MOISTURE IN INSULATION

Final Report

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1.0 Introduction

The use of insulation in buildings has grown steadily over the past quarter-century. This has been a positive improvement in building technology. The results have been warmer, more comfortable buildings at lower energy costs and with only minimal added initial cost. No one would debate the net positive effect of the widespread use of insulation.

In his text *Building in the North*, Rice argued for an "optimum thickness" of insulation based on economic considerations and tempered with engineering judgement. He explained a method for calculating this optimum thickness and taught a generation of engineering students the use of this method, along with the need for installing proper "vapor barriers" to protect the insulation from moisture.

The Canadian Building Research Council published several reports on insulation that generally support Rice's position. But designs have to be based on engineering data available to the profession at the time of the design. This means the "economic thickness" has to be based on the thermal properties published by the manufacturer for new, dry insulation. This is insulation that has never been subjected to the adverse conditions under which it must operate during the rest of its service life.

Once built, buildings must be heated and maintained for a lifetime which spans several decades. If the insulation is adversely affected by environmental conditions such that the thermal performance deteriorates, then the owner is saddled with higher energy costs for the life of the building. A proper design should consider the thermal deterioration and make allowances so that the performance of the insulation will approach optimum throughout the lifetime of the building not just when it is new. This requires information not now available to the designer.

This study will attempt to provide some of that information and better enable the designer to make a more complete and adequate design that will perform properly over the lifetime of the building.

1.1 Background

The advent of higher heating costs brought on over the past eight years by the increasing price of crude oil has imposed an economic burden on structures which were built to previous standards. The resulting energy conservation programs that were developed sought to cure the problem with additional insulation. The practical limitations involved in adding insulation to existing structures led to the use of new products such as foil-clad foam and other products that either have their own vapor barrier attached, or in themselves constitute a vapor barrier. When these products are added to the outside of a structure that was previously insulated, the original insulation becomes sandwiched between two vapor barriers. Moisture entering the insulation from the interior becomes trapped and may build up inside the original insulation. Although it is generally considered to adversely affect the insulating qualities of the product, very little is really known about the magnitude and degree to which insulation is degraded by the addition of water vapor. Even less is known about the rate at which moisture collects in insulation within the wall of a structure.

1.2 Scope

This report will discuss research on the effect of moisture in insulation. It gives detailed information based on laboratory measurements of the thermal performance of several commonly used building insulations which have accumulated various degrees of moisture in their structure.
The thermal conductivity of two groups of samples was measured. The first group of insulation samples was collected from structures in the field. The second consisted of dry samples which were moisturized in the laboratory in order to give a complete moisture range on which to base the resulting thermal performance vs. moisture graphs.

The final portion of the project was aimed at determining the general state of moisture intrusion in buildings throughout interior Alaska.

The means of measuring the moisture within the walls of a structure had to be developed. This was a major effort in itself; it became a project within a project. The measurement technique had to be perfected and calibrated against insulation samples with known moisture contents. Only then could the field measurements be carried out.

1.3 Purpose

The aim of this report is to give designers more complete data on the effects of moisture in various types of insulation, and to give them some information on the amount of moisture to which their design might be exposed during its lifetime. With this information they will be better able to design for energy efficiency during the entire lifetime of the building.

2.0 Theory and Methodology

2.1 Moisture measurements

There are numerous ways to measure the presence of water, however to nondestructively determine the quantity of water in an insulation sample which is encapsulated in the wall of a structure is not trivial. A thorough search for ready-made instrumentation for this purpose was conducted in the early stages of this project. No commercially available instrument within budget constraints was found which could meet the needs of the project.

2.1.1 Weight Difference The time-honored means of determining moisture content is by comparing the weight of the material before and after the water is extracted from it. A sample is carefully weighed, then placed in an oven to dry (often overnight). The sample's weight is periodically checked until it is determined that the weight is no longer decreasing. The insulation is then assumed to be dry and that weight is subtracted from the original weight to obtain the weight of the water extracted. In the case of field samples, the thermal conductivity had to be measured before the moisture was extracted from the sample.

Care must be taken when drying foam insulation, particularly closed cell foam insulation. During the drying process the internal water vapor pressure can become so high that the insulation sample will puff up in much the same way as popcorn pops. The volume must therefore be measured before the drying process, and the drying oven must be carefully maintained at a low enough temperature to avoid such swelling.

2.1.2 Terminology The quantity of moisture absorbed in insulation has been reported by various researchers in terms of either percent of the dry weight or percent of insulation volume. Since the original dry weight of insulation taken from field applications is unknown, this report will refer to the quantity of moisture as a percent of the insulation volume. This requires the volume to be measured, which can be accomplished either directly or by displacement. In most cases the volume of the relatively uniform, rectangular insulation samples were easily and quite accurately measured using standard calipers.

2.1.3 Use of Time Domain Technology to Determine Moisture Content.
Time Domain Reflectometry (TDR) was originally developed to find breaks or imperfections in transmission lines. An initial pulse is introduced into the line in question and reflections come back from any change in the dielectric constant along the line. A break or other imperfection in the dielectric material of the line will reflect a portion of the signal. The time between the initial pulse and the arrival of each reflection is measured. The time

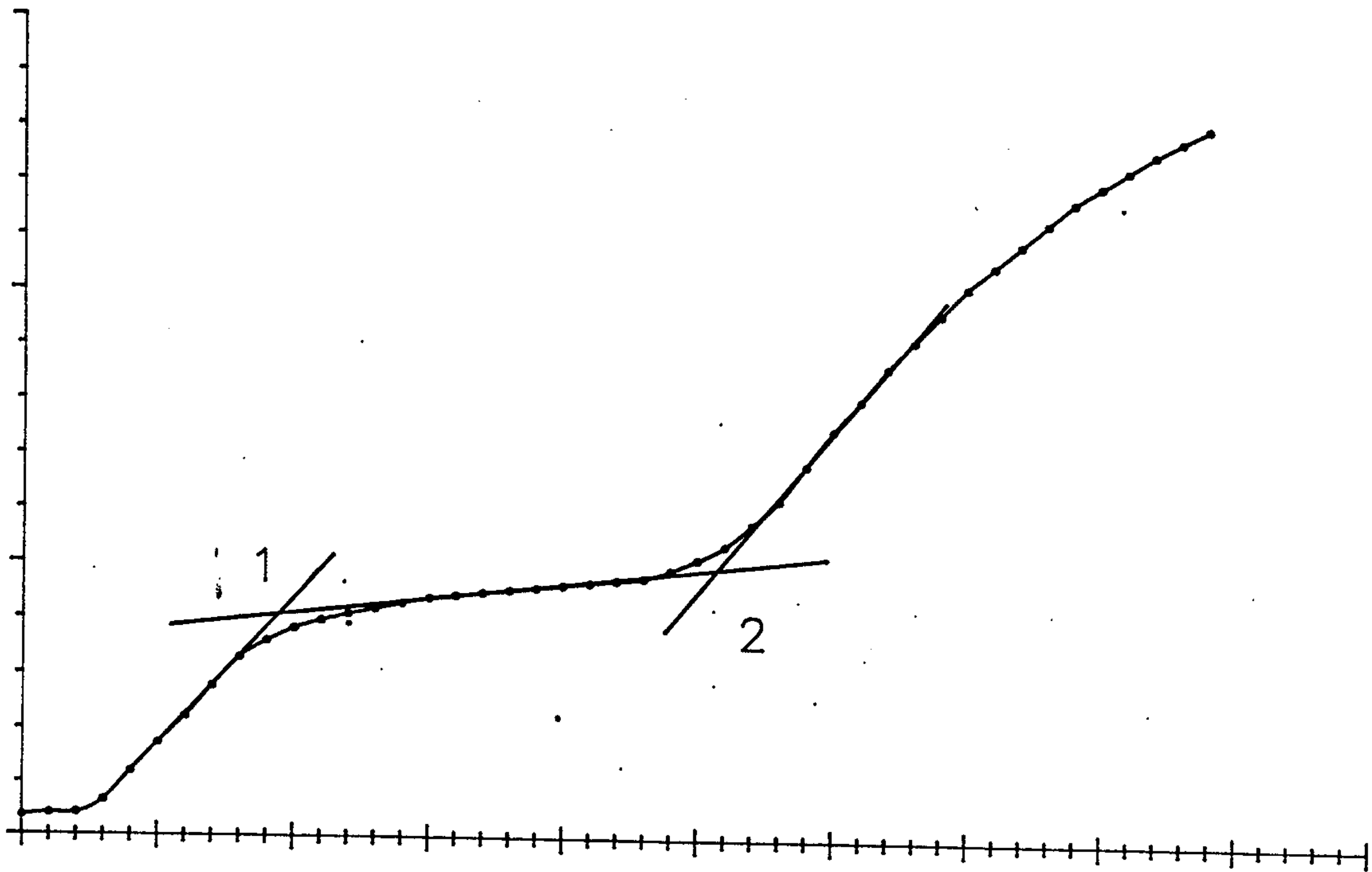

FIG. 1 TDR Trace of Moisture in Insulation

required for the reflection to arrive back at the origin is a function of the location of particular dielectric anomaly in the line and can be used to establish the location of the problem quite accurately.

If, on the other hand, the length of the line is known, this procedure can be reversed and the dielectric constant can be determined. The dielectric constant of insulation is dependent on the moisture content of the insulation. Therefore, the amount of moisture within the insulation inside a wall can be measured by determining the dielectric constant. To do this, a set of probes of predetermined length and spacing are inserted into the wall and a TDR pulse is used to determine the dielectric constant of the insulation material which completes the circuit between the two probes.

The TDR trace shown in Figure 1 is actually a composite of a series of samples of the dielectric pulse along the length of the probes. Extracting the dielectric constant is a matter of measuring the slope of the trace between points 1 and 2. The intersections of these tangents with the tangent between 1 and 2 are taken to define the ends of the dielectric trace. The length of this line can be correlated to yield the dielectric constant. The dielectric constant has been show to correlate to moisture content of the insulation (Wandover 1988, Stein and Kane 1983, Topp and Davis 1985, Patterson and Smith 1980, Ansould et al. 1985).

To correlate dielectric constant to moisture content a large number of specimens of insulation with known moisture content were sampled with the TDR. The resulting data established the relationship between dielectric constant and moisture content. This calibration procedure was performed for all five insulation types that were encountered in the study i.e., fiberglass batt, extruded polystyrene, expanded polystyrene beadboard, and polyurethane foam.

2.2 Thermal Conductivity Measurements

Thermal conductivity was determined by three means: 1. a guarded hot plate, 2. a thermal conductivity probe, and 3. an instrumented full-sized wall. Two types of guarded hot plates were used. One was a small partially automated unit manufactured by Anacon Corp. This unit had a standard fixed temperature difference of 50 to 100°F (10 to 38°C) and a processor that converted raw data directly into thermal conductivity. The second unit was manufactured by Dynatech Corp. It was capable of maintaining below freezing temperatures, and the temperature differences across the insulation could be varied over a wide range.

Thermal conductivity probes were used to measure the energy dissipation around a small self-heated thermistor located at the tip of the probe. Thermal conductivity is a function of the energy dissipation from the thermistor bead and the temperature difference. This allows the determination of thermal conductivity at discrete points within an insulation. Under most conditions, moisture enters insulation from a preferred side. The quantity of moisture therefore varies from one side to the other within the insulation. (During the long winter months in cold regions, moisture enters a wall or ceiling from the inside of the building.) The conductivity probe allows the thermal conductivity to be sampled at specific locations throughout the thickness of the insulation. (The thermal conductivity probe was constructed in the laboratory of the Alaska Department of Transportation and Public Facilities Research Division (DOT/PF) at the University of Alaska Fairbanks.)

The guarded hot plate, on the other hand, measures an average overall thermal conductivity for the entire sample under test. If the moisture and the thermal conductivity are uniform throughout the sample, then both methods should give the same value. This is rarely the situation encountered in samples collected from functioning insulation systems outside the laboratory. Nevertheless, the average of a set of several thermal conductivities measured throughout the sample by the probe technique should be comparable to the overall value obtained from the guarded hot plate.

The overall thermal conductivity under field conditions is usually what interests the designer, so the guarded hot plate value is more useful to engineers in practice.

<u>2.2.1 Insulation Samples</u> Insulation samples were taken from a variety of sources. Wherever they could be found, samples were taken from applications in the field. Several extruded polystyrene samples were obtained from roofs that were under reconstruction. Some urethane and fiberglass samples were also obtained from the field. When a sample was collected in the field, it was placed in an airtight plastic bag to be transported to the laboratory where it was processed.

However, in order to obtain more complete data sets when insulation samples with specific moisture contents were not found in the field, samples of insulation were moisturized in the laboratory to the required moisture content. Laboratory moisturizing usually results in samples that have a more uniform moisture content throughout the sample than those from the field. The thrust of this paper is to measure the effect of moisture on thermal conductivity, therefore uniformly moisturized samples were equally acceptable. Although samples from the field showed considerable stratification, the moisture in some samples was redistributed by prolonged exposure to the temperature difference of the guarded hot plate. The samples ended up having a more uniformly distributed moisture content, but were otherwise unaffected.

2.3 Field Investigations

Once the laboratory work had established the relationship between moisture and thermal conductivity and the TDR technique for moisture measurement had been developed and calibrated, a field study was undertaken to determine the extent of moisture intrusion in insulation systems in service. Homes and buildings were sampled in both Fairbanks and Delta Junction. The results of this portion of the study are presented in section four of this report.

2.4 Theory of Insulation

Insulations slow the transfer of heat energy by interfering with at least two of the three basic methods of heat transfer, usually conduction and convection. The insulating material is generally a low thermal conductivity material itself, which slows the flow of energy from the hot side of the material to the cold. Further reduction of conduction heat transfer is then achieved by arranging a difficult thermal path between the hot and cold sides of the insulation. Fiberglass, for example, provides only long thin strands of glass that are generally laid perpendicular to the heat flow path. Heat must transfer from strand to strand where they touch each other and then move down the strand to the next intersection. This tortuous path keeps conduction heat transfer to a minimum. While foam insulations usually offer a less tortuous path for conduction, the cell walls are very thin, allowing little cross-sectional area through which heat can flow, and the thermal conductivity of the plastic is less than that of glass.

A good insulation also restricts convection heat transfer as much as possible. Air within the cell structure or fiber matrix will allow energy to flow from hot to cold by either direct conduction between gas molecules when they collide or by forming convection cells where energy is carried along with the moving air molecules from the hot side of the cell to the cold side. In insulations, convection heat transfer is generally faster than conduction between air molecules, but convection cells cannot develop in very small air pockets, or if they do, the viscous effects of the fluid make them very sluggish and ineffective. The insulation's function is to make the individual pockets of air so small that convective action is inhibited as much as possible.

A good insulation, therefore, strives to reduce two of the three basic modes of heat transfer, conduction and convection. Most common insulations used in the building industry either ignore the radiation heat loss effect or at best provide a foil reflector on one side. This is, in this author's opinion, an area that needs further serious research consideration. It is not, however, addressed in this report.

3.0 The Effect of Moisture on Thermal Conductivity

3.1 Background

The presence of moisture within the insulation has long been known to be detrimental. The exact quantitative nature of the effect, however, is not well understood. It is difficult to predict how much water can be tolerated before the detrimental effect becomes unacceptable. For example, is the effect linear (i.e., the thermal conductivity of the insulation increases in direct proportion to the amount of moisture that is introduced) or is the effect more complex? Also, is the effect the same for all types of insulations, both foam and fiber type? The results of this study suggest that the rate of degradation of the insulating properties of the material varies from one material to another and appears to be a function of the physical form of the material (i.e., solid, liquid, foam, fiber, open cell, closed cell etc.).

Several others have investigated this effect. Dechow and Epstein (1979) reported the detrimental effect of moisture on several foam insulations. Tobiasson and Ricard (1979) studied the effect of moisture on common roofing insulations. Woodbury and Thomas (1985) reported on the effect of moisture on glass fiber insulation. Little work, however, has been done to compare the effect of moisture on different types of insulations commonly used in construction using the same measurement techniques and conditions. Some of the newer insulations such as foamed isocyanurate and its close cousin polyurethane are noticeably absent.

As a practical matter, the question arises as to just how much moisture can be expected in the insulation of a building, particularly considering modern vapor barrier (retarder[1]) technology and the ability of modern construction

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[1] It has been suggested that the material used to restrict the flow of moisture be named "vapor retarder" rather than "vapor barrier." This is a moot point. Both "retarder" and "barrier" refer to a restriction to flow. However, in the authors opinion, "retarder" has other connotations that are not consistent with the description of the material. Also, "vapor barrier" is well established and understood in the construction

to install vapor barriers that offer excellent restriction of vapor flow. Modern technology not withstanding, a considerable problem with moisture in older construction exists. Vapor barrier standards in older structures were often inferior to today's. Materials were not as good or were often installed poorly for vapor barrier service. Even today, some construction workers do not understand the necessity of sealing even small tears or cuts in the vapor barrier membrane. Frequently openings for electrical convenience outlets or plumbing penetrations are not sealed. These small openings are devastating to the insulation and the integrity of the vapor barrier which cannot then provide adequate protection to the insulation in the vicinity of the openings.

Even foamed-plastic insulations are found to absorb considerable amounts of water vapor to the detriment of their insulating ability. Esch (1986) reports moisture absorption by insulations used in road subgrades over permafrost. Tobiasson and Ricard (1979) and McFadden (1986) found several foamed-plastic roof insulation samples which had absorbed large amounts of moisture while in service. Dechow and Epstein (1979) studied foamed plastics that were saturated in the laboratory.

The open-cell structure of polyurethane and isocyanurate absorbs more water than extruded polystyrene foam which has a closed structure. However, even extruded polystyrene will absorb substantial amounts of water under some extreme conditions, (McFadden 1986), but under most applications it absorbs very little. Esch (1986) retrieved extruded polystyrene foam insulation that had been in service in road subgrades for up to 15 years and yet had accumulated an average of only 1.168% moisture by volume during its time in service.

The range of moisture found in insulation under actual use conditions seems to be much larger than has been attained in laboratory moisturization (McFadden 1986, Dechow et al. 1979). In particular, insulation subject to many repeated freeze-thaw cycles and very high thermal gradients (such as in roof applications) suffers more moisture penetration than is normally seen in other applications such as in walls or buried in the soil.

3.1.1 Limiting Moisture Influx Vapor barriers can be used to reduce and in some cases eliminate the intrusion of moisture into insulation. Several vapor barrier materials are available to the construction industry. By far the most

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industry. Therefore "vapor barrier" will be used in this paper to refer to any material that is used for the purpose of restricting vapor passage.

commonly used vapor barrier material is 4 and 6 mil thick polyethylene sheet. The amount of moisture that will pass through a material can be calculated by standard techniques and is dependent on the permeability of the material. Tables of permeability for most construction materials are available in the literature (ASHRAE 1986).

Some insulating materials such as closed-cell foam (extruded polystyrene foam) are very resistant to moisture invasion. These insulations do not need another vapor barrier under most normal service conditions. Exceptions, however, are when the insulation is subject to many freeze-thaw cycles while in the presence of standing water, such as when it is used for an Inverted Roofing Membrane Assembly (IRMA [2]) roof. A more thorough discussion of this will be found in section 3.3.

3.1.2 Scope Although there are many different insulations available, because of budget restrictions the study had to be restricted to four of the most commonly used insulations. These are classified in two basic types: foamed plastics and fibers. The foamed plastics include polyurethane, isocyanurate, extruded polystyrene and expanded polystyrene beads (beadboard). The fiber-type insulation used in these studies was fiberglass batt.

3.1.3 Water and Thermal Conductivity Water increases the thermal conductivity (therefore degrading the insulating value) by filling the air pockets with water, which is much more efficient than air at transferring heat. In addition, water tends to coat the fibers and cell walls of the insulating material making them thicker in cross section and therefore better heat flow paths. This is particularly significant at locations where fibers touch each other. When dry, the area of contact available for energy transfer from one fiber to the next is exceedingly small; just a line or point of contact in the case of fibers. Water coating the fibers provides a meniscus at each point of contact between fibers. This significantly increases the area through which heat can transfer. As described above, water also provides increased conduction along the fibers from contact point to contact point.

Although the water quantity never gets high enough to fill the air pockets between fibers, it can fill the small air cells in plastic foam insulation. It might be expected therefore, that water would have a greater adverse effect on foams than on fibers. This was not found to be the case.

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[2] Inverted Roof Membrane Assembly is patented by Dow Chemical Company.

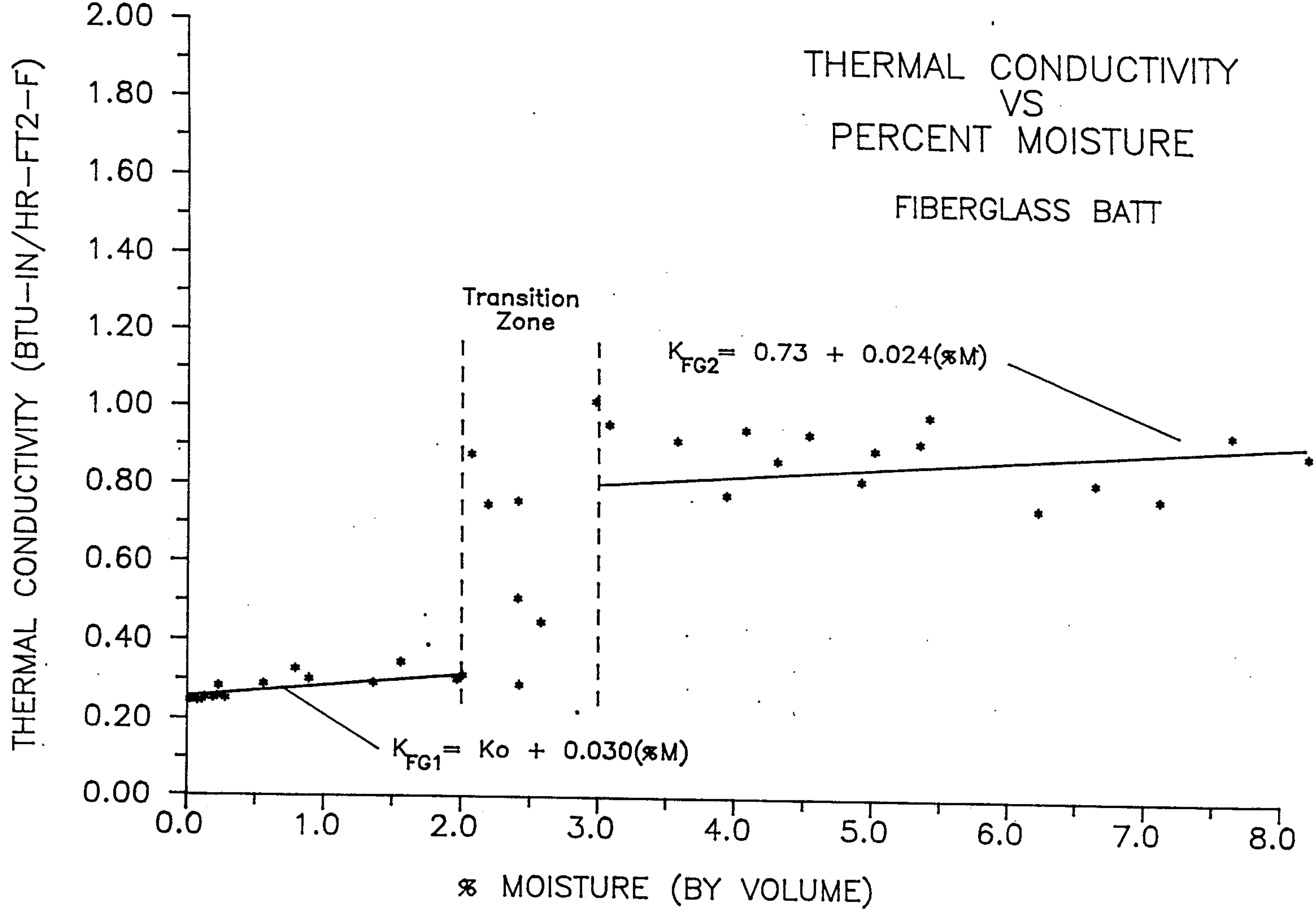

FIG. 2 – Thermal Conductivity vs Percent Moisture in Fiberglass Batt

3.2 Fiberglass Insulation

Fiberglass batt is the most common insulation used in building construction. It is economical, easily installed, and provides a stable thermal barrier. However, intrusion of moisture into the fiberglass batt often occurs due to natural vapor pressure gradients present between the inside and outside of every structure. As water vapor passes through fiberglass, if the temperature within the insulation falls below the dew point of the vapor, liquid water condenses on the glass fibers and remains in the system. As the quantity of moisture increases, the thermal conductivity also increases.

Figure 2 shows the thermal conductivity of laboratory moisturized fiberglass batt insulation. The addition of only a small amount of moisture decreases the thermal resistance significantly. This is probably due to beads of moisture forming at the intersection of the fibers, as mentioned above. Since the nature of fiberglass makes it nearly impossible to fill the air pockets between fibers, the principal increase in thermal conductivity comes from increased conduction through the fibers, and little increase is due to the presence of water in the convection process. The thermal conductivity increases only slightly until enough moisture has accumulated to begin forming menisci at the intersections between fibers. As this is taking place, the conductivity increases dramatically and there is a transition zone in the thermal conductivity/moisture relationship. After the transition is over, thermal conductivity again increases at a slower rate as moisture continues to accumulate. If this scenario is correct, then the damage to the thermal resistance is mostly over as soon as the moisture accumulation has coated the fibers and provided increased contact area (menisci) at the fiber contact points. The transition zone in Figure 2 suggests that this region lies between 2 and 3 per cent moisture. Additional moisture then has a much smaller effect on the thermal conductivity of fiberglass insulation, since it only serves to coat the fibers more heavily. The big increase comes from improving heat flow at the point contact between fibers.

A two-step approach gives the best means of describing the thermal conductivity/moisture relationship. From zero to 2% moisture the following relationship gives a good approximation to the data:

$$K_{FG1} = K_o + 0.030(\%M) \qquad 0\% < \%M < 2\% \qquad (1)$$

Where:

K_{FG1} is the thermal resistance of the wet insulation in (hr-ft^2-°F/BTU),

K_o is the thermal resistance of the dry insulation, and

%M is the percent by volume of moisture in the sample.

For moisture contents above 3% the following relationship is recommended to give a better representation of measured values in that range:

$$K_{FG2} = 0.73 + 0.024(\%M) \qquad 3\% < \%M < 8\% \qquad (2)$$

The transition region from 2% to 3% moisture requires further investigation.

3.3 Open-Cell Foam Insulations

Two very similar foam insulations were tested in this group, polyurethane and polyisocyanurate. They have a number of advantages to the construction industry. They can be foamed at the site directly onto the surface to be insulated, covering any complex shape. This is a particularly valuable feature when insulating pipe fittings, tanks and other curved or compound surfaces. Expanding foams will also fill and seal cracks around architectural openings such as windows and doors. Also, sprayed foam resin sticks to the surface onto which it is applied, making adhesives unnecessary.

Unfortunately, as the foam is generated, these materials form a large percentage of open cells which freely fill with liquids. Although the absorption of water does not cause the material to degrade structurally, it does adversely affect its thermal conductivity.

Figure 3 shows the results of tests on samples of polyurethane and polyisocyanurate foam which have been moisture conditioned in the laboratory. Like fiberglass, a two step linear approach gives the best correlation to measured values. Thermal conductivity rises rapidly as the percentage of absorbed moisture initially increases. However, the slope change in the curve is closer to 1% than the 2% to 3% transition zone found in fiberglass. After one percent is reached, a slower, more linear increase prevails.

A dual approach best describes the relationship between thermal conductivity and moisture. For moisture contents of 0 to 0.5%:

$$K_{U1} = K_o + 0.085(\%M) \qquad 0 < \%M < 0.5\% \qquad (3)$$

Where:
K_{U1} is the thermal conductivity (BTU-in/hr-ft^2-°F), and
K_o is the dry thermal conductivity.

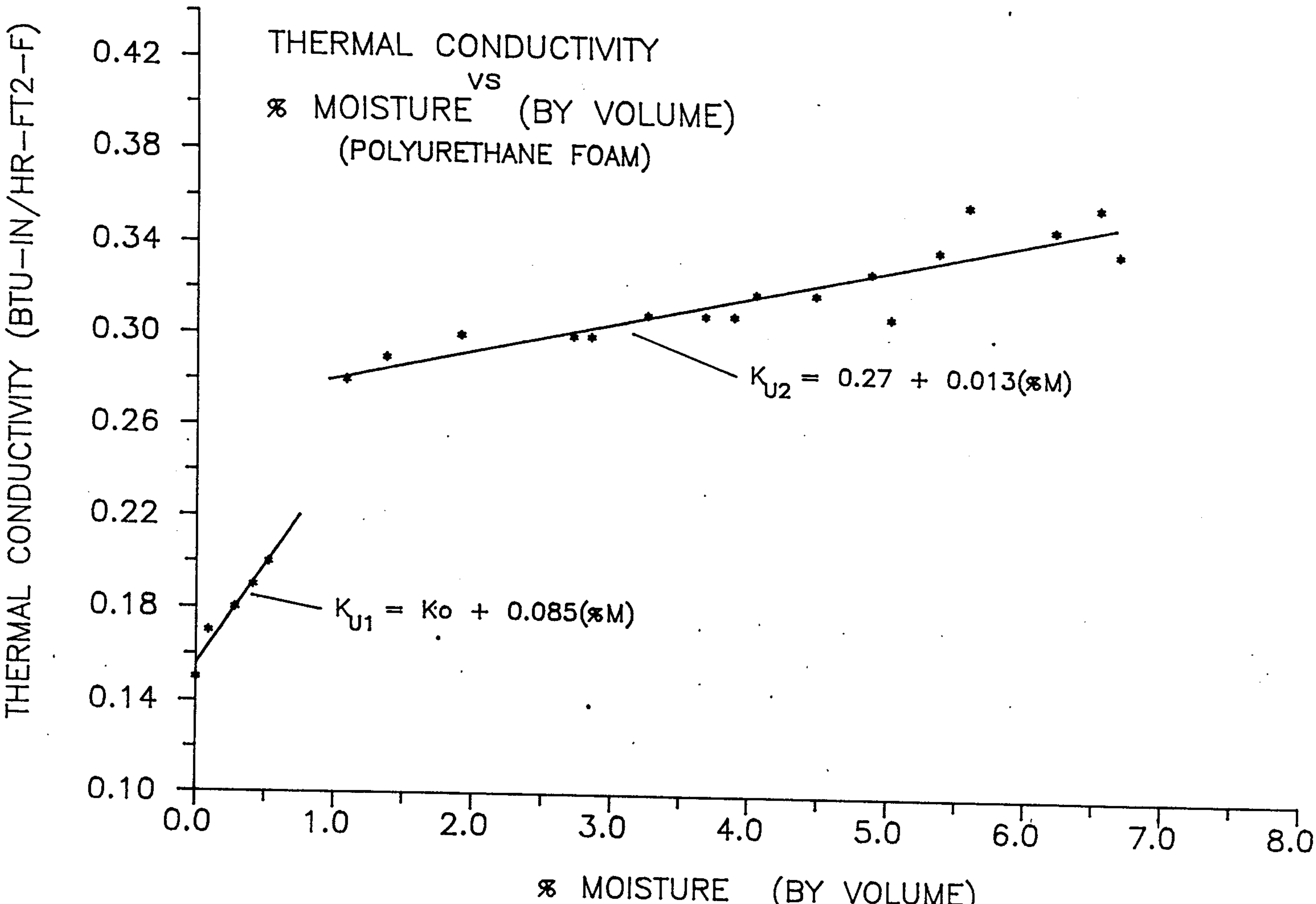

FIG. 3 – Thermal Conductivity vs. Percent Moisture in Polyurethane Foam

While for moisture contents from 1% to 7%:

$$K_{U2} = 0.27 + 0.013(\%M) \qquad 1 < \%M < 7\% \qquad (4)$$

Note that the relationships that best describe the data are linear except for the transition area where the slope changes.

3.4 Closed Cell Foam Insulation

Foamed polystyrene insulation is commercially available in two forms; molded sheets of expanded beads, and extruded continuous sheet foam. The cell structure of both types is closed-cell. That is, the cell walls are generally continuous and do not allow fluid or air to freely pass through. Molded sheets of expanded beads have air pockets between each bead of polystyrene foam, whereas extruded polystyrene (EPS) is a continuous matrix of foam cells. EPS does not have beads of foam with open spaces between. With the possible exception of cellular glass, extruded polystyrene foam is one of the most water resistant insulations available on the market today. It is the preferred choice if the insulation is to be in contact with water. Nevertheless, under some extreme conditions, extruded polystyrene foam has been found to absorb significant amounts of water. (McFadden 1986, Tobiasson 1979).

3.4.1 Extruded Polystyrene Foam For this study, samples of EPS were taken from two roofs in the Fairbanks, Alaska area. The samples had moisture contents as high as 21% by volume (670% by weight). The first EPS samples to become available were taken from a roof at the University of Alaska Fairbanks. Additional samples from the second source, a roof on a shop building at Fort Wainwright Army Post, added confidence and additional statistical weight to the earlier data from the University of Alaska samples.

Figure 4 shows the thermal resistance of EPS insulation as a function of moisture content. The data points above 5% are all taken from roofs in service in the field. In order to obtain a more complete range of moisture in the samples used for the thermal conductivity measurements, new dry insulation was moisturized in the laboratory until it contained the desired moisture content. This, however, proved difficult. Laboratory samples could only be prepared with moisture contents up to 5%. The cluster of data points in the 0 to 0.5% range of the chart are both field samples and laboratory moisturized samples. Data points from 0 to 5% are also both from samples obtained from the roofs and laboratory prepared samples.

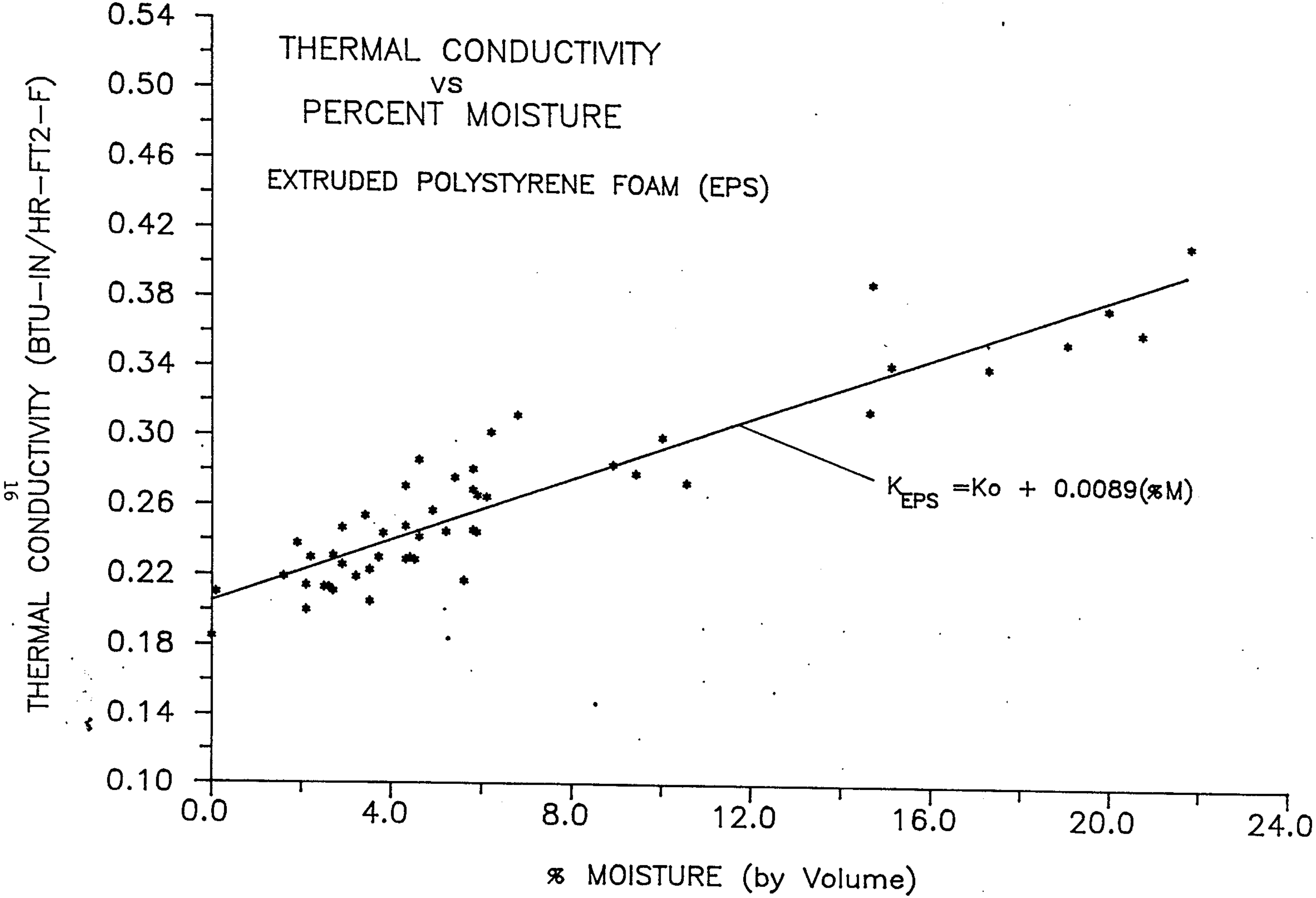

FIG. 4 – Thermal Conductivity vs Percent Moisture in Extruded Polystyrene Foam

The following formula represents a reasonable description of the relationship between thermal conductivity and moisture in extruded polystyrene (EPS) insulation based on the data in the figure.

$$K_{EPS} = K_o + 0.0089(\%M) \qquad (5)$$

As in the case of open-cell foam, the relationship that best represents the data is linear. However, the effect of moisture in this case does not show the discontinuity exhibited by open-cell insulations in figure 3. The overall effect of moisture on this insulation is less degrading than for the urethane and polyisocyanurate insulations (70% as great as in the open cell varieties.)

3.4.2 Molded Expanded Polystyrene (Beadboard) Unlike the uniform cell matrix of extruded polystyrene, molded expanded polystyrene insulation board is fabricated by pre-expanding small beads of polystyrene resin with heat (usually steam). The beads are then aged and poured into mold where they are again heated to give a final expansion. During the final expansion, the beads fill the mold, become sticky and bond together to form a billet whose structure is a porous matrix of styrene beads and air spaces. The billets are then cut into board stock of various thicknesses.

Each individual foam bead consists of closed cells similar to extruded polystyrene (EPS). The difference is that in beadboard there are spaces between the expanded beads which are open to the air. Thus while much of the board is closed cell structure, a sizeable portion of it is open air spaces which are readily filled with water. The ratio of the percentages of open air spaces to closed cell beads varies with the molding conditions and may be different from fabricator to fabricator and even from batch to batch. It is often deliberately controlled at different densities to obtain certain desired properties.

This insulation easily absorbs a sizeable percentage of water between the beads. However, since the openings between beads are larger than the cells of open cell foam, beadboard is quicker to drain and dry when the source of the water is removed. No information is available concerning whether the closed cells in the individual beads pick up water, but it is likely that they are as water resistant as extruded polystyrene (EPS). All the samples measured in this study were moisturized in the laboratory. Figure 5 shows the thermal conductivity of molded polystyrene beadboard insulation at moisture contents from 0% to 10%.

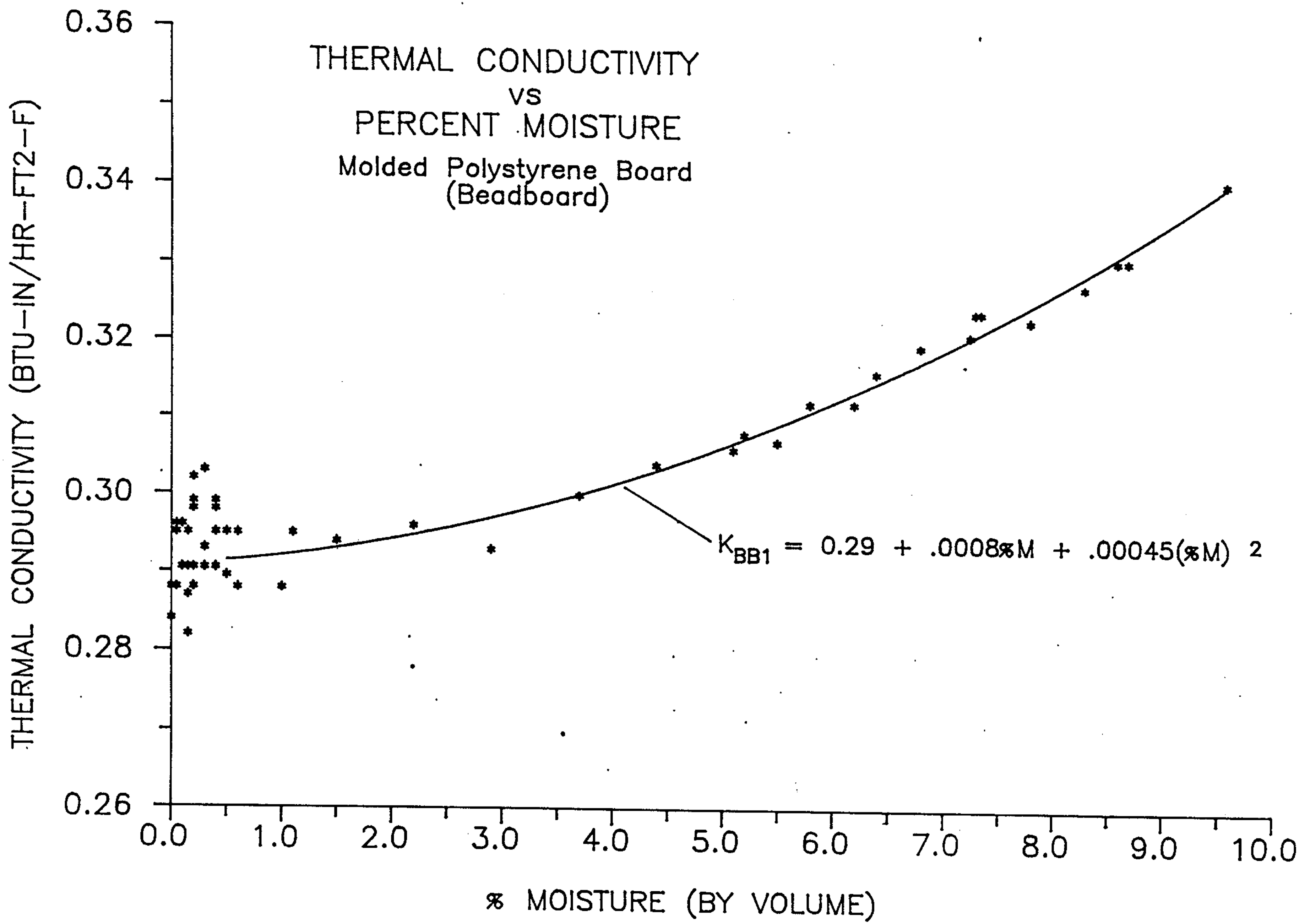

FIG 5.— Thermal Conductivity vs Percent Moisture of Molded Polystyrene Board

The following relationship can be used to predict the thermal conductivity of wet molded polystyrene beadboard insulation for moisture contents below 1%:

$$K_{BB} = K_o \exp(0.017\%M) \qquad 0< \%M <1 \qquad (6)$$

Where:
K_{BB} is the thermal conductivity (BTU-in/hr-ft^2-°F), and
K_o is the dry thermal conductivity

The scatter of data points of nearly dry insulation is probably due to the variability in density of the product which results in wide differences in the amount of air spaces in the fabricated board.

It is interesting to note that the open cell portion of this insulation does not show the marked increase in thermal conductivity that is so obviously present in other open-cell insulations. The higher initial thermal conductivity suggests that the porous nature of the material may allow considerable circulation of air. Filling the voids with water, which is more viscous and thus has lower convective activity, may nearly balance its higher heat loss by conduction.

It should be noted that molding techniques vary widely, and therefore the percentage of open spaces between beads will also vary. Better molding and quality control can produce beadboard insulation which is claimed to approach the permeability and therefore moisture resistance of EPS. However, the samples taken for this study were obtained from the local market and were found to vary significantly in moisture resistance. None of these samples approached the moisture resistance of EPS.

Slightly better accuracy can be obtained for moisture contents above 0.5% by the following relationship:

$$K_{BB1} = 0.291 + 0.0008\%M + 0.00045(\%M)^2 \qquad 0.5< \%M <10 \qquad (7)$$

Where:
K_{BB1} is the thermal conductivity (BTU-in/hr-ft^2-°F)

3.5 Conclusions from the Insulation Studies.

While much work remains to be done, the relationships presented should allow designers in cold regions to predict the effect of moisture intrusion into insulation systems. The accuracy of these relationships should be within engineering needs. Prediction of actual in-service moisture gains in insulation systems will be addressed in section 4 of this report.

The effect of moisture on the partially open-cell structure of polyurethane insulation is approximately 40% higher than on the closed-cell structure of either EPS or molded polystyrene foam. This in addition to the faster absorption of water by polyurethane and polyisocyanurate makes it important to allow for moisture degradation when designing with these materials.

Fiberglass batt suffers from moisture intrusion more than any of the foam insulations, its thermal conductivity increasing nearly 300% by the time it has accumulated 3% moisture. This gives renewed support for good vapor barrier design and especially for proper installation procedures.

4.0 Moisture in Insulation Systems Installed in Alaska

4.1 Vapor Barriers

It has long been recognized that moisture from the air condenses and accumulates inside wall cavities of structures. The detrimental effect on the thermal performance of insulation systems of buildings which have collected excess moisture has been the subject of several previous studies. Dechow and Epstein (1979), Tobiasson et al.(1984), McFadden (1988), and Joy (1959) have all addressed this problem. Builders have gradually acknowledged the problem and are now installing vapor barriers to reduce the influx of moisture into the insulation. However, specific information on the success of conventional vapor barrier practice is very limited. One of the purposes of this study was to determine how much moisture inhabits the insulation of buildings. We were specifically interested in high latitude localities such as interior Alaska where moisture accumulation time during the winter is considerably longer than the drying time during the short summer.

Two developments have brought the question of moisture accumulation in insulation systems to the mind of many building specialists. The first is that over the past decade, vapor barrier installation practice by the construction industry has improved significantly. Contractors and craftsmen have finally become convinced of the benefits of vapor barriers. They now realize that proper installation procedures are very important in achieving a successful vapor barrier. Proper installation includes attention to the details of placement, careful sealing around all openings and the need to avoid compromising the integrity of the vapor barrier membrane by unnecessary penetrations. Properly trained craftsmen no longer make a large slash in the vapor barrier film for electrical and plumbing access. In quality construction a carefully cut and resealed penetration is now more often the norm.

The second development is the somewhat more recent practice of applying retrofit insulation to older existing buildings which have insulation systems that are not adequate for today's energy costs. Most of these buildings have vapor barriers already installed. Many of the older vapor barriers are not up to today's standards.

One of the concerns in this regard is that when insulation is retrofit on the outside of these older buildings, the original insulation is sandwiched between an inside vapor barrier and the new insulation which may itself be a vapor barrier. In some cases, when closed-cell foam insulation is applied in the retrofit over an older building with a poor or deteriorated vapor barrier, the new insulation may be more efficient at stopping the passage of moisture than the older vapor barrier. In cold regions, the interior of the structure is the major source of moisture. This could create a moisture build-up in the old insulation which would lower its thermal conductivity and counteract much of the advantage gained in the addition of the new retrofit insulation.

4.2 Approach

The primary purpose of this portion of the study was to establish an initial data base of information on the present state of moisture intrusion in homes in the north. To achieve the objective, a non-destructive method of moisture measurement within a wall was developed (Wandover 1988). The non-destructive nature of the procedure helped convince home owners to volunteer their homes for measurement of the moisture in the exterior walls. It should be noted that although the technique was essentially non-destructive, it did require the drilling of two 3/16" diameter holes in the outside siding of the house. The holes were caulked shut and painted after the measurements were complete. Some home owners did not object to the holes, but on the other hand, many were not willing to volunteer their homes for the experiment. In all, 39 structures were studied and the resulting data allowed some preliminary conclusions.

4.3 Moisture Measurement in the Field

As discussed above, the method developed to collect moisture data had to be basically non-intrusive. Access to the interior of the walls of homes and buildings would be very difficult, not to mention time consuming and expensive. There are only a very limited number of owners who are willing to allow the walls of their structures to be torn open to collect moisture data. Besides, collecting samples in this manner would soon exhaust the project's budget and the number of samples would be too limited to be statistically significant. Not only that, the process of opening the wall would risk significantly changing the moisture content present and yield a flawed study. A remote or at least a semi-remote method was needed both for accuracy and economy.

Several possibilities were considered. Commercially available hygrometer probes could have been used, but they all required access holes in the wall that were too large to be practical. Circulation of dry air throughout the wall cavity using small holes at the bottom and top of the wall was considered. Moisture content of the air could then be measured before and after, and the moisture content within the wall could be calculated. This was determined to be too time consuming and thus too costly.

The technique chosen used the technology of Time Domain Reflectometry (TDR). It proved to be reasonably fast, required very limited intrusion into the wall cavity, and appeared to yield the required accuracy (Wandover 1987).

The measurement technique required two 3/16" holes with a one-inch space between to be drilled into the outer siding of the wall. The TDR probes were inserted into the walls through the holes and the instrument was triggered for a 10 second trace. Figure 1 shows a sample trace.

The small holes were easily caulked shut. Several locations on the structure could be measured by a two-person team in a short time. Although the holes were caulked shut as a courtesy to the cooperating owners, this was neither necessary or really desirable in this area. The holes were too small to allow insects or animal pests access to the interior of the wall. The holes would, on the other hand, have allowed moisture inside the wall a slightly better opportunity to escape, and the wall could have dried out better during the summer. If a wall were accumulating moisture due to a poor vapor barrier, or any other reason for that matter, drilling of many such small holes in the outside siding would probably provide one of the better corrective actions available, short of removing the outside siding altogether.

4.4 Scope of the Field Study

Samples were collected from sites in interior Alaska near Fairbanks and Delta Junction. The Fairbanks location is approximately 100 miles south of the Arctic Circle. Elevation varies from 430 to 2000 ft. Weather conditions are classified as continental. Temperature range from summer to winter is large (+90°F to -65°F), and the mean annual temperature is 25.4°F. The long winter and relatively short summer provide ideal conditions for moisture accumulation. The short summer is not considered long enough by many engineers to allow sufficient drying, particularly on northerly-facing walls.

This area is typical of many localities in the north, but perhaps on the more severe side of average.

The structures tested were predominantly one and two story homes and apartments ranging from less than one to approximately 35 years old. Some had been retrofit with additional insulation. The predominant original insulation was fiberglass batt, but plastic foams were the most common retrofit insulations.

Samples were collected during two periods. Late spring, soon after the air temperature had stabilized above freezing, (May in interior Alaska) was chosen to represent the extreme time for moisture buildup. Early fall before freezing weather had commenced was chosen to evaluate the effect of summer drying on those walls that contained significant amounts of moisture.

One of the limitations of the Time Domain technique was that it required the moisture in the wall to be in the liquid or vapor state. The dielectric constant of ice is too close to that of the insulation to allow accurate moisture determination. This limited all field work to time periods when the outside air temperature had been above freezing for at least two days. This ensured that the insulation moisture would have sufficient time to return to the liquid state.

4.5 Field Sampling

Measurements of moisture content within walls required two 3/16" diameter holes to be drilled through the exterior siding and underlying sheeting. This allowed the TDR probes to be inserted into the insulation in the stud space. The holes were spaced one inch apart by use of a drilling jig. In this manner the spacing between the probes was the same for all measurements.

The TDR was battery operated and portable, allowing measurements to be made at any location in the field without requiring a power source at the site.

To get volunteers to offer their buildings and homes to be used for the study required a number of approaches. Associates and colleagues were approached first, then an advertisement describing the study and its goals was run in a local newspaper. The ad promised to report to the owner the moisture condition of his insulation. Finally the local office of the Corp of Engineers was contacted. They provided several buildings both new and old from which much valuable data was obtained. A total of 221 samples were taken throughout the Fairbanks and Delta Junction localities in interior Alaska. This provided a wide variety of site settings from north through south-facing slopes and valley bottoms to hilltops. Both new and older construction and everything in between. Building uses ranged from residential to business to maintenance buildings and three aircraft hangars. Although the total number of samples is relatively small, it is enough to be statistically significant for most of the comparisons of interest.

Obviously, economics played an important part in the number of samples taken. When the cost of advertising, travel time to and from the site, sampling, restoration work after sampling, and analysis of each sample were all summed, the cost of each sample became significant. All structures offered were sampled, and of course multiple samples were taken at every site. This allowed the variables at each location to be compared to determine their influence on the moisture content of the insulation.

4.6 Discussion of Results

4.6.1 Overall Averages Moisture content of the insulations studied ranged from zero to a high of 6.5% (by volume). While this high a moisture content is cause for alarm, the overall average for all samples was only 1.4%. This is not alarmingly high. In section three of this report it was found that the thermal conductivity of fiberglass insulation did not increase dramatically until a moisture content of 2% was attained. At that moisture content, the conductivity increased sporadically through a transition region until at around 3% moisture it stabilized at a higher value which was over three times as high as dry fiberglass insulation. As moisture content increased above 3%, the thermal conductivity continued to increase, but more slowly. The overall average percent moisture of the 211 samples in this data base is below the 2% transition zone. If only the samples collected at the end of winter when moisture contents should be the highest are considered the overall average is 1.4%.

4.6.2 Direction of Exposure A closer analysis, however, shows some areas for concern. If the samples are separated according to the direction the walls face (i.e. north, south, east, west etc.) an interesting surprise is found. It might be expected that the maximum moisture would be found in the north-facing walls. These walls are subject to direct sunlight only during early morning and late evening hours, and only for a short period during the weeks surrounding June 21st (the summer solstice). For this reason they might have less chance to dry out during the summer. Thus more moisture could be expected to accumulate over time. This did not in fact turn out to be the case. In the overall data base, the moisture content of the south-facing walls was considerably higher than of those facing any of the other directions. The overall average moisture content of south-facing walls was 2.3%. This is well into the transition zone to higher thermal conductivities

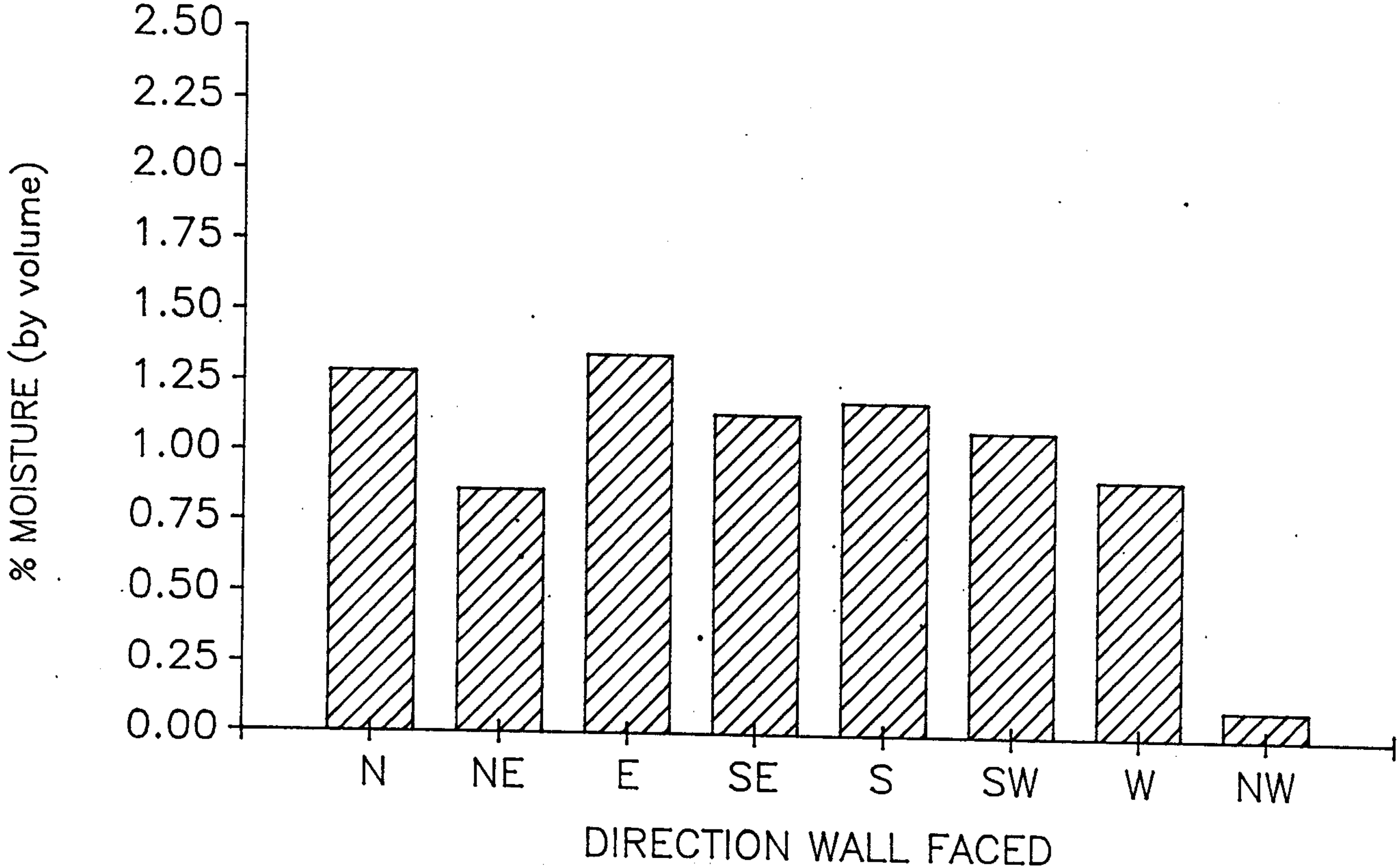

FIG. 6 Moisture Content vs Direction Walls Faced

for fiberglass (McFadden 1988). Moistures of this magnitude can increase the thermal conductivity and the resulting heat losses by up to 300%. This, however, is a statistical anomaly that results from the skewing effect of several samples which were taken from three aircraft hangar buildings on Ft. Wainwright. The sixteen samples from these buildings were all abnormally high, averaging 4.32%, and they were all taken from south walls. No samples from walls of these building which faced other directions were available to balance the data base. When these samples are removed from the data base, the south-facing walls have an average moisture content of 1.3%. North-facing walls produced 49 samples and the average moisture content of these walls was 1.4%.

As can be seen in Figure 6 the difference in moisture content of walls facing different directions is too small to be significant. Apparently north-facing walls are not at more risk that those facing other directions. Likewise, the data suggests that whatever the direction of exposure of the wall this factor does not have a significant influence on the amount of moisture accumulation.

<u>4.6.3 Summer Drying Effect</u> Several sites were selected to be resampled in September to asses the drying effect of the summer. In this more limited portion of the data base, the average south-facing wall had a moisture content of 1.54% in the spring, while in the fall it had dropped to 0.54%, a 65% decrease. The average north wall in this group contained 3.5% moisture. By fall this value had dropped to 0.62%. This is a encouraging decrease of 82%. It must be remembered that the sample size of the summer drying experiment was small and can only be considered an indication of drying effect.

While averages may present a picture of the condition of insulation in general, individual values are more informative when considering the potential problems that moisture can create. Maximum moisture content in the walls sampled was as high as 6.5%. Moisture contents this high were found in both north and south-facing walls. Interestingly, these samples both came from military-owned buildings, one a hangar on Ft. Wainwright, the other a residence in Ft. Greely 100 miles away. The residence was resampled in the fall as part of the summer drying experiment. The moisture had dropped to 4.4%, a 32% decrease but still very wet. This building had metal siding which may at least partially account for the poor summer drying effect. The hangar was in excess of 25 years old, while the residence was new, less than a year old. Moisture contents this high are well into the higher thermal conductivity range for all types of insulation included in section three of this report. Clearly, walls with this much moisture need remedial action, while those with less than 2% moisture have little increase

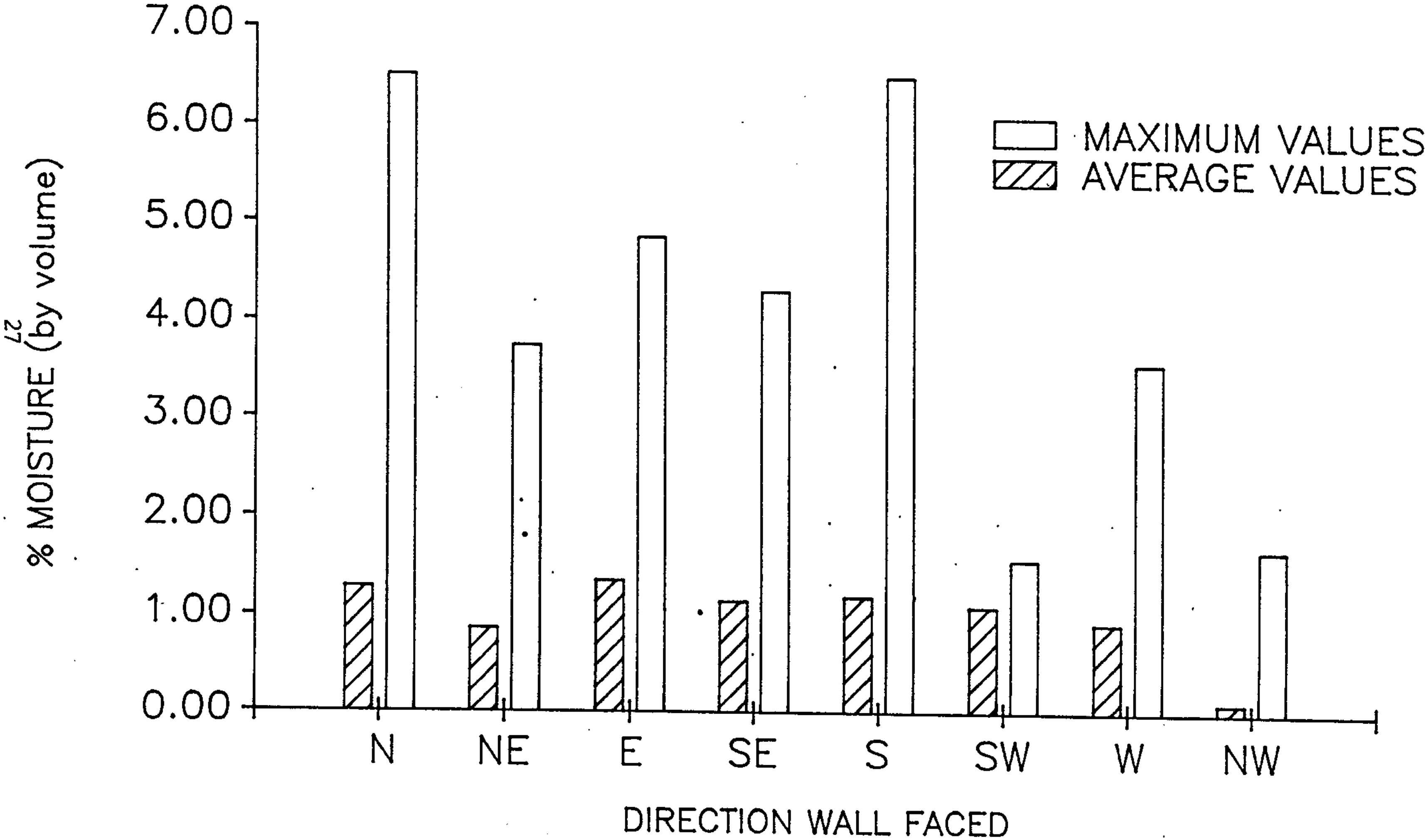

FIG. 7 Moisture Accumulation in Walls

in their thermal conductivity and may dry out during the summer. As seen in Figure 7 high moisture contents (over 3%) were found in walls facing all directions except northwest and southwest. Although the overall average moisture content of insulation systems was below the high thermal conductivity range, this is little comfort for the owner of a structure whose insulation has lost much of its thermal resistance due to high moisture. There were a sizeable number of structures that fell into this category. Remedial action for these structures would be very cost effective. Under these conditions, the owner pays for the remedial action in higher energy costs anyway.

4.6.4 Moisture Accumulation Over the Years One of the sample structures was more than 25 years old. This was a residence which had frame construction with fiberglass insulation and 1960 vapor barrier technology. This sample should give an indication of the amount of buildup that can occur over the years. In the spring the moisture contents of the walls in this structure varied from a low value of 0.3% to a high value of 2.4%. The average for nine samples taken on this building was 1.5%. During the summer the drying effect lowered the overall average to 0.7%, a 55% decrease.

The question of when an insulation system becomes a candidate for remedial action and what should be the nature of that action still remains. One consideration is the amount of drying that takes place over a typical summer. Unfortunately this study did not extend over a sufficient time period to obtain any statistically valid average drying data as a function of the climate. Nevertheless, some information can be obtained from the available data. Figure 8 shows the drying that was measured at several sample sites during the summer of 1986. This was a typical warm summer in interior Alaska where the samples were taken. Average daily temperature for Fairbanks during June, July, and August was 60°F with a high temperature of 91°F in July. A total of 2613 degree-Fahrenheit days of thawing were accumulated. The daily average relative humidity varied between 35% and 86% and the daily average windspeed varied between 6 and 7.5 mph during the period (AEIDC 1988).

North-facing walls showed the greatest drying effect (an 82% decrease in moisture). North-facing walls only receive direct sunlight at this latitude during early morning and late evening; the direct solar input is therefore minimal. The overall warmer air temperatures were probably the most significant factor in drying of these walls. South-facing walls showed a 65% drop in moisture. These walls had the largest moisture source and the greatest exposure to the sun to drive the moisture out. This suggests that the direct solar input was not as important as the warmer summer

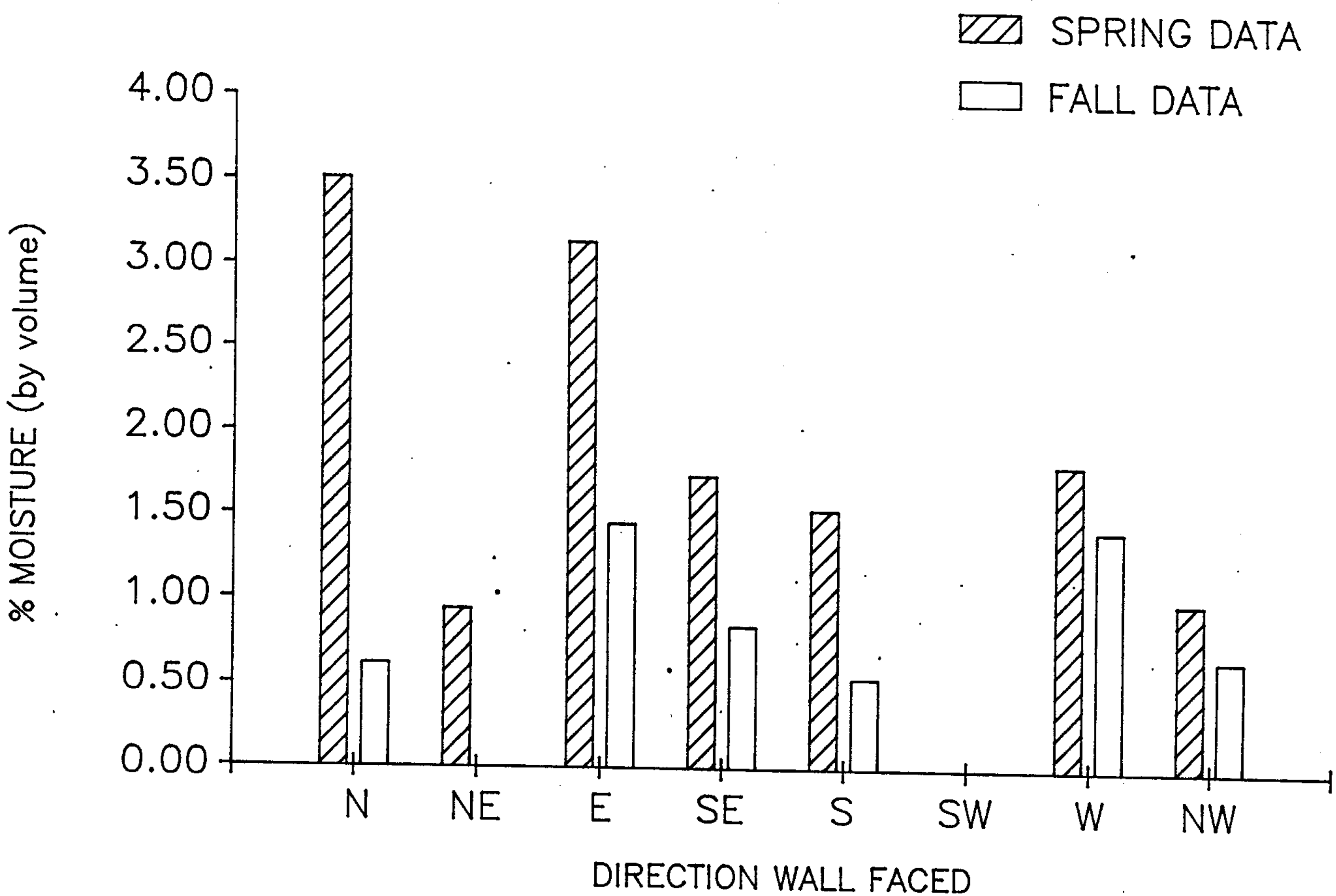

FIG.. 8 Moisture Content in the Spring and Fall temperatures. This may be partially due to the solar altitude at this latitude. During midday the sun is high in the sky and strikes the vertical south wall at an angle which has a very small perpendicular component to the wall, whereas (at this latitude) the sun's altitude is much lower during the morning and evening so that it strikes north, east and west walls at an angle much closer to 90 degrees. However, by the time of day the sun strikes the north-facing walls, it has lost most of its intensity. The loss of intensity is somewhat offset by the better angle of incidence. The direct solar input then is not all that much different on walls which face east and west than on south-facing walls.

If summer were longer (and thus winter shorter) as in a more southerly latitude, the drying effect might well be sufficient to remove all of the water. At latitudes such as Fairbanks (64° N) or in coastal areas where the summers are cooler and damper, summer drying does not appear to be sufficient to restore the insulation to its original dryness and low thermal conductivity. Rehabilitation of the insulation by artificial drying may be economically justified in these areas.

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APPENDIX

Units

To change the English measurements of thermal conductivity to SI units, multiply BTU-IN/HR-FT^2-F by 0.144 to get W/M-K.