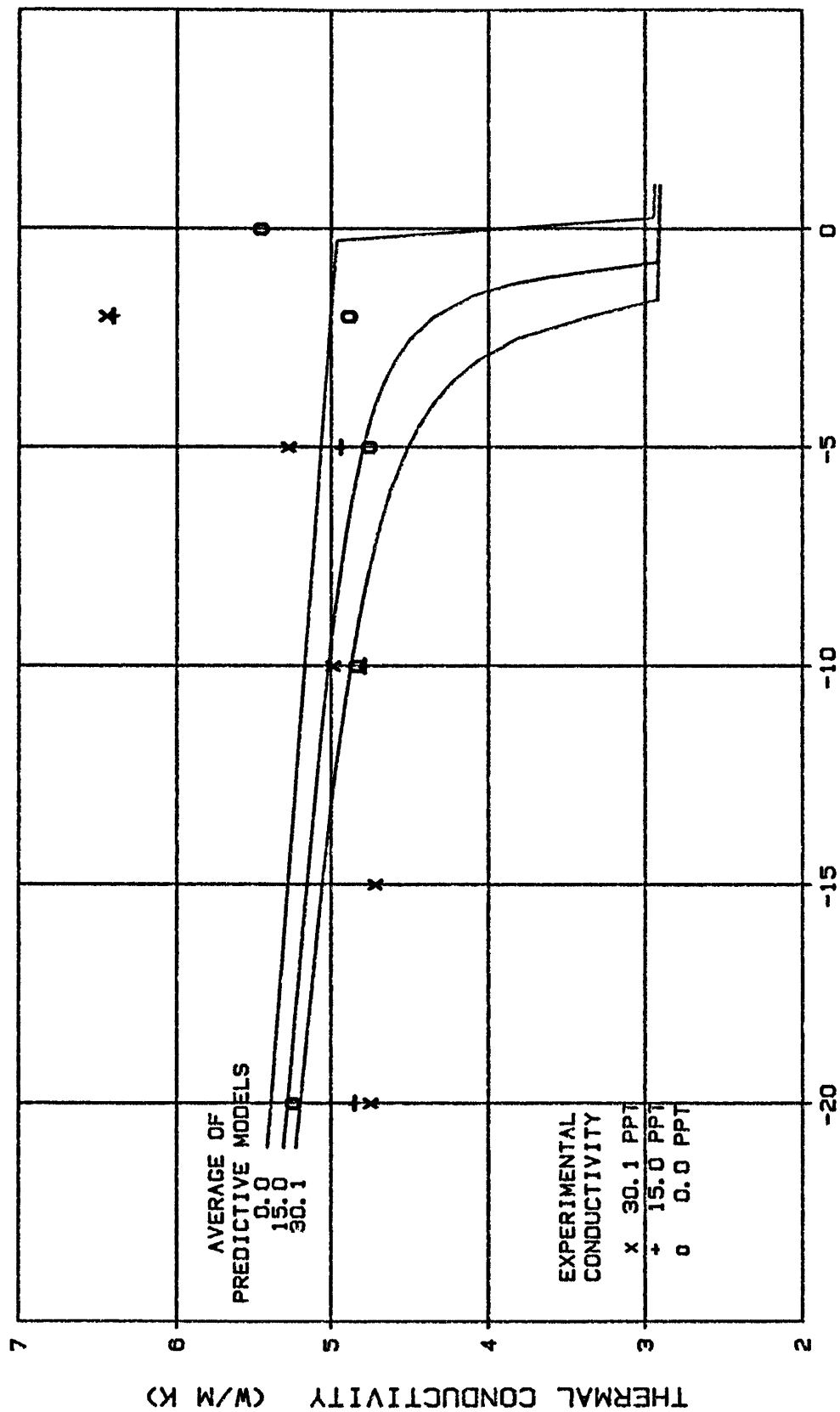
COMPARISON OF DATA TO PREDICTIVE MODELS
ARCTIC GRAVEL
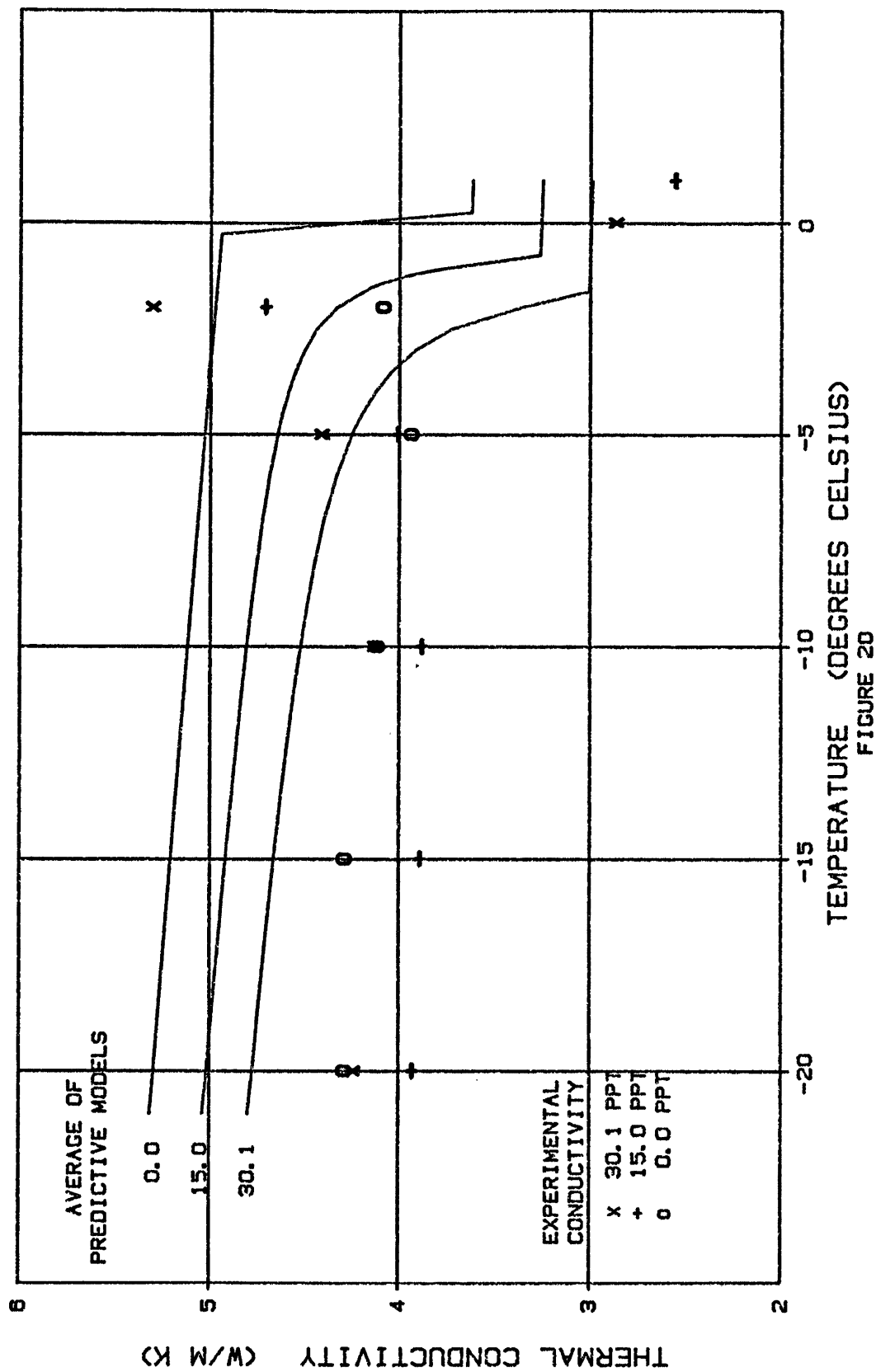
FIGURE 20

COMPARISON OF DATA TO PREDICTIVE MODELS
FAIRBANKS SILT
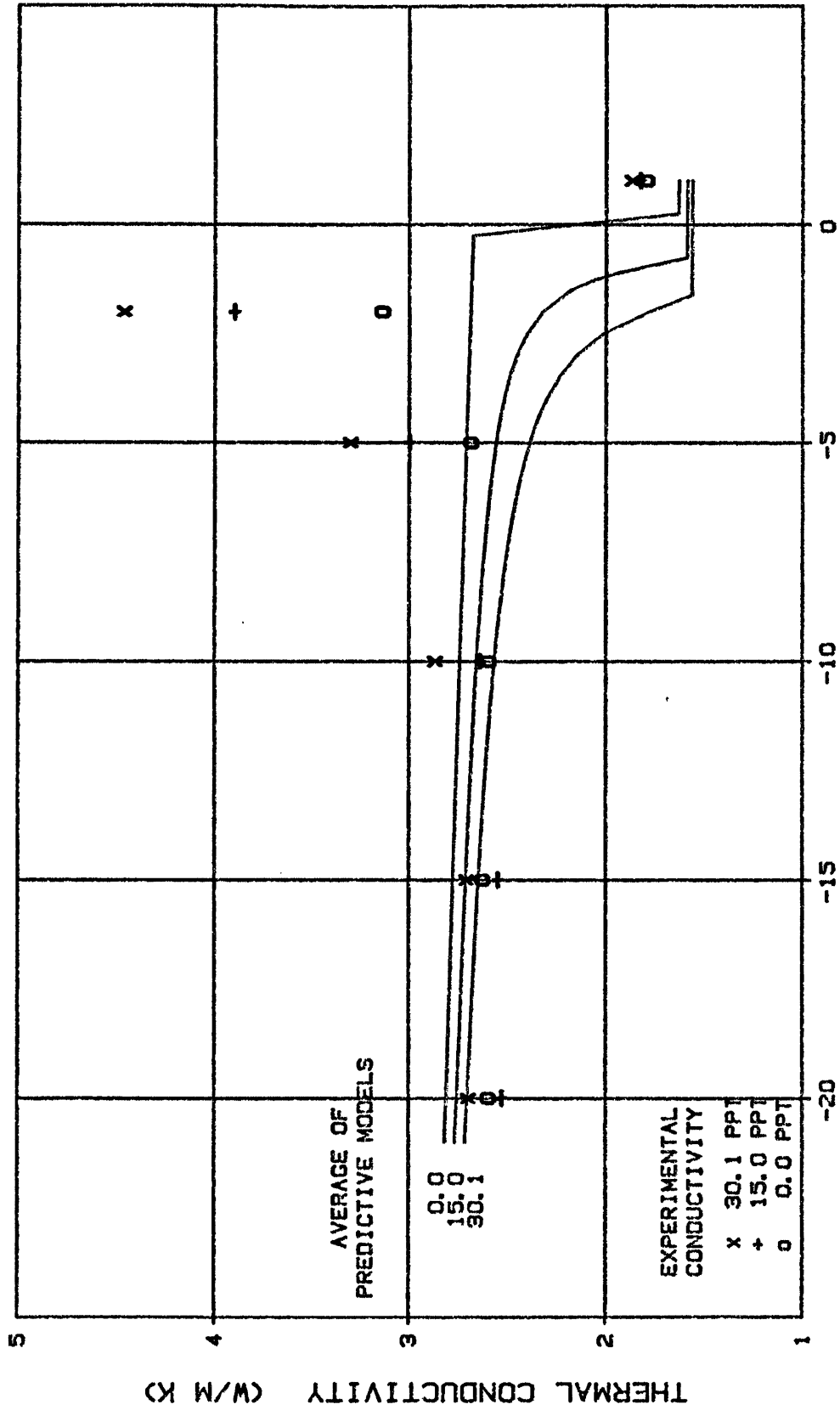
FIGURE 21

indicated by the predictions. Only a slight decrease is noticed in conductivity for increasing temperatures. In some cases, the conductivity increases with temperature, particularly in the phase change region. Then, in some cases, the sharp drop in conductivity across the melting point is seen. For a few of the samples, the conductivity at the point closest to the melting temperature increased dramatically and can not be shown on the figures. These values are listed in Tables 5, 6, and 7.

In the coldest regions, the predicted conductivities are either right at or slightly above the experimental values. The differences between the experimental and predicted conductivities in the sand and silt results are no greater than 10%, while the differences in the gravel results are around 25%. This indicates that the methods can be used to closely estimate the thermal conductivity in the colder regions.

The results in the phase change region behave erratically, hence no significant comparisons can be made. Above the melting point, where the experimental results are reasonable and shown, the models also give fairly close predictions to those results.

C. Discussion of Results

The results presented above seem to show no clear trends for the thermal properties as a function of the salinity of the porewater or as a function of the

temperature. No trends are evident as a result of the dif-
ficulties mentioned above. The data in the warmer regions
behave unexpectedly. The melting of the soil sample had a
significant impact on these results. Then, for the gravel
samples, the apparatus used to secure the exterior thermo-
couples in place led to some error.

With the use of saline water as the pore fluid, the
melting points of the soil samples are lowered below 0°C.
In fact, it appears that the phase change occurs, not at the
melting points of the waters, but in a range of temperatures
from as low as 5°C up to 0°C. This has caused the results
of the thermal properties measurements to behave erratically
in the warmer temperatures studied.

The thermal conductivity values determined at these
points are higher than expected. They are greater than the
conductivities at the colder temperatures and they are
significantly higher than the predicted averages. Two
factors could lead to these differences. First, the un-
frozen water content of the frozen soil plays an important
role in the thermal properties.

The Johansen model gives different conductivity values
if unfrozen water is taken into account. His predictive
model would give a lower conductivity when unfrozen water is
present, due to the lower conductivity of water than ice.
Other investigators, however, have noted that the conducti-
vity of the unfrozen water may actually be higher than that

of ice. This is detailed by Farouki [1] and could be pos-
sible because of an increase in the effectiveness of the
thermal contacts in the soil when unfrozen water is present.
If this is the case, then the conductivities in the phase
change region would increase, particularly with the use of
saline waters, which melt at lower temperatures and in a
wider range of temperatures.

The second, and more important, factor in the phase
change region is found in the experimental theory. The
equations developed in Section IV do not take into consider-
ation the effects of the latent heat of melting of the soil.
The thermal probe technique measures the temperature re-
sponse at two locations in the soil to determine the thermal
properties. The conductivity is found by measuring the heat
retained in the probe, as recorded by the temperature at the
interior thermocouple. Thus, by subtraction from the total
heat input (the probe power), the heat conducted into the
soil is determined. When melting is occurring, not only
will the heat be conducted into the soil by normal means,
but that used in the melting will be drawn away from the
probe. Less heat is retained by the probe giving a smaller
temperature rise at the interior thermocouple. Thus, the
theory on which the data reduction is based is violated and
higher values for the conductivity would be expected because
more heat is conducted away from the prove. This apparent
conductivity effect is seen in the results presented.

The temperature response data would also be expected to have more scatter, because of the isolated random melting. The statistical data seems to show this to be happening, as the correlation coefficients are lower and the standard deviations higher for the results in the phase change regions.

These regions are, as evidenced by the data, between -5°C and 0°C for the saline water samples and between -2°C and 0°C for the fresh water samples.

The temperature responses at the exterior thermocouples, which measure the thermal diffusivity, would also be effected by the phase change, although in different ways. Their measurements would be effected by the location in which they were imbedded. In a location experiencing a phase change, little or no temperature rise would be expected until the localized phase change has been completed. The length of time needed for this phase change to occur is unknown and would be variable. For several tests, an insignificant or non-existent temperature rise was found. These tests are given as 'no results' in Appendix B.

In a frozen area adjacent to an area which experiences a phase change, the temperature response would be affected. The temperature rise would be lower than expected if a portion of the heat normally conducted through the soil was diverted to the adjacent phase change. Thermocouples

located in either of these two regions would give inconsistent results.

This also appears in the results presented in Figures 9 through 17. The diffusivity values at -2°C and 0°C are erratic, sometimes lower than the diffusivity of the adjacent temperature levels, sometimes higher, and occasionally non-existent where no temperature rise was measured.

Because of these problems in the results of the tests in the phase change regions of the soils, the values for the thermal properties are not considered representative of the true thermal properties for that region. These ranges include the temperatures from -5°C to 0°C for the saline soils and from -2°C to 0°C for the fresh water samples. This conclusion was also reached by Penner [9] in his investigation using the thermal probe technique to find the thermal properties of soils. His tests included only fresh water samples, and he could find no representative data between -2°C and 0°C, the phase change region.

Two exceptions to the above conclusions are for two of the gravel samples. First, the results at 0°C for the 30.1 PPT water sample appear to be in line with the expected values. Secondly, the +1°C result for the fresh water gravel sample is unrealistically high. It is possible that complete melting did not occur in this sample.

The difficulties encountered with the exterior thermocouple results of the gravel tests were caused by the

composition of that soil. The diffusivity is found from Equation 40, using the coefficient of the curve fits. The equation,

$$\alpha = \frac{r^2}{4B}, \tag{40}$$

uses the coefficient B of the curve fit and the radius r, the distance from the center of the probe to the measuring junction of the thermocouple. Any inaccuracy in the measurement of the distance r, which was found immediately before a sample was prepared, would have a significant effect on the diffusivity value, owing to the power of 2 in Equation 40. The individual results of two of the Arctic Gravel tests seem to show just this type of error.

The Arctic Gravel samples contained gravel up to 3/4" in size. This particle size was greater than the distances between the thermal probe and the plexiglas tubes used to locate the exterior thermocouples (see Figure 4). A large piece of gravel becoming wedged between the probe and the tube could cause the tube to be bent, dislocating the thermocouple from its measured location. Care was taken to see that this problem might be avoided, but the soil packing used to achieve the high dry densities desired allowed only a visual inspection of the soil surface. During the subsequent saturation and during the expansion of the sample during freezing, no controls whatsoever were available to prevent a dislocation of the gravel.

If a small deflection of thermocouple, caused by the procedure used, of just 1 millimeter (or approximately 10% of its distance away from the probe) occurred, the calculated diffusivity could be up to 21% higher than the actual value if measured correctly. Thus, the square of the radius has a significant effect, and only a 2 to 3 mm dislocation of the thermocouple could cause a 50% error in deriving the diffusivity. This is the effect noted in Figures 13 and 14 for the 15.0 PPT and 0.0 PPT gravel samples. This problem was not apparent in either the 30.1 PPT gravel sample or in the sand or silt samples, leading to the conclusion that the composition of the gravel and the packing used in the preparation caused the problem. The average of the near and far thermocouple diffusivities is used as the representative value.

After removing the results in the phase change region because they are not representative, only four and sometimes only three satisfactory conductivity and diffusivity values remain for each sample. This is such a small number of results, that no correlations relating the thermal properties of the soils as a function of either salinity or temperature are given. The results do not show any trends, as expected from the results of predictive models. The conductivity should decrease with increasing temperature. This has been found by previous investigators, and the theoretical models represent this. However, the trend of the

experimental data found here is flat, at best, and sometimes increasing with temperature. Since so few results (2 or 3) are given for the range of -20°C to -10°C, no trend should be expected to be found after allowing for any experimental errors. The properties could reasonably be expected to be determined within about 25% of their actual values, as that range would be sufficient for most practical applications. Since the variations found in the conductivity over the 10°C range are typically 5% or less and 10% or less over the range of porewater salinities, no adequate correlations can, or should, be found.

The trends in the diffusivity data are more apparent, in some cases varying by 40-50% over the 10°C range and up to 100% over the three salinities. However, because of the location problem and the less consistent curve fits found, these results are considered less accurate than the conductivity values. Thus, more variation is expected, and found, especially considering the small amount of data.

It was desired to study only the effects of salinity and temperature on the thermal properties in this work. Fully saturated samples and dry densities as close together as possible for the three samples of each soil were desired. Consistent soil specimens were used to achieve similar soil compositions, especially in regards to the quartz content. Thus the effects of three other soil parameters, the dry density, the percent of full saturation, and the quartz

content were not evaluated. However, their effects will be briefly mentioned.

The dry density gives a measure of the amount of soil solids in the sample. Higher dry densities will yield lower porosities (less void space) and hence less water in the sample. Since the soil solids have a higher conductivity than water, the dry density would have a significant effect on the thermal properties. In this work, for the sand and silt samples, very close dry densities were produced for all three samples. However, the densities obtained in the gravel samples were not quite as close, varying by about 10%. The effects of this show up dramatically in the results of the predictive methods. In Figures 19 and 21, the averages of the predictive models for the three salinities used are very close. The curves in Figure 20 are much farther apart. The main reason is the difference in the porosity, n, which is used directly in the conductivity calculations and is based entirely on the dry density of the soil. The relationship is given in the discussion of the soil conditions above.

The percent of full saturation dramatically effects the conductivity values. The conductivity of dry soils is approximately an order of magnitude less than the conductivity of fully saturated soils. Inbody [4] considers the evaluation of the thermal properties of dry soils. Johansen [5] relates the conductivity of dry soil as a logarithmic

function between the two extremes of dry and fully saturated soil.

The effects of the quartz content of the soil are also quite dramatic. As previously discussed, the conductivity of the soil solids is a function of the quartz content, since quartz has such a high conductivity in relation to the other soil components. A good estimate of the quartz content of the soil is necessary to use the predictive models. The results shown for the models in Figures 19 through 21 use the quartz content as discussed in Section III.F. above. The values used for the sand and silt show close correspondence to the experimental data. However, the results for the gravel from the predictive methods are higher than the experimental results. This could be, and likely is, a result of using an inaccurate value for the quartz content. The average value determined by EPR of 81.3% for the gravel may vary from the actual quartz contents of the samples used in the tests. This would account for the larger difference between the experimental values and the predicted values.

While the effects of these parameters were not studied, it appears that the thermal properties have more of a dependence on these three parameters than on the salinities or temperatures studied in this work. However, no definite conclusions can be drawn on these effects from the results presented here.

VI. SUMMARY AND CONCLUSION

The need to know the thermal properties of frozen saline soils is based on the ability to predict the thermal effects on the soil of projects undertaken in Arctic regions. In such projects as the construction of offshore ice-gravel islands, the exact conditions of the frozen soil, the salinity of the water, the dry density and composition of the soil, among others, will probably not be known a priori. Therefore, since the contribution of many factors affect the thermal properties, even the use of the theoretical predictive methods might be precluded. From the results presented above and the comparison to the models, the contributions from the soil conditions studied in this work are small, indeed almost insignificant in relation to the experimental error.

Based on the representative results and the discussion given above, the most appropriate way in which to view the thermal properties is not as a function of the porewater salinity and temperature, but as constant values within the ranges of the parameters studied. There should be no physical problems associated with the use of such constant values because the conditions of the soils to be used will not be known well enough to justify more than a range of error of less than about twenty five percent. The results found in this work are within these bounds.

The constant values recommended for use are found as the approximate averages of the results for the three soils in the range of -20°C to -10°C for the three porewater salinities. These values, for fully saturated soils, are

Ottawa Sand, 100% Quartz

k = 4.9 W/m k

α = 0.019 cm^2/sec

Arctic Gravel, 81.3% Quartz

k = 4.1 W/m k

α = 0.019 cm^2/sec

Fairbanks Silt, 30% Quartz

k = 2.65 W/m k

α = 0.011 cm^2/sec

Any of the five predictive methods could be used to determine an acceptable value for the conductivity, however due to their complexity and cumbersome use, the constant values above give just as reasonable results, with no calculations required. If the dry density and quartz content should vary significantly from the values for these soils studied, the predictive methods can be used in place of the above values for use in engineering applications.

Should further work be undertaken in the study of the thermal properties of frozen soils, several recommendations can be made. First, this application of the thermal probe

technique is not applicable in the phase change region. The theory on which the data reduction technique is based is violated by not taking into consideration the latent heat effects, which are significant factors in the phase change region. Further study into this area is merited, although satisfactory results have not been seen in the literature and may not be possible given the unknown effects of the phase change.

A second recommendation would be to gather data in a wider range of temperatures than -20°C to -10°C and at smaller intervals than 5°C. A trend in the properties as a function of temperature might be found under these conditions.

The gathering of more data would necessitate the third recommendation of automating the experiment. The data collected in this work for ninety-six individual tests was simply overwhelming. An automated data recording system would allow immediate results and analysis of the data.

Finally, the effects of other parameters can be studied extensively. Only the effects of salinity and temperature were evaluated in this work. The apparently more important effects of the dry density and percent of full saturation were not considered.

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APPENDIX A: THE MODEL PROGRAM

The FORTRAN listing of the computer program used to evaluate the thermal conductivity by the five predictive methods described in Section II is given below. The application of the program is straight forward. The subroutine ZRPOLY(XCOF, M, ROOTR, IEF) called in Mickley's Method is a polynomial solving routine.

After the FORTRAN listing, a format sheet for the data input is provided with an example for Ottawa Sand.

```
C****************************************************************
C       THERMAL PROPERTIES OF FROZEN SALINE SOIL
C           THEORETICAL CONDUCTIVITY MODELS
C          CALCULATION AND PRINTOUT OF PREDICTIONS
C****************************************************************

        IMPLICIT REAL (A-H,K,O-Z)
        COMPLEX Z(3)
        EQUIVALENCE(Z(1),ROOTR(1))
        DIMENSION K(6,3,6),KI(3,6),KS(3,6),KW(3,6),KQ(6),
       1 WU(3,6),S(3),T(3,6),NT(3),SG(3),DRYDEN(3),G(3),
       2 THETA(2),PHI(2),XCOF(4),ROOTR(6),POR(3)

        DATA SG/2.65,2.6,2.6/

C     Read in the inputs

        READ(5,1010) IST,Q
C IST=1: Ottawa Sand  IST=2: Arctic Gravel IST=3: Fairbanks

C     Read in the salinities, number of temps, dry density

        DO 5 IS=1,3
          READ(5,1030) S(IS),NT(IS),DRYDEN(IS)
      5 CONTINUE

C     Read in the temperatures, experimental conductivities
C        and unfrozen water content

        DO 10 IS=1,3
          N=NT(IS)

          DO 10 IT=1,N
            READ(5,1050) T(IS,IT),K(1,IS,IT),WU(IS,IT)
     10 CONTINUE


        DO 20 IS=1,3
        DO 20 IT=1,6
        DO 20 IM=2,6
     20 K(IM,IS,IT) = 0.0

C       Calculate the conductivity of salt ice and salt water
        CALL SEAICE(S,T,KI,KW)

C       Do calculations for each salinity
        DO 700 IS=1,3
          N=NT(IS)
        DO 700 IT=1,N
```

```
C          Calculate remaining model parameters

      POR(IS) = 1.0 - DRYDEN(IS)/SG(IST)
      OMP = 1.0 - POR(IS)
      DO 40 ITI=1,6
        KQ(ITI) = 8.163926282 - 0.033774038*T(IS,ITI)
        KS(IS,ITI) = (KQ(ITI)**Q)*(2.**(1.-Q))
   40 CONTINUE




C******************************************************************
C     THE PREDICTION METHODS
C******************************************************************


C          JOHANSEN METHOD   IM=2
C          --------------------

  200 K(2,IS,IT) = (KS(IS,IT)**OMP)*(KI(IS,IT)**(POR(IS)-
     C WU(IS,IT))) * (KW(IS,IT)**WU(IS,IT))




C          DEVRIES METHOD   IM=3
C          --------------------

C          Set the constants

  300 FS = 0.0
      G(1) = 0.125
      G(2) = 0.125
      G(3) = 0.75

C          Sum and calculate for the constant F

      DO 310 I=1,3
  310    FS=FS + 1./(1.+(KS(IS,IT)/KI(IS,IT)-1.)*G(I))

      F= FS/3.

      K(3,IS,IT)=(POR(IS)*KI(IS,IT) + F*OMP*KS(IS,IT))/
     2  (POR(IS) + F*OMP)
```

```
C              MICKLEYS METHOD   IM = 4
C              ----------------------------

C      Set the coefficients for the poly. solving subroutine

  400 XCOF(1) = 2.0
      XCOF(2) = -3.0
      XCOF(3) = 0.0
      XCOF(4) = POR(IS)
      M=3

C         Call the IMSL subroutine ZRPOLY

      CALL ZRPOLY (XCOF,M,ROOTR,IER)

C         Check for any errors
C           IER = 0     no errors
C               = 129   degree of equation > 100
C               = 130   leading coefficient = 0
C               = 131   found fewer than M zeros.
C                       (rest set to infinity)

      IF(IER.EQ.0) GOTO  410
      WRITE(6,1080) IER
      GOTO 500


C         Eliminate the roots greater than 1 and less than 0

  410 DO 420 IR=1,5,2
      IF (ROOTR(IR).GT.1. .OR. ROOTR(IR).LT.0.) GO TO 420
         A= ROOTR(IR)
  420 CONTINUE


      K(4,IS,IT) = KI(IS,IT)*A*A + KS(IS,IT)*(1.-A)*(1.-A)
      C+KS(IS,IT)*KI(IS,IT)*(2.*A-2.*A*A)/(KS(IS,IT)*A+
      C KI(IS,IT)*(1.-A))



C         MODIFIED RESISTOR METHOD   IM= 5
C         --------------------------------

  500 PORP = POR(IS) - 0.03
      OMPORP = 1.-POR(IS)


      K(5,IS,IT) = PORP*KI(IS,IT) + OMPORP/
      C(OMPORP/(OMPORP*KS(IS,IT)) + 0.03/(OMPORP*KI(IS,IT)))
```

```
C            KUNII-SMITH METHOD    IM=6
C            -----------------------------

  600 KR = KS(IS,IT)/KI(IS,IT)
      KRMO = KR - 1.

C         Find the angles Theta

      THETA(1) = ARSIN(SQRT(1./1.5))
      THETA(2) = ARSIN(SQRT(1./6.9))

C         Calculate the cosine and sine of angles Theta

      DO 610 ITH = 1,2
        COSTH = COS(THETA(ITH))
        OMC = 1.-COSTH
        SINTH = SIN(THETA(ITH))

C         Find the angles Phi

  610 PHI(ITH) = ((KRMO/KR)*SINTH)**2./(2.*
     C (ALOG(KR - KRMO*COSTH)-(KRMO/KR)*OMC))   - 2./(3.*KR)

C         Find the angle Phi used in the calculation

      PHIU = PHI(2)+(POR(IS)-0.259)*(PHI(1)-PHI(2))/0.217


      K(6,IS,IT)= KI(IS,IT)*(POR(IS)+OMP/(PHIU+2.*KI(IS,IT)
     C/(3.*KS(IS,IT))))


  700 CONTINUE

C***********************************************************
C        NOW PRINTOUT THE RESULTS
C***********************************************************
      WRITE(6,1100)
      IF(IST.NE.1) GOTO 720
      WRITE(6,1102) Q
      GO TO 750
  720 IF (IST.NE.2) GO TO 730
      WRITE(6,1104) Q
      GO TO 750
  730 IF (IST.NE.3) GO TO 740
      WRITE(6,1106) Q
      GO TO 750
  740 WRITE(6,1108) Q
```

```
  750 WRITE(6,1110)
      DO 800 IS=1,3
        WRITE(6,1115) S(IS),POR(IS)
        WRITE(6,1120) T(IS,1),WU(IS,1),(K(IM,IS,1),IM=1,6)
        N=NT(IS)
        DO 800 IT=2,N
      WRITE(6,1130) T(IS,IT),WU(IS,IT),(K(IM,IS,IT),IM=1,6)
  800 CONTINUE
      WRITE(6,1140)


C*****************************************
C       FORMAT STATEMENTS
C*****************************************



 1010 FORMAT(I1,F7.3)


 1030 FORMAT(F6.3,I1,F7.4)


 1050 FORMAT(3F7.3)

 1080 FORMAT(' ERROR IN THE ZRPOLY SUBROUTINE.   IER = ',I3)


 1100 FORMAT('1'/'0'/'0'/'0'/29X,'EXPERIMENTAL DATA AND
     1THEORETICAL PREDICTIONS'/35X,'THERMAL CONDUCTIVITY
     2DATA (W/M K)')

 1102 FORMAT(32X,'OTTAWA SAND      QUARTZ CONTENT = ',F5.3)
 1104 FORMAT(32X,'ARCTIC GRAVEL    QUARTZ CONTENT = ',F5.3)
 1106 FORMAT(32X,'FAIRBANKS SILT   QUARTZ CONTENT = ',F5.3)
 1108 FORMAT(32X,'UNIDENTIFIED     QUARTZ CONTENT = ',F5.3)

 1110 FORMAT(/46X,'METHOD OF:'/10X,'TEMPERATURE   UNFROZEN
     1EXPERIMENTAL JOHANSEN   DEVRIES    MICKLEY   MODIFIED
     2KUNII-'/11X,' (DEG C)      WATER    CONDUCTIVITY',33X,
     3'RESISTOR    SMITH')

 1115 FORMAT(/8X,'SALINITY =',F5.1,' PPT   POROSITY = '
     2,F5.3)
 1120 FORMAT(13X,F5.1,7X,F4.2,6X,F5.3,6X,5(F6.3,5X))
 1130 FORMAT(13X,F5.1,7X,F4.2,6X,F5.3,6X,5(F6.3,5X))

 1140 FORMAT(//27X,'IF EXPERIMENTAL CONDUCTIVITY = 0.0,
     2NO DATA WAS FOUND')

      STOP
      END
```

```
C*************************************************************
C          SUBROUTINE SEAICE
C*************************************************************

           SUBROUTINE SEAICE(S,T,KI,KW)
           IMPLICIT REAL (A-H,K,O-Z)
           REAL MB
           DIMENSION T(3,6),KI(3,6),S(3),KW(3,6)


           DO 100 IS=1,3
           DO 50 IT=1,6
             WMT = -54.11*S(IS)/1000.
             KW(IS,IT) = 0.566
             IF (T(IS,IT).LT.WMT) GO TO 20
             KI(IS,IT) = KW(IS,IT)
             GO TO 50
    20       IF (S(IS).NE.0) GO TO 30
             MB = 0.0
             SB = 0.0
             GO TO 40
    30       MB = 0.001*S(IS)*(1.-54.11/T(IS,IT))
             SB = S(IS)/MB
    40       KICE = 0.00535 - 0.00002568*T(IS,IT)
             KB = 0.00125 + 0.000030*T(IS,IT) + 0.00000014*
        2    T(IS,IT)*T(IS,IT)
             RHOI = 0.9168 - 0.00014*T(IS,IT)
             RHOB = 1.0 + 0.0008*SB
             RHO = RHOI/RHOB
             KI(IS,IT) = (KICE*(1.-(1.-RHO*KB/KICE)*MB)/
        C    (1.-(1.-RHO)*MB))/0.00238846
    50 CONTINUE

   100 CONTINUE


           RETURN
           END
```

The format for the input is as follows. The blank lines
between the three data sections are for clarity in this
example only. They are not included in the datafile.
See the example on the next page.

IST Q   Soil type,I1;Fractional Quartz content,F7.3

S(1) NT(1) DD(1)   The water salinity, F7.3;
S(2) NT(2) DD(2)   number of temperature levels;I1
S(3) NT(3) DD(3)   and sample dry density, F7.4

T(1,1) K(1,1) WU(1,1)
T(1,2) X.XXX   X.XXX   The temperatures followed by
X.XXX   X.XXX   X.XXX   the experimental conductivity
X.XXX   X.XXX   X.XXX   and unfrozen water content at
T(1,N) X.XXX   X.XXX   that temperature
T(2,1) K(2,1) WU(2,1)
X.XXX   X.XXX   X.XXX   all F7.3
X.XXX   X.XXX   X.XXX
X.XXX   X.XXX   X.XXX
X.XXX   X.XXX   X.XXX
T(2,N) X.XXX   X.XXX
T(3,1) K(3,1) WU(3,1)
X.XXX   X.XXX   X.XXX
X.XXX   X.XXX   X.XXX
X.XXX   X.XXX   X.XXX
T(3,N) X.XXX   X.XXX

The example of the data input file below is for Ottawa Sand (IST = 1,Q = 1.0) with 6 temperature levels (the maximum allowed) for each of the three (must be exactly 3) porewater salinities. The temperatures are then listed with the experimental conductivities and the unfrozen water contents (all 0.0).

```
1 1.000
30.1   6 1.6044
15.0   6 1.6059
 0.0   6 1.6182
-20.0    4.750    0.0
-15.0    4.720    0.0
-10.0    4.990    0.0
-5.0     4.940    0.0
-2.0     6.450    0.0
0.0      0.0      0.0
-20.0    4.850    0.0
-15.0    0.0      0.0
-10.0    4.791    0.0
-5.0     4.939    0.0
-2.0     6.414    0.0
0.0      0.0      0.0
-20.0    5.245    0.0
-15.0    0.0      0.0
-10.0    4.839    0.0
-5.0     4.761    0.0
-2.0     4.738    0.0
0.0      5.458    0.0
```

APPENDIX B: RESULTS OF THE INDIVIDUAL TESTS

The results given below for the individual tests are those calculated by the data reduction programs.   In each case, the test number refers to the sample parameters.   The test number is given as:

$$crr.sstt$$

where   c = soil code number

   c = (blank) — Ottawa Sand

   c = 1   — Arctic Gravel

   c = 2   — Fairbanks Silt

   rr = run number on sample

   1 < rr < 15

   ss = salinity (in PPT) of sample

   ss = 00 — fresh water

   ss = 15 — 15.0 PPT water

   ss = 30 — 30.1 PPT water

   tt = nominal test temperature (absolute value)

   tt = 20 — −20°C nominal temperature

   •

   •

   •

   tt = 00 — 0°C <u>or</u> +1°C normal temperature

For each test, the data and results are given in four tables. Those tables postnoted with 'a' give the experimental data (the line heat source strength, the initial measured test temperature, and the maximum temperature rise) at the interior thermocouple. Tables postnoted with 'b' give the time of heating and total test time, along with the determined thermal conductivity (0.01 W/cm K = 1.0 W/m K) and the statistical results for the heating and cooling periods, as shown.

Tables postnoted with 'c' and 'd' give similar results for the exterior thermocouple. However instead of conductivity, the thermal diffusivity is listed and instead of the line heat source strength, the radius to the exterior thermocouple from the center of the probe is given.

The data and results for the sand are given in Table B.1 pages 105 through 116. The listings for the gravel are in Table B.2 on pages 116 through 131 and for the silt in Table B.3 on pages 133 through 148. Within each table lines delineate salinity levels.

TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
1.3020	0.052830	-18.86	0.431735
3.3015	0.053589	-14.27	0.441926
6.3010	0.053520	-8.93	0.539474
7.3005	0.053212	-4.02	0.392435
8.3002	0.053376	-1.28	0.335704
10.3000	0.053412	-0.06	0.310110
1.1520	0.053068	-20.47	0.428641
2.1520	0.053327	-20.54	0.540492
3.1510	0.053284	-9.75	0.447339
4.1510	0.053465	-9.88	0.465342

EXPERIMENTAL DATA AND RESULTS
OTTAWA SAND - INTERIOR PROBE DATA

TABLE B.1a

TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - INTERIOR PROBE RESULTS			
1.3020	180	0.048028	0.003837	0.998772
	360	0.046890	0.005302	0.996530
3.3015	180	0.047508	0.005000	0.998011
	360	0.046981	0.004993	0.996930
6.3010	600	0.049585	0.004992	0.998784
	1200	0.050313	0.006375	0.997223
7.3005	180	0.049431	0.008580	0.994727
	360	0.056241	0.007001	0.992627
8.3002	180	0.061713	0.006712	0.993941
	360	0.067190	0.007350	0.985350
10.3000	180	0.068661	0.008249	0.988775
	360	0.093855	0.004294	0.988736
1.1520	180	0.049059	0.005093	0.998544
	360	0.049385	0.005971	0.997072
2.1520	480	0.047329	0.005112	0.998814
	960	0.048214	0.004192	0.998647
3.1510	180	0.047643	0.004704	0.998838
	360	0.047677	0.005982	0.997213
4.1510	300	0.048111	0.003463	0.999215
	600	0.048191	0.005833	0.996829
TABLE B.1b				

	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
1.3020	0.635	-19.66	0.233581
3.3015	0.635	-14.89	0.241818
6.3010	0.635	-10.07	0.323241
7.3005	0.635	-5.01	0.156551
8.3002	0.635	-2.18	0.076347
10.3000	0.635	-1.14	0.034662
1.1520	0.635	-19.86	0.276902
2.1520	0.635	-19.92	0.377597
3.1510	0.635	-9.95	0.267637
4.1510	0.635	-10.06	0.316957
	TABLE B.3c		

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS **OTTAWA SAND − EXTERIOR PROBE RESULTS**				
1.3020	180	0.014001	0.002271	0.999310
	360	0.017744	0.003563	0.997032
3.3015	180	0.013634	0.002639	0.999099
	360	0.014724	0.002840	0.998064
6.3010	600	0.010315	0.002814	0.999486
	1200	0.006349	0.012204	0.981842
7.3005	180	0.005033	0.002440	0.998620
	360	0.006292	0.005132	0.988982
8.3002	180	0.002811	0.003364	0.976950
	360	0.001142	0.003370	0.858012
10.3000	180	0.001300	0.002478	0.975207
	360	0.000933	0.002434	0.000000
1.1520	180	0.029714	0.003182	0.999126
	360	0.024319	0.003155	0.998505
2.1520	480	0.026878	0.004416	0.998816
	960	N O	R E S U L T	S
3.1510	180	0.023801	0.002426	0.999477
	360	0.031983	0.005933	0.995220
4.1510	300	0.021532	0.002352	0.999509
	600	0.018054	0.004345	0.997331
TABLE B.1d				

	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
5.1505	0.053457	-4.61	0.406352
7.1505	0.053443	-4.62	0.472580
8.1502	0.053278	-1.45	0.320775
9.1502	0.053335	-1.62	0.369210
10.1500	0.053404	-0.10	0.254291
12.1500	0.070228	-0.26	0.394651
1.0020	0.053630	-19.88	0.438580
2.0020	0.052303	-19.95	0.456918
3.0010	0.052717	-9.81	0.430390
4.0010	0.052725	-9.70	0.457173
	TABLE B.1a (continued)		

TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - INTERIOR PROBE RESULTS				
5.1505	180	0.049419	0.005697	0.998179
	360	0.050191	0.005244	0.997610
7.1505	300	0.048186	0.007442	0.997543
	600	0.049764	0.006262	0.997423
8.1502	180	0.064991	0.004938	0.997611
	360	0.067043	0.007114	0.992064
9.1502	300	0.059334	0.009660	0.993736
	600	0.065195	0.009482	0.989512
10.1500	180	0.091404	0.004777	0.995629
	360	0.099923	0.003078	0.996634
12.1500	180	0.070623	0.007099	0.996663
	360	0.080591	0.010975	0.984445
1.0020	180	0.051025	0.004005	0.999050
	360	0.052923	0.005771	0.996819
2.0020	300	0.051389	0.005094	0.998631
	600	0.054483	0.008448	0.994236
3.0010	180	0.046378	0.006337	0.997960
	360	0.046689	0.005231	0.997916
4.0010	300	0.049559	0.005395	0.998949
	600	0.050922	0.007289	0.996452
TABLE B.1b (continued)				

TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
5.1505	0.635	-5.11	0.245069
7.1505	0.635	-5.05	0.283539
8.1502	0.635	-2.13	0.138460
9.1502	0.635	-2.16	0.186923
10.1500	0.635	-0.60	0.055414
12.1500	0.635	-0.53	0.110810
1.0020	0.889	-20.04	0.201819
2.0020	0.889	-20.08	0.241471
3.0010	0.889	-10.01	0.197327
4.0010	0.889	-10.01	0.246646

EXPERIMENTAL DATA AND RESULTS
OTTAWA SAND - EXTERIOR PROBE DATA

TABLE B.1c (continued)

	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - EXTERIOR PROBE RESULTS			
TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
5.1505	180	0.012451	0.002316	0.999500
	360	0.010205	0.002449	0.998953
7.1505	300	0.012532	0.003247	0.999231
	600	0.009535	0.002945	0.998980
8.1502	180	0.004663	0.003584	0.996544
	360	0.003846	0.002298	0.996744
9.1502	300	0.005139	0.004935	0.996145
	600	0.002893	0.002966	0.996915
10.1500	180	0.004513	0.002828	0.985923
	360	0.002516	0.002694	0.950072
12.1500	180	N O	R E S U L T	S
	360			
1.0020	180	0.026153	0.002598	0.999083
	360	0.018600	0.005599	0.991329
2.0020	300	0.026706	0.003793	0.998372
	600	0.013889	0.008496	0.984633
3.0010	180	0.022463	0.003587	0.998241
	360	0.022010	0.002906	0.997783
4.0010	300	0.020394	0.002350	0.999489
	600	0.014384	0.008096	0.987989
TABLE B.1d (continued)				

TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - INTERIOR PROBE DATA			
5.0005	0.053344	-4.61	0.451696
6.0005	0.053420	-4.68	0.504880
7.0002	0.053402	-2.04	0.502423
8.0002	0.053377	-1.90	0.440640
10.0000	0.053079	0.40	0.386048
11.0000	0.053287	0.40	0.434288
TABLE B.1a (continued)			

	TIME	CONDUCTIVITY		
TEST NUMBER	-of heat -of test (SEC)	-heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - INTERIOR PROBE RESULTS				

TEST NUMBER	TIME (SEC)	CONDUCTIVITY (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
5.0005	180	0.047276	0.004380	0.999010
	360	0.047299	0.005615	0.997576
6.0005	300	0.047016	0.006197	0.998375
	600	0.048843	0.009312	0.994751
7.0002	300	0.047177	0.004162	0.999261
	600	0.053262	0.007041	0.996222
8.0002	180	0.047722	0.004729	0.998826
	360	0.047243	0.004713	0.998317
10.0000	180	0.055828	0.006264	0.997155
	360	0.053299	0.004938	0.997659
11.0000	300	0.054979	0.005259	0.998392
	600	0.054204	0.004108	0.998702

TABLE B.1b (continued)

	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
5.0005	0.889	-5.24	0.209713
6.0005	0.889	-5.24	0.237670
7.0002	0.889	-2.33	0.239834
8.0002	0.889	-2.31	0.191172
10.0000	0.889	-0.24	0.141773
11.0000	0.889	-0.24	0.165976
TABLE B.1c (continued)			

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS OTTAWA SAND - EXTERIOR PROBE RESULTS			
5.0005	180	0.020636	0.002365	0.999343
	360	0.018341	0.002460	0.998627
6.0005	300	0.020676	0.002350	0.999433
	600	0.016973	0.005798	0.993538
7.0002	300	0.022428	0.002976	0.999608
	600	0.012470	0.007086	0.989873
8.0002	180	0.020773	0.003500	0.998344
	360	0.019370	0.003308	0.996892
10.0000	180	0.014589	0.003092	0.997776
	360	0.014253	0.004244	0.992067
11.0000	300	0.015498	0.003272	0.998010
	600	0.010048	0.002335	0.998066
TABLE B.1d (continued)				

	EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL — INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
101.3020	0.053586	-19.47	0.502986
103.3020	0.053609	-19.71	0.498677
105.3010	0.053477	-9.82	0.493431
106.3010	0.053100	-9.86	0.484499
107.3005	0.053216	-5.16	0.460262
109.3005	0.053316	-4.98	0.442070
111.3002	0.066179	-2.01	0.525171
112.3002	0.065805	-2.01	0.525171
113.3000	0.053137	-0.01	0.678978
114.3000	0.053266	-0.07	0.687855
TABLE B.2a			

	TIME	CONDUCTIVITY		
TEST NUMBER	-of heat -of test (SEC)	-heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - INTERIOR PROBE RESULTS				
101.3020	180	0.042470	0.005452	0.998773
	360	0.041201	0.005684	0.998177
103.3020	180	0.043699	0.004815	0.998988
	360	0.042228	0.005975	0.997870
105.3010	180	0.041085	0.004664	0.999156
	360	0.040794	0.005095	0.998528
106.3010	180	0.042419	0.005546	0.998781
	360	0.040766	0.006302	0.997754
107.3005	180	0.044654	0.009695	0.995673
	360	0.045704	0.007615	0.995772
109.3005	180	0.042403	0.007134	0.997888
	360	0.043580	0.007611	0.996166
111.3002	300	0.052671	0.016205	0.991015
	600	0.055517	0.012697	0.991290
112.3002	300	0.050085	0.016151	0.991827
	600	0.054053	0.012860	0.991352
113.3000	180	0.029087	0.006995	0.999037
	360	0.028552	0.007964	0.998230
114.3000	180	0.028930	0.007246	0.998837
	360	0.028096	0.006636	0.998824
TABLE B.2b				

	EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
101.3020	0.889	-19.89	0.230579
103.3020	1.016	-19.82	0.212537
105.3010	0.889	-10.08	0.197462
106.3010	1.016	-9.97	0.183318
107.3005	0.889	-5.24	0.132368
109.3005	1.016	-5.17	0.132352
111.3002	0.889	-2.30	0.107441
112.3002	1.016	-2.22	0.103961
113.3000	0.889	-0.12	0.220830
114.3000	1.016	-0.15	0.234641
	TABLE B.2c		

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS **ARCTIC GRAVEL - EXTERIOR PROBE RESULTS**			
101.3020	180	0.020298	0.003028	0.999061
	360	0.014800	0.003852	0.997161
103.3020	180	0.018536	0.002605	0.999211
	360	0.016559	0.003807	0.996351
105.3010	180	0.010703	0.002168	0.999430
	360	0.013752	0.004781	0.994818
106.3010	180	0.014333	0.003076	0.998598
	360	0.013346	0.002812	0.997491
107.3005	180	0.005516	0.002697	0.998200
	360	0.006170	0.003834	0.990352
109.3005	180	0.008652	0.002631	0.997921
	360	0.006820	0.002471	0.994376
111.3002	300	0.021254	0.003701	0.991845
	600	0.001602	0.004890	0.709280
112.3002	300	0.004292	0.003016	0.993882
	600	0.002267	0.004624	0.848188
113.3000	180	0.007888	0.002894	0.999164
	360	0.010640	0.004965	0.994146
114.3000	180	0.011635	0.002039	0.999656
	360	0.011685	0.002128	0.999083

TABLE B.2d

	EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL — INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
101.1520	0.053003	-19.71	0.513546
102.1520	0.052116	-19.68	0.508740
103.1515	0.052245	-15.04	0.534871
104.1515	0.052484	-14.89	0.507534
106.1510	0.052427	-9.92	0.503540
107.1510	0.052508	-9.91	0.503531
108.1505	0.052288	-5.00	0.484852
109.1505	0.052357	-4.92	0.489222
110.1502	0.053069	-2.04	0.425043
111.1502	0.053186	-1.97	0.398435
TABLE B.2a (continued)			

TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
		EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - INTERIOR PROBE RESULTS		
101.1520	180	0.040524	0.004277	0.999297
	360	0.040081	0.005553	0.998288
102.1520	180	0.038725	0.007740	0.997830
	360	0.038021	0.007605	0.997064
103.1515	180	0.037204	0.005532	0.998980
	360	0.040032	0.006481	0.997543
104.1515	180	0.040234	0.004567	0.999150
	360	0.038038	0.007645	0.997113
106.1510	180	0.039520	0.004587	0.999214
	360	0.038178	0.005152	0.998649
107.1510	180	0.040306	0.005206	0.998951
	360	0.037106	0.005523	0.998572
108.1505	180	0.040735	0.006804	0.998156
	360	0.038605	0.007605	0.996993
109.1505	180	0.041801	0.005929	0.998529
	360	0.039088	0.006963	0.997442
110.1502	180	0.048253	0.012579	0.991500
	360	0.045797	0.010545	0.992072
111.1502	180	0.048212	0.011593	0.992811
	360	0.046299	0.011004	0.991155

TABLE B.2b (continued)

EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL – EXTERIOR PROBE DATA			
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
101.1520	0.635	-19.96	0.302621
102.1520	0.9525	-19.83	0.187545
103.1515	0.635	-15.05	0.300507
104.1515	0.9525	-14.93	0.189582
106.0510	0.9525	-10.01	0.176898
107.1510	0.635	-10.11	0.283062
108.1505	0.635	-5.09	0.265956
109.1505	0.9525	-5.13	0.157505
110.1502	0.9525	-2.25	0.093901
111.1502	0.635	-2.31	0.194760
TABLE B.2c (continued)			

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS			
	ARCTIC GRAVEL - EXTERIOR PROBE RESULTS			
101.1520	180	0.023766	0.003042	0.999350
	360	0.033680	0.004206	0.998002
102.1520	180	0.015262	0.002699	0.998980
	360	0.015287	0.002970	0.997470
103.1515	180	0.023667	0.004444	0.998640
	360	0.023876	0.002997	0.998973
104.1515	180	0.014968	0.003194	0.998645
	360	0.011784	0.001917	0.998916
106.1510	180	0.012290	0.002696	0.998903
	360	0.011324	0.003326	0.996211
107.1510	180	0.018897	0.003511	0.999120
	360	0.030743	0.006356	0.995555
108.1505	180	0.015581	0.003298	0.999111
	360	0.016398	0.005460	0.996247
109.1505	180	0.010286	0.003443	0.997367
	360	0.008327	0.002936	0.995758
110.1502	180	0.003885	0.004101	0.982688
	360	0.003518	0.004897	0.885340
111.1502	180	0.006259	0.004688	0.996452
	360	0.005236	0.003982	0.995012
	TABLE B.2d (continued)			

	EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL — INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
112.1500	0.053237	+1.19	0.740382
113.1500	0.053027	+1.12	0.736045
101.0020	0.052323	−19.56	0.479270
102.0020	0.053092	−19.64	0.483960
103.0015	0.052315	−14.60	0.474058
104.0015	0.053297	−14.68	0.487801
105.0010	0.052347	−9.80	0.501109
106.0010	0.052737	−9.79	0.487563
107.0005	0.053171	−5.07	0.537143
108.0005	0.053177	−4.92	0.505685
	TABLE B.2a (continued)		

	TIME	CONDUCTIVITY		
TEST NUMBER	-of heat -of test (SEC)	-heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
		EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - INTERIOR PROBE RESULTS		
112.1500	180	0.026105	0.010761	0.998173
	360	0.024818	0.008870	0.998373
113.1500	180	0.026012	0.009669	0.998523
	360	0.025466	0.008806	0.998278
101.0020	180	0.044717	0.003865	0.999283
	360	0.043297	0.006110	0.997574
102.0020	180	0.041428	0.005809	0.998650
	360	0.042132	0.005879	0.997885
103.0015	180	0.044308	0.003679	0.999362
	360	0.041480	0.005270	0.998352
104.0015	180	0.043635	0.006027	0.998402
	360	0.042267	0.003997	0.999035
105.0010	180	0.039510	0.005407	0.998906
	360	0.040257	0.003917	0.999112
106.0010	180	0.043002	0.004838	0.998978
	360	0.042216	0.005329	0.998252
107.0005	180	0.038515	0.005470	0.998968
	360	0.041494	0.005677	0.998045
108.0005	180	0.039123	0.006338	0.998572
	360	0.038576	0.005361	0.998536

TABLE B.2b (continued)

EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL – EXTERIOR PROBE DATA			
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
112.1500	0.635	+0.93	0.374056
113.1500	0.9525	+0.88	0.200924
101.0020	0.7938	−19.82	0.220295
102.0020	1.1113	−19.83	0.213078
103.0015	0.7938	−14.83	0.220892
104.0015	1.1113	−14.83	0.210206
105.0010	0.7938	−9.84	0.218718
106.0010	1.1113	−9.77	0.208111
107.0005	0.7938	−5.06	0.213537
108.0005	1.1113	−5.06	0.217036
TABLE B.2c (continued)			

	TIME	DIFFUSIVITY		
	EXPERIMENTAL DATA AND RESULTS			
	ARCTIC GRAVEL - EXTERIOR PROBE RESULTS			

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
112.1500	180	0.012476	0.003514	0.999537
	360	0.019147	0.011446	0.992517
113.1500	180	0.007585	0.002728	0.999157
	360	0.007965	0.002505	0.998100
101.0020	180	0.015186	0.003628	0.998415
	360	0.018546	0.003330	0.997854
102.0020	180	0.024907	0.003793	0.998456
	360	0.024556	0.003582	0.997052
103.0015	180	0.016384	0.002722	0.999171
	360	0.021113	0.003387	0.997898
104.0015	180	0.028061	0.003567	0.998607
	360	0.026205	0.002820	0.998225
105.0010	180	0.014721	0.003923	0.998389
	360	0.015060	0.003795	0.997103
106.0010	180	0.029351	0.002971	0.998966
	360	0.030000	0.003377	0.997680
107.0005	180	0.013082	0.002958	0.999098
	360	0.011945	0.002515	0.998622
108.0005	180	0.022429	0.003172	0.998944
	360	0.022602	0.007747	0.998445

TABLE B.2d (continued)

	EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
109.0002	0.053105	-1.82	0.515509
110.0002	0.052624	-1.70	0.466543
111.0000	0.052483	+0.66	0.119714
113.0000	0.102290	+0.88	0.403269
TABLE B.2a (continued)			

	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)		
		EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL - INTERIOR PROBE RESULTS		
TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
109.0002	180	0.038987	0.004642	0.999237
	360	0.040728	0.007452	0.996811
110.0002	180	0.042641	0.005246	0.998815
	360	0.041050	0.004730	0.998695
111.0000	180	0.168017	0.004285	0.987842
	360	0.207555	0.006196	0.937190
113.0000	180	0.078267	0.046691	0.925298
	360	0.168114	0.019221	0.885171
TABLE B.2b (continued)				

TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
109.0002	0.7938	-2.14	0.205307
110.0002	1.1113	-2.14	0.201828
111.0000	0.7938	+0.42	0.0
113.0000	1.1113	+0.42	0.0

EXPERIMENTAL DATA AND RESULTS
ARCTIC GRAVEL - EXTERIOR PROBE DATA

TABLE B.2c (continued)

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
		EXPERIMENTAL DATA AND RESULTS ARCTIC GRAVEL – EXTERIOR PROBE RESULTS		
109.0002	180	0.012329	0.002686	0.999147
	360	0.014267	0.003074	0.997933
110.0002	180	0.024680	0.002656	0.999159
	360	0.017567	0.002455	0.998395
111.0000		N O R E S U L T S		
113.0000		N O R E S U L T S		
		TABLE B.2d (continued)		

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
201.3020	0.052353	-19.64	0.702568
202.3020	0.053022	-19.64	0.711805
203.3015	0.053088	-14.57	0.685090
204.3015	0.052821	-14.65	0.689759
205.3010	0.052849	-9.72	0.682598
206.3010	0.053257	-9.57	0.673367
207.3005	0.053058	-4.34	0.577558
208.3005	0.053209	-4.49	0.577716
209.3002	0.053077	-1.77	0.440632
210.3002	0.051737	-1.78	0.427463
TABLE B.3a			

TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS **FAIRBANKS SILT - INTERIOR PROBE RESULTS**				
201.3020	180	0.026712	0.011717	0.997656
	360	0.027631	0.009796	0.997344
202.3020	180	0.026643	0.011199	0.997923
	360	0.026929	0.013447	0.995412
203.3015	180	0.027050	0.010049	0.998279
	360	0.026846	0.012383	0.996172
204.3015	180	0.027023	0.011792	0.997613
	360	0.027474	0.011071	0.996732
205.3010	180	0.027325	0.015211	0.995954
	360	0.029899	0.010857	0.996154
206.3010	180	0.028202	0.013472	0.996667
	360	0.029176	0.013282	0.994730
207.3005	180	0.032288	0.015256	0.994376
	360	0.033454	0.014203	0.991998
208.3005	180	0.032437	0.014724	0.994740
	360	0.033970	0.015526	0.990143
209.3002	180	0.041411	0.015377	0.990660
	360	0.046567	0.012039	0.988398
210.3002	180	0.041975	0.017403	0.987133
	360	0.048811	0.014102	0.981286

TABLE B.3b

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT – EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
201.3020	0.9525	-19.85	0.230833
202.3020	1.1906	-19.50	0.216241
203.3015	0.9525	-14.75	0.210372
204.3015	1.1906	-14.47	0.185306
205.3010	0.9525	-9.78	0.172809
206.3010	1.1906	-9.55	0.162154
207.3005	0.9525	-4.92	0.097910
208.3005	1.1906	-4.41	0.083843
209.3002	0.9525	-2.11	0.0
210.3002	1.1906	-1.80	0.0
	TABLE B.3c		

	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS			
	FAIRBANKS SILT - EXTERIOR PROBE RESULTS			
TEST NUMBER				
201.3020	180	0.007619	0.002002	0.999653
	360	0.007799	0.002017	0.999004
202.3020	180	0.010623	0.003793	0.998474
	360	0.008665	0.002625	0.997693
203.3015	180	0.006813	0.002733	0.999208
	360	0.005986	0.002305	0.998157
204.3015	180	0.007383	0.002528	0.999147
	360	0.008009	0.002552	0.996783
205.3010	180	0.004908	0.001991	0.999360
	360	0.004636	0.002139	0.997006
206.3010	180	0.006046	0.002229	0.998982
	360	0.005390	0.002000	0.994804
207.3005	180	0.001618	0.002400	0.994365
	360	0.001884	0.002480	0.915443
208.3005	180	0.002850	0.001911	0.995425
	360	0.002602	0.002122	0.955511
209.3002		N O R E S U L T S		
210.3002		N O R E S U L T S		

TABLE B.3d

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
211.3000	0.052978	1.55	0.966566
212.3000	0.051846	1.55	0.948844
201.1520	0.053414	-19.47	0.760732
202.1520	0.053023	-19.54	0.736603
203.1515	0.052472	-14.72	0.743835
204.1515	0.052306	-14.60	0.729981
205.1510	0.052746	-9.67	0.719109
206.1510	0.053445	-9.67	0.728148
207.1505	0.053149	-4.48	0.630823
208.1505	0.053199	-4.55	0.635382
	TABLE B.3a (continued)		

TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - INTERIOR PROBE RESULTS			
211.3000	180	0.018546	0.027312	0.994038
	360	0.019135	0.024495	0.992213
212.3000	180	0.018140	0.025161	0.994938
	360	0.018931	0.023082	0.992905
201.1520	180	0.025330	0.012259	0.997783
	360	0.025337	0.011154	0.997265
202.1520	180	0.025442	0.012225	0.997743
	360	0.025235	0.011629	0.997019
203.1515	180	0.024516	0.013205	0.997504
	360	0.026548	0.011592	0.996529
204.1515	180	0.025485	0.010970	0.998125
	360	0.025360	0.011471	0.996978
205.1510	180	0.025657	0.015431	0.996313
	360	0.027251	0.011472	0.996466
206.1510	180	0.026041	0.012058	0.997736
	360	0.026756	0.012089	0.996375
207.1505	180	0.029433	0.011942	0.997134
	360	0.030093	0.011878	0.995523
208.1505	180	0.029819	0.015810	0.994871
	360	0.030647	0.013724	0.993797
TABLE B.3b (continued)				

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
211.3000	0.9525	0.83	0.242089
212.3000	1.1906	0.99	0.217831
201.1520	0.9525	-19.78	0.291925
202.1520	1.2700	-19.43	0.248492
203.1515	0.9525	-14.64	0.274005
204.1515	1.2700	-14.35	0.231173
205.1510	0.9525	-9.92	0.247529
206.1510	1.2700	-9.96	0.226214
207.1505	0.9525	-5.01	0.171404
208.1505	1.2700	-4.78	0.153850
	TABLE B.3c (continued)		

TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
		EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT – EXTERIOR PROBE RESULTS		
211.3000	180	0.003516	0.001966	0.999641
	360	0.003649	0.002056	0.997816
212.3000	180	0.004894	0.002089	0.999484
	360	0.004912	0.001805	0.997030
201.1520	180	0.010600	0.002196	0.999745
	360	0.012285	0.004238	0.998000
202.1520	180	0.013606	0.002674	0.999458
	360	0.015024	0.003568	0.997671
203.1515	180	0.009597	0.002956	0.999450
	360	0.011692	0.004065	0.997847
204.1515	180	0.012554	0.002278	0.999564
	360	0.013278	0.002172	0.998881
205.1510	180	0.007340	0.002684	0.999462
	360	0.008554	0.004217	0.996790
206.1510	180	0.010806	0.002587	0.999371
	360	0.010090	0.002539	0.997854
207.1505	180	0.004503	0.001981	0.999344
	360	0.004313	0.002211	0.996390
208.1505	180	0.006296	0.002106	0.998967
	360	0.006141	0.001908	0.994666
		TABLE B.3d (continued)		

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - INTERIOR PROBE DATA		
TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
209.1502	0.053037	-1.90	0.498899
210.1502	0.052870	-1.76	0.494317
211.1500	0.053092	1.43	1.000074
212.1500	0.053260	1.57	0.999865
201.0020	0.052500	-19.33	0.717727
202.0020	0.052497	-19.38	0.722398
203.0015	0.052539	-14.62	0.702260
204.0015	0.053554	-14.70	0.734283
205.0010	0.053342	-9.59	0.738441
206.0010	0.052868	-9.66	0.720541
TABLE B.3a (continued)			

| | TIME | CONDUCTIVITY | | |
TEST NUMBER	-of heat -of test (SEC)	-heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
EXPERIMENTAL DATA AND RESULTS				
FAIRBANKS SILT - INTERIOR PROBE RESULTS				
209.1502	180	0.037511	0.017022	0.990596
	360	0.040170	0.014356	0.988044
210.1502	180	0.037839	0.014636	0.992856
	360	0.040651	0.012850	0.990101
211.1500	180	0.017669	0.029652	0.993652
	360	0.018727	0.023752	0.992944
212.1500	180	0.018026	0.027136	0.994495
	360	0.018632	0.023217	0.993445
201.0020	180	0.026398	0.011091	0.997959
	360	0.026334	0.011451	0.996781
202.0020	180	0.025817	0.010786	0.998153
	360	0.025478	0.010809	0.997327
203.0015	180	0.027052	0.011277	0.997788
	360	0.025808	0.010547	0.997430
204.0015	180	0.026111	0.012752	0.997466
	360	0.026200	0.011256	0.997031
205.0010	180	0.025839	0.013816	0.997065
	360	0.025696	0.013960	0.995580
206.0010	180	0.026039	0.012056	0.997688
	360	0.026249	0.012651	0.996125
TABLE B.3b (continued)				

	EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - EXTERIOR PROBE DATA		
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
209.1502	0.9525	-2.00	0.066008
210.1502	1.2700	-1.83	0.052096
211.1500	0.9525	0.96	0.273650
212.1500	1.2700	1.13	0.235494
201.0020	0.9525	-19.53	0.345721
202.0020	1.3494	-19.58	0.205326
203.0015	0.9525	-14.77	0.352463
204.0015	1.3494	-14.82	0.224348
205.0010	0.9525	-9.65	0.338280
206.0010	1.3494	-9.71	0.207954
	TABLE B.3c (continued)		

	TIME	DIFFUSIVITY		
	EXPERIMENTAL DATA AND RESULTS			
	FAIRBANKS SILT - EXTERIOR PROBE RESULTS			
TEST NUMBER	TIME -of heat -of test (SEC)	DIFFUSIVITY -heating -cooling (CM**2/SEC)	STANDARD DEVIATION ·'	CORRELATION COEFFICIENT
209.1502	180	0.001240	0.001828	0.980025
	360	N O	R E S U L T	S
210.1502	180	0.002528	0.001888	0.963798
	360	N O	R E S U L T	S
211.1500	180	0.004539	0.002599	0.999568
	360	0.004691	0.002908	0.997826
212.1500	180	0.005765	0.001956	0.999637
	360	0.006348	0.001878	0.997960
201.0020	180	0.018137	0.002902	0.999660
	360	0.018685	0.003202	0.999200
202.0020	180	0.010937	0.002133	0.999516
	360	0.011906	0.002525	0.997694
203.0015	180	0.016927	0.002618	0.999729
	360	0.017187	0.002116	0.999640
204.0015	180	0.013784	0.002711	0.999266
	360	0.010244	0.002814	0.997021
205.0010	180	0.017221	0.003627	0.999447
	360	0.020387	0.006678	0.996689
206.0010	180	0.011550	0.002504	0.999285
	360	0.011662	0.002753	0.997285

TABLE B.3d (continued)

TEST NUMBER	LINE HEAT SOURCE STRENGTH (W/CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
207.0005	0.053282	-4.64	0.703154
208.0005	0.052632	-4.64	0.712105
209.0002	0.053290	-1.61	0.622667
210.0002	0.053218	-1.60	0.609326
213.0000	0.052109	0.75	0.944908
214.0000	0.053159	0.89	0.966871

EXPERIMENTAL DATA AND RESULTS
FAIRBANKS SILT - INTERIOR PROBE DATA

TABLE B.3a (continued)

EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - INTERIOR PROBE RESULTS				
TEST NUMBER	TIME -of heat -of test (SEC)	CONDUCTIVITY -heating -cooling (W/CM C)	STANDARD DEVIATION	CORRELATION COEFFICIENT
207.0005	180	0.027375	0.012325	0.997372
	360	0.027324	0.015264	0.993998
208.0005	180	0.026265	0.013272	0.997125
	360	0.026605	0.013567	0.995365
209.0002	180	0.030891	0.010691	0.997482
	360	0.031517	0.011227	0.995640
210.0002	180	0.031423	0.012030	0.996696
	360	0.031881	0.016709	0.990112
213.0000	180	0.018381	0.021299	0.996306
	360	0.017278	0.023902	0.994009
214.0000	180	0.018658	0.022727	0.995842
	360	0.017708	0.025911	0.992860
TABLE B.3b (continued)				

EXPERIMENTAL DATA AND RESULTS FAIRBANKS SILT - EXTERIOR PROBE DATA			
TEST NUMBER	RADIUS TO EXTERIOR THERMOCOUPLE (CM)	INITIAL TEMPERATURE (DEG C)	MAXIMUM TEMPERATURE RISE (DEG C)
207.0005	0.9525	-4.91	0.342115
208.0005	1.3494	-5.05	0.199066
209.0002	1.3494	-1.93	0.142543
210.0002	0.9525	-1.90	0.291983
213.0000	0.9525	0.39	0.127741
214.0000	1.3494	0.33	0.089775
TABLE B.3c (continued)			

| | TIME | DIFFUSIVITY | | |
TEST NUMBER	-of heat -of test (SEC)	-heating -cooling (CM**2/SEC)	STANDARD DEVIATION	CORRELATION COEFFICIENT
207.0005	180	0.015389	0.003755	0.999402
	360	0.013149	0.002878	0.999248
208.0005	180	0.011577	0.002803	0.999034
	360	0.009762	0.002288	0.997450
209.0002	180	0.009374	0.002352	0.998415
	360	0.006443	0.001694	0.994246
210.0002	180	0.013226	0.003413	0.999321
	360	0.010671	0.002438	0.999244
213.0000	180	N O	R E S U L T	S
	360	0.042221	0.008945	0.969744
214.0000	180	0.008854	0.002947	0.993576
	360	0.012840	0.006251	0.945044

EXPERIMENTAL DATA AND RESULTS
FAIRBANKS SILT - EXTERIOR PROBE RESULTS

TABLE B.3d (continued)