ANALYSIS OF ROOF SYSTEMS THERMAL PERFORMANCE FROM FIELD DATA

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Since 1985 the U.S. Department of Energy Roof Research Center at Oak Ridge National Laboratory (ORNL) has operated an outdoor test facility for monitoring the thermal performance of different roof systems. This facility, the Roof Thermal Research Apparatus, (RTRA) is a 8.5m by 3.0m conditioned building with space on the roof for four 1.2m by 2.4m replaceable test samples. These samples as well as the building are fully instrumented and connected to a data acquisition system that records hourly average data on a continuous basis. The majority of testing in the RTRA has been on the long-term thermal performance of different roof systems. In addition, the facility has been used to develop field diagnostic procedures, to validate mathematical models, and to provide calibration data for an indoor climate chamber that can simulate real weather conditions. This report summarizes results from RTRA testing. Techniques for analysis of thermal drift, for determining temperature dependence of thermal conductivity, and for comparing the thermal performance of roof systems identical except for membrane solar reflectance are discussed. Some data is presented on the long-term (one to two year) thermal performance of roof systems insulated with fiberglass, expanded polystyrene, spray-applied polyurethane foam, polyisocyanurate foam and lightweight insulated concrete.

KEYWORDS

Fibrous glass, lightweight insulating concrete, molded expanded polystyrene foam, Oak Ridge National Laboratory (ORNL), polyisocyanurate foam, Roof Thermal Research Apparatus (RTRA), spray-applied polyurethane foam, thermal performance.

INTRODUCTION

According to the most recent Project Pinpoint, the percentage of new and replacement low-slope roofs in the United States now being insulated exceeds 88 percent.[1] This is dramatic evidence that good thermal performance is a worthy investment and has become an accepted design characteristic of roof systems despite higher initial costs. As the interest in thermal performance increases so do concerns that insulation performance meet design expectations over the life of the roof system. Several widely used standardized laboratory procedures are available for evaluating the thermal performance of insulations. These include ASTM Standards C-177, C-518, C-236 and C-976.[2] Laboratory measurements, while being valuable for product control, are useful as performance indicators only to the extent that they can predict material performance in an in-service roof system. In the last several years field measurements have shown that there are many instances when effects, not readily quantifiable by laboratory measurements, can significantly change the thermal performance of roofs from design values. Examples illustrated in this report are thermal drift in CFC-blown foam insulations, drying of lightweight insulating concrete fills, condensation-evaporation cycling of moisture in fibrous glass insulation, and temperature changes caused by changes in surface solar reflectance. These effects alter the thermal performance of roofs from design values and affect the cost of heating and cooling buildings.

THE ROOF THERMAL RESEARCH APPARATUS

The purpose of this paper is to provide highlights from a lengthy series of field tests carried out with the RTRA at ORNL. The RTRA, shown in Figure 1, has been described previously.[3,4] Briefly, it is a 3m by 8.5m by 2.4m high conditioned building that can accommodate two 1.2m by 2.4m (4 ft. by 8 ft.) removable test specimens on either side of a fixed center section. The RTRA is instrumented with a complete weather station for continuous monitoring of ambient conditions as well as solar and infrared radiation. This information, as well as data from thermocouples, heat flux transducers and moisture probes attached to test roof panels, is recorded at one-minute intervals and averaged hourly before storage on computer disks.[5] Disk capacity is sufficient so that one disk is sufficient to hold all the data from any single experiment, some of which have lasted as long as two years.

The most frequent test panel configuration used on the RTRA is for the panel to be sectioned in half with different constructions on each of the two sides as shown in Figure 2. Computer modelling has shown that edge temperature effects are negligible within the central 0.61m x 0.61m (24 in. by 24 in.) region on each side. This has been confirmed by thermocouple measurements and by surface infrared scanning. Thus, thermal test results from the central regions will be characteristic of field conditions. This two specimen configuration has made it possible to conduct many side-by-side comparisons. For example, when comparing the thermal effects of different membrane colors, a single 1.2m by 2.4m (4 ft. by 8 ft.) instrumented insulation system is installed in a panel and two 1.2m by 1.2m (4 ft. by 4 ft.) membranes are attached and seamed together in the middle. The second panel from the right in Figure 1 is a example of this type of system.

Figure 3 shows data taken directly from the file disk for the two-membrane panel mentioned in the preceding paragraph. Both sides are similar, 4.8cm (1.9 in.) of fibrous glass insulation over a metal deck, except for the membrane. One side has a black ethylene propylene diene terpolymer (EPDM) with solar reflectance, $r \cong 0.07$, and the other has the same membrane with a white elastomeric coating to increase its reflectance ($r \cong 0.86$). Figure 3 has hourly values of the temperature directly under the membrane on each specimen along with the inside and outside ambient air temperatures. Values are representative of results for RTRA specimens during the summer. Ambient daytime temperatures between 26°C and 32°C (80°F and 90°F), and between 13°C and 21°C (55°F and 70°F) during the night. Peak membrane temperatures depend upon cloud cover and humidity, but, have been occasionally observed to reach 82°C (180°F) for dark membranes on clear days. For white membranes, daytime temperatures rarely exceed 60°C (140°F). Without question, white roofs are cooler than black roofs. However, energy savings predictions are difficult since they depend on energy use patterns in individual buildings and on the affect of changes in physical properties and dust buildup (i.e., "in-service aging") on membrane color. Whole building mathematical modeling, validated by RTRA data, has provided a guidebook for predicting the energy consequences of changing roof reflectance.[6] Very little quantitative testing has been done on the affect of in-service aging.

Another feature illustrated in Figure 3 that is typical for all roof specimens is nighttime cooling of the surface to temperatures below the outdoor ambient temperature because of radiative cooling to the night sky. On clear nights the cooling during the summer is between 3°C and 6°C (5°F and 10°F) and during the winter it is from 6°C to 12°C (10°F to 20°F). Cooler skies during the winter are partly responsible for differences. In addition, the range of values in either season is primarily due to humidity variations. For all the materials tested, none have been found that have significantly different nighttime cooling effects. That is, all conventional roofing membrane materials tested have about the same value for the optical emittance in the thermal infrared portion of the radiation spectrum. White polyisobutylene (PIB) and black PIB are similar as are white EPDM and black EPDM.

Figure 4 is a plot of the weekly arithmetic mean temperature at the mid-plane (the mean temperature) of the two insulation specimens, described above, plotted as a function of the time of year. As one would expect, the mean temperature varies cyclically. It is also interesting to note that the average mean temperature over the full test period is 23.6°C (74.5°F) and 20.8°C (69.5°F), respectively, for the black and the white membrane systems. These values are typical for all the systems tested on the RTRA and, therefore, for in-service roofs in similar climate zones. Thus, the practice in the U.S. of specifying thermal properties at 23.9°C (75°F) for simple design calculations is perhaps fortuitously satisfactory for roof systems in Tennessee.

THERMAL PERFORMANCE CALCULATIONS

The principal RTRA results that characterize the thermal performance of roof systems have been obtained using the computer program PROPOR (PROPerties—Oak Ridge). PROPOR is a one dimensional, nonlinear regression theory program that combines solution of the fundamental heat transfer equation with least squares analysis techniques. It was developed at Michigan State University[7] and modified at ORNL to estimate the thermal conductivity and specific heat of building materials from transient temperature and heat flux data.[8,9]

PROPOR is preferred by ORNL over other available procedures, e.g., the "averaging technique."[10] It gives thermal conductivity as a function of temperature, it provides useful results over a wide range of weather conditions, it includes estimates of uncertainty and it is the only means to estimate the specific heat of building materials from in situ data. PROPOR analysis of RTRA data has been used in this report to measure the thermal conductance and its temperature dependence for several roof insulations to monitor the thermal drift of gas-blown foam insulations, and to chart the drying of lightweight concrete roof decks.

In use, PROPOR requires hourly values over several days for temperature or heat flux at the top and bottom of the insulation, and the temperature or heat flux at one or more interior points in the insulation. Basically, the program solves the one dimensional transient heat conduction equation subject to the measured boundary conditions and initial estimates for the thermal conductivity, k, and the density-specific heat product, pC_p of the insulation. Calculated temperatures and heat fluxes at interior points are then compared to measured values, and a better set of material property estimates are predicted. These are then used to predict new calculated interior temperatures and heat fluxes. The process repeats until some specified error criteria is satisfied. The final values for k and pC_p are accepted as the best values for the test. ROPOR has sub-routines that allow one to determine either the best constant k of the insulation for the range of test temperatures or the best fitting linear curve for k as a function of temperature.

SPRAY-APPLIED POLYURETHANE FOAM

Figure 5 shows a cross-sectional view of the roof test specimen used to provide thermal performance data on spray-applied polyurethane foam (PUB) insulation. Values for the thermal conductivity, k, as a function of arithmetic mean mid-plane insulation temperature for the PUF under a gray colored silicone coating are shown in Figure 6. The purpose of this test was to compare the thermal performance of PUF under two different coatings; one a so-called permeable coating of a gray colored silicone and the other an impermeable coating of white Hypalon (CSPE). The full results of this study are intended to be reported later. Here, only the variation in the thermal conductivity over an extended time period will be discussed. Some explanation of the graph in Figure 6 is required. Each data point represents the value of k, determined by PROPOR from a seven-day test period, calculated at the mean insulation temperature for that test period. Testing for this curve started in May 1988 (mean temperature of about 30°C or 86°F), continued into the hot summer (higher mean temperature) and into winter (low mean temperature), and finally terminated in May 1989 one year from the start. The reason the lines connecting the data points jump about is because they connect points in a time sequence. Thus, a cool week followed by a warm week and then another cool week will cause the lines to move first to the right and then to the left. Note, however, that the results show a fairly orderly seasonal behavior. That is, in the spring the mean temperature tends to increase with time, and in the fall it tends to decrease with time. The most striking feature of the curve is the fact that k, at a specific mean temperature, is not the same after some time passes before the temperature is again at that mean temperature. This is, of course, an example of the thermal drift effect present in all CFC-blown foam insulations tested at ORNL. In this particular instance, the initial k = 0.0242 W/mK (0.167 Btu in./°F h ft.^{2}) and, after one year of field exposure k = 0.0272 W/mK (0.189 Btu in./°F h ft.^{2}). Thus, the first year thermal drift for this sample of PUF was about 12.4 percent.

MOLDED EXPANDED POLYSTYRENE FOAM

Molded expanded polystyrene foam (MEPS) board insulation uses air as the expanding gas. Thus, it should not be subject to thermal drift. A MEPS specimen, shown schematically in Figure 7, was exposed for several years on the RTRA. Partial results are shown in Figure 8 which is the same type of presentation as Figure 6. In this case, testing started in December 1985 and continued for one year. Thus, the curve darts on the left, moves to the right as spring brings warm temperatures, and then reverses after the warm summer. Note that the cooling curve retraces the warming curve which confirms the absence of a thermal drift for MEPS. Also, since there is no change in k with time, the curve reflects the true temperature dependence of the thermal conductivity of MEPS. Using linear regression, the data fits the curve $k = 0.033 + 1.79 \times 10^{-4} T^1$ (W/m k) and at T = 23.9°C (75°F) k = 0.0373 W/m k (0.259 Btu-in./°F h ft.^{2}) which differs by 0.5 percent from laboratory measurements.[11]

POLYISOCYANURATE FOAM

A major project currently underway at ORNL involves RTRA measurements of the thermal performance of polyisocyanurate foam (PIR) board insulation using conventional CF-11 and alternative HCFC blowing agents. One purpose of the program is to determine whether non-CFC PIR foam performs similar to conventional PIR over an extended time under field conditions. Preliminary results on this project are being reported in detail in another paper at this symposium.[12] The purpose here is to show only that the interpretation of these preliminary results is consistent with other RTRA projects and that thermal drift in PIR is but another example of roof thermal in-service performance changing with time and roof conditions.

Each PIR specimen consists of two 3.8cm (1.5 in.) thick boards over a metal deck and under a black EPDM membrane. The thermal conductance for two specimens, one with CFC-11 and the other with HCFC-141b, are shown as functions of mean temperature in Figure 9 for the time period from August 1989 to June 1990. As in the previous examples, both curves are made up of data points, each representing a seven-day average and connected in time sequence. Thermal drift is present for both curves, being about nine and 12 percent over 10 months for the HCFC-141b and the CFC-11 foams, respectively. In this case, it is also interesting to note that there apparently was little thermal drift during the cold winter weeks compared to the warmer spring. Another preliminary observation is that the thermal performance of the two specimens is similar over the study period. A different way to present this data is shown in Figure 10. Here, the thermal conductivity is plotted against time and an additional curve, for HCFC-123, is added. It is again apparent that the insulations have similar behavior. The fact that k for both HCFC-123 and HCFC-141b foams is greater than for the CFC-11 is consistent with published values of the thermal conductivity of the gases.

LIGHTWEIGHT INSULATING CONCRETE

Wet insulation can also degrade the thermal performance of insulated roofs. Leaks in the waterproof membrane or transport of vapor from a humid interior space are common sources for which design corrections to the system R-value are impractical. It is common, however, in some countries (e.g., Sweden and Denmark) to provide an R-value design correction to protected membrane roofs (PMR) because of slow or incomplete drainage of rainwater. Two additional situations when moisture-related R-value corrections may be appropriate, lightweight concrete systems and mineral wool systems, are demonstrated by RTRA testing. The first is an examination of results from tests of two specimens using lightweight, perlite aggregate concrete. The roof systems under test are shown in Figure 11. On the right is a homogeneous lightweight concrete fill with thermocouples and a heat flux transducer embedded at measured intervals to provide the input for PROPOR. The system on the left includes an MEPS insulation board set into the lightweight concrete. Both systems are under a modified bitumen membrane and over a slotted metal deck that allows drying to the interior of the RTRA. Figures 12 and 13 summarize the results of the RTRA testing. Figure 12 gives values of the pC_p product determined from PROPOR for the top 7.6cm (3 in.) of concrete for each system. Note that while they have different initial values, after about six months they have become nearly equal and both tend toward an equilibrium value by the end of the 18-month test. Available property data for the dry lightweight concrete includes p = 380 kg/m3 (24 lb/ft3) and C_p = 910 J/kgK (0.22 Btu/lb F) or pC_p = 345 10^3 J/m^3 K (5.28 Btu/ft^3°F).[13] This is seen to be approximately the value obtained by the two specimens after 18 months in the field. Thus, the interpretation is that the lightweight concrete initially contained construction water which, over time, was driven downward through the clotted deck to the interior space. The driving pressure for the water vapor was the temperature difference across the roof, particularly during the two summer-fall periods. Further calculations show that the two systems initially contained about 30 percent and about 45 percent water by weight. The point here is that this roof construction has insulating value which is largely negated by the presence of water for a long period of time. This is seen in Figure 13 which is a plot of the thermal conductivity for the same top 7.6cm (3 in.) of lightweight concrete in both specimens. For reference, the summer and winter expected ranges for the thermal conductivity for dry lightweight concrete are shown by the bars. Thus, the initial thermal conductivity is 200 percent to 300 percent higher than the dry value because of construction water. Also, it takes about 18 months for the systems to dry out for the system listed and the local climatic conditions.

FIBROUS GLASS

A more subtle example of the degradation effect of moisture on thermal performance is observed in fibrous glass insulation. This effect is described more fully elsewhere.[14] Here, the purpose is only to show that the thermal performance of fibrous glass can be less than anticipated and that care must be taken when interpreting field data using heat flux transducers. The specimens tested are shown in Figure 14. They both consist of two layers of fibrous glass insulation over a metal deck and under different colored membranes.

The primary purpose of this testing was to validate a model for predicting the effect of membrane color on roof thermal performance and to help prepare the guidebook on the surface reflectance effects mentioned earlier. Figure 15 shows the thermal conductivity for both samples over a 22-month time period. Also plotted in Figure 15 is the approximate variation of the thermal conductivity for dry fibrous glass over the same period. This latter variation is only due to seasonal changes in the mean temperature. It is observed that the measured thermal conductivity of both specimens is higher than that for the dry material and is more random. The suggested explanation for this behavior is that a small amount of moisture, the equilibrium concentration for ambient conditions (less than 0.25 percent by volume), is being moved up and down daily by the water vapor pressure drive due to temperature difference.[14,15] This rapid response is unique to fibrous glass among common roof insulation boards because it has a high water vapor permeability.[16]

Thus, the repetitive cycle is: moisture condensation under the impermeable membrane at night, evaporation during the hot day, and movement to the impermeable deck followed by condensation again. The significance of this transfer process is that the vapor movement is always in the direction of the conduction heat transfer and the total heat transfer is strongly augmented by the latent heat of the moisture. As described elsewhere,[14] a heat flux transducer in the middle of the fibrous glass insulation is itself an impermeable surface upon which condensation and evaporation occurs. Since this causes the transducer to be heated and cooled by phase changes of the water, the transducer gives neither the correct total heat transfer nor the correct conduction-only heat transfer. Computer simulations show that the heat transfer calculated from transducer data is greater than that for dry fibrous glass under the same conditions, but less than the correct total heat transfer. Thus, for the systems in this test with any equilibrium water concentrations present, the net effect of the latent heat transfer in fibrous glass insulation over the time period of this test is to increase the thermal conductivity by at least six percent to 10 percent over the value for dry insulation.

SUMMARY

The thermal performance of roof systems has been investigated in a series of tests using the RTRA at ORNL. Some general observations for this climate zone (40 degrees north latitude), 300m (980 ft.) elevation, 2140 HDD (Base 18°C) heating degree days and 3540 CDH (Base 23°C) cooling degree hours are that membrane surface temperature can reach 82°C (180°F), but only for a relatively few hours per year; that average mid-plane roof temperature are between about 21°C and 24°C (70°F and 75°F); and that nighttime radiation cooling is about 4.2°C (7.5°F) in the summer and 8.4°C (15°F) in the winter.

Long-term continuous data collection and use of a particular computer program, PROPOR, has shown that performance changes in the field can be documented and that in some instances these changes are significant and not readily predictable from laboratory measurements. In such instances, field measurements are necessary to provide data for development of predictive models. Examples include increases in thermal conductivity of about 10 percent in the first year after installation due to gas diffusion in gas-blown foam insulations (the thermal drift effect), initial increases in thermal conductivity of over 100 percent due to construction water in lightweight insulating concrete, and latent heat transfer effects which increase the thermal conductivity of fibrous glass insulation by six to 10 percent in tests at ORNL. In each instance, these effects appear to be predictable which suggests the possibility of using field data to validate existing thermal design correction factors (e.g., thermal drift) or for establishing additional thermal design correction factors (e.g., equilibrium concentrations of water in fibrous glass insulation).

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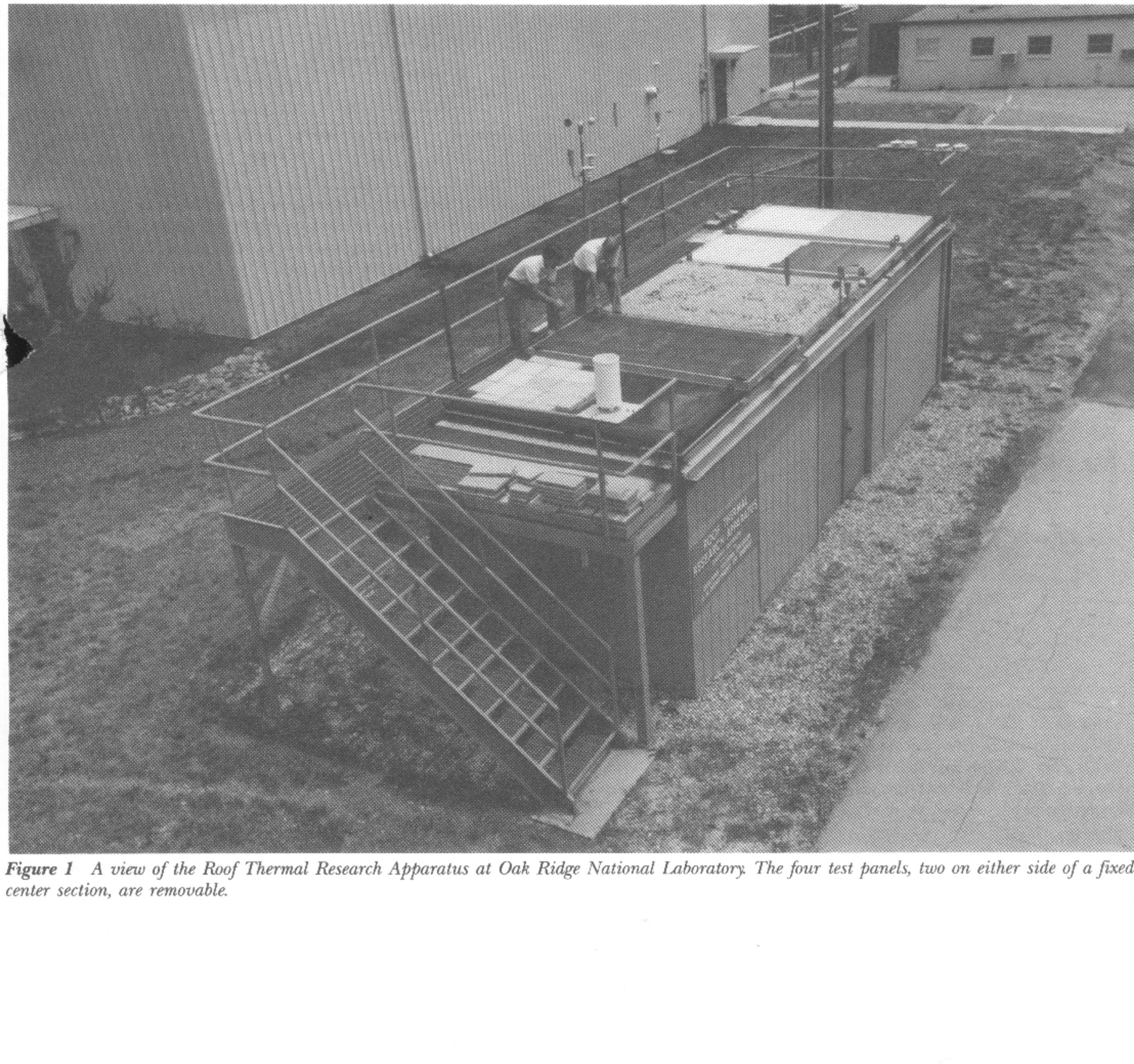

Figure 1 *A view of the Roof Thermal Research Apparatus at Oak Ridge National Laboratory. The four test panels, two on either side of a fixed center section, are removable.*

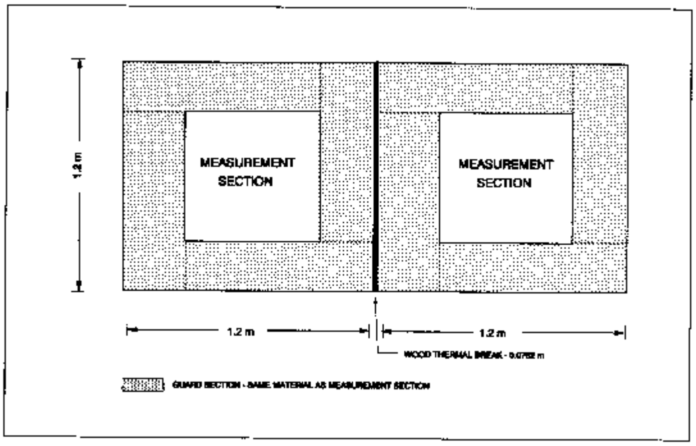

Figure 2 *Plan view of a typical test panel for the RTRA. Separate test specimens or different membranes over the same insulation specimen can be installed in the two sides of the panel. Field performance measurements are confined to the central regions as shown.*

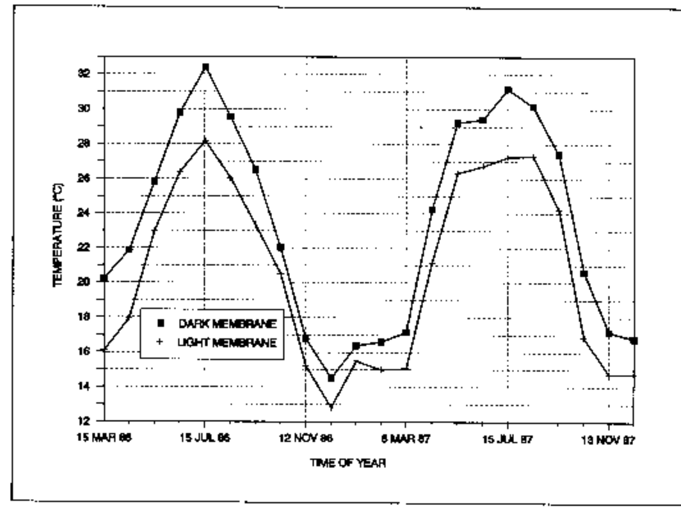

Figure 4 *Weekly average mean insulation temperatures (at the mid-plane) for roof insulations under black and white membranes. The annual average for the insulation under a black membrane is 23.6°C (74°F) and the annual average under a white membrane is 20.8°C (69.5°F).*

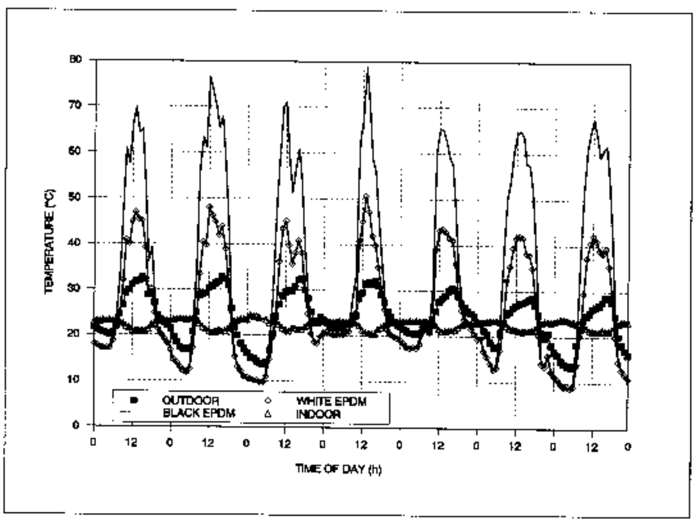

Figure 3 *Hourly averaged data from thermocouples attached to a test specimen on the RTRA. In this case a black EPDM was over one-half of a panel and a white EPDM over the other half. The insulation was 4.8cm of fibrous glass. Outdoor and indoor refer to air temperatures, and black and white EPDM refer to temperatures measured just under the surfaces of the membranes.*

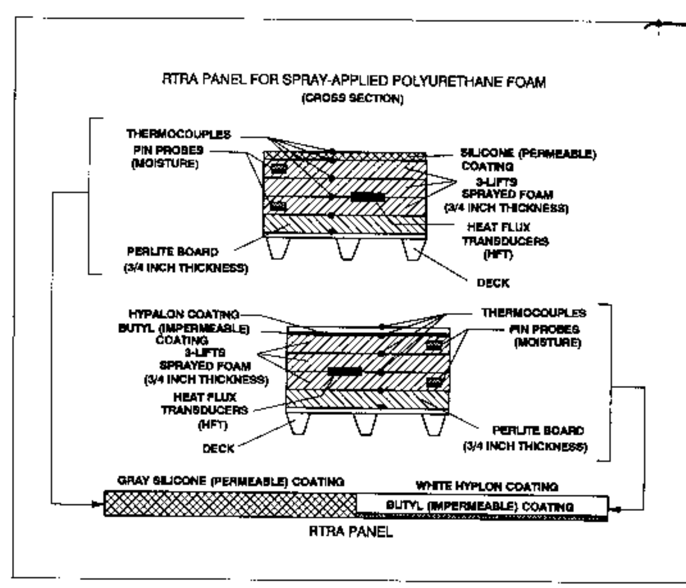

Figure 5 *Cross-sectional views of the two sides of an RTRA test panel used to evaluate some properties of spray-applied polyurethane foam insulation. Moisture probes (not discussed in the text) were inserted to evaluate their effectiveness in a field application. All sensors were inserted at the interfaces between foam lifts.*

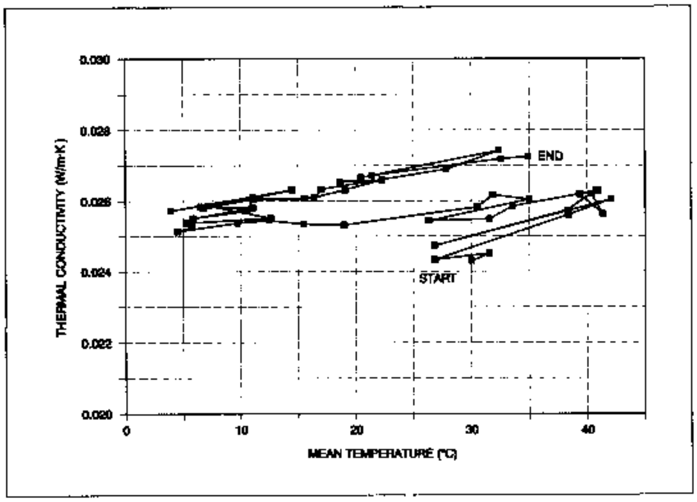

Figure 6 *Weekly values for the thermal conductivity of a spray-applied polyurethane foam specimen. The program PROPOR is used to calculate k values. Each value is plotted against the weekly mean temperature of the insulation. Data collection started in May 1988 and ended in May 1989.*

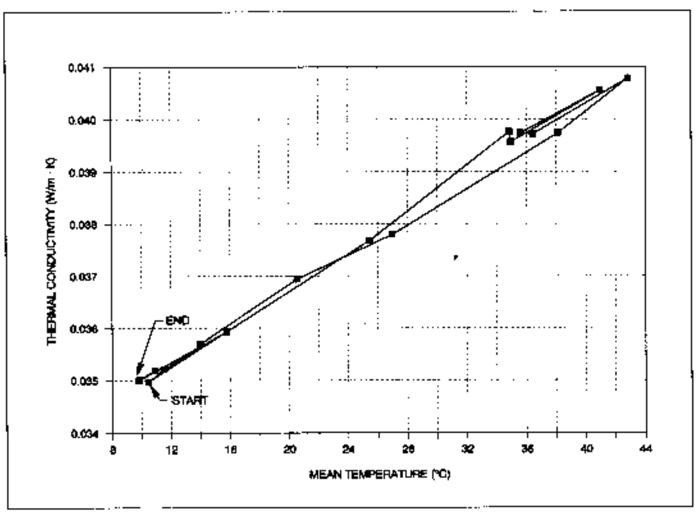

Figure 7 *Cross section of a panel containing four layers of MEPS board under a built-up roof. Thermocouples are located between each layer and a 5cm by 5cm heat flux transducer is in the middle of the stack.*

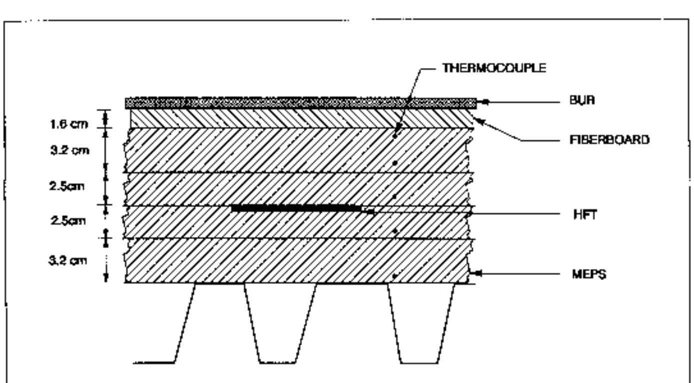

Figure 8 *Weekly values for the thermal conductivity of MEPS installed in the RTRA. The program PROPOR is used to calculate k-values. Each value is plotted against the weekly mean temperature on the insulation. The first data point is for the week of December 24, 1985 and the last data point is for the week of December 14, 1986.*

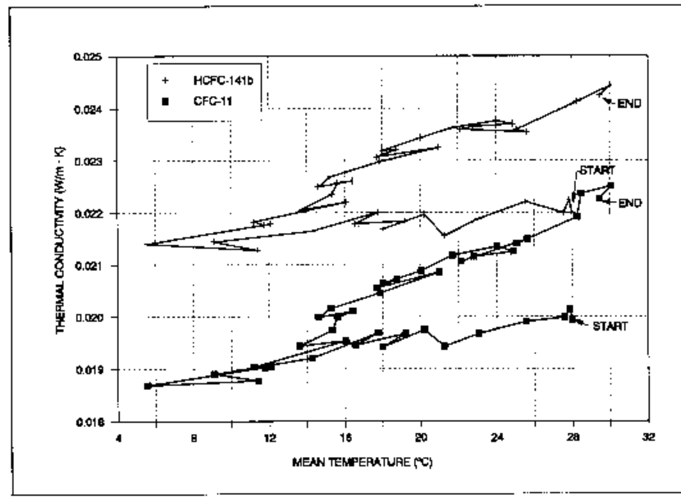

Figure 9 *Weekly values for the thermal conductivity of polyisocyanurate foam insulations blown with CFC-11 and with HCFC-141b. PROPOR is used to calculate k values. Values are plotted against the weekly mean temperature of the insulation. Each curve contains measurements starting in late August 1989 and ending in May 1990. Winter measurements are those recorded at low mean temperature (on the left).*

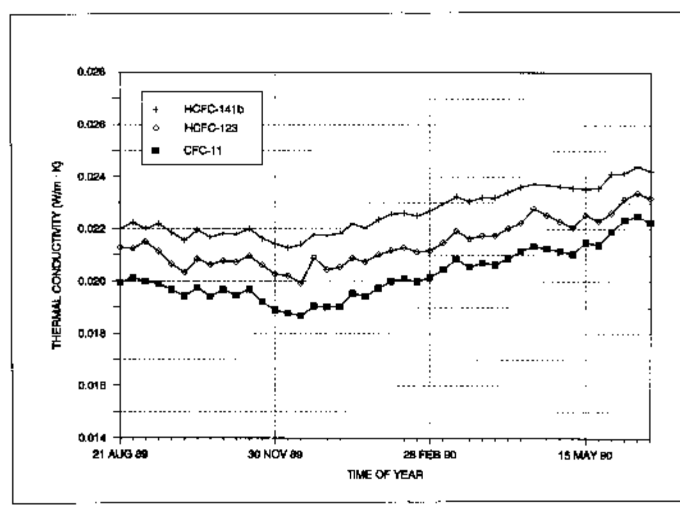

Figure 10 *The same data as in Figure 9 only plotted against real time. Data for foam blown with HCFC-123 has been added to the figure.*

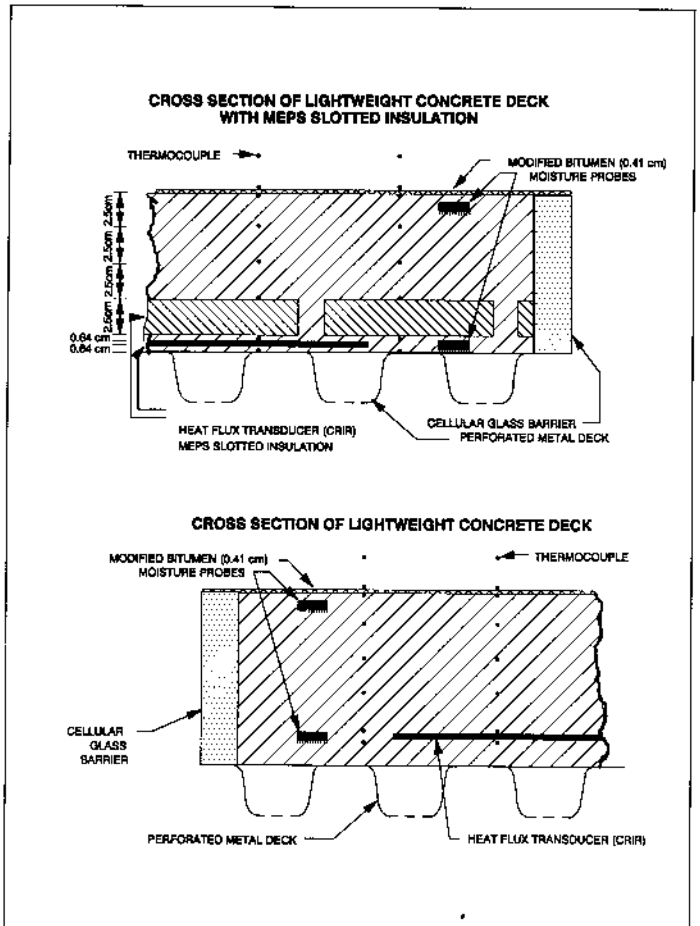

Figure 11 Cross sections of the two sides of a panel used to monitor the performance of lightweight concrete. Sensors were attached to a small rigid tree which was installed in the panel cavity before the concrete pour. Moisture probes (not discussed in the text) proved ineffective because of the high electrical conductivity of the concrete. The cellular glass foam provided a thermally insulated barrier between the two sides.

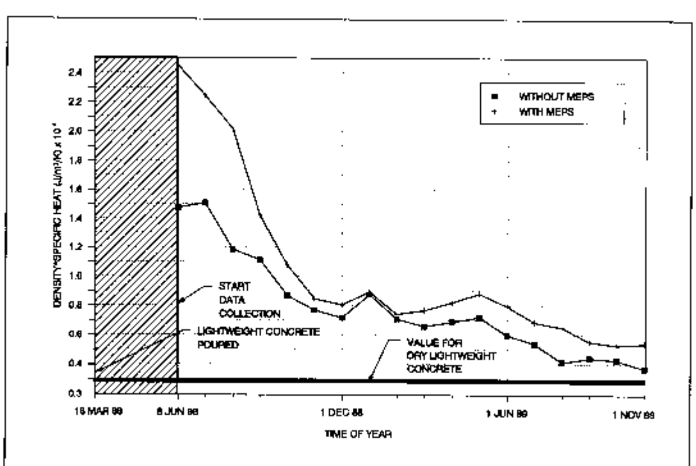

Figure 12 A plot of the measured density-specific heat product for lightweight perlite concrete against real time. For the curve labeled MEPS the MEPS is under the bottom side of the test panel. The straight line is the nominal value of the product for drying lightweight concrete. During the initial 60-day drying period the panel was kept at room conditions without a membrane covering.

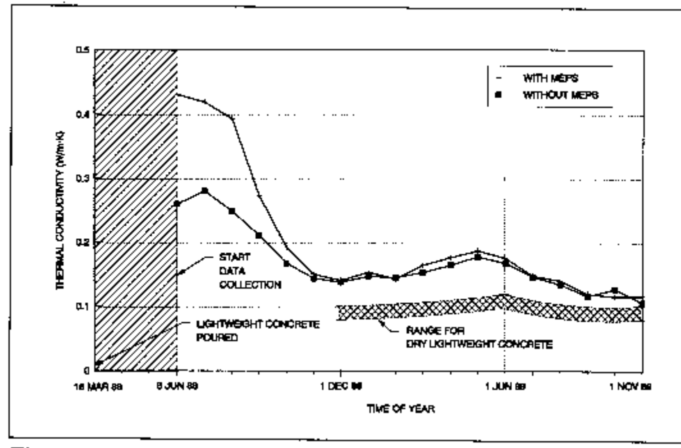

Figure 13 A plot of the measured thermal conductivity of lightweight perlite concrete for the top 7.6cm (3 in.) on both sides of the test panel. For the curve labeled MEPS, the MEPS is under the bottom side of the test area. The shaded area below the experimental curves indicates the range of thermal conductivity for dry lightweight concrete.

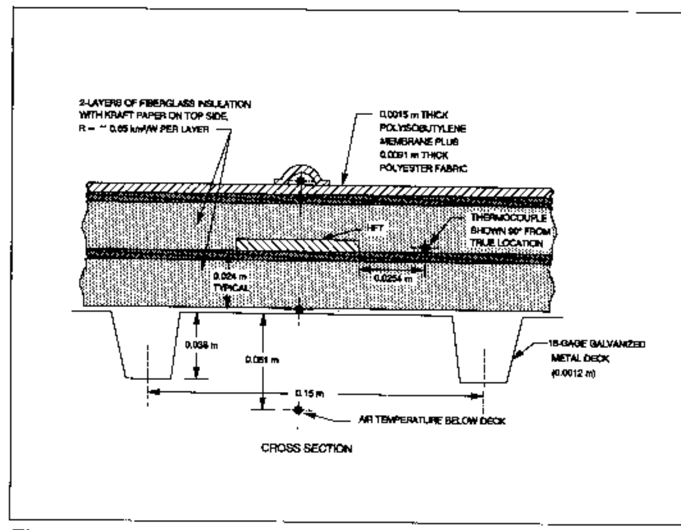

Figure 14 Cross section of the test panel used to monitor the thermal conductivity of fibrous glass insulation. One-half of the insulated panel was covered by a white polyisobutylene (PIB) membrane and the other half was covered by a black PIB membrane.

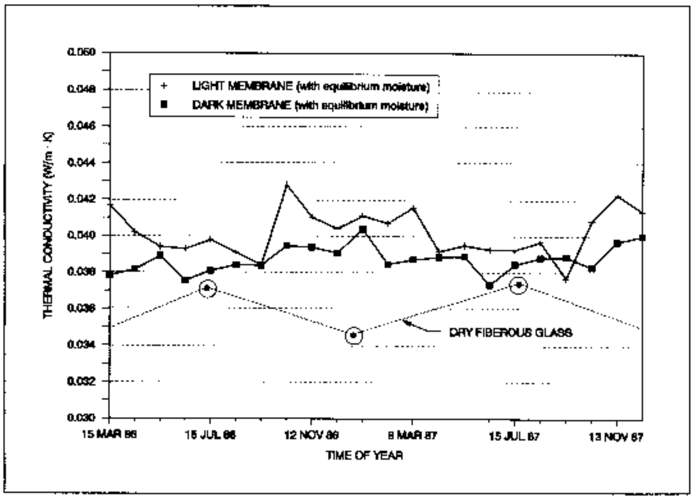

Figure 15 *A plot of thermal conductivity of fibrous glass insulation against real time. Points on the solid curves are calculated from RTRA data using the program PROPOR. The dashed curves approximate nominal values for dry fibrous glass.*