FIELD AND LABORATORY STUDIES OF THE THERMAL RESISTANCE OF MOIST BUILDING INSULATION SYSTEMS

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ABSTRACT

Fiberglass and cellulose insulation materials are commonly spray-applied onto the interior of building envelope components. The interior surfaces of these systems are generally exposed to the inside air. Water vapor in the air can migrate into the insulation and condense in regions of the insulation where the temperature is below the dew point. The effect of this condensation on the thermal resistance of these insulation systems has been studied with both laboratory and field methods. In the laboratory, transient thermal resistance and moisture gain of horizontal, 10-in-square (250-mm), 2-in-thick (50-mm) specimens have been measured. The upper metal substrate surfaces of the specimens were maintained at a constant temperature of 50 F (10°C), and the bottom free surfaces were exposed to a flow of air at 86 F (30°C) and 10% to 70% relative humidities. Moisture gain was measured by periodic weighing of the specimens, and the thermal resistance was calculated from thermocouple and heat-flow sensor readings. The insulation materials gained as much as 10% moisture by volume when exposed to air at 70% relative humidity; much lower moisture gains were observed at lower air humidity levels. A computer simulation was developed to model the moisture behavior and to predict the moisture gain of insulation. The process of vapor and liquid flow through the insulation contributed significantly to the effective thermal conductivity. Field measurements of the thermal resistances were made on horizontal 4-ft-square (1.2-m), 2-in-thick (50 mm) specimens. The corrugated metal substrates were exposed to outdoor ambient conditions, while the bottom free insulation surfaces were exposed to a steady flow of indoor air. The weekly averaged relative humidity of the indoor air varied from 20% to 60% during the year. Field measurements were made of the thermal resistance of the systems under both summer and winter conditions. No significant moisture contribution to the thermal conductivity was noted. The relevance of the laboratory results to the field results is also discussed.

INTRODUCTION

The presence of moisture in insulation systems can produce a degradation of the thermal performance of these systems. In order to quantify these moisture effects, laboratory and field testing methods have used to evaluate fiberglass and cellulose spray-applied insulation systems. .Such spray-applied systems have many desirable features. They are well suited to retrofit applications; they provide complete coverage for building components alleviating thermal bridging; and they can be applied conveniently and economically. Interior spray-applied systems are protected on their outer surfaces by the nearly impermeable building envelope, but their inner surfaces are generally exposed to the inside air. As a vapor retarder is seldom applied to the inner surfaces of the systems, water vapor from the inside air diffuses into the insulation and condenses in regions of the insulation where the temperature is below the dew point. Such condensation is particularly severe under conditions of high inside humidity and low outside temperature. The presence of free water in these systems produces a lowering of their thermal resistance and may possibly have an adverse effect on their mechanical properties.

The effects of moisture on the thermal properties of these systems have been studied using both laboratory and field methods. The laboratory tests were designed to determine the thermal performance of spray-applied specimens while the specimens were maintained under controlled conditions; their free surfaces were exposed to air at 86 F (30°C) and 10% to 70% relative

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humidity (RH), while their substrate surfaces were maintained at 50 F ($10^{\circ}C$). Field measurements on similar systems were made under winter conditions, similar to the laboratory test conditions, and also under summer conditions. The free surfaces of the insulation systems were exposed to air at normal indoor temperature and hymidity, and the substrate surfaces were exposed to the typical outdoor conditions of the Philadelphia area. The relevance of the laboratory tests for predicting field performance is evaluated by the comparison of the laboratory and field results. In addition, a computer program was developed to simulate the moisture behavior demonstrated by the laboratory data. Once refined, the simulation will be used to preduct the moisture gain and effective thermal conductivity of insulation under a variety of environmental conditons.

LITERATURE SURVEY

Early experimental investigations of the effects of moisture on the thermal conductivity of fibrous insulation materials were made by Jesperson (1953) and Joy (1957). According to their studies, the thermal conductivity of glass fiber insulation was found to increase by more than 100% (Jesperson 1953) and 200% (Joy 1957) relative to the dry value for moisture contents of only 2% by volume. This rapid increase in conductivity can probably be explained by water vapor movement from the hot side to the cold side of the material and to liquid-vapor movement from the hot side to the cold side of the material and to liquid-vapor phase changes within the material. The thermal conductivity is, therefore, not only a property of the moist material, but is also dependent on both the moisture and temperature distributions in the material. This interpretation has been provided by Langlais et al. (1983) and Sandberg (1984) who have performed extensive experimental studies of moisture effects on the heat transfer through fibrous insulation materials. In the former study 1-in-thick (25-mm) samples of mineral fiberboard were sprayed on one side with water, sealed in polyethylene bags, and placed in a guarded hot plate apparatus with the wetted surfaces on the hot side. The thermal conductivity was then determined as a function of time. Their results showed a sharp increase in conductivity in the first two hours and a quasi-steady-state value at about five hours. This value was not a true steady-state value since the conductivity continued to slowly decrease with time. The magnitude of the quasi-steady-state conductivity increased rapidly as the moisture content was increased from 0 to 3% by volume. When the wetted surface was placed on the cold side, however, there was almost no change in conductivity with time and moisture content.

Sandberg also made measurements with a guarded hot-plate apparatus. The samples consisted of four 0.9-in-thick (23-mm) fiberboard samples with thermocouples placed between the boards. Between the hot plate and the top board a cloth with a known amount of water was placed. A dry cloth was placed between the cold plate and the bottom board. A high apparent thermal conductivity was observed during the first 24 hours of the test after which the thermal conductivity decreased by about 50% to a steady-state value after about 36 hours. This steady-state value was very close to the dry value and the moisture added to the hot side was found to have migrated completely to the cold side of the insulation. A computer program was used to simulate the same conditions and the heat flow was calculated as a sum of three terms: (1)heat flow in a moist insulation material where thereis no movement of the moisture, (2) heat transfer by moisture flow due to the sensible heat of the moisture, and (3) heat transfer due to phase changes. The experimental results and the computer simulation both indicated that the first heat flow component was nearly the same in moist materials as in dry materials, that the second heat flow component was negligible, and that the third component of heat flow was the cause of the high initial thermal conductivity. Additional experimental studies on deliberately wetted fibrous insulation materials have been reported by Tobiasson and Ricard (1979) Thomas et al. (1983) and Bomberg and Shirtliffe (1978). Also Knab et al. (1980) exposed fiberglass buildup roofing insulation systems to extreme conditions of 100 F ($38^{\circ}C$), 100% RH on the lower surfaces, and 86 F ($10^{\circ}C$), 25% RH on the upper surfaces. All of these studies noted initially high thermal conductivity values due to moisture redistribution but steady-state values only moderately higher than those obtained for dry insulation materials. The steady state values of the thermal conductance were found to increase with increasing moisture content, but the increases were much lower than those reported by Jespersen (1953) and Joy (1957).

In the above experimental studies, the boundary conditions were fixed; whereas under actual operating conditions, the temperature and moisture conditions at the boundaries are always changing. Measurements of the moisture effects on the thermal conductivity of fibrous insulation materials under these circumstances have been reported by Powell and Robinson (1971) Hedlin (1983) Tye and Spinney (1979) and Benner et al. (1984). In the Powell and Robinson study, the samples were placed in a laboratory test chamber where one surface was exposed to normal indoor conditions and the other to simulated diurnal cycles for both winter and summer. The heat flows were measured by heat flow sensors placed on each sample. The results showed only slight increases in thermal conductivity during the winter conditions but large increases during the summer. This was due to the contribution of water vapor migration to the heat transfer, as the thermal gradient would reverse direction from day to night during the summer. During the winter conditions, the temperature gradient did not change direction and the moisture would accumulate on the cold side. Hedlin sealed samples of wetted roofing insulation in plastic and then placed them in a test house where the temperatures and heat flows for each sample were moinitored over a 7.5 to 8-month period. The data were more difficult to analyze than those obtained under steady-state conditions, but in general the results indicated similar moisture effects on the thermal conductivity of the specimens. Tye and Spinney studied the effect of moisture on loose-fill cellulose under both steady-state and dynamic conditions. The cellulose in ceiling and wall constructions was subjected to temperature and humidity gradients over a 57-day period. The samples showed little reduction in thermal resistance, especially when the cyclic conditions were used. Periodic field measurements of the thermal resistance of spray-applied fibrous insulation systems by Benner et al. also showed no appreciable moisture effects under either summer or winter conditions.

The theory for describing the behavior of moisture in a porous or fibrous media has been outlined by a number of authors over the last 50 years. Probably the earliest and best known work was done by the Soviet scientist A.A. Luikov (1966), and his mechanistic approach is used as the basis of most of the theories currently in use. The first major revisions to Luikov's theory were made by Philip and DeVries (1957). Using the simple diffusion theory (Fick's law) developed by Luikov, they broke the potential term into temperature and liquid water fraction gradients and introduced a hydraulic term for liquid movement. Haramathy (1969) and Thomas et al. (1983) developed theories that assumed all moisture movement occurs in the vapor phase. This is an implication of the evaporation-condensation theory, which states that liquid water evaporates at the higher temperature and, after diffusing as a vapor, condenses in the cooler region. This does not take into account any liquid movement by gravitational, hydraulic, or diffusional forces. The lumped parameter theory that served as the starting point for the model in this research was developed by Eckert and Faghri (1980). But, spray-applied insulation systems have a number of aspects that tend to make their modeling unique. In this system, one boundary is impermeable to both vapor and liquid movement and the other is open to air. Vapor diffuses freely into the insulation where it condenses. As the liquid moisture increases, it begins to migrate toward the open surface where it evaporates. This combination of two opposing boundary conditions, continuous condensation and evaporation, and the presense of both vapor and liquid movement is not incorporated into any existing theories and had to be developed by expansion of the theory of Eckert and Faghri.

MODEL DEVELOPMENT

A lumped parameter approach was used for the development of the model. The driving forces for vapor and liquid fluxes are assumed to be the concentration gradients of the vapor and liquid phases. Using a few simplifying assumptions such as constant coefficients, the equation for the conservation of mass (water) for the volume elements can be written as

$$\partial C_1/\partial \tau = D_v \nabla^2 C_v + D_1 \nabla^2 C_1 \qquad (1)$$

The first term on the right is the divergence of the vapor flux, and the second term is the divergence of the liquid flux. The effect of gravity is incorporated into the liquid diffusivity term. The accumulation in the vapor phase is neglected, since this is negligible when compared to the liquid phase accumulation. The plate/insulation boundary is assumed to be impenetrable to mass transfer (zero mass flux) but not to heat transfer. At the air/insulation boundary, it is assumed that there is no resistance to mass transfer. Fiberglass and cellulose tend to adsorb a small amount of moisture before condensation begins to occur. Using equilibrium moisture content data, this adsorbed moisture was incorporated into the moisture accumulation. Since condensation was occurring inside the specimens, it was necessary to determine the saturated vapor pressure at each point inside the sample as a function of temperature. This was done by using a mathematical model of the psychrometric chart. Once the temperature was known, the saturation concentration in the vapor phase could be calculated. In addition, as the liquid moisture moves toward the open surface, the moisture begins to vaporize which contributes to the concentration in the vapor phase and decreases the accumulation. This mass transfer flux from the liquid to the vapor phase is defined by the mass transfer coefficient times the difference between the saturated vapor pressure and the actual vapor pressure. Thus, if the air in the vapor space is saturated, ther is no evaporation. The mass transfer coefficient is much greater on the open surface. By incorporating this vapor diffussion, condensation, liquid movement, evaporation, and accumulation into a finite difference model, it was possible to model the moisture behavior.

Obviously, to properly model the moisture behavior, it is essential that the heat transfer characteristics also be included. In a manner similar to that for the mass conservation, the heat balance can be written as

$$\partial T/\partial \tau = K_T \nabla(T \nabla C_1) \tag{2}$$

$$K_T = [\lambda + LD_1(\partial C_v/\partial T)]\rho_s c_s \tag{3}$$

$$K_1 = D_1 c_1/\rho_s c_s \tag{4}$$

The first term on the right side of Equation 2 is effective conduction (is the effective thermal conductivity) and the latent heat, released by phase changes, lumped together and defined by the parameter K_T. The second term is the convective heat transport due to the movement of liwuid water. The convective heat transport due to vapor is neglected, since sensible heat contribution of the vapor would be small compared to the other terms.

Three parameters can now be used to describe the system: the effective vapor diffusivity, D_v, the effective liquid diffusivity, D_I, and the mass transfer coefficient. After a preliminary parameter study, it was found that the liquid diffusivity was not an important factor, and the modeling became a matter of determining the effective vapor diffusivity and the mass transfer coefficient.

EXPERIMENTAL PROCEDURES

Sample Preparation

The insulation samples used in the laboratory experiments were spray-applied fiberglass (2.9 lb/ft^3, 46 kg/m^3) and cellulose (5.6 lb/ft^3, 89 kg/m^3). Using manufacturer's specifications, each insulation was sprayed into a 10x10x2 in. (250x250x50 mm) test chamber consisting of an aluminum base with four sides of clear plastic. The one surface left exposed was leveled to make a uniform surface. The insulation samples used in the field measurements were spray-applied to the undersides of corrugated galvanized steel decks mounted on expanded polystyrene (EPS) frames (frame/deck units). The samples were 4 ft. (1.22 m) square and nominally 2 in. (50 mm) thick with densities of 4.7 and 5.6 lb/ft^3 (75 and 90 kg/m^3) for the fiberglass and cellulose materials, respectively.

Laboratory Experiments

The test chambers were placed horizontally between water chambers maintained at a constant 50 R (10°C) and air chambers as shown in Figure 1. The air entering the air chamber was maintained at 86 F (30°C) and at a relative humidity (RH) of 10% to 70%. The outer plastic surfaces were surrounded by EPS insulation to reduce lateral heat flow. A humidity probe was used to monitor the humidity, and a proportional controller was used to maintain the temperature. Each water chamber had two heat flow sensors, one inch (25 mm) diameter, embedded in their lower plate, and a sheet of ethylene propylene diene monomer rubber (EPDM) was placed between the bottom of the water bath and the sample chamber. The heat flow sensors were calibrated by replacing the samples with a standard EPS specimen. To monitor the temperature distribution in the samples, five thermocouples were placed at various depths inside the test samples, five thermocouples were placed at various depths inside the test samples while they were being sprayed. The sensors, thermocouples, and probe were connected to a microcomputer that processed and recorded the data. The sensors were read every three minutes and average values for each 30-minute interval were recorded.

Prior to the start of the test run, the samples were dried by passing air of 10% RH into the air chambers. A constant weight was assumed to be the dry weight of the sample. During the test runs, the samples were quickly removed from the test assemblies, weighed, and returned to the test assemblies every 24 hours to determine moisture gain. After approximately 300 hours, the RH in the air chambers was lowered to 10% while the moisture loss, heat flows, and temperatures were mointored as before.

Field Experiments

The frame/deck units were tested initially inside the laboratory and were then assembled into outdoor modules and tested outside on an adjacent roof. A schematic diagram of the test configuration is shown in Figure 2. The metal decks are continuously exposed to the outdoor weather of the Philadelphia area, while laboratory air is continuously circulated underneath the insulated roof systems. The RH and temperature of the laboratory air and the outside air were continuously recorded with hygrothermographs. The thermal resistance values for the systems were measured periodically with the temperature-controlled test plate shown in Figure 2. Three heat-flow sensors are attached to the plate underneath a single sheet of EPDM lid is placed over the test plate, and the test plate is either heated or cooled to an equilibrium temperature. High and low temperature testing is typically performed during the summer and winter respectively so as not to alter unnecessarily the physical condition of the insulation samples. The upper corrugated deck temperatures, the lower insulation surface temperatures, and the heat flows from the three heat-flow sensors are recorded at half-hourly intervals for a three-hour period after equilibrium is achieved. The calibration of the sensors and the application of the test plate to nonuniform insulation samples has been described previously (Larson and Corneliussen 1983; Larson, 1985).

RESULTS

The moisture gains in volume percent for fiberglass and cellulose insulation materials are almost identical with the final gain for fiberglass and cellulose reaching 1.6% and 1.7% by volume, respectively. For air conditions of 50% and 70% RH, however, the moisture gain for the fiberglass increases to apparently maximum values of 5.0% and 8.5%, respectively, while over the same period the cellulose has gained about 7.7 and 9.6% by volume without reaching steady state. The exact distribution of the moisture could not be determined, but the temperature profiles seemed to indicate a uniform distribution. There was no moisture drippage from either sample. When the humidity was reduced to 10%, both insulations dry very quickly with the fiberglass losing its moisture somewhat more rapidly than the cellulose.

In Figure 5, the results of the computer simulation are compared to the experimental results for the fiberglass sample. The moisture content versus time for the first 300 hours are shown for all three humidities. At 30% RH, the simulation and the experimental results correspond almost exactly. At 50% RH, there is good correspondence during most of the run, but as the moisture content approached steady state, the simulation results were slightly higher. For the 70% run, the experimental data showed a greater moisture content during the first 220 hours than was predicted by the model and a sharper leveling off after that point.

The apparent thermal conductivities as a function of time (and therefore moisture content) are shown in Figures 6 and 7 for the fiberglass and cellulose materials, respectively. During the wetting phase of the experiments, the conductivities for both materials are essentially constant with time and moisture gain for the 30% RH run and increased by 30-40% for the 50% RH run. At 70% RH, the conductivity values increased for the first 120 hours and then slowly decreased with the apparent thermal conductivities of both insulation materials about 50-60% higher than their dry values. At the onset of drying, the apparent thermal conductivity is observed to decrease abruptly and then slowly increase as shown in Figures 6 and 7.

The results of the field experiments are summarized on Tables 1 and 2. Nine measurements were made on each insulation system over a period of two years. The insulation thicknesses in the two systems were measured at both the crests and the troughs of the substrate corrugations; both averages are shown on the tables. The thermal resistance values were calculated using the expression $R = f \ \Delta T/Q$, where $f = 1.12$ is a correction factor, ΔT is the average heat flow as calculated from the three heat flow sensors. The factor f is calculated from repeated calibrations as discussed previously (Philip and DeVries 1957). Using the average insulation thicknesses, the average apparent thermal conductivities of the fiberglass and cellulose specimens in the high temperature runs may be calculated to be 0.0223 and 0.0289 BTU/hr•ft•F (0.0386 and 0.0500 W/m•K), respectively, at average insulation temperatures of 104 F and 106 F (39.9°C and 41.3°C). The average conductivities in the low temperature runs for fiberglass and cellulose were 0.0205 and 0.0245 BTU/hr•ft•F (0.0355 and 0.0423 W/m•K), respectively, at average insulation temperatures of 41 F and 40 F (4.9°C and 4.4°C). No systematic variation of thermal resistance with time was noted.

The field tests were performed under relatively uncontrolled conditions, where the relative humidity and temperature of the air passing under the insulation systems vary diurnally as well as seasonally. This air comes form the laboratory, which is heated during the winter and cooled during the summer. The relative humidity of the air rises during outside rainy periods but, in general, shows only gradual day-to-day variation. On a seasonal basis the monthly average relative humidity of the inside air varied from a low of 22% in December 1983 to a high of 53% in June 1984; the humidity levels were not recorded when the first two test data of Table 1 for both the fiberglass and cellulose systems were acquired.

DISCUSSION

With air conditions of 86 F (30°C) and 10 to 30% RH and a plate temperature of 50 F (10°C), there will be very little bulk condensation (relative humidity equals 100%) occuring in the insulation samples. The magnitude of the moisture gain, however, indicates that capillary moisture condensation is occurring. This is not the case when the relative humidity of the air is raised to 50% and 70%. Bulk condensation then occurs inside of the insulation with increasing sample volumes on the cold side experiencing condensation as the moisture content increases. The moisture gain process takes place very slowly so that the laboratory results must be carefully analyzed in order to predict dynamic field behavior. The larger moisture contents and the longer equilibrium times for the cellulose are probably due to its higher density, 5.6 lb/ft^3 (89 kg/m^3) compared to 2.9 lb/ft^3 (46 kg/m^3) for fiberglass, and to the existence of micropores in the cellulosic fibers. Both conditions provide greater surface area per unit volume for the physical adsorption of moisture. The moisture gain results from this study cannot be directly compared with the previously cited studies for two main reasons: 1) the insulation materials studied previously were not spray-applied and 2) the boundary conditions were different. The only study that may be comparable is the work by Knab et al. (1980) where the samples were exposed to air conditions of 100 F (38°C) and 100% RH on one side and 50 F (10°C) and 25% RH on the other. For 2-in (50-mm) glass fiber insulation, the moisture gain after 300 hours was about 8% by volume, which is close to the value obtained in this study under the less stringent conditions of 86 F (30°C) and 70% RH. No data are available on spray-applied cellulose, but some results have been obtained with loose-fill cellulose, but some results have been obtained with loose-fill cellulose by Tye and Spinney (1979). In their study, where the insulation was exposed to air conditions of 75 F (24°C) and 40% RH on one side and 3 F (-16°C) on the other, the loose-fill cellulose showed a moisture gain of 10% by volume after 50 days, which is comparable to the moisture gains for the cellulose sample in this study.

Following Langlais et al. (1983) it is possible to calculate the moisture gain contribution to the apparent thermal conductivity as

$$\lambda_v = LJ_v/(\Delta T/d) \qquad (5)$$

where L is the latent heat of condensation for water, J_v is the mass flow rate of water vapor into the insulation, ΔT is the temperature difference, and d is the thickness. The results of this calculation are shown on Table 3. The initial moisture gain rate is calculated from the data shown in Figures 3 and 4 for the first 100 hours of each run and is used to calculate J_v and then λ_v. The experimentally determined water vapor contribution is obtained from Figures 6 and 7 as $\lambda - \lambda_{dry}$, where λ is the apparent thermal conductivity after 100 hours and λ_{dry} is the initial value. The calculated values are all higher than the experimental values (especially for 30% RH) but show the expected trends.

The experimental results differ from some previous works (Jesperson 1953; Joy 1957) that show a greater effect of moisture gain on the thermal conductivity and from others that show a lesser effect (Tobiasson and Ricard 1979; Knab et al. 1980; Tye and Spinney 1979), but the type of materials, boundary conditions, and method of measuring conductivity differ from earlier studies. In general, the higher thermal conductivity values were obtained under transient conditions, while the lower values were obtained under near equilibrium conditions. For glass fiber insulation materials, Tobiasson and Ricard (1979) and Knab et al. (1980) showed increases in thermal conductivity of 25% and 15%, respectively, for moisture gains of 5% by volume. Tye and Spinney (1979) found that the thermal conductivity of cellulose increased by only 15% for a moisture gain of 19%. In most of the earlier studies, the sample was wetted, then placed in an apparatus that subjected it to a thermal gradient to determine its thermal resistance. During the measurement, the moisture would redistribute through the sample in order to reach a new equilibrium state, and a relatively low conductivity was observed after the moisture had all transferred from the hot to the cold side. This movement of moisture by vapor diffusion has a profound effect on the apparent heat-transfer characteristics of the material (see "Literature Survey"). In the present experiments the moisture is continually provided on the hot side and an equilibrium condition of low conductivity is never reached. In the 30% RH run of the present study, the rates and steady-state values of moisture gain were small, and thus the contributions of the water-vapor migration and condensed water to the apparent conductivities were small. But, in the 50% and 70% RH runs, the moisture gain rates were two to six times that for the 30% RH conditions. Therefore, there was an appreciable increase in the apparent conductivities of the samples due to the vapor diffusion contribution.

During the drying phase, the opposite process occurs; the accumulated moisture vaporizes in the samples and diffuses toward the air chamber. As a result, there was a sharp decrease in the apparent thermal conductivity due to evaporative and convective heat transfer. Therefore, moisture redistribution has a significant effect on the heat transfer process. The manner in which moisture is gained and the conductivity is measured can play a major role in determining the values obtained for the thermal conductivities.

During the development of the computer model, it was assumed that most of the parameters, such as diffusivities and mass transfer coefficients, were not a function of moisture content and temperature. After a number of simulation runs, it was noted that there was good correspondence between the two data sets during most of the run but that the model moisture content did not level off in agreement with experimental values. This seemed to indicate that the assumption of constant parameters may not be valid. What may actually be occurring in the sample is the cross-sectional area for vapor diffussion and the surface area for condensation, and evaporation may be changing as the void spaces become filled with water. This would explain why there is good correspondence at the low humidity run, where there is low moisture content, and less correspondence as the humidity is increased. The program is still in the process of refinement but, once fully operational, should be a useful tool for the prediction of moisture gains and thermal degradation for a variety of conditions.

Only the low-temperature field test data can be compared to the laboratory data. During these tests the substrate sides of the insulation systems were maintained at low temperatures. The mean insulation temperatures were 40 F (4.7°C) in comparison with mean insulation temperatures of 68 F (20°C) for the laboratory experiments; the temperature conditions are therefore somewhat more severe than those in the laboratory environment. Although humidity levels during the cold field tests ranged from 24% to 53% RH, the air temperatues were lower than those employed in the laboratory experiments so that the water vapor concentrations were lower. Overall, no systematic variation of R-value with relative humidity was observed for the eight low temperature tests; the high humidity levels and low substrate temperatures during the 12/84 and 3/85 runs did not produce measurable decreases in the R-values. Higher indoor air humidity values were observed during the spring and summer, but the outdoor temperatures are higher during these periods. As a result, the field test data acquired to date do not show any influence of indoor air relative humidity.

The field test data are consistent with the laboratory test data. Indoor air moisture does not influence the thermal resistance of spray-applied fiberglass or cellulose insulation systems at the relative humidity levels and temperatures encountered in the field experiments. Higher humidity levels and lower substrate temperatures, of course, can produce a reduction of the thermal performance of these systems during periods where water vapor is migrating through the systems. The low-temperature field tests gave average apparent thermal conductivity values of 0.021 and 0.24 BTU/hr•ft•F (0.036 and 0.042 W/m•K) at 41 F and 40 F (4.9°C and 4.4°C) for fiberglass and cellulose, respectively, which are in reasonable accord with the laboratory average dry values of 0.018 and 0.026 BTU/hr•ft•F (0.031 and 0.045 W/m•K) at 68 F (20°C).

LIST OF SYMBOLS

c = Specific heat capacity, BTU/lb•F
C = Concentration, lb/ft^3
D = Diffusivity, ft^2/s
d = Thickness, ft
J = Mass flow rate, lb/hr•ft^2
K = Modified thermal diffusivity, ft^2/s
L = Latent heat of vaporization, BTU/lb
T = Temperature, F

Greek

λ = Thermal conductivity, BTU/hr•ft•F
ρ = Density, lb/ft^3
τ = Time, s

Subscripts

a = Dry air
l = Liquid
s = Insulation matrix

T = Thermal
v = Vapor

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TABLE 1

Field-Test Data for Fiberglass

Data	Temp. Diff. °C		Heat Flow W/m^2			Thermal Resistance[b] $m^2 \cdot K/W$ ($ft^2 \cdot hr \cdot F/BTU$)		Mean Temp. °C	Rel[c]. Hum.
	ΔT	Q_1	Q_2	Q_3	$\bar{Q}$	R		T_m	%
6/83	20.3	13.6	18.3	16.0	15.9	1.43	(8.12)	38.6	NM[e]
11/83	27.1	18.4	20.9	23.4	20.9	1.45	(8.22)	36.8	NM
12/83	17.0	10.4	13.4	13.0	12.3	1.56	(8.83)	8.0	24
3/84	14.6	8.3	9.5	9.9	9.2	1.77	(10.03)	5.5	24
6/84	26.2	17.9	21.7	20.2	19.9	1.47	(8.36)	41.9	56
9/84	30.6	20.9	22.5	24.0	22.4	1.53	(8.66)	42.2	64
12/84	19.4	13.2	16.7	14.9	14.9	1.46	(8.30)	1.9	50
2/85	12.5	7.7	9.2	9.2	8.7	1.61	(9.12)	4.2	50
6/85	28.2	18.3	24.5	24.9	21.9	1.44	(8.17)	40.2	53

Notes

a Insulation spray-applied to corrugated metal substrates with average minimum and maximum thicknesses of 5.1 and 6.2 cm respectively.

b R-value = 1.12 $\Delta T/\bar{Q}$

c Average inside air value during data acquistion

d Average inside air value during data acquisition.

e Not monitored

TABLE 2

Field-Test Data for Cellulose

Date	Temp. Diff. °C		Heat Flow W/m^2			Thermal Resistance[b] $m^2 \cdot K/W$ ($ft^2 \cdot hr \cdot F/BTU$)		Mean Temp. °C	Rel.[c] Hum.
	ΔT	Q_1	Q_2	Q_3	Q_4	R		T_m	%
7/83[d]	18.9	20.3	13.5	18.9	17.6	1.20	(6.84)	39.4	NM[e]
11/83	25.0	24.0	19.5	24.3	22.6	1.24	(7.04)	40.2	NM
12/83	16.8	12.8	11.2	13.7	12.6	1.50	(8.51)	7.0	25
3/84	22.2	16.5	14.3	18.1	16.3	1.53	(8.67)	6.2	32

6/84	26.2	23.2	18.2	23.7	21.7	1.35	(7.68)	41.8	55
9/84	29.0	27.7	22.6	27.6	26.0	1.25	(7.11)	43.6	63
12/84	20.7	18.0	13.7	17.3	16.3	1.42	(1.40)	1.4	53
2/85	10.7	7.7	6.3	8.1	7.4	1.62	(9.21)	3.1	40
6/85	30.1	25.4	19.9	27.9	24.4	1.38	(7.84)	41.4	67

Notes

a Insulation spray-applied to corrugated metal substrates with average minimum and maximum thicknesses of 5.6 and 7.2 cm respectively.

b R-value = $1.12\Delta T/\bar{Q}$

c Average inside air value during data acquisition.

d Measurement made inside laboratory.

e Not monitored

TABLE 3

Calculated and Experimental Water Vapor Contribution to the Apparent Thermal Conductivity

Description[a]	Initial Moisture Gain Rate[b]	Calculated Apparent Thermal Conductivity Contribution		Experimental Apparent Thermal Conductivity Contribution	
		10^{-3}W/m·K	(10^{-3}BTU/h·ft·F)	10^{-3}W/m·K	(10^{-3}BTU/h·ft·F)
		λ_v		$\lambda-\lambda_{dry}$	
FG-30% RH	0.21	7	(4)	2	(1)
FG-50% RH	0.47	15	(9)	12	(7)
FG-70% RH	1.29	42	(24)	26	(15)
CE-30% RH	0.25	8	(5)	3	(2)
CE-50% RH	0.60	20	(12)	14	(8)
CE-70% RH	1.20	39	(23)	29	(17)

Notes

a FG = fiberglass, CE = cellulose, RH = relative humidity

b Moisture gain rate during the first 100 hrs.

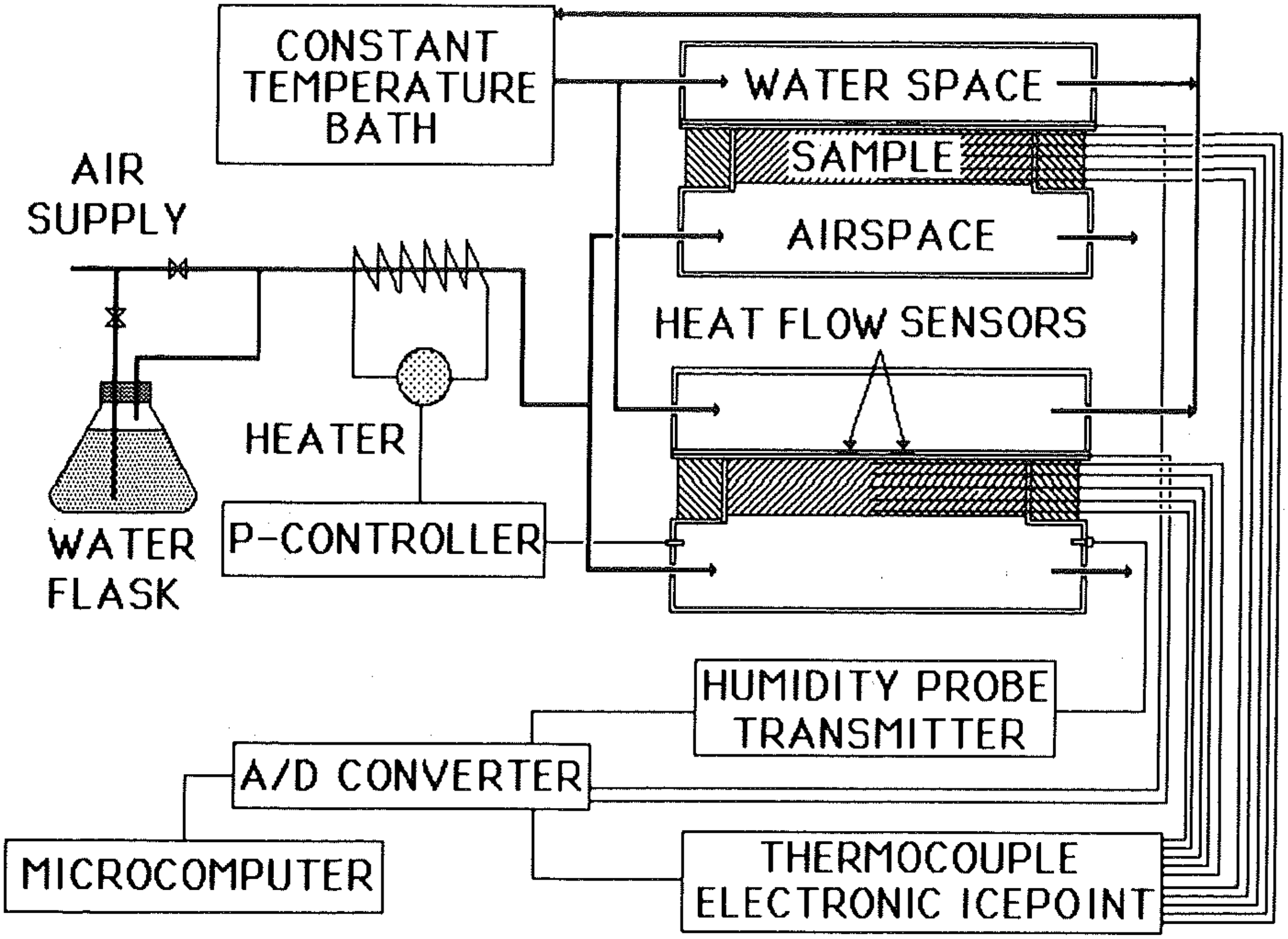

Figure 1. Laboratory experimental design

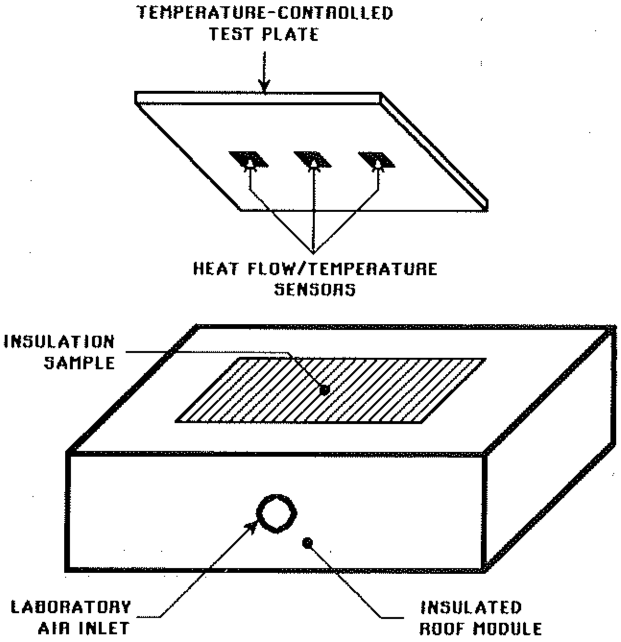

Figure 2. Schematic of field test configuration

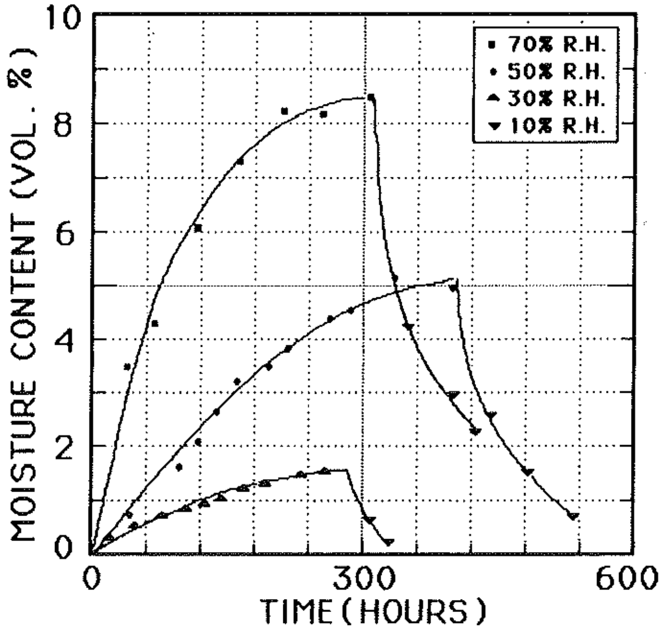

Figure 3. Moisture gain for spray-applied fiberglass with a 20°C temperature difference

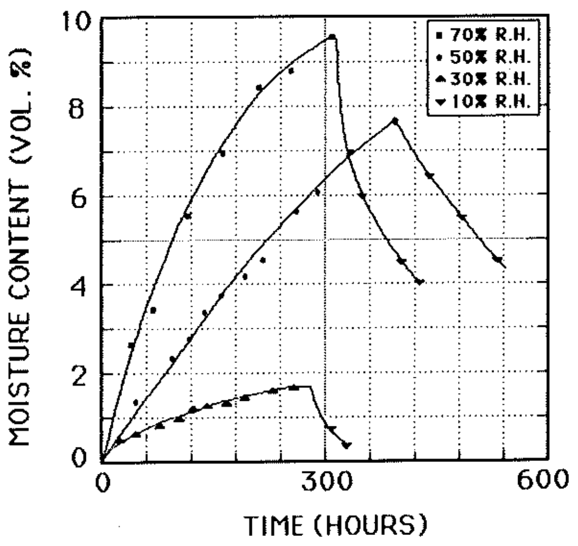

Figure 4. Moisture gain for spray-applied celluslose with a 20°C temperature difference

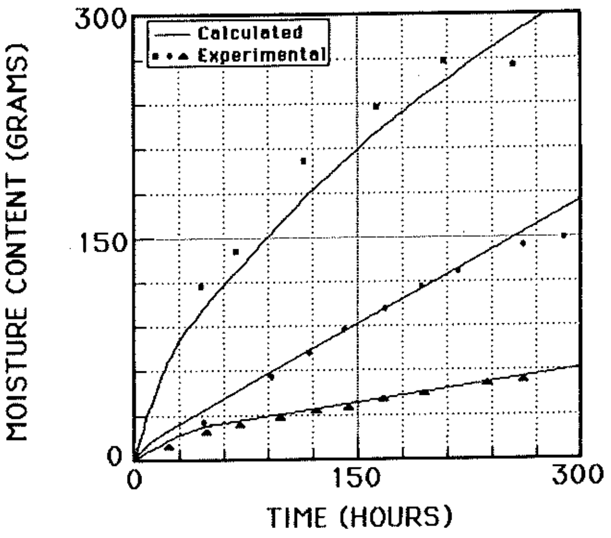

Figure 5. Comparison of experimental and calculated results for spray-applied fiberglass. (To convert from grams to pounds divide by 454)

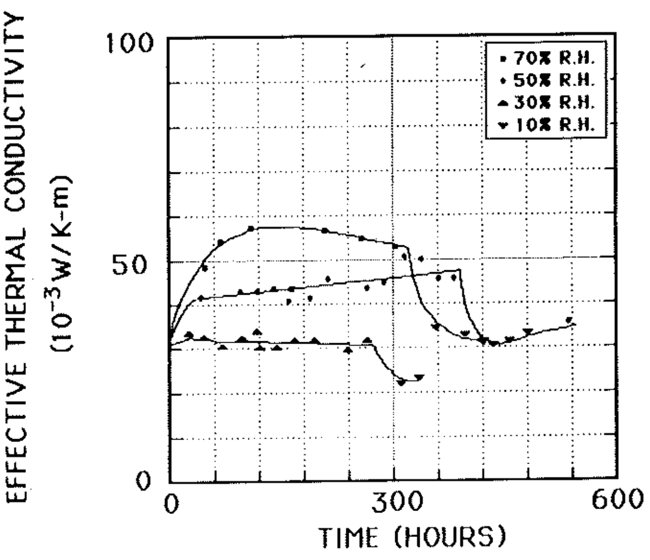

Figure 6. Apparent thermal conductivity of spray-applied fiberglass with a 20°C temperature difference. (To convert from W/k•m to Btu/h•ft•F multipy by 0.5778)

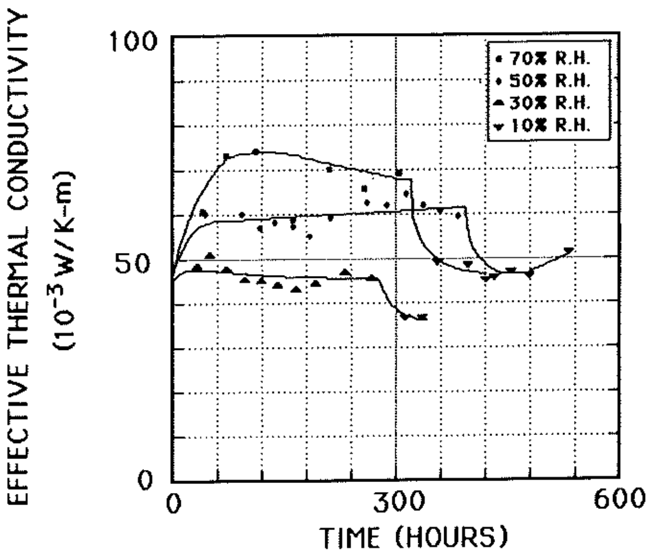

Figure 7. Apparent thermal conductivity of spray-applied cellulose with a 20 C temperature difference. (To convert from W/K•m to Btu/h•ft•F multiply by 0.5778)