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Thermal Properties of Soils and Soils Testing

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The following pages are an exact
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TABLE OF CONTENTS

1.0	INTRODUCTION.....	1
1.1	Soil Thermal Properties.....	1
1.2	In-Situ Temperatures.....	2
2.0	SOIL THERMAL PROPERTIES.....	3
2.1	Specific Heat.....	3
2.2	Thermal Conductivity.....	4
3.0	IN-SITU TEMPERATURES.....	7
4.0	EXPERIMENTAL APPARATUS.....	8
	APPENDIX A - UNITS AND DIMENSIONS.....	A-1
	APPENDIX B - BIBLIOGRAPHY.....	B-1

LIST OF TABLES

TABLE I - SPECIFIC HEAT OF VARIOUS SUBSTANCES.....	3
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REVIEW OF SOIL THERMAL PROPERTIES

1.0 INTRODUCTION

The general area of earth contact structures seeks to make use of soil and soil/groundwater masses as heat source, heat sink, or for thermal storage purposes. Since earth temperatures at quite modest depths are typically near the local average annual air temperature, the concept of employing the thermal inertia of soil to moderate extremes in the thermal loads of buildings is attractive. Implementing successful coupling of the soil and a structure requires a knowledge of the soil's thermal conductivity, heat capacity, soil property types, and the variations that may be expected in these properties.

1.1 Soil Thermal Properties

The thermal response of a soil mass may be fully defined (at least in principle) by assigning values to the thermal conductivity, k , the heat capacity, c , and the boundary conditions. Other related properties important to thermal calculations are specific heat and thermal diffusivity (Jumikis, 1966). In fact, only relatively simple geometries have been solved analytically, and soil thermal properties are seldom completely defined throughout the volume of interest. One thus must depend upon numerical solutions, recognizing that the soil thermal properties vary from point to point in the volume under consideration and again with time.

Thermal conductivity is defined as the coefficient of proportionality in Fourier's Law:

$$q = -kA \frac{\partial T}{\partial x}$$

where q = heat transfer rate in watts
 A = cross sectional area in square meters
 k = thermal conductivity in watt/meter °C
 $\partial T/\partial x$ is the thermal gradient in °C/meter.

The heat capacity is the energy required to raise the temperature of a unit mass one degree Centigrade, and is denoted by the symbol " c ", dimensions being joules per kilogram-degree Centigrade.

In soils, we are more interested in heat transfer by conduction than by convection or radiation. Holman (1976) presents the general heat conduction equation as:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c \frac{\partial T}{\partial t}$$

in which $\dot{q}$ = internally generated heat (if any)
 T = temperature
 t = time
 ρ = density
 x, y, z are spacial coordinates

and the other symbols are as previously defined. For constant thermal conductivity and no internal heat sources, this becomes:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

Transformation to the last member on the right side of the above equation depends on the definition of the parameter "Heat Diffusivity", $\alpha = k / c$. In cylindrical coordinates the general thermal conductivity equation becomes:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

Soil is not an isotropic homogeneous material having properties that are constant in time and space. Heat flow in soil is greatly influenced by the material inhabiting the pore spaces between soil grains, and the conditions at the grain to grain contact junctions (Palm, 1972). These factors will be discussed in the text of this review.

1.2 In-Situ Temperatures

In-situ soil temperatures are of obvious interest in the development of earth contact structures. To a first approximation, two factors are important. First, the temperature at depths of several meters typically are near the average annual air temperature (Geiger, 1965). Secondly, the perturbations in surface temperature caused by diurnal and annual variations in insolation, precipitation and weather propagate thermal waves into the ground at a finite velocity. Thus, the warmest time of the day at a depth of 30 cm may be about midnight, and the warmest time of the year at a depth of ten meters may be in the dead of winter. Any analysis of earth contact structures must consider the time-dependent effects of heat flow in the ground (Pearce and Gould, 1959).

2.0 SOIL THERMAL PROPERTIES

In this section we discuss the basic thermal properties of soil materials and the parameters reported to influence them. First we discuss the specific heat, and then thermal conductivity. Because diffusivity is the ratio of the two, it will not be separately discussed.

2.1 Specific Heat

Heat capacity is the energy required to increase the temperature of a material by one degree Centigrade, and specific heat is simply the ratio of the heat capacity of a substance to the heat capacity of water (Jumikis, 1966). Heat capacity may be expressed on a volumetric or density basis. Most work employs the density notation, in which heat capacity is measured in Joules per kilogram - degree Centigrade. Kersten (1949) reports the welcome information that the specific heat for all dry soils is essentially the same. Significant parameters are temperature and moisture content, but the effect of soil type is second order. Considering heat capacity as a scalar function, the heat capacity of a mixture of components such as soil and water may be arrived at by adding the values of the individual materials in the ratio of their masses. Kersten (1949) reports that the heat capacities for the six dry soils he considered could be represented by:

$$C = 700 + 2 T \frac{\text{J}}{\text{kg} \cdot ^\circ\text{C}}$$

where C is in J/kg-°C
T is temperature in °C.

Mitchell and Kao (1978) measured the heat capacity of a dry Monterey sand using a thermal needle, reporting a value of 750 J/kg- °C, and compare this with the known values of 710 J/kg- °C for quartz and 790 J/kg- °C for feldspar, the major constituents of Monterey sand. The tests on Monterey sand were done across a temperature range of 40 to 20 °C, which would give a predicted value of 740 to 780 J/kg- °C by Kersten's correlation.

Jumikis (1966) provides a list of heat capacities of various substances, an abbreviated version of which is incorporated as Table I below:

TABLE I
SPECIFIC HEAT OF VARIOUS SUBSTANCES

<u>Material</u>	<u>Temperature Range Deg.C</u>	<u>Heat Capacity J/kg-C</u>
Kaolin	20-98	937
Quartz Sand	20-98	799
Mica	20-98	862
Granite	12-100	803
Sandstone		920
Limestone	15-100	903
Quartz	12-100	786

It can be seen that these values fall into the same range as the Kersten prediction which would give values for heat capacity of 724 to 900 J/kg- °C over the temperature range of 12 to 100 degrees Centigrade.

The effect of moisture content is accounted for by a straight forward ratio of the heat capacity of dry soil and moisture content. This may be seen by realizing that the well mixed soil grains and pore water must come to the same temperature. This mixing partitions the required thermal energy into a ratio of their respective masses. Kersten states simply that:

$$C_m = \frac{100 C_s + MC_w}{1+M}$$

in which the subscripts m, w and s denote the heat capacities of the mixture, water and soil,

M = Moisture Content in percent.

2.2 Thermal Conductivity

Unlike heat capacity, which is nearly uniform across soil types, the thermal conductivity depends upon a large number of parameters. The most significant of these are soil type, dry density and moisture content.

If one considers a soil as an irregular array of solid grains in a matrix of pore water and/or gas, it is easily appreciated that heat flow through the mass may be somewhat complex. The soil grains themselves may be more or less rounded, as in beach sand, or angular as in a crushed sand. Clays are comprised of platelets which may have lateral dimensions several hundred times their thickness. These platelets may be dispersed, flocculated into a cardhouse structure or aggregated into the lamella of larger grains (Woodside, 1958). The term soil fabric refers to the organization of soil grains into the mass, and typically is anisotropic. Naturally sedimented clays, for example, may be highly ordered, with most platelets parallel to the orientation that was horizontal when the soil was deposited, or surface and fluid chemistry may have organized them into an openly flocculated structure. Even highly rounded sand displays parallel orientation of the individual grains, and typically a higher order fabric resulting from variations in deposition rate. The fabric of both undisturbed soil and that of compacted soil can have profound effects on soil properties.

Heat transfer in soil may be through the individual grains and the grain to grain contact junction points, by conduction through the pore fluid across the pore spaces from grain to grain, by radiation, or by convection (Jumikis, 1966). The contribution of the conduction through contact junctions clearly is sensitive to conditions at the contact junctions - that is, stress, surface films and any bound water or cementitious material, such as silt or clay particles packed into the junction points between the much larger sand grains.

Particulate Models

Wakao and Kato (1969) developed detailed models for the conductivity of cubic and orthorhombic arrays of spheres incorporating conduction and radiation across pore spaces. They found reasonable agreement between experimental data collected with glass beads and the model when a "definite area of contact" was assumed, but are exceptionally terse about how this assumption was made. One assumes that the process involved curve fitting to the experimental data to produce the best fit. They do note that the junction area is important when conductivity of the solid is large in comparison to conductivity of the pore fluid or the contribution of radiation.

A somewhat more realistic model is presented by Prakouras et al (1978). The model is generated by randomly filling cells in a three dimensional matrix until the desired porosity is obtained, and filling the remaining cells with the pore fluid. Contact junctions between cells containing the discontinuous phase are assigned randomly between adjacent cells until the number of junctions necessary to provide reasonable coordination numbers is achieved. Conduction and radiation across void spaces is based on assumed pore size distributions. Conduction through the grains, as well as conduction and radiation across the void spaces, are incorporated in the model. In general, empirical constants are incorporated into the various transfer functions, so that the model will fit realistic situations. Comparisons with experimental data for several materials are generally good. The authors note the dependance of the model upon the proper choice of pore-size distribution, and list several areas in which the model may depart from reality.

The primary benefit of models such as those described above is not in developing predictions of thermal conductivity, but rather in predicting trends. Soil materials typically have thermal conductivities that are perhaps half an order of magnitude greater than water and one and a half orders of magnitude greater than air. The pore fluid is usually a combination of both air and water.

Effective conductivities are given as a function of the ratio of the thermal conductivities of the discontinuous phases and the continuous phases. For soils, this ratio may vary from near one (for low density saturated clays) to several hundred (for dry soils). The curves presented by Wakao and Kato (1969) indicate that the effect of radiation and contact junction area will be small at the lower end of this range, but will be significant at the upper end. Thus we will be more concerned with in-situ stress for dry sands than for wet, and will not expect in-situ stress to be a significant parameter in clay soils. The model trends and mechanisms cannot be taken without question, however.

Soil Types

Soils are classified broadly as sand, silt, clay, and organic. Kersten (1949) groups soils as fine grained (silt and clay) and sandy. Predictors for his data are:

$$\begin{array}{lll} \text{fine grained} & k = (0.9 \log M - 0.2) 10^{0.01Y} & M > 7\% \\ \text{sandy} & k = (0.7 \log M + 0.4) 10^{0.01Y} & M > 1\% \end{array}$$

Moisture migration across a thermal gradient may occur at moderate temperatures. The effect will be to transport moisture toward the cooler side of the gradient. It will also decrease the thermal conductivity of the soil near the heat source which will be drier. The primary mechanism involved in moisture migration appears to be the increased vapor pressure on the hot side of the thermal gradient. Raudkivi and Van U'u (1976) treat the problem as a diffusion process, comparing the results of an analytic model with observed and published data. They report that moisture migration is most pronounced at a degree of saturation of about 20 percent. Woodside and de Bruyn (1958) report moisture migration in both their hot plate apparatus and thermal needle. Their tests on Leda Clay stabilized after about 150 hours with five percent moisture at the hot side (32 degrees Centigrade) and 30 percent at the cold side (18 degrees Centigrade). Mitchell and Kao (1978) argue that the most reliable determinations of soil conductivity are possible using transient tests, such as the thermal needle, which permits less time for the occurrence migration. A treatment of a more severe moisture migration is undertaken by Saito and Seki (1976), who are concerned with pore-vapor pressure during sand-casting of metal. They establish a one-dimensional model with a moving boundary between moist and dry regions which showed reasonable correlation to experimental data. Beles and Stanculescu (1958) employ moisture migration to enhance soil properties, but present little data of interest to the thermo-osmosis problem.

Other Variables

Soil thermal conductivity is influenced by a number of the variables that normally influence soil behavior in general. Kersten (1949) notes that these include temperature, texture, mineral composition and angularity in addition to the primary influences of dry density and moisture content. Prakouras et al (1978) add to this list stress, pore size and pressure of pore gas when at reduced pressures. Birch (1954) found that thermal conductivity of sandstone was influenced by stress, but not that of basaltic materials. Both, of course, are frictional materials, but the porosity of sandstone is much greater than basalt.

The basic research on soil thermal properties must be aware of the various factors that influence thermal conductivity, but the design guides that result from this contract cannot pursue greater precision into ever greater complexity of modeling. Soil is highly variable, and the practitioner interested in erecting earth contact structures cannot afford to conduct extensive modeling for each and every installation.

3.0 IN-SITU TEMPERATURES

Levels of sophistication with respect to temperatures in the earth begin with the idea that the earth is at a constant 55 Degrees F, through the concept of average annual air temperature, to recognition that local details such as groundwater flow and snow cover must be considered.

Geiger (1965) presents very graphic data compiled from several European investigators showing clearly the effects of annual and diurnal variations in the thermal input at the ground surface and their underground effects. The depth of influence for daily variations is on the order of several tens of centimeters, while annual effects can be seen at depths of several meters. A very perceptible lag in thermal response is seen in these data. The warmest time of the day at a depth of 30 centimeters is about midnight, while the warmest time of the year is in February. The effects of precipitation and extended hot or cold weather can be seen at intermediate depths which correspond to the duration of the event.

4.0 EXPERIMENTAL APPARATUS

A variety of concepts have been used for laboratory and field determinations of soil thermal properties. Not all of these are well adapted to testing of soils. Laboratory systems should be capable of testing either remolded samples or undisturbed soil samples extruded from thin-wall sampling tubes.

4.1 Heat Capacity Measurements

Heat capacity is the energy required to raise the temperature of a material. Kersten (1949) measured heat capacity by placing soil samples directly into a calorimeter, making correction for the calorimeter drift and the heat of wetting of the soil. The basic test scheme used by this group was to bring a known weight of soil to temperature equilibrium at a temperature different than that of the calorimeter. The temperature of the calorimeter was monitored before and after addition of the soil at one minute intervals. A total of six variations of this basic test method was used. Calculation methods are presented in Kersten's report.

Mitchell and Kao (1978) used a cylindrical sample compacted in a standard compaction mold with end caps of polyurethane foam to prevent non-radial heat flux. An unheated thermal needle placed at the specimen axis provided temperature variation measurements. The specimen was equilibrated at a known temperature, then placed in a constant temperature bath having a different temperature. The time history of the temperature at the axis was compared with characteristic curves developed by the use of a finite element program. The method has the advantage of being a transient system, so that the effects of moisture migration are reduced. The document does not address the question of thermal surface contact resistance.

4.2 Thermal Conductivity Measurements

Thermal conductivity has been measured by a number of steady-state and transient methods. Steady-state methods are generally less appropriate by reason of the certainty of moisture migration and the cost of long test duration.

Kersten (1949) employed an annular specimen with internal heater and a constant temperature boundary on the outer surface. Guard heaters and insulators at the specimen ends enforced radial flow in the central test section of the specimen. Times to establish an equilibrium thermal gradient were five to ten hours, by which time moisture migration had often taken place. In some very porous soils, vertical moisture migration due to gravity forces also occurred. The specimen dimensions were 50.8 cm tall, 15.5 cm outside diameter and 6 cm inside diameter. The test section was 30.5 cm in length, and was bounded by guard heaters 10 cm long at top and bottom.

Woodside and de Bruyn (1958) used a hot plate apparatus 30.5 cm square with a specimen height of 7.6 centimeters. Within the specimen were six thermocouples equally spaced across the thermal gradient, and six holes through which 0.8 cm diameter samples could be cored. The authors report significant changes in moisture content due to migration across the thermal gradient. These authors also used a thermal needle and a double hot plate apparatus called the uniflow. The thermal needle displayed changes in thermal conductivity which were attributed to migration of moisture. The Uniflow apparatus, which places soil specimens above and below a double hot plate appeared to give the most consistent data for these investigators. Moisture migration was quantified by establishing a thermo-osmosis coefficient equal to moisture gradient/thermal gradient at equilibrium. Their tests with Leda Clay indicated that this coefficient was a maximum at about 20 percent moisture.

Mitchell and Kao (1978) used the transient response of a thermal needle, which they compared to four other methods. They argue that the fast response of the thermal needle is a major advantage of this system, giving more consistent data than the other slower transient methods or steady state methods.

Interpretation of transient response has been eased in the more recent investigations by the use of numerical modeling as opposed to earlier studies which used an analytic solution based on a line heat source. The use of numerical models has permitted the use of more realistic model geometry.

Review of this literature leads to the general conclusion that thermal conductivity should be measured with apparatus having the following characteristics:

Radial geometry as in the thermal needle
or Kersten's apparatus,

Transient response to avoid the worst effects
of moisture migration. No investigator was
found who used a reversing thermal gradient,
but this might be a possibility in combination
with an annular geometry,

Ability to work in both remolded and undisturbed
soil specimens.

These criteria might best be met by the thermal needle for field and lab work, or by laboratory apparatus using annular geometry with a somewhat larger diameter heater. The primary difficulty with the needle is its small surface area, which in a laboratory test can be remedied by scaling up the heater diameter. The needle can then be used in the field, and may also be thrust directly into thin-wall sample tubes for undisturbed laboratory determinations. Any probe that is thrust into the soil should be used with the recognition that the soil may develop radial tensile cracks around the probe. The apparatus should have the ability to operate in conventional soils testing apparatus such as unconfined or triaxial test systems. This will permit tests to be conducted under tailored stress conditions.

APPENDIX A

6

UNITS AND DIMENSIONS

APPENDIX A

UNITS AND DIMENSIONS

The heat transfer literature contains a remarkable variety of different dimensional systems. Some segments of the discipline prefer to deal with the concept of thermal resistivity (inverse conductivity) and others invent a bewildering variety of units.

All dimensions and units in this review and in the associated contract and reports will be converted to SI units.

The SI dimensions for thermal conductivity are Watt per meter-degree Centigrade. A short table of conversion factors for some of the more bizarre dimensions discovered to date in the literature is appended below. We expect that even more unusual units and dimensions will be unearthed in the future, so this list must be considered incomplete.

Heat capacity, in addition to being reported in strange units, is sometimes reported as specific heat capacity (a dimensionless ratio), as a volumetric parameter, or as a mass parameter. Our practice will be to report heat capacity as the energy required to increase a unit mass one degree Centigrade. Dimensions are Joules per kilogram-degree Centigrade.

Table A-1
Conversion Factors

<u>Thermal Conductivity</u> to Obtain Watts meter-°C		<u>Heat Capacity</u> to Obtain Joule kg-°C	
Multiply	by	Multiply	by
cal/(cm-hr-°C)	0.1162	cal/(g-°C)	4184
cal/(cm-min-°C)	6.973	cal/(g-°F)	2324
cal/(cm-sec-°C)	418.4	BTU/(°F-lb)	4184
BTU/(ft ² -hr-°F/in)	0.1441		
BTU/(°F-ft-hr)	0.5779		

A.2 SOIL MECHANICS NOMENCLATURE

It appears to be the case that some investigators working in the area of heat transfer might be slightly less than well founded in Geo-technical Engineering. To open the channels of communication, we offer the following definitions and relationships between common soils parameters.

Employing the following symbols and subscripts:

<u>Symbols</u>	<u>Subscripts</u>
W for mass	s for solids
V for volume	v for voids
γ for density	w for wet or water
G for specific gravity	d for dry
	t for total

we then define the following parameters:

dry density	$\gamma_d = \frac{W_s}{V_t}$
moisture content	$M = \frac{W_w}{W_s} \quad 100\%$
void ratio	$e = \frac{V_v}{V_s}$
porosity	$n = \frac{V_v}{V_t} \quad 100\%$
degree of saturation	$S = \frac{V_w}{V_v}$

Some useful relationships between these include the following:

$$\begin{aligned} Se &= GM \\ n &= \frac{e}{1+e} \\ e &= \frac{1-n}{n} \\ \gamma_t &= \frac{1+M}{1+e} \gamma_d \quad \text{for bulk density} \end{aligned}$$

Note that the generally most useful parameters defining the gross physical condition of soil are the dry density and moisture content.

APPENDIX B

BIBLIOGRAPHY

APPENDIX B

BIBLIOGRAPHY

A tentative bibliography is included below. We first provide an alphabetized list of the documents included in the bibliography to date, and then the annotated bibliography itself. Accession numbers in the bibliography are as noted. Missing numbers indicate documents that were, for one reason or another, dropped from consideration after having been indexed into the system.

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Andrews, R. V. (1955), "Solving Conductive Heat Transfer Problems with Electrical-Analogue Shape Factors"; Chemical Engineering Progress, Vol. 51, No. 2, Feb. 1955, pp 67-73.

Descriptors: Conductivity / Electrical Methods / Heat / Heat Flow / Heat Model / Heat Transfer / Heat Transfer Coefficient / Laboratory Thermal Data / Potential / Resistivity / Thermal Calculations / Thermal Conductivity / Thermal Properties Tests (lab) / Theoretical Thermal Models.

This article assumes all heat flow in the Z direction to be unity, which reduces the heat flow problems to 2 dimensions, which the author modeled on 31" conductive paper. Various geometric configurations were made and solved both analytically and experimentally. Results agreed within 10% ($\pm 5\%$). The author states without reference that the accuracy of values of thermal conductivity is considered to be approximately 10%.

Annan, A. P. and Davis, J. L., "High Frequency Methods for the Detection of Freeze-Thaw Interfaces", Proc. III Intl. Conf. Permafrost, Edmonton, Canada, Vol. I, pp 496-500, 1978.

Descriptors: Dielectric Constant / Artificial Freezing / Groundwater / Time Domain Reflectometry / Soil Types/Laboratory Thermal Data / Density.

Used TDR and pulse radar to identify ice/water interfaces. Note drops in dielectric constant at 0°C. Radar used for survey and TDR for spot determinations.

Arulanandan, K., and Smith, S. S., "Electrical Dispersion in Relation to Soil Structure", Journal of the Soil Mechanics and Foundations Division, Dec. 1973, pp 1113-1131.

Descriptors: Capacitive Moisture Transducer / Compressed Samples / Conductivity / Density / Diffusivity / Dielectric Constant / Electrical Methods / Groundwater / Moisture Sensing / Moisture Transport / Particle Size / Permittivity / Porosity / Potential / Resistivity / Saturation / Soil Moisture / Soil Property Tests / Soil Texture / Soil Types / Void Ratio / Water Saturation / Field Instrumentation (moisture).

This article describes response characteristics to electric current in saturated clay - water - electrolyte systems. Dielectric constant and conductivity between 10^6 Hz and 10^8 Hz varied with frequency dependent on the composition of the sample and the heterogeneous nature of the system. The thrust of the article is to verify the use of electrical response characteristics to reflect soil properties such as moisture content. The electrolyte type in the system is critical at these frequencies. As the number of particles decreases, the ambient of electrolyte increases, and so the dielectric constant. The dielectric constant of dry clay is about 4, and for water 78. The methodology is being developed for determination of soil properties in-situ.

Beles, A. A. and Stanculescu, I. I. (1958), "Thermal Treatment as a means of Improving the Stability of Earth Masses"; Geotechnique (London) Vol, No. 4, December 1958, pp 158-165.

Descriptors: Density / Field Thermal Experiments / Groundwater / Heat / Heating / Moisture Content / Pore Pressure (in-situ) / Moisture Migration / Moisture Transport / Saturation / Soil Firing / Soil Moisture / Soil Types / Thermal Gradient / Thermal Properties Tests (field) / Underground.

The paper outlines some characteristic aspects of the available methods for improving the stability of earth masses through thermal treatment. It includes the description of some practical applications of the new thermal treatment procedure as a method for improving the stability of clay soil masses.

Berntsson, T., Franck, P., Jacobson, L., Modin, B., Wilen, P. (1980), The Use of the Ground as a Heat Source for Heat Pumps in Urban Areas. Research Grant 770611-4 from the Swedish Council for Building Research to the Earth Heat Pump Group. Chalmers University of Technology. Goteberg, Sweden, 1980.

Descriptors: Convection / Cost Analysis / Economics / Efficiency / Ground Water / Heat / Heat Flow / Heat Pipes / Heat Pumps / Heat Storage / Heat Transfer / Latent Heat / Soil Types / Thermal Capacity / Thermal Coupling / Thermal Models / Underground

Methods of using the earth's heat to heat homes or apartment buildings are examined. Various configurations of plastic hose with a circulating coolant are evaluated. The use of lakes and ground water are examined as a potential source of heat. The basic concept is that of pumping the water through dwellings and returning it to its source. In this method, the deeper the extraction point, the higher the ground water temperature. Work of this nature is currently being explored in Germany, France, Switzerland, Denmark, and Sweden. Convectors require about 1m^2 surface area per meter of pipe run. The higher the radioactive content of the ground, the higher the temperature, and the greater the amount of heat that can be extracted. Contains an excellent bibliography, with language listings.

Birch, Francis, (1954), "Thermal Conductivity, Climatic Variation, and Heat Flow Near Calumet, Michigan", American Journal of Science, Vol. 252, January, 1954, pp 1-25.

Descriptors: Thermal Conductivity / Soil Types / Thermal Diffusivity / Thermocouples / Compressed Samples / Groundwater / Lake Influence / Soil Depth / Heat Profiles / Water Saturation / Density.

This article by Birch deals with measurements of thermal conductivity for some 90 rock samples from the vicinity of Calumet, Michigan. These measurements are given for rock samples and for the rate of heat conduction to the earth's surface from deep underground samplings.

Thermal conductivity measurements were taken on discs 1.5" in diameter and 0.25" thick, via the "divided bar" pyrex glass balance technique which utilizes thermocouples, with junctions sunk into copper separating discs.

It was found that loads of 5,000 psi on the samples produced changes of <1% in the thermal conductivity of most basic rocks. Porous sandstones, however, changed as much as 10% under such pressures. Typical tabulated results were taken under pressures of 2,500 psi.

The effect of water saturation was not investigated for these samples. It was assumed that the "moderate" compression of 2500 psi was nearly equivalent to saturation.

Thermal conductivity is reported in "millical/cm sec. deg."; heat conduction to the surface is given as 0.93 microcal per (cm²sec) from the depths of the mine shafts (about 4 to 10k') $\pm$ 5%.

Denser rocks usually showed a higher thermal conductivity. As a soil or rock type alters to another type, the usual result is a higher conductivity. Conductivity of all 90 samples ranged between 2.2 and 9.0 millical/cm sec. deg.

(Continued)

Birch, Francis, (1954) (Continued)

Page 2

Birch concludes that statistically there is no evidence of departure from linearity in a depth vs $^{\circ}\text{C}$ graph between 2800' and 5600'. At a depth of about 300 the temperature begins to rise at a rate of about $7.8^{\circ}\text{F k ft.}$ Groundwater circulation is credited with a great effect on this temperature change, as well as the fairly constant temperature above 300'.

Lake Superior is credited with producing a cooling effect of only 1°F at 600' depth sampling in the vicinity.

The article fluctuates between $^{\circ}\text{F}$ and $^{\circ}\text{C}$ and between millical/cm sec. deg. and microcal/cm² sec. These changes make for difficult interpretations and comparisons.

Birch, F., and Clark, H. (1940) "The Thermal Conductivity of Rocks and Its Dependence Upon Temperature and Composition" American Journal of Science, Vol. 238, No. 8, Aug 1940, pp 529-558.

Descriptors: Thermal Conductivity / Heat / Heating / Conductivity / Density / Diffusivity / Heat Flow / Heat Model / Heat Profiles / Heat Transfer / Heat Transfer Coefficient / Laboratory Thermal Data / Particle Size / Porosity / Resistivity / Soil Texture / Soil Types / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (lab) / Thermal Resistance.

An apparatus for the measurement of thermal conductivity between 0°C and 500°C is described. Results are given for igneous, sedimentary, and metamorphic rock samples. Conductivity of poor conductors increases with temperature. Conductivity of other samples decreases as temperature increases. Conductivity results are given in 10^{-3} calories/cm sec. °C and converted to 10^{-3} watts/cm °C on multiplication by 4.18. Values lie between 4 and 14 (10^{-3} cal/cm sec. °C). Gives a good "ball park" idea of conductivity values for carefully done laboratory specimens.

Blackwell, J.H., (1956), "The Axial-Flow Error in the Thermal-Conductivity Probe", Canadian Journal of Physics, Vol., 34, No. 1, 1956, pp 412-416.

Descriptors: Thermal Conductivity / Conductivity / Heat Flow / Heat / Heating / Thermocouple / Convection / Heat Transfer Coefficient / Laboratory Thermal Data / Potential / Resistivity / Thermal Calculations / Theoretical Thermal Models / Vapor Pressure

Blackwell points out that when using a heat probe to determine the coefficient of thermal conductivity the minimum length of the probe must be known so that the simple radial flow theory is valid. It is assumed that the probe is immersed in a medium of infinite extent where boundary conditions are negligible. Convection then becomes a problem in theoretical calculations. Blackwell admits (pg 413) that his axial flow restrictions have little experimental significance.

Bligh, T. P., Shipp, P., and Meixel, G., "Energy Comparisons and Where to Insulate Earth-Sheltered Buildings and Basements", Energy, Vol. 5, pp 451-465, 1979.

Descriptors: Cost Analysis / Field Thermal Experiments / Heat / Heat Model / Heat Flow / Heat Transfer / Heating / Soil Depth / Solar Collectors / Thermal Coupling / Thermal Models / Underground / Waste Heat Utilization.

Presentation of computer study comparing earth-sheltered with above-ground residential structures, with attention to wall, roof and window details.

Bonacina, C. et. al., (1974) "On the Estimation of Thermophysical Properties in Nonlinear Heat Conduction Problems", International Journal of Heat and Mass Transfer, Vol. 17, 1974, pp 861-867.

Descriptors: Artificial Freezing / Density / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Storage / Heat Transfer / Heat Transfer Coefficient / Laboratory Thermal Data / Latent Heat / Saturation / Specific Heat / Thermal Calculations / Thermal Capacity / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests (lab) / Volume.

This article deals with heat transfer in foodstuffs during freezing, and gives special attention to heat storage and transfer during a phase change. Specific heat is given in J/kg ⁰K. For experimental convenience the freezing (hamburger and mashed potatoes) was reduced to a one dimensional nonlinear heat-conduction problem with solution and analysis of estimated error.

Bouyoucos, George (1920) "A New Classification of the Soil Moisture", Soil Science, Vol. XI, No. 1, 1921, pp 33-47.

Descriptors: Agriculture / Artificial Freezing / Density / Film Moisture / Film Transport / Groundwater / Moisture Content (in-situ) / Moisture Migration / Moisture Transport / Plant Growth / Saturation / Soil Moisture / Soil Property Tests / Soil Types / Volume / Void Ratio / Water Saturation.

This pioneer work done in 1920 describes moisture in soils as 1.) gravitational, 2.) capillary adsorbed and, 3.) combined. The combined water does not freeze even at -78°F . The amount of free water increases with successive freeze-thaw cycles. Moisture-type contents for a variety of soil types are listed.

Burggraf, F. (Editor) (1961). Discussions on Water and Its Conduction in Soils. National Academy of Sciences - National Research Council. Highway Research Board, Bulletin 287, January, 1961. 86 pp

Descriptors: Conductivity / Convection / Density / Diffusivity / Film Moisture / Film Transport / Groundwater / Heat Profiles / Heating / Isotherm / Laboratory Thermal Data / Moisture Content (in-situ) / Moisture Migration / Moisture Sensing / Moisture Transport / Porosity / Potential / Saturation / Soil Moisture / Thermal Gradient / Thermal Properties Tests (lab) / Thermo-osmosis / Translocation / Underground / Vapor Transport / Water Saturation.

This document contains several papers on water transport. Pertinent comments are given by author.

1. E. Penner:

It is generally believed that thermally activated diffusion results from a potential created by a temperature gradient across the vapor phase. Thus, vapor flows in the direction of decreasing vapor pressure gradients and may be combined with series flow in the liquid phase.

2. P. E. Law:

Water in soil will move in response to a salt concentration gradient. Sometimes water molecules move because of an electrically imposed pressure. The molecules will tend to diffuse away from the surfaces of specific colloidal particles. Water moves along on electric potential gradient. Water also moves along a potential energy gradient (e.g. downhill).

3. G. C. Blomquist:

Soil moisture can be transported upward through porous soil upon freezing as a liquid, a vapor, or a film. All three can take place at the same time.

4. R. L. Rollins:

In a soil system subjected to a thermal gradient, the temperature gradient across the pores in the system are several times the average temperature

(Continued)

Burggraf, F. (Continued)

Page 2

gradient of the system. Hence transfer by convection assumes a great importance in soil. Percent adsorption of water vs. temperature is given for different clay types.

Busse, F. H., and Joseph, D. D. (1972), "Bounds for Heat Transport in a Porous Layer, Journal of Mathematics and Physics, Vol. 54, No. 521, 1972, pp 521-543.

Descriptors: Convection / Film Moisture / Film Transport / Heat / Heat Flow / Heat Flux / Heat Model / Heat Transfer / Isotherm / Laboratory Thermal Data / Moisture Migration / Nusselt No. / Porosity / Saturation / Thermal Calculations / Thermal Gradient / Thermal Models / Thermal Properties Tests (lab) / Translocation / Vapor Transport / Water Saturation

This article is chiefly concerned with heat transport via convection within specified finite boundary condition. A single overall wave number is assumed to facilitate the methodology solution finding.

Caltagirone, J. P. (1975) "Thermo-convective Instabilities in a Horizontal Porous Layer", Journal of Fluid Mechanics, Vol. 72, Part 2, 1975, pp 269-287.

Descriptors: Convection / Isotherm / Heat Flow / Nusselt No. / Thermal Calculations / Vapor Transport.

A saturated porous layer was placed between two horizontal plates with a thermal gradient between them. It was found that as the Rayleigh number increased, the seemingly stable conduction gave way to "fluctuating" convection. Total heat transport in the fluid, as defined by the Nusselt Number was found to vary as much as $\pm 40\%$ of the mean value.

Carlsson, Hans (1978), "A Pilot Heat Test in The Stripa Granite", Technical Project Report #6, Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock. LBL-7806

Descriptors: Field Instrumentation (moisture) / Field Thermal Experiments / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Transfer / Heat Transfer Coefficient / Resistivity / Soil Depth / Soil Types / Specific Heat / Thermal Calculations / Thermal Capacity / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (field) / Thermal Resistance / Thermocouples / Underground.

A pilot heater test was carried out at the 348 m depth in the Stripa Mine. A central, main heater was placed in a 10 m deep borehole. Temperature changes were monitored from 0.85 up to 2.95 m from the heater. Maximum heater temperature was 333.9°C. The maximum temperature in the granite at 0.85 m from the heater was 102.7°C. The thermal conductivity of the granite was calculated to be 4.8 W/m°C. The heater remained on for 65 days to establish equilibrium conditions. In the theoretical calculations, a thermal conductivity of 3.4 W/m°C was used. Calculations were carried out on both the heating and the cooling data recorded.

Chandra, S., Fairey, P. W., Cermak, J. E., and Bowen, A., (1980), "Passive Cooling by Natural Ventilation", Contract DE-AC03-SF11510, 1980-82.

Florida Solar Energy Center, Cape Canaveral, Florida, 32920. Project Overview.

Descriptors: Convection / Economics / Solar Collectors / Waste Heat Utilization.

Preliminary report gives an assessment of naturally ventilated residential and small commercial buildings. Describes moveable venetian blind-type ventilation mechanism. Annotated bibliography on heat transfer to be forthcoming.

Chan, Tin, Cook, N. W., and Tsang, C., (1978), Theoretical Temperature Fields for the Stripa Heater Project, Vol. 1, Sept. 1978, LBL-7082 1/2. In Swedish American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock.

Descriptors: Density / Diffusivity / Field Thermal Experiments / Ground Water / Heat / Heat Flow / Heat Flux / Heat Transfer / Heat Transfer Coefficient / Heating / Isotherm / Specific Heat / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (field) / Thermal Resistance / Underground.

Of primary concern is the comparison between point, line and plane heat sources in a granite medium. The variation is greater than a factor of 2, despite identical loadings. Distances were considered up to 10 m. and time projected to 30 years.

1 Kw output	Height = 8 ft.
$k = 2.5 \text{ W/m}^0\text{C}$	Diameter = 1 ft.
Diffusivity = $1.078 \times 10^{-6} \text{ m}^2/\text{s}$	
$P = 2.6 \times 10^3 \text{ kg/m}^3$	

Rock within a 2 m radius of the heater reached a quasi-steady state in 2 years.

The 25% incremental isotherm migrates by less than 1 meter vertically and 2 meters radially in 2 years.

Several field models are set up on paper, and extrapolated in time. Contains graphs for specific isotherms.

Chang, Y.P. and Tsou, R.C.H., (1977) "Heat Conduction in an Anisotropic Medium Homogeneous in Cylindrical Regions - Unsteady State", Journal of Heat Transfer, Vol. 99, No. 1, Part C, February 1977, pp 41-46.

Descriptors: Heat / Heat Transfer / Mass Transfer / Porosity / Conductivity / Heat Flux / Thermal Conductivity / Thermal Calculations / Heat Transfer Coefficient / Heat Model / Heating / Thermal Gradient / Thermal Models / Theoretical Thermal Models / Vapor Transport / Volume

Anisotropic media is divided into 3 classes: 1) The region bounded by 2 or less surfaces which are normal to any one spatial coordinate, 2) The region bounded by surfaces with mixed type boundary conditions with only 2 surfaces normal to any one spatial coordinate, and 3) Mixed boundary conditions on more than 2 surfaces. The authors utilize Green's function in their spatial coordinate set-up, and then obtain the temperature by using Green's formula, - all of which requires computer assistance. The system is then limited to a closed system which is homogeneous in circular cylinder coordinates. They do consider the specific problem of an infinite region bounded internally by a cylindrical surface. They define unsteady state as that set of conditions in which temperature is time dependent. Having stated the possibility of the exact conditions of our in-situ experiment, the authors eliminate those conditions, and work only with the first condition, - as stated above. Page 43, Col. 1 gives the general equation for the hollow cylinder case, but it is not carried through to a solution. In the examples on page 45, the cylinder is subjected to convective heat transfer only.

Corte, Arturo E. (1962), "The Frost Behavior of Soils", In Highway Research Board Bulletin #317. National Academy of Sciences Publication #963, pp 9-34.

Descriptors: Particle Size / Sorting / Density / Thermal Gradient / Translocation / Saturation / Volume

Density change is a function of the initial density and the speed of freezing. A mixed soil sample subjected to freeze-thaw cycles becomes vertically sorted with the fines at the bottom. Energy for the sorting is expended only under a thermal gradient. Larger particles (e.g. stones) move upward. Smaller particles move downward. Density changes are a direct function of the # of freeze-thaw cycles and also the rate of freezing. Volume changes are functions of the No. of cycles. Volume and density changes took place, but much slower, across a thermal gradient without freeze-thaw cycles. Vertical sorting occurs in well-graded materials with or without fines if they are or were saturated.

Davis, J. L. and Annan, A. P., "Electromagnetic Detection of Soil Moisture: Progress Report I", Can. Journal of Remote Sensing, Vol. 3, No. 1, pp 76-86, Dec 1977

Descriptors: Dielectric Constant / Artificial Freezing / Groundwater / Laboratory Thermal Data / Soil Moisture Content / Soil Property Tests / Heat / Time Domain Reflectometry / Soil Types

Using TDR at 10^6 to 10^9 Hz to correlate apparent dielectric constant and moisture

$$k_a = (3.34 \pm 1.05) \exp (4.56 \pm 0.21) m$$

Notes temperature effect for water 1.5°C yields $k_a = 87$ and 35°C yields $k_a = 75$, below zero $^\circ\text{C}$ k_a drops.

Imaginary portions of dielectric constant ignored.

Davis, J.L. and Chudobiak, W.J., "In-Situ Meter for Measuring Relative Permittivity of Soils", Paper 75-1A Geol. Surv. Can., Ottawa, pp 75-79, 1975.

Descriptors: Dielectric Constant / Groundwater / Permittivity / Soil Moisture / Soil Property Tests / Heat / TDR

Describes wideband TDR as a tool for measuring soil moisture content in-situ. Uses a balanced parallel transmission line comprised of two rods augered into the soil. Depth marks are required as speed of light in soil varies. Depths to one meter investigated.

Davis, J. L., "Relative Permittivity Measurements of a Sand and Clay Soil In-Situ", Paper 75-10 Geol. Surv. Can., Ottawa, pp 361-365, 1975

Descriptors: Dielectric Constant / Groundwater / Permittivity / Soil Moisture / Soil Property / Heat / Thermocouples / Time Domain Reflectometry / Soil Types.

Wide band TDR is used to measure moisture content over depths of one and two meters. Data presented show relative permittivity and moisture content as a function of time for a nine month period. Effects of precipitation and freezing are seen. Discontinuities in the rod diameters are used to give depth markers.

$$\epsilon_r = 3 \times 10^8 t^2 / L$$

Thermocouples measure soil temperature. Authors note that TDR rods may have helped cool the nearby soil as much as 5°C during winter weather.

deVries, D. A. (1952), "A Non-Stationary Method for Determining Thermal Conductivity of Soil In-Situ", Soil Science, Vol. 73, No. 2, pp 83-89.

Descriptors: Thermal Conductivity / Thermal Properties Tests (field) / Heat Flow / Heat Transfer / Field Thermal Experiments / Moisture Migration / Electrical Methods / Thermocouple / Conductivity / Heat / Heating / Potential / Thermal Calculations / Soil Depth / Resistivity / Soil Types

deVries introduces a long (known length) electrical wire of known resistance/unit length into homogeneous material. He turns on the electricity for a known time, and measures the rise in temperatures. He then plots the rise in temperature against the log of the time. The slope of this straight line is the thermal conductivity of the homogeneous material in question. The same procedure can be followed after the heat is turned off. If the cold junction of the thermocouple is kept in ice, then all temperature readings can be assumed as increment readings. Current is about 0.1 amp at 6v for about 3 minutes. Accuracy of measurement depends on the accuracy with which the slope is plotted and can be determined. A steep moisture gradient makes for lack of duplication in results. Results are given in $\text{mcal/cm.sec.}^{\circ}\text{C}$ at different depths. The big advantage of the method is its relative rapidity, and ease of measurements.

DeWall, David R. and Chapura, A. M., (1978), "Soil Warming for Utilization and Dissipation of Waste Heat in Pennsylvania", Nuclear Technology, Vol. 38, April 1978, pp 83-89.

Descriptors: Soil types / Heating / Heat Transfer / Waste Heat Utilization / Thermal Power Plants / Crops / Agriculture / Productivity / Plant Growth / Pipes / Underground / Efficiency / Economics / Thermal Conductivity.

This article describes the attempt and evaluates the practicality of utilizing waste heat from a nuclear reactor to warm soil to facilitate farming. A field 15x60 m was used as a prototype.

The network consisted of 26 parallel 60 m long, 50 mm od pE pipes buried at 300 mm depth and 600 mm spacing. Soil was a stony, sandy loam, level and unshaded. Water temperature was 311 to 313⁰K (38-40⁰C) at the inlet. It is assumed the piping system became uniformly heated by the average flow rate equivalent to a Reynolds number of 1900.

Air temperatures measured at 1 m height over the surface of the heated and control plots each day were not significantly affected by the soil warming.

Monthly average heat loss from the buried pipes ranged from a maximum of 91 W/m² in January to a minimum of 41 W/m² in June. Maximum was 100 W/m² nadir was 22 W/m².

In winter, downward heat flow at 1.35 m was generally <2% of the heat loss of the pipe system. Heat loss at the 1.35 m depth was greatest in summer (due to temperature gradient).

Generally, heat was stored in the soil on summer days and lost on winter days.

The 1.35 m depth sensors showed an average heat flux of 1 W/m² in winter and 2 W/m² in summer from the pipes buried at a depth of 30 cm.

(Continued)

DeWall, David R. and Chapura, A. M.

Page 2

Equations (2 types) worked out on pages 87 and 88 assume the thermal conductivity (taken from a table for a soil type) to calculate back to heat loss from the pipes. The thermal conductivity is said to vary with seasons due to moisture variation and temperature gradient variations. The "K" used in the equations varied from 1.90 to 2.38 W/m⁰C.

Donaldson, I. G., (1962) "Temperature Gradients in the Upper Layers of the Earth's Crust Due to Convective Water Flows"; Journal of Geophysical Research, Vol. 67, No. 9, August 1962, pp 3449-3459.

Descriptors: Convection / Density / Ground Water / Heat Capacity / Heat Flow / Heat Flux / Heat Model / Heat Profiles / Heat Transfer / Heat Storage / Isotherm / Moisture Migration / Moisture Transport / Porosity / Soil Depth / Soil Moisture / Thermal Calculations / Thermal Conductivity / Thermal Gradient / Thermal Models / Thermal Properties Tests (lab) / Theoretical Thermal Models / Underground / Vapor Transport / Volume / Water Saturation

Two dimensional flow patterns in a square celled geometry are considered. It is assumed that a permeable layer of the earth's crust is 300 meters thick with a consistent thermal conductivity of 3×10^{-3} cal/cm sec $^{\circ}\text{C}$. The average geothermal flux is assumed to be 10^{-6} cal/cm sec $^{\circ}\text{C}$. These small amounts of heat are claimed to be responsible for the temperature gradients that induce convection in the upper 300 meters of the earth's crust.

Eckert, E.R.G. et. al, "Heat Transfer - A Review of 1977 Literature", International Journal of Heat and Mass Transfer", Vol. 21, pp 1269-1298.

Descriptors: Heat / Heating / Heat Storage / Mass Transfer / Heat Transfer / Porosity / Conductivity / Convection / Film Moisture / Film Transport / Thermal Gradient / Moisture Migration / Moisture Transport / Heat Flux / Stefan's Formula / Heat Model / Isotherm / Thermal Conductivity / Heat Transfer Coefficient / Resistivity / Diffusivity / Nusselt No. / Latent Heat.

This article contains a general review of the 1977 literature divided into 20 pertinent categories. It also contains a section on various symposia held in 1977 with information on the topics covered, and where to get manuscripts or copies of proceedings.

In the section on conduction, Haito and Seki (1977) stress the experimental result of a sudden temperature change at the boundary of a moist porous material. This thermal gradient, they claim, activates a moving interface, which in turn separates wet and dry portions of the material. For the solution of moving boundary problems, a stationary grid of finite elements was used to measure conduction rate in conjunction with finite element models. Temperature conduction in underground cables can be determined from a one-dimensional transient conduction model.

In the section on convection, P. Chang (1977) reported solutions for a uniform heat flux to a fluid in a porous layer with natural convection.

In the section on Heat Transfer Applications, calculations were based on the assumption that the heat transfer coefficient varies according to a power law with distance or temperature.

In the General section mention is made of non-linear heat conduction in pavement structures, of experimental results in Norway, and of transient heat and mass transfer in soils close to heated porous pipes.

The Bibliography of the article is in sections, and very well done.

Elder, J. W. (1967) "Transient Convection in a Porous Medium", Journal of Fluid Mechanics, Vol. 27, Part 3, pp 609-623.

Descriptors: Convection / Density / Film Moisture / Heat / Heat Flow / Heat Flux / Heat Transfer / Isotherm / Laboratory Thermal Data / Moisture Migration / Nusselt No. / Porosity / Saturation / Thermal Calculations / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests (lab) / Vapor Transport / Water Saturation.

This article concerns itself with heat flow via convection in two particular and specific laboratory set-up cases. The first describes both graphically and numerically the heat transfer via convection that takes place when a "blob" of hot fluid (usually an organic) is released at the base of a porous slab. The second case describes the convective flow along with the conductive flow that takes place when only a part of the base of a porous slab is suddenly heated.

Ferrara, A.A., and Yenetchi, G., (1976) Prevention of Preferential Bridge Icing Using Heat Pipes. Final Report. Federal Highway Administration Report No. FHWA-RD-76-167. Federal Highway Administration, Office of Research and Development, Washington, DC 20590, 138 p.

Descriptors: Heat Pipes / Roadway / Deicing / Pilings / Thermal Models / Thermal coupling / Fluid Loops / Corrosion / Solar Collectors / Cost Analyses / Heat Model / Heat Transfer / Heat Flow / Conductivity / Soil Types / Moisture Content (in-situ) / Economics / Heating / Soil Depth / Thermal Calculations / Thermal Conductivity / Heat Pumps.

This document is the final report of an attempt to model and carry out the heating of bridge decks via heat pipes connected into the earth proximate to the decks. Tests were carried out in N.Y.C., Oklahoma City, and Fresno, California.

About 464 Whr/m^2 was required to prevent icing on a cold (below 32°F day). On a spring day when the atmospheric temperature stayed near the freezing point, the heat pipe system was active longer, and about 545 Whr/m^2 (173 Btu/ft^2) were used.

The earth heat pipe length to bridge surface area heated ratio is that of 2:3. The average total energy draw was about 2.05 kwh (6980 Btu). This is about $.4 \text{ m}^2$ of land area/ m^2 of deck area.

Preferential icing occurs when the bridge temperature is below both the freezing and the dewpoint.

Earth temperatures range from 7.2°C to 15.5°C (45°F to 60°F) throughout the contiguous USA.

Joints in the heat pipes have a low maximum value of conductivity of about $14 \text{ W/m}^{\circ}\text{C}$., with a temperature drop of about 2.78°C across the joint.

There is a slight increase in conductivity with heat flow, credited to improved internal fluid film coefficients.

Ferrara, A.A., and Yenetchi, G., (Continued)

Page 2

A 2" nominal heat pipe inserted 65' (19.8m) into the earth would supply $1.14 \text{ kw/m}^2(^{\circ}\text{C})$. This was considered insufficient, and ammonia pumped loops were used to up the conductivity. The fluid loops were buried 3 to 4' for protection against vandalism.

Corrosion of typical heat pipes in the earth depends on soil type and moisture. An average of 0.005" (5 mils)/yr. was the anticipated average design goal. Has graph of expected corrosion rates for both open hearth iron and Bessemer steel vs. soil types, pg. 98.

Low earth temperature limits the allowable spacing between bridge heat pipes to 15 to 23 cm.

Conclusion: for economic reasons 2" pipes should be charged with NH_3 working fluid. Modeling carried out P 124T includes fluid loops and solar panels.

Ferrara, A.A., and Yenetchi, G., (1976) Prevention of Preferential Bridge Icing Using Heat Pipes; Executive Summary, Federal Highway Administration Report No. FHWA-76-168, Sept. 1976, 14 p.

Descriptors: Heat Pipes / Solar Collectors / Deicing / Roadway / Economics / Pilings / Thermal Coupling / Fluid Loopes / Corrosion / Cost Analysis / Heat Model / Heat Transfer / Heat Flow / Conductivity / Soil Types / Moisture Content (in-situ) / Heating / Soil Depth / Thermal Calculations / Thermal Conductivity / Heat Pumps

This document is a report preparatory to the final report, which is annotated as FHWA-RD-76-167, as document #21, by the same authors.

Fritton, D. D., Busscher, W. J. and Alpert, J. E. (1974), "An Inexpensive But Durable Thermal Conductivity Probe for Field Use", Proc Soil Science Soc. Amer., Vol. 38, pp 854-855, 1974.

Descriptors: Cost Analysis / Field Thermal Experiments / Heat Transfer Coefficient / Thermal Conductivity / Thermal Coupling / Thermal Properties Tests (lab) / Thermocouples.

Construction details of a fieldable thermal conductivity needle.

Frivik, P.E., Thorbergsen, E., Guidice, S.D., and Comini, G., (1977)
"Thermal Design of Pavement Structures in Seasonal Frost Areas", Journal
of Heat Transfer, Vol. 99, Nov. 1977, pp 533-540.

Descriptors: Roadway / Moisture Migration / Heat Transfer / Heat Model /
Heat Flow / Soil Moisture / Density / Moisture Transport / Conductivity /
Thermal Gradient / Thermal Calculations / Radiation (thermal) / Thermal
Properties Tests (field) / Thermal Conductivity / Heat Capacity / Latent
Heat / Soil Texture / Saturation / Convection / Heat Flux / Theoretical
Thermal Models / Thermal Diffusivity / Isotherm / Deicing/ Heat Profiles

This article discusses some computer-assisted experimentation which took place in Norway. A control and an insulated roadway were built and instrumented. It was found that in a two dimensional analysis, heat from the road boundaries does not reach the center on a "typical" January winter day. The insulation and drainage proposed was sufficient to prevent under road-bed freezing and consequent heave. The article contains little or not information on in-situ thermal properties of soils. A field under snow cover, adjacent to the test roadbed was monitored for freezing depth and "cryosuction", but not for temperature profiles.

Geiger, Rudolf (1965), The Climate Near the Ground, Harvard University Press, Cambridge, Mass. (1965), 611 p.

Descriptors: Agriculture / Artificial Freezing / Coefficient of Blackness / Conductivity / Convection / Crops / Density / Economics / Efficiency / Field Instrumentation (moisture) / Field Thermal Experiments / Ground Water / Heat / Heat Capacity / Heat Flow / Heat Pipes / Heat Profiles / Heat Storage / Heat Transfer / Heating / Isotherm / Lake Influence / Latent Heat / Moisture Content (in-situ) / Moisture Migration / Plant Growth / Porosity / Productivity / Radiation / Roadway / Saturation / Soil Depth / Soil Moisture / Soil Refrigeration / Soil Texture / Soil Types / Solar Collectors / Specific Heat / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests (field) / Thermocouples / Vapor Pressure / Void Ratio / Volume / Waste Heat Utilization / Water Saturation

Section 1 points out that the coarser the ground particles, the deeper the sun's rays penetrate. The more grass cover there is, the more moisture, and consequently the cooler the particles will be. Moisture retards radiant heating. Temperature increases: $3^{\circ}\text{C}/\text{m}$ of earth depth. The upward flow of heat is about $1 \times 10^{-4} \text{ cal}/\text{cm}^2 \text{ min}$. (pg 26). The density of ground samples varies directly with thermal capacity and is greatly affected by water content (pg 28). Technical definition of thermal conductivity on pg 30. Penetration depth of surface temperature fluctuation on pgs. 33 is of importance to our study. Depth of the daily heat wave into the ground averages 30 cm, assuming no ground cover (pg 56 - chart). The annual variations penetrate to a depth of several meters. The wave front velocity is on the order of 1 cm/hour, being displaced approximately 12 hours at a depth of 30 cm (2.5 cm/hr) for diurnal variation and 6 months at a depth of 12 meters (0.3 cm/hr) for the annual variation. Tautochrones on an undisturbed summer day - (pg 57 - chart). There is great influence from solar radiation in heat measurements taken at the top of the soil (pg 89). Pg 171 points out the "to be expected" daily variation of both thermal conductivity and thermal diffusivity.

Goldsmid, H. J., and Bowley, A. E. (1960), "Thermal Conduction in Mica Along the Planes of Cleavage", Nature, Vol. 187, Sept. 3, 1960, pp 864-865.

Descriptors: Density / Diffusivity / Heat / Heat Flow / Heat Flux / Heat Transfer / Heat Transfer Coefficient / Laboratory Thermal Data / Thermal Conductivity / Thermal Properties Tests (lab) / Thermocouples / Thermal Diffusivity / Thermal Resistance / Specific Heat.

The authors cemented (araldite) planes of phlogopite into a block between copper plates. Temperatures were measured at varied distances with thermocouples along the cleavage planes. A specific heat of 0.86 joule/gm °C was assumed. Experimental results between -85° and 35°C were consistent. The thermal conductivity of 0.05 w/cm °C is about an order of magnitude larger than the results for measurements perpendicular to the lines of cleavage.

Hadas, A. (1974) "Problems Involved in Measuring the Soil Thermal Conductivity and Diffusivity in a Moist Soil", Agricultural Meteorology, Vol. 13 Pub. Elsevier, Amsterdam pp 105-113, 1974.

Descriptors: Critical Diameter / Diffusivity / Field Thermal Experiments / Heat Flow / Heat Flux / Heat Transfer / Heat Transfer Coefficient / Heating / Moisture Migration / Moisture Transport / Porosity / Resistivity / Soil Moisture / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (field) / Thermal Resistance / Thermocouples / Underground.

Discussion of probe/soil contact surface resistance and moisture migration effects on diffusivity and conductivity measurements. Planer or cylindrical probes may be used in moist soils provided that low thermal outputs of short duration are used.

Holman, Jack P., (1976); Heat Transfer, McGraw-Hill, New York, 1976
(4th ed.) 530 p.

Descriptors: Heat / Heat Transfer / Conductivity / Convection / Radiation / Thermal Calculations / Thermal Conductivity / Stefan's Formula / Capacitive Moisture Transducer / Density / Diffusivity / Electrical Methods / Film Moisture / Film Transport / Graetz No. / Groundwater / Heat Capacity / Heat Flow / Heat Flux / Heat Transfer Coefficient / Heating / Laboratory Thermal Data / Latent Heat / Mass Transfer / Moisture Migration / Nusselt No. / Porosity / Resistivity / Saturation / Soil Moisture / Soil Types / Specific Heat / Thermal Capacity / Thermal Conductivity / Thermal Gradient / Thermal Models / Thermal Properties Tests (lab) / Thermal Resistivity / Vapor Pressure / Void Ratio / Volume/Water Saturation / Solar Collectors

Textbook on understanding of the non-equilibrium states of heat transfer. Chapter 1 has a good explanation of the SI units usage in heat transfer. Chapter 3 has an excellent review of numerical analyses for varied geometric configurations of heaters, with different boundary constraints. Most of these examples are solved via the relaxation method. Solution techniques are given for Cartesian, Cylindrical and Spherical coordinate systems. Chapter 4 (Section 4) treats convection boundary conditions. The same chapter references software for solving heat flow problems. Chapter 5, Section 39, has a good presentation and comparison of the SI units vs. the English units for describing heat transfer. Sections 46 and 47 of the same chapter apply to our research in that they deal with film transport temperature and give calculations for the same. Chapter 7 discusses convection from various geometric configurations, including cylinders, but with the assumption that the cylinders are standing free in air.

In Chapter 8, Section 7, the geometric configuration of concentric cylinders with the area of the larger cylinder much more than the area of the

Holman, Jack P. (1976)

Page 2

smaller cylinder has applications in our field set-up. Chapter 10 deals with heat exchange, but within a very limited geometric configuration, and almost exclusively in a housing or home set-up.

Chapter 11, on Mass Transfer, assumes a turbulent flow as characteristic of or a prerequisite for the mass transfer. This does not hold true for our in-situ experimentation. Page 511 has useful SI conversion Units.

Horai, Ki-iti (1971) "Thermal Conductivity of Rock-Forming Minerals", Journal of Geophysical Research, Vol 76, No. 5, Feb. 10, 1971, pp 1278-1308.

Descriptors: Thermal Conductivity / Soil Types / Soil Moisture / Density / Conductivity / Thermal Properties Tests (lab) / Heat Flow / Thermal Gradient / Saturation / Thermal Calculations / Heat / Heat Transfer Coefficient / Laboratory Thermal Data / Dielectric Constant

The author took 166 rock forming minerals, and determined the thermal conductivity of each, using a heat probe, a powdered aggregate and distilled water. Water made up about 33% of the volume. Horai justifies his results with similar data to be found in the literature. His lab methodology appears relatively simple and straight forward.

His results are between 1 and 30 mcal/cm.sec.^{°C}. Horai experimented further and found that conductivity decreases with increasing mean atomic weight. As minerals change in composition, the thermal conductivity varies and reaches a media between phase types or during intermediate composition. Investigations were also carried on for the thermal conductivity variances in the carbonates and the polymorphs, and silica materials. These were all done in a laboratory setup. Thermal conductivity increases with increasing density, as Woodside (1961) showed with compressed sandstone.

Horton, C. W., and Rogers, F. T., "Convection Currents in a Porous Medium", Journal of Applied Physics, Vol. 16, June 1945, pp 367-370.

Descriptors: Convection / Field Thermal Experiments / Heat Flux / Heat Transfer / Soil Property Tests / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Translocation.

The prerequisites for convection in a porous media heated from below are mathematically set forth. These conditions are then applied to the Woodbine Sand of East Texas. Since the distribution of NaCl in the area cannot be explained, convection most probably played a part in its distribution in this geographical area.

Jumikis, A. R., (1962) "Effective Soil Moisture Transfer Mechanisms Upon Freezing", In Highway Research Board Bulletin #317, National Academy of Sciences, Publication #963, pp 1-8.

Descriptors: Soil Moisture / Moisture Transport / Film Transport / Vapor Transport / Thermal Gradient / Translocation / Porosity

This paper compares soil moisture transport via film mechanism and the vapor phase. Under the influence of a temperature gradient, soil moisture flows toward the cold front via film coated soil particles.

The mechanical work performed in moisture transport per absorbed unit of volume of water by the soil is independent of the type of driving force(s), and holds for all types of soils.

Vapor transport is secondary to film transport, and decreases with decreasing soil particle size. Within a range of $n = 27.8\%$ to 47.8% , the soil moisture transport is via the unsaturated or film flow. Between $n = 60\%$ to 100% the effective soil moisture transport is via vapor diffusion, and about $1/5$ the volume of the film transport.

The smaller the soil porosity, the greater the film transport to the cold front.

Jumikis, Alfreds R. (1966), Thermal Soil Mechanics, Rutgers University Press, New Brunswick, NJ, 1966, 267 p.

Descriptors: Moisture Migration / Potential / Streaming Potential / Thermo-osmosis / Heat / Isotherm / Latent Heat / Heat Capacity / Thermal Diffusivity / Thermal Resistance / Thermal Conductivity / Conductivity / Convection / Radiation / Stephan's Formula / Coefficient of Blackness / Critical Diameter / Soil Firing / Vapor Pressure / Film Moisture / Artificial Freezing Functions / Soil Refrigeration / Thermal Calculations / Tautochrones.

Classical discussion of thermal osmosis as the process of moisture migration in soil (or any porous media) by means of a thermal gradient. Discusses the various mechanics by which moisture moves in soil from warm to cool places. These means include electro-osmosis, an induced secondary potential, thermal gradients, freezing processes, vapor pressure, and filming.

Streaming potential is defined as an induced secondary potential, or the cation flow in the direction of a system's temperature drop. Thus, it is the converse of electro-osmosis.

Deals at length with the rate of heat flow across a given area or through a given thickness. This rate is described as directly proportional to the cross-sectional area, and to the temperature gradient. It is inversely proportional to the thickness or distance. The examples given and problems all deal with an assumed homogeneous matter that is either freezing or thawing in addition to the transfer of heat.

Gives good examples of Stephan's formula as applied to a cylinder which has a degree of "blackness", where 100% or 1.00 means all heat is absorbed. If a cylindrical substance has a "blackness" of 0.85, this indicates that 85% of the heat is absorbed, and 15% is reflected.

$$\xi = \frac{\sqrt{2KT}}{L_p} \cdot \sqrt{t.}$$

(Continued)

Jumikis, Alfreds R. (1966)

Page 2

Has a section on the temperatures of electric wires, assuming a constant current. The temperature of an insulated wire is less than the temperature of the same wire type insulated if the diameter of the insulated wire is less than the "critical" diameter of the insulation. The calculation of the criticality for the insulation diameter was not discussed in this reference.

The finer the material, the more important the role of film transport plays (as opposed to vapor transport).

Kayan, D.F. "An Electrical Egometrical Analogue for Complex Heat Flow"
Trans. ASME, Heat Transfer Div., pp. 713-718 Nov. 1945

Descriptors: Heat / Heating / Heat Flow / Electrical Methods / Isotherm /
Heat Model / Potential / Resistivity / Thermal Calculations / Film Moisture /
Film Transport / Thermal Capacity / Void Ratio / Thermal Properties (lab)

Proposes use of electrical analogue for heat flow problems having difficult geometry. Notes that can model transient flow if have capacitance in the system, steady state with simple resistive sheet cut to appropriate form. Example given includes resistive film to model interface between air and solid.

Use of electrolytic bath instead of conductive sheet - may incorporate materials of different conductivity by using a non-conductive porous filler (e.g. sand) for the more resistive portions, or a jellied electrolyte with differing concentrations of salt. For convenience, use both liquid and jelly to get good contact between materials.

Obtains higher resistivity in sheet by cutting a mesh. For anisotropic material, could use a mesh with rectangular openings rather than square.

Kersten, M. S., 1949, Laboratory Research for the Determination of the Thermal Properties of Soils. Engineering Experiment Station, University of Minnesota. From NTIS: AD712516.

Descriptors: Thermal Properties (lab) / Thermal Conductivity / Specific Heat / Diffusivity / Soil Types / Density / Moisture Content / Thermocouples / Thermal Gradient / Heat / Heating / Heat Capacity / Heat Flow / Heat Transfer / Heat Transfer Coefficient / Laboratory Thermal Data / Moisture Transport / Porosity / Soil Firing / Thermal Calculations / Void Ratio.

This is pioneering work in laboratory determination of soil thermal conductivity and heat capacity. Conductivity test apparatus based upon an annular specimen 6 cm. ID by 14 cm OD by 51 cm tall, with heat source on the interior and heat sink (constant temperature bath) on the outer cylindrical surface. Specimen ends insulated and guard heaters 10 cm. in length on both ends, leaving the central test heater 30 cm. in length. Conductivity tests were made by establishing a 10 deg. F temperature difference across the specimen radius, and measuring the thermal input. The primary fault of the test method is the many hours required to reach equilibrium. Moisture migration occurred in the wet soils across the thermal gradient, and to some extent, vertical moisture migration under the influence of gravity in the more porous soils.

Specific heat capacity was measured by bringing a soil sample to equilibrium at a temperature different than that of a calorimeter, and placing the soil directly into the calorimeter. The calorimeter temperature was recorded at one minute intervals, starting 12 minutes prior to introduction of the loose soil. With this configuration, intimate mixing of the calorimeter water and soil is assured, with rapid test results, but the heat of wetting must be subtracted from the temperature change that occurs when the hot soil is placed in the bath.

(Continued)

Kersten, M. S. (Continued)

Page 2

Primary factors affecting conductivity were found to be moisture content and dry density. Secondary effects were seen to be due to soil type, mineralogical content, temperature. Grain size did not affect soils of constant mineral content, but grain angularity did.

Heat capacity of all dry soils was found to be dependent only upon temperature. Heat capacity of wet soils found by the ratio of soil and water masses present.

Dimensions: $K = \text{BTU}/^{\circ}\text{F in. ft}^2 \text{ hr}$

Heat capacity given as Specific Heat capacity (Dimensionless).

Lurie, David and Wagensberg, J. (1980). "Concepts of Non-equilibrium Thermodynamics in Discrete Model of Heat Conduction", American Journal of Physics, Vol. 48, No. 10, Oct 1980, pp 868-872.

Descriptors: Heat Flow / Heat Model / Conductivity / Specific Heat / Density / Thermal Gradient / Volume / Heat Transfer / Thermal Calculations.

The concepts of nonequilibrium thermodynamics are introduced through the example of one-dimensional conduction in a bar. Numerical solution of entropy balance equations are generated for volume and time elements, and compared with a Fourier solution for a similar diffusion problem. Time histories are given temperature distributions relaxing from various initial distributions to a minimum entropy productions condition.

McGaw, R. W., Outcalt, S. I., and Ng, E., "Thermal Properties and Regime of Wet Tundra Soils at Barrow, Alaska", Proc 3rd Intl Conf Permafrost, Edmonton, Alberta, Canada, Vol. I pp 48-53, July 10-13, 1978.

Descriptors: Density / Diffusivity / Field Instrumentation (moisture) / Field Thermal Experiments / Heat Capacity / Heat Transfer Coefficient / Isotherm / Moisture Content (in-situ) / Moisture Migration / Resistivity / Soil Depth / Soil Moisture / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Properties Tests (field) / Thermal Resistance / Thermocouples / Underground.

Laboratory and field measurements of thermal conductivity using a thermal needle, and field measurements of soil temperature. Description of thermal needle and thermistor array (mounted in acrylic fixture). Developed apparent diffusivity data from finite difference approximations to depth-time-temperature matrix. Apparent diffusivity defined by: α'

$$\alpha' \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t}$$

Millard, D. J. (1952), "The Electrical Measurement of Moisture in Granular Materials", British Journal of Applied Physics, Vol. 4, March 1953, pp 84-87.

Descriptors: Electrical Methods / Capacitive Moisture Transducer / Soil Types / Moisture Content / Particle Size / Dielectric Constant / Conductivity

Millard discusses the variation in conductivity in coal and varied soil types due to variations in moisture content. He then points out the value of "independent" measurements of capacitance, leading to the dielectric constant as an indicator of moisture content. A working and allowable range of 27.1 Mc/s was chosen, and gave desirable and workable results.

Mitchell, J.K. and Kao, T.C. "Measurement of Soil Thermal Resistivity" proc. Am Soc Civil Engineering, Journal of Geotechnical Engineering, Vol. 104, No. GT 10 pp 1307-1320, Oct 1978.

Descriptors: Heat / Heating / Heat Transfer / Diffusivity / Resistivity / Conductivity / Thermal Capacity / Thermal Properties Tests (lab) / Heat Transfer Coefficient / Moisture Migration / Thermal Gradient

Short review of methods for measurement of conductivity, capacity (and diffusivity). Prefers thermal probe (quick, applicable to lab or field, doesn't require knowledge of C to get k,) and that of Shannon and Wells for diffusivity.

Shannon & Wells - Bring soil sample to temperature equilibrium at temperature T_1 , then place in a bath at temperature T_2 . Specimen has insulated ends, triaxial membrane to avoid wetting and give radial flow. Measure temp/time at center, get k from chart & assumed C.

Discusses briefly guarded hot plate, annular device, called "Rhometer" and a dual hot plate (one hot and 2 cold, with two specimens). Disadvantages are lengthy time required for test, making possible moisture migration.

Discusses possible errors in design of thermal probe, comparing the probe to theory, as represented by a finite element program "HEAT".

Mitchell, James K. and Abdel-Hadi, O. N., (1979), "Temperature Distributions Around Buried Cables" (1979) IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 4, July/Aug 1979, pp 1158-1166.

Descriptors: Critical Diameter / Density / Field Thermal Experiments / Groundwater / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Model / Heat Profiles / Heat Transfer / Heat Transfer Coefficient / Heating / Isotherm / Moisture Content (in-situ) / Moisture Migration / Resistivity / Soil Depth / Soil Moisture / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (field) / Underground

Methods for analysis of temperature distributions around buried power cables are reviewed. The cable trench backfill material differs in type and in thermal resistivity from the surrounding soil. The trench has a rectangular box configuration but the isotherms from the cable in the trench are roughly cylindrical. Estimation of moisture content in the area surrounding the cable is essential because the thermal gradient causes changes in moisture content and consequent changes in thermal resistivity. Resistivities for varied trench configurations showed little effect on the overall thermal resistivity. Trench depth was about 1.25 meters. Wind velocity and solar radiation effects were noted at this depth. Computer program HEAT by Professor Taylor is capable of handling the 3-dimensional array system, and solving for the coefficient of thermal conductivity.

Palm, E., Weber, J. E., and Kvernold, O. (1972) "On Steady Convection in a Porous Medium", Journal of Fluid Mechanics, Vol. 54, 1972, Part 1, pp 153-161.

Descriptors: Convection / Density / Diffusivity / Heat Flow / Heat Model / Heat Transfer / Isotherm / Laboratory Thermal Data / Particle Size / Porosity / Thermal Calculations / Thermal Diffusivity / Thermal Gradient / Thermal Models / Thermal Properties Tests (lab) / Vapor Transport / Nusselt No.

Discussion of convection in a porous medium composed of glass beads. Water was used in one experiment, and turpentine in the other two experiments. Isotherms were plotted, and the Nusselt and Rayleigh Numbers were compared. The assumption was made that the friction and buoyancy forces were opposite and equal, and therefore cancelled each other out. Calculations for heat transfer as fourth-order equations are given in detail.

Pearce, D. C. and Gold, L. W. (1959) "Observations of Ground Temperature and Heat Flow at Ottawa, Canada"; Journal of Geophysical Research, Vol 64, No. 9, Sept. 1959, pp 1293-1298.

Descriptors: Conductivity / Density / Diffusivity / Field Thermal Experiments / Heat / Heat Capacity/ Heat Flow / Heat Flux / Heat Storage / Heat Transfer Coefficient / Heating / Isotherm / Latent Heat / Moisture Transport / Permittivity / Resistivity / Saturation / Soil Depth / Soil Moisture / Thermal Calculations / Thermal Capacity / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (field) / Thermal Resistance / Thermocouples / Underground / Water Saturation.

Temperature measurements were taken daily via thermocouples at various depths for a year in Ottawa, Canada. Depths ranges from 5 cm (about 2") to just over 3 ft. As Geiger explains in his Climate Near the Ground, the measurements of the first 12" were greatly influenced by the soil-air interface. The k value was found to be between 1 and 10 Cal/cm $^{\circ}\text{C}$ hr. The authors concluded that the thermal conductivity of the soil could be described as a periodic function which was barely influenced by snow cover. The mean temperature to 90 cm varied almost linearly with depth.

Penner, E. (1962), "Thermal Conductivity of Saturated Leda Clay", Geotechnique, Vol. XII, No. 2, June 1962.

Descriptors: Thermal Conductivity / Soil Moisture / Soil Texture / Soil Property Tests / Density / Thermal Properties (lab) / Soil Types / Heat Flow / Porosity / Thermocouples / Thermal Gradient / Potential / Moisture Sensing / Conductivity / Moisture Content / Volume / Particle Size / Water Saturation.

In this paper, Penner examines the thermal conductivity of saturated Leda Clay, and extrapolates his results to solid clay. The experiment was carried out in the laboratory in a 6" diameter mold up to 4" with remolded clay. The highest consolidation load on the saturated clay was 21 tons/sq.ft. A 2" specimen was then cut and used for the actual test. Penner bases his calculations on those of Kersten (1949), but found his results considerably higher. Penner attributes this result to the high mica content in his samples. His results are consistently reported in the English System units of B.T.U./in.sq.ft.hr.^{°F}, and have to be transferred to SI units. His values are approximately between 1 and 10 B.T.U./in.sq.ft.hr.

Prakouras, A. G., et al, (1978) "Thermal Conductivity of Heterogenous Mixtures"; International Journal of Heat and Mass Transfer, Vol. 21, 1978 pp 1157-1166.

Descriptors: Thermal Conductivity / Conductivity / Heat Model / Heat Flux / Thermal Gradient / Isotherm / Thermal Calculations / Heat / Heat Transfer / Heat Flow / Porosity / Particle Size / Volume / Heat Profile / Resistivity / Void Ratio / Radiation / Soil Texture / Electrical Methods; / Heat Capacity / Heat Transfer Coefficient / Heating / Laboratory Thermal Data / Thermal Models / Theoretical Thermal Models.

The authors take great care in pointing out the complexity of solving heat transfer problems. They describe approaches using Ohm's law models or flux law models, and then explain the shortcomings of each, which leaves the direct numerical analysis approach. The numerical development is pursued via a constant density function random number generator to predict numerically the thermal conductivity of heterogeneous mixtures. This model includes the effect of contact areas between the particles, the effect of contact areas between the particles, the effect of reduced pressure, and the influence of radiation heat transfer.

Pravda, M.F. et.al. (1978), Augmentation of Earth Heating for Purposes of Road Deicing. Final Report - Federal Highways R&D Report #FHWA-RD-79-81, December 1978. 193 p.

Descriptors: Deicing / Roadway / Solar Collectors / Heat Capacity / Economics / Heat Model / Heat Storage / Heat Pipes / Pipes / Cost Analysis / Thermal Conductivity / Thermal Coupling / Thermal Calculations / Underground / Thermal Gradient / Thermal Properties Tests (field) / Thermocouples / Thermal Model

This report describes in detail how Earth heat has been used to warm a bridge deck to prevent icing and thaw snow and ice. The pipes were one inch schedule 40 iron pipes, (.106m o.d.) about 75' long, containing a helical coiled spring, and anhydrous ammonia, with the ends welded shut. There was, on the average, 1 ft. of pipe length per sq. ft. of pavement area. The system could deliver up to 146 W/m^2 , and performed quite well. After 3 winters of operation the average temperature in the middle of the earth's field has dropped 1.2°C as compared with control plots. Thus, it is evident that the majority of the heat lost in winter is replaced in summer. Computer studies indicate that after 6 years further decreases in the average earth temperature become insignificant.

Pravda, M. F. and Marjon, P. L., (1975), "Snow and Ice Removal from Pavements Using Stored Earth Energy", Federal Highway Administration Report No. FHWA-RD-75-6, 1975, 27 pp.

Descriptors: Artificial Freezing / De-icing / Economics / Electrical Methods / Field Thermal Experiments / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Pipes / Heat Pumps / Heating / Isotherm / Pilings / Pipes / Roadway / Soil Depth / Thermal Capacity / Thermal Gradient / Thermal Properties Tests (field) / Thermal Resistance / Thermocouple / Underground / Waste Heat Utilization.

This project studied the feasibility of using waste heat from fission products to keep roadways clear of snow and ice, but was abandoned largely because of the stringent safety measures required.

Hollow heat pipes sealed with a working fluid and a "wick" were used to connect the earth to a roadway slab for de-icing purposes. Calculations indicate a need for 85 ft^3 of earth contact to each ft^2 of roadway. This brought about snow melting rates up to $1\frac{1}{2}$ " per hr. when ambient temperatures were below freezing. The stored energy in the earth was calculated to be about $40 \text{ BTU/ft}^3 \text{ } ^\circ\text{F}$. The typical value for total resistance for average soil and concrete is 0.1°F/watt . The experiment is being continued to determine the extent of earth heat storage recover during the warm summer months.

Raudkivi, A. J. and Van U'u, N., (1976), "Soil Moisture Movement by Temperature Gradient", Journal of the Geotechnical Engineering Division, December 1976, pp 1225-1244.

Descriptors: Convection / Film Moisture / Film Transport / Ground Water / Moisture Migration / Moisture Transport / Porosity / Soil Moisture / Soil Texture / Thermal Gradient / Thermo-osmosis / Underground / Vapor Transport / Void Ratio / Water Saturation / Roadway.

Stresses the fact that a thermal gradient causes moisture movement in both liquid and vapor form. Thermo-self-diffusion at the molecular level causes moisture transport to the cooler regions. Slippage flow occurs when pore radii are nearly equal to the mean free path of the molecules. The amount of moisture transfer due to thermal gradients is maximum when the initial saturation is about 20%. Main applications are to roadbeds. Excellent bibliography.

Rogers, F.T., and Morrison, H.L. (1950), "Convection Currents in Porous Media, III. Extended Theory of the Critical Gradient", Journal of Applied Physics, Vol. 21, Nov. 1950, pp 1177-1180.

Descriptors: Convection / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Transfer / Heat Transfer Coefficient / Heating / Laboratory Thermal Data / Diffusivity / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (lab) / Thermal Resistance / Vapor Pressure / Vapor Transport.

This article is a continuation and a refinement of the material contained in document #68 by Horton & Rogers. The object of the experiment was to define as closely as possible the critical values and ranges of the parameters which will induce convection in a given fluid. The authors did a few experiments with water, but most of their work was done with organic solvents.

Saito, H. & Seki, N., "Mass Transfer and Pressure Rise in Moist Porous Material Subjected to Sudden Heating" Trans. ASME Journal of Heat Transfer, Part C, pp 105-112, Feb 1977.

Descriptors: Mass Transfer / Porosity / Moisture Content / Moisture Transport / Latent Heat / Water Saturation / Heat Transfer / Vapor Transport / Thermal Calculations / Heat Model / Thermal Gradient / Vapor Pressures.

Presents finite difference solution for heat and mass transfer in one-dimensional porous material. Model is for sand casting. Assumption of low degree of saturation may invalidate results for our purposes. Mechanisms active include evaporation of moisture and recondensation at the leading edge of the dry region boundary, leading to increased moisture content immediately beyond that point. Temperature distribution is concave up, decreasing from surface to boundary of dry region, then concave down for a short depth beyond - latent heat being released tends toward a plateau - and then concave up decreasing toward uniform initial low temperature at depth. Pressure in the dry region is constant across depth. In effect, moisture at the moving boundary between wet and dry evaporates, moves to the wet side and condenses, delivering the latent heat just beyond the boundary. Data from lab test is included for comparison with predicted pressures at various depths.

Sass, J. H. (1965), "The Thermal Conductivity of Fifteen Feldspar Specimens", Journal of Geophysical Research, Vol. 70, No. 16, Aug. 15, 1965, pp 4064-4065.

Descriptors: Heat Flow / Heat Transfer Coefficient / Laboratory Thermal Data / Soil Types / Thermal Conductivity / Thermal Properties Tests (lab).

The author measured the thermal conductivity perpendicular to the optic axis of 15 selected feldspar specimens. His results have a mean value of 5.9 ± 0.2 mcal/cm sec.⁰C. Previously reported and accepted values were $4.5 \pm 2\%$. The work was done at 25⁰C with aggregate grain size 1 to 1 mm.

Sass, J. H. and Munroe, R. J. (1970) "Heat Flow from Deep Boreholes on Two Island Arcs", Journal of Geophysical Research, Vol. 75, No. 23, Aug. 10, 1970, pp 4387-4395.

Descriptors: Field Thermal Experiments / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Storage / Particle Size / Radiation / Soil Depth / Soil Property Tests / Soil Types / Thermal Conductivity / Thermal Gradient / Underground.

Temperature profiles with depth were made in 5 deep boreholes. Temperatures differed slightly, but increased with depth in all cases. Some of the temperature variations, especially near the crust of the earth, are attributed to the heat produced by radioactive decay. This heat is measured in heat forming units (hgu) equal to 10^{-13} sec.

Schrauf, T., Pratt, H., Simonson, E., Hustrulid, W., Nelson, P., DuBois, A., Binnall, E., and Haught, R. (1979), "Instrument Evaluation Calibration, and Installation for the Heater Experiments at Stripa", LBL-8313, Swedish American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock, Technical Information Report No.25, DOE Contract W-7405-ENG-48.

Descriptors: Density / Efficiency / Field Instrumentation (Moisture) / Field Thermal Experiments / Groundwater / Heat / Laboratory Thermal Data / " Resistivity / Soil Depth / Thermal Coupling / Thermal Properties Tests (lab) / Thermocouples / Underground.

This article is devoted to the stringent quality control and quality assurance test methods for the instrumentation to be used in the Stripa experiment. Holes bored for expansion measurements were backfilled with fiberglass. Holes for thermal measurements were all backfilled with sand. Grout (standard) was used for anchoring instrumentation for the creep tests.

Selig, E.T, and Mansukhani, S. "Relationship of Soil Moisture to the Dielectric Property", Journal of the Geotechnical Engineering Division, Vol 101, No. GT8, Aug. 1975, pp 755-770.

Descriptors: Moisture Content / Field Instrumentation (moisture) / Heat / Dielectric Constant / Electrical Methods / Moisture Sensing / Resistivity / Capacitive Moisture Transducer / Permittivity

This article is devoted to the methods, calculations, and reliability of remotely sensing moisture content of soil in-situ by means of the dielectric constant. Electrical resistance has been used for at least 70 years to remotely monitor in-situ soil moisture, but is not accurate enough for engineering purposes. The dielectric constant is very dependent on the amount of moisture present. The authors experimented with various soil types in a 100 Hz to 10 MHz frequency range as most reliable for their desired sensitivity of readings. Sensitivity of readings increases as moisture content increases. The article contains an excellent literature review on various experiments to determine the in-situ soil moisture content via the dielectric constant. Other investigators (Mitchell et al, Davis et al) have found that soil type, bound water and pore water chemistry affect the dielectric constant in this frequency range, necessitating detailed calibration if maximum precision is to be obtained.

Small, R.D. and Weihs, D., "Thermal Traces of a Buried Heat Source", Trans. ASME Journal of Heat Transfer, Feb 1977, pp 47-52.

Descriptors: Thermal Gradient / Thermal Calculations / Convection / Heat Transfer / Conductivity / Film Moisture / Film Transport / Isotherm / Heat Transfer Coefficient / Thermal Properties Tests (lab) / Thermal Models / Heat / Heat Profiles / Laboratory Thermal Data / Soil Depth / Thermal Conductivity / Theoretical Thermal Models.

Closed form solution for buried spherical heat source. Heat transfer at surface by convection film. Problem approached via bi-spherical coordinate system which is everywhere normal to both the ground surface and the buried heat source.

The heated sphere in this experimental set-up is situated very close to the surface. Only 3% of the sphere is buried at its uppermost point. Provision is made near the end of the article (p 50, col. 2) to transform the sphere into a cylinder, maintaining the same biospherical coordinate system.

Smith, W.O. (1942), "The Thermal Conductivity of Dry Soil", Soil Science, Vol. 53, 1942, pp 435-459.

Descriptors: Thermal Properties Tests (lab) / Porosity / Heat Transfer / Soil Moisture / Heat Flow / Soil Types / Thermal Conductivity / Density / Thermal Calculations / Thermal Resistance / Sorting

Smith works with variables in soil types and variable porosities, but with dried samples in a lab set-up. He concludes that soils with a low porosity are the best heat conductors, and that open soils are poor conductors. His thermal conductivity data are given in (Cal/cm. sec. deg. C.). Smith's lab apparatus takes soil bounded by 2 parallel planes, with k in only 1 direction, normal to these planes. He compares calculations in structureless soil to that in a structured soil. In each case a soil volume is considered to be homogenous, dry, of only 1 soil type and containing a "certain" volume of air within its pores. Calculations are given for granular, platy and blocky soil structures, with assumptions made about the air spaces in the various samples. Moisture is not a factor in the derivations given. Thermal conductivities of a low of 1.6×10^{-4} cal/cm. sec. deg. C., to a high of 9.15×10^{-4} cal/cm. sec. deg. C. are reported. Thus all results are within an order of magnitude for the soil types used. Smith concludes that thermal resistance is directly dependent on the shape of the pore spaces, and differs between a lab and an in-situ set-up.

Straus, Joe M. (1974) "Large Amplitude Convection in Porous Media",
Journal of Fluid Mechanics, Vol. 64, 1974, Part 1, pp 51-63.

Descriptors: Convection / Density / Heat Flow / Heat Flux / Heat Model / Isotherm / Laboratory Thermal Data / Nusselt No. / Porosity / Saturation / Thermal Calculations / Thermal Diffusivity / Thermal Models / Thermal Properties Tests (lab) / Thermal Resistance / Vapor Transport / Thermal Gradient.

A continuation of the work done by Elder (1967), Palm (1972) and Busse (1972). The thermal gradient acts as the driving force for the convective action. Thermal calculations concerning the thermal stability of the finite amplitude two-dimensional solutions are given. The experimental set-up for these calculations is a square box with definite boundary influences.

Straus, J. M. and Schubert G. (1977), "Thermal Convection of Water in a Porous Medium: Effects of Temperature and Pressure - Dependent Thermodynamic and Transport Properties." Journal of Geophysical Research, Vol. 82, No. 2, Jan 10, 1977, pp 325-333.

Descriptors: Convection / Density / Heat Flow / Heat Flux / Heat Model / Isotherm / Laboratory Thermal Data / Nusselt No. / Porosity / Saturation / Thermal Calculations / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests / Vapor Pressure / Vapor Transport / Water Saturation.

This article considers water in a porous medium with attention to which parameter variations are responsible for the onset of turbulence; which signifies convection. The water in the experiment is assumed to have the properties of surface water, which limits applications of the results. The heat flux for the entire earth is given as an approximate average of $1.5 \text{ W cal/cm}^2 \text{ sec}$.

Topp, G. C., Davis, J. L., and Annan, A. P., "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines", Water Resources Research, Vol. 16, No. 3, pp 574-582, June 1980.

Descriptors: Dielectric Constant / Laboratory Thermal Data / Soil Moisture / Soil Types / Time-Domain Reflectrometry.

Laboratory tests using TDR to measure moisture content of soils. Sample container was coaxial transmission line (outer conductor 5 cm ϕ , length either 0.33 or 1.0 meter) with provision for adding moisture. Electronics are described about commercial TDR system. Soils tested include sandy loam, clayey loam, clay, organic soil, vermicutite and glass beads. Moisture included salt solutions. Data and curve fitting for polynomial regression.

Frequencies between 1 MHz and 1 GHz were used.

Topp, G. C. and Davis, J. L. "Detecting Infiltration of Water Through Soil Cracks by Time Domain Reflectrometry" accepted for publication in Geoderma, 1981.

Descriptors: Dielectric Constant / Conductivity / Soil Moisture/
Soil Types / TDR / Moisture Content In-situ.

TDR was used to monitor soil moisture near and at some distance from soil cracks during and subsequent to simulated rainfall. Tests were conducted in soybean and corn fields. TDR data compared favorably with estimates based on field-measured hydraulic conductivity, initial moisture content and density data.

Tsyтович, N. A. (1970) The Mechanics of Frozen Ground, George K. Swinzow (ed.), New York: McGraw-Hill, 1970, 275 p.

Descriptors: Particle Size / Moisture Migration / Artificial Freezing / Moisture Transport / Thermal Gradient / Moisture Content

This book has a whole chapter devoted to reasons for moisture transport in soils. If the soil is about to freeze, then there are six specific theories for water migration to the point of freezing.

1. Capillary theory of freezing pores (1885)
2. Pressure head theory (1912)
3. Film migration of water in moist particulate soils (1920's)
4. Theory of crystallization forces (1929)
5. Theory of Osmotic pressures (1948)
6. Theory of absorption forces (1943)

In non-freezing soils, moisture migrates across a thermal gradient for 2 reasons:

1. Film transport, with energy derived from the warmer side.
2. Vapor transport. The cooler and/or deeper the area, the lower the vapor pressure. Vapor migrates to the lower pressure areas.

VanderHeld, E.F.M., and VanDrunen, F.G. (1949), "A Method of Measuring the Thermal Conductivity of Liquids", Physica, Vol. XV, No. 10, Oct. 1949, pp 865-881.

Descriptors: Thermal Conductivity / Thermal Properties / Thermal Calculations / Thermal Properties Tests (lab) / Thermal Diffusivity / Resistivity / Thermo-couple / Heat Flow

This article is devoted to an elaborate lab set-up to carefully measure heat changes in carbon tetrachloride within a given area and volume. The heater-coil is enclosed within the liquid. The volume of the heater vs. the volume of the CCl_4 are carefully calculated. Later, the same lab set-up is used for other organics and for water. The thermal conductivity of water at different temperatures is shown as a curve on page 879. At 80° it has a slope of about 45° . Values of thermal conductivity are given in $\text{Kcal/MH}^\circ\text{C}$.

Van Rooyen, M. and Winterkorn, H. F. (1959) "Structural and Textural Influences on Thermal Conductivity of Soils", Proceedings of Highway Research Board, Vol. 38, 1959, pp 576-621.

Descriptors: Thermal Conductivity / Thermal Properties Tests (lab) / Thermal Resistivity / Density / Moisture Migration / Moisture Transport / Volume / Particle Size / Specific Heat / Diffusivity / Thermocouples / Theoretical Thermal Models / Thermal Calculations / Convection / Critical Diameter / Conductivity / Heating / Thermal Diffusivity / Soil Refrigeration

The authors determined empirically and experimentally (thermal needle) the coefficient of thermal conductivity for a steady state model, and for methods involving variation of temperature with time (periodic, aperiodic, and transient). They assumed that only the first term in an infinite convergent series is significant. The slope of the plot of time vs. the log of the temperature rise gives the coefficient of thermal conductivity of the tested material. The ratio of length to diameter should not be less than 100. Beyond that number, correction factors for cable length are needed (for in-situ measurements). An evaluation of a lab setup via the thermal probe method is given.

Copper constantan thermocouples were used in the lab setup. Various homogenous soil samples were packed to an approximate controlled density, and subjected to both cooling and heating via their thermal probe. The coefficient of thermal conductivity (k) was found for each sample. The article presents a tremendous amount of lab work methodology and results.

Wakao, N. and Kato, K. (1969) "Effective Thermal Conductivity of Packed Beds", Journal of Chemical Engineering of Japan, Vol. 2, No. 1, pp 24-33.

Descriptors: Thermal Conductivity / Void Ratio / Radiation / Thermal Calculations / Thermal Properties (lab)/ Heat Flux / Isotherms / Thermal Model / Conductivity / Heat Transfer / Heat Transfer Coefficient

This article reviews the literature for the theoretical derivation of the constant of thermal conductivity for spherical solids when the void ratio is either known or can be readily found. At relatively low temperatures radiation is not a vital factor and is usually disregarded. Calculations were carried out in a regular lattice and in a unit cell orthorhombic lattice setup. The heat transfer coefficient was assumed to be equal between spheres, units and within a lattice unit. The authors used the "relaxation method" to determine what part of the heat transfer was due to radiation. This is assumed true because air is in effect an insulator, so thermal conductivity is carried out only by conduction and radiation, since no liquids are involved. The experiment was carried out in air and also in a vacuum. The thermal conductivity was not constant in the bed of beads, but varied with radial position. Results are given in K cal/m.hr.⁰C.

Ward, W. H. and Sewell, E. C., (1950). "Protection of the Ground from Thermal Effects of Industrial Plant", Geotechnique, Vol. 2, No. 1, June 1950, pp 64-81.

Descriptors: Diffusivity / Field Thermal Experiments / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Storage / Heat Transfer / Heat Transfer Coefficient / Heating / Isotherm / Moisture Content (in-situ) / Resistivity / Soil Depth / Soil Firing / Soil Moisture / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Power Plants / Underground.

This article deals with the thermal conductivity of soils beneath industrial plants that have excessive heat or excessive cold. The rational developed is to provide adequate insulation to protect the structure from frost heave or excessive drying and eventual collapse. No mention is given to particular soil types with the exception of clay.

Waters, Dale E., (1974), "Heat Pipes to Stabilize Pilings on Elevated Alaska Pipeline Sections", McDonnell Douglas Astronautics Company Bulletin, Richland Washington, Reprinted from Pipeline and Gas Journal, Aug. 1974, 7 pp.

Descriptors: Artificial Freezing / Cost Analysis / Efficiency / Field Thermal Experiments / Heat / Heat Flow / Heat Pipes / Heat Pumps / Heat Storage / Pilings / Pipes / Soil Depth / Soil Refrigeration / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests (field) / Underground.

Multi-finned objects were connected to heat pipes to act as a means of soil refrigeration around piles holding the pipes. This refrigeration (air to ground conduction only) prevents the formation of ice lenses in the permafrost. Ice lenses are undesirable because they are the predominant cause of severe frost heave and pole jacking of up to 18"/yr. Maintaining a "cold" permafrost increases the load bearing capacity of the permafrost-pile adfreeze bond, which is economically highly desirable. No calculations given, but Cryo-Anchor claims an effective conductivity of 140,000 BTU/hr ft ⁰F with proper design. The Cryo-Anchor is a one-way passive system, incapable of returning heat to the ground in summer.

Wechsler, A. E., Glaser, P. E. and McConnell, R. K., Jr. (1965), Methods of Laboratory and Field Measurements of Thermal Conductivity of Soils, Special Report 82 Cold Regions Res & Engin Lab, Hanover, New Hampshire, 31 pp, Sept 1965.

Descriptors: Conductivity / Critical Diameter / Diffusivity / Electrical Methods / Field Instrumentation (Moisture) / Field Thermal Experiments / Heat / Heat Flow / Heat Profiles / Heat Transfer / Heat Transfer Co-efficient / Isotherm / Moisture Migration / Potential / Resistivity / Thermal Calculations / Thermal Conductivity / Thermal Diffusivity / Thermal Gradient / Thermal Properties Tests (lab) / Thermal Properties Tests (field) / Thermal Resistance / Thermocouples.

Reviews methods for field and lab measurements of thermal conductivity, concluding that the thermal probe (needle) employing transient methods is superior to available alternatives. Included among a list of desirable design criteria are high thermal conductivity and low thermal mass. Small diameter probes are preferred for dry materials, for rapid testing, but larger probes for moist materials to reduce thermal gradients. Optimum diameter for large probe surface area, low gradient and short test time are not derived: report suggests optimization studies. Historical references and some tabular data on previous probe designs and investigations are given.

Whitaker, Stephen (1967), "Diffusion and Dispersion in Porous Media", American Institute of Chemical Engineers Journal, Vol. 13, No. 3, May 1967, pp 420-427.

Descriptors: Theoretical Mathematical Model / Diffusivity / Heat Flow / Translocation / Saturation

The article deals with the special case of a laminar, incompressible flow of an entirely homogeneous fluid. No assumptions were made about the structure of the porous media. Dispersion and tortuosity are treated as variables. The article concludes that the fourth order tensor which governs dispersion is, under the assumed conditions, completely symmetric.

One may note that isotropic permeabilities are rather the exception than the rule in soil materials.

Wilson, E.L. and Nickell, R.E., "Application of the Finite Element Method to Heat Conduction Analysis", Nuclear Engineering and Design, Vol. 4, 1966, pp 276-286.

Descriptors: Conductivity / Heat / Heating / Heat Capacity / Heat Flow / Heat Flux / Heat Transfer / Heat Model / Radiation / Specific Heat / Thermal Calculations / Thermal Capacity / Thermal Conductivity / Thermal Models / Theoretical Thermal Models.

This article sets forth a mathematical technique for the analysis of heat conduction. It assumes that there is a state of heat flux equilibrium, and works from there. As a result, its application to a transient heat transfer problem is severely limited. The methodology utilizes the finite element idealization about an assumed axis of symmetry. Then varied arrays are set up and solved, largely with computer assistance, for practical reasons. The final section of the article deals with multi-element arrays, so you can use the array of your choice with the number of variables you must work with. This is, however, all based on the assumption that the temperature field is continuous throughout the solid (e.g. no variation in soil structure).

Witzig, W. F. and DeWalle, D. R., "A Summary of U.S. Activities in Low Temperature Reject Heat Utilization", Nuclear Technology, Vol. 38, April 1978, pp 25-34.

Descriptors: Agriculture / Cost Analysis / Crops / Economics / Field Thermal Experiments / Heat / Heat Flow / Heating / Latent Heat / Plant Growth / Productivity / Soil Firing / Thermal Power Plants / Thermal Properties Tests (field) / Underground / Waste Heat Utilization.

This article summarizes and evaluates the uses of low level waste heat. Some typical uses are soil warming, aqua culture, livestock warming, greenhouse warming, warm water irrigation. One section of the article deals with integrated systems, e.g. grow algae, feed fish, and supplement livestock feed. Contains a good bibliography for the different projects currently in commercial operation.

Woodside, W. and de Bruyn, C.M.A., "Heat Transfer in Moist Clay", Soil Science, Vol. 87, No. 3, pp 166-173.

Descriptors: Conductivity / Convection / Density / Film Moisture / Film Transport / Heat / Heat Capacity / Heat Flow / Heat Flux / Heat Profiles / Heat Transfer / Heat Transfer Coefficient / Heating / Laboratory Thermal Data / Latent Heat / Moisture Migration / Moisture Transport / Particle Size / Porosity / Soil Moisture / Soil Property Tests / Thermal Calculations / Thermal Conductivity / Thermal Gradient / Thermal Properties Tests (lab) / Thermo-osmosis / Translocation / Vapor Transport / Void Ratio / Water Saturation.

The thermal conductivity (lab tested) of remoulded Leda clay increases with both moisture content and with density (dry). Conductivity is given in BTU in/hr ft² °F. Thermo-osmosis between the hot and cold plates during the testing period was very evident. For a thermal gradient of 30°F an 18% uniform moisture sample had 5% moisture at the hot plate and 30% moisture near the cold plate. The higher the moisture content, the lower the amount of thermo-osmosis which took place. Values of from 1 to 4 BTU in/hr ft² °F were found in Leda clay up to 18% moisture content. Good bibliography.

Conductivity tests were conducted with a 12x12 inch guarded hot plate, an 8x8 inch Uniflow hot plate and thermal probe. Seemed to feel that the Uniflow apparatus was best, the temp probe worst. Small diameter yields high gradients and fast moisture migration.

Gives THERMO-OSMOSIS COEFFICIENT:

$$\beta = - \frac{\nabla m}{\nabla T}$$

states that temperature at a thermal probe is given by:

$$k = \frac{Q \ln(t_2/t_1)}{4 \pi (T_2 - T_1)}$$

Several references to previous work on thermoosmosis given.

Thermal conductivity of dry led clay reported as 1.04 BTU/in.hr.ft² °F.

Woodside, W. and Messmer, J. G. (1961), "Thermal Conductivity of Porous Media", Journal of Applied Physics, Vol. 32, No. 9, pp 1688-1706.

Descriptors: Thermal Conductivity / Conductivity / Volume / Soil Types / Thermal Calculations / Thermal Gradient / Heat Capacity / Heat Transfer / Porosity / Thermal Diffusivity / Specific Heat / Density / Thermal Models / Thermo-osmosis / Soil Moisture

The authors used a variety of soils in a strictly controlled laboratory setup to determine the coefficient of thermal conductivity. Porosities were varied over 50%. K is reported in units of $\text{mcal/cm} \cdot \text{sec} \cdot ^\circ\text{C}$. For saturating fluids, as porosity increased, K increased. Consolidation of sandstone and/or applying pressure to the same significantly increases K . Some samples were saturated with gas instead of a liquid, with varying results. The adsorption or desorption of the gas to the particles greatly influenced the thermal conductivity of the sample. The author's resistor model gave low K values. They used a geometric mean equation to predict K for rocks and got good agreement.

$$K = \frac{0.1947i^2 \log (t_2/t_1)}{V_2 - V_1} \quad \text{mcal/cm} \cdot \text{sec} \cdot ^\circ\text{C}$$