A FIELD SURVEY OF THE PERFORMANCE PROPERTIES OF INSULATION USED TO RETROFIT CAVITY WALLS OF RESIDENCES

Walter J. Rossiter, Jr., John L. Weidt and Robert J. Saxler

ABSTRACT

A study was conducted to obtain information on the performance of retrofit insulations which had been installed in the sidewalls of existing residences. Most of the thirty-nine houses included in the study had wood-frame sidewall construction and were located in the mid-West, mid-Atlantic and Northeast.

The insulations represented those commonly used in the United States to retrofit sidewalls of housing: urea-formaldehyde based foam, loose-fill cellulose, and loose-fill mineral fiber. With few exceptions, the insulations had been installed in the sidewalls at least 2 years prior to their examination and their ages ranged from about one and a half to ten years.

In the field phase of the study, small sections of sidewalls were opened in the late fall or early winter and the retrofit insulations were examined. Observations were made on performance factors such as: the completeness of filling the cavity, the condition of the insulation and wall components, and evidence of moisture accumulation such as water stains on sheathing, studs and other wall components.

Shrinkages of urea-formaldehyde based foams, and voids within loose-fill insulations were measured. Shrinkage was observed to have occurred for all urea-formaldehyde based foam specimens. For those seventeen cases in which the foam was not excessively cracked and the linear shrinkage was measurable, it was found to be within a range of 4 to 9 percent. For the six test houses containing loose-fill insulation which were opened at the top of the wall cavity, only one with cellulose contained a void at that location. It could not be determined whether the void was attributable to settling of the insulation or initial incomplete fill of the cavity.

In the laboratory phase of the study, insulation specimens removed from the walls of the residences were tested to determine their density, thermal resistivity and moisture content. In addition, the pH of the urea-formaldehyde based foam specimens was determined. Results of the laboratory measurements are discussed and compared with data and information obtained from other studies. Results indicated that the retrofitting of the inspected sidewalls was for the most part accomplished without adverse effect upon them.

1. INTRODUCTION

A result of the energy crisis has been the retrofitting of residences. Effective retrofitting not only contributes to the nation's efforts to conserve energy, but provides a means for the individual homeowners to reduce heating-fuel consumption and save heating-fuel costs. Shortly before the onset of the energy crisis in 1973 it was estimated[1] that nearly 20 percent of the energy used for residential heating and cooling could be conserved by effective retrofitting of residences. Common techniques for the retrofitting of residences include the addition of thermal insulation to walls, ceilings and floors, the installation of storm windows and doors,

* Walter J. Rossiter, Jr., Research Chemist - Center for Building Technology National Bureau of Standards, Washington, DC; John L. Weidt, Architect and Robert J. Saxler, Architect - John Weidt Associates Inc., Chaska, Minnesota.

and caulking and weatherstripping of windows, doors and cracks where air may infiltrate. Effective retrofitting not only requires that proper and durable materials be used, but that the materials be correctly installed.

Of the retrofit techniques mentioned above, perhaps that most generally questioned is the addition of insulation to walls. This technique has been open to question mainly because it involves the application of insulation to an inaccessible cavity which may contain unknown and unseen objects or obstructions. Moreover, the insulation usually cannot be inspected after installation, although infrared thermography may be used for inspection of the insulated wall. Changes which may occur to reduce the effectiveness of the insulation or deleterious effects on wall components due to retrofitting may go undetected or not be observed until long after the insulation has been installed.

This paper presents a summary of the major observations and findings of a study of cavity walls of residences which have been retrofitted with thermal insulation. An expanded report describing the results of the study is also intended for publication.[2] The objectives of the study were to determine several properties and performance characteristics of retrofitted insulations removed from cavity walls, and to obtain information concerning the effects of the retrofitted insulations on the walls of residences. Information obtained from the study may be used in formulating guidelines to assure the proper and adequate retrofitting of sidewalls to conserve energy.

1.1 Background

The thermal insulations commonly used to retrofit exterior walls of residences for energy conservation are loose-fill cellulose, loose-fill mineral fiber, and urea-formaldehyde based foam. A considerable body of information concerning the properties and performance of these insulations has been developed from laboratory studies. A review of this information has recently been given[3]. Less information is known about the properties and performance of these insulations after they have been installed in walls of residences.

An economic basis for retrofitting sidewalls exists, since Petersen has shown[4] that blowing insulation into exterior walls may be cost-effective in many areas of the United States. It is noted that Petersen's analyses incorporated laboratory measured thermal properties of the insulation. Burch, Siu and Powell have indicated[5] that the total thermal transmittance of retrofitted walls may sometimes be higher than the predicted values, which are based on laboratory-determined thermal conductivity values.

Factors such as the settling of loose-fill insulation, shrinkage of foam insulation and the accumulation of moisture within insulations may reduce their insulating effectiveness. Moreover, according to these authors,[5] substantial moisture accumulation may result in unwanted effects such as paint failures, buckling and warping of wooden siding and, in isolated cases, rotting of wood. Other performance factors which are important to the successful retrofitting of sidewalls include the completeness of the installation and compatibility with components of the wall. For example, the insulation should not contribute to corrosion of metal objects in the wall.

In spite of concerns such as these, few field studies on the effects of retrofitting exterior walls have been reported. As part of their comprehensive study to evaluate the energy conservation achieved in retrofitting a wood-frame residence, Burch and Hunt[6] compared the thermal performance of loose-fill cellulose, loose-fill mineral fiber and urea-formaldehyde foam insulations which were used to retrofit the exterior walls of a residence in suburban Washington, D.C. Among their findings they reported that approximately 3 years after installation, no settling of the loose-fill materials was observed in the walls, while approximately 2 years after application, the urea-formaldehyde foam was seen to have undergone a linear shrinkage of about 8 percent.

The most extensive field examination involving retrofitted residential sidewalls, reported to date, was conducted by Weidt.[7] As part of the study performed in Minnesota, the sidewalls of twenty-two residences were opened to examine the insulations and measure their properties. Six of the houses contained loose-fill cellulose, four contained loose-fill mineral fiber and twelve had urea-formaldehyde based foam. In general, the thermal conductivities of all insulations removed from these houses were found to be relatively close to expected values determined from laboratory measurements. Moisture contents of the insulations were found to be low, particularly in the case of the cellulose specimens which were lower than expected. It is noted that the investigation was conducted during the summer time. Settling of loose-fill insulations was not a parameter investigated in the Minnesota study. Linear shrinkage of urea-formaldehyde foams was determined and found to range from 2.5 to 9 percent. The average linear shrinkage of the foam specimens in the twelve houses was reported to be 4.5 percent.

Another field survey, sponsored by the U.S. Department of Energy, the Oregon State Department of Energy and others, was conducted in early 1979 in the state of Oregon. This study was intended to determine the moisture contents of installed insulations and wooden wall components. Results of this study were recently presented at the ASHRAE/DOE Conference on the thermal performance of the exterior envelopes of buildings.

Because few field studies have been conducted to determine the properties and performance of insulation used to retrofit exterior walls, additional information from field studies was considered necessary to assist in formulating recommendations and guidelines for the retrofitting of residences. If field studies indicated that retrofitting of sidewalls could be accomplished successfully and without adverse effect, encouragement to install wall insulation might be given to homeowners.

2. CONDUCT OF THE STUDY

Thirty-nine houses were included in this study. The sidewalls of most of these houses were of typical wood-frame construction, although one house consisted of masonry construction. The insulations were those commonly used in the United States to retrofit sidewalls. Twenty-five of the houses contained urea-formaldehyde based foam insulation, eight contained loose-fill cellulose insulation, and six contained loose-fill mineral fiber insulation. The field examinations were conducted between late November, 1978, and early January, 1979.

The general procedure for determining the retrofit insulations was as follows: a small section of the sidewall, about 0.4 to 0.6 m^2 (4 to 6 ft^2), was opened from the exterior by removing the siding and sheathing, or less commonly, from the interior by removing the gypsum board or other interior surface material; the insulation was inspected, and appropriate measurements and observations recorded; wall component materials were also observed to determine if they had been affected by the presence of the insulation; a sample of the insulation was removed, sealed in polyethylene, and packaged for shipment to the testing laboratory; the mass (weight) of the insulation sample and the volume of the wall cavity from which the insulation was removed were determined; the wall cavity was re-insulated with glass fiber batt insulation; and, finally, the wall was closed and restored to its original condition.

Volunteer homeowners were the source of test houses included in the study. Many homeowners offered the use of their residences as test houses in response to a widely-published news release which outlined the study and asked for volunteers. The volunteered houses were considered as being eligible for inclusion in the study according to the following set of criteria:

- the insulations should have been installed as a retrofit material and consist of loose-fill cellulose, loose-fill mineral fiber or urea-formaldehyde based foam;
- the installation should in general have occurred two years prior to examination;
- each generic type of insulation examined should have been produced by a number of different manufacturers and/or applied by a number of different installers; and
- the test houses should have been located in various geographic areas including the north-eastern, mid-Atlantic, mid-western, and south-eastern regions of the country.

The thirty-nine houses in the study were chosen from among those considered eligible to provide a convenient schedule with minimal travel costs. The criterion concerning location of the test house was considered to be particularly important in the case of urea-formaldehyde based foam insulations. It was desired to examine foams in houses located in areas which experience prolonged seasons of relatively high temperatures and high humidities such as the lower south-east. The performance of foam insulations exposed to combined high temperatures and high humidities had been previously questioned and considered to be suspect.[8] However, few houses containing urea-formaldehyde based foams were volunteered from the lower southeastern region of the country. The practical aspects concerning time and travel prohibited the examinations of those few houses containing foam which were volunteered from the lower southeastern regions.

The houses selected for study were located in Connecticut, Indiana, Kentucky, Maryland, Minnesota, Ohio, Virginia, and the District of Columbia. A two-person team consisting of a skilled carpenter and a project manager conducted each wall opening and field inspection of the insulation. At times, observers such as National Bureau of Standards' research staff were present at the field site. Table 1 lists the cities near which the test houses were located, the months and years in which the field examinations occurred, the total number of insulations examined in each city, and the number of each type of insulations examined in each city. The order of the cities listed in Table 1 gives the itinerary followed by the inspection team.

During the examination of the retrofitted sidewalls, visual observations were made concerning the condition of the insulation and of the wall components. Observations included such parameters as the condition of the paint and/or siding, corrosion of metal wall objects such as electrical boxes and accessories, the color of the insulation, cracking or separation in the insulation and evidence of moisture accumulation, odor, wood rot, fungus or mold, and vermin. Other factors noted were the completeness of the insulation application and the presence of membrane type vapor barriers within the insulated cavity.

Laboratory determinations of density, thermal resistivity and moisture content were conducted on all insulation samples. In addition, measurements were made of the pH of the foam samples at the surfaces corresponding to the inner and outer faces of the wall cavity, and also within the center of the foam. The size of voids due to settling or incomplete application of loose-fill materials was measured and linear shrinkage of urea-formaldehyde based foam insulation was determined.

3. RESULTS

3.1 Field Observations

3.1.1 Conditions of Insulations and Wall Components. Voluminous notes concerning the condition of the insulations and wall components were assembled during the field examinations. It may be generally summarized that no observations were recorded for the thirty-nine houses which indicated that the retrofitting of the sidewalls had adversely affected the conditions of the wall components in the examined wall areas. No visible evidence of excessive moisture accumulation or damage was found, except in the case of one house. However, in this case, the moisture was attributed to a leak around a window frame which caused wood rot of the framing studs and a high moisture content in the cellulose insulation within the cavity. With this exception, no deterioration of studs, sheathing or siding was seen in the test houses at the locations where the sidewalls were opened.

It should not be construed that all walls and components examined were free of problems. However, observed problems were minor and could not in general be directly attributed to the retrofit. For example, fourteen of the twenty-nine painted houses were described as having paint problems including cracking, blistering, peeling and mold growth. In all these cases, the problems were observed on both insulated and uninsulated painted walls (for example, the walls of garages and gables). The few electrical junction boxes or other metal components found in the opened walls of five of the houses were in good condition and corrosion, if any, was minimal.

Very minor fungus or mold growth was visible in the cavities of three houses. None of the walls was examined with a magnifying lens. An unusual case of fungus growth was found for one urea-formaldehyde based foam installation. The fungus was growing on the exterior painted surface of the plugs which sealed the insulation application holes. Dark round spots were visible on many sections of the walls, even when viewed at some distance from the house. These spots reduced the attractiveness of a well-maintained home. No fungus was seen within the open wall cavities of this house.

It is interesting to note that a homeowner who had installed a urea-formaldehyde based foam stated that a formaldehyde odor had lingered in the house (no. 10) several months after completion of the retrofit, but the odor had stopped before the field investigation. The field investigators did not detect any formaldehyde odor within the residence. However, upon opening the sidewall from the exterior, an odor described as that of formaldehyde was detected within the cavity by the investigators. Formaldehyde odors were not reported by homeowners nor detected by the investigators in the cavities of the other twenty-four houses surveyed in which foam had been applied. In one house, a urea-formaldehyde based foam had been installed from the interior of the residence and many application holes were left free and not sealed for many months after the foam was installed. In this case, it might be assumed that if excess formaldehyde was liberated from the foam, an odor would have readily been detected by the occupants of the house. It is emphasized that these findings concerning formaldehyde release from foams are subjective. The field survey was not intended to address directly the subject of formaldehyde release.

3.1.2 Settling of Loose-Fill Insulations. Settling of loose-fill insulations is a phenomenon which may result in decreased thermal performance of the insulated wall. The tops of the wall cavities in six of the fourteen houses retrofitted with loose-fill insulation were inspected to determine the completeness of the application or the presence of voids at these locations. Three of these houses contained cellulose and three had mineral fiber insulations. It was the intent of the study to examine the tops of the wall cavities in all houses containing loose-fill insulations. Unfortunately, factors such as the type of construction, ease of siding and sheathing removal without damage to the residence, and restrictions set by homeowners concerning wall areas available for examination limited the number of test houses which could be opened at the top of the cavity.

For the six houses inspected at the top of the wall cavity, five were found to be filled completely with the loose-fill insulation and no voids were evident. One loose-fill cellulose insulation was seen to have voids at the top of the opened cavities. It could not be determined whether the voids were attributable to settling of the insulation or initial incomplete filling of the cavity.

3.1.3 Shrinkage of Urea-Formaldehyde Based Foam Insulations. Shrinkage of urea-formaldehyde based foam insulations is an important performance factor, since gaps, cracks, and splits resulting from shrinkage are void spaces in which air may circulate and thus reduce the thermal efficiency of the foamed wall.[5,8] Based on the results of the field inspections of twenty-five houses which were retrofitted with foam insulations, and for the performance factors for which information was recorded, foam shrinkage was considered to be of most concern.

Shrinkage had occurred in all inspected sidewalls containing urea-formaldehyde based foam insulation. Table 2 presents the percent linear shrinkage as well as the age and density of the foams, the designation of the manufacturer, and the city in which the test houses were located. In general, the percent linear shrinkage was calculated from measurements of the width of the foam specimen and of the wall cavity. Shrinkage was measured in the width of the cavity since this dimension was accessible without disturbance of the foam. It can be seen in Table 2 that shrinkage values were obtained for seventeen of the twenty-five houses inspected. The linear shrinkage values ranged from about 4 to 9 percent, with an average value of 6.0 percent. The average value of 6.0 percent was slightly greater than the 4.5 percent previously reported by Weidt in the Minnesota study[7] and considerably higher than the 1 to 3 percent range often quoted in many sources.[8] The percent linear shrinkage could not be measured for eight of the twenty-five houses for two reasons. In four of the eight houses, gaps, cracks, and voids in the foam specimens were too numerous to allow a shrinkage determination. In the other four cases, the presence of batt insulation within the cavities precluded the shrinkage measurements.

Comparisons of the percent linear shrinkage with parameters such as foam density, age, and geographic location indicated little relationship between the compared variables. As one example of such a comparison, Figure 1 is a plot of the density of the foam specimen versus the percent linear shrinkage.

3.1.4 Workmanship. Workmanship during retrofitting is an important parameter influencing the thermal performance of a retrofitted sidewall, and poor workmanship may result in insulated walls with less than expected thermal efficiencies. Factors associated with poor workmanship include incomplete application of the insulation, installation of an inferior quality material (which, for example, may settle or shrink excessively), and damage to the wall or wall components. Observations relating to workmanship were noted where possible during the field survey.

For the thirty-nine houses inspected, workmanship was in general found to be satisfactory, although the inspected houses were not free of workmanship problems. The survey produced no evidence to indicate widespread problems due to poor workmanship. Nevertheless, sufficient isolated problems were seen to serve as a warning that acceptable practice should be diligently followed during the retrofitting of sidewalls. Some of the problems found in the study which may be associated with the quality of workmanship included: the previously-mentioned house containing cellulose insulation which may have settled in the cavity or which may have been incompletely installed; one cellulose installation in which a cavity contained no insulation; four urea-formaldehyde based foam installations in which cavities were not completely filled with the insulation; and two cases (one foam and the other mineral fiber) wherein excessive pressure was applied during application which resulted in cracking and bowing of interior wall surfaces.

Qualitative comparisons of foam samples of the same brand name indicated that quality varied within a brand. Some of the foams were considered to be relatively good, while others with the same brand name were described as relatively poor. The relatively good foams had undergone a lesser amount of shrinkage and contained fewer cracks, gaps and voids than those which were relatively poor. The question may be asked whether these observed differences between the quality of foams with the same brand names were due to differences in workmanship during application.

The interiors of electrical outlet and switch boxes in a few houses were inspected for the presence of insulation. Each type of material was found to some degree in some boxes. A urea-formaldehyde based foam had completely filled one outlet box. In one case each, a cellulose and a mineral fiber sample were found in electrical boxes, and filled about 25 percent of the volume of the boxes. In other cases, the inspected electrical boxes were free of insulation. Reasons why insulation was found in some electrical boxes and not others were not determined. It was not known whether any installers had removed insulation from electrical boxes.

It is interesting to note that for seven of the test houses, a retrofit insulation (six urea-formaldehyde based foams and one cellulose) was applied to wall cavities which contained batt insulation. For the small sections of the wall cavities inspected in these seven cases, the presence of batt insulation did not adversely affect the application of the retrofit insulation. The wall cavities were completely filled, since the retrofit insulation compressed the batt to one side of the cavity. In two of the seven cases, the urea-formaldehyde based foam was seen both to have compressed the batt and intermingled with it. Even in these cases, the wall cavities were filled with insulation.

3.2 Laboratory Measurements

Insulation samples were removed from the walls of the houses, sealed in plastic and sent to a commercial testing laboratory. This laboratory was chosen because of its capability and experience in testing thermal insulations. Laboratory measurements of density, thermal resistivity and moisture content were conducted on all samples. The pH of the urea-formaldehyde based foams was also determined.

3.2.1 Density. Density is an important property for characterizing retrofit insulations. Manufacturers generally have installation guidelines regarding the proper density at which their materials should be applied. Application of the retrofit insulations at densities other than recommended may result in decreased thermal performance of an insulated wall. For example, loose-fill insulation applied at loo low a density may settle.

The density of the retrofit insulation was determined by one of two methods, depending upon whether the material was a loose-fill or foam insulation. For loose-fill insulation, a sample was removed from the wall and the volume of the resulting void was determined using a rule graduated in millimeters. The mass of the sample was measured both in the field and in the laboratory. The density was calculated from the mass and volume measurements. For urea-formaldehyde based foam, the density was calculated from mass and volume measurements conducted in the laboratory on foam samples which contained no cracks or fissures.

The densities of the loose-fill insulations are given in Table 3 and the foam densities are presented in Table 2. The cellulose samples showed a density range of 41.6 to 67.2 kg/m^3 (2.6 to 4.2 lbm/ft^3), with an average density of 54.8 kg/m^3 (3.4 lbm/ft^3). The density values for cellulose were considered to be close to values reported in other field studies.[6,7] For example, in the Minnesota field study, Weidt found[7] that the density of cellulose ranged from 52.9 to 67.5 kg/m^3 (3.3 to 3.9 lbm/ft^3) with an average density of 58.5 kg/m^3 (3.7 lbm/ft^3).

The mineral fiber samples in the present study were seen to have a wide range of values, from 27.2 to 140.9 kg/m^3 (1.7 to 8.8 lbm/ft^3), and thus no average value was calculated. One rock or slag fiber sample (no. 34) with the density of 27.2 kg/m^3 (1.7 lbm/ft^3) contained a a number of voids which mice apparently created in the insulation. The calculated density of this sample was not corrected to consider the presence of the voids. The other two rock/slag fibers samples (nos. 37 and 38) were found to have densities higher than expected, with values of 140.9 and 126.5 kg/m^3 (8.8 and 7.9 lbm/ft^3).

foam had been applied. In one house, a urea-formaldehyde based foam had been installed from the interior of the residence and many application holes were left free and not sealed for many months after the foam was installed. In this case, it might be assumed that if excess formaldehyde was liberated from the foam, an odor would have readily been detected by the occupants of the house. It is emphasized that these findings concerning formaldehyde release from foams are subjective. The field survey was not intended to address directly the subject of formaldehyde release.

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For the six houses inspected at the top of the wall cavity, five were found to be filled completely with the loose-fill insulation and no voids were evident. One loose-fill cellulose insulation was seen to have voids at the top of the opened cavities. It could not be determined whether the voids were attributable to settling of the insulation or initial incomplete filling of the cavity.

3.1.3 Shrinkage of Urea-Formaldehyde Based Foam Insulations. Shrinkage of urea-formaldehyde based foam insulations is an important performance factor, since gaps, cracks, and splits resulting from shrinkage are void spaces in which air may circulate and thus reduce the thermal efficiency of the foamed wall.[5,8] Based on the results of the field inspections of twenty-five houses which were retrofitted with foam insulations, and for the performance factors for which information was recorded, foam shrinkage was considered to be of most concern.

Shrinkage had occurred in all inspected sidewalls containing urea-formaldehyde based foam insulation. Table 2 presents the percent linear shrinkage as well as the age and density of the foams, the designation of the manufacturer, and the city in which the test houses were located. In general, the percent linear shrinkage was calculated from measurements of the width of the foam specimen and of the wall cavity. Shrinkage was measured in the width of the cavity since this dimension was accessible without disturbance of the foam. It can be seen in Table 2 that shrinkage values were obtained for seventeen of the twenty-five houses inspected. The linear shrinkage values ranged from about 4 to 9 percent, with an average value of 6.0 percent. The average value of 6.0 percent was slightly greater than the 4.5 percent previously reported by Weidt in the Minnesota study[7] and considerably higher than the 1 to 3 percent range often quoted in many sources.[8] The percent linear shrinkage could not be measured for eight of the twenty-five houses for two reasons. In four of the eight houses, gaps, cracks, and voids in the foam specimens were too numerous to allow a shrinkage determination. In the other four cases, the presence of batt insulation within the cavities precluded the shrinkage measurements.

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For the thirty-nine houses inspected, workmanship was in general found to be satisfactory, although the inspected houses were not free of workmanship problems. The survey produced no evidence to indicate widespread problems due to poor workmanship. Nevertheless, sufficient isolated problems were seen to serve as a warning that acceptable practice should be diligently followed during the retrofitting of sidewalls. Some of the problems found in the study which may be associated with the quality of workmanship included: the previously-mentioned house containing cellulose insulation which may have settled in the cavity or which may have been

A recent reference has indicated[3] that the range of installed densities for loose-fill rock or slag wool is about 24.0 to 40.0 kg/m^3 (1.5 to 2.5 lbm/ft^3), and for loose-fill glass fiber 9.0 to 16.0 kg/m^3 (0.6 to 1.0 lbm/ft^3). This reference does not distinguish between the density of these insulations applied in open areas such as attics and closed spaces such as wall cavities. In particular, the cited values for the density of loose-fill glass fiber are considered to pertain to applications in open areas. The upper limit of the cited density range for rock or slag wool is applicable to wall cavities. In this regard, it has been reported[9] that the densities for loose-fill glass fiber and loose-fill rock or slag wool, as recommended by the industry for application of these insulations in wall cavities, should be 32.0 kg/m^3 (2.0 lbm/ft^3) and 40.0 kg/m^3 (2.5 lbm/ft^3), respectively.

From Table 3, it can be seen that with the exception of the sample with voids (no. 39) density values for the loose-fill rock/slag fiber samples in this study were higher than the density values cited in the literature.[3,8] On the other hand, the literature cited density of 32.0 kg/m^3 (2.0 lbm/ft^3) for loose-fill glass fiber was within the range of values found for the samples in the field survey. The density of sample no. 36 was 45 percent higher than the literature value. This percentage represented the largest variation of the density values of the glass fiber samples from the literature cited value. In addition Burch, Siu and Powell reported that the density of the glass fiber specimen in their study was 32.2 kg/m^3 (2.1 lbm/ft^3).[5] This value was also within the range of densities for the glass fiber samples in the present study.

The densities (Table 2) of the urea-formaldehyde based foam insulations ranged from 5.4 to 18.4 kg/m^3 (0.34 to 1.15 lbm/ft^3), with an average value of 11.5 kg/m^3 (0.72 lbm/ft^3). The range of densities for these foams is generally reported to be about 10.0 to 14.0 kg/m^3 (0.6 to 0.9 lbm/ft^3).[8] Seven samples (nos. 1, 4, 6, 7, 8, 13, and 21) had densities below the expected range. Sample 1 had a density of 5.4 kg/m^3 (0.34 lbm/ft^3) which is considered unacceptably low for a urea-formaldehyde based foam insulation. Only one foam sample (no. 25) had a density which was greater than the generally recommended maximum of 14.0 kg/m^3 (0.9 lbm/ft^3).[8]

3.2.2 Thermal Resistivity. The thermal resistivity (resistance per unit thickness) for the insulation samples was determined based on the test procedure given in ASTM C 518-76 at a mean temperature of 24 °C (75 °F), using a commercially available heat flow apparatus. For the thermal resistivity measurements of the urea-formaldehyde based foam insulations, the dimensions of the test specimens were less than 300 x 300 mm (12 x 12 in) as specified by the procedure in ASTM C 516-76 for the heat flow apparatus used in the study. Foam pieces of these dimensions were not available. All insulation samples were intentionally not oven dried, and thermal resistivity measurements were conducted on the samples as they were received from the field. This practice was adopted to make the laboratory measured thermal resistivities more representative of the thermal resistivities of the installed insulations, since laboratory tests are normally conducted on dried samples.

Table 3 shows the thermal resistivities of the loose-fill insulations, while those of the urea-formaldehyde based foam insulations are given in Table 4. As determined in the laboratory the three types of retrofit insulations were seen to have good thermal insulating properties. The thermal resistivity values of the urea-formaldehyde based foam insulations were on the average higher than those of the loose-fill insulations. This is in accord with the findings of Burch, Siu and Powell.[5]

When discussing laboratory measured values of thermal resistivity, it is important to note that the thermal performance of an insulation in building walls may be less than indicated from the laboratory measurements. In particular, the shrinkage of urea-formaldehyde based foam may significantly effect the properties of foamed walls.[8]

The thermal resistivities of the eight cellulose samples ranged from 23.6 to 26.0 m·K/W (3.40 to 3.75 h·ft^2·°F/Btu·in), with an average value of 24.9 m·K/W (3.58 h·ft^2·°F/Btu·in). The range of thermal resistivity values for the loose-fill mineral fiber insulations was 24.7 to 29.2 m·K/W (3.55 to 4.20 h·ft^2·°F/Btu·in) with an average value of 26.4 m·K/W (3.8 h·ft^2 °F/Btu·in). The two loose-fill mineral fiber samples (nos. 37 and 38) having relatively high densities of 140.9 and 126.5 kg/m^3 (8.8 and 7.9 lbm/ft^3) had thermal resistivities of 26.0 and 25.3 m·K/W (3.75 and 3.65 h·ft^2·°F/Btu·in), respectively.

The thermal resistivity was determined for twenty-four of the twenty-five urea-formaldehyde based foam insulations examined in the field survey. One foam sample (no. 9) was too cracked to serve as a test specimen for the determination of the thermal resistivity. The thermal resistivity range of the tested foam specimens was from 20.8 to 31.9 m·K/W (3.0 to 4.6 h·ft^2·°F/Btu·in), with an average of 28.0 m·K/W (4.03 h·ft^2·°F/Btu·in). The foam specimen (no. 1) which had the unacceptably low density of 5.4 kg/m^3 (0.34 lbm/ft^3) was found to have the lowest thermal resistivity of any of the insulations tested in the study.

For both loose-fill cellulose and urea-formaldehyde based foam insulations, data analysis indicated relationships between the installed density and thermal resistivity. These relationships are given in Figure 2. It may be seen that as the density of the urea-formaldehyde based foam increased, the thermal resistivity tended to increase. On the contrary, for the loose-fill cellulose samples in question, the thermal resistivity tended to decrease as the density increased.

In relating the density of a loose-fill mineral fiber insulation to its thermal resistivity, the relationship should consider the type of mineral fiber such as glass, rock or slag. Since this study only evaluated three glass fiber samples and three rock and/or slag wool samples, establishment of relationships between density and thermal resistivity for these mineral fiber materials was not attempted.

3.3.3 Moisture Content. As previously mentioned, moisture accumulation within insulation or wall components may adversely affect the thermal performance of the insulated wall or result in deterioration of the wall component materials. The percent volatiles by mass, lost from each insulation sample upon heating, were determined according to the test method described in ASTM D 644-55 (1976). The percent volatile loss determined for each specimen was taken to be its moisture content. Insulation samples removed from the houses for determination of moisture content were immediately sealed in polyethylene jars to prevent moisture loss or gain during shipment to the testing laboratory. Mass measurements of these jars in the field and upon arrival at the laboratory indicated negligible changes in mass during shipment.

The results of the moisture content determinations for the loose-fill insulations and for the urea-formaldehyde based foams, reported as the percent by mass, are given in Tables 3 and 4, respectively. A comparison of the moisture content data shows that the loose-fill mineral fiber materials had a moisture content of less than 1 percent, which was the lowest percentage for the types of retrofit insulations. The cellulose specimens showed a moisture content range of 8.8 to 13.4 percent, with the exception of one sample (no. 31) which had a moisture content of 21.2 percent. This sample was removed from a wall area in the vicinity of a leaky window frame. The higher moisture content measured for this house was attributed to the leaks. Excluding the value for this sample (no. 31), the average moisture content of the other seven cellulose insulation specimens was about 11 percent. This average value is close to the 10 percent value reported by Burch, Siu and Powell for a loose-fill cellulose sample conditioned to constant mass at 23.9 °C (75 °F) and 40 percent relative humidity.[5] The average value of 11 percent may also be compared with values of the equilibrium moisture content of wood, as reported by Nottage.[10] According to him, the equilibrium moisture content of wood determined at temperatures of about 21 to 27 °C (70 to 80 °F) and at relative humidities of about 40 to 60 percent ranged from approximately 7 to 11 percent by mass.

The moisture contents of the urea-formaldehyde based foam samples exhibited the widest range among all of the retrofit insulations and varied from 3.2 to 22.0 percent. The average value was 12.1 percent. The reasons for this wide variation were not determined but may be influenced by differences between foam samples. Factors such as differences in chemical formulation, cell size, and open cell content may influence the moisture absorption properties of foams. Also some foam samples may lose other volatiles upon heating in addition to moisture. In at least one case, a chemical odor was detected while the foam was heated during drying. Previous data[8] summarized by Rossiter et al. indicated that the moisture content of foams may be in the range of 8 to 18 percent by weight, depending upon the temperature and humidity conditions.

3.3.4 pH of Urea-Formaldehyde Based Foams. Urea-formaldehyde based foam insulations are in general produced at the job-site through an acid-catalyzed chemical reaction. It may be hypothesized that the acid catalyst may migrate to the foam surface along with the water present during foam formation, as the freshly-prepared foam dries. Migration of the acid catalyst might be expected to result in its accumulation at the surfaces of the foam, provided that no other reactions occur within the foam to neutralize the acid-catalyst or that it is not absorbed into other building materials in contact with the foam such as sheathing or gypsum wall-board. If the surfaces of the foam were to accumulate the acid-catalyst, the insulation may be rendered susceptible to acid-catalyzed hydrolytic decomposition at these locations. Measurements which might provide evidence of this phenomenon were included in this study.

The pH of the foam insulations was determined for three sections of each test specimen removed from each house: at the interior and exterior surface of the foam and at the middle.

The test procedure involved extracting a small quantity of the foam with water and measuring the pH of the resulting solution. Since the same procedure was used for all specimens, it was considered that comparisons between results obtained from different specimens or sections of the same specimen could be made. The results of the measurements indicated that the average pH of the foam surface next to the interior side of the cavity wall was slightly lower than that of the foam surface at the exterior, which had approximately the same average pH as the middle sections of the test specimens. The average pH values of the interior, exterior, and middle sections of the test specimens were determined to be 3.9, 4.9, and 4.7, respectively.

4. SUMMARY AND CONCLUSIONS

This study involved the opening of sidewalls of residences which had been retrofitted with loose-fill cellulose, loose-fill mineral fiber and urea-formaldehyde based foam insulations. The study was intended to obtain information concerning the properties and performance of retrofit insulations, as they are found in place in the walls. A major reason for conducting the study was the lack of data on retrofit insulations in place. Another reason was the concerns which have been associated with the process of retrofitting sidewalls since it generally involves the addition of an insulation to an inaccessible space which cannot be inspected before or after the job is finished. Thus, the quality of the end product is difficult to evaluate.

In the field survey which was conducted in late fall, 1978, and early winter, 1979, observations were made regarding factors which affect the performance of the insulated wall. These factors included the condition of the insulation and wall components, moisture accumulation, settling of loose-fill insulations, shrinkage of urea-formaldehyde based foams, and workmanship during application. In general, for the thirty-nine houses surveyed, the observations showed no evidence of major problems associated with the retrofitting, although minor problems were evident for some houses. To investigate settling of loose-fill insulation, the walls of six houses containing these types of materials were opened at the tops of the cavity. Only one of these six houses was found to contain a void in the insulation at that location. It could not be determined whether the void was due to settling or initial incomplete fill of the cavity.

Linear shrinkage had occurred for all urea-formaldehyde based foam insulations. Shrinkage values ranged from about 4 to 9 percent and averaged 6.0 percent for the seventeen houses in which it was measured. Concerning workmanship, the results of the survey were generally favorable. However, sufficient minor problems were seen to reinforce the general guideline that quality workmanship is important to the successful retrofitting of sidewalls.

As part of the study, insulation specimens were removed from the inspected sidewalls and sent to a testing laboratory for the determination of density, thermal resistivity and moisture content. In general, values of these properties were found to agree closely with other values for these properties cited in the literature. In the case of two rock and/or slag wool insulation samples, the densities were higher than expected. However, the values of thermal resistivity for the two samples were comparable to those found for the other mineral fiber insulations included in the survey. The density of one urea-formaldehyde based foam sample was unacceptably low and, in this case, its thermal resistivity was quite low.

Laboratory measurements were also conducted to determine the pH of the foam insulation samples at the surfaces and in the center. The average pH value of the sample surfaces at the interior of the cavity walls was slightly lower than those of the sample surfaces at the exterior of the cavity walls or center sections of the foams. The average values at these latter two locations were approximately identical.

In the strictest sense, the information obtained in this study applies only to the thirty-nine houses surveyed. The sample size was limited and only small sections of the walls of the houses were opened for inspection. Nevertheless, some conclusions may be made which may have broader implications.

The results of the survey were encouraging in so far as they indicated that the retrofitting of the sidewalls was for the most part accomplished without adversely affecting them. Damage to wall components in the observed areas which could be attributed to the retrofitted insulation was not found. Although the few metal electrical components in the walls of some houses showed little, if any, signs of corrosion, the number of observations was extremely limited. Further information is needed to answer the important question concerning the effect of insulation on the corrosion of metals in service.

From laboratory tests conducted on insulation samples removed from the houses, it was concluded that the installed insulations had good thermal insulating properties. However, from the field observations, it was concluded that the cavity walls were not always completely filled either because of workmanship problems during application or dimensional instability of the installed insulation. The observation that some walls with loose-fill insulations contained no voids at the top of the cavities indicated that settling may not always occur with these materials. On the other hand, it was concluded that all urea-formaldehyde based foam samples had undergone linear shrinkage greater than the 1 to 3 percent often quoted in the literature.[8] This factor was of most concern, since shrinkage may result in insulated walls with reduced thermal performance.[5,8]

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6. ACKNOWLEDGMENT

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Finally, special mention should be made of the contributions of Mr. Dave Benoy. Mr. Benoy was the carpenter with the responsibility to open the sidewalls of the houses and close them to the satisfaction of the homeowners. As judged by the comments of the homeowners, he completed his task very successfully.

TABLE 1. INSULATION SAMPLE DISTRIBUTION BY CITY AND TYPE OF MATERIAL, AND DATE OF THE FIELD INSPECTION.

CITIES WHERE INSPECTION WAS CONDUCTED	DATE	NUMBER OF INSULATION SAMPLES			
		TOTAL	UF[a]	CELLULOSE	MINERAL FIBER
1. Minneapolis, Minn.	11/78	4	4	–	–
2. Hartford/New Haven, Conn.	11/78	6	5	–	1
3. Washington, D.C.	12/78	10	4	5	1
4. Richmond, Va.	12/78	4	–	1	3
5. Louisville, Ky.	1/79	7	7	–	–
6. Dayton, Ohio	1/79	8	5	2	1
TOTALS		39	25	8	6

(a) UF indicates urea-formaldehyde based foams.

TABLE 2. AGE, DENSITY AND PERCENT LINEAR SHRINKAGE OF UREA-FORMALDEHYDE BASED FOAM SPECIMENS.

SAMPLE	CITY[a]	MFR.[b]	AGE	DENSITY		LINEAR SHRINKAGE
No.			yrs	kg/m^3	lbm/ft^3	percent
1	1	H	2.0	5.4	0.34	6.5
2	1	F	2.4	9.9	0.62	4.1
3	1	F	2.1	12.8	0.80	4.4
4	1	B	2.1	7.8	0.49	---(c)
5	2	C	1.9	9.6	0.60	7.4
6	2	C	2.3	9.1	0.57	9.0
7	2	C	2.6	9.0	0.56	5.7
8	2	A	3.3	8.8	0.55	6.2
9	2	D	3.4	11.5	0.72	---(d)
10	3	F	1.8	13.4	0.84	---(c)
11	3	C	4.1	14.4	0.90	7.4
12	3	F	2.9	13.8	0.86	---(c)
13	3	F	2.8	9.4	0.59	---(d)
14	5	G	3.1	10.9	0.68	4.4
15	5	G	3.5	12.6	0.79	5.1
16	5	G	2.8	14.4	0.90	---(c)
17	5	C	2.0	13.9	0.87	6.7
18	5	G	2.5	11.2	0.70	6.6
19	5	C	3.3	13.4	0.84	5.6
20	5	G	2.1	12.2	0.76	4.9
21	6	E	2.3	9.0	0.56	---(d)
22	6	C	3.7	12.8	0.80	---(d)
23	6	G	1.4	9.6	0.60	8.1
24	6	E	2.0	13.6	0.85	3.9
25	6	G	3.2	18.4	1.15	6.0

(a) Number corresponds to that given in Table 1.
(b) MFR. indicates manufacturer.
(c) Shrinkage not determined because of the presence of batt insulation.
(d) Excessive gaps, cracks and voids precluded shrinkage determination.

TABLE 3. DENSITY, THERMAL RESISTIVITY AND MOISTURE CONTENT OF THE LOOSE-FILL INSULATIONS

SAMPLE		CITY[a]	INST.[b]	AGE	DENSITY		THERMAL RESISTIVITY		MOISTURE CONTENT[c]
No.	Type			yrs	kg/m^3	lbm/ft^3	m·K/W	$h \cdot ft^2$ F/Btu·in	percent by mass
26	Cell.[d]	3	A	1.8	64.0	4.0	24.3	3.50	12.4
27	Cell.	3	B	2.0	67.2	4.2	23.6	3.40	13.4
28	Cell.	3	C	1.9	59.2	3.7	25.0	3.60	12.4
29	Cell.	3	B	2.4	64.0	4.0	24.7	3.55	9.2
30	Cell.	3	D	5.2	41.6	2.6	24.3	3.50	10.1
31	Cell.	4	B	1.7	51.2	3.2	25.0	3.60	21.2
32	Cell.	6	E	2.3	44.8	2.8	26.0	3.75	12.4
33	Cell.	6	F	10.3	46.4	2.9	25.7	3.70	8.8
34	MF-Gl.[e]	2	G	9.1	27.2	1.7	25.3	3.65	< 1.0
35	MF-Gl.	4	H	1.8	36.8	2.3	28.1	4.05	< 1.0
36	MF-Gl.	6	I	2.4	46.4	2.9	29.2	4.20	< 1.0
37	MF-R/S[f]	3	J	7.8	140.9	8.8	26.0	3.75	< 1.0
38	MF-R/S	4	K	5.3	126.5	7.9	25.3	3.65	< 1.0
39	MF-R/S	4	L	3.8	27.2[g]	1.7[g]	24.7	3.55	< 1.0

(a) Number corresponds to that given in Table 1.
(b) INST. indicates installer.
(c) Moisture content taken to be the same as the percent volatile loss upon heating the insulation sample.
(d) Cell. indicates cellulose insulation.
(e) MF-Gl. indicates mineral fiber insulation consisting of glass fiber.
(f) MF-R/S indicates mineral fiber insulation consisting of rock or slag fibers.
(g) Sample contained voids and the density measured in the field was 27.2 kg/m^3 (1.7 lbm/ft^3). No correction was made for the voids. This density was not duplicated in the laboratory for the thermal resistivity measurement which was conducted on a sample with a density of 41.6 kg/m^3 (2.6 lbm/ft^3).

TABLE 4. THERMAL RESISTIVITY AND MOISTURE CONTENT OF UREA-FORMALDEHYDE BASED FOAM SPECIMENS.

SAMPLE	THERMAL RESISTIVITY		MOISTURE CONTENT[a]
No.	m•K/W	h•ft^2•°F/Btu•in	percent by mass
1	20.8	3.00	9.1
2	26.7	3.85	10.5
3	27.8	4.00	3.2
4	26.4	3.80	12.5
5	26.7	3.85	6.5
6	28.1	4.05	17.5
7	26.0	3.75	11.5
8	26.7	3.85	11.7
9	---[b]	---[b]	13.1
10	25.7	3.70	14.9
11	29.9	4.30	11.1
12	28.5	4.10	10.3
13	28.1	4.05	4.5
14	27.8	4.00	14.0
15	25.3	3.65	18.6
16	31.6	4.55	14.8
17	29.5	4.25	7.8
18	31.3	4.50	15.1
19	30.6	4.40	10.9
20	29.2	4.20	13.0
21	25.0	3.60	13.6
22	29.5	4.25	11.5
23	27.8	4.00	22.0
24	31.9	4.60	13.3
25	31.3	4.50	10.9

(a) Moisture content was taken to be the same as the percent volatile loss upon heating.
(b) A test specimen with dimensions large enough for determination of the thermal resistivity was not available.

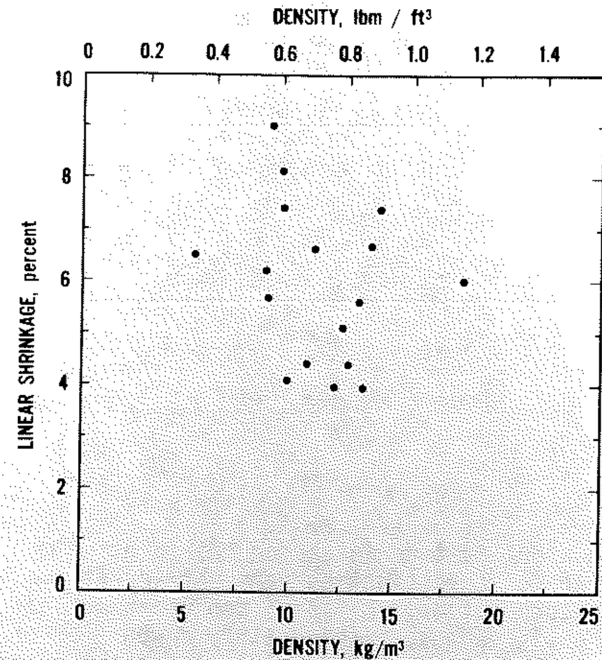

Fig. 1 Plot of the percent linear shrinkage of the urea-formaldehyde based foam specimens vs density

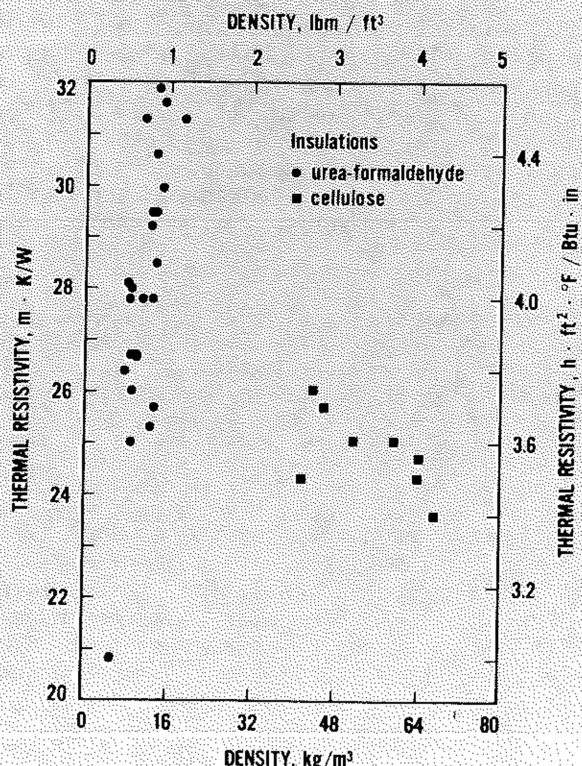

Fig. 2 The relationship between density and thermal resistivity for the urea-formaldehyde based foam and loose-fill cellulose insulation samples