Field Monitoring of the Performance of Insulated Joisted Floors

G.A. Tsongas, Ph.D., P.E. *Member* **ASHRAE**

J. Dickinson

ABSTRACT

This paper describes the first known field study initiated to measure the performance of floor insulation over a crawl space in an actual residence. It was decided to monitor the in situ performance of insulated joisted floors to determine the actual heat loss performance and to examine the possible influence of such factors as two-dimensional heat transfer (especially in the vicinity of the joists), crawl space ventilation, airflow around or within the insulation, transients effects, and actual rather than nominal material properties. Six configurations were tested, including a conventional R-19 (R-3.3) batt installation, the same batt but dropped in the joist space with its foil facing up and in another test section with it facing down, a conventionally installed R-11 (R-1.9) batt with rigid foil-faced insulation added to the bottom of the joists, the same rigid insulation added to the bottom of the joists of an uninsulated floor section, and a completely uninsulated floor section as a control configuration. Monitoring took place over a six-month winter and spring period using heat flux meters, temperature sensors, and a field data logger.

A major purpose of the study was to determine if the performance of nominal R-19 (R-3.3) batt insulation installed conventionally in a joisted floor could be substantially improved by dropping the batts with their single foil faces to the bottom of the joist spaces. The gains from the reflective foil were much smaller than anticipated. In every case but the control section, the heat loss through the floor was higher and the total floor R-value was lower than expected. For all the insulated floor test sections, the measured R-values were at least about 30% lower than predicted using ASHRAE-type calculations. There appear to be two reasons for the performance degradation in floors that have not previously been recognized. For the test sections containing batt insulation, the presence of the floor joists caused two-dimensional heat transfer that led to about one-third of the R-value degradation. The other two-thirds appeared to be caused by air circulation associated with open crawl space vents and natural air infiltration through the floor. We believe the batt insulation would perform as rated if air infiltration were suppressed and the heat transfer were one dimensional. In addition, the R-values for rigid foil-faced insulation and enclosed air spaces with a reflective surface were found to be lower than the values listed in the ASHRAE Handbook of Fundamentals (1989). Finally, the crawl space, even when ventilated, was warmer than the outside temperature; with insulated floors the additional R-value of the ventilated crawl space as a buffer zone was about R-7 (R-1.2).

INTRODUCTION

Previous In Situ Floor Studies

While considerable field testing has been done on ceilings, and to a lesser extent on walls, there is very little published work on in situ measurement of floor R-values. Only 11 of the 169 papers listed in the comprehensive Thermal Performance of Buildings and Building Envelope Systems: An Annotated Bibliography (Carroll 1979) deal with floors, and, of those, only one discusses field measurement of R-values (Dill et al. 1945). That involved measurement of heat loss through several uninsulated floors, including a wood-framed floor over a crawl space. A more recent publication (Bales et al. 1985) included an extensive bibliography on applications of heat flux transducers (Bomberg 1985) without any mention of floor studies. In addition to searching the open literature for published studies of the performance of in situ insulated floors, some of the major fiberglass batt insulation manufacturers were contacted. None had undertaken any floor insulation field tests that were unpublished (Wilkes 1987; Ober 1986).

Purpose of This Study

Given the total lack of field tests to determine the in situ performance of floor insulation or insulated floor systems, it was deemed worthwhile to initiate such tests. Calculations of the overall R-value for a floor system are typically made using procedures described in the ASHRAE Handbook of Fundamentals (1989) assuming idealized, one-dimensional heat flow without taking into account any of many factors that might typically influence performance. Yet, the results of such calculations for floors have not been verified with results from actual field monitoring studies.

Therefore, it seemed worthwhile to determine if the simplifying assumptions used when making floor R- or U-value calculations were valid. For example, does a nominal R-19 (R-3.3) batt perform like R-19 (R-3.3) in the field? And what is the equivalent additional R-value that accounts for the moderating effect of a tempered crawl space? What, if any, is the difference in that effect if the crawl space vents are open rather than closed? What is the influence of the joists on the thermal performance of the floor as a complete system? These were questions without answers. Thus, this research was initiated to measure the performance of floor insulation in an actual residence.

Floor Insulating Systems to Be Tested

It was decided to examine the performance of six selected floor insulating systems. They are shown schematically in Figure 1 and described below.

1. Conventional installation practice: Nominal R-19 (R-3.3) fiberglass batts with permeable foil facing on the top installed between floor joists adjacent to undersurface of subfloor.

2. Unconventional installation #1: Nominal R-19 (R-3.3) fiberglass batts with permeable foil facing dropped down in the joist spaces so that their bottom foil surfaces face downward and are even with the bottom surface of the joists.

3. Retrofit option #1: R-11 (R-1.9) fiberglass batt conventionally installed adjacent to floor and an additional one-inch-thick foil-faced isocyanurate rigid foam board installed spanning the bottom surface of the joists.

4. Unconventional installation #2: Nominal R-19 (R-3.3) fiberglass batts with foil facing (facing on upper, warm side) dropped down in the joist spaces so that their bottom surfaces are flush with the bottom surface of the joists. This creates a reflective surface facing an air space between the subfloor and the top of the batts.

5. Retrofit option #2: One inch of rigid foil-faced insulation installed spanning the bottom surface of the joists of the uninsulated floor.

6. Control: Floor uninsulated.

The #4 technique has been proposed (and even recommended by the Tennessee Valley Authority [TVA]) as a means of improving the effective performance of batt insulation at little or no extra cost. According to the 1989 ASHRAE Handbook of Fundamentals (p. 23.5), the reflective foil surface-air space combination created by lowering the batt can add an additional R-6 (R-1.1) to R-10 (R-1.8) or so, depending on the air space thickness and the foil's emmissivity. While the foil and air space combination may improve the floor system's performance, the actual magnitude of the improvement, if any, or of the combined performance, has not been measured in a real installation in an existing residence. Thus, it was proposed to test this scheme.

The similar #2 scheme was proposed for testing by one of the project sponsors. The difference between #4 and #2 was that in #2 the perforated foil was installed on the bottom of the lowered batt rather than on the top. It was anticipated that the low-emissivity lower surface also would reduce heat loss to the crawl space.

A new technique for either new construction or retrofitting both insulated and uninsulated floors was believed to have potential for improved performance at reduced installation cost. For instance, for homes with existing floor insulation where more is desired, it might prove most cost effective to simply staple up foil-faced rigid insulation to the bottom of the floor joists. Then a foil-air space combination again exists and provides some insulating value in addition to that of the existing batt and the newly added rigid board. This approach might also prove most effective for residences with no floor insulation. In that case, the R-value of the full air space-foil combination could greatly add to that of the rigid insulation. Both these schemes appeared worthy of field testing.

As a special feature of this field study, one of the project sponsors agreed to laboratory test the various floor insulation schemes in its large calibrated hot box facility. This allowed comparison of laboratory and field test results and aided in determining the influence of the crawl space on the overall floor heat loss. Moreover, it was agreed to check our calibration of the heat flux sensors and also supply selected batt insulation of uniform thickness and R-value for this field testing.

EXPERIMENTAL DESIGN AND SETUP

The test room was an unoccupied bedroom of a house located in Portland, OR. The crawl space measured approximately 3 ft (911 mm) high from ground to subflooring. The floor consisted of 1.5 in. (38 mm) of wood subflooring (3/4-in. [19 mm] plywood on top of 3/4-in. [19 mm] tongue-in-groove) on 2 by 12 in. (50 by 305 mm) joists 16 in. (406 mm) on center. The entire floor except for the bedroom test area had R-19 (R-3.3) insulation. Five separate 4 ft by 4 ft (1.2 m by 1.2 m) test sections under the bedroom were insulated in accordance with the chosen insulation configurations, and one was left uninsulated as a control.

It was decided to measure the heat flux through each floor test section using relatively large heat flux meters (HFM). R-values of each overall floor section as well as individual parts were determined from the measured heat flux and temperatures measured at each interface. Large heat flux meters were used to provide enough signal at the low heat flux levels expected in these tests; they measured 8 by 8 by 1/8 in. (203 by 203 by 3 mm) and had a nominal sensitivity of 1.2 Btu/h-ft^2-mv (3.8 W/m^2-mv). The HFM were applied to the plywood floor top near the center of each 4 ft by 4 ft (1.2 m by 1.2 m) test section. The meters were installed with one edge along the center of a joist and the other in the middle of the 16 in. (406 mm) wide joist space. We chose this arrangement to get an average heat flux across each section that included the influence of the joists. The meters were applied to the floor with a conducting gel, and spackling was applied around the edge of each meter to act as an edge guard and to minimize any convection effects out of the edges. To avoid effects from bedroom heat sources on the HFM, we reinstalled the carpeting (without its padding) over the HFM. Two in. (51 mm) thick foil-faced rigid insulation was installed at the end of each 4 ft (1.2 m) long section between the joists to somewhat thermally isolate adjacent test sections. In addition, the reflective foil surfaces at the ends of each of the 4 ft (1.2 m) long test section air spaces helped them to act like longer air spaces without end effects from a radiation heat transfer point of view.

For each of the six test configurations, temperatures were measured at all the intersections between the various components, as well as in the air inside the room and the crawl space and outdoors. Temperatures were measured with precision linearized thermistors located in the vertical plane through the center of each HFM. The thermistors in the room air and outside air were fitted with radiation shields.

A field-type data logger recorded data from the six heat flux meters located inside the bedroom and from 48 thermistors. Data were collected every minute and averaged for one hour before being stored in long-term memory.

We used a portable electric heater with a small fan and an anticipating thermostat to maintain a fairly constant room temperature of about 70°F (21°C) with about a 1°F (0.6°C) daily swing. Since the HFM were very sensitive to heat sources, the radiant heater was pointed toward the ceiling so that there was no direct line of sight from the heating element to the HFM. We also covered the windows in the room with rigid insulation to minimize the influence of outdoor conditions, and we left the lights in the room off to avoid any radiant heat from the bulbs.

Due to the variation of crawl space temperature with the daily cycle, the insulation systems never reached a fairly steady temperature. When nonsteady temperatures existed, the sections exhibited a thermal lag which complicated the data analysis. The heat flow readings were out of phase with the readings of temperature difference across the various insulation system components. Therefore, we decided to reduce the temperature fluctuations in the crawl space by closing off the air vents. Besides, we also wanted to observe the effect of closed vs. open vents on the performance of the insulation systems. After this, the crawl space temperature fluctuation was reduced to a daily swing of about 1°F (0.6°C).

We also suspected that airflow through the test sections might have been causing a reduction in the effective R-values of the insulation systems. The airflow appeared to be caused, at least in part, by the normal stack effect- induced air infiltration into the house through leaks in the floor. We attempted to eliminate any such air infiltration into the sections by removing the insulation from the sections and caulking all of the cracks in the tongue-in-groove subflooring.

When we first examined the measured R-values we discovered some unexpected results which led us to remeasure the thickness of the fiberglass batting. We discovered that the dropped R-19 (R-3.3) batting in sections 2 and 4 had fluffed up after installation to about 9 in. (229 mm) thick. We adjusted the batting to the prescribed 6 3/4 in. (171 mm) thickness using a twine net on the top and bottom.

We took data from February through July 22, 1987. The thermal gradient across the test sections generally was great enough in the latter part of the test period to gather meaningful data even though we were well into the summer. Sometimes it was necessary to heat the test room to as high as 85°F (29°C).

DATA ANALYSIS

We developed a technique for reducing the data which involved dividing the data into four-day periods with nominally constant average insulation temperatures. Four-day periods were used to provide a long enough time to average out any short-term transients while minimizing any long-term trends. We chose four-day periods in which the average insulation temperatures did not change more than 5%. There were 25 such four-day data periods during the test. The 5% limit was very arbitrary and chosen in an attempt to minimize energy storage effects caused by rising or falling average temperatures. Such transient effects could result in significant differences in the calculated R-values. We did not want the results to be influenced by the fact that the six-month test period was one in which average temperatures were rising as the outdoor weather warmed from February to July. In essence, this data analysis procedure was used to throw out data from periods when temperatures were changing substantially. Ultimately, slightly less than half of the data taken continuously during the six-month test period was not used.

Once an acceptable period was identified, the data were extracted and the average temperature for each thermistor and the average heat flux for each section were calculated by integrating the data over the four-day period and then dividing by the total time of the data period. Integrated values are required because the sections have a thermal capacitance which can produce wild swings in the instantaneous hourly calculated R-values. We then used the integrated hourly values of temperature differences and heat flux to produce a single R-value for the four-day period, as follows:

$$R \text{ average} = [(\Sigma T1 - \Sigma T2)/(\text{no. of hours})] \div [(\Sigma \text{ heat fluxes})/(\text{no. of hours})] \quad (1)$$

In addition, all the measured and calculated quantities were averaged over the full six-month test period.

For all the test sections, temperatures were measured at the intersections between the various components, as well as in the air inside the room and in the crawl space and outdoors, allowing determination of all pertinent R-values. That included the overall R-value for each test section (indoor air to crawl space air), the R-value of the individual components of each section, and the R-value based on the inside to outside air temperature difference.

SENSOR CALIBRATION

Each of the 48 precision linearized thermistors was individually calibrated over the range from 32°F (0°C) to 90°F (33°C) and found to be linear within 1% over that range. The thermistors were calibrated before the experiment was started, and then several were spot-checked after the conclusion of the field test. The calibration factors did not change over that 10-month time span.

We built a laboratory hot box to calibrate the six HFM following the approach used by Bligh and Apthorp (1987). The hot box had a temperature-controlled warm water bath in contact with an aluminum plate on top and an ice water bath also in contact with an aluminum plate on the bottom. In between we placed a piece of insulation with a precisely known R-value, the HFM of interest, and several pieces of rigid expanded polystyrene board (see Figure 2). The insulation was a National Institute of Standards and Technology (NIST) standard reference piece of rigid fiberglass with an R-value of 4.415 h-ft^2-°F/Btu (0.777 m^2-°C/W). We surrounded the entire stack with insulation to promote one-dimensional heat transfer through the system. To calibrate the HFM we measured the temperature across the known piece of insulation and the output voltage from the HFM. The ratio of temperature drop across the insulation and the R-value of the insulation gave the heat flux through the stack. We then correlated the output voltage from the HFM to the calculated heat flux to produce the calibration factor.

The heat flux through the stack was varied to determine the calibration factor for each HFM over the range of heat flux levels and meter temperatures expected during the field test. We controlled the temperature of the HFM by judiciously placing the HFM in the stack, changing the temperature of the warm water bath, or changing the total amount of insulation in the stack.

We collected the sensor data on the field data logger, which allowed us to take samples every minute and average the results over an hour. The heat flux calibration tests were repeated several times for different heat flux levels that corresponded to the conditions found in the test house. We usually collected data at each condition for 18 to 24 hours and then used the data that best represented steady-state conditions.

We calibrated all of the HFM twice. Due to time limitations, we calibrated the HFM at one temperature before the field test, and then after the field test we calibrated them over a range of temperatures and heat flux values. The pre- and post-test calibrations (at the same single temperature) agreed to within about 5%. Because the range of temperatures in the test bedroom was limited to about 10°F (6°C), and because there was little variation of the calibration factors with temperature in that small temperature range, only one calibration factor was used. The heat flux meter temperatures averaged about 65°F (18.3°C), so we used the calibration factors for that temperature. The calibration factors that we derived were up to 39% higher than the factory calibration factors. The average difference was 35%, as noted in Table 1.

After the field test was completed, we sent the HFM and the NIST standard insulation to one of the project sponsors to check our calibration factors and the insulation's R-value. The R-value was almost identical with the value cited by the NIST. The sponsor also found a temperature dependency of the calibration factors, although it was not as strong as what we noted. However, their calibration test setup and conditions were somewhat different. They used an ASTM C518 HFM-type apparatus. On average, their values were 9% higher than those given by the manufacturer (factory). Upon inspection of the calibration factors in Table 1, it appears that the sponsor's factor for HFM #1 is relatively low. HFM #1 was sent to an independent testing lab to check its calibration factor. It was 12% higher than the factory value, which is close to the average of the sponsor's factors for the other meters.

TABLE 1
Comparison of HFM Calibration Factors

HFM	Factory	PSU	Sponsor	Lab	PSU/Factory	Spon/Fact
	Calibration Factor [Btu/h-ft^2-mv (W/m^2-mv)]					
1	1.21 (3.81)	1.59 (5.01)	1.22 (3.84)	1.35 (4.25)	1.31 (4.13)	1.01 (3.18)
2	1.01 (3.18)	1.39 (4.38)	1.12 (3.53)		1.38 (4.35)	1.11 (3.50)
3	1.04 (3.28)	1.45 (4.57)	1.14 (3.59)		1.39 (4.38)	1.10 (3.47)
4	1.03 (3.24)	1.33 (4.19)	1.10 (3.47)		1.29 (4.06)	1.07 (3.37)
5	1.02 (3.21)	1.39 (4.38)	1.16 (3.65)		1.36 (4.28)	1.14 (3.59)
6	1.13 (3.56)	1.57 (4.95)	1.26 (3.97)		1.39 (4.38)	1.12 (3.53)

We believe our calibration factors are correct and have used them to reduce the HFM data. Further discussion regarding why we believe our calibration factors are correct is presented in the next section.

RESULTS

Heat Flux

The mean and standard deviation values of the measured heat flux through the top of each test section, including the influence of the joists, over the six-month winter and spring test period are shown in Table 2. Generally speaking, the heat flux was fairly constant for about the first one-third of the test period. Then the weather got warmer, and the heat flux stayed relatively constant for the next one-third of the test period, but at a somewhat reduced level. Finally, the weather got much warmer, and the heat flux dropped significantly until the indoor temperature was raised to increase the heat flux levels again. By and large, the crawl space air temperature followed the outdoor air temperature and was fairly constant over each third of the total data period.

For the three insulated floor configurations that contained nominal R-19 (R-3.3) batt insulation, the base case is the case (#1) with the batt installed conventionally in contact with the subfloor. The heat flux was 8% lower for the #2 floor with the batt dropped to the bottom of the joist space so that an air space existed above it, with its foil facing the crawl space. For the #4 case with the dropped batt, but with the foil on top facing the air space, the heat flux was 17% lower than that of the conventionally installed batt. The overall floor R-values (indoor air to crawl space air, or R/i-c) for these three floor sections (#1, #2, and #4) followed the same trend, with section #4 having the highest measured R-value of the three.

Ober (1989) found somewhat similar results from calibrated hot box tests. His tests also showed that, compared with conventionally installed batt insulation, dropping the batt to the bottom of the joist space with reflective foil on the bottom or the top of the batt somewhat improved the floor's R-value performance, although not markedly. However, he found that the floor with the foil on the bottom of the batt outperformed the floor with the foil on the top of the batt. That is just the opposite of what we found. The difference between our results probably can be explained by the fact that the air space above his insulation was thinner (2 in or 51 mm compared to 4.25 in or 108 mm), hence reducing the R-value of the air space with a reflective surface in his case. Moreover, the laboratory test results lacked the influence of a real crawl space with foundation walls. The cold walls would presumably result in additional radiation losses and induced air convection losses. That would likely reduce the effectiveness of foil on the bottom of a batt, as Ober also suggests. In addition, Basset and Trethowen (1984) noted a considerable reduction in performance due to the effect of condensation on the emittance of reflective foil, and that too could have caused the field performance of the batt with foil on the bottom to be lower than measured in the laboratory. Unfortunately, in this field test the foil surfaces were not inspected for condensation, nor were any dew point or relative humidity measurements made.

Air Space Performance

The measured and ASHRAE (1989) R-values for the air spaces in sections 2 through 5 are presented in Table 2. For the air space without any reflective surfaces (#2), as well as the open air space below the uninsulated floor (#6), the measured and predicted values are in close agreement. However, for those air spaces with a reflective boundary, the measured values are significantly lower than the ASHRAE values. The emmissivity of the foil surfaces was measured after the end of the field tests to be about 0.04.

Actually, the ASHRAE values must be used with considerable caution, because they are only four cases where the vertical separation is much smaller than the horizontal dimension of the bounding surfaces such that the radiation view factor is large (~1). In our case, the horizontal extent of the cavity was on the same order as the separation so that the view factor was lower (~0.75 for test configuration #4 and ~0.55 for test #5). In other words, a good portion of the radiation heat flux from the bottom surface of the floor impinged on the joists and short-circuited the air space path. The reflective bottom surface simply enhanced that effect. Hence, the actual R-value for the air space with one reflective surface should not be expected to be as large as the Handbook value. The values measured in this study bear that out.

In an analytical modeling study, Farrington (1989) predicted that foil-faced glass fiber insulation was much more effective in reducing the rate of floor heat loss than glass fiber insulation. However, the floor was modeled without joists (and crawl space ventilation). Both our field results and the laboratory results of Ober (1989) suggest that Farrington's model is deficient and so his results are incorrect for crawl spaces with joists.

Influence of the Crawl Space and Airflow

As indicated in Figure 3, there were small improvements in the total R-value (R/i-c) of test section 1 about one-third through the test period and again about two-thirds through the test period. Similar results occurred for the other insulated test sections, but not for the uninsulated section. It would appear that these small increases were caused by closing the crawl space vents and sealing foundation leaks and floor cracks. The main lower vents were closed during the middle of data period 10, and additional hidden upper vents were closed and foundation cracks sealed at the beginning of data period 17. In addition, tongue-in-groove floor and joist cracks were sealed between periods 18 and 19.

In order to show the magnitude of the increase in measured R-value that resulted from closing the vents and sealing the floor cracks, the mean values of the indoor air to crawl space air R-value, R/i-c, for the first nine data periods before any changes were made and the last seven after all were made are presented in Table 2. In addition, the percentage increase, denoted as %R, is also tabulated there. For example, for the conventional nominal R-19 (R-3.3) floor configuration, the average R-value for the first nine data periods was 14.3 h-ft^2-°F/Btu (2.5 m^2-°C/W), whereas the R-value for the last seven periods was 16.8 hr-ft^2-F/Btu (3.0 m^2-°C/W). That is an 18% increase. During the same time span the mean insulation temperature increased 6°F (3°C), so the temperature effect alone should have caused a slight decrease (on the order of a few tenths) in the R-value. Thus, the measured R-value increase from the beginning of the tests to the end of the tests appears to be due primarily to the vent closing and the floor sealing.

It is surmised that closing the vents and sealing the floor reduced airflow through the crawl space and air infiltration that bypassed the insulation as well as possibly airflow through the insulation. Both before and after the crawl space vents were sealed, smoke sticks were used to look for air currents in the vicinity of the insulation. Very small airflows were detected, but only right next to the small spaces between the tongue-in-groove subflooring. They appeared to be associated with the natural infiltration through the floor caused by the normal stack effect or house depressurization. Bullock (1986) and Berlad (1983) have noted that air convection within fiberglass batts can reduce the effectiveness of ceiling and wall insulation, respectively, but this is the first time that an influence of airflow has been noted in insulated floor systems. There did not appear to be any such influence for the uninsulated control section.

R-value improvements (%R) of as high as 24% were measured for the other floor systems. The results show an interesting pattern that is worthy of speculation as to its cause. The largest improvements occurred in the floors that were least likely to be influenced by airflow, namely floors 2, 3, and 5 that had either foil on the bottom of the dropped batt or rigid insulation sealing the bottoms of the floor joists. The R-value increase was not as large for floor 1. It had conventionally installed nominal R-19 (R-3.3) batts that were recessed up 4.75 in (121 mm) from the bottom of the floor joists, yet exposed to the crawl space air on the bottom of the batts. The R-value increase was the lowest, and relatively much lower than for the other insulated floors, for floor 4, which had batts whose unfaced bottom surface was even with the bottom edges of the joists. Thus, this floor was most susceptible to crawl space airflow influences. While these arguments are clearly speculative, they nonetheless appear to give credence to the argument that the R-value increases were indeed primarily the result of vent closing and floor crack sealing. It would be interesting to undertake further tests to see if the presence of a floor polyethylene air barrier would eliminate or greatly reduce the R-value degradation associated with open vents and unsealed floors.

Crawl Space R-value. The initial and final values of the total indoor air to outdoor air R-value (R/i-o) and the total indoor air to crawl space air R-value (R/i-c) for each floor are presented in Table 2. The initial values are the mean values for the first nine data periods at the beginning of the field tests with the crawl space vents open, whereas the final values are the means for the last seven data periods after the crawl space vents had been closed and the floor cracks sealed. The weather was rather warm during the last seven data periods.

The difference between the two R-values (R/i-o and R/i-c) should be that associated with the influence of the crawl space acting as a kind of buffer space (R/c). For the part of the test period with the vents open the differences are about R-7 or 8 (R-1.2 or 1.4) for the better insulated floors, with the R-value decreasing as the amount of insulation decreases. That is in close agreement with the value of R-6 (R-1.1) used by the California Energy Commission for a vented crawl space without heating ducts, whereas it is larger than the value of R-2.5 (R-0.4) used by the Bonneville Power Association (1982). For the warmer weather period after the vents were closed, the buffer space R-values were much lower. That is most likely due to the warm weather such that the difference between the outdoor air and crawl space air temperatures was relatively small. During some of that period the indoor temperature was increased by heating the room in order to get satisfactory floor heat loss.

Measured Vs. Calculated R-Values

The measured and calculated indoor air to crawl space air R-values (R/i-c) are shown in Table 2. The calculated values were determined using the procedure described in the ASHRAE Handbook of Fundamentals (1989) assuming one-dimensional parallel heat flow and including the effects of the floor joists. Floor component R-values were taken from the Handbook tables, except for the fiberglass insulation R-values. For those the values measured in the laboratory by one of the project sponsors were used; the values (R/ins-Lab Meas) are shown in Table 2. The calculated R-values for those floor systems with tall air spaces with a reflective boundary (#3 and #5) are subject to some uncertainty. That is because R-values for reflective air spaces of heights greater than 3.5 in. (89 mm) had to be extrapolated from the Handbook data.

Except for the uninsulated floor, the measured values are substantially lower than the corresponding calculated values. For the conventionally insulated floor, the ratio of the measured to calculated initial R-values is 0.71. The ratios are even lower for the other insulated floors. That suggests that either the floors are not performing as well as expected, or the heat flux meter calibration factors are incorrect.

The real field performance of the insulated floors could be lower than expected for a number of reasons. A major factor reducing their performance is likely the airflow noted earlier that bypasses the insulation. It also is possible that the presence of the joists caused two-dimensional heat transfer through the insulation, thus reducing its effectiveness. Wilkes and Rucker (1983) have noted that effect in ceiling insulation. We developed a finite element model of the floors and found two-dimensional heat transfer to exist near the joists, and that was borne out by our detailed temperature measurements for floor 1. Ober (1989) found the R-value for floor 1 measured in a calibrated hot box at mean insulation temperatures similar to ours to be 9% lower than the calculated value. Thus, part but not all of the cause of the poor actual performance could be two-dimensional thermal short-circuiting through the joists.

For the conventional floor 1 the measured R-value was 29% lower than the calculated value. Airflow effects were shown to produce 18% R-value degradation. Adding the 18% to the 9% due to two-dimensional heat flow gives a total measured degradation of 27%. That is almost exactly the same as the measured 29% degradation. Thus, overall the combination of airflow and two-dimensional effects seems to fully account for the less-than-expected R-values.

One way of getting better agreement between measured and calculated values in floors with joists partly exposed to the crawl space air is to perform the parallel heat flow calculations using a joist height no greater than the batt thickness. That accounts for the fact that the part of the joist directly exposed to crawl space air below the batt is essentially isothermal and should not be considered as a resistive element. Such an approach was used for ceiling calculations by Trethowen (1978) and in our calculations.

From the measured floor system R-values that incorporate the effect of the joists, the R-values of the insulation alone can be calculated. Again, the ASHRAE (1989) parallel heat flow calculation procedure was used. The results for the final seven data periods are shown in Table 2. Two sets of results are presented: those labeled "PSU" using the measured results based on our heat flow meter calibration values, and those labeled "Sponsor" using our measured results but adjusted as if the sponsor's heat flow meter calibration values were correct. Those latter results will be discussed in a later section. The PSU insulation R-values are lower than the nominal or the laboratory-measured values; they simply indicate the influence of two-dimensional heat transfer in reducing the effective R-value of the insulation. If those effects were not present, the measured R-values presumably would be very close to the values that were measured when testing the insulation alone in the laboratory.

It should be noted that the R-values of the 1 in. (25.4 mm) thick rigid isocyanurate insulation in floors 3 and 5 were 4.7 and 4.9 h-ft^2-°F/Btu (0.83 and 0.86 m^2-°C/W), which is lower than the value of 7.2 h-ft^2-°F/Btu (1.27 m^2-°C/W) listed in the <u>ASHRAE Handbook of Fundamentals</u> (1989). Pieces of insulation similar to those field monitored that were purchased about six months before they were laboratory tested were found to have R-values of 7.0 and 8.0 h-ft^2-°F/Btu (1.23 and 1.4 m^2-°C/W) at 75°F (24°C). Based upon the previous finding that airflow degraded the R-value performance of the insulated floor systems, it is speculated that the reason for the difference between the field and laboratory results is the measured temperatures on the surfaces of the rigid insulation used to determine its R-value were influenced by airflow through the enclosed air space.

<u>Heat Flux Meter Calibration Error</u>. One question that remains is whether or not the heat flux meter calibration factors that we determined are accurate. As was discussed in the section on Sensor Calibration, there are differences between the calibration factors we measured both before and after the field monitoring and the calibration factors determined by the meter manufacturer, an independent test lab, and one of the project sponsors. The reasons for the differences are not entirely clear, although a major effort was made to try to determine possible causes. Each group used a somewhat different measurement apparatus setup.

For our heat flux meter calibrations, we used a methodology developed by Bligh and Apthorp (1983) for the U.S. DOE. They found that one manufacturer's calibration factors were highly inaccurate and varied substantially from sample to sample. The reasons for the inaccuracy were unknown. Moreover, Bligh and Apthorp (1983) contend that the device without a guard heater used by the manufacturer of our heat flux meters does not generate a uniform one-dimensional heat flux through the meter being calibrated. The calibration setup of our project sponsor used low-density fiberglass batt insulation to produce the correct heat flux levels; it was placed in contact with the HFM without an edge guard. That might have led to two-dimensional heat flow as well. The independent lab used a standard thermal conductivity apparatus. Its HFM calibration configuration closely resembled the actual test configuration, including the edge spackling used in the field test HFT installation. Ours used an edge guard similar in effect to the actual spackling. Moreover, our test was the only calibration setup with heat flow down, although that may not be important.

The calibration factors (Btu/h-ft^2-mv) for HFM #1 measured by us, the independent lab, the project sponsor, and the heat flux meter manufacturer are in the ratio of 1.31 : 1.12 : 1.02 : 1.00. It is interesting to note that O'Brien (1988) measured the calibration factor of a heat flux meter of the same manufacturer using both an approach similar to ours and a thermal conductivity apparatus. He compared those calibration factors with those of the manufacturer and found them to be in the ratio of 1.43 : 1.29 : 1.00. Thus, he found differences that were even greater than ours. What is worth noting is that the ranking of the different techniques was in the same order as what we found. This suggests that the different results may simply be the result of using different techniques.

In the end one must make a judgment call as to which set of calibration factors one believes is most accurate. We can only speculate about the reasons for the differences between the values determined by us and the others. We feel the Bligh and Apthorp approach is the most accurate. Thus, we trust our results the most and have decided to use them for analysis. Clearly, however, one should not put too much emphasis on the magnitude of the R-value results. The relative results are not calibration factor dependent and so are of most value.

It should be noted that the HFT were calibrated using one-dimensional heat flow but used to measure two-dimensional heat flow. There is no evidence known to the authors that indicates that a one-dimensional calibration is or is not appropriate for measuring two-dimensional heat flow. Since an HFT is basically an integrating device, there should be no problem, but this question needs further study. Trethowen (1988) has suggested in private discussions with one of the authors that using a one-dimensional calibration for two-dimensional measurements appears reasonable. Furthermore, it is not likely that two-dimensional calibration effects could account for the substantial differences in the calibration factors determined by us and the others noted earlier.

In all fairness, if we were to use the project sponsor's or the manufacturer's calibration factor results, then the differences between the measured and calculated results would be much smaller in most of our six test cases. However, as shown by comparing the "R/ins/Lab Meas" and the "R/ins/Sponsor" values in Table 2, in all but one of the floor cases, using those factors would lead to batt insulation R-values that were greater than the values measured by one of the project sponsors in the laboratory. In the case of the nominal R-11 (R-1.9) batt, using our PSU calibration factor gives very close agreement, whereas using the sponsor's calibration factor gives an insulation R-value of 18.2 (3.2), which is considerably larger than the measured value of 10.6 (1.9). That seems unrealistic. Furthermore, the effects of air convection and two-dimensional heat transfer appear to fully account for the differences between the measured and calculated R-values.

MAJOR FINDINGS AND CONCLUSIONS

To our knowledge this is the first time the performance of an insulated floor has been monitored in a real field situation. One major purpose was to determine if the performance of nominal R-19 (R-3.3) batt insulation installed conventionally could be substantially improved by dropping the batts to the bottom of the joist spaces. With the batts' foil facing the crawl space, the heat flux was 8% lower than for the conventionally insulated floor, whereas with the foil on the top of the batts the heat flux was 17% lower. The gains expected from the reflective foil were much smaller than anticipated.

The measured R-values of the enclosed air spaces with one reflective surface were much less than the values listed in the ASHRAE Handbook of Fundamentals (1989). The best measured value was only about 30% of the corresponding tabulated value. The existence of the reflective foil surface did somewhat improve the air space's R-value from about R-1 (R-0.2) to about R-3 (R-0.5). The probable reason for the relatively poor actual performance was the existence of radiation heat transfer to the joist walls, which short-circuited the air space path. The air spaces we monitored had a low width-to-depth ratio and therefore had a different radiation view factor than those cited by ASHRAE. Since this effect is not mentioned in the ASHRAE Handbook, caution needs to be exercised when using the ASHRAE values. It is also possible that air circulation developed within the enclosed air spaces, and that reduced the effective R-values. These results point out that when modeling the performance of floors, the effects of the joists must be included.

In every case but the uninsulated control section, the heat loss through the floor was higher and the total floor R-value was lower than expected. For all the insulated floor test sections, the measured R-values were at least about 30% lower than predicted using ASHRAE-type calculations. There appear to be two reasons that fully account for the performance degradation: two-dimensional heat transfer and airflow that short-circuited the insulation.

For the test sections containing batt insulation, the presence of the joists caused pronounced two-dimensional heat transfer that appears to account for about one-third of the R-value degradation. The other two-thirds appear to be caused by air movement through the insulated floors, caused both by the air circulation associated with open crawl space vents and the natural air infiltration through the floor due to the normal stack effect or house depressurization. The air movement bypasses the insulation and reduces its effectiveness. This appears to be the first time such an effect has been noted in floors. The effect would most likely not exist in a typical laboratory test. Closing the vents reduced but did not eliminate the problem, whereas sealing off the floor did get rid of most of it.

Using the measured results, the R-value of the conventionally installed fiberglass batt insulation was found to be significantly lower than the nominal laboratory-tested value of R-19 (R-3.3). However, the degraded performance of the fiberglass batt insulation was likely due to air convection and multi-dimensional heat flow within the insulated floor system. Further testing would help to verify this point.

The crawl space, even when ventilated, in general was warmer than the outside temperature. Thus, when calculating floor heat loss, especially in mild climates, it is not correct simply to assume the ventilated crawl space air temperature is the same as the outside air temperature, as suggested in the ASHRAE Handbook (1989). For the one unique set of conditions of this field test, including insulated floors and a ventilated crawl space without heating ducts, the additional R-value of the crawl space as a buffer zone was found to be about R-7 (R-1.2). While the actual R-value of the buffer zone may be different in different situations, the results of this field test re-emphasize the need to include some buffering R-value when calculating heat loss from floors over a crawl space.

These findings also suggest a modification to the normal procedure for performing parallel heat flow calculations to account for the presence of joists in a conventionally insulated floor. The R-value of the joist should be calculated assuming a joist height no greater than the batt thickness. That is because the exposed portion of the joist is essentially at the crawl space temperature and should not be included as a resistive element. That will provide better agreement between measured and calculated R-values.

The R-values for rigid foil-faced isocyanurate insulation monitored in the field were found to be lower than the values listed in the ASHRAE Handbook of Fundamentals (1989) and measured in the laboratory. The R-value of the 1 in. (25.4 mm) thick rigid insulation was found to be about R-5 (R-0.9) rather than the Handbook or laboratory value of R-7 (R-1.2). The reduction appears to be due to air circulation bypassing the insulation. The presence of the rigid insulation under the bottom of the joists tended to reduce, but not eliminate, thermal bridging and the associated two-dimensional heat transfer effect.

Finally, we measured the calibration factors of the heat flux meters we used, and then we had the factors checked by the project sponsor and an independent testing lab since our values were considerably different (about 30% to 40% greater) than those determined by the manufacturer. The widely varying results appear to be the result of using different measurement apparatus.

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Floor	Description	Heat Flux Mean/SDev	R/i-c Init/Finl	%R (F-I)/I	R/i-c Calc	R/i-o Init\Finl	R/c	R/ins Lab Meas	R/ins PSU\Sponsor	R/air gap Meas/ASHRAE
1	Conventional R-19 (nominal) batt installation	0.95\0.30 (2.99\0.95)	14.3\16.8 (2.5\3.0)	17.7	20.1 (3.5)	20.9\17.8 (3.7\3.1)	6.6\1.0 (1.2\0.2)	18.3 (3.2)	14.1 \ 20.8 (2.5 \ 3.7)	- -
2	Air gap above R-19 batt; foil on bottom of batt	0.87\0.27 (2.74\0.85)	15.3\18.9 (2.7\3.3)	23.5	22.1 (3.9)	22.8\20.1 (4.0\3.5)	7.3\1.2 (1.3\0.2)	18.2 (3.2)	14.4 \ 19.9 (2.5 \ 3.5)	0.9 1.2 (0.2) (0.2)
3	R-11 batt/air gap/foil-faced rigid insulation	0.72\0.23 (2.27\0.72)	19.1\23.7 (3.4\4.2)	23.8	30.4 (5.4)	27.1\23.2 (4.8\4.1)	8.0\-0.5 (1.4\-0.1)	10.6 (1.9)	10.6 \ 18.2 (1.9 \ 3.2)	3.1 >9 (0.5)(>1.6)
4	Air gap above R-19 batt; foil on top of batt	0.79\0.23 (2.49\0.72)	18.2\19.5 (3.2\3.4)	6.7	29.7 (5.2)	25.6\20.3 (4.5\3.6)	7.4\0.8 (1.3\0.1)	19.3 (3.4)	14.2 \ 19.1 (2.5 \ 3.4)	1.6 >9 (0.3)(1-1.6)
5	Foil-faced rigid insulation on bottom of joists	1.24\0.39 (3.91\1.23)	10.8\13.2 (1.9\2.3)	22.2	20.4 (3.6)	15.6\14.3 (2.7\2.5)	4.8\1.1 (0.8\0.2)	7.5 (1.3)	5.4 \ 8.0 (1.0 \ 1.4)	3.2 >9 (0.6)(>1.6)
6	Uninsulated wood floor with joists	3.43\0.90 (10.8\2.84)	4.0\4.1 (0.7\0.7)	2.3	4.0 (0.7)	5.8\4.0 (1.0\0.7)	1.8\-0.1 (0.3\-0.0)	-	- -	0.9 1 (0.2) (0.2)

R-value units: hr-ft2-F/Btu (m-C/W); heat flux units: Btu/hr-ft2 (W/m2)

Table 2. *Floor insulation monitoring field test results*

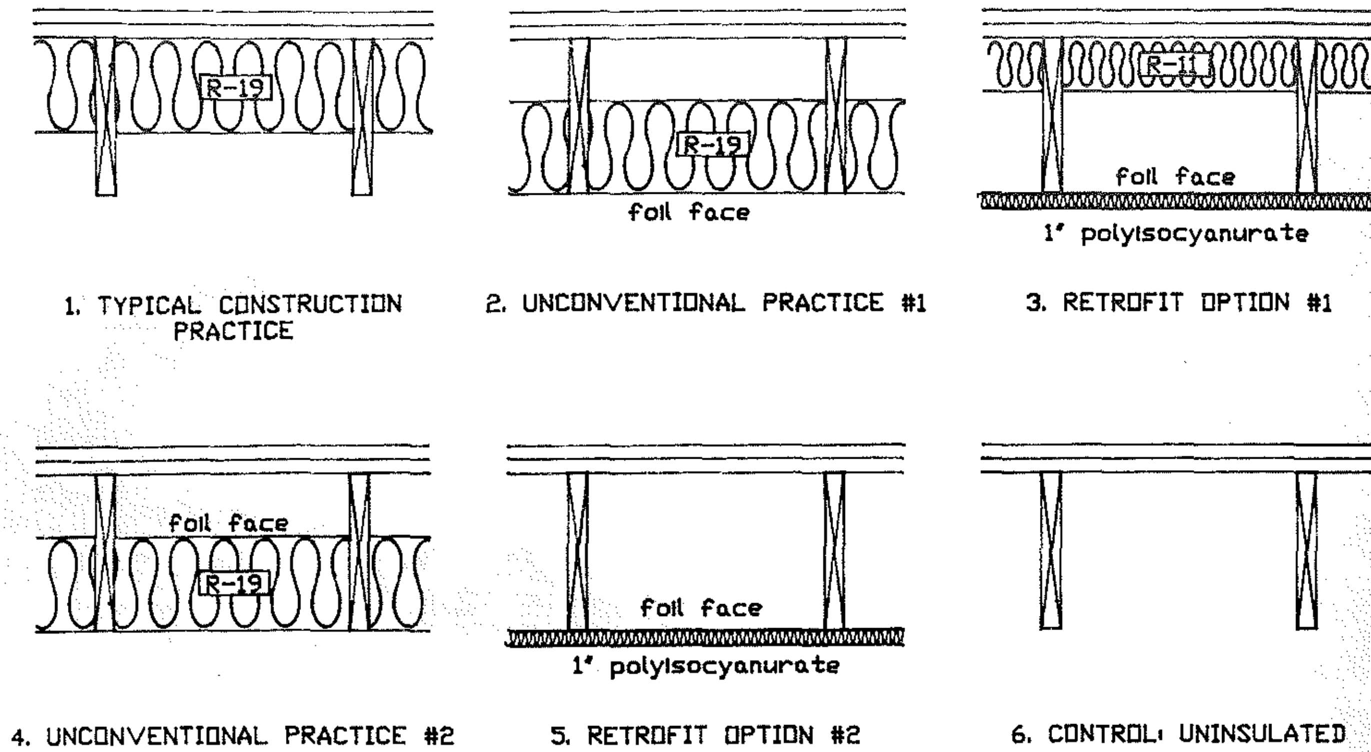

Figure 1. Floor insulation techniques to be studied

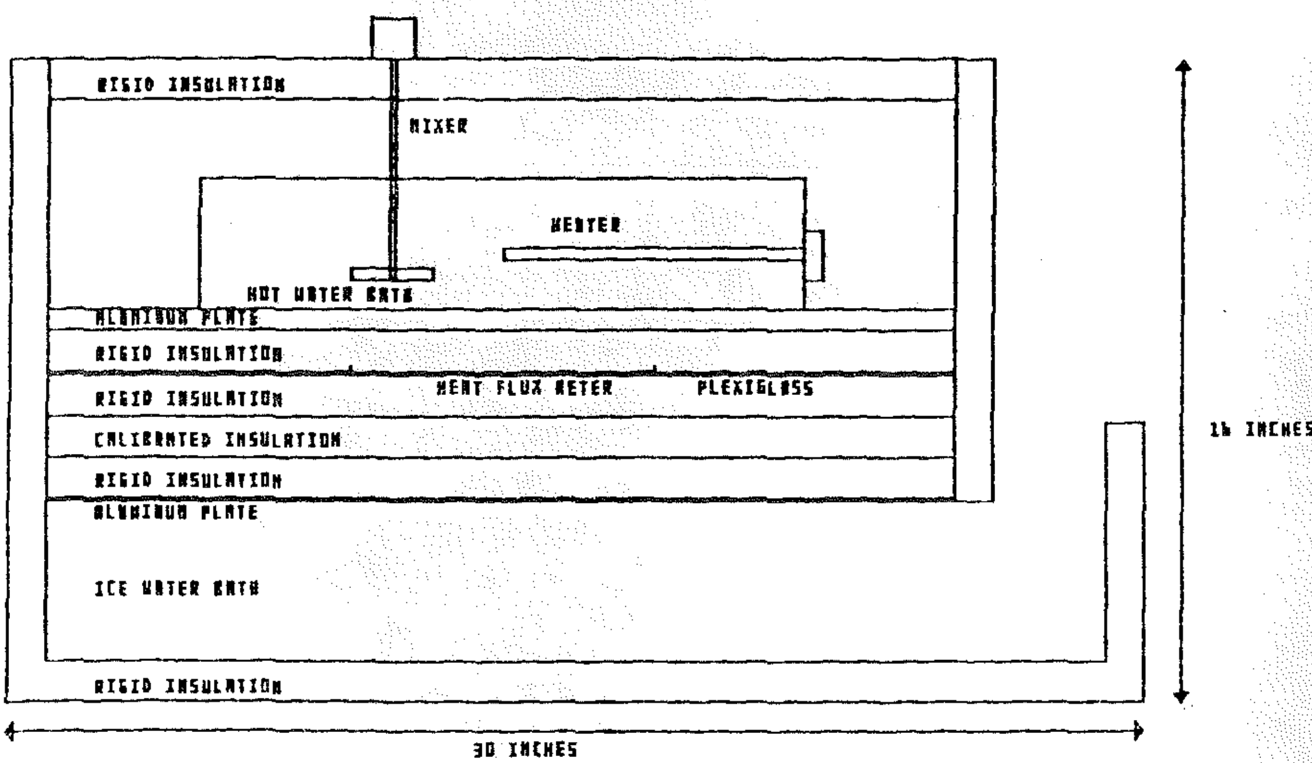

Figure 2. Calibration hot box schematic

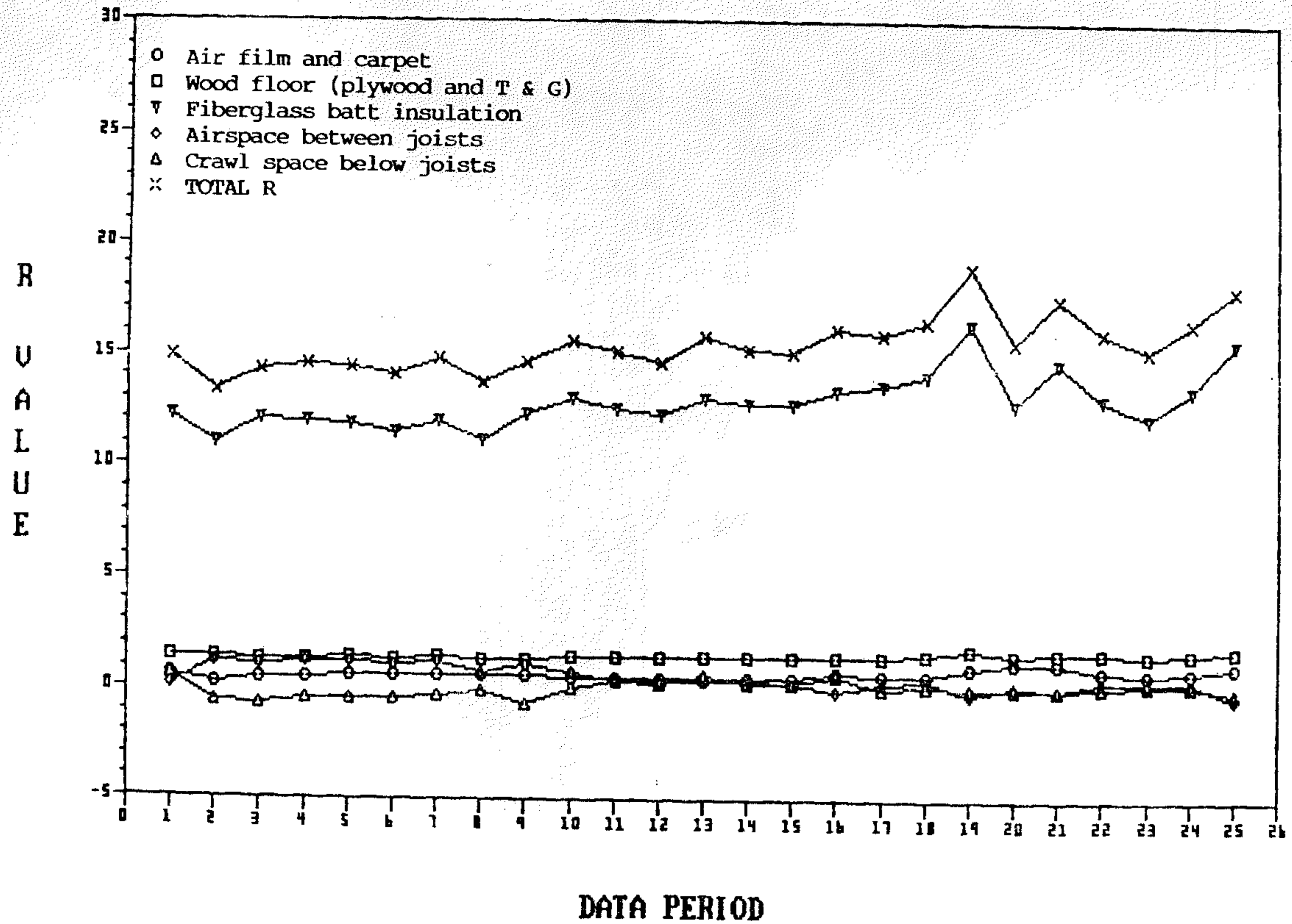

Figure 3. Conventionally insulated floor (section #1) R-values