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An In Situ Study of Attic Loose-Fill Thermal Insulation in Residential Applications

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ABSTRACT

The extent of settling of loose-fill insulations with time is being studied in 16 pre-instrumented attics in Bucyrus, OH. In February 1982, immediately after installation, measurements were made of insulation depths and densities in eight attics insulated with loose-fill cellulose and eight attics insulated with loose-fill fiberglass. Depth measurements were made one, three, and six months after installation, and density measurements at six months to assess the degree of settling for the two products. The average depth of the cellulose decreased about 13% in six months; that of the fiberglass decreased about 3.4% during the same period. Average density increases are consistent with these depth changes to within 10%. Monitoring of the 16 attics is continuing.

INTRODUCTION

The thickness, L, of loose-fill insulation needed to produce a specified thermal resistance, R, depends on the apparent thermal conductivity, k, as

$$R = \frac{L}{k} \approx \frac{L_0 \rho_0}{\rho \times k(\rho)} \qquad (1)$$

where the value of k depends on the insulation density, ρ. Thus, the R-value depends on ρ through the k dependence.

The coverage, C, achieved by a given mass of insulation depends on the installed thickness, L_0, and the installed density ρ_0. The values of L and ρ at any time after installation are related to the installed values by $C = \rho_0 L_0 = \rho L$, if C is uniform for the attic and constant with time. The proper density for use in determining R and C is that density attained after installation and present for the life of the structure. This is called design density ρ_D, or settled density, ρ_S, and is a critical property in insulation economics.

Unfortunately, there is no recognized laboratory test for determining ρ_D or ρ_S for loose-fill fiberglass or rock wool. Although tests[1,2,3] exist for loose-fill cellulosic insulation, they are often criticized as being unrealistic. Laboratory vibration and impact tests on various loose-fill insulations produce settling.[4,5,6] Previous field

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tests on attic installations[7,8] have not shown whether the measured densities were the result of settling or of high installed densities. In this study, a data base was obtained by measuring the extent of settling of loose-fill insulations in attics as a function of time after installation and by comparing alternate thickness and density measurement techniques to produce a valid test procedure. Field and laboratory tests for fiberglass, rock wool, and cellulose are needed to describe appropriate thermal resistance and coverage values.

EXPERIMENTAL PROCEDURE

The field study site was west of Bucyrus, OH in two new two-story apartment complexes having six or eight apartments per unit and apartment attic areas of 400 to 430 ft^2 (37 to 40 m^2). Figure 1 shows views of two such units. At each building in the study, the central four apartments were selected to minimize possible end effects. The construction plan called for installation of an insulation having a thermal resistance of 30 $h \cdot ft^2 \cdot °F/Btu$ (5.3 m^2K/W) in the attic of each apartment. Table 1 compares the loose-fill cellulose and loose-fill fiberglass materials selected to create this thermal barrier.

Attic Instrumentation (Depth)

When the two apartment complexes were at different stages of construction, several means to determine depth and density of the loose-fill insulations were installed in the attics. Table 2 lists the techniques and the estimated measurement uncertainty for each. Figure 2 shows the nominal position of each measurement in an attic. The ceiling joists were used as a linear grid and assigned numbers by counting from the scuttle hole. The Bucyrus Estates attics contained 11 or 12 joists and the Bucyrus Plaza attics contained seven or eight. Having a similar measurement layout in the attics was helpful in conducting the examinations.

Seven 18-in. wooden rulers,[9] marked to the nearest 1/16 in., were nailed to joists in a vertical position in each attic. Prior to positioning, the rulers had been drilled with holes near the one and two-inch marks for nailing to the joists. The rulers were positioned visually as near vertical as possible with one end contacting the gypsum board ceiling. Each set of rulers was coded: BC1-1, BC1-2, ... or BF1-1, BF1-2, ... for the cellulose or fiberglass installations. These rulers provided fixed positions at rafters three, five, and seven for observing depth changes. After the insulation was installed, manila file folders were slotted and slipped over the rulers to rest on the insulation and provide a level indication of the top of the insulation to ±1/16 in. (±0.16 cm). The uncertainty in a measurement is reduced to less than 1%. Each file folder weighs about 0.033 lb. (15 gm) and has an area of 0.66 ft^2 (0.06 m^2), so the compressive stress on the material below the folder is 0.05 lb/ft^2 (0.25 kg/m^2).

A pointed wire probe was used to measure the insulation depth six times between rafters 2–3 and 3–4. The probe was 19 in. (48 cm) long, 0.125 in. (3.2 mm) in diameter and the depth was measured to ±0.25 in. (±0.6 cm) with a steel rule graduated in millimeters. Even though the measurement uncertainty is estimated as ±0.7% and ±1.2% for fiberglass and cellulose, respectively, for a set of six readings a sizable factor should be included for the irregularity of the insulation surface.

After each attic was insulated, a polystyrene board was positioned over one ruler and supported by the insulation. As did the file folders, this provided a precise depth measurement at a single position in the attic. For a study of depth versus time, this was found to be a very useful test constituent, especially as a means of reducing depth uncertainties resulting from surface irregularities. The boards were 1 in. (2.5 cm) thick, 1 ft (0.3 m) wide, and 4 ft (1.2 m) long, providing a large sampling of the surface area. The polystyrene boards weighed approximately 0.3 lb. (between 125 and 150 gms) causing a compressive stress of less than 0.082 lb/ft^2 (0.4 kg/m^2). Yarbrough and Wright[10] have noted thickness decreases under this stress of about 0.15 in. (0.38 cm) for cellulose and 0.20 in. (0.51 cm) for fiberglass. The use of polystyrene boards should reduce the depth by these amounts. The compression of the insulation resulting from the weight of the file folders is estimated to be 0.09 in. (0.23 cm) for the cellulose and 0.12 in. (0.31 cm) for fiberglass.

Three other means installed for depth measurement did not work, for various reasons. A steel wire, 1/8 in. (0.3 cm) in diameter, was stretched between trusses two and four at a height of 10 in. (25.4 cm) in the attics to be insulated with cellulose and at a height of 15 in. (38.1) in the attics to be insulated with fiberglass. In both cases, these wires were too close to the aluminum walkway used during attic reentry, disturbing the insulation and precluding valid measurements. In addition, the fiberglass installation depth covered the wire, and the cellulose insulation installer tripped over the steel wire in several attics.

A grid of steel reinforcing wire was installed to span three joists and used in much the same way as the steel wire. The grid rested on the top of joists and touched the bottom of the top piece of wood near the roof (the grid was 2 by 4 ft [0.6 by 1.2 m] with a 0.5 ft [0.15 m] wire spacing). This grid was too tightly spaced for the clumps of fiberglass insulation to pass through without the spacings clogging or hanging up. Thus, a covering of fiberglass developed and prevented the grid from being useful for the fiberglass attics. The concept worked for the cellulose insulation but there was no means to measure the depth along the grid length.

Before the insulation was installed, several places on the trusses were spray painted through a pegboard template, producing an array of 1/4 in. (0.6 cm) diameter dots on a 1 in. (2.5 cm) spacing. The array was too coarse to read the insulation surface level to better than about ±1/4 in. (0.6 cm), but this method would probably work well if the array of dots were finer and were available as an adherent film. This technique would offer the possibility for depth measurement using the attic trusses that span the entire area with a minimum of examination tools.

Experimental Procedure for Measuring Density

As Table 2 indicates, three methods were used to determine density. The cylindrical method was used to measure ρ_0 between trusses 7–8 and 6–7. For each density determination, five measurements of the insulation depth were made inside a 12 in. (30 cm) diameter circle with a pointed 0.125 in. (3.2 mm) diameter welding rod. The average of these measurements was used as the insulation thickness. A cylindrical specimen of the loose-fill insulation was then isolated by a 12.0 in. (30 cm) diameter sheet metal cylinder. The insulation from the inside of the cylinder was removed and weighed ±0.002 lb to (±1.0 gm) on a digital electronic balance.[11] The density at particular attic locations was determined to an accuracy of ±2%. After six months, the density was determined between trusses 4–5 and 5–6, using the same method.

A basket formed from hardware cloth and having a 1/2 in. (1.2 cm) spacing was placed between joists two and three. This basket was in place during installation and then removed to determine initial density. The baskets were nominally 12 in. (0.3 m) wide, 18 in. (0.45 m) long, and 12 or 18 in. (0.3 or 0.45 m) tall. The installers had difficulties filling these as a natural part of the installation because of the small size; the scuttle hole blocked use of a larger basket.

Initial density, estimated from the attic area, the insulation depth, and the number of bags used to insulate each attic, was determined. The volume occupied by the joists, exhaust fans, recessed lights, junction boxes, and vent pipes was subtracted from the total volume to estimate the volume occupied by the insulation. Depending on the number and design of joists in the attics, the expected initial thickness yielded corrected volumes of 305 ft^3 (8.68 m^3) for the cellulose and 456 ft^3 (12.94 m^3) for the fiberglass. The ±1/4 bag count uncertainty, combined with the uncertainty of the average depth obtained from 22 probes, gives a ρ_0 uncertainty of 1.7% for the cellulose and 2.5% for the fiberglass, if average bag weight is taken as the label value.

EXPERIMENTAL RESULTS

Insulation was installed in the 16 instrumented attics on Feb. 4, 1982, with clear and cold weather conditions 10 to 20°F (-12 to -7°C). The loose-fill cellulosic insulation was installed using an electric-driven tornado blower operating at 12,500 rpm. The loose-fill cellulose was blown through 75 ft (23 m) of 2.5 in. (6.3 cm) diameter corrogated hose and traveled 2 to 4 ft (0.6 to 1.2 m) past the end of the hose. The loose-fill fiberglass insulation was blown using a blowing machine operating at 1200 rpm and having the slide in the full open position and two rings on the air-relief valve. The loose-fill fiberglass was blown through 150 ft (46 m) of 3 in. (7.6 cm) diameter rubber hose and traveled 8 to 12 ft (2.4 to 3.7 m) past the end of the hose. Installation data, including installation time and amount of material installed, are listed in Table 3, along with coverages, loadings, and installation rates calculated from the bag counts and observed times.

The cellulose insulation loadings achieved in the attics ranged from 1.45 lb/ft^2 (7.09 kg/m^2) to 1.67 lb/ft^2 (8.16 kg/m^2) with an average value of 1.57 lb/ft^2 (7.67 kg/m^2). Label value for the cellulose insulation is 1.66 lb/ft^2 (8.11 kg/m^2), which is within the range of the observed loadings. The fiberglass insulation loadings achieved in the attic ranged from 0.762 lb/ft^2 (3.72 kg/m^2) to 0.990 lb/ft^2 (4.84 kg/m^2) with an average value of 0.856 lb/ft^2 (4.18 kg/m^2). The label value for the fiberglass insulation is 0.768 lb/ft^2 (3.75 kg/m^2) which is within the range of the observed values. Thickness measurements indicate that the fiberglass insulation was above the thickness specified on the bag label for R-30, and the cellulose insulation was slightly below the thickness specified on the bag label.

Initial insulation densities for the 16 attics, obtained in three ways, are reported in Table 4. The initial densities obtained using the cylinder method showed the least variation (smallest sample standard deviation). The cylinder values for initial density were close to the bag label values for both products. The average value for the cellulose insulation equaled the label value of 2.25 lb/ft^3 (36 kg/m^3) and the average value for the fiberglass insulation was four percent higher than the label value of 0.67 lb/ft^3 (10.7 kg/m^3). Initial densities obtained using bag count and nominal bag weight showed more scatter than the cylinder data but are reasonable measures of the initial density. The initial densities obtained from material blown into baskets showed the greatest scatter and are unrealistically high for the fiberglass insulation.* The initial density data for the first four fiberglass entries in Table 4 do not differ significantly from the data in the last four entries, although the blowing machine's air rate was increased to the maximum for the last four attics.

Variation with Time of Density and Thickness

Insulation thickness measurements were made 31, 88, and 180 days after installation. A set of density measurements were made, using the cylinder method, 180 days after installation. The thickness and density data for the 16 sites are given in the Appendix to this report. The thickness and density data were used to represent averages of the values obtained at a specific site and time. The data were transformed to dimensionless ratios for each site by dividing by the initial thickness or density.

The results obtained for loose-fill cellulose are shown in Figure 3. The thickness data were used to determine the coefficients in Eq 2 using the method of least squares:

$$L/L_o = 1 + At + Bt^2 \qquad (2)$$

The curves labeled a, b, and c in Figure 3 are graphs of Eq 2 for probe, rulers, and float, respectively. The float curve (c) terminates at 88 days because of physical disturbance of the area being used to monitor thickness. Curve (d) in Figure 3 is an average of the measurements made by probes (a) and rulers (b) and represents the best estimate available for the change in insulation thickness during the first 180 days after installation. The data show a decrease in thickness of 13.1% during the 180-day period. A single point, e, summarizes the cylinder's density data. The point shown is the average value for ρ_o/ρ, which should be compared with L/L_o. The data show an increase in cellulose density of 20.9% for the 180-day period. The density measurements indicate more settling than the thickness measurements but involve only two measurements other than the initial values per site. The average thickness curve, on the other hand, is a composite of two methods and is a much larger data set. Curve (d) is, therefore, a more valid measure of the settling of the loose-fill celulosic insulation being monitored than is the density measurement.

*Installation of material in the baskets required a downward deflection of blown material and the mass determination required moving the basket with insulation out of the attic. Both of these factors contribute to the basket determined initial densities being higher than the other methods.

The results obtained for loose-fill fiberglass insulation are shown in Figure 4. The fiberglass data were analyzed in the same way as the cellulose data. The composite curve (d) in Figure 4 shows average behavior determined three ways and shows a thickness decrease of 3.4% after 180 days. The density data obtained 180 days after installation show a density increase of 13.6%. As in the case of the cellulose measurements, however, the composite thickness curve is based on a large number of measurements, and the density set is limited to two measurements per site. The best estimate, therefore, for the change in the fiberglass insulation is a 3.4% decrease in thickness during the 180-day period after installation.

Settling of the two types of loose-fill insulations being observed is not complete at 180 days. The thickness curves in both cases have a negative slope. Coefficients for Eq 2 have been included in the Appendix for reference.

CONCLUSIONS AND RECOMMENDATIONS

The data obtained during the installation of the two loose-fill products studied and periodically after the installation show both materials are settling. The loose-fill fiberglass insulation and the loose-fill cellulosic insulation do not appear to have come to equilibrium after 180 days. The best estimate of the amount of cellulose settling is 13.1% obtained from thickness measurements. The best estimate of the amount of fiberglass settling is 3.4%, also obtained from thickness measurements. Settling determined with the cylinder method was substantially greater for both materials than that obtained using thickness measurements, but less cylinder density data exists.

The data obtained during the 180 days after installation clearly show that additional measurements must be taken to determine equilibrium thickness and density values. A statistically valid evaluation of loose-fill settling must involve additional test sites. The 16 attics under study represent an input to the growing data base for loose-fill insulations.

NOMENCLATURE

A = coefficient of time, $(\text{days})^{-1}$

B = coefficient of $(\text{time})^2$, $(\text{days})^{-2}$

C = coverage, lb/ft^2 (kg/m^2)

k = apparent thermal conductivity, $\frac{\text{Btu} \cdot \text{in.}}{\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}} \left(\frac{\text{W}}{\text{mK}}\right)$

L_0 = installed thickness, ft (m)

L = thickness at time t, ft (m)

ρ_0 = installed density, lb/ft^3 (kg/m^3)

ρ = density at time t, lb/ft^3 (kg/m^3)

ρ_D = design density, lb/ft^3 (kg/m^3)

ρ_S = settled density, lb/ft^3 (kg/m^3)

R = thermal resistance, $\frac{\text{h ft}^2 \cdot {}^\circ\text{F}}{\text{Btu}} \left(\frac{\text{m}^2\text{K}}{\text{W}}\right)$

t = time, days

σ = one standard deviation $\left[\sum (x^2 - n\bar{x}^2)/n\right]^{1/2}$

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TABLE 1

Comparison of Loose-Fill Insulation For Test Sites

	Materials			
	Cellulose		Fiberglass	
	Bucyrus Estates		Bucyrus Plaza	
Structure	Two story		Two story	
Units	8		8	
Attic area ft^2 (m^2)	430	(39.9)	404	(37.5)
Design value for R $\frac{h \cdot ft^2 \cdot °F}{Btu}$ $\left(\frac{m^2 K}{W}\right)$	30	(5.3)	30	(5.3)
Product properties*				
Weight per bag, lb (kg)	30	(13.6)	24	(10.9)
ρ_o, lb/ft^3 (kg/m^3)	2.25	(36.0)	0.67	(10.7)
L_o, in. (cm)	8.8	(22.4)	13.75	(34.9)
C, lb/ft^2 (kg/m^2)	1.66	(8.12)	0.768	(3.75)
Attic needs, lb (kg)	684	(310)	291	(132)
bags	22.8		12.1	
Ruler locations, number per site	6		3	
Float locations, number per site	1		1	
Probe locations, number per site	6		6	

*These nominal or minimum properties are based on product sheet and bag labels.

TABLE 2

Types of Instrumentation for Depth and Density Measurements

	Estimated Measurement Uncertainty		
	Value error	Cellulose%*	Fiberglass%†
Depth			
Wooden rulers, file folders	0.25 in. (0.6 cm) 0.06 in. (0.16 cm)	2.8 0.7	1.8 0.4
Wire probe (6)††	0.25 in. (0.6 cm)	1.2	0.75
Polystyrene board	0.06 in. (0.16 cm)	0.7	0.4
Taut steel wire	Disturbed by walkway		
Steel grid	Clogged during installation		
Stenciled dots on trusses, joist	Too coarse to read		
Density			
Cylindrical method (2)††		2.5	2.3
Bag count		1.7	2.5
Wire basket		2.9	3.2

*Cellulose 9 in. (23 cm) deep.
†Fiberglass 13.7 in. (35 cm) deep.
††Indicates repetitions.

TABLE 3

Installation Data

Site	Number of Bags Installed	Time to Install, Minutes	Mass of Insulation* Installed (lb)	Mass of Insulation* Installed (kg)	Rate of Installation (lb/h)	Rate of Installation (kg/h)	Rate of Installation (Bags/Min)	Loading† (lb/ft^2)	Loading† (kg/m^2)
Loose-fill Cellulose									
1	22.0	33	660	299	1200	544	0.67	1.53	7.48
2	24.0	35	720	327	1234	561	0.69	1.67	8.16
3	23.0	39	690	313	1062	482	0.59	1.60	7.82
4	23.8	36	690	313	1150	522	0.66	1.60	7.82
5	20.8	33	624	283	1135	515	0.63	1.45	7.09
6	23.2	35	696	316	1193	542	0.66	1.62	7.92
7	23.0	34	690	313	1218	552	0.68	1.60	7.82
8	21.5	32	645	293	1209	549	0.67	1.50	7.33
Average	22.6	34.6	677	307	1175	533.4	0.66	1.57	7.67
One Std. Dev. of Sample††	1.0	2.1	29	13	52.9	24.1	0.03	0.067	0.33
Loose-Fill Fiberglass									
1	14.5	50	362	164	434	197	0.29	0.896	4.38
2	14.5	55	362	164	395	179	0.26	0.896	4.38
3	12.3	45	308	140	411	187	0.27	0.762	3.72
4	12.7	45	317	144	423	192	0.28	0.785	3.84
5	13.5	60	337	153	337	153	0.23	0.834	4.08
6	14.0	60	350	159	350	159	0.23	0.866	4.23
7	13.3	70	332	151	285	129	0.19	0.822	4.02
8	16.0	50	400	181	480	217	0.32	0.990	4.84
Average	13.9	54.4	346	157	389	177	0.26	0.856	4.18
One Std. Dev. of Sample††	1.1	8.1	27.4	12.2	58.1	26.3	0.04	0.068	0.33

*Calculated using nominal bag weights 30 lb. (13.61 kg) for cellulose and 25 lb. (11.34 kg) for fiberglass.

†Calculated using mass installed and total attic areas of 430 ft^2 (39.9 m^2) for cellulose and 404 ft^2 (37.5 m^2) for fiberglass.

††Calculated using $\left[\sum (x^2 - n\overline{x}^2)/n\right]^{1/2}$ as one standard deviation.

TABLE 4

Initial Density of Installed Loose-Fill Insulation
(Obtained by Three Methods)

Site	Cylinder method* (lb/ft^3)	Cylinder method* (kg/m^3)	Bag count method† (lb/ft^3)	Bag count method† (kg/m^3)	Basket method (lb/ft^3)	Basket method (kg/m^3)
			Loose-Fill Cellulose			
1	2.147	34.39	2.290	36.68	2.198	35.21
2	2.293	36.73	2.203	35.29	2.286	36.62
3	2.262	36.23	2.356	37.74	2.422	38.80
4	2.184	34.98	2.202	35.27	2.392	38.32
5	2.280	36.52	2.272	36.39	2.277	36.47
6	2.239	35.87	2.147	24.39	2.137	34.23
7	2.346	35.58	2.393	38.33	2.501	40.06
8	2.226	35.66	2.037	32.63	2.392	38.32
Average	2.247	36.00	2.238	35.84	2.326	37.32
Std. dev. of sample††	0.059	0.94	0.108	1.73	0.114	1.88
			Loose-Fill Fiberglass			
1	0.760	12.17	0.748	11.98	0.802	12.85
2	0.716	11.47	0.705	11.29	0.925	14.82
3	0.644	10.32	0.595	9.53	0.559	8.95
4	0.676	10.83	0.583	9.34	0.724	11.60
5	0.605	9.69	0.554	8.87		
6	0.764	12.24	0.574	9.19	0.746	11.95
7	0.661	10.59	0.591	9.47	0.693	11.10
8	0.761	12.19	0.804	12.88	0.879	14.03
Average	0.698	11.19	0.644	10.32	0.761	12.19
Std. dev. of sample††	0.057	0.91	0.088	1.41	0.113	1.81

*Average of two measurements.
†Computed using average probed thickness. No joist correction was applied.
††See last footnote of Table 3.

APPENDIX*

TABLE A-1

Probe Measurements for Eight Sites with Loose-Fill Cellulosic Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BC-1	8.01	8.44	8.04	7.33
BC-2	9.09	8.92	8.38	7.92
BC-3	8.15	8.00	7.95	7.26
BC-4	8.72	8.67	8.05	7.50
BC-5	7.66	7.97	7.57	7.04
BC-6	9.05	8.92	8.44	7.71
BC-7	8.02	8.08	8.00	7.30
BC-8	8.83	8.12	8.02	7.74
Average	8.44	8.39	8.06	7.48
Standard Deviation of Sample	0.51	0.38	0.25	0.28

TABLE A-2

Ruler Measurements for Eight Sites with Loose-Fill Cellulosic Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BC-1	8.9	8.53	8.21	7.71
BC-2	9.35	9.10	8.58	8.18
BC-3	8.85	8.48	8.12	7.69
BC-4	8.96	8.73	8.38	7.94
BC-5	8.45	8.15	7.95	7.50
BC-6	9.62	9.06	8.68	8.09
BC-7	8.85	8.46	8.18	7.65
BC-8	9.10	8.75	8.47	8.00
Average	9.01	8.66	8.32	7.84
Standard Deviation of Sample	0.33	0.30	0.23	0.22

TABLE A-3

Float Measurements for Eight Sites with Loose-Fill Cellulosic Insulation

Site	t = 0 d	t = 31 d	t = 88 d
BC-1	7.67	7.43	7.17
BC-2	8.84	8.48	8.11
BC-3	9.06	8.68	8.37
BC-4	8.17	7.93	7.42
BC-5	7.86	7.50	—
BC-6	7.98	8.41	—
BC-7	8.44	8.32	—
BC-8	8.44	8.20	—
Average	8.31	8.12	7.77
Standard Deviation of Sample	0.45	0.43	0.49

*Values are given in inches and pounds per cubic foot because this was the original data format.

TABLE A-4

Insulation Density Measurements for Eight Sites with Loose-Fill Cellulosic Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BC-1	2.147	—	—	2.778
BC-2	2.293	—	—	2.745
BC-3	2.262	—	—	2.660
BC-4	2.184	—	—	2.668
BC-5	2.280	—	—	2.715
BC-6	2.239	—	—	2.764
BC-7	2.346	—	—	2.730
BC-8	2.226	—	—	2.668
Average	2.247			2.716
Standard Deviation of Sample	0.059			0.043

TABLE A-5

Probe Measurements for Eight Sites with Loose-Fill Fiberglass Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BF-1	14.40	15.27	14.68	14.59
BF-2	15.3	15.64	15.21	15.04
BF-3	15.76	15.77	15.45	14.96
BF-4	16.1	15.83	15.84	15.42
BF-5	18.2	18.40	17.76	17.92
BF-6	18.2	17.85	17.37	17.19
BF-7	16.6	17.19	16.94	16.31
BF-8	17.76	17.99	17.59	17.31
Average	16.54	16.74	16.36	16.09
Standard Deviation of Sample	1.32	1.17	1.12	1.18

TABLE A-6

Ruler Measurements for Eight Sites with Loose-Fill Fiberglass Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BF-1	14.16	13.87	13.88	13.66
BF-2	15.0	14.75	14.75	14.69
BF-3	14.97	14.63	14.50	14.38
BF-4	13.7	13.75	13.5	13.38
BF-5	16.25	16.0	15.94	15.88
BF-6	16.75	16.38	16.31	16.25
BF-7	16.0	15.44	15.38	15.31
BF-8	17.7	17.25	16.88	16.75
Average	15.57	15.26	15.14	15.04
Standard Deviation of Sample	1.26	1.15	1.11	1.14

TABLE A-7

Float Measurements for Eight Sites with Loose-Fill Fiberglass Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BF-1	15.4	14.75	14.75	14.62
BF-2	15.25	14.75	14.62	14.25
BF-3	16.9	16.75	16.38	16.06
BF-4	15.5	15.25	15.00	14.38
BF-5	16.1	15.88	15.88	15.81
BF-6	17.5	17.25	17.12	17.06
BF-7	15.6	15.25	15.12	15.19
BF-8	17.0	16.25	16.25	16.25
Average	16.16	15.77	15.64	15.45
Standard Deviation of Sample	0.81	0.87	0.84	0.94

TABLE A-8

Insulation Density Measurements for Eight Sites with Loose-Fill Fiberglass Insulation

Site	t = 0 d	t = 31 d	t = 88 d	t = 180 d
BF-1	0.760	—	—	0.768
BF-2	0.716	—	—	0.927
BF-3	0.644	—	—	0.637
BF-4	0.676	—	—	0.727
BF-5	0.605	—	—	0.782
BF-6	0.764	—	—	0.749
BF-7	0.661	—	—	0.814
BF-8	0.761	—	—	0.940
Average	0.698			0.793
Standard Deviation of Sample	0.057			0.094

TABLE A-9

Values for the Coefficients A and B in Equation (2)*

Data Set	A	B
	Loose-Fill Cellulose	
Probe Data	-0.2810×10^{-3}	-0.1989×10^{-5}
Ruler Data	-0.1100×10^{-3}	0.2150×10^{-5}
Float Data	-0.1292×10^{-2}	0.4482×10^{-5}
	Loose-Fill Fiberglass	
Probe Data	0.7178×10^{-4}	-0.1246×10^{-5}
Ruler Data	-0.4884×10^{-3}	0.1700×10^{-5}
Float Data	-0.5844×10^{-3}	0.1915×10^{-5}

*$L/L_0 = 1 + At + Bt^2$, L_0 is initial thickness, and L is thickness after t days.

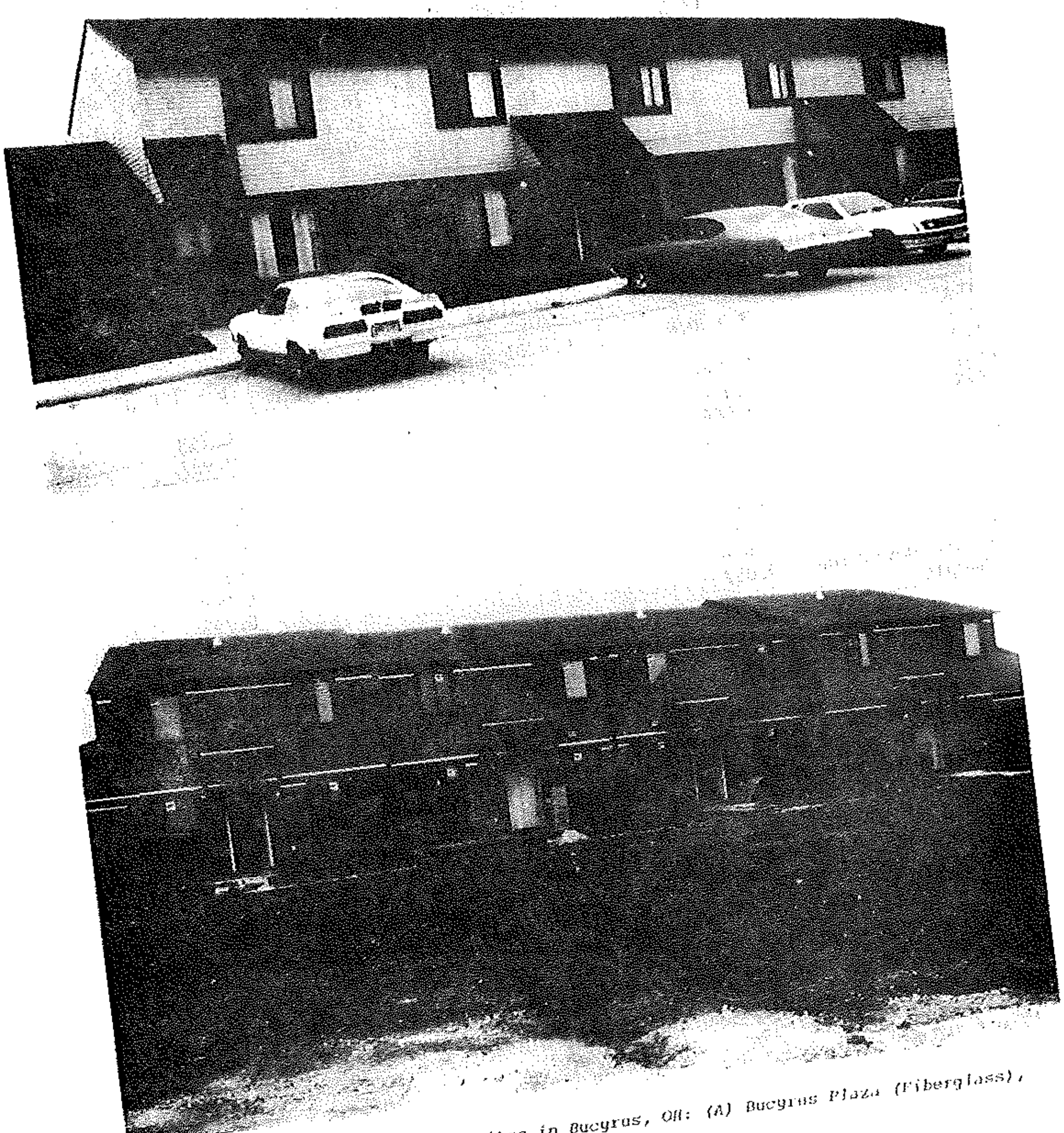

Figure 1. Apartment test sites in Bucyrus, OH: (A) Bucyrus Plaza (Fiberglass), (B) Bucyrus Estates (Cellulose)

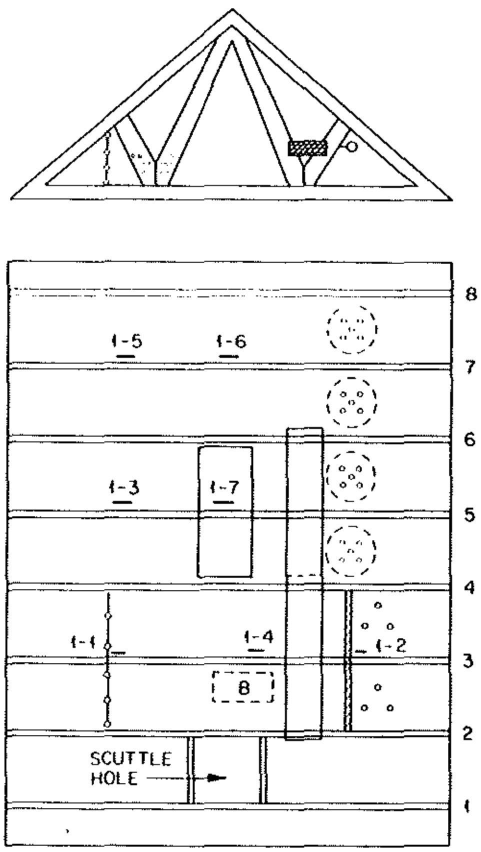

Figure 2. Schematic of attic showing depth and density measurement locations

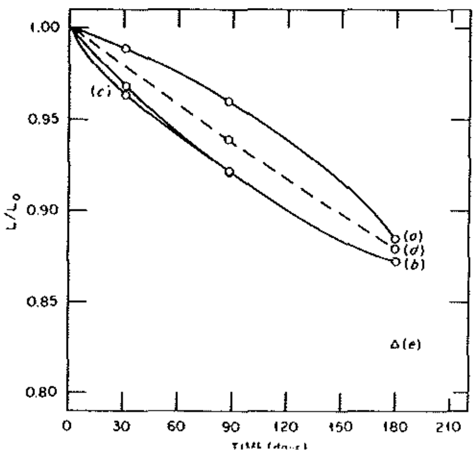

Figure 3. L/L_o for eight loose-fill cellulose installations using three measurement techniques. Curve (a) probe data, curve (b) ruler data, curve (c) float data, curve (d) average of curve (a) and (b), and point (e) (Density at t=0)/(Density at t=180 days) (cylinder data)

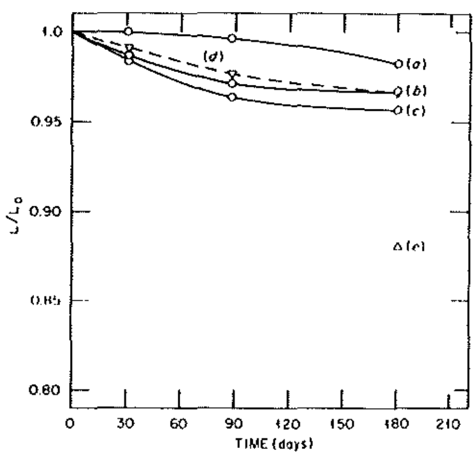

Figure 4. L/L_o for eight loose-fill fiberglass installations using three measurement techniques. Curve (a) probe data, curve (b) ruler data, curve (c) float data, curve (d) average of curve (a), (b), and (c), and point (e) (Density at t=0)/(Density at t=180 days) (cylinder data)