NBS TECHNICAL NOTE 1131

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Field Investigation of the Performance of Residential Retrofit Insulation

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John L. Weidt
Robert J. Saxler

John Weidt Associates, Inc.
Chaska, MN 55318

Walter J. Rossiter, Jr.

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

Sponsored by:
Office of Weatherization Assistance
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

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Issued September 1980

National Bureau of Standards Technical Note 1131
Nat. Bur. Stand. (U.S.), Tech. Note 1131, 67 pages (Sept. 1980)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1980

For Sale by the Superintendent of Documents, U.S. Government Printing Office,
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FIELD INVESTIGATION OF THE PERFORMANCE OF RESIDENTIAL RETROFIT INSULATION

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

ABSTRACT

A study was conducted to obtain information on the performance of in-service insulations of the type commonly used in the United States to retrofit side-walls of housing: urea-formaldehyde based foam, loose-fill cellulose, and loose-fill mineral fiber.

In the field phase of the study, observations were made on performance-related 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. Shrinkage was observed to have occurred for all urea-formaldehyde based foam specimens. Where 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 of undetermined origin at that location.

Insulation specimens removed from the walls were tested to determine their density, thermal resistivity and moisture content. The pH and moisture absorption of the urea-formaldehyde based foam specimens were also determined. Results of the laboratory measurements are discussed and compared with data from other studies. Relationships between the moisture contents of the samples and their thermal resistivities were not found. Results indicated that the retrofitting of the inspected sidewalls was for the most part accomplished without adverse effect upon them.

Key words: Conservation; energy; field survey; insulation; moisture content; residences; retrofit; thermal resistivity.

*John Weidt Associates Inc., Chaska, Minnesota.

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1.0 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-and cooling-fuel consumption and save heating and cooling costs. Shortly before the onset of the energy crisis in 1973, it was estimated that nearly 20 percent of the energy used for residential heating and cooling could be conserved by effective retrofitting of residences [1]*. 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, and caulking and weather-stripping 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 common retrofit techniques mentioned above, 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 insulation, 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.

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 [2]. Less 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 that blowing insulation into exterior walls may be cost-effective in many areas of the United States [3]. It is noted that Petersen's analyses incorporated laboratory measured thermal properties of the insulation. Burch, Siu and Powell have indicated that the total thermal transmittance of retrofitted walls may be sometimes higher than the predicted values, which are based on laboratory-determined thermal conductivity values [4].

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* Numbers in brackets refer to references given in Section 7.

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 [4], if substantial moisture accumulation occurs, it may result in unwanted effects such as paint failures, buckling and warping of wooden siding and, in isolated cases, rotting of wood. Other 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 accelerated corrosion of metal objects in the wall.

In spite of concerns such as these, few field studies of 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 compared the thermal performance of loose-fill cellulose, loose-fill mineral fiber and urea-formaldehyde based foam insulations which were used to retrofit the exterior walls of a residence in suburban Washington, D.C. [5]. 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 based foam had undergone a linear shrinkage of about 8 percent.

The most extensive field examination involving retrofitted residential sidewalls, published to date, was conducted by Weidt [6]. 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 the insulations removed from these houses were relatively close to values referenced in the literature for these types of insulations. Moisture contents of the insulations were found to be low. In particular the moisture contents of the cellulose specimens 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 based foams ranged 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, and it is anticipated that they will be published in the Conference Proceedings.

Grot has reported on a field survey involving the use of thermography for the determination of the effectiveness of retrofit techniques [7].

Thermographic inspections of sixty-five homes located in eight cities in the United States were conducted during the 1978-1979 heating season after the residences had been retrofitted. The purpose of the thermographic surveys was to assess the quality of workmanship, to determine the percentage of wall area which was uninsulated after the retrofit, and to observe the thermal defects which still existed in the residences. A number of retrofit techniques was used including insulation of the walls of the residences with either urea-formaldehyde based foam or cellulose insulation. Grot's findings included observations concerning the completeness of filling the walls with insulation. Within the limits of the thermographic technique for surveying houses for heat loss, he found that two-thirds of the residences contained fissures in the insulated wall and shrinkage of the urea-formaldehyde based foam. In addition, some areas of the exterior walls of the residences were not insulated: 20 percent of the residences had greater than 10 percent of the total wall areas uninsulated; 30 percent of the residences showed between 5 and 10 percent of the wall areas uninsulated; and 50 percent of the residences had less than 5 percent of the wall areas uninsulated.

Inspite of the field studies many unanswered questions concerning the properties and performance of insulations used to retrofit exterior walls still remained. Thus, 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. This report presents the findings of a field and laboratory study to inspect and examine cavity walls of residences which have been retrofitted with thermal insulation. A summary report of the study has been presented [8].

1.2 OBJECTIVES

One objective of the study was to determine properties and performance characteristics of the retrofitted insulations installed in cavity-walls. Retrofit insulations included in the study were urea-formaldehyde based foam, loose-fill cellulose and loose-fill mineral fiber. Values of the properties of insulation specimens removed from the inspected houses were to be compared to the properties of comparable insulation specimens which had been tested in laboratory studies. The study was to provide information concerning questions such as to what extent do loose-fill materials settle and foam insulation shrink. A second objective was to obtain information concerning the effects of the addition of insulation on the walls of existing residences. Data and information obtained from the study may be used in formulating guidelines to assure the proper and adequate retrofitting of sidewalls of residences to conserve energy.

1.3 IMPORTANCE OF LABORATORY TESTS

Laboratory tests to measure density, thermal resistivity and moisture content were conducted on all insulation samples removed from the test houses. The pH and water absorption were also determined for the urea-formaldehyde based foam samples. Values of density, thermal resistivity and moisture content for the insulation samples from the test houses may be compared to values of these properties reported in the literature or other sources.

The pH of the urea-formaldehyde based foam insulations was measured at the center of the foam sample and at its surfaces corresponding to the interior and exterior sides of the wall cavity. It was of interest to determine whether the acid catalyst, present for foam production, had accumulated at the surfaces. An accumulation of acid catylyst at the surfaces might be expected to make the foam susceptible to acid-catalyzed hydrolytic decomposition at those locations. The water absorption tests were conducted to determine whether foams which had aged in service would absorb more water than freshly-prepared foams. It had been suggested that surface deterioration of the foam specimens due to aging might result in greater water absorption of the aged foams.

2.0 CONDUCT OF THE STUDY

Thirty-nine houses were included in this study. The side-walls 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.

2.1 IDENTIFICATION AND SELECTION OF THE TEST HOUSES

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 asked for volunteers. The text of the news release is given in Appendix A. 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 at least 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 certain geographic areas including the northeast, mid-Atlantic, mid-western, and southeast regions of the country.

More than 1100 responses were received from homeowners who volunteered to participate, as shown in Table 1. Only about 25 percent of the volunteered houses met the above criteria. Although an adequate distribution of the loose-fill cellulose, loose-fill mineral fiber and urea-formaldehyde based foam insulations were volunteered, many of these houses were widely-separated from each other and could not be conveniently reached. It was interesting that almost 25 percent of the homeowners who volunteered did not know the type of insulation within the cavity walls of their houses. These houses could not be considered for examination. The thirty-nine test houses finally selected from among the 310 qualified residences were chosen to provide an efficient schedule for the field examinations and to minimize travel costs.

TABLE 1.

DISTRIBUTION OF THE RETROFIT INSULATIONS IN THE HOUSES VOLUNTEERED FOR INCLUSION IN THE FIELD INSPECTION

Type of Insulation in The Volunteered House	Total Responses	Qualified Residence(1)
Cellulose	331	128
Mineral Fiber	111	54
Urea-Formaldehyde Foam	430	128
Unknown	252	-
TOTAL	1124	310

(1) A qualified residence was considered to meet the criteria for determining the eligibility of a test house for inclusion in the field study.

The selection criterion concerning the geographic area where the test house was located was considered to be particularly important in the case of urea-formaldehyde based foam insulations. It was desired to examine the foams in houses located in areas which experience prolonged seasons of relatively high temperatures and high humidities such as the lower Southeast. The durability of foam insulations exposed to combined high temperatures and high humidities had been previously questioned and considered to be suspect [9]. However, few houses containing urea-formaldehyde based foams were volunteered from the lower southeast region of the country. The practical aspects concerning time and travel prohibited the examinations of those few house containing foam volunteered from the lower southeast region.

The houses selected for the 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, National Bureau of Standards' research staff members were present at the field site. Table 2 lists the cities near which the test houses were located, the date of the field examinations, the total number of insulations examined, the number of each type of insulation examined, and the number of manufacturers of foam insulation and installers of loose-fill insulation. The itinerary followed by the inspection team is represented by the order of cities listed in Table 2.

TABLE 2. INSULATION SAMPLE DISTRIBUTION BY CITY, DATE OF THE FIELD INSPECTION, TYPE OF MATERIAL, AND NUMBER OF FOAM INSULATION MANUFACTURERS AND LOOSE-FILL INSULATION INSTALLERS

Cities Where Inspection Was Conducted	Date	Total	Insulation Samples: UF[a] NO.	UF[a] MFR.[b]	Cellulose NO.	Cellulose INST.[c]	Mineral Fiber NO.	Mineral Fiber INST.
1. Minneapolis, Minn.	Nov. 78	4	4	3	-	-	-	-
2. Hartford/ New Haven, Conn.	Nov. 78	6	5	3	-	-	1	1
3. Washington, D.C.	Dec. 78	10	4	2	5	4	1	1
4. Richmond, Va.	Dec. 78	4	-	-	1	1	3	3
5. Louisville, Ky.	Jan. 79	7	7	2	-	-	-	-
6. Dayton, Ohio	Jan. 79	8	5	3	2	2	1	1
TOTALS		39	25	*[d]	8	**[e]	6	**[e]

(a) UF indicates urea-formaldehyde based foam.
(b) MFR. indicates the number of foam manufacturers.
(c) INST. indicates the number of loose-fill insulation installers.
(d) The total number of different manufacturers was eight.
(e) The total number of different installers was six.

2.2 FIELD EXAMINATION OF THE TEST HOUSES

The general procedure for examining 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 (Figure 1), 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 (Figure 2); 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 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. A summary of the general procedure is listed in Table 3 and a description is given in Appendix B.

During the examination of the retrofitted sidewalls, visual observations were made concerning the condition of the insulation and of the wall components (Table 3). Observations included such parameters as the presence of cracks and voids in the insulation, insulation color, the condition of the paint and/or siding, corrosion of metal wall objects such as electrical boxes and accessories, 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 (flow retarders) within the insulated cavity. The sizes of voids due to settling or incomplete application of loose-fill materials were measured and linear shrinkages of urea-formaldehyde based foam insulations were determined.

2.3 LABORATORY TESTS OF INSULATION SAMPLES

Insulation samples were removed from the walls of the houses, sealed in polyethylene bags or jars, and sent to a commercial testing laboratory. The 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. In addition, a few foams were sent to the National Bureau of Standards laboratories for determination of moisture absorption.

Details of the test procedures used to measure the insulation properties are given in Appendix C. In general, the density was calculated from measurements of the mass and volume of the removed insulation specimens. The thermal resistivity (resistance per unit thickness) was determined based on the test procedure given in ASTM C 518-76. The insulation samples were intentionally not oven dried, and thermal resistivity measurements were conducted on samples as they were received from the

Figure 1. Executing an Exterior Wall Opening

Figure 2. Photographing Mineral Wool Insulation in an Opened Wall Cavity

TABLE 3

SUMMARY OF THE TASKS PERFORMED DURING THE FIELD INSPECTIONS

Task	Considerations
Select wall area for examination	o Area should be repairable o Area should contain electrical components, if possible o Area should be at the top of the cavity, if possible, in the case of loose-fill insulations
Open the wall	o Either from the interior or exterior
Observe the condition of the insulation and wall components	o Cracks and voids in the insulation o Color of the insulation o Paint o Siding/sheathing/studs/other components o Moisture o Presence of membrane-type vapor barriers o Electrical components o Corrosion o Odor o Rot o Fungus/mold o Vermin
Record appropriate information	o Photographs o Sketches o Comments
Measurements	o Shrinkage (urea-formaldehyde based foam) o Settling (loose-fill materials) o Voids o Mass (weight) o Volume
Remove insulation samples	o In general seal in plastic bags for shipment to lab o Seal samples for moisture measurements in plastic jars
Restore wall	o Reinsulate with glass fiber batt o Close wall to original condition

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. Figures 3 and 4 show the laboratory apparatus used for the determination of the thermal resistivities of loose-fill materials and urea-formaldehyde based foams, respectively.

The percent volatile loss by mass upon heating to 105°C (221°F)* was determined according to the test method described in ASTM D 644-55 (1976). The percent volatile loss was taken to be the moisture content. As noted in Table 3, insulation samples removed from the houses for the determination of moisture content were immediately sealed in polyethylene jars to prevent moisture loss or gain during shipment to the testing laboratory. Mass determinations of the polyethylene jars containing insulation conducted both in the field and upon arrival at the testing laboratory indicated no significant changes during shipment.

Since no standard test procedure was available for measuring the pH of the urea-formaldehyde based foam insulations, a test method developed in an industrial laboratory which had experience with foams was employed. This procedure involved extracting a small quantity of the foam specimen with water and measuring the pH of the resulting solution. The moisture absorption of the foams was determined according to the test procedure described in U.S. Department of Housing and Urban Development (HUD) Use of Materials Bulletin No. 74.

3.0 RESULTS AND DISCUSSION

3.1 LABORATORY TESTS

The results of the density, thermal resistivity, and moisture content determinations conducted on the urea-formaldehyde based foam and loose-fill insulations are given in Tables 4 and 5, respectively. Discussions of these results follow in Sections 3.1.1 to 3.1.3. The results and discussions of the pH and water absorption tests for urea-formaldehyde based foams are given in Sections 3.1.4 and 3.1.5.

3.1.1 Density

Density is an important property for characterizing retrofit insulations. Manufacturers generally have insulation 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 too low a density may settle.

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* Definitions of the S.I. (International System) units and customary units are given in Appendix D.

Figure 3. Laboratory Apparatus for Determination of the Thermal Resistivity of the Loose-Fill Insulations.

Figure 4. Laboratory Apparatus for Determination of the Thermal Resistivity of the Urea-Formaldehyde Based Foams.

TABLE 4

AGE, DENSITY, THERMAL RESISTIVITY, MOISTURE CONTENT, AND LINEAR SHRINKAGE OF THE UREA-FORMALDEHYDE BASED FOAM SAMPLES

SAMPLE	CITY[a]	MFR.[b]	AGE[b]	DENSITY		THERMAL RESISTIVITY		MOISTURE CONTENT[c]	LINEAR SHRINKAGE
No.			yrs.	kg/m^3	lbm/ft^3	m·K/W	$h \cdot ft^2 \cdot °F/Btu \cdot in$	percent by mass	percent
1	1	H	2.0	5.4	0.34	20.8	3.00	9.1	6.5
2	1	F	2.4	9.9	0.62	26.7	3.85	10.5	4.1
3	1	F	2.1	12.8	0.80	27.8	4.00	3.2	4.4
4	1	B	2.1	7.8	0.49	26.4	3.80	12.5	---(e)
5	2	C	1.9	9.6	0.60	26.7	3.85	6.5	7.4
6	2	C	2.3	9.1	0.57	28.1	4.05	17.5	9.0
7	2	C	2.6	9.0	0.56	26.0	3.75	11.5	5.7
8	2	A	3.3	8.8	0.55	26.7	3.85	11.7	6.2
9	2	D	3.4	11.5	0.72	---(d)	---(d)	13.1	---(f)
10	3	F	1.8	13.4	0.84	25.7	3.70	14.9	---(e)
11	3	C	4.1	14.4	0.90	29.9	4.30	11.1	7.4
12	3	F	2.9	13.8	0.86	28.5	4.10	10.3	---(e)
13	3	F	2.8	9.4	0.59	28.1	4.05	4.5	---(f)
14	5	G	3.1	10.9	0.68	27.8	4.00	14.0	4.4
15	5	G	3.5	12.6	0.79	25.3	3.65	18.6	5.1
16	5	G	2.8	14.4	0.90	31.6	4.55	14.8	---(e)
17	5	C	2.0	13.9	0.87	29.5	4.25	7.8	6.7
18	5	G	2.5	11.2	0.70	31.3	4.50	15.1	6.6
19	5	C	3.3	13.4	0.84	30.6	4.40	10.9	5.6
20	5	G	2.1	12.2	0.76	29.2	4.20	13.0	4.9
21	6	E	2.3	9.0	0.56	25.0	3.60	13.6	---(f)
22	6	C	3.7	12.8	0.80	29.5	4.25	11.5	---(f)
23	6	G	1.4	9.6	0.60	27.8	4.00	22.0	8.1
24	6	E	2.0	13.6	0.85	31.9	4.60	13.3	3.9
25	6	G	3.2	18.4	1.15	31.3	4.50	10.9	6.0

(a) Number corresponds to that given in Table 2.
(b) MFR. indicates the manufacturer; letter designations are used to indicate different manufacturers.
(c) Moisture content was taken to be the same as the percent volatile loss upon heating to 105°C (221°F).
(d) A test specimen large enough for determination of the thermal resistance was not available.
(e) Shrinkage not determined because of the presence of batt insulation.
(f) Large gaps, cracks and voids precluded shrinkage determination.

TABLE 5

AGE, DENSITY, THERMAL RESISTIVITY, AND MOISTURE CONTENT OF THE LOOSE-FILL INSULATION SAMPLES

SAMPLE		CITY[a]	INST.[b]	AGE	DENSITY		THERMAL RESISTIVITY		MOISTURE CONTENT[c]
No.	Type			yrs	kg/m^3	lbm/ft^3	m·K/W	$h \cdot ft^2 \cdot {}^\circ F/Btu \cdot in$	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 2.
(b) INST. indicates the installer.
(c) Moisture content was taken to be the same as the percent volatile loss upon heating to 105°C (221°F).
(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).

It may be seen from Table 4 that densities of the twenty-five urea-formaldehyde based foam insulations ranged from 5.4 to 18.4 kg/m^3 (0.34 to 1.15 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) [2,9]. Figure 5 compares the range of densities determined in this study with those given in the literature. The average value of 11.5 kg/m^3 (0.72 lbm/ft^3) is within the range cited in the literature, while the extremes of the range of the test samples were much broader than those given in the literature [2,9]. Seven samples (nos. 1, 4, 6, 7, 8, 13, and 21) had densities below the literature 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 literature-cited maximum of 14.0 kg/m^3 (0.9 lbm/ft^3).

The eight cellulose samples (Table 5) 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 insulations were considered to be close to values reported in other field studies [4,6]. For example, in the Minnesota field study, Weidt found that the density of cellulose insulations 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)[6]. Burch, Siu and Powell reported a density of 56.0 kg/m^3 (3.5 lbm/ft^3) for one specimen [4]. One reference [10] has indicated that the installed density for loose-fill cellulose ranges from approxmately 48.0 to 64.0 kg/m^3 (3.0 to 4.0 lbm/ft^3). The range of densities found in this study were slightly broader than that cited in this reference [10]. Figure 6 compares the range of densities of the cellulose samples in this study with ranges given in the literature.

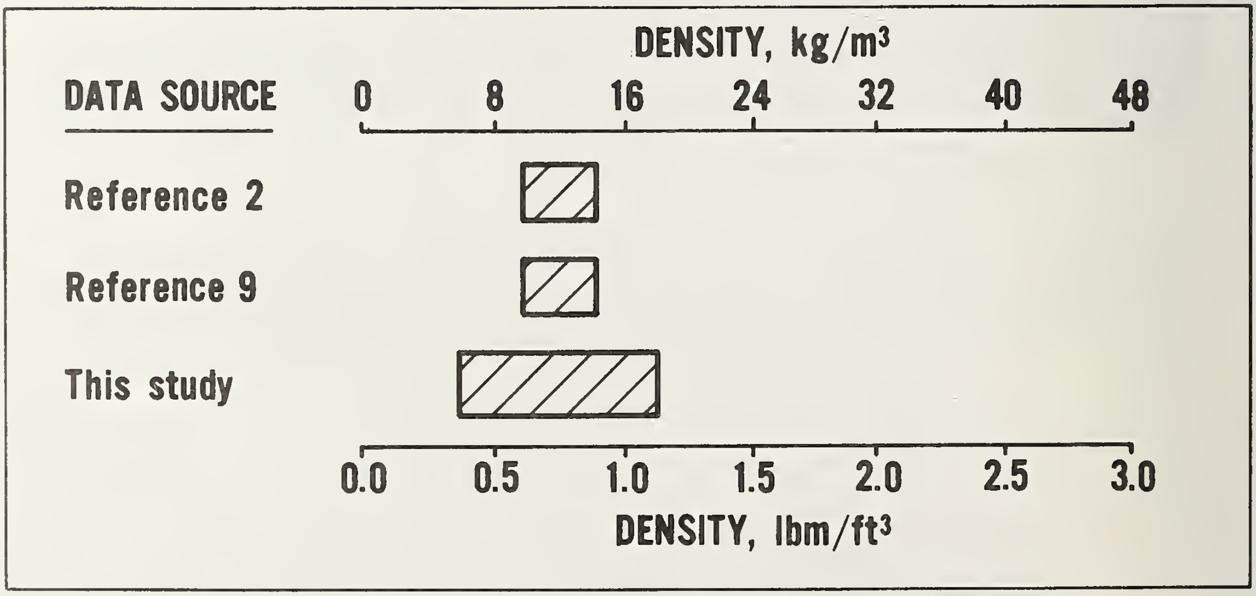

Figure 5. Range of Installed Densities of Urea-Formaldehyde Based Foam Insulations from References and from this Study.

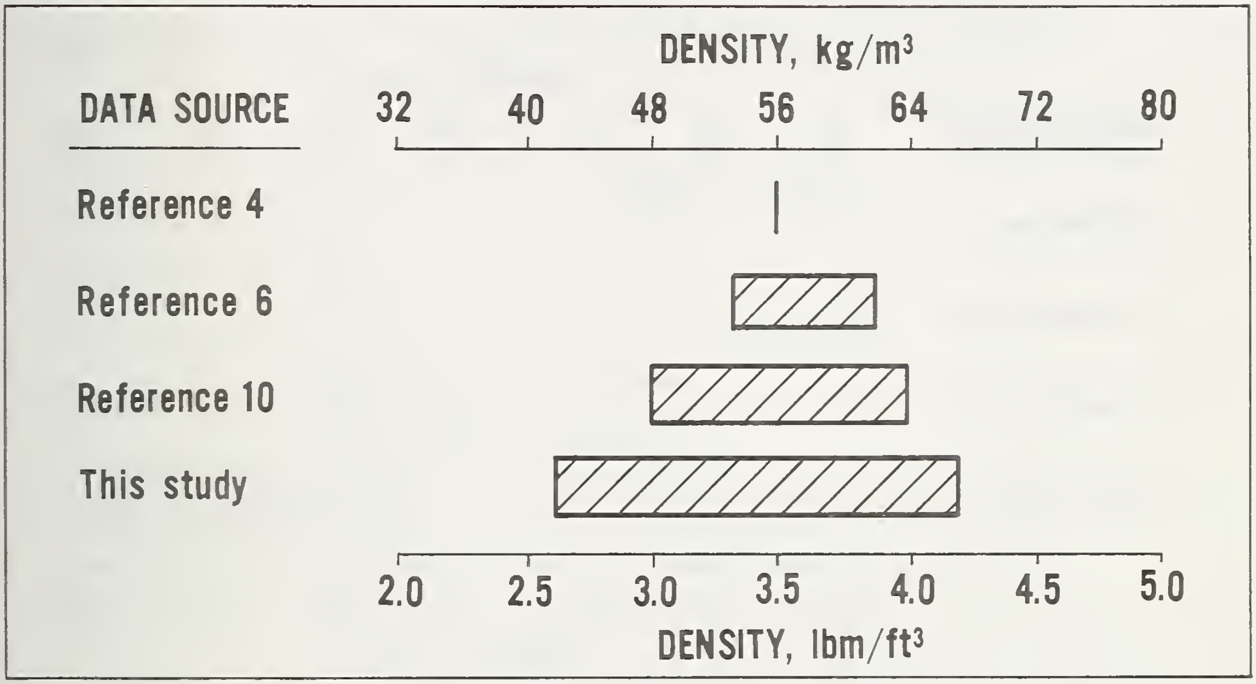

Figure 6. Range of Installed Densities for Cellulose Insulations from References and from this Study.

Of the six mineral fiber insulations in the study, three were glass fiber and three were rock/slag wool* samples. Densities of the glass fiber samples varied considerably from those of the rock/slag wool (Table 5). The range of densities of the glass fiber samples in the study was 27.2 to 46.4 kg/m^3 (1.7 to 2.9 lbm/ft^3). It has been reported that the density for loose-fill glass fiber insulation, as recommended by the industry for application in wall cavities, should be about 32.0 kg/m^3 (2.0 lbm/ft^3) [10]. 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) [4]. The ASHRAE Handbook of Fundamentals indicates a density range of about 9.0 to 32.0 kg/m^3 (0.6 to 2.0 lbm/ft^3) [11]. This reference does not distinguish between density of these insulations applied in open areas such as attics and closed spaces such as wall cavities. Loose-fill glass fiber installed in wall cavities has a higher density than that installed in attics [10]. The upper limit of the ASHRAE density range applies to

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* The term, rock/slag wool, indicates that the insulation consisted of either rock or slag wool fibers. The specific type of insulation could not be identified.

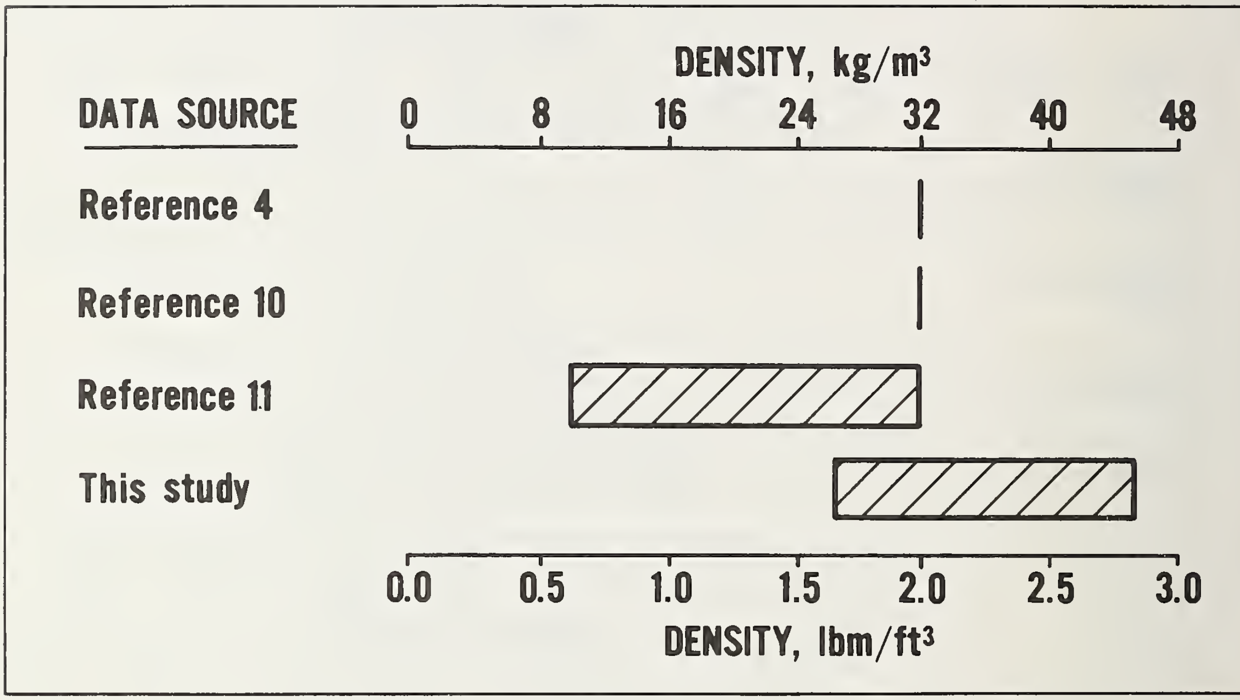

Figure 7. Range of Installed Densities of Loose-Fill Glass Fiber Insulations from References and from this Study.

cavity wall insulations. Figure 7 compares the densities from the literature and from this study. It may be seen that the literature values of approximately 32.0 kg/m^3 (2.0 lbm/ft^3) lie within the range of values found for the samples in the field survey. The density of 46.4 kg/m^3 (2.9 lbm/ft^3) for sample no. 36 was about 45 percent higher than the maximum density value cited in the literature.

The density range of 27.2 to 140.9 kg/m^3 (1.7 to 8.8 lbm/ft^3) for the three rock/slag wool samples in the study was found to be broader than expected, based on a comparison with the minimum recommended value of 40 kg/m^3 (2.5 lbm/ft^3) cited in the literature [10]. Figure 8 shows this comparison. The densities of two samples (nos. 37 and 38) were much beyond the literature density, with values of 140.9 and 126.5 kg/m^3 (8.8 and 7.9 lbm/ft^3), respectively. These high densities may have been due to factors such as fiber size, shot content among the fibers, and the degree of packing of the insulations in the cavities. One rock/slag wool sample (no. 39) contained a number of voids which were apparently created by mice in the cavity. The density of this sample was not corrected to account for the voids.

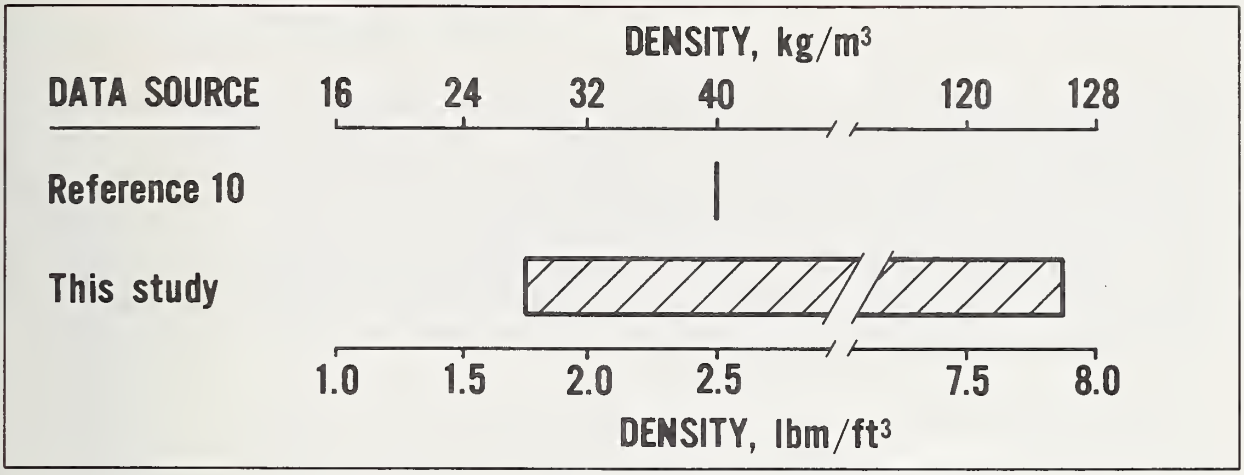

Figure 8. Range of Installed Densities of Loose-Fill Rock/Slag Wool Insulation from Reference and from this Study.

3.1.2 Thermal Resistivity

The primary function of retrofitted sidewall insulation is the reduction of heat flow through the wall. Thermal resistance is a measure of a material's ability to resist heat flow. The thermal resistivities (resistances per unit thickness) for the urea-formaldehyde based foam and loose-fill insulation samples in the study are given in Tables 4 and 5, respectively. As determined in the laboratory, the three types of retrofit insulations had 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 was in accord with the findings of Burch, Siu and Powell [4]. When discussing laboratory measured values of thermal resistivity, it is important to note that the thermal performance of an insulation in a wall may be less than indicated from the laboratory measurements. In particular, the effect of shrinkage of urea-formaldehyde based foam insulations on the insulating properties of foam-filled walls has been reported to be important [9,12-14]. For example, it may be calculated that if the foam shrinks 6 percent linearly, its effective thermal resistivity in service in a wood-framed cavity wall may be 28 percent less than its thermal resistivity measured in the laboratory, due to the air gaps created by the foam shrinkage [14]. It is noted that examples of calculating the total thermal transmittance of insulated walls may be found in the ASHRAE 1977 Handbook of Fundamentals.

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) as found in the wall 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 (3.00 to 4.60 $h \cdot ft^2 \cdot °F/Btu \cdot in$), with an average value of 28.0 m•K/W (4.03 $h \cdot ft^2 \cdot °F/Btu \cdot in$). The foam specimen (no. 1) which had the unacceptably low density of 5.4 kg/m^3 (0.34 lbm/ft^3) had the lowest thermal resistivity of any of the insulations tested in the study.

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.

3.2.1.1 Relationship between Thermal Resistivity with Density

Figure 9 is a plot of the thermal resistivity of the urea-formaldehyde based foam samples versus density for the data in Table 4. It can be seen that as the density of the foam sample increased, the thermal resistivity tended to increase. The solid line in Figure 9 was obtained from a linear regression analysis relating the the density versus the thermal resistivity. The equation in S.I. units for this relationship was $y = 0.66\ x + 20.4$ (Customary Units, $y = 1.51\ x + 2.95$) where y and x were the thermal resistivity and density, respectively. The correlation coefficient for this relationship was 0.73. The solid line may be compared with the dashed line which represents data from Weidt's field study [6]. The comparison shows that the lines are in close agreement over the thermal resistivity range for which data are available from both studies.

Using the data in Table 5, the thermal resistivity of the cellulose samples was plotted as a function of density. Figure 10 shows that as the density of the cellulose samples increased, the thermal resistivity tended to decrease. The solid line in Figure 10 was generated from the data in Table 5 by linear regression analysis which related the thermal resistance to the density. The equation in S.I. Units for this relationship was $y = -\ 0.047\ x + 27.42$ (Customary Units, $y = -\ 0.11\ x + 3.96$) where y and x represent the values for thermal resistivity and density, respectively. The correlation coefficient was − 0.62. This solid line in Figure 10 lies slightly above the dashed line which represents data from Weidt's field study [6].

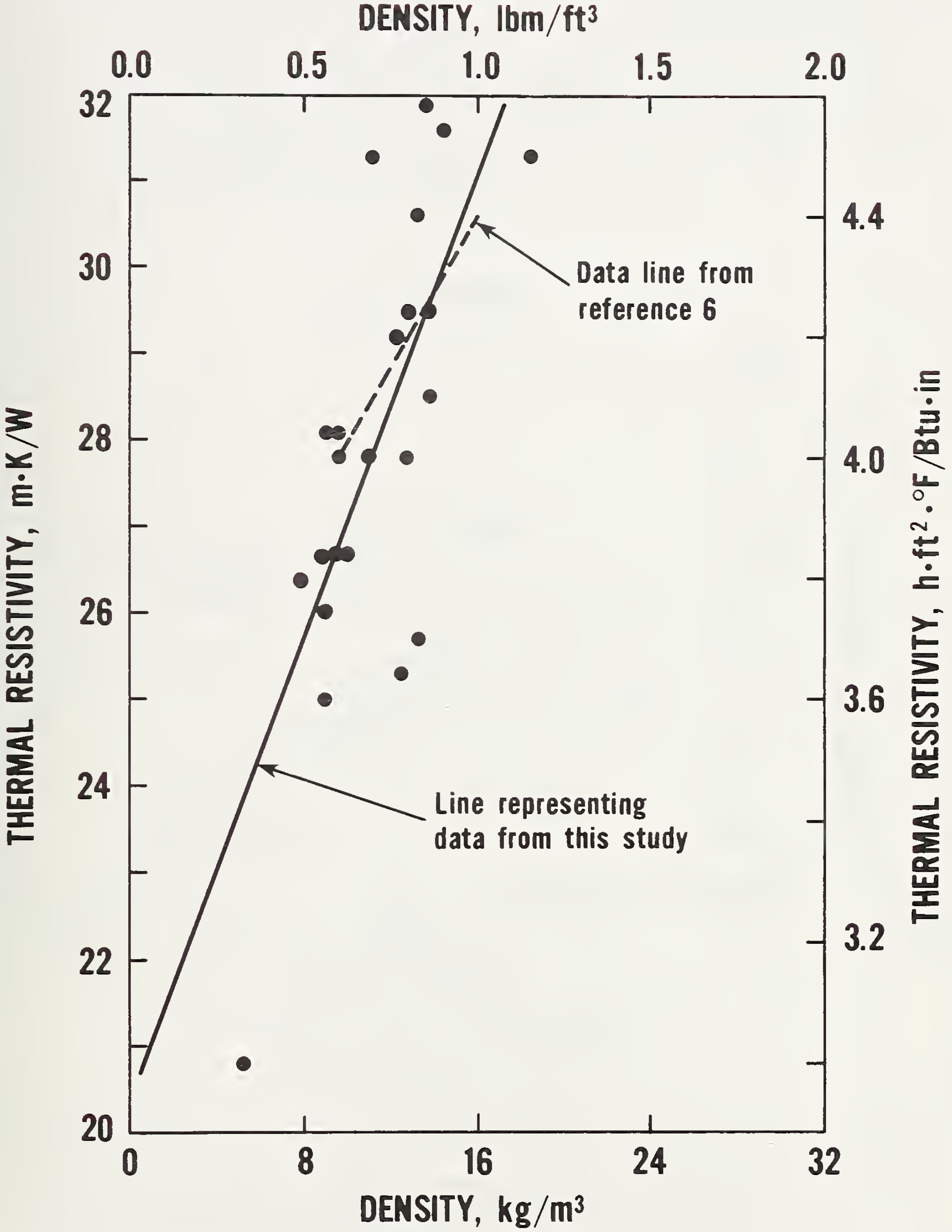

Figure 9. The Relationship Between Density and Thermal Resistivity for for the Urea-Formaldehyde Based Foam Insulation Samples.

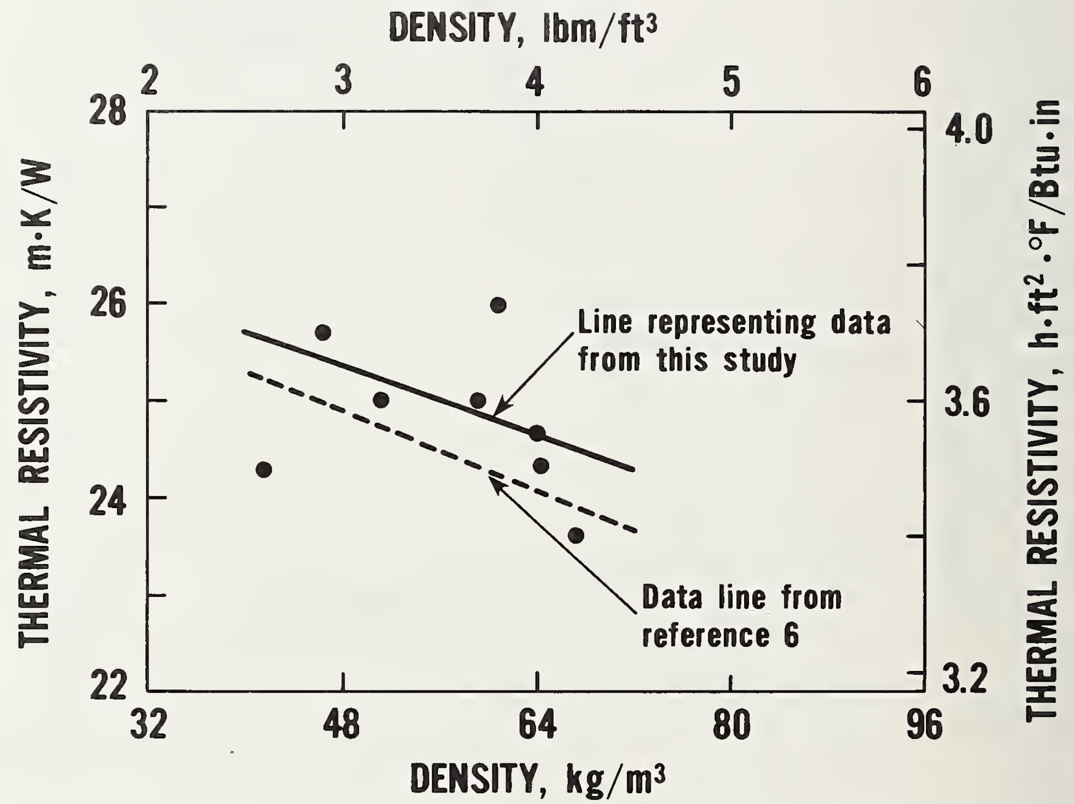

Figure 10. The Relationship Between Density and Thermal Resistivity for the Loose-Fill Cellulose Insulation Samples.

In seeking a relationship between the density of a loose-fill mineral fiber insulation and its thermal resistivity the type of fiber such as glass, rock or slag should be considered. Since this study only evaluated three glass fiber and three rock and/or slag wool samples, establishment of relationships between denity and thermal resistivity for these mineral fiber materials was not attempted. Figure 11 shows five curves drawn from data in the ASHRAE Handbook of Fundamentals relating the thermal conductivity to density for loose-fill glass fiber insulations consisting of fibers with different diameter thicknesses [15]. The points in Figure 11 represent the data points from the present field study (Table 5). These three data points are seen to lie within the range of curves generated from the ASHRAE data.

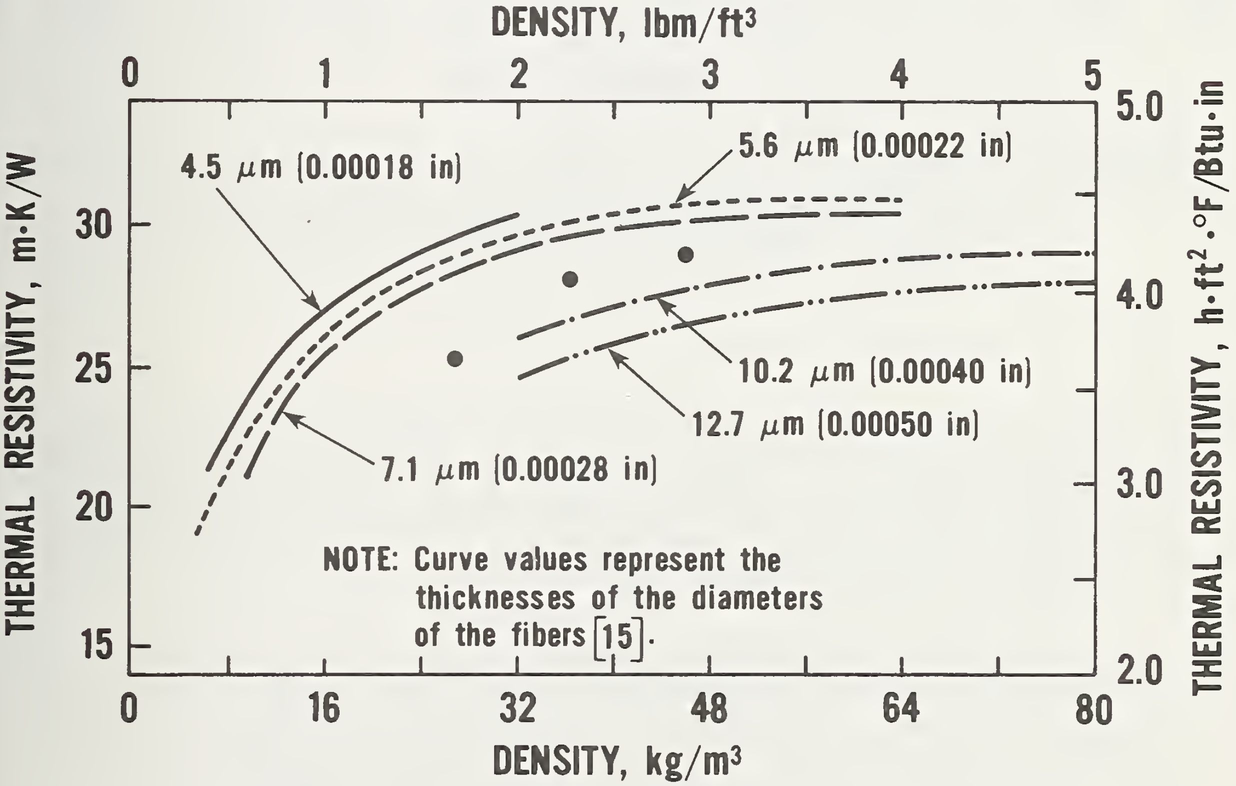

Figure 11. The Relationship Between Density and Thermal Resistivity for Glass Fiber Insulations, as given in the Literature [15], and from this Study.

Figure 12 contains a curve plotted from data given in the literature [2], which relate thermal conductivity and density for loose-fill rock/slag wool samples. The data points from this study (Table 5) are also included in Figure 12. The data points for the two samples (nos. 37 and 38) with the high densities lie well beyond the range of the curve given in the literature [2].

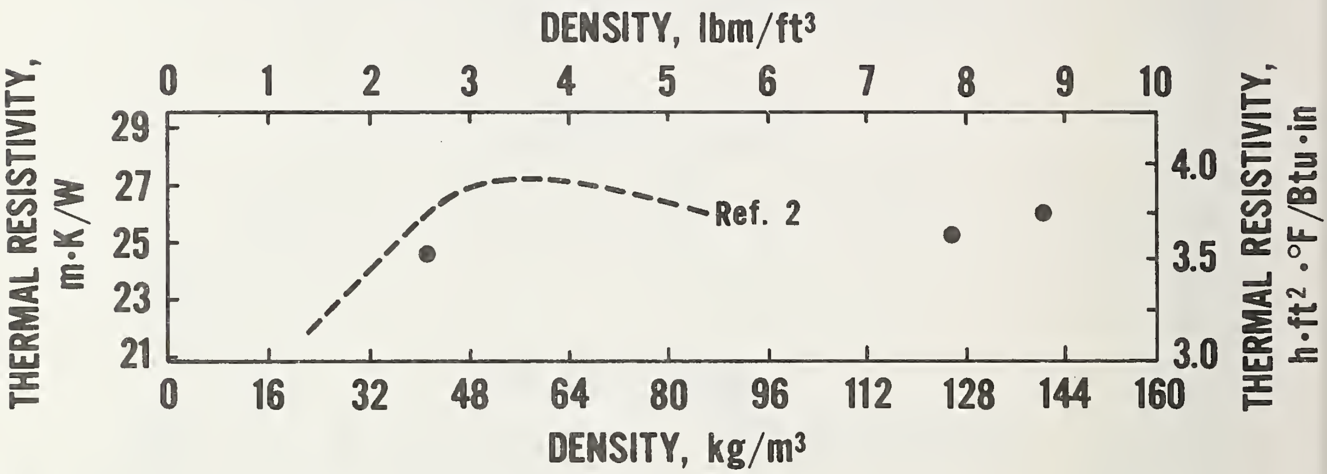

Figure 12. The Relationship Between Density and Thermal Resistivity for Loose-Fill Rock/Slag Wool Fiber Insulations as given in the Literature [2] and from this Study.

3.1.2.2 Effect of Age on Thermal Resistivity

An insulating material is expected to remain effective in reducing heat flow for many years. The thermal resistivities of the urea-formaldehyde based foam and loose-fill cellulose samples were analyzed in relation to their age. It was obviously not possible to observe whether any changes in thermal resistivity occurred in time, since the materials were tested at one point in time only.

The urea-formaldehyde based foam samples for which the thermal resistivities were determined ranged in age from 1.4 to 4.1 years (Table 4), with an average of 2.7 years. The age of the cellulose samples ranged from 1.7 to 10.3 years (Table 5), with an average of 3.5 years. Analysis of these data indicated no correlation between thermal resistivity and age of the samples. It is noted that the oldest cellulose sample with 10.3 years of age had a thermal resistivity of 25.7 m•K/W (3.70 h•ft^2•°F/Btu•in), which was among the highest value of all cellulose samples. Establishment of relationships between thermal resistivity and age for the glass fiber and rock/slag wool insulations was not attempted because of the small number of samples of each type of material.

3.1.2.3 Relationship Between Thermal Resistivity and Geographic Location

The climatic environment to which an insulation is subjected may affect its performance. It was thus of interest to tabulate the thermal resistivities of the insulations according to the geographic location of the test house from which each insulation was removed. Tables 6 and 7 list the ranges and average thermal resistivity values for the urea-formaldehyde based foam and loose-fill cellulose samples, respectively, according to geographic location. These tables did not show any important trends.

Although the average thermal resistivity for the four urea-formaldehyde based foam samples from Minneapolis was the lowest of the five geographic locations, this average included the value for sample no. 1 which was quite low and not typical of foam insulations [9]. No further analysis of the tabulated data was performed, since the number of samples in any city was limited.

3.1.2.4 Relationships Between Thermal Resistivity with Manufacturer or Installer

The thermal resistivities of the urea-formaldehyde based foam insulations are listed in Table 8 along a letter designating the manufacturer of the component materials. Table 9 presents the thermal resistivities and the numerical designations of the installers of the cellulose insulations. It was of interest to compare the thermal resistivities with the manufacturer or installer, since these variables may contribute to differences in material performance. Although the tables show slight variations in thermal resistivities as related to foam manufacturers or cellulose installers, the differences were not considered to be important. The number of the test samples per manufacturer or installer was very limited.

3.1.3 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. Table 4 gives the moisture contents of the urea-formaldehyde based foam samples. The moisture contents of the foams 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 on odor was detected while the foam was heated during drying. Previous data 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 [9]. It is of interest to note that no correlation was found between moisture content and thermal resistivity for the foam samples.

TABLE 6. RANGE AND AVERAGE OF THERMAL RESISTIVITY VALUES FOR UREA-FORMALDEHYDE BASED FOAM INSULATIONS BY GEOGRAPHIC LOCATION

Geographic Location	Number of Samples	Range of Thermal Resistivity		Average Thermal Resistivity	
		m·K/W	h·ft²·°F/Btu·in	m·K/W	h·ft²·°F/Btu·in
Minneapolis	4	20.8 to 27.8	3.00 to 4.00	25.4	3.66
Hartford/New Haven	5[a]	26.0 to 28.1	3.75 to 4.05	26.9	3.88[a]
Washington, D.C.	4	25.7 to 29.9	3.70 to 4.30	28.1	4.04
Louisville	7	25.3 to 31.6	3.65 to 4.55	29.3	4.22
Dayton	5	25.0 to 31.9	3.60 to 4.60	29.1	4.19

[a] Although five samples were examined in the Hartford/New Haven location, the thermal resistivity of one sample (no. 9) was not determined, since an adequate test specimen was not available. Therefore, the average value of thermal resistivity is for four specimens.

TABLE 7. RANGE AND AVERAGE OF THERMAL RESISTIVITY VALUES FOR CELLULOSE INSULATIONS BY GEOGRAPHIC LOCATION

Geographic Location	Number of Samples	Range of Thermal Resistivity		Average Thermal Resistivity	
		m·K/W	h·ft²·°F/Btu·in	m·K/W	h·ft²·°F/Btu·in
Washington, D.C.	5	23.6 to 25.0	3.40 to 3.60	24.4	3.51
Richmond	1	---[a]	---[a]	25.0	3.60
Dayton	2	25.7 to 26.0	3.70 to 3.75	25.9	3.73

[a] No range is given since only one sample was examined in the Richmond location.

TABLE 8. RANGE AND AVERAGE OF THERMAL RESISTIVITY VALUES FOR UREA-FORMALDEHYDE BASED FOAM INSULATIONS BY MANUFACTURER

Manufacturer	Number of Samples	Range of Thermal Resistivity		Average Thermal Resistivity	
		m·K/W	h·ft²·°F/Btu·in	m·K/W	h·ft²·°F/Btu·in
A	1	--[a]	--[a]	26.7	3.85
B	1	--[a]	--[a]	26.4	3.80
C	7	26.0 to 30.6	3.75 to 4.40	28.6	4.12
D	1[b]	--[b]	--[b]	--[b]	--[b]
E	2	25.0 to 31.9	3.60 to 4.60	28.5	4.10
F	5	25.7 to 28.5	3.70 to 4.10	27.4	3.94
G	7	25.3 to 31.6	3.65 to 4.55	29.2	4.20
H	1	--[a]	--[a]	20.8	3.00

[a] No range is given since only one sample from this manufacturer was examined.
(b) The thermal resistivity of this sample was not determined, since an adequate test specimen was not available.

TABLE 9. RANGE AND AVERAGE OF THERMAL RESISTIVITY VALUES FOR CELLULOSE INSULATIONS BY INSTALLER

Installer	Number of Samples	Range of Thermal Resistivity		Average Thermal Resistivity	
		m·K/W	h·ft²·°F/Btu·in	m·K/W	h·ft²·°F/Btu·in
1	1	--[a]	--[a]	24.3	3.50
2	3	23.6 to 25.0	3.40 to 3.60	24.4	3.52
3	1	--[a]	--[a]	25.0	3.60
4	1	--[a]	--[a]	24.3	3.50
5	1	--[a]	--[a]	26.4	3.75
6	1	--[a]	--[a]	25.7	3.70

[a] No range is given since only one sample applied by this installer was examined.

The cellulose samples showed a moisture content range of 8.8 to 13.4 percent, with the exception of one (no. 31) which had a moisture content of 21.2 percent (Table 5). This sample was removed from a wall area in the vicinity of a window frame which leaked rain water. 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 insulations was about 11 percent. The average value is close to the ten 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 [16]. 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 weight. No correlation was found between moisture content and thermal resistivity for the cellulose samples.

The data in Table 5 show that the loose-fill mineral fiber samples had moisture contents of less than 1 percent. This was the lowest percentage for the three types of retrofit insulations, and is identical with the value reported by Burch, Siu and Powell for a glass fiber sample conditioned to constant mass at 23.9°C (75°F) and 40 percent relative humidity [4]. The moisture contents of the mineral fiber samples showed no relationship to their thermal resistivities. The samples exhibited a range of resistivities, while the moisture contents were constant at less than 1 percent, as shown in Table 5.

3.1.4 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 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 take place within the foam to neutralize the acid-catalyst or that the acid 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 might be rendered susceptible to acid-catalyzed hydrolytic decomposition at those 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 surfaces of the foam and at the middle. The pH values are given in Table 10 for the three sections of the foam samples. The results indicated that the average pH of the foam surface next to the interior side of the wall-cavity 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. Only eight samples (nos. 1, 5, 11, 15, 20, 21, 22, and 24) showed the middle sections to have pH values which were greater than those of both surfaces.

TABLE 10. VALUES OF pH AT THE SURFACES AND CENTER OF THE UREA-FORMALDEHYDE BASED FOAM SAMPLES

Sample Number	pH Value		
	Interior[a]	Middle	Exterior [a]
1	6.0	6.5	6.3
2	5.8	6.0	6.0
3	3.3	3.4	6.1
4	5.8	5.5	6.5
5	3.6	6.6	4.5
6	3.1	3.3	3.5
7	3.2	3.4	4.0
8	3.8	3.1	3.6
9	4.6	4.9	6.0
10	3.0	4.7	5.1
11	3.8	6.4	4.8
12	4.0	6.2	6.4
13	3.6	3.8	5.2
14	2.9	4.6	5.1
15	3.3	6.0	4.0
16	3.1	3.2	3.3
17	3.1	3.8	5.8
18	3.3	4.6	4.7
19	5.1	4.0	3.3
20	2.8	4.2	3.9
21	3.6	5.4	5.1
22	2.9	3.4	3.0
23	4.2	3.9	4.8
24	5.6	6.5	5.7
25	2.7	4.2	4.7
Average	3.9	4.7	4.9

(a) Surface of the foam which faced the exterior side of the wall cavity.
(b) Surface of the foam which faced the interior side of the wall cavity.

3.1.5 Water Absorption of Urea-Formaldehyde Based Foams

The Canadian Standard [13] developed by the Canadian Government Specifications Board (CGSB) and the Use of Materials Bulletin No. 74 [14] issued by the U.S. Department of Housing and Urban Development for urea-formaldehyde based foam insulations both require a water absorption test (Appendix C). The test is performed on samples which have been conditioned at about 23°C (73°F) and 50 percent relative humidity for 28 days. The procedure involves floating the specimen on water and determining the quantity of water which is absorbed after 7 days. In order to meet the requirement of the standards, the water absorption of the foam sample should not exceed 15 percent by volume. It is noted that, as specified in the standards, the test is normally conducted on freshly-prepared dried foam samples and not on aged samples.

Although foam samples may meet the water absorption requirement 28 days after preparation, data were not available which describe the performance of aged foams in the test. It has been suggested that foam deterioration due to aging might result in an increase in the amount of water absorbed by foams [17]. Thus, it was of interest to determine the water absorption of some of the urea-formaldehyde based foam samples from the field study, since they were in general more than 2 years old and had been exposed to various environmental conditions. The water absorption test was not conducted on all foams because of a lack of test samples.

The results of the water absorption tests are given in Table 11, along with comments pertaining to the pre-test condition of the foam surface which was in contact with the water during the float test. Whenever sufficient test samples were available, duplicate tests were conducted on each surface of the foam. In other cases, only one test was performed on each surface, and for some samples, a single test was conducted on one surface only. The foam surface in contact with the water during the test had been oriented towards either the interior or exterior side of the cavity wall of the test house. No distinction was made as to whether the tested surface of the foam faced the interior side or the exterior side of the cavity wall.

As can be seen from Table 11, only one sample (no. 24) of the thirteen foams included in the test had a water absorption which exceeded the maximum value of 15 percent by volume stated in the Canadian Standard [13] and the HUD Use of Materials Bulletin [14]. This sample (no. 24) had a value of about 18-19 percent for three determinations and 11 percent in a fourth determination. The majority of the foams exhibited water absorptions which were less than 5 percent by volume, even though the conditions of the foam surfaces varied between samples. Sample no. 24 which had the highest water absorption was described as having surfaces which would be expected of foam in normal condition. This sample showed no signs of surface deterioration. On the other hand surface B of sample no. 11 was powdery and slightly friable, indicating some deterioration. However, the water absorption of this surface was only 1.2 percent by volume.

TABLE 11. WATER ABSORPTION OF UREA-FORMALDEHYDE BASED FOAMS

Sample Number [a]	Surface [b]	Water Absorption Percent by Volume	Comment on the Condition of the Foam Surface [a]
6	A	0.5	Both surfaces were soft and somewhat spongy.
	A	0.7	
	B	0.5	
	B	0.6	
7	A	0.7	Surface was soft and somewhat spongy.
8	A	1.2	Surface A was soft, while surface B was firm.
	A	1.1	
	B	0.4	
	B	0.5	
11	A	7.5	Both surfaces were powdery and slightly friable to the touch.
	B	1.2	
14	A	2.8	Surface A was slightly yellow.
	A	3.1	
	B	1.9	
15	A	1.6	Both surfaces were considered normal.
	A	2.1	
	B	1.0	
	B	0.6	
17	A	1.2	Both surfaces were very firm.
	A	1.4	
	B	3.2	
	B	2.2	
18	A	1.2	Both surfaces were very firm.
	A	1.3	
	B	2.1	
	B	2.0	
19	A	7.6	Both surfaces were yellow and not smooth.
	B	6.8	
21	A	1.1	Surface was soft and spongy.
23	A	1.6	Both surfaces were soft and spongy.
	B	1.9	
24	A	19.0	Both surfaces were considered normal.
	A	19.2	
	B	18.0	
	B	11.2	
25	A	15.0	Surface was yellow and contained a few small cracks and voids

(a) Test was not conducted on all samples because sufficient insulation was not available for all samples.

(b) Surface refers to the surface of the foam which was in contact with the water during the float test. Letter designations A and B were used only to distinguish one surface of the foam from the opposite surface.

These results do not appear consistent with the suggestion that the water absorption properties for foams may increase if the surfaces deteriorate with age. It is noted that the data in this study are limited, and because of the nature of the field survey, they do not include water absorption values for the freshly-prepared foams. A laboratory study or extended field survey would be needed to determine changes in water absorption properties of foam specimens as a function of time. Until such a study is conducted, it may be assumed that water absorption may not be used as an indication of foam deterioration due to aging.

3.2 Field Examinations

3.2.1 Shrinkage of Urea-Formaldehyde Based Foams

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 [9,12]. The Canadian Standard indicates that because of shrinkage, when installed in cavity walls, the effective thermal resistance of foam insulations may be 40 percent less than the laboratory-measured values of thermal resistance [13]. In a similar manner, the HUD Use of Materials Bulletin No. 74 states that the effective thermal resistance may be 28 percent less than the laboratory-measured value, provided that the foam shrinks 6 percent linearly [14]. The HUD Bulletin also presents a curve relating shrinkage to effective thermal resistance. 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 or data were recorded, foam shrinkage was considered to be of most concern.

Shrinkage had occurred in all inspected sidewalls containing urea-formaldehyde based foam insulation. Table 4 presents the percent linear shrinkage values. The procedure for calculating the percent shrinkage is given in Appendix E. For those test houses where more than one wall cavity was opened, shrinkage values were determined for each separate cavity and an average value was calculated. It can be seen in Table 4 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 [6] and considerably higher than the 1 to 3 percent range quoted in many sources [9]. 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.

Plots of the percent linear shrinkage with foam density and age indicated little relationship between the variables. As one example, Figure 13 is a plot of the density of the foam specimens versus percent linear shrinkage.

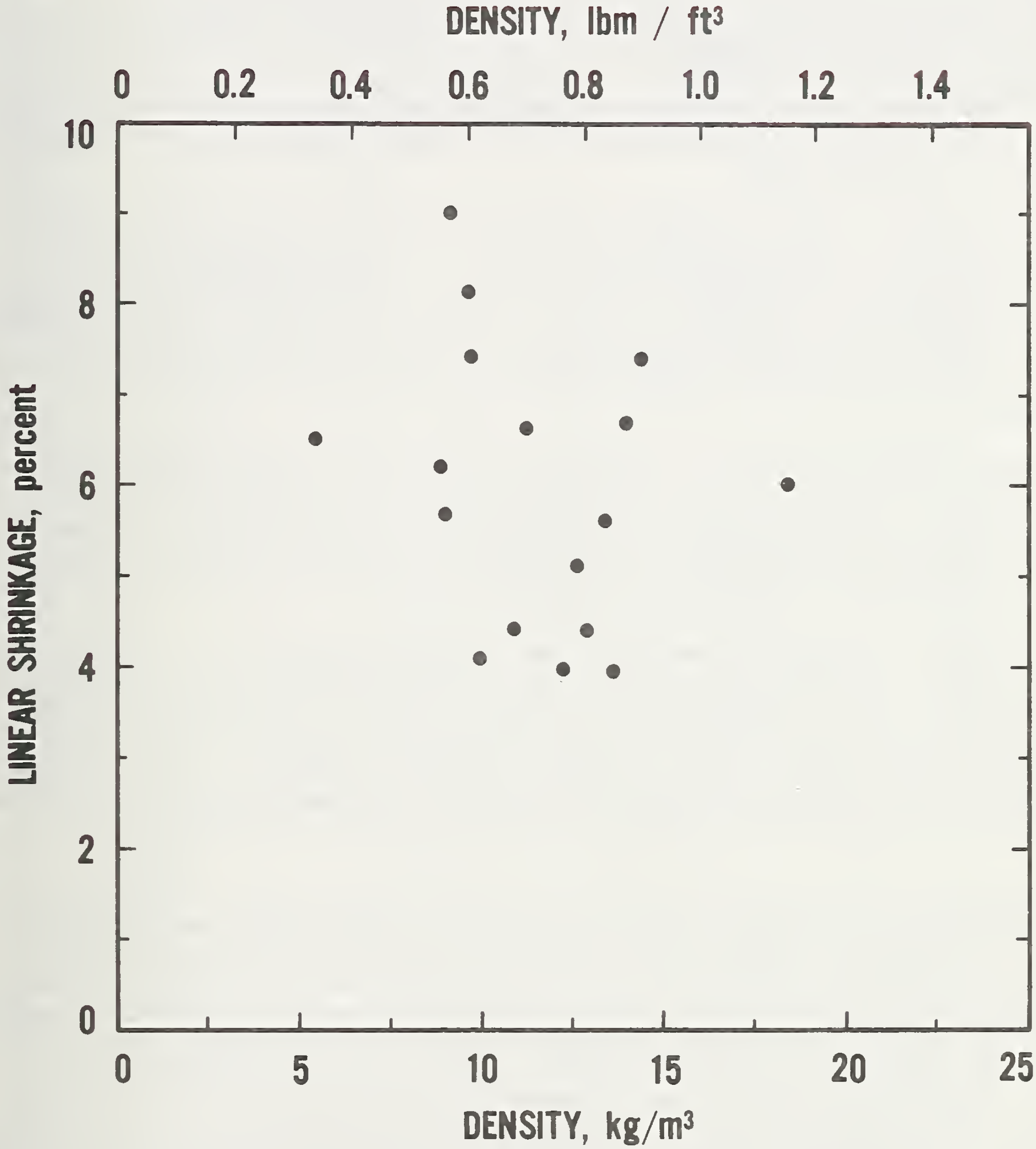

Figure 13. Plot of the Percent Shrinkage of the Urea-Formaldehyde Based Foam Specimens Versus Density.

Table 12 summarizes the percent linear shrinkage data by geographic location (city), component material manufacturer and installation season. No important differences in shrinkage values were found. As has been mentioned previously, the number of samples was limited and in some cases only one sample comprised a specific category. For example, only one house was inspected in which the foam was installed in the spring. Statistical analysis of the data in Table 12 was not attempted to determine whether the differences in the shrinkage values between categories were significant, since it could not be established that the houses included in the survey comprised a random sample.

In observing the foam in various houses, it was seen that the shrinkage patterns were not identical for all samples. In some cases, the foam was undistorted which indicated that the rear, center and front areas of the foam had shrunk uniformly. In other cases, the foam samples had warped and the shrinkage was more pronounced towards the exterior side of the cavity wall. Reasons for these different patterns of shrinkage were not determined.

In comparing the shrinkage of a single foam in two cavities of the same test house, it was found that shrinkage might vary considerably in the two cavities. In some cases, the difference in foam shrinkage between two cavities was over two percent. In one case, the foam shrinkage between cavities differed by about one-fourth of a percent.

As previously mentioned, foam shrinkage was generally measured across the cavity width. For four test houses, the percent shrinkage was determined from measurements of the cavity wall depths and foam thicknesses. These results are presented in Table 13 along with the shrinkage values based on measurements of the cavity wall and insulation widths. Table 13 shows that the shrinkage values using cavity depth measurements were greater than those from cavity width measurements for three of the four houses.

In addition to the formation of gaps and air spaces between wall studs and sheathing and the foam, shrinkage of urea-formaldehyde based foam insulations sometimes results in cracks or fissures, and voids within the sample. Cracking from shrinkage in general followed one of two patterns: the foam sample contained many small cracks which broke it into many small pieces (Figure 14); and the foam sample contained a few large cracks, generally horizontally oriented, which split it into several distinct pieces (Figure 15). The width of some of these large cracks ranged from 10 to 40 mm (0.4 to 1.6 in). In many cases, the foam samples contained many small fissures which did not penetrate completely through the insulation. Although all foams had undergone shrinkage to varying degrees, the surfaces of the foams were generally in good condition. One sample (no. 11) had surfaces described as powdery and slightly friable to the touch.

TABLE 12. RANGE AND AVERAGE VALUES OF LINEAR SHRINKAGE FOR UREA-FORMALDEHYDE BASED FOAMS BY CITY, MANUFACTURER AND INSTALLATION SEASON

Variables	No. of Samples	Range of Shrinkage percent	Average Shrinkage percent
° City			
Minneapolis	3	4.1 to 6.5	5.0
Hartford/New Haven	4	5.7 to 9.0	7.1
Washington, D.C.	1	--[a]	7.4
Louisville	6	4.4 to 6.7	5.6
Dayton	3	3.9 to 8.1	6.0
° Manufacturer			
A	1	--[a]	6.2
B	--[b]	--[b]	--[b]
C	6	5.7 to 9.0	7.0
D	--[b]	--[b]	--[b]
E	1	--[a]	3.9
F	2	4.1 to 4.4	4.3
G	6	4.4 to 8.1	5.9
H	1	--[a]	6.5
° Installation Season			
Summer	6	4.1 to 9.1	6.5
Fall	5	4.4 to 7.4	5.7
Winter	5	3.9 to 7.4	5.8
Spring	1	--[a]	5.7

[a] No range is given since only one sample was in this category.

[b] Shrinkage values were not determined for this manufacturer's insulation.

TABLE 13. A COMPARISON OF SHRINKAGE VALUES FROM CAVITY WIDTH AND CAVITY DEPTH MEASUREMENTS

Sample No.	Shrinkage Value from Cavity Width Measurements Percent	Shrinkage Value for Cavity Depth Measurement Percent
5	7.4	8.2
8	6.2	6.7
17	6.7	5.1
18	6.6	8.1

3.2.2 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, as shown in Figure 16. It could not be determined whether the voids were attributable to settling of the insulation or initial incomplete fill of the cavities. The voids in the cavities ranged in height from about 30 to 130 mm (1.2 to 5.1 in).

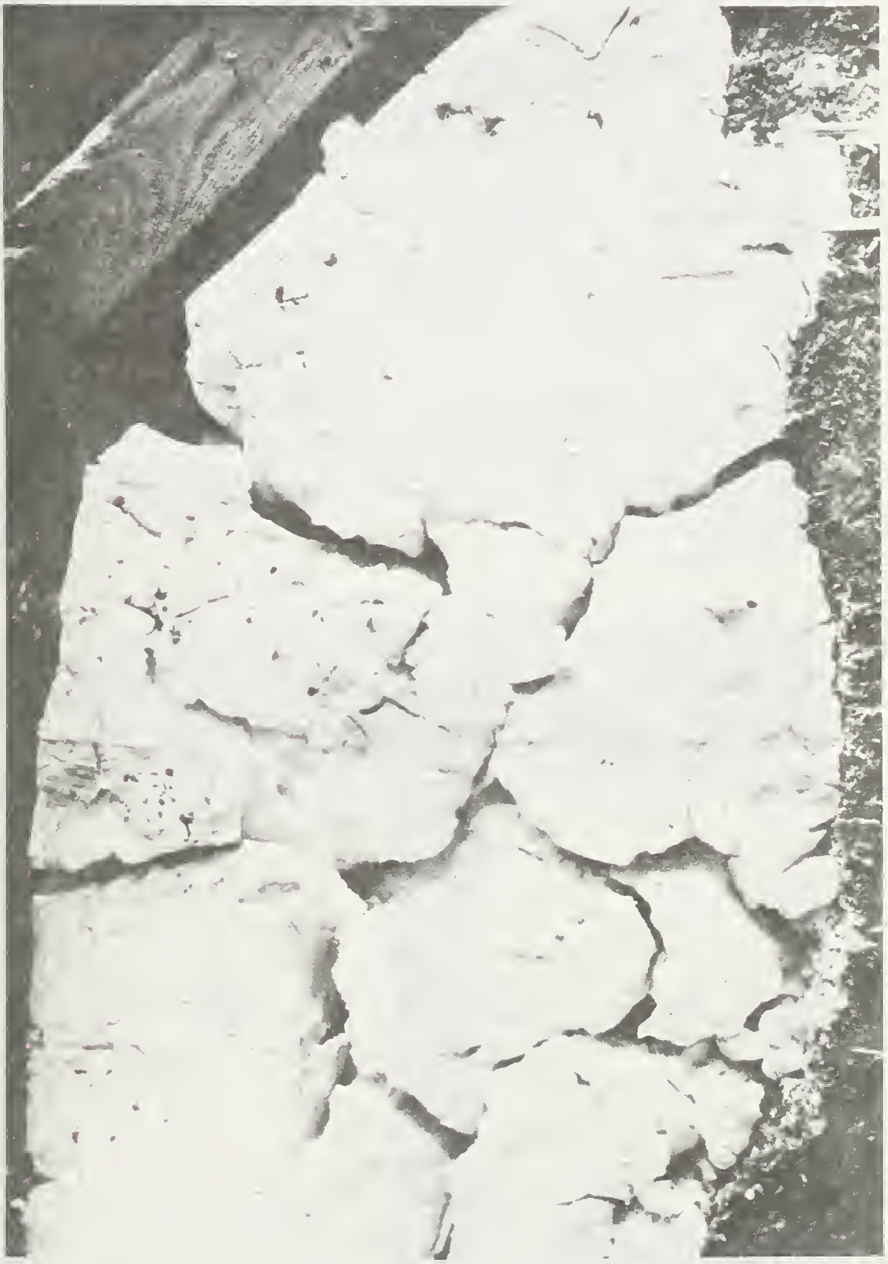

Figure 14. Example of Urea-Formaldehyde Based Foam Sample Which Cracked into Small Pieces

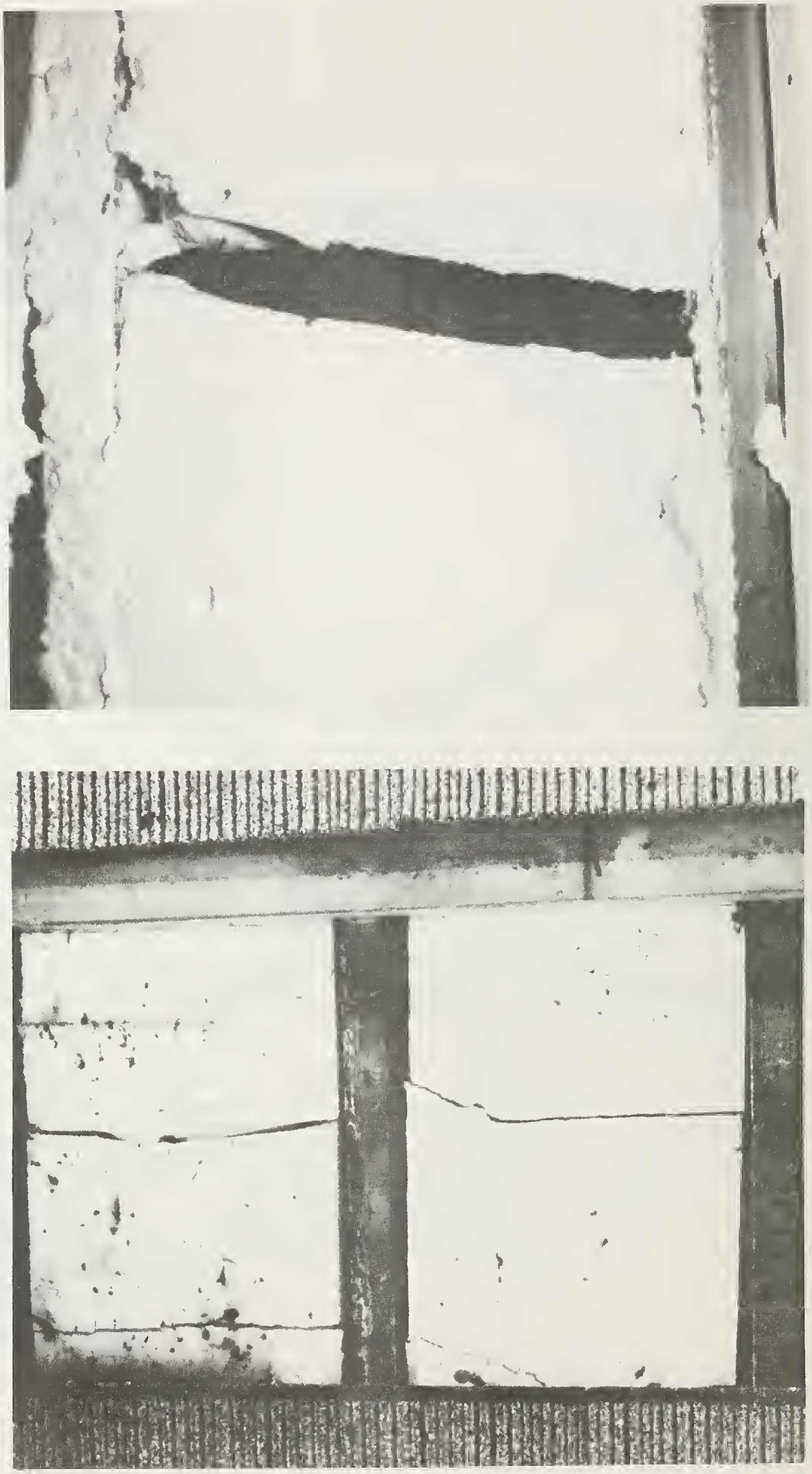

Figure 15. Examples of Urea-Formaldehyde Based Foam Samples Which Contained Large Horizontal Cracks.

Figure 16. The Void Observed at the Top of the Cavity Insulated with Loose-Fill Cellulose Insulation.

3.2.3 Condition of Wall Components

Voluminous notes concerning the general 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 at the location where the sidewalls were opened. No visible evidence of moisture accumulation and condensation or damage was found, except in the case of one house (no. 31). 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.

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 five of the houses were in good condition and corrosion, if any, was minimal. Non-galvanized common nails were present in most wall cavities and, as would be anticipated, they showed some rust.

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 quite 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, it would have readily been detected by the occupants of the house. It is emphasized that these findings concerning formaldehyde release from foams are subjective. This field survey was not intended to address directly the subject of formaldehyde release and no measurements of the concentration of air-borne formaldehyde were made in the test houses.

Evidence of vermin activity in the retrofitted sidewalls was seen in the case of a rock/slag fiber installation. The insulation contained voids or tunnels which were apparently made by mice. In another case, a mouse nest which was probably present before the application of the insulation was found within the urea-formaldehyde based foam.

3.2.4 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 resistances. 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. Wall cavities which are incompletely filled may be less thermally efficient than those which are completely filled [4, 12-14, 18]. 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 wide-spread 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 observed problems 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 insulations in which the cavities were not completely filled (Figure 17); and two cases (one foam and the other mineral fiber) wherein excessive pressure was applied during application which resulted in cracking and bowing of the interior wall surfaces.

The observation that some houses had cavities which were not completely filled with insulation is consistent with the findings from Grot's field survey using thermographic techniques [7].

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 then those described as 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.

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. Figure 18 shows an urea-formaldehyde based foam which 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 seen to be 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 wall cavities inspected in these seven cases, the presence of the batt insulation did not adversely affect the installation of the retrofit insulation. The wall cavities in the areas of inspection were completely filled, since the retrofit insulation compressed the batt to one side of the cavity (Figure 19). 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 inspected wall cavities were filled with insulation. This was in accord with Weidt's previous finding that presence of insulation within the wall cavity did not necessarily preclude the successful application of the retrofit insulation [6].

3.2.5 The Presence of Membrane-Type Vapor Barriers

Accepted practice is to place a vapor barrier on the warm side (during the winter) of a wall to prevent moisture accumulation within the wall due to vapor transmission. Improperly placed vapor barriers may result

Figure 17. Incomplete Application of Urea-Formaldehyde Based Foam Insulation.

Figure 18. Electrical Outlet Box Filled With Urea-Formaldehyde Based Foam Insulation.

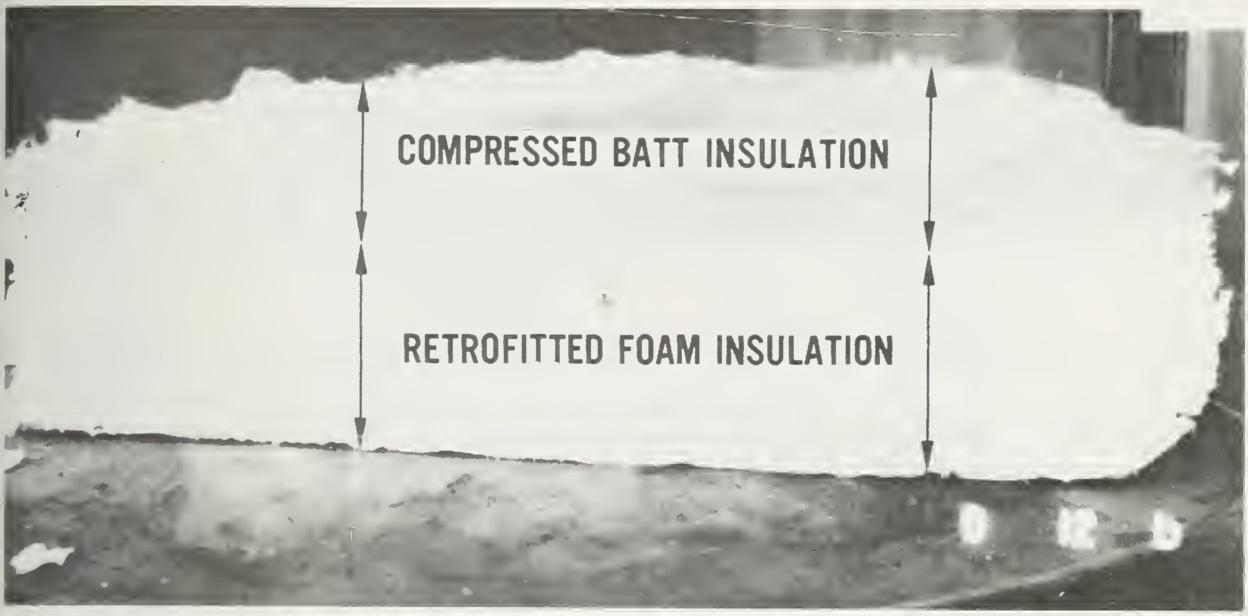

Figure 19. Existing Batt Insulation Compressed by the Retrofit Insulation.

in excessive accumulation of moisture within the wall. Membrane-type vapor barriers were found in the wall cavities of ten of the surveyed houses. The scope of this study did not include a determination of the permeance of the interior facing of the cavities. Table 14 gives the types and locations of the membrane vapor barriers found in the study, and the moisture contents of the insulations in the cavities. The moisture contents for the insulations installed in cavities with vapor barriers were close to the average values of moisture content for each of the three types of retrofit insulations. As presented in Section 3.1.3 the average moisture contents of urea-formaldehyde based foam, loose-fill cellulose and loose-fill mineral fiber insulations were 12, 11, and < 1 percent, respectively. Although the observation may have little significance, it is interesting to note from Table 14 that the urea-formaldehyde based foam samples in cavities with the vapor barriers on the exterior side had on the average lower moisture contents than foams in cavities with interior side vapor barriers.

4.0 SUMMARY AND CONCLUSIONS

The study was intended to obtain information concerning the properties and performance of retrofit insulations, as they are found in place in the walls. 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. 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.

TABLE 14. TYPE AND LOCATION OF VAPOR BARRIERS FOUND IN WALL-CAVITIES AND CORRESPONDING MOISTURE CONTENTS OF INSULATIONS

Sample No.	Retrofit Insulation	Vapor Barrier Type	Vapor Barrier Location	Moisture Content Percent by Mass
2	UF Foam	Foil	Exterior[(a)]	10.5
5	UF Foam	Foil	Exterior	6.5
19	UF Foam	Foil	Exterior	10.9
21	UF Foam	Foil	Exterior	13.6
4	UF Foam	Batt Facing	Interior[(b)]	12.5
8	UF Foam	Foil	Interior	11.7
10	UF Foam	Foil	Interior	14.9
16	UF Foam	Batt Facing	Interior	14.8
26	Cellulose	Batt Facing	Middle[(c)]	12.4
35	Glass Fiber	Foil	Exterior	< 1.0
AVERAGE:	UF Foam with exterior vapor barriers			10.5
AVERAGE:	UF Foam with interior vapor barriers			13.5

(a) Exterior indicates that the vapor barrier was located on the exterior side of the wall cavity.

(b) Interior indicates that the vapor barrier was located on the interior side of the wall cavity.

(c) Insulation was on both sides of the vapor barrier.

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.

Shrinkage had occurred for all urea-formaldehyde based foam insulations. Linear shrinkage values ranged from about 4 to 9 percent and averaged 6.0 percent for the seventeen houses in which it was measured. Shrinkage could not be related to any observed variable including density, age, geographic location, component material manufacturer, and season of installation. 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. The average densities for the loose-fill cellulose and urea-formaldehyde based foam insulation samples were 54.8 kg/m^3 (3.4 lbm/ft^3) and 11.5 kg/m^3 (0.72 lbm/ft^3), respectively. These values were in agreement with values reported in the literature. No average value of density was calculated for the loose-fill mineral fiber samples because of the wide range. In general, the densities were higher than some values cited in the literature. In the case of two rock/slag wool insulation samples, the densities were much higher than expected, based on a comparison of literature values. 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. In addition, the density of one urea-formaldehyde based foam sample was unacceptably low and, in this case, its thermal resistivity was quite low.

The average values of thermal resistivity of the loose-fill cellulose, loose-fill mineral fiber and urea-formaldehyde based foam insulation were 24.9, 26.4 and 28.0 m·K/W (3.58, 3.80 and 4.03 $h \cdot ft^2 \cdot °F/Btu \cdot in$), respectively, and their respective average moisture contents were about 11, 1 and 12 percent by mass. In general, values of these properties were found to agree favorably with other values for these properties cited in the literature. For each type of retrofit insulation, no correlation was found between thermal resistivity and moisture content.

Relationships between density and thermal resistivity were found for the loose-fill cellulose and urea-formaldehyde based foam insulations. In the case of cellulose, the thermal resistivity decreased as the density increased. For the foam insulations, the thermal resistivity increased with an increase in density.

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 wall was slightly lower than those of the sample surfaces at the exterior of the wall or center sections of the foams. The average values at these latter two locations were approximately the same.

A laboratory test to determine the percent (by volume) water absorbed by urea-formaldehyde based foam insulations after floating on water for 7 days was conducted on some samples. With one exception, these samples absorbed less than 15 percent by volume. One sample which showed no signs of surface deterioration had an average water absorption of about 17 percent by volume. This test should not be used to indicate deterioration of foam insulations, unless further data are developed to relate water absorption and surface condition.

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 in general accomplished without causing adverse effects. One of the houses surveyed contained a mineral fiber insulation which was about 10 years old. In this case, no problems were observed by the field investigators nor indicated by the homeowner in an interview. For the survey in general, damage to wall components 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. Furthermore, the electrical components were not examined microscopically for the presence of oxide coatings. Electrical connections in junction boxes found to contain insulation were not inspected for corrosion. 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 wall cavities were not always completely filled either because of workmanship problems during application or settling and shrinkage 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 much greater than the 1 to 3 percent often quoted in the literature. This factor was of most concern, since shrinkage may result in insulated walls with reduced thermal performance.

5.0 RECOMMENDATIONS

This study consisted of a field phase to observe retrofit insulations installed in the cavity walls of houses and a laboratory phase to measure some performance properties of the insulations after removal from the walls. Based upon the field observations and results of the laboratory tests, the following recommendations are made:

° Voluntary consensus standard practices for the application of retrofit insulations should be developed. Application of the insulations according to standard practices should reduce the possibility of workmanship problems during installation. Standard practices have been developed for the DoE Residential Conservation Service Program. The development of these DoE practices as voluntary consensus practices should be encouraged to broaden their application.

- If urea-formaldehyde based foam insulations are to be commonly used for retrofitting walls of residences, criteria should be developed to establish the maximum allowable shrinkage which foams may undergo in-service. Factors affecting shrinkage of foams should be understood so that shrinkage may be minimized. The foam insulations examined in the field survey were found to have shrunk greater than about 4 percent, with the maximum shrinkage being 9 percent. It is noted that some foam manufacturers have indicated that newly-developed foam insulations shrink to a lesser extent that their earlier-available products. Data are not available from field studies to determine the extent of shrinkage which these newly-developed foams undergo in service.

- The development of voluntary consensus standard practices for re-insulating sidewalls containing batt insulation which does not completely fill the cavity should be undertaken. This would assure that the addition of retrofit insulation to existing insulation is performed adequately. Observations from this study indicated that wall cavities with existing batt insulation may be completely filled during retrofitting.

- A performance criterion should be established concerning the effect of retrofit insulations on the corrosion of metals in walls. Little information was obtained during this study on the important question regarding corrosion.

6.0 ACKNOWLEDGMENTS

This study was sponsored by the Department of Energy (DoE), Office of Weatherization Assistance. Ms. Sandra S. Monje and Mr. Heinz R. Trechsel provided liaison between DoE and the Center for Building Technology, NBS, respectively. The authors wish to express their appreciation to those homeowners who extended their hospitality to the field investigators and allowed their residences to be used as test houses. The response of many hundreds of individuals to our news release in volunteering their residences for inspection was also appreciated.

Thanks are given to those Dynatech R/D Company staff members who conducted the laboratory tests: Stu Spinney, former Manager, Measurements Laboratory; Bill Terranova, Project Technician; and Ann Bersani, Technician. The authors also thank Ms. Madeleine Jacobs, formerly of NBS, for her effort in preparing the news release which attracted the helpful responses from homeowners, and Mr. Robert G. Mathey, NBS, for providing many useful comments and technical suggestions concerning the field inspection and this report. Discussions with Dr. Geoffrey Frohnsdorff, NBS, concerning this report also provided many useful suggestions and were appreciated.

Thanks are also given to the staff members of John Weidt Associates, Kathy Thorstensen, Linda Heinman and Jenny Weidt, for their efforts in corresponding with the volunteer homeowners and coordinating the itinerary for the field inspections.

Finally, special mention should be made to 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.

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Appendix A. NEWS RELEASE REQUESTING VOLUNTEERS FOR PARTICIPATION IN THE STUDY

This Appendix presents the news release published to seek homeowners who would volunteer their residences as test houses in the field study. The news release contained a telephone number which is deleted herein.

HOMEOWNERS SOUGHT TO PARTICIPATE IN STUDY OF WALL INSULATION

The Federal government is seeking homeowners to participate in a study aimed at developing better information about the performance and use of thermal wall insulation.

The study is being carried out by architect John Weidt of Minnesota under contract to the Commerce Department's National Bureau of Standards (NBS). The project is sponsored by the Department of Energy Office of Weatherization Assistance. Weidt recently completed a similar study of insulation in Minnesota houses.

Homeowners who have had thermal insulation installed in the walls of their houses at least two years ago are eligible to participate. The three types of insulation that will be studied are urea-formaldehyde foams, cellulosic loose-fill, and mineral fiber loose-fill.

Weidt is looking for homeowners in these different climatic regions of the country:

- --Northern (Minnesota, New England)
- --Middle Atlantic (Maryland, Virginia, District of Columbia)
- --Southern (North and South Carolina, Georgia, Alabama, Louisiana, Florida)
- --Midwest (Ohio, Kentucky).

In the study small portions of the wall will be removed either from the outside or inside of the house. The insulation will be inspected and observations noted on such factors as corrosion of metal objects, moisture accumulation, odor, fungus or mold growth, and workmanship during installation. Weidt will also be studying settling of loose-fill insulations and shrinkage of foam insulations.

Small samples of the insulation will be removed and sent to the laboratories for testing their thermal conductivity, density, and moisture content.

Homeowners will also be interviewed by Weidt to determine their satisfaction with the results obtained from insulating the walls of their houses and to determine the effects on their fuel consumption.

Weidt has indicated that the walls of the homes will be repaired and restored to the homeowner's satisfaction. For participating in the study, homeowners will receive a clock thermostat, an energy saving device that automatically controls the temperature of the house according to an adjustable time schedule.

Wall insulations are of particular concern to the federal government since there is insufficient information about the performance of these materials once they are installed. Although unseen, wall insulation must continue to retain its insulating properties and remain compatible with the structural and other materials with which it is in contact.

"The government is sponsoring the study because substantial energy savings as well as the health and safety of the occupants depend on the quality and performance of these largely unseen insulations," says NBS Project Leader Dr. Walter J. Rossiter, Jr. "In addition, millions of dollars will be spent by homeowners installing insulation in their houses."

The results of the study, he notes, will be used to develop needed information on the performance of insulations in order to update guidelines and standards for their application and use.

To participate, homeowners should know the type of insulation in their homes and approximately when it was installed. Only retrofitted houses, i.e., houses with insulation installed after the completion of constuction and being occupied, will be considered for the study; houses originally built with wall insulation are not included. Interested persons should contact:

John Weidt Associates Inc.
Jonathan Lake Village Center
Post Office Box 401
Chaska, Minnesota 55318, or call Weidt collect at ____________.

Deadline for participation in this study is December 1, 1978.

APPENDIX B

PROCEDURES USED IN THE FIELD EXAMINATIONS

B.1 Selection of Sample Area

The residence was surveyed to locate an area for sampling that could be repaired to the homeowner's satisfaction and would be likely to contain electrical wiring or outlet boxes. The presence of electrical wiring or other metallic objects in the cavity could not always be ascertained prior to the opening.

The procedure was designed to remove loose-fill insulation from the top of a cavity; however, in certain cases, taking samples from the top of the cavity was impossible because of structural framing of older homes, access to the top of the cavity with the portable equipment or specific requirements of individual homeowners restricting the test location. In these instances, if the sample area was close to the top of a cavity, the area above the sample was probed manually to ascertain whether the cavity was filled completely.

B.2 Opening of Cavity

After a suitable test area had been identified, an opening of approximately 0.4 to 0.6 m^2 (4 to 6 ft^2) was made in either the exterior or interior surface of the wall. Where an exterior opening was made, the siding was first removed; any other subsiding or concealed material was next removed; the building paper, if present, was cut away; and finally the sheathing was cut and removed to expose the insulated cavity. The types of exterior siding removed included wood clapboard, wood shingles, wood ship-lap, plywood, asbestos shingles, composite wood products and aluminum siding. No masonry or stucco homes were opened from the exterior. Where an interior opening was made, the interior surface was cut away to expose the insulated cavity. Interior openings included paneling, gypsum wallboard, rock-lath and plaster, and wood-lath and plaster materials.

B.3 Observations

Field observations were noted of the following: the condition of the outside and inside paint surfaces, siding, sheathing, structure, wiring; the presence and location of physical vapor barriers; evidence of moisture, odor, rot, fungus, mold, vermin and corrosion; presence of cracks or voids in the insulation; and the insulation color.

B.4 Sampling

After observations concerning the condition of the installed insulation were noted and field measurements of factors such as settling or shrinkage age were recorded, a number of insulation samples were taken from each sidewall cavity as follows:

Thermal Resistivity and Density Samples - The primary sample was a large section of insulation that was used for the determination of thermal resistivity and density. This sample was removed from the cavity and placed in tared double polyethylene bags which were labeled, weighed, sealed and sent to the laboratory.

Moisture Content Samples - A sample to be used for the determination of moisture content was taken across the total depth of the cavity. A measurement conducted on this sample would yield an average moisture content from interior to exterior face. The sample was placed in a pre-labeled, tared, one liter polyethylene jar which was sealed to prevent loss or gain of moisture, weighed and sent to the laboratory.

pH Samples - For those sidewalls which contained urea-formaldehyde foam retrofit insulations, additional insulation samples were taken of the interior surface, the exterior surface and the middle of the foam material. These samples were placed in individual pre-labelled polyethylene containers and sent to the laboratory for pH measurements.

Absorption Samples - Samples of some urea-formaldehyde foam insulations were sent to the National Bureau of Standards for moisture absorption testing.

B.5 Observations

Several methods were used on site to note the observations and record the measurements made on the insulation of each test site. Color photographs of each step of the work were taken to record specific conditions encountered on each site and close-up detail photographs were made wherever any anomalies were found in specific cavities. Photographs of each test site were coded directly on the film with a data-back number relating to the specific test site. Figures in the text may show this number visible in one corner of the frame.

A field worksheet was prepared which included a variety of comments, data points and a sketch of the observed cavity. General comments on each test site were made and recorded on a field comments worksheet. These comments included notes on observations, the comments of the homeowner relative to his opinion of the retrofit application and the impact on his fuel consumption and personal comfort. The comments of the homeowners were not discussed in this report, since the opinions were considered subjective. In most cases, homeowners did not have documentation supporting opinions.

B.6 Data

Data taken in the field included: measurements of the dimensions of the cavity after removal of the insulating material to determine volume; measurements of shrinkage (urea-formaldehyde foam insulation); and mass of all samples. Depth measurements were made with a probe caliper and dimension measurements made with a steel rule, both graduated in millimeters. Masses of samples less than 1.5 kg (3.3 lbm) were obtained on a triple-beam balance which was calibrated prior to each test using weights of known mass. Tare masses of containers determined made prior to filling them with insulation. Samples over 1.5 kg (3.3 lbm) were weighed on a spring scale. These sample masses were compared with laboratory measured values.

B.7 Closing of the Cavity

Upon completion of the observations, measurements and sampling, the opened wall cavity was repaired to the satisfaction of the homeowner. Exterior openings normally involved replacing all materials previously removed, caulking, sealing and touch-up painting if required. Interior openings required resurfacing of the opening with gypsum wall board and taping as required. Both interior and exterior openings were reinsulated with a glass fiber batt.

APPENDIX C

LABORATORY TEST PROCEDURES

A commercial laboratory received the samples of urea-formaldehyde based foam, loose-fill cellulose, and loose-fill mineral fiber insulations to measure density, thermal resistivity and moisture content. In addition, the pH and moisture absorption of the urea-formaldehyde foam specimens were determined.

C.1 Density

Upon arrival of the loose-fill insulation test specimen at the testing laboratory, its mass was determined to compare it with the mass measured in the field. Its density was then calculated from the mass and the volume of the cavity from which the insulation was removed as follows:

$$D = \frac{m}{(l)\ (w)\ (d)}$$

where D = density
m = mass of material measured in the field
l = length of selected cavity section
w = width of cavity
d = depth of insulation

In the case of the urea-formaldehyde based foam samples, it was desired to prepare with a mill 50 x 300 x 300 mm (2 x 12 x 12 in) test specimens in the laboratory from larger sized samples received from the field. However, the milled specimens were less than 50 x 300 x 300 mm (2 x 12 x 12 in), since the field samples were not large enough to obtain specimens of the desired size. The dimensions of the urea-formaldehyde based foam samples used for the density and thermal resistivity tests are presented in Table C.1. The density of the foam samples was determined from;

$$D = \frac{m}{v}$$

where D = density of prepared sample
m = mass of prepared sample
v = volume of prepared sample

C.2 Thermal Resistivity

C.2.1 Urea-Formaldehyde Based Foam Insulation

The thermal resistivity of the urea-formaldehyde based foam samples would have been determined using specimens with dimensions of 50 x 300 x 300 mm (2 x 12 x 12 in), if large enough pieces of foam had been available. Since samples from the field with these dimensions were not available, the test specimen for the determination of thermal resistance was cut as large as possible (Table C.1). The thickness of the urea-formaldehyde

TABLE C.1 DIMENSIONS OF THE UREA-FORMALDEHYDE BASED FOAM SAMPLES USED IN THE DETERMINATION OF THEIR DENSITIES AND THERMAL RESISTIVITIES

SAMPLE	DIMENSIONS					
	Thickness		Length		Width	
No.	mm	in	mm	in	mm	in
1	41	1.6	119	4.7	112	4.4
2	51	2.0	145	5.7	107	4.2
3	56	2.2	297	11.7	277	10.9
4	51	2.0	236	9.3	206	8.1
5	58	2.3	300	11.8	249	9.8
6	64	2.5	254	10.0	234	9.2
7	53	2.1	221	8.7	188	7.4
8	51	2.0	302	11.9	231	9.1
9[a]	48	1.9	124	4.9	74	2.9
10	56	2.2	150	5.9	145	5.7
11	51	2.0	216	8.5	201	7.9
12	48	1.9	119	4.7	71	2.8
13	36	1.4	119	4.7	119	4.7
14	53	2.1	287	11.3	236	9.3
15	56	2.2	292	11.5	269	10.6
16	43	1.7	239	9.4	188	7.4
17	53	2.1	257	10.1	213	8.4
18	56	2.2	254	10.0	196	7.7
19	56	2.2	272	10.7	231	9.1
20	53	2.1	297	11.7	269	10.6
21	46	1.8	208	8.2	185	7.3
22	58	2.3	188	7.4	168	6.6
23	53	2.1	272	10.7	268	10.5
24	64	2.5	246	9.7	216	8.5
25	53	2.1	208	8.2	188	7.4

(a) Sample was only used for the determination of density.

based foam test sample was measured and a 300 x 300 mm (12 x 12 in) piece of extruded polystyrene foam was cut to the same thickness as the test sample. An outline of the test sample was traced on the center of extruded polystyrene and cut out. The urea-formaldehyde based foam test sample was then inserted into this hole and its thermal resistivity was measured. As the actual heat flow transducer size was 100 x 100 mm (4 x 4 in), accurate measurements could be made on test samples at least this size. The resistance was measured based on the procedure given in ASTM C 518-76, "Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter", using a commercially available apparatus. The upper and lower plates of the instrument with dimensions of 300 x 300 mm (12 x 12 in) were blackened aluminum sinks containing heaters which were temperature controlled with proportional/reset temperature controllers. Both plates were instrumented with Type T (copper/constantan) thermocouples. The bottom plate, or cold face, was instrumented with a calibrated heat flux transducer. The temperatures of the upper and lower plates were controlled at 34 and 14 °C (93 and 57 °F), respectively.

C.2.2 Loose-Fill Insulation

The thermal resistivities of the loose-fill cellulose and mineral fiber insulations were determined in accordance with ASTM C 518-76, using a commercially available heat flow meter apparatus except that the samples were not dried. The upper and lower plates of the instrument with dimensions of 600 x 600 mm (24 x 24 in) were blackened aluminum sinks containing heaters which were temperature controlled with proportional/reset temperature controllers. Both plates were instrumented with a calibrated integrating heat flow transducer. The temperatures of the upper and lower plates were controlled at 10 and 38 °C (50 and 100 °F) respectively. The thickness of the samples was 90 mm (3.5 in) and it was maintained by use of a sample containment ring.

C.2.3 Thermal Resistivity Calculation

At equilibrium, the thermal resistivity for urea-formaldehyde based foam and loose-fill insulations was calculated as follows:

$$R = (q/A)^{-1} \, [(T_h - T_c)/x]$$

Where q/A = heat flux as measured by the heat flow transducer
T_h = temperature of upper hot face
T_c = temperature of lower cold face
x = specimen thickness

C.3 Moisture Content

The moisture content or total volatile content was determined in accordance with the procedure given in ASTM D 644-55 (1976), "Moisture Content of Paper and Paperboard by Oven Drying". In the laboratory, the insulation specimens were removed from the sealed polyethylene jars and immediately weighed. The nominal sample masses of the loose-fill and urea-formaldehyde based foam samples were 5 g and 1 g (0.18 oz and 0.04 oz), respectively. The samples were placed in tared evaporating dishes which were weighed, placed in an air-circulating oven at 105 °C (221 °F) for 48 hours, removed, cooled to room temperature in a desiccator and reweighed. Any loss in mass was recorded as moisture content. The percent volatiles was taken to be the moisture content was calculated from:

$$\% \text{ Moisture Content} = \frac{100\ (W_1 - W_2)}{W_2}$$

where W_1 = original sample mass
W_2 = mass of sample after oven drying

C.4 pH of Urea-Formaldehyde Based Foam Insulations

Since no standard test procedure for the determination of the pH of urea-formaldehyde based foam insulations was available, the following procedure, used by the testing and quality control laboratories of a manufacturer of urea-formaldehyde based foam, was employed.

The pH of the urea-formaldehyde based foams was determined by removing a small amount of the foam from each of three places during sample removal. Material was removed from the surface facing the interior of the residence, the middle of the foam and the surface facing the exterior of the residence. Each sample was sent to the laboratory in a small plastic container. The samples were removed from the containers and 1 g (0.04 oz) was crushed into a 250 ml (8.5 fl oz) beaker. To the beaker was added 100 ml (3.4 fl oz) of distilled water. The beaker was covered with a watchglass, and the solution was boiled for 5 minutes. The solution was cooled to room temperature, the beaker sides rinsed with distilled water and the volume of water was made up to 100 ml (3.4 oz). The pH of the solution was measured with a standard pH meter which was calibrated with standard buffered solutions of pH 4 and pH 7.

C.5 Moisture Absorption of Urea-Formaldehyde Based Foam Insulations

The moisture absorption of the urea-formaldehyde based foam insulation samples was determined according to a test procedure which was essentially the same as that given in Section 6.2.9.1 of HUD Use of Materials Bulletin 74 [14]. Foam specimens with dimensions of 100 x 100 mm (4 x 4 in) were cut from larger pieces of foam which were removed from the walls of the test houses. The thicknesses of the specimens were as found in the wall cavities. However, all specimens had comparable thichnesses of 88 mm (3.5 in) $\pm$ 6 mm (0.25 in). The volume of the specimens were determined using a rule graduated in millimeters. The specimens were weighed to the nearest 0.1 g on a laboratory balance to determine their mass.

The specimens were placed on the surface of distilled water in a plastic pan. The surfaces of the specimens placed on the distilled water were those obtained from foaming during the retrofitting of the test houses and corresponded to the exterior and interior sides of the wall cavities. After 7 days at 23 $\pm$ 2°C (73 $\pm$ 4°F) and 50 $\pm$ 5 percent relative humidity, the specimens were removed from the water and any water visible on their surfaces was blotted with a paper towel. The blotted specimens were reweighed on the laboratory balance. The water absorbed was calculated as a percent of the volume of the original foam specimen.

APPENDIX D

TABLE D.1 DEFINITIONS OF S.I. AND CUSTOMARY UNITS USED IN THIS REPORT

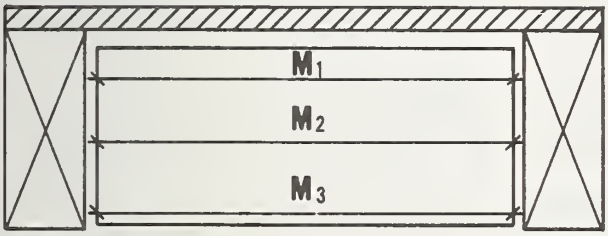
Property	Units S.I. (Customary)	Definition S.I. (Customary)
Density	kg/m^3 ($\ell bm/ft^3$)	kilogram/meter cubed (pound-mass/foot cubed)
Temperature	°C (°F)	degree Celsius (degree Fahrenheit)
Thermal Resistivity	m•K/W ($h \cdot ft^2 \cdot °F/Btu \cdot in$)	meter • degree Kelvin/Watt (hour • foot squared • degree Fahrenheit/British Thermal Unit • inch)

APPENDIX E

LINEAR SHRINKAGE OF UREA-FORMALDEHYDE BASED FOAMS

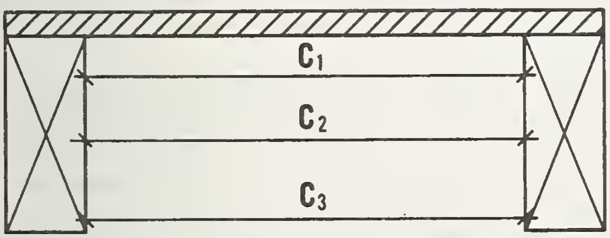
Linear shrinkage was calculated as a percent of original specimen width. The measured width of the cavity was taken as the original width of the urea-formaldehyde based foam specimen.

All measurements were made at a clean horizontal section through the insulation where the foam had not cracked, as described in Section B.6.



$$\text{Material Width} = \frac{M_1 + M_2 + M_2}{3}$$

Measurement of Foam Width In-Situ



$$\text{Cavity Width} = \frac{C_1 + C_2 + C_3}{3}$$

Measurement of Cavity Width

$$\text{Percent Shrinkage} = \frac{\text{Cavity Width} - \text{Foam Width}}{\text{Cavity Width}} \times 100\%$$

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS TN 1131	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Field Investigation of the Performance of Residential Retrofit Insulation

5. Publication Date September 1980

6. Performing Organization Code

7. AUTHOR(S)

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

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Office of Weatherization Assistance
U.S. Dept. of Energy, 1000 Independence Ave., SW
Washington, D.C. 20585

13. Type of Report & Period Covered Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A study was conducted to obtain information on the performance of in-service insulations of the type commonly used in the United States to retrofit sidewalls of housing: urea-formaldehyde based foam, loose-fill cellulose, and loose-fill mineral fiber.

In the field phase of the study, observations were made on performance-related 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. Shrinkage was observed to have occurred for all urea-formaldehyde based foam specimens. Where 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 of undetermined origin at the location.

Insulation specimens removed from the walls were tested to determine their density, thermal resistivity and moisture content. The pH and moisture absorption of the urea-formaldehyde based foam specimens were also determined. Results of the laboratory measurements are discussed and compared with data from other studies. Relationships between the moisture contents of the samples and their thermal resistivities were not found. Results indicated that the retrofitting of the inspect sidewalls was for the most part accomplished without adverse effect upon them.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Conservation; energy; field survey; insulation; moisture content; residences; retrofit; thermal resistivity

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19. SECURITY CLASS (THIS REPORT)	21. NO. OF PRINTED PAGES
UNCLASSIFIED	67
20. SECURITY CLASS (THIS PAGE)	**22. Price**
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