IN-SITU ASSESSMENT OF TWO RETROFIT INSULATIONS

S.N. Flanders

ABSTRACT

Two retrofit wall insulations were the subject of in-situ R-value measurement and economic assessment of their success for energy conservation. Ft. Lewis, Washington, installed cellulose fiber insulation in the walls of more than 1000 housing units where moisture potentially presented a problem. Ft. Monmouth, New Jersey, added an exterior expanded polystyrene foam insulation system to its many concrete masonry buildings. These represent retrofit insulation methods that have yet to be applied to thousands of military frame and masonry buildings.

The R-value measurement included the use of thermography, heat flux transducers, thermocouples and data acquisition equipment. Holes bored in walls gave independent confirmation of composition of the construction layers. Boroscope inspection of wall interiors and moisture meter readings of framing sought evidence of moisture and confirmation of voids in cellulose insulation. Measurements of the same or similar buildings occurred approximately a year apart. The economic assessment employed Department of Army life-cycle cost criteria.

The results showed no deterioration or moisture effects in the cellulose insulation over the year. However, the installed R-value was between 5% and 19% lower than might be expected from a handbook calculation, depending on the density assumed for the insulation. Thermography revealed that approximately 5% of the wall exteriors received no insulation. The exterior insulation system performed 20% to 50% worse than predicted. Lateral heat flux from the ground is a possible cause.

The cellulose, as installed, delivered a 7 to 1 savings-to-investment ratio (SIR). The exterior insulation system provides an SIR of 1.2 in some cases. This insulation system warrants further study to determine whether lateral heat flow is perhaps a cause of the worse-than-expected performance.

INTRODUCTION

The U.S. Army still has significant numbers of inadequately insulated frame, frame with brick veneer, and concrete block buildings. Blown-in insulation is a likely means for improving frame and brick veneer buildings. Exterior insulation is a possible means for improving concrete block buildings.

The U.S. Army is seriously committed to meeting goals for reducing building energy consumption. It requires that energy conservation improvements be cost-effective under the Energy Conservation Investment Program (ECIP) rules. These rules are based on principles of life-cycle costing, employing a discount rate of 7%, a project life of 15 years, and regional energy cost escalation rates for each fuel. In past projects, improvements in energy system controls and in combustion and energy delivery systems have shown the most potential for cost-effective improvement.

*S.N. Flanders, Research Civil Engineer, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Recently, blown-in insulation and exterior insulation have been employed on building walls on a large scale. For example, more than 1000 family housing units at Ft. Lewis, Washington, received cellulose insulation in empty stud wall cavities, and many buildings at Ft. Monmouth and Ft. Dix in New Jersey and at Ft. Hamilton, New York, have received exterior insulation on concrete block buildings.

The facilities engineering staff at Ft. Lewis was concerned that the cellulose insulation installed in their family housing units would suffer ill effects from vapor drive from within or from the moist Pacific Northwest climate. Cellulose was a contractor-proposed alternative to mineral fiber. The contractor claimed that the cellulose product would be more cost-effective. A purpose of the investigation reported here was to determine whether the product met expectations when freshly installed and after a year in place.

Exterior insulation appears, in principle, to be a cost-effective retrofit technique for masonry buildings in climates with a significant heating season. It typically comprises a thickness of expanded polystyrene insulation bonded or fastened to the exterior surface, and a layer or two of reinforcing plastic or glass mesh imbedded in a stucco-like layer that has a permanently pigmented finish. The product costs 10 to 20 times as much as blown-in insulation per unit of R-value. This requires a colder climate or a more poorly insulated building to justify its use.

Masonry buildings promote lateral heat flow. Exterior insulation makes an important contribution toward diminishing thermal bridges to the outside, but there are still potential problems with window details, wall to roof details, and thermal contact with the ground. These effects are difficult to assess through handbook methods and are part of the motivation for the study reported here.

Previous work (Flanders 1984) has described techniques for obtaining R-values from temperature and heat flux data and for using infrared thermography to place sensors at appropriate locations for monitoring for several days.

FIELD INVESTIGATION

The investigations of blown-in cellulose insulation took place at Ft. Lewis, Washington, in February 1984 and January 1985. The investigations of exterior insulation at Ft. Monmouth, New Jersey, took place in March and December 1984.

The winter climates are typified as 5339 heating-F degree-days (2966 C degree-days) for Ft. Lewis and 5128 F-days (2849 C-days) for Ft. Monmouth. Their respective 97.5% heating design days are 24 and 12 F (-4 and -11 C).

Building Types

Ft. Lewis: The buildings studied were seven wood-frame, single-story family housing duplexes. Figure 1 shows a typical example. The walls, subject to study, were of 2 x 4 construction with 5/8-in (16-mm) sheetrock on the inside and 5/8-in (16-mm) plywood on the outside. These represented an R-value of 2.2 (RSI = 0.39) without added cellulose and an R-value of 12 (RSI = 2.1) at the assumed density of 3.2 lb/ft^3 (51 kg/m^3), according to ASHRAE (1981) handbook data and procedures. Two buildings were the subject of the earlier visit and five the second visit.

The insulation was installed from the outside in two lifts per eight-foot segment of wall because of fire blocking at mid-height. Insulation was installed through a hole at the top of each half-height section.

Ft. Monmouth: Two concrete block barracks-type buildings (360 and 1204) were eachinvestigated twice. Figure 2 shows the two buildings. The R-value measurement of building 360 employed the same sensor sites for both visits. The measurements on building 1204 occurred at sites across the hall from each other. Building 360 with two layers of 4-in (102-mm) concrete block had a handbook R-value of 11 (RSI = 1.9), assuming the 2-in (51-mm) of expanded polystyrene had a density of 1.0 lb/ft^3 (16 kg/m^3). The interior surface was of painted concrete blocks. Building 1204, with 1.5-in (38-mm) expanded polystyrene insulation, one layer of 8-in (203-mm) concrete blocks and a layer of gypsum wall board, had a handbook R-value of 8.4 (RSI = 1.5). The interior surface was painted gypsum wallboard.

Measurement Procedure

The measurement technique combined infrared thermography, the use of heat flux transducers (HFTs) and thermocouples with a data acquisition system, and independent verification methods.

Infrared thermography serves two purposes: to provide an overall appreciation for the types of thermal behavior exhibited by buildings and their extent, and to provide a means for selecting representative sites for placing sensors. A van ride through a neighborhood of family housing with an infrared scanner gives a good appreciation for how many stud bays have not been filled or whether other types of thermal anomalies exist. At closer range from indoors, thermography can highlight the presence of convection cells, studs, webs in concrete blocks, and other anomalies so that the investigator can choose appropriate sensor sites. Successful thermography for these purposes requires anadequate difference in temperature across the construction for an adequate period of time, which varies with the thermal insulation and mass of the construction.

The investigation employed 19 or 20 sensor sites at each building studied. Each sensor site comprised a surface-mounted HFT imbedded in gel toothpaste on the inside and a thermocouple mounted on the outside. Both sensors were covered with masking tape to make them reflect radiant heat in a manner similar to their surroundings. The HFTs had integral thermocouples; this permitted calculation of an estimated R-value according to the formula:

$$R_e = \sum \Delta T / \sum q \qquad (1)$$

where

ΔT = the temperature difference between the inside and outside surface
q = the heat flux through the inside surface.

As reported earlier (Flanders 1985), the use of the heat flux and temperature sensors has a standard deviation of less than 10% from the mean. However, building measurements frequently result in standard deviations of more than 20% because of the variations in building construction.

Sensors were placed in vertical lines of six each on frame walls at Ft. Lewis midway between studs. Sensors were placed 6 in (152 mm) from the top and bottom of the wall and 6 in above and below the fire blocking at mid-height and midway between the fire blocking and the ceiling or the floor.

At Ft. Monmouth, building 360, sensors were placed in four vertical lines of five, spaced to occur at mid-height on every other painted concrete block. Two different data acquisition systems with their dedicated sets of sensors were employed at the same locations during the tests. On building 1204, the sensors were clustered in groups of four at mid-height beneath the nearly full-width windows for the March 1984 measurement. For the December 1984 measurement, they were placed in three vertical lines of six, spaced 6 in (152 mm) apart vertically and 18 in (456 mm) apart horizontally. The horizontal spacing tested the effect of the furring behind the gypsum wallboard as a thermal bridge, since the vertical lines were 2, 4, and 6 in (51, 102 and 152 mm) away from the vertical furring.

Calibration of sensors employed a calibrated hot box. The sensors were placed in the same manner as in the field on a 8- x 8-ft (2438- x 2438-mm) test wall made of polystyrene insulation with a gypsum wallboard surface. Both layers had a known R-value. The sensor locations were randomized for each of three runs. The temperatures, the average EMF from the HFT and the R-value of the test wall were employed to compute a conversion constant for HFT output appropriate for the conditions of measurement, not a pure calibration constant. The results of the calibrated hot box measurement agreed within 3% with the theoretical R-values of the test wall materials.

Independent verification of measured values obtained from HFTs and temperature sensors consisted primarily of drilling holes into walls and using a probe for depth measurements and a boroscope for inspection. No measurements of insulation density were possible because they would have caused unacceptable damage to building finish. At Ft. Lewis an electrical resistance probe-type moisture meter was employed in the sill plates to detect the possible presence of excess moisture. No reading was greater than 12%.

FIELD STUDY RESULTS

The Fort Lewis wall R-value measurement results were, on the average, 5% lower than ASHRAE handbook values both years. Ft. Monmouth produced R-value measurement results that were 50% lower than ASHRAE handbook values in building 360 and, at best, 15% lower than handbook in building 1204. The measured estimates of R-value (R_e) at Ft. Monmouth increased between March and December. Details of the results for the two bases follow.

Fort Lewis

The temperatures in February 1984 ranged from the low 40s F (≈4°C) at night to the high 50s F (≈10°C) during the daytime. In January 1985 the temperatures were cooler - reaching the freezing mark at night and warming up to the low 50s in the day.

ASHRAE (1981) offers handbook R-values based on assumed densities which range from 3.2 to 2.3 lb/ft^3 (51 to 37 kg/m^3). Decreasing density implies increasing R-value for a 3.5-in (89-mm) thickness. Therefore, the corresponding range of handbook R-values for the filled cavity plus the indoor and outdoor wall surfaces would be from 12 to 14 (RSI = 2.1 to 2.5). The average field measurement of R_e = 11.8 (RSI = 2.07) means that the results were between 5% and 19% less than the handbook, depending on which density assumption one chooses. The following discussion assumes a handbook R-value of 12 and an insulation density of 3.2 lb/ft^3.

Table 1 summarizes the differences between measured R_e and the handbook R-value of 12 (RSI = 2.1) as a percentage of the expected value by orientation of the wall measured. The 43 northerly sensor locations rendered results slightly better than handbook and the 24 westerly sensor locations had the lowest results at 12% below handbook.

Convection appeared not to be a significant phenomenon in insulated walls, as Figure 3 (top) demonstrates. However, uninsulated stud bays (Figure 3, bottom) showed distinct evidence of convection with higher normalized R_e values near the top of the space than at the bottom, indicating stratification within the space. In this case, warm air at the top of the space causes low heat flow per unit of temperature difference across the wall and cool air at the bottom causes higher heat flow.

The R_e values for uninsulated bays at Ft. Lewis were double the handbook R-values obtained from casual inspection of a hole drilled into the empty wall. However, closer inspection revealed that the gypsum wallboard had a foil face toward the stud cavity interior. This would increase the empty R-value from 2.2 (RSI = 0.39) to 3.9 (RSI = 0.68). This causes the average R_e to be only 17% greater than the handbook value with an assumed E (internal reflectivity of the combined surfaces) of 0.05.

Independent verification of the R-value measurements came from 0.5-in (13-mm) holes drilled in walls for a depth probe and boroscope. The boroscope demonstrated that all insulation observed was light and fluffy (Figure 4), whether the inspection hole was near the sill plate, the middle of a wall, or near the top. Nine inspection holes were drilled near the tops of stud cavities just below the top plate or the fire blocking. In only two of those instances was there a gap, 0.75 in (19 mm) where present.

Outdoor thermography revealed that, at most, 5% of the wall area in the neighborhoods sampled did not receive insulation. Figure 5 shows an outdoor thermogram of a wall with an unusually large number of inadequately filled bays.

Discussion - Fort Lewis

Fractional standard deviations (the standard deviation/the mean value) of R_e values for groups of sensors or for the entire building give an appreciation for how much the building construction varies from one sensor location to another and how much buildings vary from one to another.

The fractional standard deviation around the mean R_e was computed as a percentage of the mean R_e for each group of three sensor locations. The mean value for the 31 fractional standard deviations obtained was 16%. This value itself varied with a standard deviation of 9%. Contrast this with the 10% fractional standard deviation obtained during calibration and one can conclude that the variability in construction adds about 6% variation to field measurement.

A look at the R_e values obtained for the seven buildings studied gives an indication of the variability of installation of insulation from building to building. The mean R_e for each of the seven buildings was obtained from the 19 R_e values for individual sensor sites. The mean value of these individual means was an R_e of 11.8 (RSI = 2.07). The fractional standard deviation for this grand mean was 12%, which indicates a high consistency of insulation quality.

A designer is likely to base expectations of wall R-value on ASHRAE handbook data. These indicate some variation as a function of density - a 39 percent change in density from 2.3 to 3.2 lb/ft^3 (37 to 51 kg/m^3) gives an 18 percent increase in resistivity. This might suggest density as an explanation of difference between measured R_e and expected R-value.

Other sources, however, suggest a weaker relationship between density and resistivity. Shirtliffe and Bomberg (1978) give an empirical formula which describes thermal resistance as a function of thickness, density, and mean temperature. Substitution of the ASHRAE range of density values into their formula suggests only a 2 percent increase in thermal resistance. Tye, et al. (1980) confirm that thermal resistivity in cellulose is insensitive to density. In their data a 22 percent increase in density caused a 2.1 percent decrease in resistivity. This result is about halfway between the results of Shirtliffe and Bomberg and those in ASHRAE.

Excessive density of cellulose insulation is therefore a weak candidate for explaining the difference between the expected R-value and the measured R_e.

The lack of evidence of moisture in the insulation or framing obtained by boroscope inspection or by the moisture meter indicates that moisture is also not a likely cause of the slightly lower-than-expected R_e values. The absence of moisture problems is consistent with the findings of Tsongas et al. (1981) who inspected 71 homes in Portland, Oregon, which were retrofitted with insulation. They found no evidence of settling or damage from condensation in either cellulose or mineral fiber insulation. The homes involved typically had wood siding and no vapor retarder. The few instances of moisture damage were attributable to a defect in the exterior skin. The study indicated that the principal pitfall for both cellulose and mineral fiber is improper installation.

Measurement error in the aggregate does not appear to be a likely cause of lower-than-expected R_e values because the empty bays consistently have a higher-than-expected Re, even considering the reflective inside surface of the wall cavity.

Fort Monmouth

Whereas the difference in average R_e between the 1984 and 1985 measurements at Ft. Lewis was insignificant, the differences at Ft. Monmouth between the March and December 1984 measurements were great. In both cases the R_e was much lower than the handbook R-value. The temperatures in March were in the 40s F (≈4°C) and in December were in the 50s F (≈10°C) with little diurnal variation.

Building 360, which had sensors placed on exactly the same locations during both measurements, had a mean R_e of 4.5 (RSI = 0.80) in March and 5.9 (RSI = 1.0) in December. These were 58% and 46%, respectively, lower than handbook calculations would predict.

Building 1204, which had measurement sites on opposites sides of a hall and had different sensor configurations both times, had a mean R_e of 3.4 (RSI = 0.59) in March and 7.2 (RSI = 1.3) in December. These were 41% and 15%, respectively, lower than handbook calculations would predict.

When the R_e values for building 360 were normalized by dividing the average Re for four sensor locations at a given height and divided by the average R_e for all sensor locations, the result was nearly identical for both March and December. Figure 6 is a plot of the normalized values, which shows essentially the same curve and error bars for both times, although the absolute R_e values for each curve are different. This indicates that the building - and not the measurement process - caused different R_e values on the two occasions.

To test the hypothesis that the results were different because two different sets of sensors were employed in the successive measurements of buildings 360 and 1204, I looked at the overall pattern for when each set of sensors resulted in a smaller R_e than the handbook R-value or a greater R_e for all the measurements done with the system. Neither system showed a bias in either direction. Furthermore, in the Ft. Monmouth measurements, both systems reported an increased R_e. If they held biases, their biases would have reversed with the two measurement events.

In the December measurements of building 1204 the bottom row of sensor locations, 12 in (305 mm) from the floor, gave R_e values 24% better than the norm for that wall. The top row, about 6 in (152 mm) below the window, gave results 14% lower than the norm. The four in-between rows were within 6% of the norm. This may point out the thermal bridging effect near a window and, conversely, the influence of an interior floor slab on raising surface temperatures of nearby wall areas.

The R_e values at sites 2 and 4 in (51 and 11 mm) away from furring in building 1204 (December) were essentially the same. R_e values at sites 6 in (152 mm) away from furring were about 8% higher than those at 2 and 4 in. The furring was behind a system of masonry and external insulation, so no great variation was expected.

Why is there an apparent change in R-value between March and December 1984? Inspection of the as-built drawings for building 360 reveals that there are ample opportunities for lateral heat flow. For instance: "The exterior finish system shall completely cover exterior columns, except that insulation shall not be installed at the column." Such a column was visible only on the exterior on building 360. Likewise, the roof slab was within a short distance of the top sensors. This would help explain the shape of the curve in Figure 6. It's possible that storage effects, combined with lateral heat flow from massive elements like the roof and columns, affected the repeatability of the measurement of R_e. Uninsulated concrete pilasters were also present in building 1204 both times but were farther removed.

Since the exterior insulation extends only 6 in (152 mm) below grade on both buildings, thermal coupling with the ground is another possible factor. This last possibility is more seasonally appropriate, since the ground would probably still be cooling down in December and might be warmer than in March. The opportunities for these storage and lateral heat flow effects are more pronounced in building 360 than in 1204, which may explain building 360's worse performance in comparison with handbook R-values.

POTENTIAL FOR ENERGY CONSERVATION INVESTMENT

The Army's Energy Conservation Investment Program (ECIP), mentioned in the introduction, is based on life-cycle cost parameters that are tailored to regional economic conditions. The Army ECIP allows heating degree-days to represent seasonal heating loads. As described in previous work (Flanders 1984), it's possible to combine all the criteria into one factor unique to an Army base, or any other economic circumstances, to serve as a quick means for assessing economic return for insulation projects. This factor, the climate-heating cost parameter (CHC), comprises:

$$CHC = 24\ (HDD)\ (PWF)\ (FC)/(EFF) \qquad (2)$$

where

24 = number of hours per day
HDD = heating degree-days (F-day, C-day)
PWF = present worth factor for fuel used (dimensionless)
FC = fuel cost (\$/Btu, \$/W-h)
EFF = efficiency of energy delivered (fraction).

Table 2 outlines the values for computing the CHC parameter for Ft. Lewis and Ft. Monmouth. The section of Ft. Lewis that was studied uses number 2 fuel oil in individual plants for dwellings. This analysis assumes 75% efficiency of the burner and heat distribution system. Likewise, the buildings at Ft. Monmouth have individual oil-fired heating plants.

CHC is the basis for generic curves (Figure 7) for determining the insulation budget ($\$/ft^2$, $\$/m^2$) that will break even under ECIP criteria based on the difference between the initial U-value (1/R-value) and the U-value resulting from the insulation improvement:

$$\text{Budget} = \text{CHC}\ (1/R_i - 1/R_f) \tag{3}$$

where

R_i = initial R-value ($hr \cdot ft^2 \cdot F/Btu$, $m^2 \cdot K/W$)
R_f = final R-value

To use the graph in Figure 7, one chooses the curve that has its base at the initial R-value before re-insulation, R_i, e.g. the curve labeled "handbook" which represents the calculated R_i of 2.24. Follow the curve until it is over the final R-value, in this case the average R_e at Ft. Lewis, and read across to the insulation budget - $\$4.98/ft^2$ ($\$53.61/m^2$). This amount would be justified to break even under the life cycle cost guidelines of ECIP. The "measured" curve represents the average R_i = 4.56 obtained from measuring empty stud bays, offering a budget of $\$1.85/ft^2$ ($\$19.91/m^3$). The error bars show one standard deviation and are flat enough in slope to have a small impact on the budget.

Investment Potential at Fort Lewis

The generalized insulation budget curves for Ft. Lewis demonstrate the difference an assumption about initial R-value can make. The handbook R-value for an uninsulated stud space would be about 2.2 (RSI = 0.39), if one were to ignore the presence of a reflective interior. The average final R_e is about 12 (RSI = 2.1). This results in a budget of about $\$4.97/ft^2$ ($\$53.50/m^2$). However, measurement of several empty stud bays demonstrated that the initial R-value was about 4.6 (RSI = 0.80). This reduces the installation budget to $\$1.84/ft^2$ ($\$19.81/m^2$). Since the actual cost of insulation was about $\$0.25/ft^2$ ($\$2.69/m^2$), the savings to investment ratio (SIR = Budget/cost) was more than seven even with an effective reflecting layer.

Investment Potential at Fort Monmouth

Insulation is blown into a fixed width of cavity at Ft. Lewis; therefore, for a given type and density of insulation there is only one resulting R-value. At Ft. Monmouth the retrofit insulation comes in increments, and this changes how to decide the appropriate insulation thickness.

Figure 8 depicts external insulation costs superimposed on the generalized insulation budget curves. The base of the insulation cost coincides with the initial R-value on the budget curve. The cost line rises vertically to represent the cost of the finish system before any insulation is even installed. Then the cost rises ramp-wise as the thickness of insulation increases. The distributor of a major brand of exterior insulation system in the Ft. Monmouth area gave the figures of $\$2.75/ft^2$ ($\$29.60/m^2$) for the basic system less the insulation and $\$0.50/ft^2 \cdot in$ ($\$2.12 \times 10^{-4}/m^3$) of insulation as a basis for estimation.

If the budget curve that starts at the same point as the cost line rises above the cost line (see the "Bldg 1204" line, Figure 8), then for that segment the SIR is greater than one. That project saves more than it costs for the R-values between points A and B. The building 1204 R-value measurements for both March and December fall between these indicating that the measured value for the insulating system is economically justified, according to current criteria. Note that the building 360 budget line never reaches the insulation cost line.

Figure 8 shows another cost of insulation line (labeled "borderline") which is tangential to a budget curve. These lines start at the maximum initial R-value (2.7 on the graph) which can justify the cost of using the candidate exterior insulation. If the building insulation has a higher initial R-value, the savings will never exceed the cost of insulation, given the life cycle cost parameters that define the budget line. It's possible to determine this maximum initial R-value, R_{ima}, with the equations:

$$R_f = (CHC/CI)^{1/2} \tag{4a}$$

$$F = (CI)\, R_f + (CHC)/R_f + CO \tag{4b}$$

$$R_{ima} = \frac{F - \sqrt{F^2 - 4\,(CI)(CHC)}}{2\,(CI)} \tag{4c}$$

<u>where</u>

CI = Cost per R-value ($\$\cdot Btu/ft^2\cdot hr\cdot F$, $\$\cdot W/m^2\cdot K$)
CO = Cost of system without the insulation ($\$/ft^2$, $\$/m^2$).

These equations derive from the assumption that the slope and value of the cost line is equal to those of the budget curve at R_f.

Figure 8 also illustrates how sensitive the viability of an insulation project is to the initial R-value.

The ratio between insulation cost for a given R-value and insulation budget defines SIR. SIR is greater than one for the points between A and B on Figure 8. But what determines the optimum insulation thickness? Figure 9 shows SIRs for several assumed combinations of CO and CI. All thicknesses between 1 and 2.5 in (25 and 64 mm) give about the same SIR for a given set of assumptions. One can choose lowest first cost above SIR = 1, the optimum thickness where SIR is a maximum, or save the most energy where SIR dips toward 1.0 on the right. Life-cycle cost is insensitive to choice of insulation thickness, if the thickness is greater than 1 in (25 mm).

CONCLUSION

This paper demonstrates that favorable energy conservation investments in additional insulation are possible for some of the Army's underinsulated building types, those of frame or masonry block construction.

The study of cellulose insulation installed in walls at Ft. Lewis showed that the resulting R-value can be significantly below that specified, possibly due to higher-than specified insulation density, only if the relationship between density and resistivity in ASHRAE is plausible. Nevertheless, the installed insulation was an excellent investment with an SIR of better than seven. Inspection of installed insulation through holes in the wall and measurement with an electrical resistance moisture meter showed no evidence of a moisture problem in the Pacific Northwest climate.

The R-value measurement results for two masonry buildings at Ft. Monmouth were lower in March than in December. In both cases, they were significantly lower than handbook calculations would indicate. This is probably attributable to lateral heat flow in the masonry masonry construction beneath the exterior insulation system. The accuracy of the sensors is not implicated here. The sensors in building 360 were mounted on concrete blocks, a material thermally different from the gypsum wallboard on which they were calibrated, but the sensors in building 1204 were on gypsum wall board, consistent with calibration.

A powerful tool, the climate-heating cost (CHC) parameter, allows easy preliminary investment decisions for considering additional insulation. In the case of exterior insulation, this concept allows one to eliminate from consideration all buildings with greater than a threshold initial R-value, given the cost of the insulation finish system and the incremental cost of the insulation itself.

The results of the study demonstrate the value of in-situ measurement of building R-values for assessing the effectiveness of retrofit insulation for purposes of contract monitoring. The results also show how important the technique can be for determining whether a masonry building warrants insulating. At low R-values, a small shift in initial R-value has a big impact on the energy conservation investment potential. Masonry buildings contain concrete of unknown densities that make handbook calculations uncertain. Results of measurement can establish a good estimate of R-value.

Lateral heat flow in the reinsulated buildings at Ft. Monmouth was apparently a cause for worse-than-expected R-values. Better understanding of lateral heat flow in masonry block buildings would help make the finished exterior insulation retrofit design more effective.

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TABLE 1

Differences between R_e and the Handbook R-value of 12 (RSI = 2.1), as a Percentage of the Handbook Value, Organized According to the General Orientation of the Wall at Ft. Lewis. The Handbook Value Is Based on 3.2-lb/ft^3 (51-kg/m^3) Density Cellulose Insulation

Building	North	no.	East	no.	South	no.	West	no.	Total	no.
5954	+7	19							+7	19
9874			-7	16					-7	16
5784	-4	6					+5	6	+1	12
5451					-13	13	-33	6	-19	19
8552			+1	6	-12	7	-18	6	-10	19
5454	-10	12					-1	6	-7	18
8556	+7	7	+7	6	-1	6			+5	19
Totals	+1	43	-2	28	-10	26	-12	24	-5	122

TABLE 2

Economic and Climate Assumptions for Computing CHC for Ft. Lewis and Ft. Monmouth. Explanation of the Variables is in the Text with Equation 2.

Parameter	Ft. Lewis	Ft. Monmouth
HDD (F-days)	5339	5128
PWF*	11.45	11.345
FC ($/BTU)	$6.98*10^{-6}$	$7.5*10^{-6}$
EFF	0.75	0.75
CHC (F·h/Btu)	13.78	13.97

*(oil, i = 7.5%, t = 15 years)

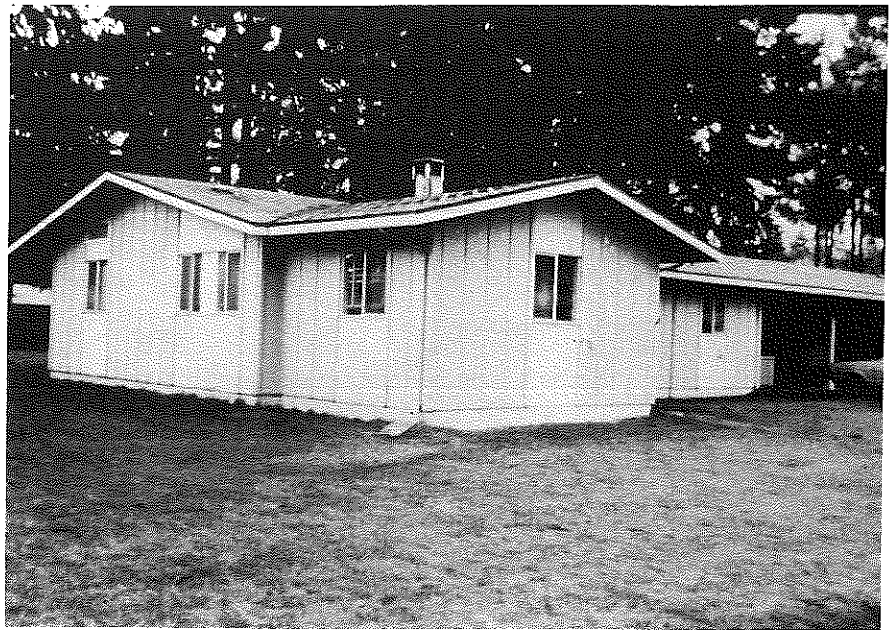

Figure 1. Typical frame duplex family dwelling subject to R-value measurement at Fort Lewis, WA

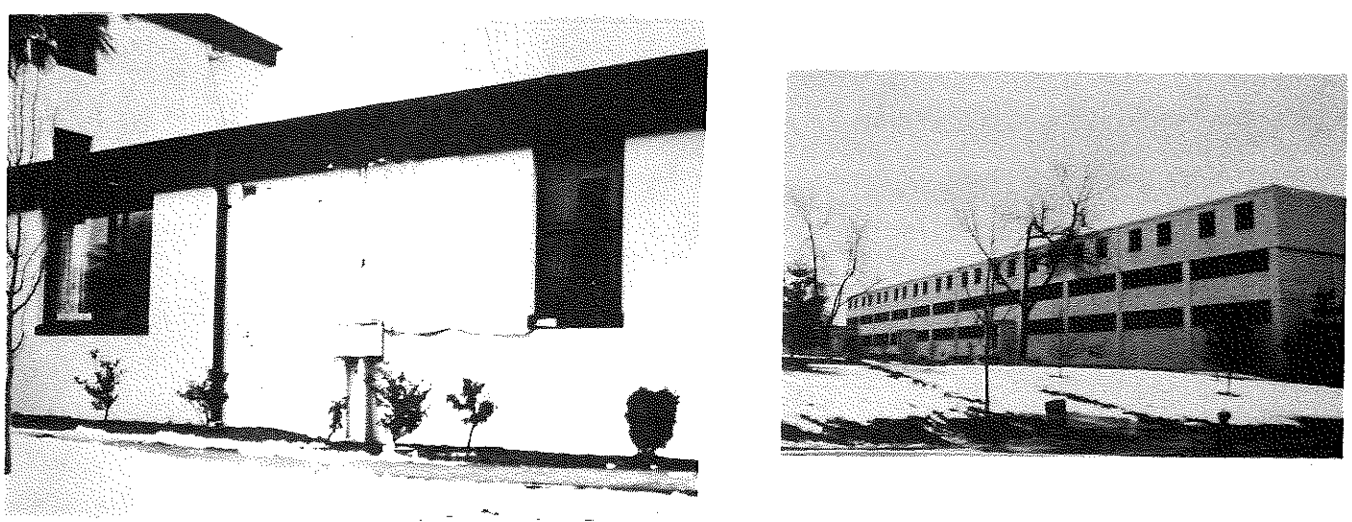

Figure 2. Masonry buildings with exterior insulation systems subject to study at Fort Monmouth, NJ. Building 360 (left) had 2.0 in (51 mm) of expanded polystyrene (EPS) insulation; Building 1204 (right) had 1.5 (38 mm) of EPS insulation

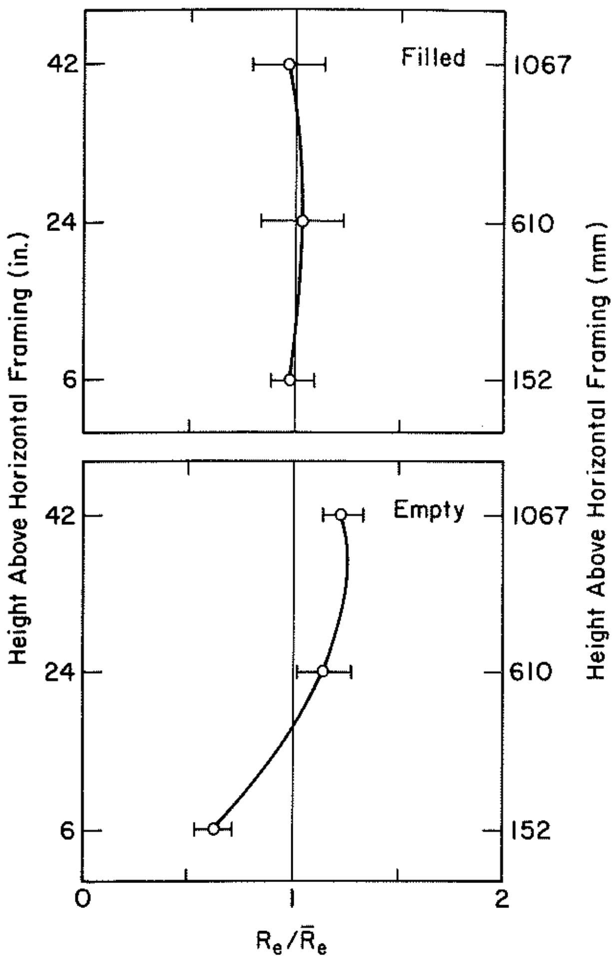

Figure 3. Average measured estimate of R-value (Re) at each height above the horizontal framing normalized to the average Re for all heights for buildings studied at Fort Lewis. The top represents all uninsulated portions of buildings which were studied. Error bars represent one standard deviation. Horizontal framing here may be either the sill plate or the mid-height fire blocking in a wall

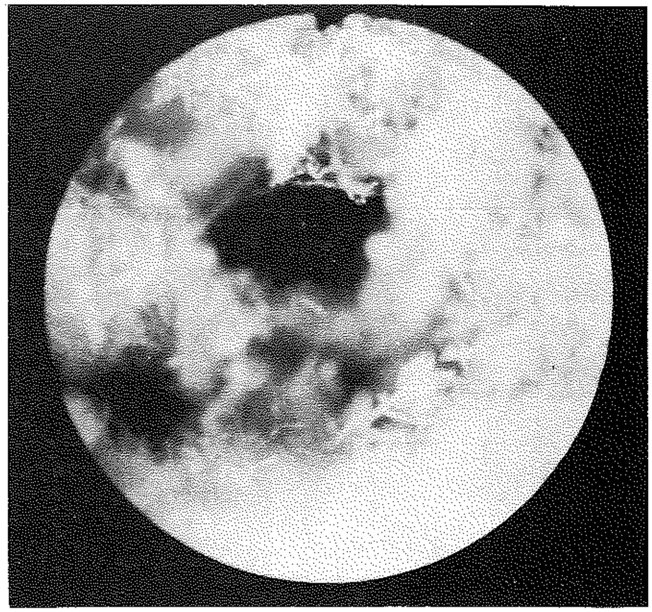

Figure 4. Typical view of cellulose fiber insulation obtained with a boroscope after making a hole in the wall. Note the fluffy quality of the insulation

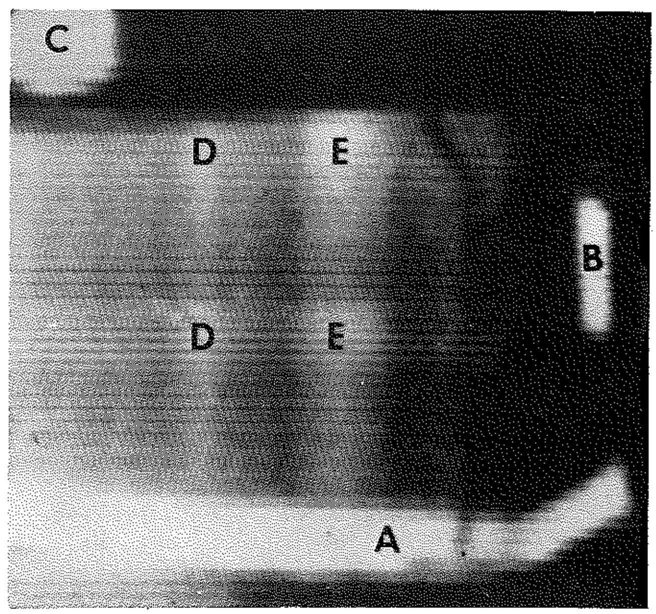

Figure 5. Typical thermogram of exterior of a Fort Lewis dwelling. The foundation slab (A) loses heat readily and shows as a light band at the building's base. A window (B) and a chimney (C) are also radiant heat sources. Two empty stud bays are evident (D and E)

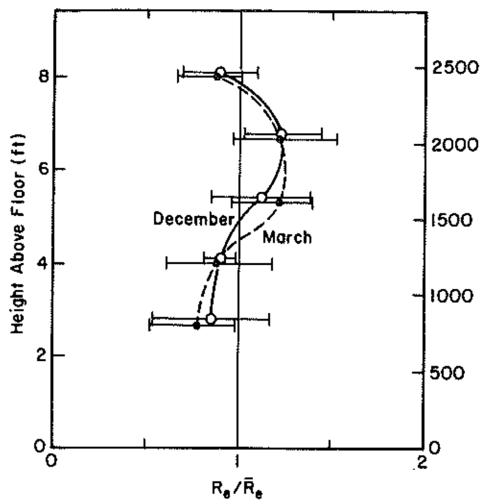

Figure 6. Average Re for each height above the floor of building 360 normalized to the average Re for all readings for two separate measurement periods in 1984. Error bars represent one standard deviation

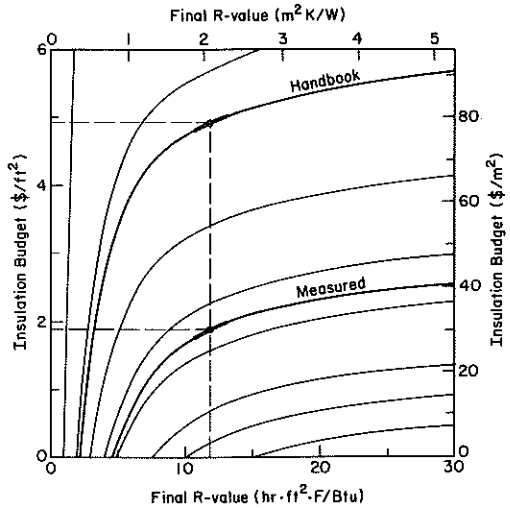

Figure 7. Insulation budgets for Fort Lewis. To use the graph, one chooses the curve that has its base at the initial R-value before reinsulation, Ri, e.g., the curve labeled "handbook" which represents the calculated Ri of 2.24. Follow the curve until it is over the final R-value, in this case the average Re at Fort Lewis, and read across to the insulation budget - $4.98/ft²$ ($53.61/m²$). This amount would be justified to break even under the life cycle cost guidelines of ECIP. The "measured" curve represents the average Ri = 4.56 obtained from measureing empty stud bays, offering a budget of $1.85/ft²$ ($19.91/m²$). The error bars show one standard deviation and are flat enough in slope to have a small impact on the budget

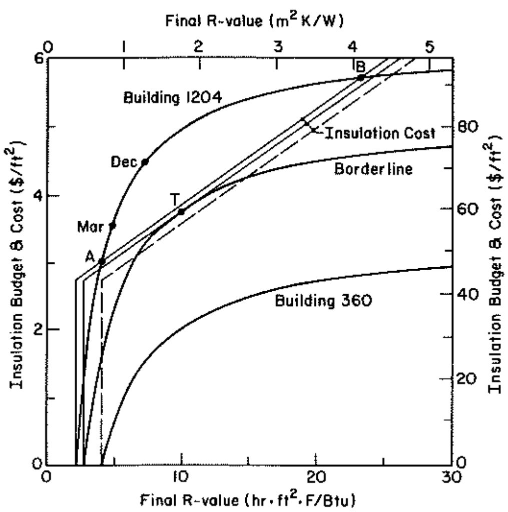

Figure 8. Insulation budgets and costs per unit are for Fort Monmouth buildings 1204 and 360. The cost lines rise vertically from the initial R-values which they share with the budget lines; this represents the cost of the finish system alone. The cost lines then slope with increasing final R-value to represent the cost of adding insulation. Building 1204 has a bigger budget than insulation cost between points A and B. The average R_e values for both March and December fall within this region. The budget line, labeled "borderline", rises from R = 2.7, the maximum R_i that still warrants insulating R_{ima}, and is tangential to the cost line at T

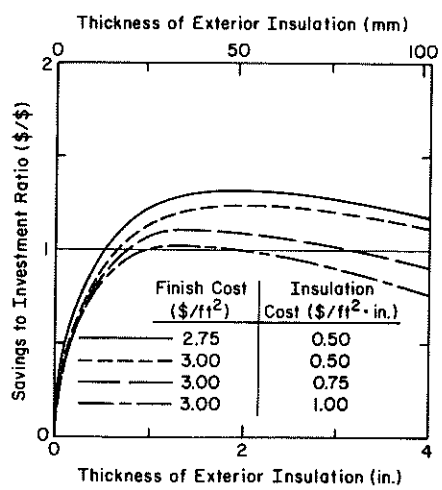

Figure 9. Savings to investment ratios for building 1204 at Fort Monmouth. The top curve represents the ratio of budget to cost for the building 1204 obtained from Figure 8