73-24,062

BERG, Richard Leon, 1939-
THERMOINSULATING MEDIA WITHIN EMBANKMENTS ON PERENNIALLY FROZEN SOIL.

University of Alaska, Ph.D., 1973
Engineering, civil

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THERMOINSULATING MEDIA WITHIN EMBANKMENTS

on

PERENNIALLY FROZEN SOIL

A

DISSERTATION

Presented to the Faculty of the

University of Alaska in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

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College, Alaska

May 1973

THERMOINSULATING MEDIA WITHIN EMBANKMENTS

ON

PERENNIALLY FROZEN SOIL

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ABSTRACT

Numerous transportation facilities have been proposed for arctic and subarctic regions. Most will be constructed on embankments. Incorporation of a thermoinsulating layer within the embankment may permit use of reduced quantities of embankment material.

Thermal design and analysis procedures applicable to embankments are reviewed and a two-dimensional numerical method coupling heat and mass transfer and vertical displacement is proposed. The modified Berggren equation, a method developed by Lachenbruch, and a finite difference technique are used to illustrate design and analysis methods for insulated embankments on permafrost.

More than sixty thermoinsulating materials suitable for incorporation into embankments are currently available; however, only seventeen materials have been used. Most applications of insulation have been in seasonal frost areas but a few test sections have been constructed on permafrost.

Stability of thermal and physical properties is a desirable characteristic of thermoinsulating layers. Moisture absorption causes increased thermal conductivity and degradation of strength of some insulating materials. Several types of moisture barriers have been used but the most successful have been polyethylene sheets.

Laboratory tests presently used to evaluate properties of insulating materials do not provide quantitative design information. A new device that could provide this information is proposed. Other suggestions for future research are made.

PREFACE

The concept of embankment construction incorporating thermoinsulating media above perennially frozen soil has only recently been developed and utilized in functional roadways and runways. Prior to this study, only empirical design procedures had been formulated and laboratory tests developed for other applications of insulation were utilized. Laboratory tests had not been critically analyzed and correlated with insulation performance in an embankment environment. In researching this subject, deficiencies and discrepancies were observed. Supplementary tests made two major problems apparent, one relates to thermal design methods and the other concerns laboratory testing methods. The purpose of this study was to extract pertinent data from existing literature, validate it by additional testing if necessary, and extend the state-of-the-art by additional testing and analysis of information. In the body of the dissertation a format incorporating observations made in this study, with pertinent applicable information from the literature, is used.

Information in Chapter I suggests that development of areas underlain by permafrost is imminent. Embankment construction for roads, airfields, pipelines, and other facilities will be required. Transportation networks will be necessary to carry hydrocarbons and minerals to existing markets. These networks will also permit a more adequate supply system to villages which are now remote from existing land transportation networks. Use of insulating materials in embankments over permafrost will minimize requirements for granular material and, in many instances, can diminish construction costs. The primary use of insulating layers will be in areas of high ice-content permafrost which would become unstable and cause undesirable subsidence after thawing.

In Chapter II the primary methods of thermal analysis and design for insulated embankments are presented. The author prepared, or assisted in the preparation of, three computer programs which are used to analyze existing embankments and to design new embankments in Chapter IV. These three programs assume unidirectional heat flux through the embankment. Others have used these programs, or similar ones, for design and analysis. A more comprehensive two-dimensional heat and mass transfer model which also considers consolidation and heaving is proposed.

In Chapter III laboratory and field studies conducted in the United States, Canada, and several European countries are summarized. The most widely used materials are petrochemical products which have been developed in the last few years. This is a rapidly expanding, ever changing category of materials. Technological advances, formulation changes, and fabrication techniques influence the properties of these materials. The laboratory tests conducted in this study provided data that is presented with applicable research findings from the literature. The oldest insulated embankment which has been continuously subjected to vehicular traffic is less than ten years old; thus in-service, long-term durability has not been proven. Results from different types of laboratory tests have been used to estimate field performance of insulating materials. The effect of moisture intrusion into the insulating materials and resulting changes in thermal and mechanical properties is the primary concern. None of the laboratory tests suitably couples the thermal and moisture regime within an embankment environment with dynamic loads imposed on it. A new apparatus is proposed which will perform this function. It will provide quantitative design data rather than information which can only be used in a qualitative manner to compare materials. Some insulating materials may require a permanent moisture barrier around them, but field experience is limited and barriers used with foamed-in-place polyurethane have not performed adequately for application to permanent facilities. The proposed device may also be used to evaluate various moisture barriers.

In Chapter IV the three computer programs developed for design and analysis of insulated embankments are applied. The three-layer technique illustrates a design procedure for complete protection, *i.e.* seasonal thaw does not penetrate the insulating layer. The modified Berggren equation illustrates a design method allowing limited seasonal thaw penetration beneath the insulating layer, and a finite differencing technique illustrates the possible long-term behavior of an insulated embankment on warm permafrost. This capability is a definite advantage for numerical methods because the three-layer method and the modified Berggren equation must be applied on a seasonal basis.

Chapter V reiterates conclusions and recommendations for further advancing the state-of-the-art as presented in prior chapters. The functional life of an insulating material within an embankment environment has not yet been established, but for extruded polystyrene it is greater than ten years. The proposed laboratory apparatus will closely simulate an embankment environment and will provide data for evaluating the durability of various materials. The two-dimensional numerical procedure considering simultaneous heat and mass flux and consolidation or heave

should be developed. This refinement of existing capabilities will permit a more complete evaluation of alternate designs.

The U.S. Army Corps of Engineers and the U.S. Army Cold Regions Research and Engineering Laboratory sponsored an international symposium on the use of insulating materials in runways and roadways at my suggestion. Approximately 100 persons from state and federal government agencies, consulting firms, and chemical manufacturing companies participated in the meeting. Some information from the symposium is used herein. These two agencies also sponsored the work reported in this dissertation. Special thanks go to Mr. W. F. Quinn, Mr. E. F. Clark, and Mrs. V. Daugherty of USACRREL.

Special appreciation is given to Professor George R. Knight, who was chairman of my advisory committee. His counseling and encouragement have been greatly appreciated.

The assistance and advice of my other advisory committee members, Dr. F. L. Bennett, Dr. G. L. Guymon, and Dr. J. L. Morack, is appreciated.

Thanks are extended to the many companies, agencies, and individuals who provided data and information for this study.

Lastly, sincere gratitude is expressed to my wife Sue for her patience, support, and assistance during this study.

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CHAPTER I

INTRODUCTION

The concept of embankment construction incorporating thermoinsulating media above perennially frozen soil has only recently been developed and utilized in functional roadways and runways. Prior to this study, only empirical design procedures had been formulated and laboratory tests developed for other applications of insulation were utilized. Laboratory tests had not been critically analyzed and correlated with insulation performance in an embankment environment. In researching this subject, deficiencies and discrepancies were observed. Supplementary tests made two major problems apparent, one relates to thermal design methods and the other concerns laboratory testing methods. The purpose of this study was to extract pertinent data from existing literature, validate it by additional testing if necessary, and extend the state-of-the-art by additional testing and analysis of information. In the body of the dissertation a format incorporating observations made in this study with pertinent applicable information from the literature is used.

PERMAFROST DISTRIBUTION

Black (1954) estimated that approximately 26% of the land surface of the world is underlain by permafrost. This is an area of about 14.7 million square miles. Approximately 9 million square miles of this total are in the Northern Hemisphere. He estimates that approximately 40-50%

of the land surface of Canada is underlain by permafrost, and about 80% of Alaska contains permafrost. Tsytovich (1958) estimated that over 47% of the USSR is underlain by permafrost.

Permafrost has been defined in several ways (Sterns, 1966). In this report, permafrost is defined as material which has remained below 32° F continuously for more than two years. A more complete definition of permafrost and other terms used in this report are in Appendix A.

Geographical distribution of permafrost is commonly divided into two zones, continuous and discontinuous. If the permafrost is uninterrupted in lateral and vertical extent, except under large bodies of water, it is continuous permafrost. Widely scattered thawed areas may exist. When the occurrence of unfrozen islands, layers, or strips becomes the rule rather than the exception, permafrost is discontinuous. Thawed portions may occur laterally or vertically to break the continuity of the permafrost. Figure 1, from Sterns (1966), shows the distribution of permafrost in the Northern Hemisphere.

Development of the permafrost regions in North America has been sporadic. Initial growth was due to development of gold deposits in the late nineteenth and early twentieth centuries. Construction of the Distant Early Warning System (DEW Line) was accomplished during the late 1950's. Vast oil reserves were discovered near Prudhoe Bay, Alaska, in 1968. Subsequently, oil and gas deposits have been found in the Canadian Archipelago and the McKenzie River delta area. Other regions in Canada and Alaska are being explored for additional hydrocarbon deposits.

Oil and gas deposits have also been discovered in northern Russia. Exploration and development in these regions are continuing. Figure 2,

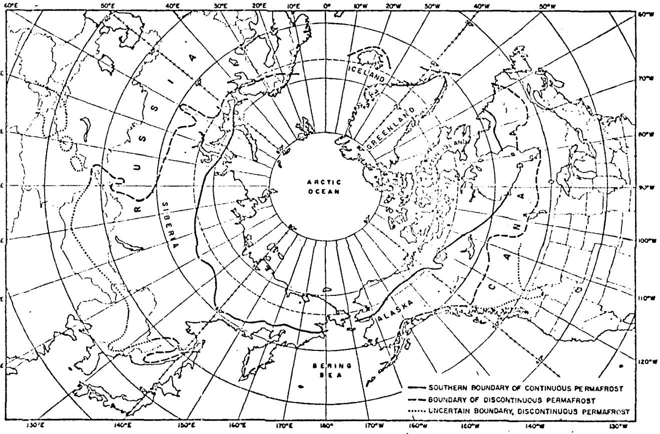


Figure 1
Permafrost distribution in the northern hemisphere, from Sterns (1966).

Figure 2
Major hydrocarbon deposits and mines in the Far North, courtesy of the Greenarctic Consortium (1973).

courtesy of the Greenarctic Consortium, shows several hydrocarbon deposits and potential mining sites in the Far North.

TRANSPORTATION FACILITIES

The existing transportation network, from the Arctic Institute of North America (1969), is shown in Figure 3. Few roads and railroads exist and primary transportation routes are via sea and river. Aircraft also play an important role in Far North transportation. To transport oil and gas, and other minerals, from the northern areas to existing markets it will be necessary to develop additional transportation facilities. Many of the recently proposed roads, railroads, and pipelines for the North American arctic and subarctic are shown in Figure 4. Some routes are alternates; however, others have been studied by different groups, each recommending slightly different alignment. Due to the scale of this map the alignments are approximate.

Oil and gas deposits in North America will be developed primarily for economic and political reasons. Government and industry funding may be used. Initially, the transportation routes will be established to serve the oil and gas resources. Several of these routes, however, will serve as a base for secondary transportation routes to serve other mineral resources in northern areas.

EMBANKMENT DESIGN

Nearly all segments of roadways, airfields, and railroads in permafrost areas will be constructed on embankments providing some thermal protection to the permafrost. Portions of pipelines will be constructed on

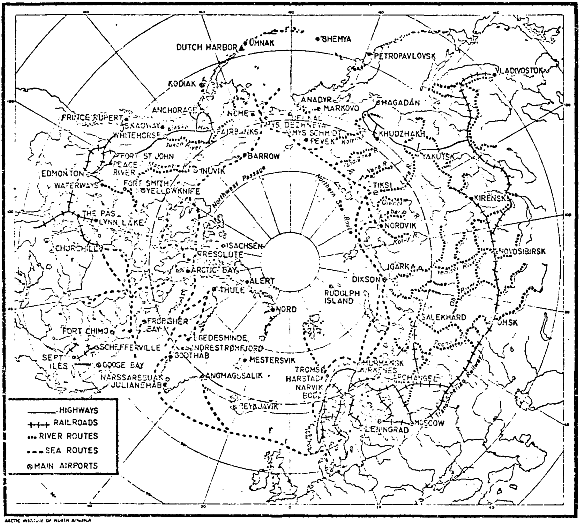


Figure 3
Present transportation routes in the arctic, from Sater (1969).

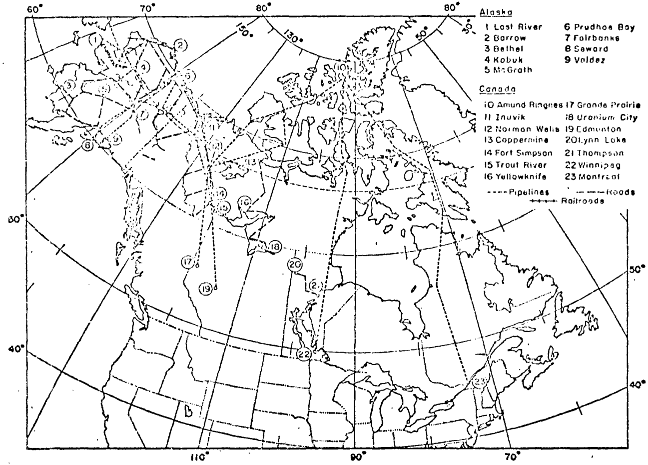


Figure 4
Proposed transportation facilities in North American permafrost regions.

Table I

SOURCES OF INFORMATION FOR FIGURE 4

Canadian Institute of Guided Ground Transport (1972).

Consedine (1972).

Kipling (1972).

Pipe Line Industry (1972).

State of Alaska (1972).

Tudor, Kelly and Shannon (1972).

Wolff, Lambert, Johansen, Rhoads, and Solie (1972).

Woodward (1971).

or built from embankments. One important reason for placing transportation facilities on embankments is to contain thaw within the embankment or to reduce thaw into the subgrade. Embankments designed for thermal protection are usually essential over soils which are saturated or oversaturated with ice. Exceptions may occur when conditions allow pre-thawing and consolidation of the ice rich soils. Embankments are unnecessary, or much thinner ones can be used, where the subgrade soils are unsaturated, coarse-grained materials or competent rock. The embankment thickness necessary for thermal protection of the subgrade varies geographically and is also influenced by the use and design life of the facility. Ferrians, *et al* (1969), describe and discuss several situations where insufficient embankment thickness effected problems due to melting of the permafrost.

Inclusion of thermal barriers within embankments may reduce the required thicknesses. Two types of thermal barriers are available: (1) heat sink materials, *i.e.* those containing large volumes of water, thereby having large volumetric latent heats of fusion, and (2) materials of high thermal resistance, *i.e.*, thermal insulators. The use of thermal barriers may permit using less granular material, thereby causing less environmental disturbance.

SYNTHESIS OF CURRENT KNOWLEDGE

Beskow (1935) reported the original studies with thermal barriers. In 1946 several test sections were constructed near Fairbanks, Alaska (U.S. Army Corps of Engineers, 1950). Several types of insulating materials were used, including cellular glass boards, lightweight concrete, and compacted branches. The cellular glass boards were most effective in reducing seasonal thaw but were very expensive, due in part to their high installation cost caused by their small size. No additional studies on insulated embankments were reported until Quinn and Lobacz (1962) published data from some small test sections in Waltham, Massachusetts.

Young (1965), and Oosterbaan and Leonards (1965) discussed performance of test sections in seasonal frost zones of Canada and Michigan. Extruded polystyrene boards were used in both of these studies. Development continued, using these materials, in both highway and railroad embankments. Williams (1968 and 1971) and Berg (1972) provide more detailed summaries of insulated embankments.

In 1969 three projects employing insulating layers were constructed on permafrost in Alaska. The Alaska Department of Highways (Esch, 1973) constructed test sections near Chitina, incorporating boards of Styrofoam HI, an extruded polystyrene. The same material was also used at Kotzebue, Alaska, where a portion of the runway was insulated. Knight and Condo (1971) report that various plank materials and different grades of polyurethane developed by ARCO Chemical Company were installed near Prudhoe Bay, Alaska. More recently, several "expedient road" test sections incorporating insulating layers have been constructed near Fairbanks, Alaska, by USACRREL. Insulating materials used include: foamed-in-place polyurethane, foamed-in-place sulfur, Styrofoam HD-300, a composite insulator incorporating polystyrene beads bound by Portland cement, and another composite incorporating polystyrene beads bound by sulfur. In all of these tests an expedient metal or glass-fiber matting was placed on the insulating material and traffic was imposed on the matting. Construction information and test results are described in Smith, Berg and Muller (1973), and Pazsint and Smith (1972a and 1972b). In 1972 the Alyeska Pipeline Service Company (ALPS) constructed and trafficked "construction pad" test facilities near Fairbanks, Alaska, and Glennallen, Alaska. Each facility was comprised of eighteen test sections. Seven of the sections in each facility contained an insulating layer. Various types and thicknesses of insulation were used (Alaska Construction and Oil, 1972, and Langan, 1972). Johnston (1972) reported two installations using Styrofoam were constructed near Inuvik, Canada.

Most insulating materials currently used in building construction may have application for incorporation into embankments. Malloy (1969) lists five major categories of insulation: (1) flake, (2) fibrous, (3) granular, (4) cellular, and (5) reflective. A particular insulating system may be a hybrid of several types.

Insulating materials may be available in one or more of six general forms. They are loose fills, blankets or batts, flexible stock, reflective materials, aerated or lightweight concretes, and rigid or semi-rigid boards and slabs. Flexible stock has not been considered for use in embankments. And with the exception of a few light-colored pavement surfaces to reflect larger quantities of incident solar radiation, reflective materials have not been used either. Reflective insulating materials beneath the embankment surface have not been considered for incorporation into embankments. A summary of other materials and selected properties is shown in Appendix B. Considerable data are available on some properties of the materials. However, since insulating materials are not normally required to carry loads in building construction, little information is available concerning their behavior under dynamic load conditions.

Insulating systems, rather than insulating materials alone, are generally designed in building construction. The insulating systems include a vapor barrier where necessary, and materials for abrasion and/or impact protection. For embankment insulation a barrier resistant to petroleum products may be desirable in some locations.

REQUIREMENTS FOR EMBANKMENT INSULATION

Insulated embankments are one of several alternate designs, rather than a panacea for all embankments. A schematic illustration of the recommended design procedure is shown in Figure 5.

A systematic procedure is employed to select the final design, Figure 5. First, construction constraints are established. They are normally levied by the funding agency and include geometric criteria, thermal and structural loads, environmental constraints, and longevity of the facility. Next, a survey and cataloguing of available material is accomplished. Then several design procedures, which may also be directed by the funding agency, are applied to establish congruous uninsulated cross sections. Thermal and structural design methods must be applied simultaneously in developing suitable insulated cross sections. An iterative process, using the materials available in various combinations, is used to establish the cross sections. A cost estimate of each cross section is determined and optimum designs of insulated and uninsulated embankments are selected. Other considerations, *e.g.* political constraints, may be included before the final design recommendation is resolved.

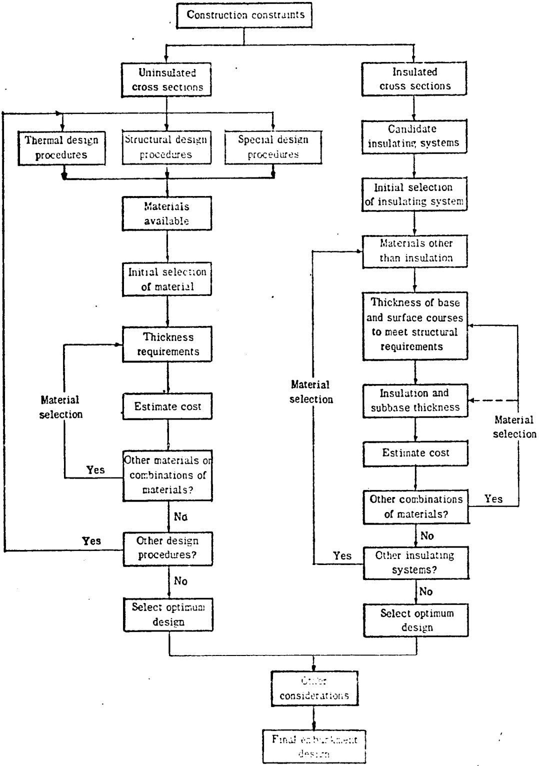


Figure 5
Recommended design procedure.

CHAPTER II

THERMAL MODELS

Generally, the thermal regime in existence prior to construction of a surface facility will be altered by constructing the facility. In permafrost areas it is frequently necessary to estimate the extent of this change. Fluctuations in the permafrost table are of primary interest and if the in-situ soils contain large quantities of ice, estimates of changes in the permafrost table are of utmost importance. Computations of thaw depths into the original soil are usually necessary. Surface subsidence can then be estimated from these depths and the known ice volume in the soil. Calculation of frost penetration is also important as it represents frost heaving potential. If the seasonal frost depth does not reach the permafrost table, a talik is formed. If the talik is enlarged in subsequent thawing seasons, the facility may be unstable for several years.

In this chapter techniques which may be used to estimate seasonal thaw and seasonal frost depths are reviewed and a two-dimensional numerical method which considers simultaneous heat and mass flux, and consolidation or heave, is proposed. The proposed method more closely represents most embankment environments than presently used techniques.

FUNDAMENTAL PRINCIPLES

In the absence of sources and sinks, the local time rate of change of internal energy (μ) must equal the net heat flux ($\vec{q}$) at any instant of time (τ) and at any point in a given space. This is the principle of conservation of energy. The continuity equation states this principle:

$$\frac{\partial \mu}{\partial \tau} + \nabla \cdot \vec{q} = 0 \qquad 1.$$

The heat flux vector has been found, experimentally, to be proportional to the gradient of temperature (T). The constant of proportionality is defined as the thermal conductivity (k_T). Thus a second fundamental heat flow equation can be written:

$$\vec{q} = -[k_T]\ \vec{\nabla}\ T \qquad 2.$$

where $[k_T]$ is a tensor of thermal conductivity data.

Experimental data also illustrate that the internal energy is dependent on temperature. Under constant volume conditions, the constant of proportionality, or slope of the temperature versus internal energy diagram, is defined as the volumetric specific heat at constant volume (C). For a system which is not undergoing a phase transition, the following equation is valid:

$$C = \frac{\partial \mu}{\partial T} \qquad 3.$$

Rewriting equation 3 and placing it and equation 2 into equation 1, equation 4 is obtained:

$$C\ \frac{\partial T}{\partial \tau} + \nabla \cdot (-[k_T]\ \vec{\nabla}\ T) = 0 \qquad 4.$$

If the thermal conductivity is constant throughout the region, *i.e.* if the region is homogeneous and isotropic, and if no portion of the region is at the phase transition temperature, equation 4 can be rewritten in differential form:

$$C\ \frac{\partial T}{\partial \tau} = k_T\ \nabla^2\ T \qquad 5a$$

or

$$\frac{\partial T}{\partial \tau} = \alpha\ \nabla^2\ T \qquad 5b$$

where the thermal diffusivity (α) is defined as:

$$\alpha = \frac{k_T}{C} \qquad 6.$$

While equations 1 through 5,

> "describe the frost penetration problem in a mathematically correct fashion, exact solutions can be found only for a small number of idealized cases, due to the complex conditions of latent heat transfer and other effects." Aldrich and Paynter (1953).

Subsequent sections of this chapter discuss empirical and approximate techniques for solving problems including phase change of soil moisture.

ANALYTICAL SOLUTIONS

Carslaw and Jaeger (1959) present solutions to many one, two, and three dimensional heat flow problems. Homogeneous isotropic materials are used in most solutions; however, some solutions are presented for layered systems. Lachenbruch (1959) developed a technique for predicting the damping of a periodic surface perturbation at different depths in a two and three layered soil system. Unidirectional heat flux was considered. Lachenbruch (1957) developed a method for estimating the three dimensional thermal regime in a homogeneous isotropic soil beneath a heated structure. None of these techniques considers phase change of the soil moisture. Neglecting the effects of latent heat of fusion (abbreviated to latent heat in the remainder of this report) of the soil moisture normally does not cause substantial error in location of frost depths provided the soils are low-moisture content materials. Differences between actual and computed thaw depths increase rapidly with increasing moisture content due to the increased volumetric heat capacity and larger latent heat of the wetter soil.

Several empirical and semi-empirical equations have been developed which consider latent heat. The Stephen Equation, equation 7, was originally developed for calculating the thickness of ice on a calm body of water, which was isothermal at the freezing temperature.

$$X_i = \sqrt{48 k_{Ti} F / L_i} \qquad 7.$$

where: X_i = ice thickness, ft

k_{Ti} = thermal conductivity of ice, Btu/ft hr °F

F = freezing index, °F - days

L_i = volumetric latent heat of fusion of ice, Btu/cu ft

The Stephen equation has been modified by many individuals and agencies, and many similar equations have been developed. Some of the equations use slightly different functions or slightly different initial conditions from the original Stephen model. The most widely used equation for estimating seasonal frost and seasonal thaw depths is the modified Berggren equation developed by Aldrich and Paynter (1953). Application of this equation has been very widespread in North America. Sanger (1963) discusses many of the variables and parameters influencing the modified Berggren equation, and the Departments of the Army and Air Force (1966) suggest using this technique to estimate seasonal thaw depths in arctic and subarctic regions. Aitken and Berg (1968) developed a computer program for calculating frost and thaw depths in layered systems using the modified Berggren equation, equation 8.

$$X = \lambda \sqrt{48\, k_T\, N\, I / L} \qquad 8.$$

where: X = thaw depth, ft.

k_T = average thermal conductivity, Btu/ft hr °F

N = an empirical constant relating air and surface thawing indexes, dimensionless

I = air thawing index, °F - days

L = latent heat, Btu/cu ft

λ = a coefficient which considers the effect of temperature changes within the soil mass. It is a function of the thawing (or freezing) index, the mean annual temperature, and the thermal properties of the soils.

An equation very similar to the Stephen Equation is currently used in the USSR to calculate the "standard" depth of freezing for foundation design purposes (Porkhaev and Zhukov, 1971). Many other closed form analytical techniques are also used in the USSR, as evidenced by Luk'yanov (1963) and Kudryavtsev (1971). Aldrich and Paynter (1953) show other equations which have been used in the USSR and elsewhere.

GRAPHICAL AND ANALOG METHODS

Graphical methods have also been used to calculate frost and thaw depths. The flow net technique, commonly applied to seepage problems, can be used to estimate steady-state temperature conditions. Brown (1963) presents another graphical procedure.

Analog techniques are also used to estimate frost and thaw depths. Table II shows thermal, fluid, and electric analogies. Electrical analog computers are available and are relatively low cost and reasonably simple to use. The primary disadvantages of these machines are that re-programing is normally necessary for each problem and complex geometries are difficult to simulate adequately. Hydraulic analog computers are also available. Hawk and Lamb (1963) used a small hydraulic analog computer belonging to USACRREL to study heat flow through building walls. Luk'yanov (1963)

Table II

THERMAL - FLUID - ELECTRIC ANALOGIES

ITEM		MEDIUM		
		THERMAL	FLUID	ELECTRIC
A - Variables	(1)	Heat μ	Volume S	Charge density ρ
	(2)	Heat flux $\vec{q}$	Flow $\vec{Q}$	Current density $\vec{j}$
	(3)	Temperature T	Head H	Voltage e
B - Principles:				
Continuity	(1)	$\frac{\partial \mu}{\partial \tau} + \vec{\nabla} \cdot \vec{q} = 0$	$\frac{\partial S}{\partial \tau} + \vec{\nabla} \cdot \vec{Q} = 0$	$\frac{\partial \rho}{\partial \tau} + \vec{\nabla} \cdot \vec{j} = 0$
Conductivity	(2)	$\vec{q} = -k\vec{\nabla}T$	$\vec{Q} = -k\vec{\nabla}H$	$\vec{j} = -\sigma\vec{\nabla}e$
Capacitance	(3)	$d\mu = CdT$	$dS = AdH$	$\rho dV = Cde$

discussed a large hydraulic analog computer used in the USSR. The primary disadvantages of these computers are their complex "plumbing systems" and the necessity to reconstruct them for each problem. However, at any instant of time they exhibit graphically the temperature distribution.

NUMERICAL TECHNIQUES

Due to greater availability of electronic digital computers, their application to numerical solutions to the continuity equation, equation 1, has increased. Numerical procedures are approximations to the partial differential equation; however, they are normally much more accurate in transient heat flow problems than the analytical techniques previously available. Computer programs have been written with sufficient flexibility to allow input of various boundary and initial conditions. Solutions to one and two dimensional problems have been obtained. Dusinberre (1961) discussed the general finite difference methods available for solving heat flow problems. With this technique explicit and implicit procedures have been applied. Since rectangular elements are normally used, complex geometries are difficult to simulate unless small element sizes are employed. The finite element technique has been developed more recently (Zienkiewicz, 1967 and 1971). Elements of various shapes can be used with this technique; however, the triangular shape is normally used in two dimensional problems. Boundaries in complex geometries can be more closely simulated using finite element procedures. For multi-dimensional flow problems the finite element procedure is frequently more efficient, *i.e.* requires less computer time, than the finite difference technique.

Table III is a summary of numerical methods which have been applied to heat transfer problems in soil/water systems. Twenty computer programs are currently available. Others undoubtedly have been developed but similar information concerning them has not been published. Three finite element programs and 17 finite difference programs are available. The explicit procedure has been used in ten of the finite difference programs and five have used the implicit procedure. Solutions to one dimensional problems can be obtained from all but one of the programs and radial or two dimensional solutions can be obtained from nearly one-half of them. None of the programs has been written to solve three dimensional problems directly. All of the programs have been written to accept homogeneous soil systems and most allow layered systems. Only the three finite element programs and the McDonnell-Douglas finite difference program allow non-layered, non-homogeneous soils. Dow Chemical Company's finite element program will accept anisotropic materials. Several types of upper boundary conditions have been used and nearly all of the programs allow more than one type. Normally a constant temperature is used for the lower boundary condition; however, some programs allow a variable temperature or heat flux at the lower boundary. In most programs the initial temperature distribution is specified. Only one of the programs assumes an initial uniform temperature distribution. All except one of the programs include consideration of latent heat and several allow for unfrozen moisture near the freezing front. All except one of the computer programs permit the thermal conductivity and volumetric heat capacity to vary with temperature. In several of the programs, however, these two properties vary with the state of the soil moisture rather than temperature; *i.e.*, they are functions

Table III

Numerical Methods Applied to
Heat Transfer in Soil-Water Systems

Name	Date	Type			Dimension				Soil				Upper Boundary Conditions			Lower Boundary Conditions				Init. Conditions		Thermal Properties						Heat Transfer Mechanism					Type of Solution			
		Finite Diff.							Isotropic																			Mass Flux								
		Explicit	Implicit	Finite Element	One Dimensional	Radial	Two Dimensional	Three Dimensional	Homogeneous	Layered	Non-homogeneous	Anisotropic	Air temperatures	Programmed temperature	Surface heat flux	Constant temperature	Periodic temperature	Variable temperature	Heat flux	Constant temperature	Specified temperature	Latent heat	Unfrozen moisture	K constant with temp.	K varies with temp.	C constant with temp.	C varies with temp.	Vapor	Vertical liquid	Hor. liquid	Conduction	Radiation	Temperature profile	32° F isotherm	Tabular	Graphical
Hashemi & Sliepcevich	1965		X		X	X	X		X	X			X		X			X	X		X	X	X		X		X			X	X		X	X		X
Carroll, Schenck, & Williams	1966	X			X				X	X			X		X	X					X	X			X		X				X		X		X	
Dempsey & Thompson	1969	X			X				X	X			X		X	X					X	X			X		X				X		X	X	X	
Ho	1969		X		X		X		X	X			X	X		X					X	X	X		X		X				X		X	X	X	
Doherty	1970	X					X		X					X		X					X	X			X						X		X		X	
McDonnell-Douglas	1971	X			X	X	X		X	X	X		X	X	X	X					X	X	X		X		X				X		X	X	X	X
Nakano & Brown	1971		X		X				X	X			X	X		X					X	X	X		X		X				X		X	X	X	
Pal'Krn	1971	X			X	X	X		X	1			X	X		X					1	X			X		X				X		X	X	X	
Berg & McDougall	1972	X			X				X	X			X	X		X					X	X		X		X					X		X	X	X	X
Christison & Anderson	1972	X			X				X	X					X	X					X	X	X		X		X				X		1		1	
Dow Chemical Company[2]	1972	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		X				X		X	X	X	
Goodrich	1972	X			X				X	X			X	X				X	X		X	X	X		X		X				X		X	X	X	X
Harlan	1972		X		X				X					X		X				X		X	X		X		1		X		X		1		1	
Hwang, Murray, & Brooker	1972			X	X	X	X		X	X	X		X		X	X			X		X	X	X		X		X				X		X	X	X	
Meyer, Kaller, & Couch	1972		X		X				X	X				X		X					X	X			X		X				X			X		X
Mohan	1972			X	X	X	X		X	X	X		X			X					X	X			X		X				X		X	X	X	
Williamson	1972	X			X				X	X			X		X	X					X				X		X				X		1		1	
Esso Production Res.	1970		X			X	X		X	X	X		X	X	X	X			X		X	X	X		X		X				X		X	X	X	X
Chwang	1967	X					X		X	X	X		X	X		X					X	X			X		X				X				X	

NOTES: [1] Not stated or unclear. [2] Dow Chemical Company has two programs.

of whether the material is frozen or thawed. Heat transfer by conduction is used in all programs and two allow for mass flux. Types of solutions or types of output varied considerably and all of the programs provide more than one type of information.

PROPOSED MODEL

Ideally mathematically exact analytical equations could be derived to predict the time-dependent thermal and moisture regimes in embankments. However, the mathematics become complex and cumbersome when non-homogeneous, anisotropic, two-dimensional problems involving simultaneous heat and mass transfer are considered. Further complications are introduced when moveable boundaries to consider thaw consolidation and/or frost heaving are introduced. Additionally, several parameters are dependent on the thermal and/or moisture regimes. Due to these complications, the proposed model deviates from a mathematically exact one in that empirical and semi-empirical methods and approximation techniques, *i.e.* numerical methods, are employed.

The basic difference between most numerical methods summarized in the preceding section and the one proposed in this section is that the proposed model combines heat and mass flux and allows heaving and/or consolidation. Frost heaving and thaw consolidation are visible results of mass flux; changes in the subsurface thermal regime due to mass flux are less obvious. Although the author believes that the proposed model is a significant improvement over most existing ones, no instances attributing mass flux to differences between thaw depths computed from conduction models and measured thaw depths have been documented. There are several reasons for the lack of documentation, but the three most important are (1) lack of instrumentation to adequately monitor in-situ moisture conditions over a period of time; (2) application of closed-form solutions which provide only maximum seasonal thaw depths, *i.e.* thermal properties can be "refined" to provide the desired correlation between calculated and measured data; and (3) moisture migration may not be a significant factor in many situations.

Only mass flux in the liquid phase is considered in the proposed model. Harlan (1972) and Jumikis (1967) state that mass transport in the vapor phase is considerably less than moisture movement in the liquid phase via capillaries and film flow. Heat transfer by radiation is not considered due to the relatively small temperature gradient normally present in soils. The void spaces are also generally small, thus radiating surfaces have small temperature differentials between them.

Only the constitutive equations for the proposed model are presented in this dissertation. Relatively few attempts have been made to couple heat and mass transport in porous media. Due to the interdependence and/or non-linearity of several parameters, development of an operational computer program will be a time-consuming and perplexing process. Development of the program was beyond the scope of this study.

Preceding portions of this chapter provide sources of information concerning the thermal properties and heat flux aspects of the proposed model. Various methods have been used by different authors.

Freeze (1967) presented a summary of "Available numerical solutions to one-dimensional, vertical, unsaturated, unsteady flow problems" and

Jumikis (1967), Harlan (1972), and Hoekstra (1972) investigated moisture movement during the freezing process. The thermodynamic free energy concept discussed in detail by Knight (1967) and Low, Anderson, and Hoekstra (1966 and 1967) may be the most simple method of estimating the unfrozen moisture content and latent heat in this ephemeral system.

Equation 9 is similar to that presented in Bird, Stewart, and Lightfoot (1960) except that the porosity has been added and the viscous dissipation components have been neglected. It is valid for a non-rigid, non-homogeneous, anisotropic porous medium with no sources or sinks. It is the two-dimensional equation in terms of the transport properties in a porous medium:

$$\rho c \left[\frac{\partial T}{\partial \tau} + n\left(v_x \frac{\partial T}{\partial x} + v_z \frac{\partial T}{\partial z}\right)\right] = k_{Tx} \frac{\partial^2 T}{\partial x^2} + k_{Tz} \frac{\partial^2 T}{\partial z^2} \qquad 9.$$

where ρ = density, lb/cu ft

c = specific heat, Btu/lb °F

T = temperature, °F

τ = time, hr

n = porosity, dimensionless

v_x, v_z = fluid velocities in the x and z directions, respectively, ft/hr

k_{Tx}, k_{Tz} = thermal conductivities in the x and z directions, respectively, Btu/ft hr °F

Equation 10 is the two-dimesional continuity equation describing moisture movement in an anisotropic, heterogeneous porous media with no sources or sinks.

$$\frac{\partial\left(k_{\Phi x} \frac{\partial \Phi}{\partial x}\right)}{\partial x} + \frac{\partial\left(k_{\Phi z} \frac{\partial \Phi}{\partial z}\right)}{\partial z} = \frac{\partial w}{\partial \tau} \qquad 10.$$

$$\Phi = \psi + hg \qquad 11.$$

Φ = total head, ft

ψ = pore water pressure, ft

hg = gravitational head, ft

w = moisture content, %

τ = time, hr

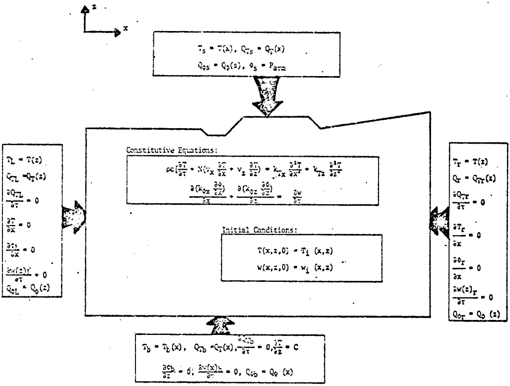
$k_{\Phi x}$ and $k_{\Phi z}$ are coefficients of permeability in the x and z directions respectively, ft/hr

One-dimensional conolidation theory was developed from equation 10 by Terzaghi (Taylor, 1948), and De Wiest (1965) developed a three-dimensional equation for estimating one-dimensional consolidation of an aquifer. The possibility that thaw consolidation may deviate considerably from the classical one-dimensional consolidation theory was discussed by Aldrich and Paynter (1953). Morgenstern and Nixon (1971) and Crory (1973) developed analytical methods for estimating thaw consolidation in soils. Moisture movement and frost heaving during freezing periods must also be considered in the proposed model. Work by Jumikis (1967), Harlan (1972), and Hoekstra (1972) was previously discussed.

Although the equations presented above are readily adaptable to numerical methods, practical considerations will complicate coupling and programming. The complications will arise primarily from interdependence and/or non-linearity of several parameters.

Further development of the proposed numerical model is not within the objectives of this investigation. However, in Chapter IV a one-dimensional finite differencing technique is used to illustrate the capability of numerical methods for design applications. Several of the simplifying assumptions necessitated for the design examples therein could be more satisfactorily considered by developing and applying the proposed model.

Figure 6 illustrates the boundary conditions, initial conditions, and constitutive equations for the proposed model.



NOMENCLATURE

Q_T = heat flux	ϕ = total head
Q_ϕ = mass flux	k_T = thermal conductivity
T = temperature	k_ϕ = permeability
τ = time	ρ = density
w = moisture content	C = specific heat
x = horizontal coordinate	z = vertical coordinate
v = velocity	

Figure 6
Boundary conditions, initial conditions and constitutive equations for proposed model.

CHAPTER III

THERMOINSULATING MATERIALS

The thermoinsulating material used in a specified embankment may be chosen by optimizing several parameters, including:

1. Thermal conductivity (retention of low values desirable).
2. Strength (retention of high values desirable).
3. Property degradation (minimal reduction due to environmental conditions desirable).
4. Economics (low cost desirable).

In addition to the cost of the thermoinsulating material, other prime cost considerations are: placement rate, membrane costs, sub base preparation, backfill precautions, and forming for the insulating layer. Incorporation of thermoinsulating materials into embankments may permit savings of other materials, reduced environmental damage, and reduced construction time. The life cycle cost, *i.e.* initial cost plus maintenance costs, etc., of an insulated embankment may be less than that of an uninsulated embankment.

The list of thermoinsulating materials in Appendix B contains more than 60 items. However, only the 13 materials listed in Table IV have been used in insulated embankments. Composite materials have been manufactured from those listed in Appendix B; for example, item 3 in Table IV used a higher strength material over a lower strength material for load distribution. Other techniques for strengthening the insulating layer include

Table IV

Insulating materials used in embankment construction.

1. Cell concrete.
2. Cellular glass blocks.
3. Composite - polystyrene beads with cement binder and molded polystyrene boards.
4. Expanded clay - unbound and bound with bitumen or cement.
5. Expanded shale - unbound and bound with bitumen or cement.
6. Insulating asphalt.
7. Mineral wool.
8. Polystyrene - molded boards and extruded boards.
9. Polyurethane - boards and spray-in-place.
10. Polystyrene beads with cement binder.
11. Polystyrene beads with sulfur binder.
12. Sulfur - spray-in-place.
13. Wood - chips, logs, and bark.

incorporating the material into a paper, plastic, or metal honeycomb. Fiber reinforcement may also be incorporated into the insulating material for added strength. Reichard (1972) discusses the physical properties of honeycomb materials which have been used in building construction. Kritz and Wechsler (1967) discussed the use of honeycomb materials for roadway embankments. Cement and sulfur have been mixed with polystyrene beads to make a relatively high strength, low thermal conductivity material, and both bitumen and cement have been added to expanded clay materials to increase their strength. It is possible that sulfur, bitumen, or cement can be used with other loose-fill materials to provide insulating layers suitable for incorporation into embankments.

"One-way" insulators are attractive for embankments where subgrade temperatures are slightly below 32° F. The heat pipe principle could be used. Two types are available. The first type operates by convection and its function is due to natural convection caused by density differences between warmer and colder zones in the working fluid. The second type is a two-phase system and operates by vaporization and condensation of the working fluid. Heat pipes function only when their upper surface is colder than their lower surface, and no valves are necessary for their operation. The heat pipes would not operate during the summer months but during the winter months they would remove additional heat from beneath the insulating layer. The geometric arrangement of the heat pipes would be controlled by their heat removal rate and also by the quantity of heat to be removed. This is a new concept and has not been tested in embankments.

RHEOLOGICAL STUDIES

Rheological studies of insulating materials can be categorized into two groups depending on the mode of failure. The more rigid brittle materials fail by fracture in unconfined compression, whereas failure, *i.e.* the unconfined compressive strength, is defined at some arbitrary deformation for cellular plastics. For embankment materials the deformation is normally 5% or 10% strain based on the original thickness. ASTM Standard D 1621-64, "Compressive Strength of Rigid Cellular Plastics", states that the compressive strength should be determined at 10% deformation unless a maximum load occurs before that time. Figure 7 shows the variation of compressive strength with density for molded polystyrene and polyurethane. Figure 8 shows compressive strength versus density of selected higher density materials which can be used for embankment insulation. Ferrigno (1963) and Mark, *et al* (1965), contain information on other lightweight plastic materials. Data in Figure 7 indicate that the compressive strength of polystyrene and polyurethane vary widely at a given density. In discussing the two-component polyurethane materials used in a test road near Prudhoe Bay, Alaska, Knight and Condo (1971) state,

> "A typical polyol master batch may have as many as 15 additives to develop the special properties desired. By changing the base material of the polyol, the strength, closed cell content, and thermal properties can be greatly varied."

Ferrigno (1963) suggests that the variation in compressive strength of the molded polystyrene materials is caused by the manufacturing processes of the materials. He also states that the strength properties of the extruded polystyrene are considerably different from those of the molded

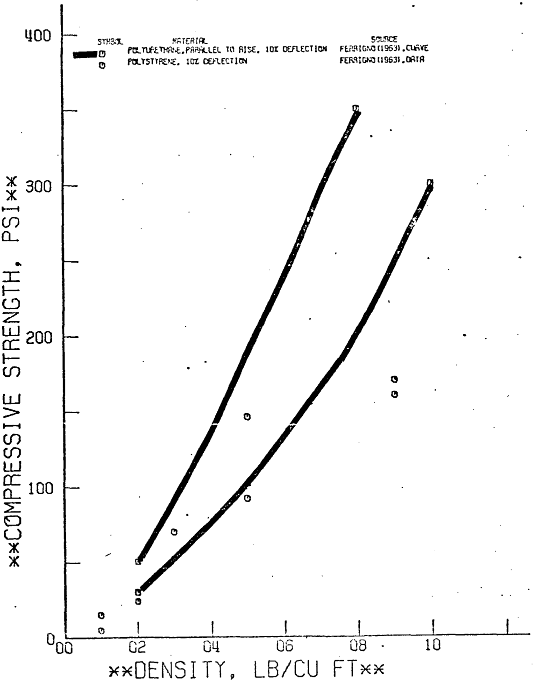


Figure 7
Density-compressive strength relationships for polyurethane and molded polystyrene.

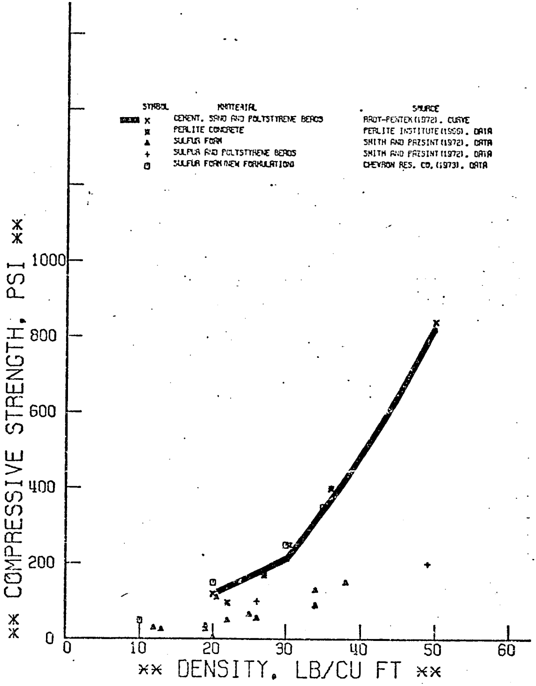


Figure 8
Density-compressive strength relationships for high density insulating materials.

material. At a given density the extruded materials normally have higher compressive strengths than the molded ones.

The behavior of thermoinsulating materials when subjected to repetitive dynamic loading is of interest if the material will be used in embankments subjected to vehicular traffic. Williams (1968), Weil (1969), Saetersdal (1971), and Knight (1972) describe laboratory devices for conducting tests of this type. They also reported test results. Williams and Saetersdal used pistons moving vertically in applying loads to the samples. Equipment used by Saetersdal produced a step function and Williams stated that his device could apply either a step function or a sinusoidal stress function to the top of the sample. The device described by Weil consisted of a lever whose vertical movement was controlled by an off-centered circular cam, and the device used by Knight applied a hydraulic load to the surface of a simulated granular embankment containing the insulating materials. Williams (1968) noted that results of laboratory studies do not necessarily reflect the behavior of a material in actual roadways. His laboratory results indicated that short loading cycles of the same magnitude as longer loading pulses resulted in greater permanent deformation. He also stated that the application of a confining pressure increased the deformation after a given number of load cycles.

Representative results of all four studies are shown in Figure 9. One material, 2.1 lb/cu ft extruded polystyrene, was used in three of the tests. Saetersdal applied an 8.5 psi stress to the samples, and his data indicated that after approximately one million load cycles little additional permanent deformation occurred through three million load cycles.

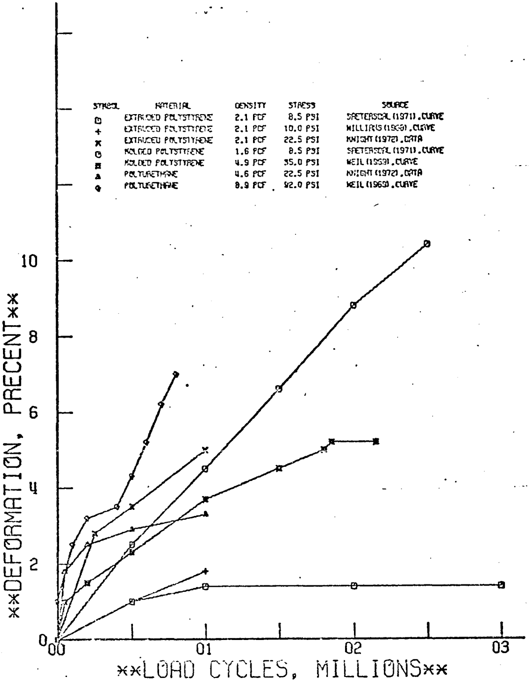


Figure 9
Deformation from cyclic loading, laboratory studies.

Williams used a 10 psi stress and his results indicated that the deformation after one million load cycles was slightly greater than that observed by Saetersdal after a similar number of cycles. The deflection observed by Knight after one million load cycles was approximately three times greater than that observed by Saetersdal. Knight used a 22.5 psi peak load which is approximately equivalent to 1/2 of the compressive strength of the material. The peak stress applied in tests reported by Saetersdal was less than 1/3 of the compressive strength of the material. These data indicate that as the maximum stress increases, the permanent deflection also increases after a given number of load cycles.

Various types of loading tests have also been conducted on full scale field test sections. Joseph, Jackson, and Rosser (1971) reported the use of thick cellular plastic layers as load distributing media over low-load bearing capacity soils. A polypropylene membrane was placed over the cellular plastic material and trafficking was conducted immediately on the polypropylene. They report that the equation developed by the U.S. Army Corps of Engineers for estimating the thickness of flexible pavements can be used to estimate the thickness of cellular plastic material over a weak subgrade. The insulating potential of the cellular plastic materials was not of concern in these tests. Smith, Berg, and Muller (1973) discuss somewhat similar tests conducted near Fairbanks, Alaska. Insulating materials were used to reduce thaw into ice-rich subgrade soils and metal or glass-fiber matting was placed on the insulating layers. Vehicular traffic was imposed on the matting.

Andersson, *et al* (1972) present results of repetitive plate loading tests on insulated and uninsulated test sections in Sweden. Their data are summarized in Table V. The insulated sections showed greater permanent deformation than did the uninsulated sections after a similar number of loading cycles. Their "crack index", defined in Table V, determined prior to conducting the dynamic loading tests also indicated that degradation of the insulated sections had progressed more rapidly than degradation of the uninsulated sections.

The Maine State Highway Commission (1965) and Schneider (1969) conducted Benkelman beam studies at various times of the year on insulated and uninsulated roadways. In the Maine studies the thickness of pavement and base above the insulating layer varied. Table VI contains a summary of these data taken prior to opening the roadway to traffic. Prior to spring thaw deflections in the uninsulated section ranged from 0.011 to about 0.017 inches. Deflections of the insulated pavement with approximately 29 inches of pavement and base above the insulation were approximately equivalent to those in the uninsulated section. The insulated section with only 21 inches of pavement and base above the insulating layer deflected approximately 0.003 to 0.004 inches more than the other two sections. During spring breakup deflections in the uninsulated section nearly doubled, while those from the insulated sections increased only slightly. Discussing these same test sections three years later, Bigelow (1968) stated,

> "Visual inspection of the pavement indicated that there are now more cracks in all three sections of this project than were found in previous years, but there are fewer cracks in the insulated sections than in the uninsulated section."

Table V

PERMANENT PAVEMENT DEFLECTION DUE TO REPETITIVE LOADING
FROM ANDERSSON, ORBOM AND RINGSTROM(1972)

TEST SECTION	CRACK INDEX	5	10	100	1000	5000	8000
		NUMBER OF LOAD CYCLES					
		DEFLECTION, INCHES					
1	1	.03	.06	.09	.14	.16	.17
2	0	.04	.06	.11	.20	.40	.47
3	2	.05	.06	.12	.22	.50	.63
4	4	.09	.11	.18	.35	.64	--
5	-	.04	.10	.20	.36	.51	.57

NOTES THE CYCLIC STRESS WAS APPROXIMATELY 87 PSI.
THE CRACK INDEX SCALE WAS 0 TO 5 WITH AN UNCRACKED PAVEMENT EQUAL TO 0 AND A PAVEMENT COMPLETELY DESTROYED BY CRACKS EQUAL TO 5.
THE LOADING CURVE HAD ESSENTIALLY A TRIANGULAR SHAPE AND THE LOADING RATE WAS 6 CYCLES PER MINUTE.
CRACK INDEX DETERMINED PRIOR TO REPETITIVE LOADING TEST.

PAVEMENT CROSS SECTIONS** (THICKNESS IN INCHES)

TEST SECTION	ASPHALTIC CONCRETE PAVEMENT	BITUMEN BOUND GRAVEL	GRAVEL BASE	INSULATING LAYER THICKNESS	INSULATING LAYER TYPE
1	1.6	0.0	9.8	0.0	UNINSULATED
2	1.6	4.7	3.9	0.0	UNINSULATED
3	1.6	4.7	3.9	1.6	EXTRUDED POLYSTYRENE
4	1.6	4.7	3.9	3.1	EXTRUDED POLYSTYRENE
5	1.6	4.7	3.9	7.9	EXPANDED CLAY

Table VI

AVERAGE BENKELMAN BEAM DEFLECTIONS ON DIFFERENT DATES
FROM MAINE STATE HIGHWAY COMMISSION(1965)

DATE OF TESTS	TEST SECTION	AVERAGE BENKELMAN DEFLECTION(INCHES) TRAVEL LANE OUTER WHEEL PATH	TRAVEL LANE INNER WHEEL PATH	PASSING LANE INNER WHEEL PATH	PASSING LANE OUTER WHEEL PATH
11-10-64	A	.018	.016	.018	.017
11-10-64	B	.016	.016	.016	.018
11-10-64	C	.016	.015	.015	.015
03-04-65	A	.020	.013	.018	.018
03-04-65	B	.011	.008	.013	.013
03-04-65	C	.012	.011	.011	.012
03-11-65	A	.019	.017	.019	.017
03-11-65	B	.016	.016	.016	.016
03-11-65	C	.016	.013	.015	.019
04-07-65	A	.021	.020	.022	.021
04-07-65	B	.020	.018	.022	.022
04-07-65	C	.028	.025	.029	.037
04-20-65	A	.021	.018	.021	.019
04-20-65	B	.019	.019	.018	.020
04-20-65	C	.030	.024	.025	.031
05-06-65	A	.025	.021	.021	.022
05-06-65	B	.021	.020	.020	.023
05-06-65	C	.025	.024	.026	.036
06-03-65	A	.021	.023	.020	.022
06-03-65	B	.022	.021	.020	.021
06-03-65	C	.021	.019	.023	.027

NOTES ROAD NOT OPEN TO TRAFFIC UNTIL FALL OF 1965.
EACH VALUE IS AN AVERAGE OF 12 TO 16 TEST POINTS.

PAVEMENT CROSS SECTIONS** (THICKNESS IN INCHES)

TEST SECTION	BITUMINOUS CONCRETE PAVEMENT	ASPHALT STABILIZED BASE	GRAVEL SURFACE	GRAVEL BASE	SAND BASE	INSULATING LAYER THICK-	INSULATING LAYER TYPE
A	3.0	4.0	1.0	7.0	6.0	1.5	EXTRUDED
B	3.0	4.0	1.0	15.0	6.0	1.5	POLYSTYRENE
C	3.0	4.0	1.0	17.0	6.0	0.0	UNINSULATED

Variables in the study reported by Schneider (1969) included thickness of pavement and base above the insulation, density of the insulation, and height of insulation. Results are summarized in Table VII. The test sections containing the low-density, molded polystyrene boards under only 12 inches of pavement and base, showed deflections nearly double those from the control section. When this same insulating material was covered with approximately 22 inches of pavement and base, the surface deflections were only slightly greater than those in the control section. In the test section containing the higher density molded polystyrene boards covered by 12 inches of pavement and base, the surface deflection was less than 20% greater than that of the control section. When 22 inches of pavement and base were used over this material, the deflections were roughly equivalent to those in the uninsulated control section. In the test sections containing polystyrene beads bound by cement, the deflections were greater than those observed in the adjacent control section. No granular base was used in either of these two sections, and in the higher density section (section 10) the bituminous pavement was placed immediately on the insulating layer.

The US Army Engineer Waterways Experiment Station (WES) has recently installed insulated test sections and subjected them to simulated heavy aircraft loadings (Hutchinson, 1972). Testing was recently completed and results are unavailable. Figures 10 and 11, from Hutchinson (1972), illustrate the sections which were tested. The Styropour referred to in the figures is composed of polystyrene beads bound by Portland Cement; extruded polystyrene materials were used.

Table VII

DEFLECTION OF INSULATED AND UNINSULATED BITUMINOUS PAVEMENTS
FROM SCHNEIDER(1969)

DATE TESTED	PERCENT OF DEFLECTION IN CONTROL SECTION									
	TEST SECTION NUMBER									
	1	2	3	4	5	6	7	8	9	10
JULY '67	100	186	140	99	112	109	92	100	129	180
OCT '67	100	215	175	107	120	128	100	100	140	182
FEB '68	100	186	145	107	118	126	108	100	145	248

THICKNESS OF LAYERS IN THE TEST SECTIONS (INCHES)	1	2	3	4	5	6	7	8	9	10
BITUMINOUS PAVEMENT	3.9	3.9	3.9	3.9	3.9	3.9	3.9	2.8	2.8	2.8
DRY-BOUND MACADAM	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.1	3.9	0.0
GRANULAR MATERIAL ABOVE INSULATION	12.8	2.0	5.9	11.8	2.0	5.9	11.8	15.8	0.0	0.0
INSULATING LAYER	0.	1.0	1.0	1.0	1.0	1.0	1.0	0.	3.2	4.7
GRANULAR MATERIAL BELOW INSULATION	-	9.8	5.9	0.0	9.8	5.9	0.0	-	0.0	0.0
TYPE OF INSULATION		MOLDED POLYSTYRENE BOARDS							POLYSTYRENE BEADS IN PC	
DENSITY OF THE INSULATING LAYER (PCF)	-	1.3	1.3	1.3	3.8	3.8	3.8	-	31.8	35.0

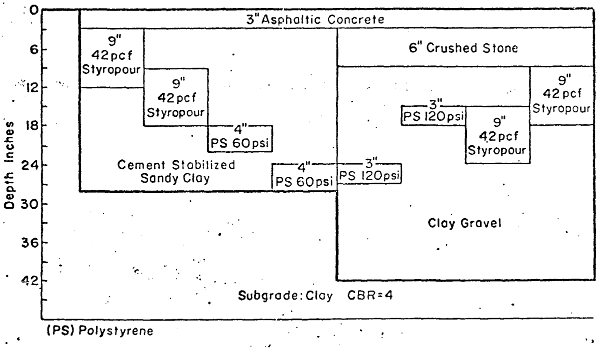


Figure 10
Flexible insulated pavement test sections at WES, from Hutchinson (1972).

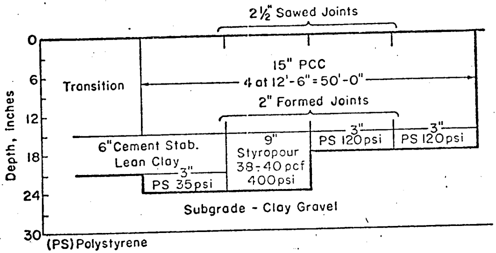


Figure 11
Rigid insulated pavement test sections at WES, from Hutchinson (1972).

In insulated embankments pavement failure can be controlled by proper design. Either the insulating layer can be placed at a sufficiently deep embedment or the asphalt pavement thickness can be increased. In North America most of the paved roadways and runways over permafrost are in Alaska. This may change radically in the future, however, and Baker (1971) states,

> "Although for many years the traveling public accepted gravel roads, it is now apparent that with the influx of people who are familiar with asphalt or concrete roads an even greater demand is being expressed to improve existing road surfaces. This must be accepted and consequently, it may not be too far in the future when all the trunk roads in the Yukon will be paved just as they now are in the State of Alaska."

THERMAL PROPERTIES

Most important of the thermal properties of candidate materials for embankment construction is the thermal conductivity. A low thermal conductivity is desirable. Ferrigno (1963) stated that the insulating efficiency depends upon many factors, including: the structure, environment, thickness, aging history, and composition of the material.

Approximate thermal conductivity values are listed for all of the materials in Appendix B. Figure 12 illustrates the effect of density on the thermal conductivity of polystyrene and polyurethane foams. The values shown for polyurethane are the "aged" values for the material. For a time after manufacture (several days to several months, depending upon the environmental conditions and types of "skins" on the surfaces) the thermal conductivity of polyurethanes increases. Landrock (1969) states,

> "It is not the loss of the fluorocarbon through the cell walls, but rather the diffusion of atmospheric gases into the foam, with resultant dilution of the fluorocarbon, that causes the drift in K-factor."

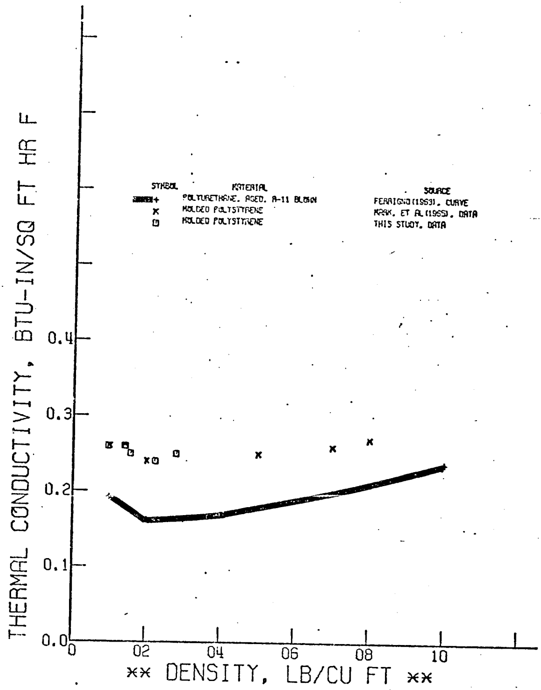


Figure 12
Density-thermal conductivity relationships for molded polystyrene and aged polyurethane foams.

The drift continues until the partial pressures of gases in the cells and in the atmosphere are at equilibrium. Ferrigno (1963) shows data indicating that a one-inch sample of urethane kept in a 140° F environment reached its "aged" thermal conductivity value in approximately 120 days. A lower temperature in the environment surrounding the sample would have increased the time required to reach the "aged" condition. The aging process of urethane foams can be essentially eliminated by placing the material between impervious membranes such as high-density plastic or metal skins. Ferrigno also indicates that the formulation of the polymer and the method of manufacture of the material also influence its aging characteristics. Most other insulating materials do not exhibit this prolonged aging process.

Relationships between thermal conductivity and density for higher-density materials are shown in Figure 13. Two curves are shown for the cement, sand, and polystyrene bead material. The lower curve is for use in low-humidity conditions and the upper curve is suggested for use when high-humidity conditions are encountered. The behavior of this material is probably typical of lightweight cement and asphalt-bound materials. They tend to have a rather porous structure and when subjected to humid conditions, the voids tend to fill with moisture and thus the thermal conductivity increases. The magnitude of this increase is dependent upon the structure of the material.

The thermal conductivity of insulating materials normally decreases with decreasing temperature. Figure 14 illustrates this behavior for several materials. Data from this figure are for dry materials; however, if the materials contain substantial amounts of moisture, an increase in

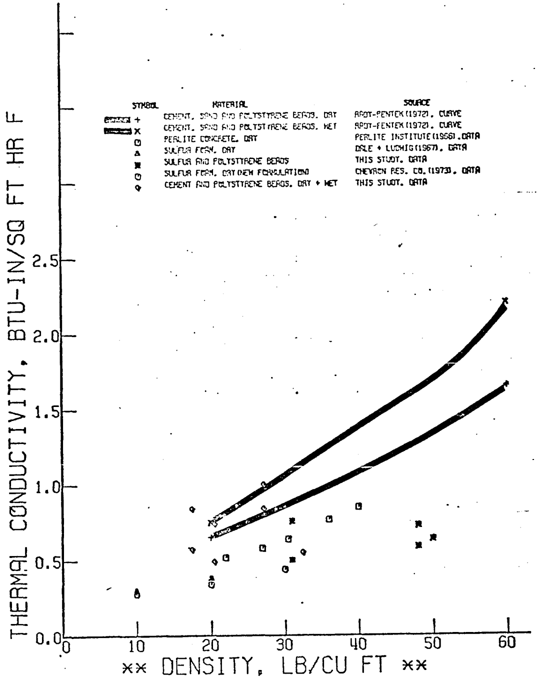


Figure 13
Density-thermal conductivity relationships for high density insulating materials.

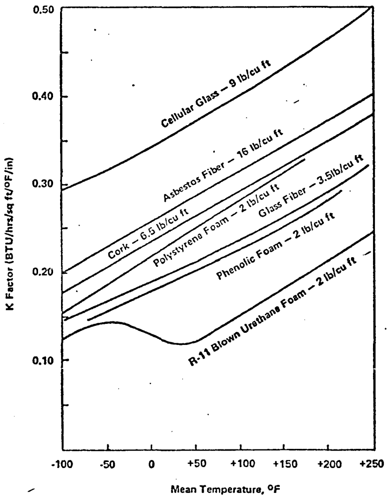


Figure 14
Temperature-thermal conductivity relationships for insulating materials, from Landrock (1969).

thermal conductivity may occur at the freezing point of moisture within the structure of the material. The thermal conductivity of polyurethanes differs from the others because between approximately +40° F and -40° F, the thermal conductivity increases slightly.

The quantity of moisture in an insulating material may have a significant influence on its thermal conductivity. Figure 15 illustrates the increase in thermal conductivity due to moisture absorption for polyurethane, molded polystyrene, and extruded polystyrene. Equations relating volumetric moisture content and thermal conductivity for the polyurethane and extruded polystyrene materials were presented by Levy (1966). Both were linear relationships and lines obtained from the equations are shown in Figure 15. Lines obtained by Saetersdal for molded polystyrene and Levy for extruded polystyrene are the same. Joy (1957) presents similar data for three other insulating materials. He does not indicate, however, what materials he tested. He shows curves similar to those in Figure 15 for the three samples, above freezing and below freezing. In general, the thermal conductivity values below freezing are slightly higher than those above freezing. Data in Figure 13 illustrate a significant increase in thermal conductivity of a cement, sand, and polystyrene bead mixture when placed in a humid environment.

Figure 16 illustrates the change in thermal conductivity versus years of service for Dow Chemical Company's Styrofoam HI, an extruded polystyrene. Data indicate that the thermal conductivity may be increasing very slowly with age. It should be noted, however, that in nearly all laboratory and field studies conducted to date, Styrofoam HI has absorbed considerably less moisture than any of the other insulating materials. This point will

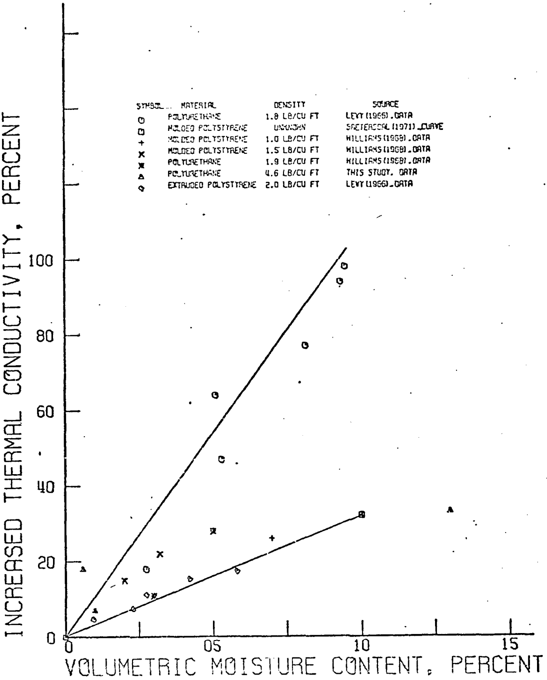


Figure 15
Influence of moisture on the thermal conductivity of polyurethane, molded polystyrene and extruded polystyrene.

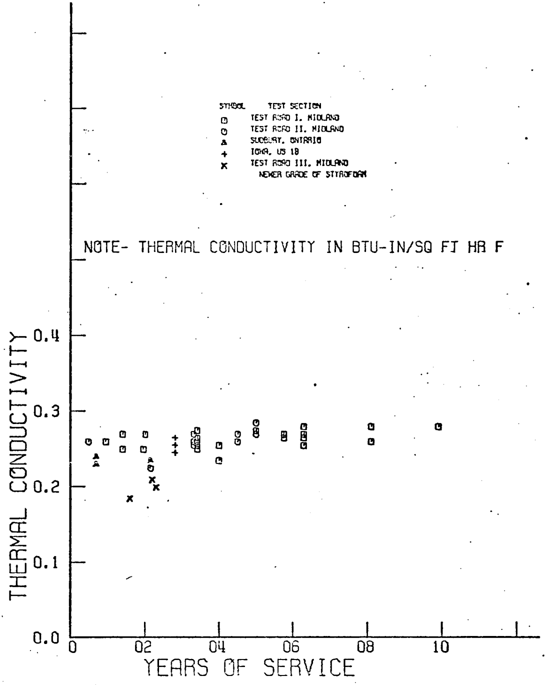


Figure 16
Thermal conductivity vs. years of service for highway installations using Styrofoam HI, from Mackey (1973).

be discussed more thoroughly in subsequent portions of this chapter. One would therefore expect that the rate of increase in thermal conductivity of Styrofoam HI is less than that of other materials unless they are protected with an impervious membrane. Discussing test sections after three years of service near Anchorage, Alaska, Esch (1971) stated,

> "Thermal analysis indicates a tendency toward increases in thermal conductivity of the foamed-in-place urethane insulation layer with time, in spite of the asphalt coatings used before and after insulation placement."

He stated that the thermal conductivity of the urethane layers apparently increased by at least 10-20% during the first three years of use.

ENVIRONMENTAL EFFECTS

Most materials listed in Appendix B are inert to the chemicals and bacteria normally found in soil water. Assuming that the thermal insulating layer has been designed for adequate strength or is buried at sufficient depth to sustain the loadings imposed, the most potentially dangerous environmental effect is that of moisture absorption by the insulating material.

Most insulating materials absorb moisture unless protected by an impervious membrane. Some materials, however, absorb significantly greater amounts of moisture than do others. The most important result of moisture intrusion into the insulating material is increased thermal conductivity. Figure 15 illustrated the effect of increased moisture on the thermal conductivity for three materials. Relatively small volumes of moisture increase the thermal conductivity significantly in these cellular plastic materials. Two additional points concerning Figure 15 must be stressed.

(1) Although the volumes of moisture absorbed and the volumetric moisture contents are relatively small, moisture contents on a dry weight basis are large due to the low density of the materials. (2) The initial thermal conductivity of polyurethane is considerably lower than those for extruded polystyrene or molded polystyrene. Thus, although data from Levy indicate a much steeper curve for polyurethane than Saetersdal determined for molded polystyrene, the thermal conductivity for moist polyurethane may be lower than that for moist molded polystyrene. Similarly, the thermal conductivity of moist polyurethane will be lower than that of moist extruded polystyrene up to some particular moisture content which can be computed.

Other potentially dangerous problems of moisture within the insulating layer are those of rupture of the cell walls or cell separation during freezing. Cell walls in most lightweight plastic materials are sufficiently elastic to allow the expansion of water upon freezing without rupturing. In more rigid materials such as cellular glass or cell concrete, cell walls may be ruptured by freeze-thaw cycles. Rupture of the cell walls may cause a decrease in the compressive strength and an increase in the thermal conductivity of the material.

Kaplar and Wieselquist (1967) summarized results of laboratory freeze-thaw cycles conducted at USACRREL. Materials included in these studies are listed in Table VIII. Each test specimen was five inches square by two inches thick. Two specimens of each material were included in the tests. One sample of each material was removed after 15 freeze-thaw cycles and the freeze-thaw tests were terminated after 30 cycles. For the freeze-thaw cycling tests nine specimens were placed in each tray with 1/16 to

Table VIII

MATERIAL SOURCES, TYPES AND DENSITIES
FROM KAPLAR AND WIESELQUIST(1967)

TRADE NAME	MANUFACTURER	TYPE	AVERAGE DENSITY, LB/CU FT FREEZE-THAW(1) SAMPLES	IMBEDED SAMPLES
ARMALITE	ARMSTRONG	MOLDED PS	0.89	0.84
FOAMGLAS	OWENS-CORNING	CELLULAR GLASS	8.66	9.26
HONEYFOAM	SERVICE PROD.	EXTRUDED PS	1.68	1.64
SCOREBOARD	DOW CHEM. CO.	EXTRUDED PS	2.51	2.54
STYROFOAM CB	DOW CHEM. CO.	EXTRUDED PS	1.94	2.04
STYROFOAM HD-1	DOW CHEM. CO.	EXTRUDED PS	2.91	2.88
STYROFOAM HD-2	DOW CHEM. CO.	EXTRUDED PS	4.42	4.45
URETHANE 200	UNION ASBESTOS	URETHANE BOARD	2.24	2.25

NOTE (1) DENSITIES ARE REPRESENTATIVE OF MATERIALS USED IN 7-DAY TESTS TO DETERMINE EFFECTS OF PRESSURE ALSO.

1/8 inch of water surrounding each specimen. The sides of the large trays were insulated to establish one-dimensional freezing and thawing of the samples. Maximum heat flow was perpendicular to the 5" x 5" faces of the samples. Usually the trays containing the samples were placed in a cold room at -10° F in the morning and removed that afternoon. The trays were then left in the laboratory environment at about 70° F overnight. After the specimen had undergone the desired number of freeze-thaw cycles, it was removed, the edges trimmed, and sectioned into approximately 1/4 inch thick pieces. The volumetric moisture content of each piece was then determined. Figure 17 illustrates sectioning of the samples, and Table IX shows the moisture distribution within the samples upon completion of the freeze-thaw studies. Moisture contents for the outer surfaces are not shown in Table IX. The amount of moisture in these areas is controlled by the surface characteristics rather than the structure of the material. Data from the interior of the samples as shown in Table IX are felt to be more indicative of the performance of the materials. Armalite and Foamglas performed much more poorly than other samples in this study. One of the Foamglas samples fractured prior to reaching 30 freeze-thaw cycles and after only 15 freeze-thaw cycles the moisture content on the upper surface was very high, indicating that several of the cell walls had been ruptured, allowing moisture to intrude into the sample. Moisture distribution through the Armalite was more uniform but very substantial. The volumetric moisture content of the urethane samples was also relatively high. The moisture content of this material increased considerably between 15 and 30 freeze-thaw cycles. None of the Styrofoam or Scoreboard materials absorbed

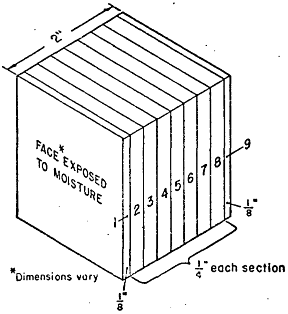


Figure 17
Sectioning samples for moisture distribution studies, from Kaplar and Wieselquist (1967).

Table IX

MOISTURE DISTRIBUTION AFTER FREEZE-THAW TESTS
LABORATORY TEST RESULTS
FROM KAPLAR AND WIESELQUIST(1967)

MATERIAL	NUMBER OF CYCLES	VOLUMETRIC MOISTURE CONTENT, PERCENT SECTION NUMBER 2	3	4	5	6	7	8	AVE
ARMALITE	15	10.1	15.4	13.3	9.8	9.4	11.8	13.8	11.9
	30	37.1	36.5	31.0	26.7	23.0	26.5	39.8	31.5
FOAMGLAS	15	48.1	36.6	4.4	1.1	1.3	0.4	0.5	13.2
	30	SAMPLE FRACTURED PRIOR TO 30 CYCLES							
HONEYFOAM	15	0.6	0.2	0.2	0.1	0.1	0.2	0.2	0.2
	30	2.6	1.0	0.7	0.6	0.6	0.7	6.4	1.8
SCOREBOARD	15	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1
	30	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
STYROFOAM CB	15	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	30	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.2
STYROFOAM HD-1	15	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0
	30	1.3	0.4	0.2	0.2	0.1	0.1	11.7	2.0
STYROFOAM HD-2	15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	30	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1
URETHANE 200	15	1.3	0.6	0.5	0.4	0.4	0.4	0.5	0.6
	30	9.3	4.7	6.7	5.6	4.0	6.0	16.5	7.5

NOTE- SPECIMEN SECTIONED AS SHOWN IN FIGURE 17.

significant amounts of moisture although it appears that the Styrofoam HD-1 had developed surficial cracks prior to 30 cycles, as indicated by the large moisture content near one face. Styrofoam HI was not used in this study; however, the performance of Scoreboard is probably indicative of Styrofoam HI.

Williams (1968) described and discussed freeze-thaw studies conducted by Dow Chemical Company. The apparatus used in these studies is shown in Figure 18. An attempt was made to simulate a roadway embankment in these tests. Samples eight inches square by one inch thick were used. Subfreezing brine was circulated through the upper plate until the temperature in the clay subgrade reached 31° F. At this time the brine temperature in the surface plate was increased and the flow of warmed liquid continued until a temperature of 34° F was reached in the clay subgrade. Then the cycle was repeated. One to three days were required for a complete freeze-thaw cycle, depending on the ambient air temperature.

Figure 19 summarizes results of the freeze-thaw tests by Dow Chemical Company. Volumetric moisture contents shown in the figure are those for the entire sample. For similar samples, then, these moisture contents should be somewhat higher than those in Table IX. Styrofoam HI absorbed the smallest amounts of moisture, its moisture content being slightly less than 1.5% by volume after 180 freeze-thaw cycles. The 1 lb/cu ft bead-board material absorbed the most moisture, being slightly over 10% at 180 cycles. Urethane had absorbed about 5% after 180 freeze-thaw cycles.

Two series of freeze-thaw tests were conducted at the University of Alaska in conjunction with this work. Materials used in the first series

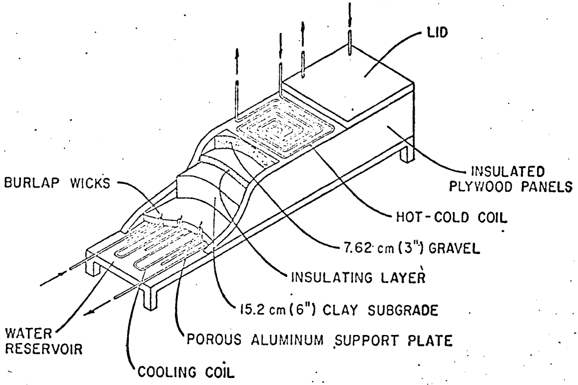


Figure 18
Freeze-thaw device used by Dow Chemical Company, from Williams (1968).

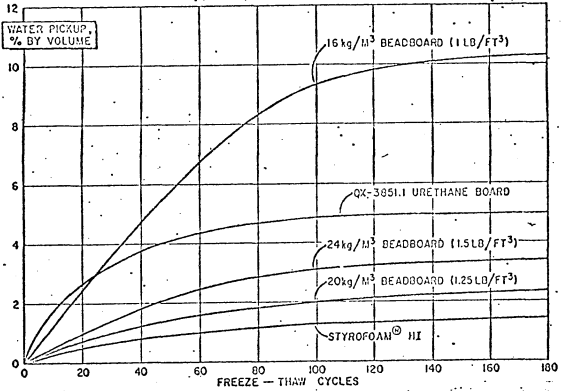


Figure 19
Results of freeze-thaw tests conducted by Dow Chemical Company, from Williams (1968).

and results obtained are shown in Appendix C. Materials and results from the second series of studies are shown in Appendix D.

Samples four inches square and of various thicknesses were used in the first series of tests. The thermal conductivity of most materials was determined prior to the freeze-thaw studies and again after freeze-thaw cycling had been completed. Each sample was subjected to 20 freeze-thaw cycles. The following procedure was used: samples were immersed beneath a 2-inch head of water for approximately six hours. At that time they were removed from the water and placed in a drip rack at room temperature for approximately 30 minutes. They were then placed in a deep-freeze at about 0° F overnight. The next morning they were removed from the deep-freeze, allowed to sit in the room temperature environment for approximately 30 minutes, reweighed, and then immersed in the water bath again. This procedure was continued until 20 freeze-thaw cycles had been achieved. Moisture absorption of these samples is shown in Figure 20 and Table X contains thermal conductivity data before and after freeze-thaw cycling. The Styrofoam HI absorbed essentially no moisture and its thermal conductivity did not change after the freeze-thaw cycles. The other materials absorbed relatively small amounts of moisture. The thermal conductivity values before and after the freeze-thaw tests were essentially the same.

Appendix D contains data from the second series of freeze-thaw tests. Molded polystyrene of various grades and densities was used in this series of tests and the samples were approximately two inches square by 1.5 inches thick. The procedure for testing the durability of these materials when subjected to freeze-thaw cycles was similar to that in series 1 with two

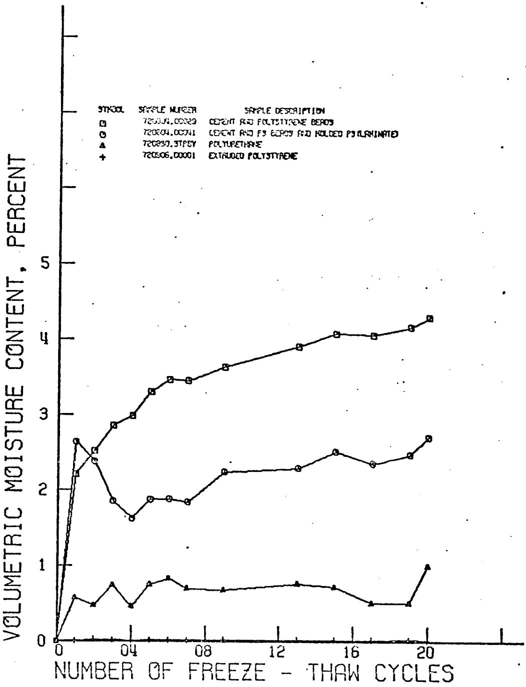


Figure 20
Moisture absorption and number of freeze-thaw cycles for Series 1 materials.

Table X

THERMAL CONDUCTIVITY OF SERIES 1 SPECIMEN
BEFORE AND AFTER
FREEZE-THAW CYCLES

SAMPLE NUMBER	MATERIAL	THERMAL CONDUCTIVITY BEFORE F-T	AFTER F-T
720804.00029	CEMENT POLYSTYRENE BEAD MIXTURE	1.11A	0.95
720804.00034	CEMENT POLYSTYRENE BEAD MIXTURE	--	1.20
720804.00037	CEMENT PS BEAD MIXTURE + MOLDED PS(LAMINATE)	--	0.50
720804.00041	CEMENT PS BEAD MIXTURE + MOLDED PS(LAMINATE)	--	0.54
720830.2TPDV	POLYURETHANE	0.18	0.18
720830.3TPAV	POLYURETHANE	0.21	0.21
720830.4TPAV	POLYURETHANE	0.19	0.19
720906.00001	EXTRUDED POLYSTYRENE	0.22A	0.21
720906.00007	EXTRUDED POLYSTYRENE	0.22A	0.21

NOTE- THERMAL CONDUCTIVITY UNITS ARE BTU-IN/SQ FT HR F.
A- SIMILAR SPECIMAN. THERMAL CONDUCTIVITY OF SPECIMAN SUBJECTED TO FREEZE - THAW CYCLES NOT MEASURED PRIOR TO F-T CYCLES.

exceptions. First, thermal conductivity values were not measured for the samples, and second, an alcohol-water mixture (0.5% by weight ethyl alcohol) was used. Alcohol was added to the water to reduce the surface tension, thus allowing more rapid and deeper penetration of the mixture into the samples without significant depression of the freezing temperature.

Moisture absorption by specimens in this test series is shown in Figure 21. Results from these tests were similar to those from the first series of tests; *i.e.*, the moisture content of most samples generally increased with increasing number of freeze-thaw cycles. The material having an average density of 1.52 lb/cu ft absorbed the largest quantities of the alcohol-water mixture. It also had the largest beads and, probably, the largest voids between adjacent beads.

As part of the tests in series 2, specimens were tested to determine their unconfined compressive strength. Similar specimens were tested with no freeze-thaw cycles and after being subjected to 20 freeze-thaw cycles. Results of tests on one set of similar samples are shown in Figure 22. No decrease in compressive strength after 20 freeze-thaw cycles is noted. This behavior was common to all six sets of similar samples.

Had the freeze-thaw testing been more severe, *i.e.* had the samples absorbed more of the alcohol-water mixture during the freeze-thaw cycling, cell walls may have separated or individual beads may have been deformed, causing a loss of compressive strength. To evaluate this possibility another series of tests is suggested. Samples of similar density and composition should be used. Samples should be allowed to drain for various time periods prior to being placed in the freezer. For example, one specimen may be placed in the freezer allowing no drainage and another after

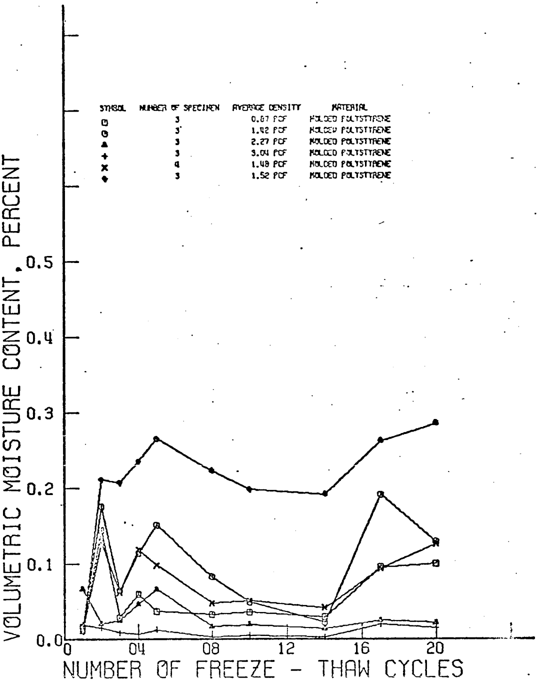


Figure 21
Moisture absorption and number of freeze-thaw cycles for Series 2 materials.

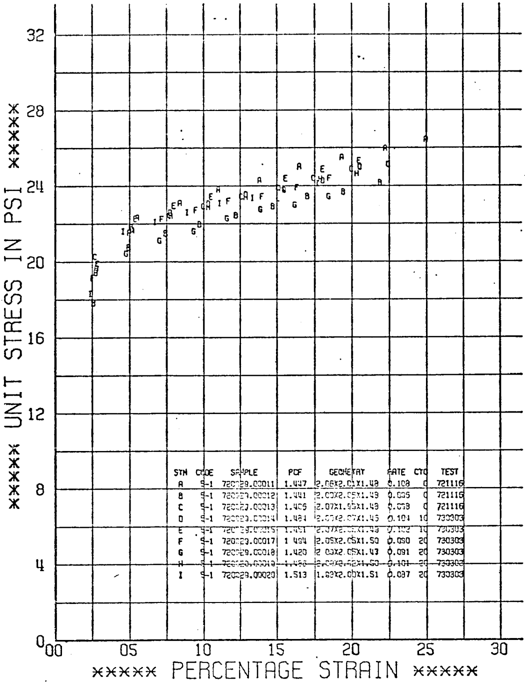


Figure 22
Compressive strength of molded polystyrene specimen with no freeze-thaw cycles and subjected to 20 freeze-thaw cycles.

two to three minutes of drainage, etc. Individual specimens should undergo the same procedure during each cycle to properly evaluate the desired effects.

Several laboratory tests have also been conducted to determine the amount of moisture absorption in various insulating materials. Powell and Robinson (1971) studied the effect of moisture on the thermal efficiency of insulated flat roofs. A few cellular plastic materials were used in their investigation; however, most of their data were obtained for lightweight concrete materials. An interesting concept discussed by Powell and Robinson is that of a "self-drying" roof insulation. It is unlikely, however, that this concept could be applied to insulated embankments.

Several tests for determining the moisture absorption and the water vapor permeability of insulating materials are available. The following standards are from the American Society for Testing and Materials (1971): Standard D 2842-69, "Water Absorption of Rigid Cellular Plastics"; Standard C 272-53 (reapproved 1970), "Water Absorption of Core Materials for Structural Sandwich Constructions"; and Standard C 355-64, "Water Vapor Transmission of Thick Materials". The American Association of State Highway Officials (AASHO) specification M 230-70, "Standard Specification for Extruded Insulation Board (Polystyrene)", suggests using ASTM Standard C 272-53 for determining the moisture absorption of this material. They recommend using a slightly different procedure in drying the sample prior to weighing, however.

The standard tests are for a duration of 24 to 96 hours; however, many investigators feel that the amount of the moisture absorbed during this short period of time is not indicative of the performance of the material during a long period of embedment in an embankment. Some materials have been soaked for up to 18 months. Table XI contains information from Kaplar and Wieselquist (1967), Orama (1972), and Saetersdal (1971). Data are shown for up to 150 days of immersion. The testing procedures varied somewhat as Kaplar and Wieselquist reported the boards in their studies were covered with approximately 1/4 inch of water and the system was isothermal. Both Orama and Saetersdal applied a temperature gradient across the sample, thereby increasing the driving potential of moisture through the insulation. Extruded polystyrene boards absorbed the smallest quantities of moisture in all three series of tests and the corkboard samples of Kaplar and Wieselquist absorbed the most moisture after 100 days. The amount of moisture absorbed by the molded polystyrene samples varied considerably and appears to be independent of the sample density. The polyurethane samples used by Saetersdal and Kaplar and Wieselquist also absorbed relatively large volumes of moisture. After 100 days of immersion, both materials contained more than 5% moisture by volume. Williams (1968) reported that a sample of urethane in tests conducted by Dow Chemical Company had absorbed approximately 2% moisture by volume after 95 days of immersion. These variations may be due to differences in formulation or differences in the manufacturing process, as discussed previously.

Williams (1968) also included samples of Styrofoam HI and two densities of molded polystyrene in his tests. The Styrofoam HI, an extruded polystyrene, absorbed the smallest amount of water in his tests and a molded polystyrene sample of 1.5 pounds per cubic foot density absorbed the most.

Assuming that the moisture content versus time curve is composed of a linear segment succeeded by a non-linear segment as the maximum moisture

Table XI

MOISTURE ABSORPTION IN INSULATING MATERIALS
LABORATORY TEST RESULTS

MATERIAL	DENSITY LB/CU FT	REFERENCE	ELAPSED TIME, DAYS 10	25	50	75	100	150
			VOLUMETRIC MOISTURE CONTENT PERCENT					
MOLDED POLYSTYRENE	1.0	KAPLAR AND WIESELQUIST(1967)	4.5	5.1	5.6	6.0	6.3	7.1
CELLULAR GLASS	9.2	KAPLAR AND WIESELQUIST(1967)	0.4	0.7	1.1	1.5		
EXTRUDED POLYSTYRENE	2.5	KAPLAR AND WIESELQUIST(1967)	0.7	0.8	0.9	1.0	1.0	1.1
EXTRUDED POLYSTYRENE	2.9	KAPLAR AND WIESELQUIST(1967)	1.4	1.8	2.2	2.4	2.5	2.9
POLYURETHANE	2.2	KAPLAR AND WIESELQUIST(1967)	2.4	3.4	4.3	5.0	5.6	7.1
CORK BOARD	16.3	KAPLAR AND WIESELQUIST(1967)	5.8	9.0	14.6	14.2	13.8	
CORK BOARD	14.7	KAPLAR AND WIESELQUIST(1967)	5.4	7.3	10.5	11.2	11.9	

NOTE SAMPLES WERE 6IN X 12IN X 2IN THICK. EDGES WERE TAPED TO MINIMIZE EDGE EFFECT. SAMPLES DRAINED 2 MINUTES PRIOR TO WEIGHING. ABOUT 1/4 INCH OF WATER OVER BOARDS. THE 6X12 SURFACES WERE IN THE HORIZONTAL PLANE. NO TEMPERATURE GRADIENT IMPOSED ON SAMPLES.

MATERIAL	DENSITY LB/CU FT	REFERENCE	10	25	50	75	100	150
MOLDED POLYSTYRENE	2.5	ORAMA(1972)	1.1	1.5	2.2	2.9	3.6	4.5
MOLDED POLYSTYRENE	2.5	ORAMA(1972)	1.5	2.1	3.2	3.9	4.2	4.8
MOLDED POLYSTYRENE	2.0	ORAMA(1972)	1.0	1.4	2.1	2.9	3.5	4.9
MOLDED POLYSTYRENE	3.1	ORAMA(1972)	1.7	2.1	3.0	3.7	4.4	5.3
MOLDED POLYSTYRENE	2.5	ORAMA(1972)	0.6	1.1	1.5	1.8	2.0	2.5
MOLDED POLYSTYRENE	2.5	ORAMA(1972)	1.2	1.8	2.6	3.5	4.4	6.1
EXTRUDED POLYSTYRENE	2.5	ORAMA(1972)	0.4	0.5	0.7	0.7	0.7	0.9
EXTRUDED POLYSTYRENE	2.5	ORAMA(1972)	0.3	0.4	0.4	0.5	0.5	0.8

NOTE SAMPLES WERE 2IN THICK. NO LENGTH AND WIDTH DIMENSIONS WERE GIVEN BUT THICKNESS WAS MINIMUM DIMENSION AS INDICATED IN FIGURES. SAMPLES WERE PLACED ON EDGE IN WATER. WATER TEMPERATURES ON OPPOSITE SIDES OF THE SAMPLES DIFFERED BY 14F TO 18F WITH THE COLD SIDE VARYING FROM 40F TO 80F.

MATERIAL	DENSITY LB/CU FT	REFERENCE	10	25	50	75	100	150
POLYURETHANE	2.2	SAETERSDAL(1971)	0.5	1.3	2.6	3.8	5.1	
MOLDED POLYSTYRENE	1.6	SAETERSDAL(1971)	1.2	3.0	6.0	9.0	12.0	
MOLDED POLYSTYRENE	2.1	SAETERSDAL(1971)	0.4	1.1	2.2	3.3	4.4	
MOLDED POLYSTYRENE	1.7	SAETERSDAL(1971)	0.6	1.6	3.2	4.8	6.4	
EXTRUDED POLYSTYRENE	2.0	SAETERSDAL(1971)	0.1	0.2	0.4	0.5	0.7	
EXTRUDED POLYSTYRENE	2.5	SAETERSDAL(1971)	0.0	0.1	0.2	0.4	0.5	

NOTE FIRST THREE SAMPLES 2IN THICK AND LAST THREE ABOUT 4IN THICK. THE 2.1LB/CU FT MOLDED POLYSTYRENE WAS MOLDED AT THE 2INCH THICKNESS, THE OTHER MOLDED POLYSTYRENE SAMPLES WERE CUT FROM THICKER MATERIAL. NO LENGTH AND WIDTH DIMENSIONS WERE GIVEN BUT FIGURES INDICATED THAT THICKNESS WAS MINIMUM DIMENSION. SAMPLES WERE PLACED ON EDGE. OPPOSITE FACES WERE KEPT AT TEMPERATURES OF 59F AND 77F. THE RELATIVE HUMIDITY ON BOTH SIDES WAS 100 PERCENT.

content is approached, *i.e.*, a shape similar to that of a stress-strain curve for an elasto-plastic material, nearly all of the materials in Table XI are still in the linear range. Using these data it is not possible to estimate the ultimate moisture content. One exception is the 16.3 lb/cu ft corkboard tested by Kaplar and Wieselquist. It reached a maximum value after only 50 days of soaking.

Hartmark (1971) stated that the properties of molded polystyrene boards cut from larger blocks are quite variable. Therefore, for Norwegian State Railways molded polystyrene boards must be cast at the desired thickness. Properties of molded polystyrene boards manufactured by this technique are much more uniform.

Kaplar and Wieselquist (1967) showed the moisture distribution within several samples after immersion for 18 months. Some of their results are reproduced in Figure 23. The moisture distribution within the Armalite was relatively uniform and varied between approximately 8.5% and 7% by volume. The moisture content in the urethane was also quite high; however, the interior contained considerably less moisture than the exterior portion. The Scoreboard and Styrofoam HD-1 contained interior moisture contents of less than 0.5% by volume. Due to the smooth texture of its surface, the Scoreboard absorbed only approximately 1% by volume near its surface. This was considerably less than the surface moisture content of any other sample.

Effects of increasing the pressure head on the quantity of moisture absorbed by various materials was reported by Kaplar and Wieselquist (1967). Samples of the same materials used in their freeze-thaw tests were included in this study. Gauge pressures of 0 and 15 psi were used. Moisture contents of the Foamglas, Honeyfoam, Scoreboard, and Urethane increased with

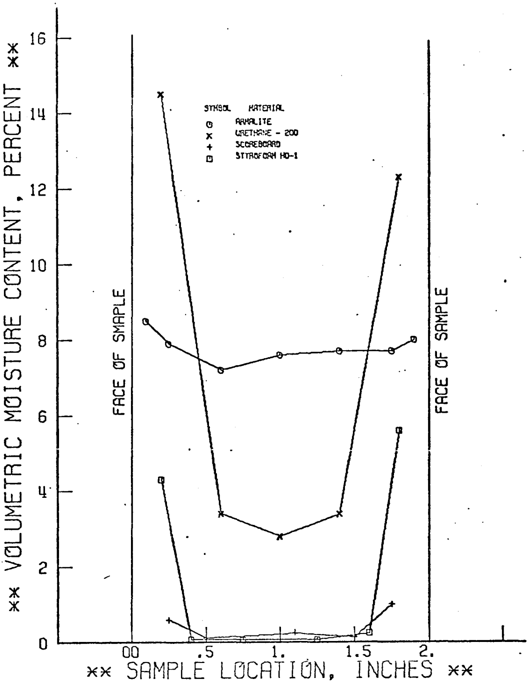


Figure 23
Moisture distribution after immersion for 18 months, from Kaplar and Wieselquist (1967).

increasing pressure, and that of Styrofoam CB was essentially unaffected by the increased pressure. The Armalite, Styrofoam HD-1, and Styrofoam HD-2 absorbed less moisture at the higher pressure. The change in Armalite was much greater than in the two Styrofoam samples, however. The decreases in moisture content may have been caused by compression of the sample under the higher pressures, thus reducing the size and amount of voids in the material. This rendered the samples more impervious to moisture. The volumetric moisture contents shown in Table XII for these tests are considerably lower than those shown in previous tables because the duration of these tests was only seven days. For these tests two specimens of each material were used. One was immersed under approximately 1/4 inch of water and the other was placed in a sealed vessel and submerged under approximately the same head; a 15 psi air pressure was applied inside the vessel.

Kaplar and Wieselquist (1967) also reported the moisture distribution within several samples after being embedded in a wet soil for up to 34 months. The following description of their apparatus was given:

> "A sheet metal tank 44 inches by 32 inches by 18 inches was constructed to contain the moist silt. A two-inch gravel layer was placed on the bottom with a one-inch thick coarse filter layer, topped with a one-inch fine filter layer. The moist soil was placed on top of the fine filter layer. This was designed so that a continuous supply of water would be available at the bottom of the tank in contact with the silt to maintain a moist condition by capillarity. The tank was equipped on the side with a 5-gallon water supply feeding to a constant-water-level control device which maintained the water level in the tank at about 6 inches from the bottom or two inches into the silt."

Samples used in this study were fives inches wide by 12 inches long by two inches thick. They were oriented such that the long dimension was in the vertical plane and approximately 1/2 inch of silt covered the upper

Table XII

MOISTURE DISTRIBUTION AFTER 7-DAY PRESSURE TESTS
LABORATORY TEST RESULTS
FROM KAPLAR AND WIESELQUIST(1967)

MATERIAL	GAGE PRES. PSI	VOLUMETRIC MOISTURE CONTENT, PRECENT SECTION NUMBER 2	3	4	5	6	7	8	AVE
ARMALITE	0	2.03	2.58	3.18	3.36	2.83	2.06	1.54	2.39
	15	1.65	1.95	1.93	2.01	1.95	1.84	1.57	1.84
FOAMGLAS	0	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01
	15	0.01	0.00	0.00	0.00	0.01	0.00	0.79	0.11
HONEYFOAM	0	0.07	0.06	0.04	0.04	0.05	0.06	0.07	0.05
	15	0.07	0.06	0.06	0.08	0.07	0.08	0.08	0.07
SCOREBOARD	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	15	0.04	0.03	0.02	0.03	0.02	0.02	0.04	0.03
STYROFOAM CB	0	0.04	0.03	0.05	0.04	0.05	0.05	0.04	0.05
	15	0.05	0.05	0.05	0.04	0.05	0.04	0.04	0.05
STYROFOAM HD-1	0	0.43	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	15	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01
STYROFOAM HD-2	0	0.07	0.18	0.11	0.12	0.11	0.09	0.05	0.09
	15	0.05	0.12	0.09	0.10	0.09	0.08	0.06	0.08
URETHANE 200	0	0.25	0.22	0.21	0.20	0.20	0.20	0.21	0.21
	15	2.14	0.93	0.41	0.27	0.24	0.23	0.51	0.67

NOTE- SPECIMEN SECTIONED AS SHOWN IN FIGURE 17.

end of the samples. The lower ends of the samples were then approximately 1/2 inch below the water level maintained in the reservoir. Samples of the same type used in the freeze-thaw studies were used in this study and their average densities are shown in Table VIII. Three specimens of each type were included and one specimen of each material was removed after six months, another was removed after 18 months, and the test was terminated after 34 months and the remaining samples removed. Upon removing the samples from the moist soil, a one-inch thick strip was cut from each end and each side. The remainder of the sample was sectioned as discussed in the freeze-thaw tests. The interior moisture distribution of these samples is shown in Table XIII. Data for 6-, 18-, and 34-months are shown for each material. The Foamglas absorbed only 0.1% by volume after 34 months. The Styrofoam and Scoreboard samples had average moisture contents of approximately 0.2% by volume, or less, after 34 months. The Armalite had a 1.6% by volume moisture content by the end of 34 months, and the Urethane had an average moisture content of 4.6% after 34 months. Moisture distribution within the Urethane and within the Armalite was relatively uniform.

In the tests described above, the Styrofoam (extruded polystyrene) materials normally absorbed less moisture than the others. The Foamglas also absorbed a small quantity of water except in the freeze-thaw tests of Kaplar and Wieselquist. Although the tests described above may provide an indication of the relative moisture absorption in laboratory studies, they may not be valid for field installations. None of the above methods provides data from which field moisture contents at future times can be estimated.

Table XIII

MOISTURE DISTRIBUTION AFTER IMBEDMENT IN WET SOIL
LABORATORY-TEST RESULTS
FROM KAPLAR AND WIESELQUIST(1967)

MATERIAL	ELAPSED TIME MONTHS	VOLUMETRIC MOISTURE CONTENT, PERCENT SECTION NUMBER 2	3	4	5	6	7	8	AVE
ARMALITE	6	1.0	0.3	0.6	0.6	0.6	0.7	0.8	0.7
	18	2.7	1.2	0.6	0.4	0.7	0.7	1.6	1.1
	34	2.4	1.3	1.0	0.9	1.2	1.5	2.6	1.6
FOAMGLAS	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	34	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HONEYFOAM	6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	18	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1
	34	1.2	0.7	0.6	0.6	0.6	0.7	1.0	0.8
SCOREBOARD	6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	18	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	34	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
STYROFOAM CB	6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	18	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	34	0.3	0.2	0.2	0.1	0.2	0.2	0.3	0.2
STYROFOAM HD-1	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	18	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2
	34	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.2
STYROFOAM HD-2	6	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	18	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
	34	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
URETHANE 200	6	2.6	1.8	1.4	1.2	1.3	1.6	2.1	1.7
	18	5.2	2.3	2.2	2.2	1.4	1.6	5.1	2.9
	34	5.8	4.2	3.9	3.8	3.8	4.1	6.4	4.6

NOTE- SPECIMEN SECTIONED AS SHOWN IN FIGURE 17.

After reviewing procedures and results from the laboratory studies discussed above, two vital questions arise: (1) "Do any of the laboratory tests provide data sufficient to predict the performance of the insulating material in an actual embankment?" and (2) "Which test or tests are the best indicators?" Answers to these questions can only be obtained by comparing laboratory and field data. Tables XIV and XV contain data from field studies, Table XIV for lightweight plastic materials and Table XV for various other types of insulating materials.

Results from the field studies are similar to those obtained in the laboratory in that for a given material the moisture content tends to increase with time. Materials which performed most suitably in the laboratory also performed most suitably in actual embankments. Extruded polystyrene boards absorbed the smallest amount of moisture and many of the molded polystyrene materials also absorbed relatively low amounts of water in field studies. Two molded polystyrene materials reported by Saetersdal (1971) absorbed very large amounts of moisture, however. The polyurethane materials also generally tended to absorb much more moisture than the extruded polystyrenes. Results from the field studies showed a wide variation similar to those observed in the laboratory, and were undoubtedly caused by the same factors such as fabrication process and materials used. In addition to these variables, insulating materials in the field studies also existed in different micro-environments. Data in Table XV indicate that the extruded polystyrene material with a plastic membrane over it absorbed slightly more moisture than the same material which had no external protection. Moisture contents of the excelsior, expanded clay, and

Table XIV

MOISTURE ABSORPTION UNDER FIELD CONDITIONS
LIGHTWEIGHT PLASTIC MATERIALS

REFERENCE	YEARS AFTER INSTALLATION	MATERIAL	DENSITY LB/CU FT	NUMBER OF SAMPLES	VOLUMETRIC MOISTURE CONTENT, PERCENT MAX.	MIN.	AVE.
WILLIAMS(1968)	1.7	PU	1.9	1	-	-	4.2
ORAMA(1972)	1.5	PU	-	3	1.1	0.7	0.9
ESCH(1969)	0.7	PU	2.1	3	3.7	1.9	2.7
SAETERSDAL(1971)	1.0	MPS	2.8	1	-	-	4.5
SAETERSDAL(1971)	1.5	MPS	2.5	1	-	-	23.0
SAETERSDAL(1971)	3.0	MPS	1.9	6	20.0	4.0	11.0
HARTMARK(1971)	1.0	MPS	-	19	-	-	1.3
HARTMARK(1971)	2.0	MPS	-	30	-	-	2.0
HARTMARK(1971)	3.0	MPS	-	43	-	-	3.0
HARTMARK(1971)	4.0	MPS	-	40	-	-	2.5
HARTMARK(1971)	5.0	MPS	-	16	-	-	3.7
HARTMARK(1971)	6.0	MPS	-	6	-	-	3.7
WILLIAMS(1968)	1.7	MPS	1.2	1	-	-	0.4
ORAMA(1972)	0.5	MPS	2.5	2	2.1	0.7	1.4
ORAMA(1972)	0.7	MPS	2.5	2	0.2	0.1	0.2
ORAMA(1972)	0.8	MPS	2.5	1	-	-	0.0
ORAMA(1972)	0.9	MPS	2.5	7	2.2	0.0	0.9
ORAMA(1972)	1.5	MPS	2.5	5	0.5	0.1	0.3
ORAMA(1972)	1.6	MPS	2.5	3	1.7	0.1	0.9
ORAMA(1972)	1.8	MPS	2.5	9	1.9	0.0	0.3
ORAMA(1972)	2.5	MPS	2.5	13	2.3	0.0	0.9
ORAMA(1972)	2.9	MPS	2.5	1	-	-	0.8
ORAMA(1972)	1.4	MPS	2.2	8	1.4	0.3	0.7
ORAMA(1972)	1.5	MPS	1.9	2	1.1	0.9	1.0
ORAMA(1972)	0.8	MPS	2.5	8	1.2	0.1	0.4
ORAMA(1972)	0.5	MPS	2.5	4	1.1	0.2	0.4
ORAMA(1972)	0.4	EPS	2.5	1	-	-	0.0
ORAMA(1972)	0.6	EPS	2.5	1	-	-	0.1
ORAMA(1972)	2.8	EPS	2.5	1	-	-	0.4
ORAMA(1972)	4.3	EPS	2.5	1	-	-	0.8
ORAMA(1972)	4.8	EPS	2.5	1	-	-	1.2
ORAMA(1972)	5.3	EPS	2.5	1	-	-	0.9
SAETERSDAL(1971)	1.5	EPS	2.5	3	2.8	1.1	1.8
SAETERSDAL(1971)	3.0	EPS	2.5	2	1.4	0.9	1.2
SAETERSDAL(1971)	3.0	EPS	2.0	4	1.8	1.0	1.4
ESCH(1969)	0.7	EPS	2.2	3	0.7	0.5	0.6
WILLIAMS(1968)	0.5	EPS	2.5	1	-	-	0.2
WILLIAMS(1968)	0.8	EPS	2.5	3	0.9	0.2	0.5
WILLIAMS(1968)	1.5	EPS	2.5	2	0.6	0.3	0.4
WILLIAMS(1968)	2.0	EPS	2.5	2	0.7	0.4	0.6
WILLIAMS(1968)	2.1	EPS	2.5	2	0.7	0.5	0.6
WILLIAMS(1968)	2.8	EPS	2.5	3	1.4	0.7	1.0
WILLIAMS(1968)	3.0	EPS	2.5	5	1.7	0.9	1.2
WILLIAMS(1968)	4.0	EPS	2.5	2	1.6	0.9	1.2
WILLIAMS(1968)	4.4	EPS	2.5	2	1.6	1.2	1.4
WILLIAMS(1968)	5.7	EPS	2.5	2	1.8	0.8	1.3

NOTES PU - POLYURETHANE
MPS - MOLDED POLYSTYRENE
EPS - EXTRUDED POLYSTYRENE

Table XV

MOISTURE ABSORPTION UNDER FIELD CONDITIONS
VARIOUS TYPES OF INSULATING MATERIALS

** DATA FROM DRAMA(1972) **

TIME AFTER CONSTRUCTION YEARS	EXCELSIOR (1)	EXCELSIOR (2)	EXCELSIOR (3)	EXTRUDED P,STYRENE (4)	EXTRUDED P,STYRENE (5)	EXPANDED CLAY (6)	MINERAL WOOL (7)
0.	-	-	-	-	-	-	-
0.5	-	-	15.	-	0.0	7.	-
2.5	-	12.	12.	1.4	0.8	9.	-
4.0	9.	19.	11.	1.4	1.2	12.	28.
5.0	13.	19.	8.	1.4	0.9	7.	-

NOTES (1) PLASTIC MEMBRANE OVER
(2) PLASTIC MEMBRANE OVER
(3) PLASTIC MEMBRANE OVER AND UNDER
(4) PLASTIC MEMBRANE OVER
(5) NO MEMBRANE
(6) PLASTIC MEMBRANE OVER AND UNDER
(7) PLASTIC MEMBRANE OVER AND UNDER
THIS TEST ROAD CONSTRUCTED IN 1966.
MOISTURE CONTENTS ARE VOLUME PERCENTAGES

****

** DATA FROM LINELL(1953) AND BANFIELD AND CSERGEI(1966) **

TIME AFTER CONSTRUCTION YEARS	CELLULAR GLASS	CELLULAR CONCRETE (1)	CELLULAR CONCRETE (2)	ZONOLITE CONCRETE (3)
0.	-	-	-	-
7.	0.	20.	35.	47.
20.	3.7	22.	22.	47.

NOTES (1) AVERAGE DENSITY APPROXIMATELY 20 LB/CU FT.IN 1953 AND 1966.
(2) AVERAGE DENSITY APPROXIMATELY 38 LB/CU FT.IN 1953 AND APPROXIMATELY 43 LB/CU FT IN 1966.
(3) AVERAGE DENSITY APPROXIMATELY 27 LB/CU FT.
TEST SECTIONS WERE CONSTRUCTED IN 1946.
NONE OF THE SAMPLES EXHIBITED VISIBLE DETERIORATION WHEN SAMPLED IN 1953. SEVERAL CRACKS WERE VISIBLE IN THE CELLULAR GLASS IN 1966. MOISTURE CONTENTS NEAR THE SURFACE OF THE CELLULAR GLASS RANGED FROM 10 TO 19 PERCENT BY VOLUME AND FROM 0 TO 1 PERCENT BY VOLUME IN THE INTERIOR OF THE BLOCKS IN 1966. NO VISIBLE DEGREDATION OF THE CELLULAR CONCRETE WAS EVIDENT IN 1966.

mineral wool are considerably higher than most of the cellular plastic materials in Table XIV.

Again referring to Table XV, data from Linell (1953) and Banfield and Csergei (1966) indicate the lightweight concretes have absorbed considerable volumes of moisture. Samples of all the materials removed in 1953 showed no visible deterioration. When excavated in 1966, 20 years after construction, the outer layer of the cellular glass material had accumulated moisture and the cells were very weak due to partial destruction by entrapped water during freezing and thawing. The lightweight concretes had been relatively unaffected by the freeze-thaw cycles although they had considerably more moisture than the cellular glass.

After comparing data from Tables XIV and XV with data obtained from laboratory studies, it is obvious that none of the laboratory tests adequately predicts the performance of a candidate material in an actual embankment. It must be noted, however, that very few of the laboratory tests were actually designed to simulate an embankment environment and most were used only to evaluate the possible relative performance of various materials.

Data from Orama in Table XV indicate that simply placing a moisture barrier above the insulating layer does not adequately protect the insulating material from moisture. The extruded polystyrene material, when so treated, actually absorbed more moisture than the material in a similar section which had no moisture barrier. The excelsior section, which had a moisture barrier on both sides, exhibited a continual decrease in moisture content; whereas the same material, with a moisture barrier on the upper surface, has apparently increased over the same time period. Volumetric moisture contents in the expanded clay material having a vapor barrier on both sides of the layer have fluctuated somewhat.

Knight and Condo (1971) described the use of a special wax material to coat polyurethane materials installed near Prudhoe Bay, Alaska. Esch (1969) stated that an asphalt coating was applied prior to and subsequent to placing a polyurethane layer near Anchorage, Alaska. Data from Table XIV indicate that the asphalt coating was not effective because moisture penetrated into the polyurethane. Additional work must be accomplished to determine the most adequate and economical moisture barrier material to use with insulating materials which absorb excessive amounts of moisture when unprotected.

The Atlantic-Richfield Company designed and constructed a prototype apparatus for applying Urethane insulation to roadway embankments (this machine is now owned by Bechtel Incorporated). The apparatus is shown in Figure 24. It was constructed so that a preliminary coating of petroleum-based material could be applied to the subgrade prior to placement of the polyurethane (Figure 25). Under contract with the US Army Cold Regions Research and Engineering Laboratory, the ARCO Chemical Company used the machine to construct a test section near Fairbanks, Alaska. The upper surface was painted and a flexible glass-fiber matting was placed directly on the insulating layer. Traffic was applied directly on the flexible surfacing material. Similar tests were discussed in the section, "Rheological Studies".

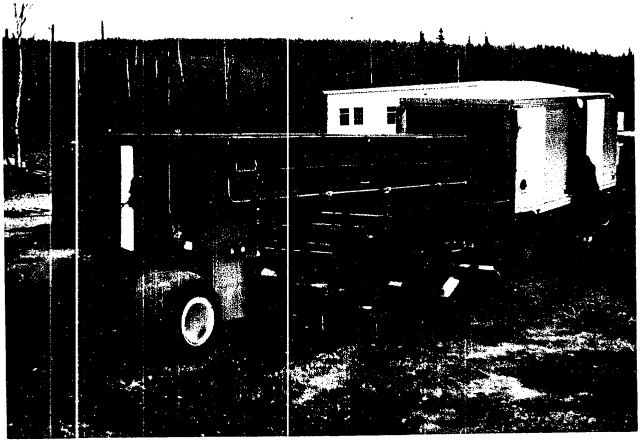


Figure 24
Prototype apparatus for applying polyurethane insulation to embankments.

Figure 25
Application of subbase seal coat prior to placing polyurethane insulation.

PROPOSED LABORATORY TEST APPARATUS

A laboratory test which more closely simulates a prototype embankment can be designed by "borrowing" concepts from the devices used in the dynamic loading tests reported by Knight (1972) and the freeze-thaw apparatus discussed by Williams (1968). A sketch of the proposed apparatus is shown in Figure 26. The insulation samples are embedded in a simulated embankment with moisture available beneath the insulating materials and a temperature gradient imposed across the simulated embankment. Since the amount of moisture intrusion into a sample is dependent upon time and the temperature gradient across the sample, various field conditions could be modeled. It would also be possible to test the effectiveness and longevity of various membranes in this apparatus.

Theoretically, samples can be forced to absorb moisture more rapidly by increasing the temperature gradient across the material. This in turn increases the vapor pressure gradient across the material. Depending on the materials under test, there may be an upper limit to the temperature difference across the sample because strength normally decreases with increasing temperature in cellular plastics.

A question arises concerning the desirability of freeze-thaw cycles in the apparatus. Although freeze-thaw cycling has not been shown to affect the strength of cellular plastic materials to any great extent, some materials such as cellular glass or lightweight concrete may be affected. By imposing dynamic loading on the insulating materials with the overlying materials always in the thawed state, maximum degradation should occur under a given number of loading cycles because the

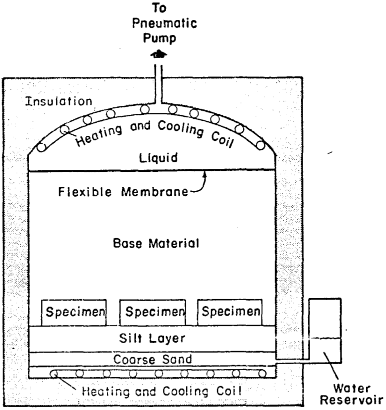


Figure 26
Proposed laboratory test device.

"reinforcing" effect of frozen material above the insulation is not allowed. This apparatus would more closely approach the conditions in an actual field installation than any previous test apparatus. The proposed device would be capable of imposing repeated dynamic loads and maintaining either a cyclic temperature variation within the apparatus or a constant temperature distribution across the specimens. The free-water table could be simulated by providing a source of moisture beneath the insulating material.

CHAPTER IV

THERMAL DESIGN

All of the computational techniques discussed in Chapter II can be applied to the thermal design of insulated embankments on permafrost. Three widely dissimilar one-dimensional techniques will be used in this chapter. The primary advantages and disadvantages of each method are described subsequently.

Pertinent physical and thermal properties of materials used for the computations in this chapter are summarized in Table XVI. In selecting materials for the computations, primary emphasis was placed on choosing a wide, but realistic, range of thermal properties. The particular combinations of thermal and physical properties may not be encountered in an actual embankment.

LACHENBRUCH 3-LAYER METHOD

Lachenbruch (1959) applied the heat conduction theory and developed equations for a multi-layer heat flow procedure. As the title implies, a 3-layer system was considered. Figure 27 illustrates the profile used in the 3-layer technique. For this discussion the upper layer is gravel, the second layer insulation, and the third layer may be either a sub-base or a subgrade material.

A sinusoidal temperature variation is applied at the surface and the amplitude of the sinusoidal temperature variation at the interface of the

Table XVI

PROPERTIES OF MATERIALS USED IN THERMAL CALCULATIONS

CODE NUMBER	DRY UNIT WEIGHT LB/CU FT	MOISTURE CONTENT (DRY WT	THERMAL CONDUCTIVITY BTU/FT HR F	VOLUMETRIC HEAT CAPACITY BTU/CU FT F	LATENT HEAT OF FUSION BTU/CU FT
1	135.	7.	1.98	30.	1360.
2	120.	5.	1.24	25.	864.
3	110.	8.	1.10	26.	1267.
4	100.	15.	0.76	28.	2160.
5	56.	100.	0.82	53.	8064.
6	55.	10.	0.1666	15.15	792.
7	35.	5.	0.0833	8.33	252.
8	2.	0.	0.0175	1.	0.

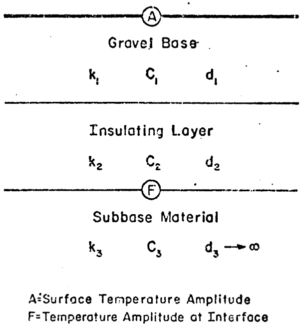


Figure 27
Conditions for the Lachenbruch 3-layer problem.

second and third layers is calculated. As shown in Figure 28, the temperature amplitude at the interface between the second and third layers is defined as "F". The surface temperature amplitude is defined as "A". The equation developed by Lachenbruch is applied to determine the ratio of F/A.

Assuming that no thaw penetration beneath the insulating layer will be permitted, the magnitude of F is simply the difference between the mean annual temperature and the freezing point of the soil moisture, normally assumed to equal 32° F. This method, then, can be used to design insulated embankments for "complete protection", that is, allowing no thaw penetration beneath the insulating layer.

As stated in Chapter II, this procedure does not consider effects of latent heat of the soil moisture. It is possible, however, to reduce the surface thawing index to consider the effects of latent heat indirectly. After the thawing index has been adjusted, it can be converted into an equivalent sine wave by using the mean annual temperature (Figure 29).

The following example illustrates the procedure for using Figure 30 to estimate the reduction in surface thawing index due to latent heat in the gravel. Assume 2.0 feet of 135 lb/cu ft gravel base (code number 1 material in Table XVI) overlay the insulating layer and the corrections to be applied to air thawing indexes at Barrow, Alaska, and Fairbanks, Alaska, are desired. From Johnson and Hartman (1969) the mean thawing indexes are: Fairbanks, 3000 °F-days and Barrow, 500 °F-days. The gravel base has the following properties: K = 1.98 Btu/ft hr °F, and L = 1360 Btu/cu ft. Then,

$$\frac{L}{48K} = \frac{1360}{48\ (1.98)} = 14.3$$

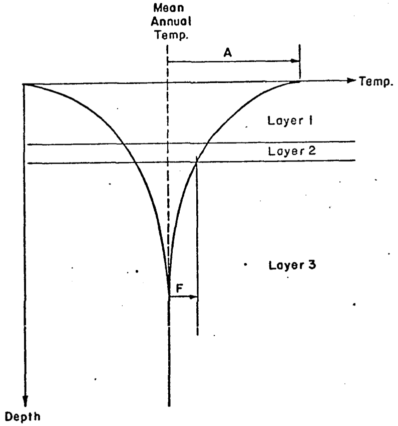


Figure 28
Relationship between surface temperature amplitude (A) and temperature amplitude at the interface between layers 2 and 3 (F).

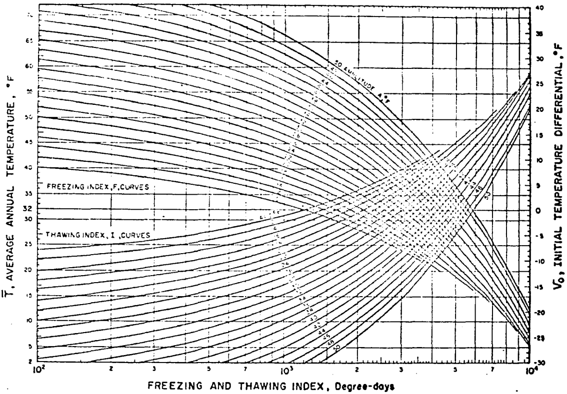


Figure 29
Indexes and equivalent sinusoidal temperature emplitude, from the Departments of the Army and Air Force (1966).

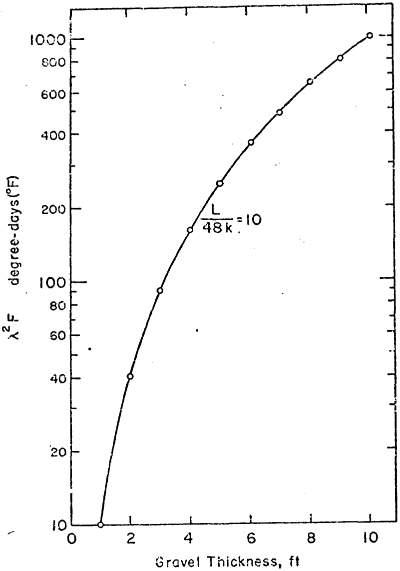


Figure 30
Method of estimating the degree-days to thaw a granular layer.

From Figure 30, 2.0 ft of material with L/48K = 10 provides an F value of 40 °F-days. For the material in this example the F value is:

$$(40)(14.3)/10 = 57 \text{ °F-days}$$

And the adjusted thawing indexes are:

Fairbanks:	3000-57 = 2943 °F-days
Barrow:	500-57 = 443 °F-days

The correction at Barrow is more important than the correction for Fairbanks due to the relative sizes of the mean thawing index and the correction. The correction will increase with added gravel thickness, as illustrated in Figure 30.

Several different 3-layer cross-sections can be constructed from the eight materials listed in Table XVI. In the subsequent studies the first three materials are used as granular base materials above the insulation; the fourth and fifth materials are those below the insulating layer and the last three materials are insulating media.

A computer program was written, in FORTRAN IV language, to solve the equation for the 3-layer model developed by Lachenbruch. The program is listed in Appendix E. It was used to develop data discussed in the remainder of this section.

Table XVII illustrates the effects of changing the thermal conductivity of the insulating layer and the influence of different thicknesses of base material over the insulating layer. For the computations in Table XVII the 135 lb/cu ft granular material (code number 1 material in Table XVI) was used above the insulating layer and the 100 lb/cu ft material (code number 4 material) was used below the insulating layer. The volumetric heat capacity for the different thermal conductivity values was

Table XVII

F/A RATIO FOR VARIOUS TYPES OF INSULATIONS AND EMBANKMENT THICKNESSES

EMB,KT DEPTH FT	THERMAL COND. BTU PER (FT HR F)	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.	11.	12.
		INSULATION THICKNESS, INCHES — F/A RATIO, DIMENSIONLESS												
1.5	0.0125	.711	.563	.391	.298	.240	.200	.172	.151	.134	.121	.110		
	0.0175	.766	.640	.475	.375	.303	.262	.227	.200	.179	.162	.148	.136	
	0.0250	.812	.711	.563	.463	.391	.338	.298	.266	.240	.218	.200	.185	.172
	0.0417	.858	.790	.677	.588	.519	.463	.417	.380	.348	.321	.298	.278	.260
	0.0833	.896	.858	.790	.730	.676	.630	.588	.551	.513	.489	.462	.439	.417
	0.1666	.915	.896	.858	.823	.790	.759	.730	.702	.676	.652	.630	.608	.588
5.	0.0125	.618	.500	.359	.278	.226	.191	.165	.145	.130	.117	.107	.098	.090
	0.0175	.661	.562	.429	.344	.287	.246	.215	.191	.172	.156	.143	.132	.122
	0.0250	.696	.618	.501	.418	.359	.313	.278	.250	.226	.207	.191	.177	.165
	0.0417	.732	.679	.591	.521	.464	.419	.381	.349	.322	.293	.273	.260	.245
	0.0833	.761	.732	.679	.601	.590	.554	.520	.491	.464	.440	.418	.398	.380
	0.1666	.776	.761	.732	.705	.679	.655	.632	.611	.590	.571	.553	.536	.520
10.	0.0125	.483	.404	.300	.238	.197	.167	.146	.129	.115	.104	.095	.088	.081
	0.0175	.511	.446	.352	.290	.245	.212	.187	.167	.151	.138	.126	.117	.109
	0.0250	.534	.483	.404	.345	.300	.266	.238	.215	.196	.181	.167	.156	.145
	0.0417	.556	.523	.465	.418	.378	.345	.317	.293	.272	.254	.238	.224	.211
	0.0833	.574	.556	.523	.492	.465	.440	.417	.397	.378	.360	.345	.330	.316
	0.1666	.584	.574	.556	.539	.523	.507	.492	.478	.465	.452	.440	.428	.417

*** PROPERTIES OF SOIL LAYERS ***

GRANULAR BASE - DENSITY=135LB/CU FT, MOISTURE CONTENT=7 PERCENT BY DRY WEIGHT THERMAL CONDUCTIVITY=1.98BTU/FT HR F, VOLUMETRIC HEAT CAPACITY=30.0BTU/CU FT F.

SILT SUBBASE - DENSITY=100LB/CU FT, MOISTURE CONTENT=15 PERCENT BY DRY WT., THERMAL CONDUCTIVITY=0.763BTU/FT HR F, VOLUMETRIC HEAT CAPACITY=23.2BTU/CU FT F.

NOTE- THE VOLUMETRIC HEAT CAPACITY OF ALL INSULATING MATERIALS WAS ASSUMED TO EQUAL 1.0 BTU/CU FT F.

assumed to be constant and equal to 1.0 Btu/cu ft °F. Thus, for a particular embankment thickness, changes in the F/A ratio are influenced only by the thermal conductivity and thickness of the insulating layer.

Figure 31 contains data from Table XVII and illustrates relationships between the thermal conductivity, gravel base thickness, F/A ratios, and the insulation thickness. As the embankment thickness above the insulating layer increases, the thickness of insulation required to provide equivalent protection decreases. Increasing the gravel layer from 1.5 ft to 5 ft thick reduces the insulation requirements more at the higher F/A ratio than at the lower value. For a given gravel thickness and a given F/A ratio, the insulation thickness is directly proportional to the thermal conductivity; *i.e.*, if the thermal conductivity is doubled, the required insulation thickness is also doubled. When the F/A ratio is reduced from 0.6 to 0.3, a decrease of 50%, the required thickness of insulation is nearly quadrupled.

Figures 32 through 37 show F/ A ratios for various combinations of materials from Table XVI. Burt (1970) developed similar curves for other combinations of materials. Data in these figures, or similarly constructed ones, may be used to determine the thermal design of insulated embankments permitting no thaw penetration beneath the insulating layer. For example, assume available materials have properties similar to those in Figure 34 and the site where the embankment is to be constructed has an F/A ratio of 0.45. Then combinations of gravel and insulation which will permit no thaw beneath the insulation are obtained by constructing a horizontal line from F/A = 0.45. Thus approximately 2-1/2 inches of

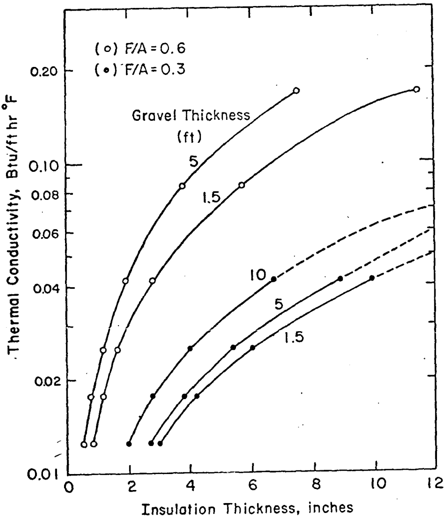


Figure 31
Relationships between thermal conductivity of insulation, F/A ratios, gravel base thickness and insulation thickness.

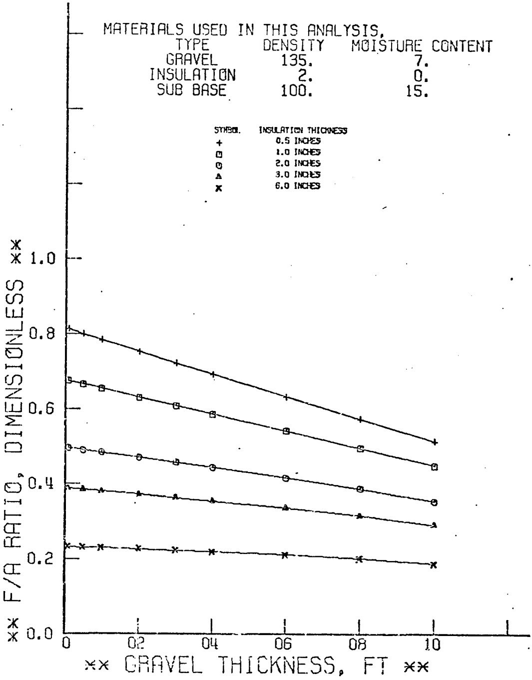


Figure 32
F/A ratios for embankments incorporating code number 1, 8 and 4 materials.

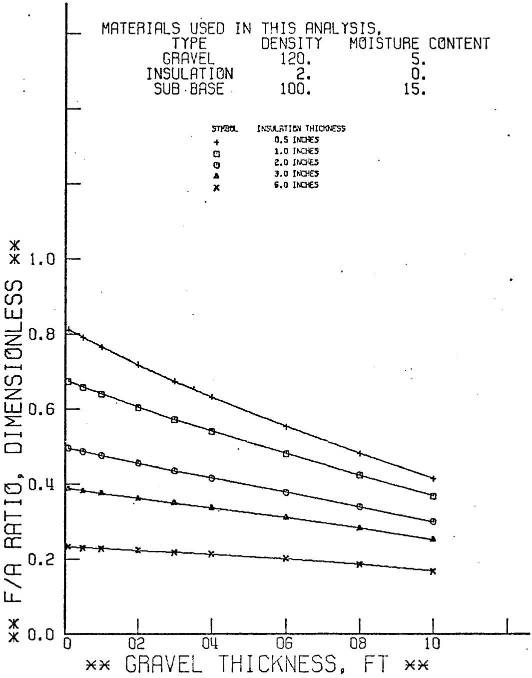


Figure 33
F/A ratios for embankments incorporating code number 2, 8 and 4 materials.

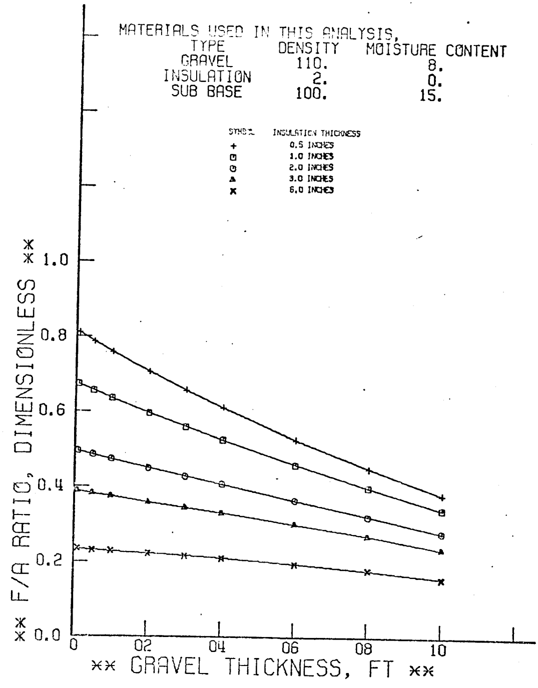


Figure 34
F/A ratios for embankments incorporating code number 3, 8 and 4 materials.

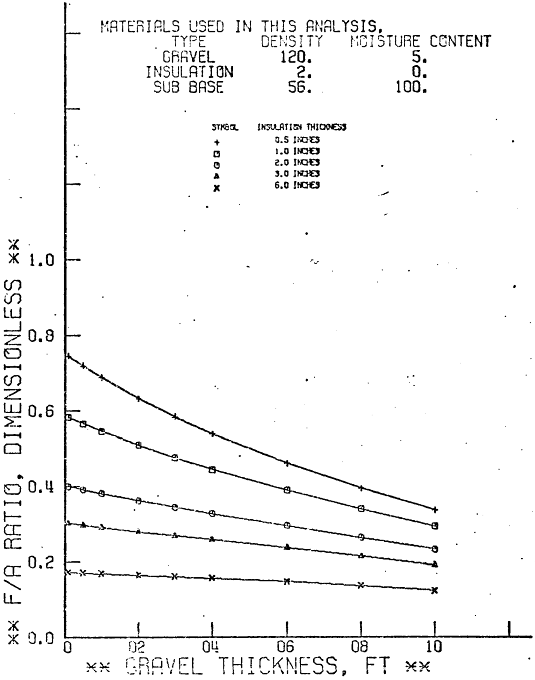


Figure 35
F/A ratios for embankments incorporating code number 2, 8 and 5 materials.

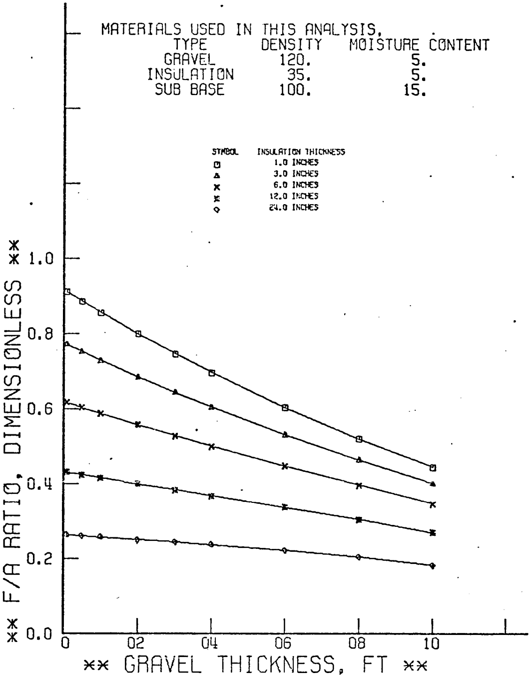


Figure 36
F/A ratios for embankments incorporating code number 2, 7 and 4 materials.

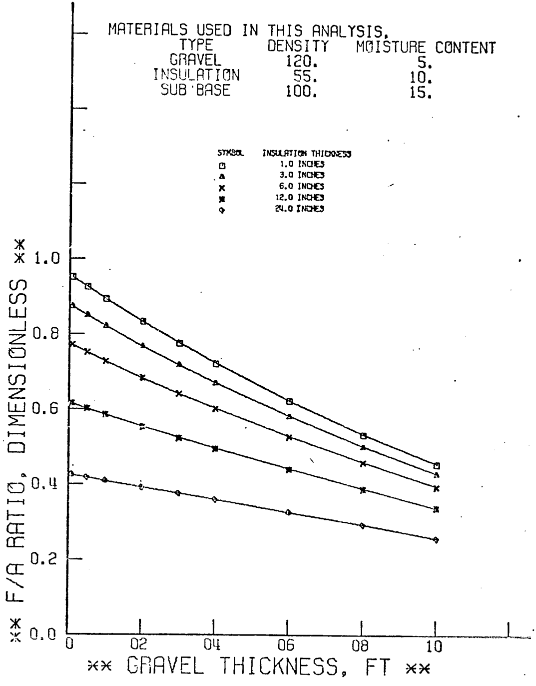


Figure 37
F/A ratios for embankments incorporating code number 2, 6 and 4 materials.

insulation and no gravel could be used. Two feet of gravel over two inches of insulation would also be adequate, as would seven feet of gravel and one inch of insulation, or nine feet of gravel and one-half inch of insulation. If structural requirements necessitated a minimum of two feet of gravel over the insulation, then two feet of gravel and two inches of insulation would provide an adequate design.

The most economical design could be ascertained by using suitable combinations of gravel and insulation thicknesses. Suitable combinations of the two materials are points on the horizontal line from F/A = 0.45.

The insulation thickness required for the example given above could be reduced by considering the latent heat of the gravel. The procedure to be used in the refinement was discussed previously in this section and necessitates using Figure 30.

Figures 32 through 37 also illustrate several other important features of insulated embankments. Data in these figures and in Table XVII illustrate the decreasing effect of greater insulation thicknesses. For example, referring to the 2-foot gravel thickness in Figure 32, the reduction in F/A ratio is nearly as great when increasing from 0.5 inches to 1.0 inches of insulation as when increasing from 3.0 inches to 6.0 inches of insulation.

Since each set of curves in Figures 32 through 37 are distinct from the others, a set of design curves will normally be required for each combination of three materials. The computer program listed in Appendix E can be used to develop data for the curves. Figures 32, 33, and 34 illustrate the effect of changing properties of the gravel base. Figures

33 and 35 illustrate the effect of changing the sub-base material, and Figures 33, 36, and 37 illustrate effects of different insulating layers. One should note that the insulation thicknesses in Figures 32, 33, 34, and 35 are 0.5, 1.0, 2.0, 3.0, and 6.0 inches; but in Figures 36 and 37, insulation thicknesses are 1.0, 3.0, 6.0, 12.0, and 24.0 inches. Figures 33 and 36 illustrate that 24 inches of the 35 lb/cu ft (code number 7) insulating layer are not as effective as 6 inches of 2 lb/cu ft (code numer 8) material. Similarly, Figures 33 and 37 show that 24 inches of the 55 lb/cu ft (code number 6) material are less effective than 3 inches of the 2 lb/cu ft (code number 8) material.

In summary, the 3-layer method can be used to determine insulation thicknesses required for complete protection of the sub-base; *i.e.*, for situations allowing no thaw penetration beneath the insulation. And the procedure for estimating the effect of latent heat of the gravel base can be applied to reduce the required insulation thickness. The importance of the latent heat correction increases as the thawing index decreases and/or as the thickness of granular material above the insulating layer increases.

MODIFIED BERGGREN EQUATION

The modified Berggren equation can be used for the thermal design of insulated embankments on permafrost. The form for a homogeneous soil was presented in Chapter II (equation 8). Since embankments are normally layered systems, a second form was developed (Departments of the Army and Air Force, 1966). In this form, the degree-days required to penetrate individual layers are accumulated until the summation equals the thawing index. The sum of the thicknesses of all the thawed layers is the thaw depth. The degree-days necessary to penetrate each layer are determined from:

$$F_n = \frac{L_n d_n}{24 \lambda^2_n} (\Sigma R + \frac{R_n}{2}) \qquad 12.$$

where ΣR is the total thermal resistance of the layers above the n^{th} layer and R_n is the thermal resistance of the n^{th} layer. The other parameters were defined in Chapter II. Computer programs have been written to determine thaw depths in layered systems using the modified Berggren equation (Aitken and Berg, 1968, and McDougall and Berg, 1970).

Unlike the Lachenbruch method discussed in the previous section, the modified Berggren equation should not be used to determine insulation thicknesses required to completely eliminate thaw penetration beneath the insulating layer. The primary reason for this is that insulating materials are normally assumed to have a negligible moisture content. Thus, these materials have no latent heat. From equation 12 it is seen that the number of degree-days required to penetrate a layer having zero latent heat is also zero. Therefore, no degree-days are accumulated in penetrating the insulating layer and an infinite insulation thickness would be required to prevent thaw penetration beneath it.

Data from Chapter III indicate that all of the materials used as insulators in embankments absorbed moisture. By including the moisture content of the insulating layer, the modified Berggren equation can be used to estimate insulation thicknesses for complete subgrade protection.

A question that immediately arises is: How accurately can thaw depths in insulated embankments be computed using the modified Berggren equation? Unfortunately, no information is available from insulated embankments where thaw penetration has penetrated only a few inches beneath the insulation. However, data from seasonal frost areas indicate that the modified Berggren equation may reliably estimate thaw depths greater than 8 to 12 inches beneath the insulating layer.

Figures 32 through 35 in the last section illustrate that F/A ratios less than 0.2 generally can only be achieved with insulation thicknesses in excess of six inches. These thicknesses are required to eliminate thaw penetration beneath the insulating layer. As illustrated by data in the figures and in Table XVII, increased thicknesses of insulation have a diminishing effect on the F/A ratio. Therefore, it may be desirable to allow some thaw penetration beneath the insulating layer in areas where the F/A ratio is small. For example, at Fairbanks, Alaska, the mean air thawing index is about 3000 °F-days and the mean annual soil temperature is approximately 30° F. To prevent thaw beneath the insulating layer, an F/A ratio of approximately 0.07 would be required. From Table XVII it is seen that a 10-foot gravel embankment overlaying 12 inches of an insulating material having a thermal conductivity of 0.0125 Btu/ft hr °F does not provide sufficient protection to eliminate thaw penetration beneath the insulating layer. A more economical design would use a thinner insulating layer and a thinner layer of gravel over the insulating layer. This design would permit a limited amount of thaw penetration beneath the insulation. Figure 38 illustrates thaw depths into insulated and uninsulated embankments near Fairbanks, Alaska. Materials used in this analysis are shown at the top of the figure and their properties can be determined from Table XVI. Computations were made for an uninsulated embankment and embankments incorporating insulation thicknesses of 1, 2, 3, and 6 inches. Various thawing indexes anticipated to occur in the Fairbanks area were utilized.

The different thawing indexes were obtained by applying "N-factors" to the mean air thawing index. "N-factors", as explained in Chapter II, are empirical relationships between air thawing indices and surface thawing indices. The Departments of the Army and Air Force (1966) provide suggested "N-factors" for various surfaces subjected to freezing or thawing conditions. Table XVIII contains "N-factors" suggested by the Army and Air Force for freezing conditions and for unpaved surfaces under thawing conditions. Figure 39 illustrates suggested values for pavements during the thawing season. "N-factors" of 1.0, 1.5, 2.0, and 2.5 were used to develop each curve in Figure 38. The air thawing index used in these calculations was 3160 °F-days and the mean annual soil temperature was equal to 30° F.

From Table XVIII it is seen that an "N-factor" of 2.0 is suggested for gravel surfaces subjected to thawing temperatures. Multiplying the air thawing index by this value provides a gravel surface thawing index in excess of 6000 °F-days. For an uninsulated embankment, a thaw depth greater than ten feet deep is calculated and when three inches of insulation are used the thaw depth is decreased to approximately 5.3 feet, or about three feet of thaw beneath the insulating layer. The curves in

Table XVIII

RECOMMENDED N-FACTORS
FROM THE DEPARTMENTS OF THE ARMY AND AIR FORCE(1966)

SURFACE TYPE	N-FACTOR
FREEZING CONDITIONS	
SNOW	1.0
PAVEMENTS FREE OF SNOW AND ICE	0.9
SAND AND GRAVEL	0.9
TURF	0.5
THAWING CONDITIONS	
SAND AND GRAVEL	2.0
TURF	1.0
PAVEMENTS — SEE FIGURE 39.	

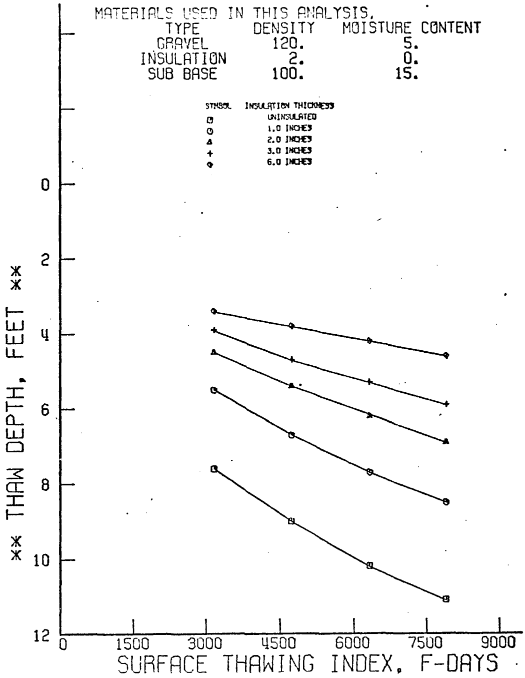


Figure 38
Calculated thaw depths near Fairbanks, Alaska.

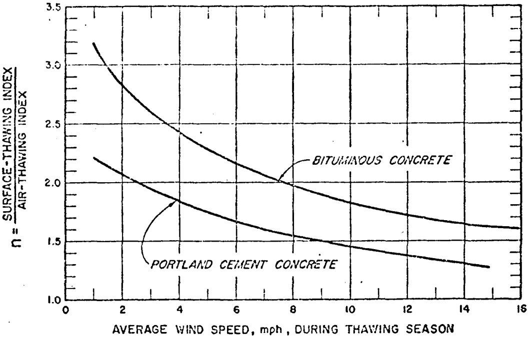


Figure 39
N-factors for paved surfaces during thawing.

Figure 38 are for a particular combination of materials and for other combinations of materials, the computed thaw depths may be different from those shown.

Figure 40 is similar to Figure 38, except a wider range of thawing indexes has been used. Mean air thawing indexes and approximate mean annual soil temperatures from four different locations in Alaska were used to construct Figure 40. The thawing indexes and mean annual temperatures are shown in Table XIX. Linear regression analyses were performed on data for each insulation thickness and the regression lines are shown in Figure 40. The equation for each line is also shown on the figure. Thawing indices less than 1400 °F-days and the corresponding thaw depths were not used in the linear regression for the uninsulated embankment because the relationship between surface thawing index and thaw depth is non-linear in this region.

Referring to the data in Figure 40, it is seen that very little reduction in thaw depth is accomplished by insulation thicknesses greater than approximately one inch when the surface thawing index is less than about 1400 °F-days. In fact, a few calculated thaw depths increase due to greater thickness of insulation.

To investigate possible changes in thaw depths in an insulated embankment due to moisture absorption by an insulating layer, five additional modified Berggren equation solutions were accomplished. Results of this study are summarized in Table XX. In the first solution a dry, high-quality, polyurethane foam was assumed. In subsequent solutions the effects of increased thermal conductivity and increased moisture content

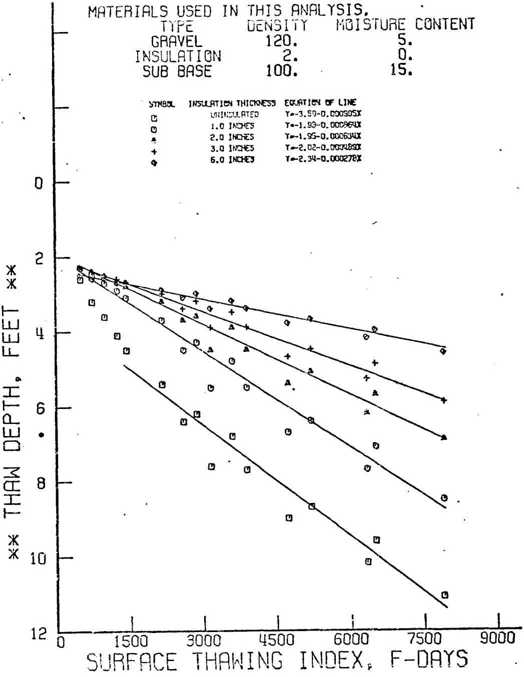


Figure 40
Calculated thaw depths for various thawing indexes and various thicknesses of insulation.

Table XIX

STATIONS USED IN MODIFIED BERGGREN EQUATION SOLUTIONS FOR FIGURE 40.

STATION NAME	MEAN AIR THAWING INDEX F-DAYS	MEAN ANNUAL SOIL TEMPERATURE F	LENGTH OF SEASON DAYS
BARROW	500.	14.	82.
BETTLES	1440.	17.	110.
FT. YUKON	2600.	26.	150.
FAIRBANKS	3160.	30.	180.

Table XX

EXAMPLES OF CHANGES IN THAW DEPTH DUE TO MOISTURE ABSORPTION BY THE INSULATING LAYER

DRY DENSITY	MOISTURE CONTENT (DRY WT	THERMAL CONDUCTIVITY BTU/FT HR F	VOLUMETRIC HEAT CAPACITY BTU/CU FT F	LATENT HEAT OF FUSION BTU/CU FT	THAW DEPTH FEET
2.0	0.	0.0125	1.0	0.	3.6
2.0	150.	0.0175	2.6	432.	4.0
2.0	240.	0.0217	4.0	690.	4.4
2.0	300.	0.0250	4.9	864.	4.6
2.0	400.	0.0333	6.4	1150.	5.2

NOTE - THE FOLLOWING DATA WERE USED IN ALL COMPUTATIONS AIR THAWING INDEX=2600. F-DAYS, MEAN ANNUAL SOIL TEMPERATURE=24. F, LENGTH OF THAWING SEASON=150 DAYS AND N-FACTOR=2.0. CODE NUMBER 2 MATERIAL(FROM TABLE XVI) WAS ABOVE THE INSULATION AND CODE NUMBER 4 MATERIAL BENEATH THE INSULATION.

were evaluated. The relationship between changes in moisture content and changes in thermal conductivity illustrated in Figure 15 was used for these computations. It should be noted that the moisture contents shown in Figure 15 are on a volumetric basis and those shown in Table XX are on a dry-weight basis.

Comparing the first solution in Table XX with the fourth solution, it is found that the thaw depth has increased approximately 28% due to a 100% increase in the thermal conductivity of the insulation layer. Assuming two dry insulating materials with one material having a thermal conductivity twice as great as the other, thaw depths in otherwise identical embankments would differ by about 41% $(1 - \sqrt{2})$. The latent heat effects of the wet insulation reduced the change from 41% to 28%. Data in Table XX illustrate that the net result of moisture absorption by the polyurethane is to increase thaw penetration. Thus, the increased latent heat and increased volumetric heat capacity of the wet insulating layer are more than offset by the increase in thermal conductivity of the material. The effect of moisture absorption by other insulating materials may be evaluated in a similar manner.

FINITE DIFFERENCE TECHNIQUE

Numerical methods can also be used to design insulated embankments on permafrost. Several of the programs described in Table III were developed for this purpose. The finite difference technique described by Berg and McDougall (1971) was used for the analyses presented herein. The basic computer program was written by Berg and Aitken at USACRREL prior to the author's studies at the University of Alaska. Since the University of Alaska digital computer has a much greater capacity than the one owned by USACRREL, the original computer program was considerably expanded and improved during the present studies. Several features were added which could not be accomplished on the USACRREL machine.

The primary advantage of using a numerical technique is that the time dependency of seasonal thaw depths and subsurface temperature fluctuations can be calculated. The long term behavior of a facility can also be evaluated with this technique. The modified Berggren equation and the 3-layer method described previously are generally applied only for a mean or design thawing season, and only the maximum thaw depth for that particular season is computed. The most important disadvantage of numerical techniques is that much larger digital computers are generally necessary than for closed form solutions.

Figure 41 is a comparison of calculated and measured subsurface temperatures in an insulated roadway near Prudhoe Bay, Alaska. The solid lines are calculated temperatures and the symbols are measured temperatures at equivalent depths. Correlation between measured and calculated data is very good.

Figure 42 illustrates the effects of two different time increments and two different upper boundary conditions on calculated thaw depths. Measured thaw depths are also shown in the figure. These data are for an uninsulated roadway embankment near Fairbanks, Alaska. The sinusoidal temperature variation applied at the surface had a thawing index equivalent to the thawing index computed from measured surface temperatures.

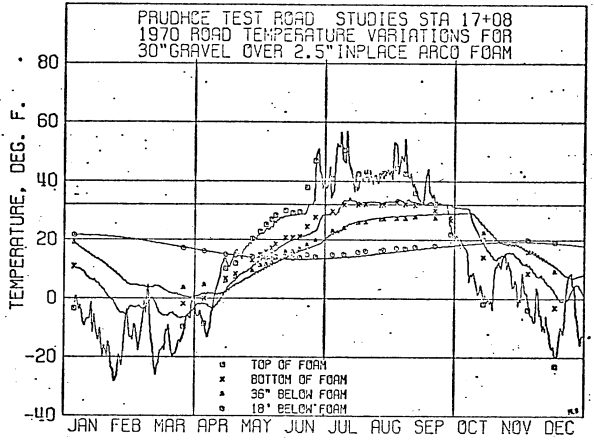


Figure 41
Comparison of calculated and measured temperatures in the Prudhoe insulated road, from Condo, McGrogan and Burt (1971).

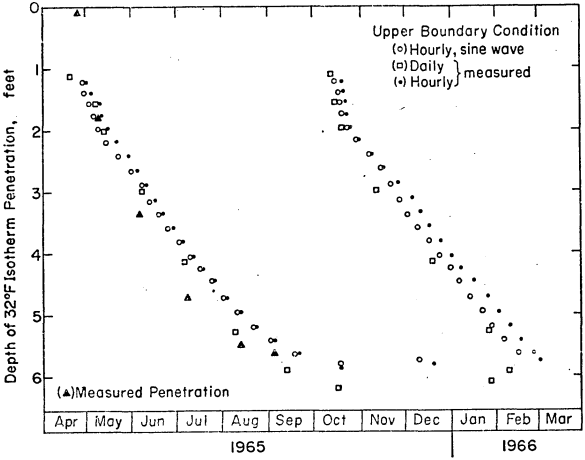


Figure 42
Measured and calculated penetration of the 32°F isotherm, highway test sections, 1965-1966, from Berg and Aitken (1973).

Correlation between measured and computed thaw depths is good and the difference between thaw depths computed using hourly time intervals and those using daily time increments is generally quite small. Calculated seasonal thaw progression using the sinusoidal surface temperature variation is similar to that computed using measured surface temperatures.

Esch (1973) described insulated roadway test sections constructed by the Alaska Department of Highways near Chitina, Alaska. The test sections were installed in 1969 and by the end of 1972 subsurface temperatures approximately 20 feet below the 1969 peat surface had increased approximately 1° F (to 31° F). Since warm permafrost, *i.e.* permafrost with temperatures about 29° F or greater, occurs in many locations in Alaska, the long term behavior of an insulated embankment on permafrost is of considerable interest. The test sections at Chitina are used to estimate the long term effects and computations were made for a twenty-year period. The soil profile consisted of the following materials: 0.08 ft of "chips and oil" pavement, 0.5 ft of crushed rock, 4.75 ft of gravel, 0.33 ft of Styrofoam HI insulation, 1.5 ft of sand, 22 ft of silty peat, and the material beneath the peat was assumed to be ice-rich silt. The temperature at a depth of 60 ft below the pavement surface was assumed to remain at a constant 31.9° F for the entire period. A sinusoidal surface temperature variation was applied. The surface thawing index was 5180 °F-days and the surface freezing index was 4700 °F-days.

Prior to making the computations for a twenty-year period, preliminary calculations were made for one year. Computed and measured temperatures were compared and the soil thermal properties were refined until good agreement was reached.

For the computations of long term behavior, moisture released upon thawing of the peat was assumed immobile and possible surface subsidence was neglected, *i.e.*, the complicating effects of thaw consolidation were not considered. Figure 43 illustrates the level of the permafrost table with time. The maximum depth of seasonal frost is also shown in the figure. Although this line is continuous in the figure, it should be understood that the position of the seasonal frost front is mobile and fluctuates on an annual cycle. Seasonal frost completely melts by late summer.

Using the same soil properties and the same initial and boundary conditions, the long term effects of an uninsulated section having the same properties as the insulated section were computed. Results of these computations are also shown in Figure 43. Considerably more permafrost degradation would have occurred under an uninsulated section than is estimated to occur under the insulated section.

From this relatively simple approach it appears that significantly less permafrost degradation and associated surface subsidence will occur during the 20-year lifetime of an insulated roadway embankment than would be expected to occur in a similar uninsulated embankment.

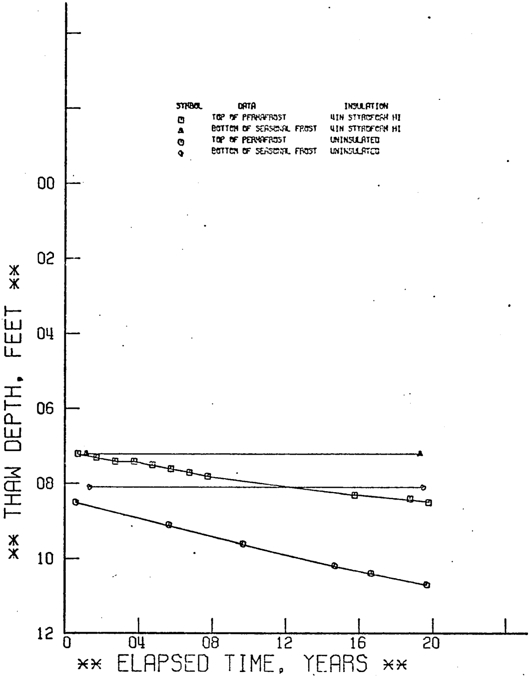


Figure 43
Long term behavior of insulated and uninsulated test sections near Chitina, Alaska.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Several hundred miles of new transportation networks have been proposed for permafrost regions in North America. Insulating layers within the embankments have been considered in several of the proposals. Incorporating insulating layers into the embankments may frequently reduce the embankment thickness, thereby reducing the requirements for backfill material and possibly reducing the overall cost and environmental effects of the project.

The concept of entirely eliminating seasonal thaw penetration beneath insulating layers appears practical in areas where the permafrost temperatures are relatively cold and the seasonal thawing indexes are relatively small, as typical of the Alaskan North Slope.

It may be economically undesirable to eliminate permafrost degradation beneath embankments in discontinuous or warm permafrost areas. However, the magnitude and rate of permafrost degradation and resultant surface subsidence can be reduced and controlled by incorporating insulating layers into the embankment. In test sections constructed near Chitina, Alaska, insulated embankments have allowed less permafrost degradation with considerably less surface subsidence than the adjacent uninsulated test sections (Esch, 1973). The embankment used at Chitina is a paved roadway. The mean annual soil temperature at the time of construction was approximately 30° F and in October 1972 (3 years after construction of the test sections) the mean annual soil temperature in nearly all locations beneath the roadway had increased to approximately 31° F. The eventual equilibrium state of these test sections remains to be determined.

Inclusion of a "one-way insulator" into the embankment may permit sufficient winter heat removal beneath the insulating layer to maintain the original warm permafrost temperatures. The efficiency and economy of a one-way insulating system remain to be determined.

Several methods can be used for the thermal design of insulated embankments on permafrost. Advantages and disadvantages of the three methods used in this study were discussed in Chapter IV. All three methods assumed one-dimensional heat flux. A two-dimensional numerical procedure is necessary to estimate edge effects and to evaluate various toe of slope designs. To date, failure of side slopes of uninsulated embankments on high ice content permafrost has been common.

All insulating materials used in embankments have absorbed moisture. However, some have absorbed considerably more moisture than others. The extruded polystyrene insulation has generally absorbed less moisture than other insulating materials.

The absorption of moisture by an insulating layer increases its thermal conductivity and permits greater thaw depths beneath the insulating layer.

Various types of field-installed membranes have been used on polyurethane materials to minimize moisture absorption; however, success has been limited. Other types of materials have been successfully enclosed in plastic membranes. The use of a plastic membrane on only one side of the insulating layer has been more detrimental than having no membrane at all. Membranes other than plastic may be used in the future and the durability of moisture-proofing membranes must be evaluated.

None of the laboratory tests currently used to evaluate moisture absorption by insulating materials can be used to provide quantitative data on the amount of moisture absorption by the material under field conditions. A laboratory test apparatus which may provide the desired data was proposed in Chapter III. The proposed laboratory test device combines the effects of cyclic loading and moisture/vapor drive due to a temperature gradient. Using this device, various insulating materials and encapsulating membranes to minimize moisture absorption can be evaluated. It will be possible to duplicate actual field conditions more closely with this device than with laboratory testing devices currently used.

In seasonal frost areas, surface deflections are normally greater for insulated roadways than for similarly constructed uninsulated roadways except during spring breakup. No conclusive evidence suggesting that these larger deflections decrease pavement life has been presented.

Freeze-thaw cycles may have detrimental effects on some materials. Materials expected to be most greatly affected are those with relatively rigid cell walls or a rigid matrix and/or those materials absorbing a relatively large amount of moisture.

The number of load repetitions to failure or the fatigue life of an insulating layer is dependent upon the ratio of the working stress to the unconfined compressive strength of the material. As this ratio approaches unity, the fatigue life decreases.

Specific recommendations for future research are:

1. Develop a two-dimensional numerical method which combines effects of heat and mass transport and consolidation and/or heaving.

2. Construct the proposed laboratory device and study the effects of cyclic loading and temperature gradient on thermal and physical degradation of thermoinsulating materials.

3. Evaluate various types of moisture barriers for durability and economic advantage.

4. Investigate the mechanism of moisture absorption by various thermo-insulating materials with the primary objective being to establish rapid laboratory tests for estimating the moisture regime within the material after installation in an embankment.

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Appendix A

Selected Definitions

Cell concrete - lightweight Portland cement concrete. The light weight is accomplished by entraining large volumes of air.

Cellular glass - a lightweight expanded glass. Foamglas manufactured by Pittsburgh-Corning is an example.

Embankment - a bank normally composed of several types of material including granular or fine-grained soils, rubble, moisture barriers, thermo-insulating layers and pavements. It may be used as a dam or to support a roadway, railroad, or runway.

Expanded clay - a lightweight aggregate manufactured by heating clay particles to a high temperature, causing expansion. Expanded shale is manufactured by a similar process.

Extruded polystyrene - the polystyrene resin is extruded through a dye to the desired thickness. The process causes a smooth skin of very low permeability. Dow Chemical Company presently holds patents on the process. Examples of this material are Styrofoam HI and Styrofoam HD-300.

Insulating asphalt - a material composed of an asphalt binder and lightweight aggregates.

Moisture absorption - addition of moisture to a specimen by any means. The transport mechanism may be diffusion or Darcian-type flow.

Moisture barrier - a material which is used to reduce or eliminate the passage of moisture. Wax, paint, asphalt, and polyethylene have been used for this purpose.

Molded polystyrene - normally manufactured from expandable polystyrene beads. In the U.S. the expansion process is normally accomplished in a stream-injection mold. An example of this material is Sinclair-Koppers' Dylite.

Permafrost - In the U.S. this term normally refers to materials whose temperature remains below 32° F continuously for more than two years. Some individuals in the U.S. and the majority of persons in some other countries add that if pore water is present, a sufficiently high percentage must be frozen to cement the mineral and/or organic particles. An abbreviation for permanently frozen ground.

Polyurethane foam - an expanded cellular product produced by a catalyzed reaction of polyisocynates with polyhydroxy compounds.

Appendix B

Types and Properties of Insulating Materials

1 Identification Number	2 Generic type and description	3 Forms Available	4 Density lb/cu ft	5 Thermal Conduct. Btu-in/sq ft hr °F	6 Specific Heat Btu/lb °F	7 Compressive Strength lb/sq in	8 Water Absorption % vol	9 Vapor Trans. perm-in.	10 Data Source
Loose Fills:									
1	Asbestos fibers	bulk fibers	20-50	.6 -1.62	.27				1
2	Cork, granulated	granules	5-12	.25- .36	.42				1, 2, 4
3	Diatomaceous earth	powder	20-31	.48- .92	.25				1
4	Expanded clay	powder	37-41	.3					2
5	Expanded perlite	powder	3-4	.28					1, 2
6	Exfoliated vermiculite	flakes	5-10	.44- .47	.20-.24				1, 2
7	Foamed slag	granules	30-45	.87					2
8	Gilsonite	granules	44-50	.65- .80					1
9	Glass fibers	fibers	2-12	.24- .25	.20				1, 2
10	Glass, cellular	pellets	6	.40	.20				1
11	Gypsum	pellets	12-20	.44-1.00					1
12	Rock wool	fibers	3-5	.24					2
13	Sawdust	granules	8-15	.45- .65	.60				3, 4
14	Seaweed	fibers	7	.36	.57				4

1	2	3	4	5	6	7	8	9	10
15	Slag wool	fibers & pellets	10-12 10	.23 .23					2 2
16	Straw	fibers	7-8	.32	.35				4
17	Wood chips	chips	12.5	.59-.96					10
<u>Blankets and Batts</u>:									
18	Asbestos fibers	blanket	9-12	.50	.28				1
19	Asbestos woven felt	felt	10	.50	.28	5@ 3%			1
20	Glass, fibrous	batt	.6-2	.31	.20		98		1
21	Mineral wool	blanket	1.5-8	.23-.30	.22		96		1, 3
22	Wood fiber	batt	3.2-3.6	.25					3
<u>Aerated and Lightweight Concretes</u>:									
23	Aerated cement and lightweight aggregates	in-situ	24 36	.57 .77	.2	130 440			2, 4 2
24	Aerated cement & sand & pulverized fuel ash	in-situ	50-60	1.4		500-800			2
25	Aerated cement	in-situ	20 40	.6 1.0	.2	50 400	20 10		2, 4 2
26	Aerated cement & sand	in-situ	50 90	1.3 3.2		100-300 800-900	20 10		2 2
27	Cement & expanded clay aggregate	in-situ	50-100	1.0-4.0		750			2
28	Cement & slag aggregate	in-situ	65-80	1.7-2.3	.19	300-450	15		2, 4
29	Cement & vermiculite aggregate	in-situ	25 50	.75 1.6		100 500	 15		2 2

1	2	3	4	5	6	7	8	9	10
30	Cement & sand & polystyrene beads	in-situ	20-60	.65-2.2		120-840			6
31	Cement & polystyrene beads	in-situ	32						11
Rigid and Semi-rigid Boards and Slabs:									
32	Asbestos sponge felts, laminated	block	26-33	.36	.25		85		1
33	Asphalt, insulating	blocks, boards, in-situ	24	.45		39	4.5		9
34	Compressed straw	slab	23	.60			absorbent		2
35	Cork, compressed	block	6-9	.24	.43	5-10 @ 5%		2-7	1
36	Diatomaceous silica & asbestos fibers & inorganic binders	block	65	1.70	.25-.34	2500 @ 10%			1
37	Expanded ebonite	block	3-4	.21			1.6 (6 wks)		2
38	Expanded urea formaldehyde	block	1	.25			20		2
39	Foamed phenol	board	1-6	.28			.8		2
40	Glass, cellular	block	7-9.5	.39	.20	100			1
41	Glass, fiber with organic binder	board	4-5	.24	.20	1.2 @ 10%	93		1
42	Mineral fiber with inorganic binder	block	15-18	.36	.22	2-18 @ 10%	85		1
43	Perlite, expanded	block	9.5-11.5	.34	.22	80 @ 5%	3.5-4	18	1
44	Plywood	sheets	34-37	0.80-1.05					3, 4

1	2	3
45	Polystyrene, cellular foam	block board
46	Polyurethane foam	block, boards in-situ
47	Rubber resin cellular foam	block
48	Siliceous fiber & binder w/aluminum facing	panels
49	Sulfur, foamed	in-situ
50	Sulfur w/polystyrene	in-situ
51	Vinyl chloride cellular foam	block
52	Wood fiber & binder	board
53	Wood, ash	board
54	Wood, beech	board
55	Wood, oak	board
56	Wood, pine	board
57	Wood, spruce fir	board
Other Materials:		
58	Asphalt concrete	in-situ
59	Aluminum	sheets
60	Concrete w/sand & stone aggregate	in-situ

4	5	6	7	8	9	10
1.5-3.3	.24	.27	10-30 @ 10%	0.1-1.25	1-2	1
1.5-3	.17	.25	15-80	1.5-3	1.5-2	1
5-8	.29	.19-.27	40 @ 10%	1	0.1	1
4.2	.26	.2				1
10-20	.3-.4		80-140		4.2	7
26-51	0.58		100-200	6.3		8
1.5-3	.16		28-50 @ 5%	4-5	.1-1.0	1
15-18	.36			3-5		1
48-72	2.02-2.40	.53-.72				4
44	1.72	.56				4
50	1.45	.42				4
44	2.02	.71				4
30	1.18	.57				4
131-138	7.3-10.3	.4				3, 4
168	1416	.21				5
140	12	.21				3

1	2	3	4	5	6	7	8	9	10
61	Concrete w/stone rubble	in-situ	125	8.9	.2				4
62	Concrete w/brick rubble	in-situ	119	8.1	.2				4
63	Concrete, reinforced	in-situ	135	10.8	.2				4
64	Fine-grained soils	-	60-130	1.2-15.6	.17				3
65	Glass	sheets	164	5.5	.20				5
66	Granular soils	-	80-150	2.4-31.2	.17				3
67	Ice	-	57	15.4	.5				3
68	Steel	sheets	487	310	.12				5
69	Still air	-	-	.17-.22	.24				5
70	Water	-	62.4	4.2	1				3

Key to references:

1 Malloy (1969)
2 The Engineering Equipment Users Association (1965)
3 Departments of Army and Air Force (1966)
4 Luikov (1966)
5 Jennings and Lewis (1968)
6 Rady-Pentek (1972)
7 Dale and Ludwig (1967)
8 Pazsint and Smith (1972)
9 Kritz and Wechsler (1967
10 USACRREL data
11 Sinclair-Koppers (1972)

APPENDIX C

************ BERG AND KNIGHT *************

*** FREEZE THAW STUDIES OF INSULATIONS ***
*** SERIES 1 ***

APPENDIX C

FREEZE THAW PROCEDURE

1 SAMPLE CONDITIONED TO CONSTANT WEIGHT IN 50C OVEN
2 SAMPLE WEIGHT WITHIN 30 MINUTES OF REMOVAL FROM OVEN
3 SAMPLE LEFT IN ROOM ENVIRONMENT 1 TO 3 HOURS
4 SAMPLE SUBMERGED 6 HOURS UNDER 2 INCH HEAD AND TEMP DATA TAKEN
5 SAMPLE REMOVED FROM BATH AND PLACED ON DRIP RACK FOR 30 MINUTES
6 SAMPLE WEIGHT OBTAINED AND NOTES MADE
7 SAMPLE PLACED IN FREEZER FOR 16 HOURS PLUS--TEMP DATA TAKEN
8 SAMPLE REMOVED FROM FREEZER TO 30 MINUTES IN ROOM ENVIRONMENT
9 SAMPLE WEIGHT OBTAINED AND NOTES MADE
10 REPEAT STEPS 4 THRU 9 THE DESIRED NUMBER OF CYCLES
11 AFTER COMPLETING STEP 9 OF CYCLES DESIRED RINSE 1 MINUTE IN DISTILLED WATER AND PLACE ON DRIP RACK FOR 30 MINUTES
12 SAMPLE WEIGHT OBTAINED AND NOTES MADE PRIOR TO PLACING IN 50C OVEN
13 STEPS 1 AND 2 REPEATED PRIOR TO FINAL EVALUATION

SAMPLES TESTED THIS SERIES

NUMBER	WEIGHT	DENSITY	L W T	VOL	COMMENTS
SAMPLE	***DRY*****	DRY********	GEOMETRY******		**OTHER NOTES***
720804.00029	193.51	30.18	3.85X3.86X1.65	401	ALL FACES SANDED
720804.00034	217.28	28.58	4.07X3.98X1.79	475	ALL FACES SANDED
720804.00037	244.78	28.27	3.99X3.93X3.38	868	ALL FC SD CONC DW
720804.00041	245.93	28.65	4.00X3.95X3.32	858	ALL FC SD CONC UP
720830.2TPDV	14.02	3.29	4.07X4.07X0.98	266	ALL FACES SANDED
720830.3TPBV	17.06	4.02	4.02X4.03X1.00	265	ALL FACES SANDED
720830.4TPAV	16.58	3.95	3.96X4.02X1.01	262	ALL FACES SANDED
720906.00001	13.72	2.15	4.07X4.04X1.48	398	ALL FACES SANDED
720906.00007	10.47	2.63	3.99X4.07X0.93	248	ALL FACES SANDED

NOTES- WEIGHTS IN GRAMS, DRY DENSITY IN LB/CU FT, DIMENSIONS IN INCHES AND VOLUME IN CUBIC CENTIMETERS. TEMPERATURES IN FAHRENHEIT DEGREES. SAMPLES SUBMERGED IN TAP WATER AT ROOM TEMPERATURE.

****

SAMPLE NUMBER	*******************SAMPLE******************* DESCRIPTION
720804.00029	CEMENT POLYSTYRENE BEAD MIXTURE
720804.00034	CEMENT POLYSTYRENE BEAD MIXTURE
720804.00037	CEMENT PS BEAD MIXTURE + MOLDED PS(LAMINATE)
720804.00041	CEMENT PS BEAD MIXTURE + MOLDED PS(LAMINATE)
720830.2TPDV	POLYURETHANE
720830.3TPBV	POLYURETHANE
720830.4TPAV	POLYURETHANE
720906.00001	EXTRUDED POLYSTYRENE
720906.00007	EXTRUDED POLYSTYRENE FROM AK. DEPT. HWYS.

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720921.0740				193.51				720804.00029
720921.0741				217.28				720804.00034
720921.0742				244.98				720804.00037
720921.0743				245.93				720801.00041
720921.0744				14.02				720830.2TPDV
720921.0745				17.06				720830.3TPBV
720921.0746				16.58				720830.4TPAV
720921.0747				13.72				720906.00001
720921.0753				10.47				720906.00007
720921.0903	66.0						SAMPLES SUBMERGED	
720921.1551	64.0						SAMPLES TO DRAIN RACK	
720921.1634					206.45			720804.00029
720921.1635					230.20			720804.00034
720921.1637					268.82			720804.00037
720921.1639					274.26			720804.00041
720921.1626					17.17			720830.2TPDV
720921.1625					20.00			720830.3TPBV
720921.1632					19.15			720830.4TPAV
720921.1628					14.88			720906.00001
720921.1630					11.45			720906.00007
720921.1650		0.0					SAMPLES TO FREEZER	
720922.0817	63.0	4.0				01	REMVD SAMPLES FRM FRZR	

****************************** ONE CYCLE COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720922.0947				202.37				720804.00029
720922.0948				224.48				720804.00034
720922.0948				262.87				720804.00037
720922.0949				268.54				720804.00041
720922.0950				14.92				720830.2TPDV
720922.0951				18.56				720830.3TPBV
720922.0952				16.79				720830.4TPAV
720922.0953				13.74				720906.00001
720922.0953				10.47				720906.00007
720922.0955	64.0						PLACED IN SUBMERG TANK	
720922.1545	64.0	5.0					SAMPLES TO DRAIN RACK	
720922.1625					205.93			720804.00029
720922.1625					228.61			720804.00034
720922.1625					266.90			720804.00037
720922.1626					270.45			720804.00041
720922.1626					15.32			720830.2TPDV
720922.1627					19.42			720830.3TPBV
720922.1628					17.54			720830.4TPAV
720922.1628					14.21			720906.00001
720922.1629					10.72			720906.00007
720922.1630		5.0					SAMPLES TO FREEZER	
720923.1320		-2.0					CHECKED SAMPLES IN FRZR	
720925.0750	59.0	-1.0	64.0			02	REMVD SAMPLES FRM FRZR	

*************************** TWO CYCLES COMPLETE ****************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720925.0820				203.61				720804.00029
720925.0820				225.64				720804.00034
720925.0821				262.53				720804.00037
720925.0821				266.32				720804.00041
720925.0822				14.29				720830.2TPDV
720925.0823				18.30				720830.3TPBV
720925.0823				17.33				720830.4TPAV
720925.0824				13.80				720906.00001
720925.0825				10.50				720906.00007
720925.0845	62.0		66.0				SAMPLES SUBMERGED	
720925.1445	63.0		67.0				SAMPLES TO DRIP RACK	
720925.1521					206.31			720804.00029
720925.1522					229.37			720804.00034
720925.1522					268.59			720804.00037
720925.1523					264.77			720804.00041
720925.1523					15.37			720830.2TPDV
720925.1524					19.82			720830.3TPBV
720925.1525					17.71			720830.4TPAV
720925.1525					13.88			720906.00001
720925.1526					10.68			720906.00007
720925.1530		2.0					SAMPLES TO FREEZER	
720926.3745		3.0	70.0			03	REMVD SAMPLES FRM FRZR	

************************** THREE CYCLES COMPLETE *************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720926.0750				204.97				720804.00029
720926.0750				227.77				720804.00034
720926.0751				265.65				720804.00037
720926.0751				261.82				720804.00041
720926.0751				14.73				720830.2TPDV
720926.0751				19.01				720830.3TPBV
720926.0752				17.03				720830.4TPAV
720926.0753				13.78				720906.00001
720926.0753				10.49				720906.00007
720926.0914	62.3						SAMPLES SUBMERGED	
720926.1530	64.0	10.0	69.0				SAMPLES TO DRIP RACK	
720926.1603					207.38			720804.00029
720926.1603					230.50			720804.00034
720926.1604					269.95			720804.00037
720926.1605					263.87			720804.00041
720926.1607					15.41			720830.2TPDV
720926.1607					19.65			720830.3TPBV
720926.1607					17.50			720830.4TPAV
720926.1608					13.78			720906.00001
720926.1609					10.52			720906.00007
720926.1610		9.0					SAMPLES TO FREEZER	
720927.0904		7.0				04	SAMPLES FROM FREEZER	

************************** FOUR CYCLES COMPLETE **************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720927.1012				205.49				720804.00029
720927.1013				228.12				720804.00034
720927.1014				265.22				720804.00037
720927.1014				259.91				720804.00041
720927.1015				14.42				720830.2TPDV
720927.1015				18.26				720830.3TPBV
720927.1016				16.95				720830.4TPAV
720927.1016				13.75				720906.00001
720927.1016				10.48				720906.00007
720927.1020							SAMPLES SUBMERGED	
720927.1640							SAMPLES TO DRIP RACK	
720927.1725		9.0	72.0				SAMPLES TO FREEZER	
720928.0755	68.0	7.0	74.0			05	REMVD SAMPLES FRM FRZR	

************************** FIVE CYCLES COMPLETE **************************

720928.0755				206.78				720804.00029
720928.0756				229.72				720804.00034
720928.0756				267.82				720804.00037
720928.0756				262.04				720804.00041
720928.0757				14.63				720830.2TPDV
720928.0757				19.05				720830.3TPBV
720928.0757				17.18				720830.4TPAV
720928.0758				13.78				720906.00001
720928.0758				10.50				720906.00007
720928.0830	67.0						SAMPLES SUBMERGED	
720928.1525	68.0		74.0				SAMPLES TO DRIP RACK	
720928.1603					208.53			720804.00029
720928.1603					231.96			720804.00034
720928.1604					272.48			720804.00037
720928.1604					264.72			720804.00041
720928.1605					15.41			720830.2TPDV
720928.1605					19.91			720830.3TPBV
720928.1605					17.64			720830.4TPAV
720928.1606					13.82			720906.00001
720928.1606					10.60			720906.00007
720928.1608		7.0				06	SAMPLES TO FREEZER	
720929.0830		3.0	74.0				REMVD SAMPLES FRM FRZR	

*************************** SIX CYCLES COMPLETE ***************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
720929.0832				207.42				720804.00029
720929.0835				230.48				720804.00034
720929.0836				269.85				720804.00037
720929.0836				262.10				720804.00041
720929.0837				14.71				720830.2TPDV
720929.0837				19.25				720830.3TPBV
720929.0838				17.02				720830.4TPAV
720929.0838				13.79				720906.00001
720929.0838	68.0			10.50				720906.00007
720929.0910	68.0						SAMPLES SUBMERGED	
720929.1532	63.0	4.0	71.0				SAMPLES TO DRIP RACK	
720929.1607					209.70			720804.00029
720929.1608					232.61			720804.00034
720929.1609					274.60			720804.00037
720929.1609					265.56			720804.00041
720929.1609					15.88			720830.2TPDV
720929.1610					20.30			720830.3TPBV
720929.1610					17.78			720830.4TPAV
720929.1610					13.90			720906.00001
720929.1611					10.60			720906.00007
720929.1612		3.0					SAMPLES TO FREEZER	
721002.0758		7.0	72.0			07	REMOVED FROM FREEZER	

************************** SEVEN CYCLES COMPLETE **************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721002.0758				207.36				720804.00029
721002.0759				230.49			WEIGHTS IMMEDIATELY	720804.00034
721002.0759				269.52			AFTER REMOVAL	720804.00037
721002.0800				261.75				720804.00041
721002.0800				14.64				720830.2TPDV
721002.0801				18.90				720830.3TPBV
721002.0801				16.94				720830.4TPAV
721002.0801				13.79				720906.00001
721002.0802				10.50				720906.00007
721002.0806	67.0		72.0				SAMPLES TO ROOM ATMOS	
721002.0834	67.0		72.0				SAMPLES REWEIGHED	
721002.0835				207.05				720804.00029
721002.0836				230.00				720804.00034
721002.0837				268.41				720804.00037
721002.0837				261.21				720804.00041
721002.0838				14.48				720830.2TPDV
721002.0838				18.52				720830.3TPBV
721002.0839								720830.4TPAV
721002.0839				13.79				720906.00001
721002.0840				10.50				720906.00007
721002.0840							SAMPLES SUBMERGED	
721002.1512							SAMPLES TO DRIP RACK	
721003.0750			70.0				SAMPLES SAT IN RM ALL NITE	
721003.0803					204.96		WEIGHT BEFORE FRZR	720804.00029
721003.0804					227.48		WEIGHT BEFORE FRZR	720804.00034
721003.0805					260.32		WEIGHT BEFORE FRZR	720804.00037
721003.0806					257.47		WEIGHT BEFORE FRZR	720804.00041
721003.0807					14.10		WEIGHT BEFORE FRZR	720830.2TPDV
721003.0808					17.08		WEIGHT BEFORE FRZR	720830.3TPBV
721003.0809					16.64		WEIGHT BEFORE FRZR	720830.4TPAV
721003.0810					13.75		WEIGHT BEFORE FRZR	720906.00001
721003.0811					10.49		WEIGHT BEFORE FRZR	720906.00007
721003.0813		8.0					SAMPLES TO FREEZER	
721003.1613	66.0	11.0	74.0				TEMPERATURE CHECK	
721004.0800	65.0	-4.0	72.5			08	REMVD SAMPLES FRM FRZR	

**************************** EIGHT CYCLES COMPLETE ****************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721004.0801				205.53				720804.00029
721004.0801				228.30				720804.00034
721004.0802				260.96				720804.00037
721004.0802				258.00				720804.00041
721004.0803				14.20				720830.2TPDV
721004.0803				17.20				720830.3TPBV
721004.0803				16.74				720830.4TPAV
721004.0804				13.78				720906.00001
721004.0804				10.50				720906.00007
721004.0825	65.0	-2.0	73.0				SAMPLES SUBMERGED	
721004.1435	65.0	-4.0	74.0				SAMPLES TO DRIP RACK	
721004.1505	65.0	8.0	74.0			09	SAMPLES TO FREEZER	
721005.0800	65.0	0.0	72.5				REMVD SAMPLES FRM FRZR	

**************************** NINE CYCLES COMPLETE ****************************

721005.0800				208.09				720804.00029
721005.0801				230.81				720804.00034
721005.0802				269.30				720804.00037
721005.0802				265.16				720804.00041
721005.0803				14.87			3.5IN CRACK LENGTH	720830.2TPDV
721005.0803				18.85				720830.3TPBV
721005.0804				17.41				720830.4TPAV
721005.0804				13.80				720906.00001
721005.0805				10.52				720906.00007
721005.0833	65.0	9.0	72.5				SAMPLES SUBMERGED	
721005.1440	66.5	-3.0	74.5				SAMPLES TO DRIP RACK	
721005.1517	67.0	0.5	75.0			10	SAMPLES TO FREEZER	
721006.0758	66.0	5.0	73.0				REMVD SAMPLES FRM FRZR	

**************************** TEN CYCLES COMPLETE ****************************

721006.1017				207.18				720804.00029
721006.1018				230.18				720804.00034
721006.1019				265.62				720804.00037
721006.1019				262.98				720804.00041
721006.1020				14.22				720830.2TPDV
721006.1020				17.41				720830.3TPBV
721006.1021				16.78				720830.4TPAV
721006.1021				13.78				720906.00001
721006.1022				10.50				720906.00007
721006.1029	66.0	9.0	73.0				SAMPLES SUBMERGED	
721006.1627	66.0	4.0	73.0				SAMPLES TO DRIP RACK	
721006.1707	66.0	3.0	73.0				SAMPLES TO FREEZER	
721009.0758	66.0	5.0	72.0			11	REMVD SAMPLES FRM FRZR	

*************************** ELEVEN CYCLES COMPLETE ***************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721009.0802				207.87				720804.00029
721009.0802				230.98				720804.00034
721009.0803				269.85				720804.00037
721009.0803				266.11				720804.00041
721009.0803				14.32				720830.2TPDV
721009.0804				17.68				720830.3TPBV
721009.0805				16.88				720830.4TPAV
721009.0805				13.79				720906.00001
721009.0805				10.51				720906.00007
721009.0838							SAMPLES SUBMERGED	
721009.1502	66.0	4.0	73.0				SAMPLES TO DRIP RACK	
721009.1545	66.0	9.0	73.0				SAMPLES TO FREEZER	
721010.0725	64.0	-3.0	72.0				SAMPLES FROM FREEZER	

*************************** TWELVE CYCLES COMPLETE ***************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721010.0750				208.79				720804.00029
721010.0750				232.08				720804.00034
721010.0750				272.30				720804.00037
721010.0751				265.75				720804.00041
721010.0751				14.39				720830.2TPDV
721010.0752				18.36				720830.3TPBV
721010.0752				16.90				720830.4TPAV
721010.0752				13.80				720906.00001
721010.0752				10.50				720906.00007
721010.0755	66.0	8.0	72.0				SAMPLES SUBMERGED	
721010.1358	66.5	4.0	74.0				SAMPLES TO DRIP RACK	
721010.1430	66.5	-3.0	74.0				SAMPLES TO FREEZER	
721011.0808	64.2	3.5	73.0				SAMPLES FROM FREEZER	

*************************** THIRTEEN CYCLES COMPLETE ***************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721011.0817				209.18				720804.00029
721011.0820				232.71				720804.00034
721011.0820				273.02				720804.00037
721011.0820				265.59				720804.00041
721011.0821				14.94				720830.2TPDV
721011.0821				19.08				720830.3TPBV
721011.0821				17.11				720830.4TPAV
721011.0822				13.80				720906.00001
721011.0822				10.50				720906.00007
721011.0855	67.0	5.0	73.5				SAMPLES SUBMERGED	
721011.1521	68.0	3.0	75.0				SAMPLES TO DRIP RACK	
721011.1520	68.0	0.0	75.5				SAMPLES TO FREEZER	
721012.0805	68.0	6.0	73.0				SAMPLES FROM FREEZER	

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***************************  FOURTEEN CYCLES COMPLETE  ************************

 DATE  TIME  TEMPERATURES  WEIGHT BEFOR FT   CALCS OR NOTES              SAMPLE
YRMODY.HRMM BATH FRZR ROOM SUBMR  FREZE CY                                NUMBER

721012.0807                 209.25                                 720804.00029
721012.0807                 232.85                                 720804.00034
721012.0807                 272.62                                 720804.00037
721012.0808                 265.74                                 720804.00041
721012.0808                  14.42                                 720830.2TPDV
721012.0809                  18.72                                 720830.3TPBV
721012.0809                  16.90                                 720830.4TPAV
721012.0810                  13.80                                 720906.00001
721012.0810                  10.52                                 720906.00007
721012.0845 68.0  2.0 74.0                  SAMPLES SUBMERGED
721012.1526 68.5  3.0 76.0                  SAMPLES TO DRIP RACK
721012.1557 68.5 11.0 76.0                  SAMPLES TO FREEZER
721013.0800 67.5  9.0 72.0                  SAMPLES FROM FREEZER

***************************  FIFTEEN CYCLES COMPLETE  *************************

721013.0803                 209.87                                 720804.00029
721013.0803                 233.48                                 720804.00034
721013.0804                 275.55                                 720804.00037
721013.0804                 267.47                                 720804.00041
721013.0804                  15.29                                 720830.2TPDV
721013.0804                  18.96                                 720830.3TPBV
721013.0805                  17.25                                 720830.4TPAV
721013.0805                  13.80                                 720906.00001
721013.0805                  10.56                                 720906.00007
721013.0833                                 SAMPLES SUBMERGED
721013.1515 68.0 -3.0 76.0                  SAMPLES TO DRIP RACK
721013.1615 68.0  6.0 76.0                  SAMPLES TO FREEZER
721014.0710 64.0  5.0 73.0                  SAMPLES FROM FREEZER

***************************  SIXTEEN CYCLES COMPLETE  *************************

721014.0740 64.0      73.0                  SAMPLES SUBMERGED
721014.1340 68.5  3.0 75.0                  SAMPLES TO DRIP RACK
721014.1415 68.0 -1.0 75.0                  SAMPLES TO FREEZER
721016.0758 68.0  9.0 73.0                  SAMPLES FROM FREEZER
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***************************  SEVENTEEN CYCLES COMPLETE**************************

 DATE  TIME  TEMPERATURES  WEIGHT BEFOR FT   CALCS OR NOTES           SAMPLE
YRMODY.HRMM BATH FRZR ROOM SUBMR  FREZE CY                            NUMBER

721016.0824                  209.78                                  720804.00029
721016.0824                  233.80                                  720804.00034
721016.0824                  274.01                                  720804.00037
721016.0824                  266.12                                  720804.00041
721016.0825                   14.50                                  720830.2TPDV
721016.0825                   18.41                                  720830.3TPBV
721016.0825                   16.91                                  720830.4TPAV
721016.0826                   13.80                                  720906.00001
721016.0826                   10.52                                  720906.00007
721016.0844 68.0  8.0 73.0                    SAMPLES SUBMERGED
721016.1448 69.0  3.0 76.0                    SAMPLES TO DRIP RACK
721016.1530 69.0  2.0 76.0                    SAMPLES TO FREEZER
721017.0950 70.0  3.0 76.0                    SAMPLES FROM FREEZER

***************************  EIGHTEEN CYCLES COMPLETE   *************************

721017.1022 70.0 -1.0 76.0                    SAMPLES SUBMERGED
721017.1705 71.0 -1.0 77.0                    SAMPLES TO DRIP RACK
721017.1825 71.0 10.0 77.0                    SAMPLES TO FREEZER
721018.0815 69.0  5.0 72.0                    SAMPLES FROM FREEZER

***************************  NINETEEN CYCLES COMPLETE   *************************

721018.0817                  210.20                                  720804.00029
721018.0818                  234.32                                  720804.00034
721018.0818                  276.10                                  720804.00037
721018.0819                  267.14                                  720804.00041
721018.0819                   14.40                                  720830.2TPDV
721018.0820                   18.40                                  720830.3TPBV
721018.0821                   16.90                                  720830.4TPAV
721018.0821                   13.82                                  720906.00001
721018.0822                   10.50                                  720906.00007
721018.0851 69.0  4.0 73.0                    SAMPLES SUBMERGED
721018.1625 69.0 -4.0 76.0                    SAMPLES TO DRIP RACK
721018.1653 69.0  9.0 76.0                    SAMPLES.TO FREEZER
721019.0935 68.0  2.0 73.0                  20SAMPLES FROM FREEZER
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****************************** TWENTY CYCLES COMPLETE ****************************

721019.0940	210.72		720804.00029
721019.0940	235.40		720804.00034
721019.0941	279.48		720804.00037
721019.0941	269.18		720804.00041
721019.0942	15.19		720830.2TPDV
721019.0942	19.71		720830.3TPBV
721019.0943	17.52		720830.4TPAV
721019.0943	13.82		720906.00001
721019.0943	10.60		720906.00007
721019.1150		SAMPLES TO DRIP RACK	
************	************	************	************
721020.0900		SAMPLES IN DRIP RACK	
721020.0903	206.96		720804.00029
721020.0904	230.60		720804.00034
721020.0906	265.22		720804.00037
721020.0907	260.84		720804.00041
721020.0907	14.08		720830.2TPDV
721020.0908	17.00		720830.3TPBV
721020.0908	16.62		720830.4TPAV
721020.0908	13.78		720906.00001
721020.0909	10.50		720906.00007
721020.0910 67.0 8.0 72.0		SAMPLES IN DRIP RACK	
************	************	************	************
721024.1130		SAMPLES FRM 50C OVEN	
721024.1230	203.60		720804.00029
721024.1231	227.23		720804.00034
721024.1231	259.13		720804.00037
721024.1232		ADD DRY WEIGHTS	720804.00041
721024.1232	14.06		720830.2TPDV
721024.1232	16.98		720830.3TPBV
721024.1233	16.60		720830.4TPAV
721024.1233	13.78		720906.00001
721024.1234	10.50		720906.00007
		SAMPLES TO 50C OVEN	

APPENDIX D

************ BERG AND KNIGHT *************

*** FREEZE THAW STUDIES OF INSULATIONS ***

*** SERIES 2 ***

APPENDIX D

FREEZE THAW PROCEDURE

1. SAMPLE CONDITIONED TO CONSTANT WEIGHT IN 50C OVEN
2. SAMPLE WEIGHT WITHIN 30 MINUTES OF REMOVAL FROM OVEN
3. SAMPLE LEFT IN ROOM ENVIRONMENT 1 TO 3 HOURS
4. SAMPLE SUBMERGED 6 HOURS UNDER 2 INCH HEAD AND TEMP DATA TAKEN
5. SAMPLE REMOVED FROM BATH AND PLACED ON DRIP RACK FOR 30 MINUTES
6. SAMPLE WEIGHT OBTAINED AND NOTES MADE
7. SAMPLE PLACED IN FREEZER FOR 16 HOURS PLUS--TEMP DATA TAKEN
8. SAMPLE REMOVED FROM FREEZER TO 30 MINUTES IN ROOM ENVIRONMENT
9. SAMPLE WEIGHT OBTAINED AND NOTES MADE
10. REPEAT STEPS 4 THRU 9 THE DESIRED NUMBER OF CYCLES
11. AFTER COMPLETING STEP 9 OF CYCLES DESIRED RINSE 1 MINUTE IN DISTILLED WATER AND PLACE ON DRIP RACK FOR 30 MINUTES
12. SAMPLE WEIGHT OBTAINED AND NOTES MADE PRIOR TO PLACING IN 50C OVEN
13. STEPS 1 AND 2 REPEATED PRIOR TO FINAL EVALUATION

SAMPLES TESTED THIS SERIES

SAMPLE	***DRY*****	*DRY*********GEOMETRY******			**OTHER NOTES***
NUMBER	WEIGHT	DENSITY	L W T	VOL	COMMENTS
720929.00059	1.5057	1.04	2.11X1.86X1.40	90	ALL FACES SANDED
720929.00060	1.3910	1.02	1.95X1.88X1.42	85	ALL FACES SANDED
720929.00114	1.1597	0.75	2.02X2.08X1.40	96	ALL FACES SANDED
720929.00116	1.2761	0.83	2.00X1.96X1.50	96	ALL FACES SANDED
720929.00117	1.2898	0.83	1.99X2.01X1.48	97	ALL FACES SANDED
720929.00099	2.1552	1.42	1.99X2.02X1.44	95	ALL FACES SANDED
720929.00100	2.2609	1.44	2.01X2.01X1.48	98	ALL FACES SANDED
720929.00101	2.1669	1.39	1.99X2.01X1.48	97	ALL FACES SANDED
720929.00040	3.6007	2.28	2.03X2.00X1.48	98	ALL FACES SANDED
720929.00041	3.6708	2.31	2.01X2.02X1.49	99	ALL FACES SANDED
720929.00042	3.7071	2.27	2.02X2.05X1.50	102	ALL FACES SANDED
720929.00048	4.9393	3.08	2.04X2.00X1.49	100	ALL FACES SANDED
720929.00049	4.9145	3.06	2.02X2.02X1.50	100	ALL FACES SANDED
720929.00050	4.5616	2.99	1.99X2.00X1.46	95	ALL FACES SANDED
720929.00014	2.3570	1.48	2.00X2.07X1.46	99	ALL FACES SANDED
720929.00015	2.4110	1.45	2.07X2.05X1.49	104	ALL FACES SANDED
720929.00017	2.4736	1.49	2.05X2.05X1.50	103	ALL FACES SANDED
720929.00018	2.3803	1.42	2.09X2.05X1.49	105	ALL FACES SANDED
720929.00019	2.3658	1.49	2.00X2.02X1.50	99	ALL FACES SANDED
720929.00020	2.3768	1.51	1.98X2.00X1.51	98	ALL FACES SANDED
720929.00032	1.9797	1.22	2.08X2.05X1.45	101	ALL FACES SANDED
720929.00033	2.6336	1.70	2.02X2.01X1.46	97	ALL FACES SANDED
720929.00034	2.6219	1.65	2.03X2.04X1.46	99	ALL FACES SANDED

NOTES- ALL SAMPLES IN THIS TEST SERIES WERE CUT FROM MOLDED POLYSTYRENE BOARDS. WEIGHTS IN GRAMS, DRY DENSITY IN LB/CU FT. DIMENSIONS IN INCHES AND VOLUME IN CUBIC CENTIMETERS. TEMPERATURES IN FARENHEIT DEGREES. SAMPLES SUBMERGED IN 0.5 PERCENT BY WEIGHT ETHYL ALCOHOL - WATER SOLUTION.

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 DATE  TIME  TEMPERATURES  WEIGHT BEFOR FT   CALCS OR NOTES            SAMPLE
YRMODY.HRMM BATH FRZR ROOM SUBMR  FREZE CY                             NUMBER

721128.1450 77.   2.  75.                   SAMPLES TO FREEZER
721128.1455 SPECIFIC GRAVITY OF ALCOHOL-WATER MIXTURE  0.995 AT 77F
            MIXTURE IS 107 G OF 70 PERCENT ETHYL ALCOHOL AND 15,000G WATER
721205.1202 SPECIFIC GRAVITY OF A-W MIX 0.997 AT 73F
721207.1002 72.0  0.0 75.0                 1REMOVED FROM FREEZER

******************************   1 CYCLE  COMPLETE  ******************************

721207.1012                  1.5159                              720929.00059
721207.1013                  1.4015                              720929.00060
721207.1014                  1.1787                              720929.00114
721207.1014                  1.2914                              720929.00116
721207.1015                  1.3059                              720929.00117
721207.1015                  2.1709                              720929.00099
721207.1016                  2.2748                              720929.00100
721207.1017                  2.1810                              720929.00101
721207.1018                  3.6210                              720929.00040
721207.1019                  3.6892                              720929.00041
721207.1020                  3.7309                              720929.00042
721207.1021                  4.9343                              720929.00048
721207.1021                  4.9355                              720929.00049
721207.1022                  4.6033                              720929.00050
721207.1022                  2.3691                              720929.00014
721207.1023                  2.4233                              720929.00015
721207.1024                  2.4874                              720929.00017
721207.1024                  2.3928                              720929.00018
721207.1025                  2.3760                              720929.00019
721207.1026                  2.3860                              720929.00020
721207.1027                  1.9936                              720929.00032
721207.1028                  2.6464                              720929.00033
721207.1029                  2.6315                              720929.00034
721207.1120                                 SAMPLES SUBMERGED WITH
721207.1120                                 TWO INCH HEAD
721207.1615 72.0  8.0 76.0                  SAMPLES TO DRIP RACK
721207.1647 72.0  0.0 76.0                  SAMPLES TO FREEZER
721208.0803 73.0  4.0 73.0                 2SAMPLES FROM FREEZER
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**************************** 2 CYCLES COMPLETE ****************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721208.0833				1.6914				720929.00059
721208.0834				1.5332				720929.00060
721208.0836				1.2966				720929.00114
721208.0837				1.3808				720929.00116
721208.0837				1.4123				720929.00117
721208.0838				2.3262				720929.00099
721208.0838				2.4711				720929.00100
721208.0839				2.2943				720929.00101
721208.0840				3.7156				720929.00040
721208.0841				3.7013				720929.00041
721208.0842				3.7602				720929.00042
721208.0842				4.9302				720929.00048
721208.0843				4.9420				720929.00049
721208.0844				4.5885				720929.00050
721208.0845				2.5440				720929.00014
721208.0846				2.5703				720929.00015
721208.0847				2.6394				720929.00017
721208.0847				2.5916				720929.00018
721208.0848				2.4496				720929.00019
721208.0848				2.4355				720929.00020
721208.0849				2.0072				720929.00032
721208.0850				3.0060				720929.00033
721208.0851				2.8536				720929.00034
721208.0858							SAMPLES SUBMERGED	
721208.1510	73.0	0.0	75.5				SAMPLES TO DRIP RACK	
721208.1555	73.0	2.0	76.0				SAMALES TO FREEZER	
721209.0939	72.0	8.0	72.0			3	SAMPLES FROM FREEZER	

****************************** 3 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721209.1016				1.6038				720929.00059
721209.1016				1.4022				720929.00060
721209.1017				1.1829				720929.00114
721209.1017				1.3140				720929.00116
721209.1018				1.3356				720929.00117
721209.1018				2.2369				720929.00099
721209.1018				2.3287				720929.00100
721209.1020				2.2046				720929.00101
721209.1020				3.6215				720929.00040
721209.1020				3.6939				720929.00041
721209.1020				3.7384				720929.00042
721209.1020				4.9273				720929.00048
721209.1023				4.9355				720929.00049
721209.1023				4.5785				720929.00050
721209.1024				2.4248				720929.00014
721209.1024				2.4739				720929.00015
721209.1024				2.5289				720929.00017
721209.1026				2.4974				720929.00018
721209.1026				2.4129				720929.00019
721209.1027				2.4064				720929.00020
721209.1027				1.9873				720929.00032
721209.1027				3.1075				720929.00033
721209.1029				2.7600				720929.00034
721209.1030				1.5513				720929.00059
721209.1030				1.3986				720929.00060
721209.1037	72.0	0.0	74.0				SAMPLES SUBMERGED	
721209.1615	72.0	-2.0	74.0				SAMPLES TO DRIP RACK	
721209.1650	72.0	0.0	74.0				SAMPLES TO FREEZER	
721210.1000		0.1	73.0				4SAMPLES FROM FREEZER	

****************************** 4 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721210.1025				1.5391				720929.00059
721210.1028				1.4403				720929.00060
721210.1030				1.2233				720929.00114
721210.1033				1.3460				720929.00116
721210.1033				1.3415				720929.00117
721210.1000				2.3172				720929.00099
721210.1000				2.3683				720929.00100
721210.1000				2.2267				720929.00101
721210.1000				3.6329				720929.00040
721210.1000				3.7179				720929.00041
721210.1000				3.7680				720929.00042
721210.1010				4.9264				720929.00048
721210.1011				4.9317				720929.00049
721210.1012				4.5785				720929.00050
721210.1012				2.4532				720929.00014
721210.1014				2.5019				720929.00015
721210.1015				2.5797				720929.00017
721210.1015				2.5505				720929.00018
721210.1015				2.4499				720929.00019
721210.1018				2.4930				720929.00020
721210.1020				1.9876				720929.00032
721210.1022				3.1580				720929.00033
721210.1025				2.7925				720929.00034
721210.1040							SAMPLES SUBMERGED	
721210.1720		7.0	72.0				SAMPLES TO RACK & FREEZER	
721211.0823	71.0	7.0	72.0				5SAMPLES FROM FREEZER	

************************************ 5 CYCLES COMPLETE ************************************

DATE TIME	TEMPERATURES			WEIGHT	BEFOR	FT	CALCS OR NOTES	SAMPLE
YRMODY.HRMM	BATH	FRZR	ROOM	SUBMR	FREZE	CY		NUMBER
721211.0930				1.5856				720929.00059
721211.0931				1.4189				720929.00060
721211.0930				1.2037				720929.00114
721211.0929				1.3355				720929.00116
721211.0928				1.3198				720929.00117
721211.0928				2.3412				720929.00099
721211.0927				2.3669				720929.00100
721211.0929				2.3130				720929.00101
721211.0925				3.6641				720929.00040
721211.0925				3.7479				720929.00041
721211.0926				3.7530				720929.00042
721211.0915				4.9266				720929.00048
721211.0915				4.9387				720929.00049
721211.0916				4.5858				720929.00050
721211.0924				2.4565				720929.00014
721211.0924				2.5510				720929.00015
721211.0923				2.5619				720929.00017
721211.0923				2.5102				720929.00018
721211.0921				2.4372				720929.00019
721211.0921				2.4637				720929.00020
721211.0917				2.0077				720929.00032
721211.0920				3.1176				720929.00033
721211.0918				2.9005				720929.00034
721211.1000							SAMPLES SUBMERGED	
721211.1605	73.0	0.0	75.5				SAMPLES TO DRIP RACK	
721211.1640	73.0	10.0	75.5				SAMPLES TO FREEZER	
721212.0812	72.0	0.0	73.0			6	SAMPLES FROM FREEZER	

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*****************************   6 CYCLES COMPLETE   *****************************

 DATE  TIME  TEMPERATURES  WEIGHT BEFOR FT   CALCS OR NOTES          SAMPLE
YRMODY.HRMM BATH FRZR ROOM SUBMR  FREZE CY                           NUMBER

721212.0844                1.5353                                   720929.00059
721212.0844                1.4205                                   720929.00060
721212.0845                1.2139                                   720929.00114
721212.0845                1.3796                                   720929.00116
721212.0846                1.3673                                   720929.00117
721212.0857                2.2549                                   720929.00099
721212.0858                2.3187                                   720929.00100
721212.0858                2.2490                                   720929.00101
721212.0855                3.6170                                   720929.00040
721212.0856                3.6879                                   720929.00041
721212.0857                3.7365                                   720929.00042
721212.0852                4.9249                                   720929.00048
721212.0854                4.9275                                   720929.00049
721212.0855                4.5765                                   720929.00050
721212.0848                2.4919                                   720929.00014
721212.0848                2.5225                                   720929.00015
721212.0849                2.5743                                   720929.00017
721212.0849                2.5108                                   720929.00018
721212.0850                2.4308                                   720929.00019
721212.0851                2.2038                                   720929.00020
721212.0851                1.9880                                   720929.00032
721212.0852                3.0062                                   720929.00033
721212.0852                2.8207                                   720929.00034
721212.0903                               SAMPLES SUBMERGED
721212.1256 72.0                         SAMPLES TO DRIP RACK
721212.1523       0.0 76.0               SAMPLES TO FREEZER
721213.0807 72.0  5.0 73.0              7SAMPLES FROM FREEZER

*****************************   7 CYCLES COMPLETE   *****************************

721213.0855 72.0  7.0 73.0               SAMPLES SUBMERGED
721213.1508 72.0  7.0 75.0               SAMPLES TO DRIP RACK
721213.1544 72.0  9.0 75.0               SAMPLES TO FREEZER
721214.0750 71.0  3.0 72.0              8SAMPLES FROM FREEZER
```

****************************** 8 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721214.0830				1.5345				720929.00059
721214.0831				1.4318				720929.00060
721214.0832				1.1799				720929.00114
721214.0833				1.3376				720929.00116
721214.0834				1.3200				720929.00117
721214.0835				2.2048				720929.00099
721214.0835				2.3678				720929.00100
721214.0836				2.2496				720929.00101
721214.0836				3.6157				720929.00040
721214.0836				3.6859				720929.00041
721214.0838				3.7276				720929.00042
721214.0838				4.9245				720929.00048
721214.0839				4.9248				720929.00049
721214.0840				4.5761				720929.00050
721214.0841				2.4242				720929.00014
721214.0842				2.4755				720929.00015
721214.0842				2.5309				720929.00017
721214.0843				2.4578				720929.00018
721214.0844				2.3975				720929.00019
721214.0844				2.4036				720929.00020
721214.0846				1.9862				720929.00032
721214.0845				3.0864				720929.00033
721214.0847				2.8270				720929.00034
721214.0855	72.0	-1.0	73.0				SP GR. 0.996	
721214.1525	72.0	0.0	75.0				SAMPLES TO DRIP RACK	
721214.1601	72.0	2.0	75.0				SAMPLES TO FREEZER	
721215.0902						9	SAMPLES FROM FREEZER	

****************************** 9 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721215.0955	71.5	7.0	75.0				SAMPLES SUBMERGED	
721215.1555	74.0	8.0	77.0				SAMPLES TO DRIP RACK	
721215.1635	74.0	10.0	77.0				SAMPLES TO FREEZER	
721216.1010		0.0	74.0			10	SAMPLES FROM FREEZER	

****************************** 10 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH FRZR ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721216.1044		1.5400				720929.00059
721216.1044		1.4351				720929.00060
721216.1045		1.1824				720929.00114
721216.1045		1.3363				720929.00116
721216.1046		1.3229				720929.00117
721216.1046		2.2007				720929.00099
721216.1047		2.3181				720929.00100
721216.1047		2.2071				720929.00101
721216.1048		3.6202				720929.00040
721216.1049		3.6856				720929.00041
721216.1050		3.7304				720929.00042
721216.1052		4.9264				720929.00048
721216.1053		4.9266				720929.00049
721216.1054		4.5782				720929.00050
721216.1054		2.4146				720929.00014
721216.1055		2.4799				720929.00015
721216.1055		2.5163				720929.00017
721216.1056		2.4631				720929.00018
721216.1056		2.4154				720929.00019
721216.1058		2.4077				720929.00020
721216.1058		1.9868				720929.00032
721216.1059		3.0086				720929.00033
721216.1100		2.8321				720929.00034
721216.1101		1.5300				720929.00059
721216.1102	REMOVED FROM CYCLING TO PERMIT COMPRESSION TEST					720929.00059
721216.1102	REMOVED FROM CYCLING TO PERMIT COMPRESSION TEST					720929.00116
721216.1102	REMOVED FROM CYCLING TO PERMIT COMPRESSION TEST					720929.00014
721216.1102	REMOVED FROM CYCLING TO PERMIT COMPRESSION TEST					720929.00015
721216.1108					SAMPLES SUBMERGED	
721216.1612	73.0 0.0 77.5				SAMPLES TO DRIP RACK	
721216.1638					SAMPLES TO FREEZER	
721218.0812	73.0 8.0 74.0			11	SAMPLES FROM FREEZER	

****************************** 11 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH FRZR ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721218.0854					SAMPLES SUBMERGED	
721218.1532	75.0 3.0 77.0				SAMPLES TO DRIP RACK	
721218.1613					SAMPLES TO FREEZER	
721219.0806				12	SAMPLES FROM FREEZER	

****************************** 12 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721219.0850							SAMPLES SUBMERGED	
721219.1600	74.0	2.0	77.0				SAMPLES TO DRIP RACK	
721219.1648	74.0	2.0	77.0				SAMPLES TO FREEZER	
721220.0808	73.0	-1.0	75.0			13	SAMPLES FROM FREEZER	

****************************** 13 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721220.0904	73.0	2.0	75.0				SAMPLES SUBMERGED	
721220.1614	74.0	5.0	77.0				SAMPLES TO DRIP RACK	
721220.1643		9.0	77.0				SAMPLES TO FREEZER	
721221.0802		7.0	73.0			14	SAMPLES FROM FREEZER	

****************************** 14 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721221.0901				1.4251				720929.00060
721221.0910				1.1782				720929.00114
721221.0910				1.3180				720929.00117
721221.0911				2.1719				720929.00099
721221.0911				2.2910				720929.00100
721221.0912				2.1837				720929.00101
721221.0912				3.6130				720929.00040
721221.0913				3.6828				720929.00041
721221.0915				3.7252				720929.00042
721221.0915				4.9236				720929.00048
721221.0920				4.9247				720929.00049
721221.0922				4.5760				720929.00050
721221.0922				2.5060				720929.00017
721221.0924				2.4545				720929.00018
721221.0924				2.4063				720929.00019
721221.0928				2.3968				720929.00020
721221.0929				1.9847				720929.00032
721221.0930				2.9900				720929.00033
721221.0931				2.8330				720929.00034
721221.0944							SAMPLES SUBMERGED	
721221.1552	75.0	-4.0	77.0				SAMPLES.TO DRIP RACK	
721221.1623	75.0	12.0	77.0				SAMPLES TO FREEZER	
721223.0910		0.0	72.0			15	SAMPLES FROM FREEZER	

****************************** 15 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721223.0929				1.4607				720929.00060
721223.0935				1.2290				720929.00114
721223.0935				1.3799				720929.00117
721223.0936				2.1997				720929.00099
721223.0937				2.3600				720929.00100
721223.0938				2.2176				720929.00101
721223.0938				3.6282				720929.00040
721223.0939				3.7010				720929.00041
721223.0940				3.7414				720929.00042
721223.0941				4.9382				720929.00048
721223.0942				4.9467				720929.00049
721223.0943				4.5894				720929.00050
721223.0944				2.6440				720929.00017
721223.0940				2.6744				720929.00018
721223.0934				2.5072				720929.00019
721223.0933				2.5077				720929.00020
721223.0933				1.9999				720929.00032
721223.0932				3.1094				720929.00033
721223.0932				2.9266				720929.00034
721223.0948	71.0	5.0	72.0				SAMPLES SUBMERGED	
721223.1610	72.0	0.0	76.0				SAMPLES TO DRIP RACK	
721223.1645							SAMPLES TO FREEZER	
721228.1000	72.0	2.0	74.0			16	SAMPLES FROM FREEZER	

****************************** 16 CYCLES COMPLETE ******************************

721228.1048						SAMPLES SUBMERGED
721228.1625	72.0	-2.0	76.0			SAMPLES TO DRIP RACK
721228.1655						SAMPLES TO FREEZER
721229.0900	72.0	-1.0	73.0		17	SAMPLES FROM FREEZER

****************************** 17 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
721229.0941				1.5024				720929.00060
721229.0941				1.2306				720929.00114
721229.0942				1.3722				720929.00117
721229.0943				2.3106				720929.00099
721229.0943				2.4801				720929.00100
721229.0944				2.3465				720929.00101
721229.0945				3.6230				720929.00040
721229.0945				3.6914				720929.00041
721229.0946				3.7375				720929.00042
721229.0946				4.9300				720929.00048
721229.0947				4.9394				720929.00049
721229.0948				4.6052				720929.00050
721229.0948				2.5870				720929.00017
721229.0948				2.4763				720929.00018
721229.0950				2.4459				720929.00019
721229.0950				2.4670				720929.00020
721229.0952				1.9902				720929.00032
721229.0952				3.1326				720929.00033
721229.0953				2.8962				720929.00034
721229.1029							SAMPLES SUBMERGED	
721229.1620	73.0	1.0	76.0				SAMPLES TO DRIP RACK	
721229.1647	73.0	5.0	76.0				SAMPLES TO FREEZER	
730102.0812	71.0	6.0	72.0			18	SAMPLES FROM FREEZER	

****************************** 18 CYCLES COMPLETE ******************************

730102.0848							SAMPLES SUBMERGED	
730102.1529	72.0	-2.0	75.0				SAMPLES TO DRIP RACK	
730102.1535							SP.GR 0.998 AT 72F	
730102.1540							SP.GR OF DISTILLED H2O 0.996 AT 78.5F	
730102.1600	72.0	7.0	75.0				SAMPLES TO FREEZER	
730103.0800	72.0	2.0	73.0			19	SAMPLES FROM FREEZER	

****************************** 19 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH	FRZR	ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
730103.0844				1.5461				720929.00060
730103.0843				1.2099				720929.00114
730103.0842				1.3482				720929.00117
730103.0841				2.2705				720929.00099
730103.0840				2.5286				720929.00100
730103.0840				2.2953				720929.00101
730103.0839				3.6267				720929.00040
730103.0838				3.7310				720929.00041
730103.0838				3.7330				720929.00042
730103.0837				4.9315				720929.00048
730103.0836				4.9463				720929.00049
730103.0836				4.5823				720929.00050
730103.0835				2.6720				720929.00017
730103.0835				2.6555				720929.00018
730103.0834				2.4936				720929.00019
730103.0834				2.5546				720929.00020
730103.0833				1.9949				720929.00032
730103.0832				3.2556				720929.00033
730103.0831				3.0243				720929.00034
730103.0848							SAMPLES SUBMERGED	
730103.1508	72.0	0.0	76.0				SAMPLES TO DRIP RACK	
730103.1542	72.0	8.0	76.0				SAMPLES TO FREEZER	
730104.0802	72.0	5.0	73.0				20SAMPLES FROM FREEZER	

****************************** 20 CYCLES COMPLETE ******************************

DATE TIME YRMODY.HRMM	TEMPERATURES BATH FRZR ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
730104.0839		1.5213				720929.00060
730104.0840		1.2281				720929.00114
730104.0841		1.3690				720929.00117
730104.0842		2.2502				720929.00099
730104.0843		2.4358				720929.00100
730104.0845		2.2696				720929.00101
730104.0846		3.6214				720929.00040
730104.0847		3.6900				720929.00041
730104.0848		3.7319				720929.00042
730104.0848		4.9232				720929.00048
730104.0849		4.9509				720929.00049
730104.0850		4.5815				720929.00050
730104.0851		2.6175				720929.00017
730104.0851		2.5216				720929.00018
730104.0852		2.4851				720929.00019
730104.0853		2.4824				720929.00020
730104.0854		1.9899				720929.00032
730104.0855		3.1835				720929.00033
730104.0856		2.9638				720929.00034
730104.0940					SAMPLES TO 50C OVEN	

****

DATE TIME YRMODY.HRMM	TEMPERATURES BATH FRZR ROOM	WEIGHT SUBMR	BEFOR FREZE	FT CY	CALCS OR NOTES	SAMPLE NUMBER
730106.1107					SAMPLES FROM OVEN	
730106.1110		1.5010				720929.00059
730106.1112		1.3900				720929.00060
730106.1113		1.1630				720929.00114
730106.1111		1.2708				720929.00116
730106.1114		1.2905				720929.00117
730106.1114		2.1562				720929.00099
730106.1115		2.2620				720929.00100
730106.1115		2.1679				720929.00101
730106.1116		3.5995				720929.00040
730106.1116		3.6680				720929.00041
730106.1117		3.7070				720929.00042
730106.1118		4.9085				720929.00048
730106.1118		4.9081				720929.00049
730106.1119		4.5600				720929.00050
730106.1109		2.3500				720929.00014
730106.1108		2.4048				720929.00015
730106.1120		2.4716				720929.00017
730106.1120		2.3802				720929.00018
730106.1121		2.3645				720929.00019
730106.1122		2.3747				720929.00020
730106.1123		1.9681				720929.00032
730106.1123		2.6341				720929.00033
730106.1124		2.6226				720929.00034
730106.1125					SAMPLES RETURNED TO OVEN	

APPENDIX E

COMPUTER PROGRAM FOR LACHENBRUCH THREE-LAYER METHOD

REFERENCE LACHENBRUCH(1959)

APPENDIX E

```
C       LACHENBRUCH THREE LAYER METHOD
C       PROGRAM WRITTEN IN FORTRAN IV WILL RUN UNDER BUFF40 ALSO.
C       18 DEC 1972   R. BERG
C       PROGRAM COMPUTES F/A VALUES FOR INCREMENTAL THICKNESSES OF
C       LAYER NUMBER 2(INSULATING LAYER) OF A THREE-LATER SYSTEM.
C       THICKNESS OF OTHER LAYERS REMAIN CONSTANT.
C
C       READ THICKNESS(X), THERMAL CONDUCTIVITY(T), AND VOLUMETRIC HEAT
C        CAPACITY(C)
        DIMENSION X(5),T(5),C(5)
   13   DO 1 J=1,3
    1   READ(1,2)X(J),T(J),C(J)
    2   FORMAT(3F10.4)
C
C       CALCULATE BETA AND ALPHA VALUES
C
        B1=(T(1)*C(1))**0.5
        B2=(T(2)*C(2))**0.5
        B3=(T(3)*C(3))**0.5
        A1=T(1)/C(1)
        A2=T(2)/C(2)
C
C       COMPUTE CONSTANTS FOR EQUATIONS
C
        C1=B3*B2
        C2=B2**2.
        C3=B3*B1
        C4=B2*B1
        C5=C1 + C2 + C3 + C4
        C6=2.*SQRT(.0007164/2.)
        C7=1./SQRT(A1)
        C8=1./SQRT(A2)
        C9=C6*C7
        C10=C6*C8
        C11=X(1)*C9
        P1=4.*C4/C5
        P2=(-C1 + C2 - C3 + C4)/C5
        P3=(-C1 - C2 + C3 + C4)/C5
        P4=(C1 - C2 - C3 + C4)/C5
C
C       PRINT HEADING
C
        WRITE(3,5)
    5   FORMAT('1','INFORMATION FOR LACHENBRUCH 3-LAYER CASE'//)
        WRITE(3,90)
   90   FORMAT(' ',' J',T11,'X',T21,'T',T31,'C'/)
        DO 7 J=1,3
    7   WRITE(3,8)X(J),T(J),C(J)
    8   FORMAT(' ',I5,3F10.4)
```

```
C
C     READ INCREMENTAL THICKNESS OF LAYER 2 AND NO OF TIMES TO INCREMENT
C
      READ(1,3)XINC,L
    3 FORMAT(F10.4,I5)
      WRITE(3,9)XINC,L
    9 FORMAT(' ',' INCREMENTAL THICKNESS=',F10.4/,'NUMBER OF INCREMENTS
     1=',I5)
C
C     COMPUTE DAMPING AS THICKNESS OF LAYER 2 INCREASES
C
      WRITE(3,91)
   91 FORMAT(' ','NUMBER OF',T15,'F/A RATIO',T32,'INSULATION')
      WRITE(3.92)
   92 FORMAT(' ','INCREMENT',T13,'DIMENSIONLESS',T30,'THICKNESS, FT'/)
      L=L+1
      DO 10 N=1,L
      C12=X(2)*C10
      C13=C11 + C12
      S1=(2.*P2*EXP(-C13))*COS(C13)
      S2=(2.*P3*EXP(-C11))*COS(C11)
      S3=(2.*P4*EXP(-C12))*COS(C12)
      S4=(2.*P2*P3*EXP(-2.*C11-C12))*COS(C12)
      S5=(2.*P2*P4*EXP(-C11-2.*C12))*COS(C11)
      S6=(2.*P3*P4*EXP(-C13))*COS(C11-C12)
      S7=(P2*P2)*EXP(-2.*C13)
      S8=(P3*P3)*EXP(-2.*C11)
      S9=(P4*P4)*EXP(-2.*C12)
      S10=1. +S1 + S2 + S3 + S4 + S5 + S6 + S7 + S8 + S9
      ANS=(EXP(-.5*C13))*P1/(SQRT(S10))
      WRITE(3,11)N,ANS,X(2)
   11 FORMAT(' ',I5,T13,F10.4,T30,F10.4)
   10 X(2)=X(2) + XINC
C
C     READ A FLAG TO DETERMINE WHETHER ANOTHER PROFILE IS DESIRED.
C     FLAG=0. IF NO ADDITIONAL PROFILES ARE WANTED.
C
      READ(1,12)FLAG
   12 FORMAT(F10.4)
      IF(FLAG.NE.0.)GO TO 13
      STOP
      END
```

```
                 EXAMPLE OF INPUT DATA FOR 3-LAYER SOLUTION
   8.0      1.01     26.0               X, T AND C FOR MATERIAL 1, SOLUTION 1.
   0.0417  0.0125     1.0               X, T AND C FOR MATERIAL 2, SOLUTION 1.
   5.0      0.895    37.0               X, T AND C FOR MATERIAL 3, SOLUTION 1.
   0.0417   12                          INCREMENTAL THICKNESS & NO. OF INCREMENTS
10.                                     FLAG FOR ADDITIONAL SOLUTION.
  10.0      1.01     26.0               X, T AND C FOR MATERIAL 1, SOLUTION 2.
   0.0417  0.0125     1.0               X, T AND C FOR MATERIAL 2, SOLUTION 2.
   5.0      0.895    37.0               X, T AND C FOR MATERIAL 3, SOLUTION 2.
   0.0417   12                          INCREMENTAL THICKNESS & NO. OF INCREMENTS
0.                                      FLAG FOR LAST SOLUTION.
```