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An Experimental Study of Stabilized Cellulosic Insulation Installed in Four Attic Sections of Manufactured Homes

R. S. Graves
D. W. Yarbrough

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03 Microfiche A01

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ORNL/TM-10775

Metals and Ceramics Division

AN EXPERIMENTAL STUDY OF STABILIZED CELLULOSIC INSULATION INSTALLED IN FOUR ATTIC SECTIONS OF MANUFACTURED HOMES

R. S. Graves and D. W. Yarbrough

Date Published: January 1989

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Prepared for
Office of Buildings and Community Systems
EC 01 00 00 0

Part of
The National Program for
Building Thermal Envelope Systems and Materials

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

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AN EXPERIMENTAL STUDY OF STABILIZED CELLULOSIC INSULATION INSTALLED IN FOUR ATTIC SECTIONS OF MANUFACTURED HOMES*

R. S. Graves and D. W. Yarbrough

ABSTRACT

The effect of vibrations due to manufacturing and over-the-road transport on the thickness, density, and calculated thermal resistance (R-value) of stabilized cellulosic insulation installed in four manufactured home units has been determined. Stabilized cellulosic insulation is produced by adding water at the time of installation to dry loose-fill cellulosic insulation containing adhesive. Insulation thickness measurements were made at the time of installation, at the end of the construction process, and after over-the-road transport. Insulation densities were measured for newly installed material at the factory and after the units had been transported.

The average overall reduction in attic insulation thickness was found to be about 5%, with most of the reduction occurring during manufacturing. The product densities were found to be greater than the label values of 2.0 lb/ft^3 both initially and after transport. The reduction in R-value due to decreased thickness was calculated to be in the range of 2.65 to 5.1%.

INTRODUCTION

The thermal resistance (R-value) of loose-fill thermal insulation installed above the ceiling in a manufactured home depends on the thickness, density, and type of fiber. Attic insulation is generally installed in manufactured homes at an intermediate stage of construction. Consequently, the insulation is subjected to vibrations and impacts due to construction that occur after the insulation has been installed. In addition, the insulation is subjected to vibrations and shifting caused by over-the-road transport. This potential for settling of insulation makes a determination of the actual settling that occurs in a manufactured home

*Research sponsored by the Office of Buildings and Community Systems, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

unit an important part of the evaluation of a candidate insulation product. When settling is known to occur, it should be compensated for by additional insulation.

A previous study[1] on loose-fill rock wool insulation installed in manufactured home units showed that settling can occur in two identifiable stages: settling due to construction that occurs after insulation is blown into the attic space and settling or shifting that occurs during over-the-road transport. In general, the procedures used in this study were the same as those used in the previous loose-fill rock wool study.[1] A significant improvement in the present study resulted from accessibility to the full length of the attic for performing the three sets of measurements.

This document reports measurements and observations associated with the use of a stabilized cellulosic insulation. This product is made by the addition of dry adhesive to loose-fill cellulosic insulation during the manufacturing process. Water is added to the adhesive-insulation mixture at the time of installation to promote interparticle bonding (stabilization).

Spray-applied cellulosic insulation has been used for many years to insulate surfaces. This product is often referred to as a wet-spray insulation because it has a high water content at the time of installation. Spray-applied cellulosic insulation is wet to the touch at the time of installation and, depending on the surroundings, typically requires several hours, days, or, weeks to dry. Many spray-applied cellulosic insulation products are self-supporting. They will stick to walls or ceilings without supports.

The insulating product examined in this report has less water added during installation than a wet-spray product. The newly installed insulation has a damp feel, but it is not possible to squeeze out water. The product is not self-supporting.

The insulation fiber used in the product is labeled for installation at 2.0 lb/ft^3, which is presumed to be the density after the product has come to equilibrium with its surroundings (dried). The label was apparently constructed using an apparent thermal conductivity (k_a) of

0.285 Btu·in./ft^2·h·°F with R-30 ft^2·h·°F/Btu requiring a thickness of 8.6 in.*

The claimed thermal resistance for this product is consistent with published data for loose-fill and spray-applied cellulosic insulation. Equation (1) gives apparent thermal conductivity as a function of density, $k_a(\rho)$, at an average temperature ($\bar{T}$) of 75°F, for loose-fill cellulosic insulation.[2] Equation (2) gives $k_a(\rho)$ at $\bar{T}$ = 75°F for spray-applied cellulosic insulation. Equation (2) was derived from k_a measurements from Dynatech Scientific Corporation and the Oak Ridge National Laboratory.[3]

$$k_a(\rho) = 0.2656 + 0.00494\ \rho \tag{1}$$

$$k_a(\rho) = 0.2242 + 0.01564\ \rho \tag{2}$$

Equation (3) is written for $k_a(\rho)$ at $\bar{T}$ = 75°F for the stabilized cellulosic product by adjusting the constant term in Eq. (1) for agreement with the product label.

$$k_a(\rho) = 0.2752 + 0.00494\ \rho \tag{3}$$

Equation (4) can be used to estimate R-values for insulation t inches thick at densities other than 2.0 lb/ft^3.

$$R = t/(0.2752 + 0.00494\ \rho) \tag{4}$$

DESCRIPTION OF THE TEST SITES AND PROCEDURE

Four manufactured home units were made available by the builder for this project. The four units represented two complete double-wide homes. The first double-wide home was nominally 26 by 40 ft and is identified in this report as units 14A and 14B. The second double-wide home was nominally 26 by 52 ft and is identified as units 15A and 15B. Both homes were constructed with roof trusses spaced 16 in. on center. Units 14A and 14B

---

*Although the policy of the Oak Ridge National Laboratory is to report its work in SI units, customary units are used in this report. The insulation industry in the United States at present operates entirely with customary units. The use of the SI units would limit the usefulness of this report for the primary readership. The SI equivalents of units used in this report are listed in Appendix A.

had 31 trusses forming 30 attic bays, while units 15A and 15B had 40 trusses forming 39 bays. The bays were numbered as shown in Fig. 1 so that thickness measurements could be repeated within a given bay.

The manufactured home units in this project had sloped roofs and ceilings as shown in Fig. 2. About 3.5 in. of depth was available for insulation along the edge of the roof, while 16 to 16.5 in. was available along the center line. The attic region available for this project extended the full length of the unit. The test region was a rectangular strip about 18 in. wide along the peak of the roof. This test region was made accessible by postponing the final runs of roof shingles until all thickness measurements were complete. The roofs of the test regions were covered by decking material during the construction after the insulation was installed. This decking was removed for thickness measurements. The test region was covered by plastic sheets for over-the-road transport. It was possible, therefore, to make thickness measurements immediately after

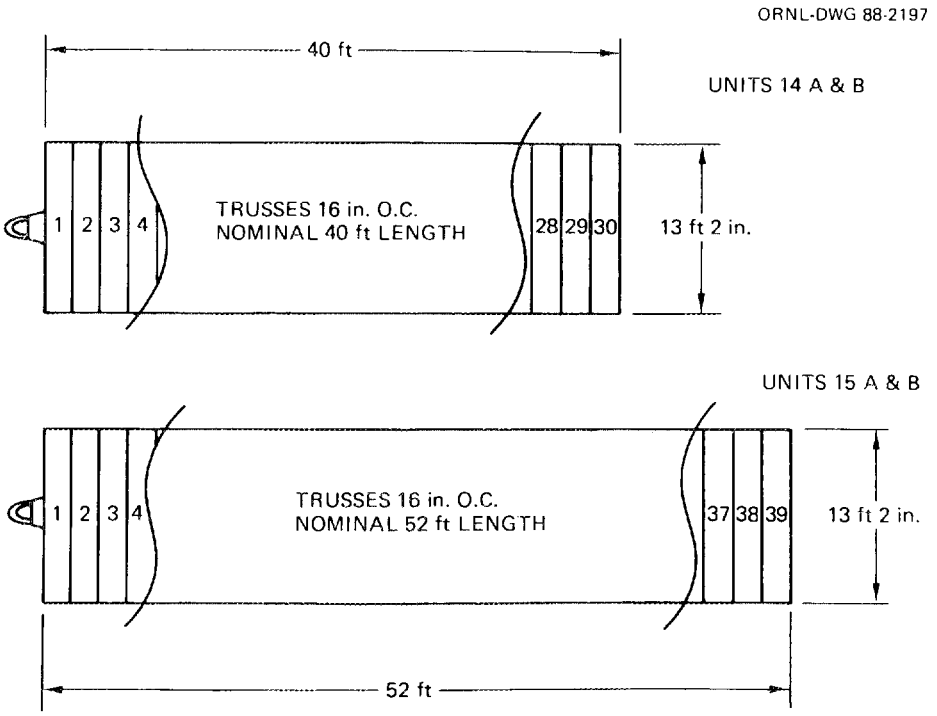

Fig. 1. Top view of manufactured home units showing bay numbers.

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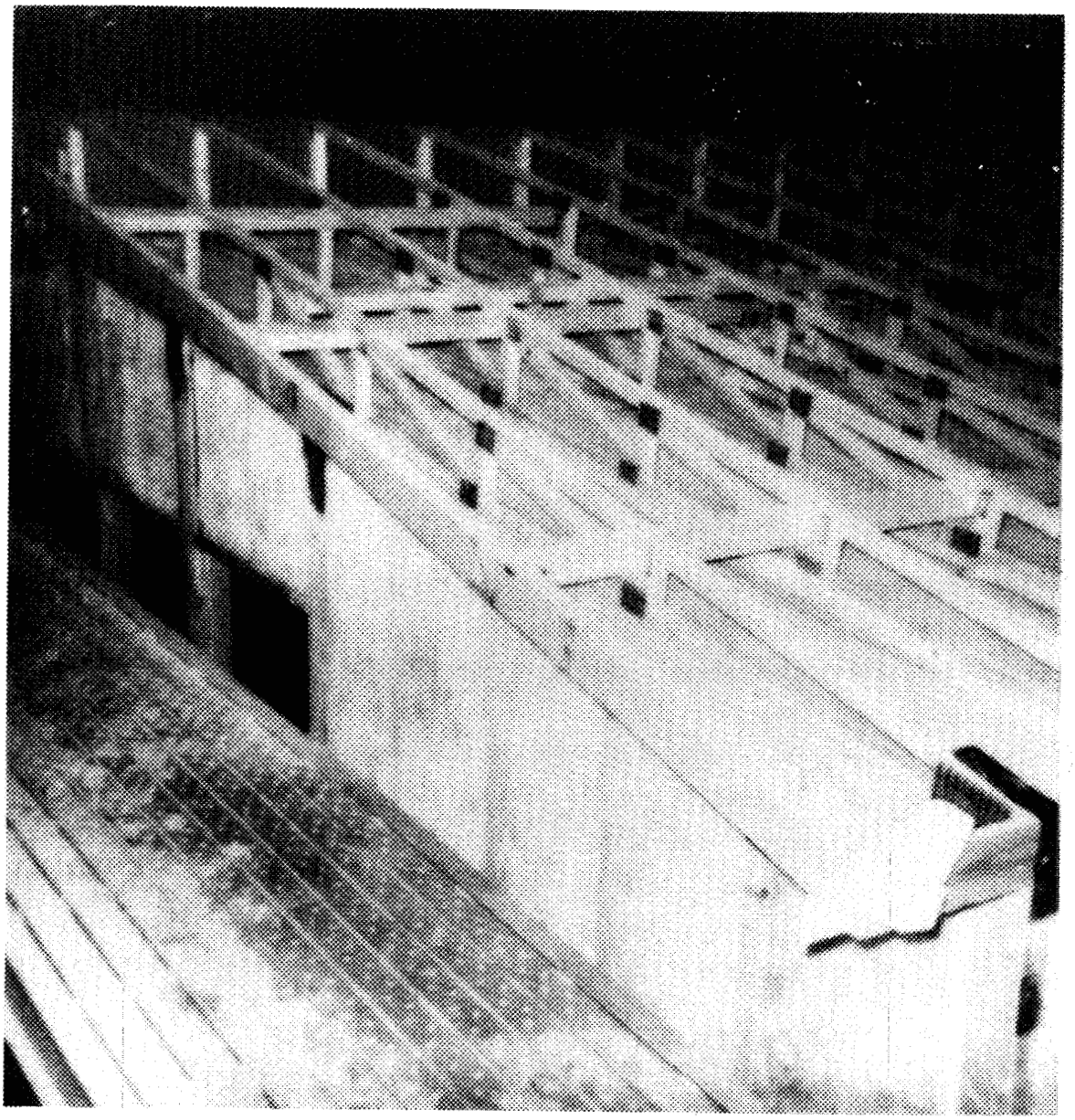

Fig. 2. Side view of attic section in a manufactured home used in this study.

the attic insulation was installed, at the end of the manufacturing, and after over-the-road transport. The four manufactured home units were towed on secondary and interstate highways at speeds up to about 60 mph. Units 14A and 14B were towed 95.7 miles, while units 15A and 15B were towed 92 miles. This over-the-road transport simulated delivery of a unit to a building site. Figure 3 is a photograph that shows the open roof area that permitted access to the attic insulation.

Thickness measurements were made in 11 bays of unit 14 and 13 bays of unit 15. The selected test bays were distributed along the length of the unit. Thicknesses were measured using a pointed 1/8-in.-diam welding rod to probe the depth. The probed depth was determined to ±0.04 in. (±1.0 mm) using a steel ruler. The thickness for a specific location and time was taken to be the average of five probe depths taken within an area of ~1.0 ft^2.

Insulation densities were determined by weighing known volumes of insulation. Density measurements were made by blowing insulation into cardboard boxes with subsequent mass and volume determinations. Densities of insulation installed in the attic were measured with either a square or circular cutter to isolate a known volume of insulation. The volume was determined in either case from an insulation thickness obtained from five probes and the cross-sectional area of the cutter. The mass of the insulation isolated by the cutter was determined to ±1.0 g using an electronic balance. Additional discussion of the techniques for measuring thickness and density is contained in a recent report on insulation in attics of site-built homes.[2] Since density measurements disturb the insulation they must be made at locations not being used to monitor thickness.

DENSITY AND MOISTURE MEASUREMENTS

Stabilized cellulosic insulation is produced by adding water in the form of a mist during installation. The added water results in an increased density at installation, and the density decreases as the water is lost. The amount of water added was determined, and insulation density measurements were made to characterize the product.

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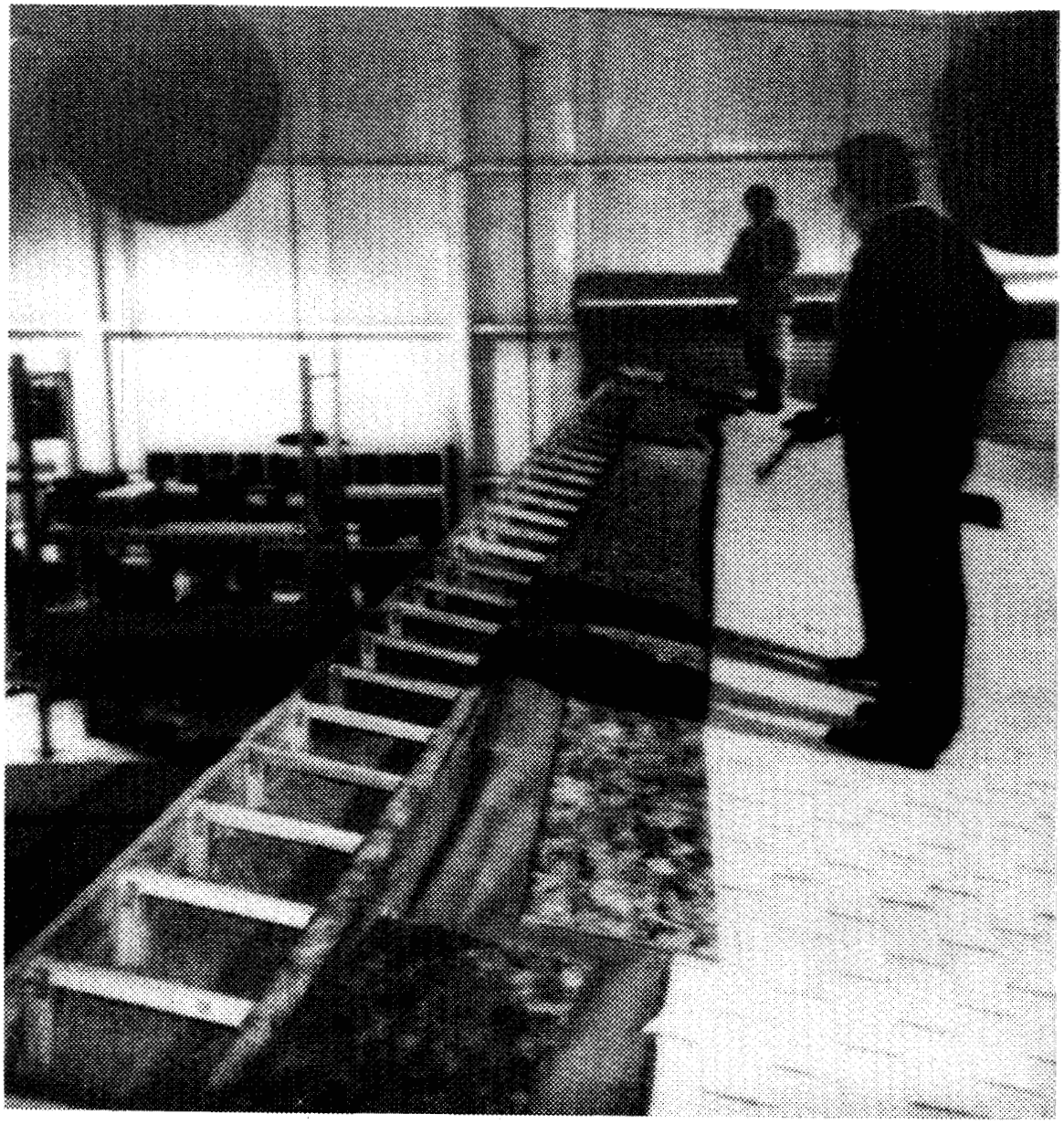

Fig. 3. Photograph of test unit showing attic access area.

Water addition rates were determined from the time required to add a measured volume of water. The data obtained are shown in Table 1. The average of the six measurements reported in Table 1 is a water addition rate of ~9.0 lb/min (68.08 g/s). This average rate, along with the time required to install a known amount of dry insulation, permits the calculation of added moisture content and dry density.

The times required to insulate the two double-wide units were determined. The installation of 47 label-value 30-lb bags of insulation in units 14A and 14B required 24.50 min, while the installation of sixty 30-lb bags of insulation in units 15A and 15B required 36.06 min. Thus, in units 14A and 14B the insulation contains 15.6% added moisture on a dry basis. The corresponding value for units 15A and 15B is 18.0%.

Four types of insulation density measurements were made. Insulation and water were blown into two cardboard boxes in an effort to monitor water-loss rates. One box of insulation was blown without the addition of water. Density measurements were also performed in each of the double-wide homes at the time of installation and after the units had been transported over-the-road. Table 2 contains the density data that were obtained.

Table 1. Rate of water addition to insulation during installation

Time (s)	Volume of water [in.^{3} (ml)]	Water flow rate [lb/h (g/s)]
15.0	16.4 (1000)	529.1 (66.67)
13.5	15.2 (930)	546.7 (68.89)
14.0	14.8 (900)	510.2 (64.29)
13.0	15.1 (920)	561.6 (70.77)
14.0	15.7 (960)	544.2 (68.57)
14.0	15.9 (970)	549.9 (69.29)
Average		540.3 (68.08)
Standard deviation		16.5 (2.08)

Table 2. Density measurements for stabilized cellulosic insulation

Material	Density (lb/ft^3)	Conditioned[a] (lb/ft^3)
Insulation with water blown into box	2.80	
Insulation with water blown into box	3.51	
Insulation without water blown into box	2.05	
Insulation installed in unit 14B	3.55	2.83
Insulation installed in units 15A and 15B	3.04[b]	2.41[b]
Insulation in unit 14A after transport	3.28	2.72
Insulation in unit 14B after transport	3.11	2.64
Insulation in unit 15A after transport	2.85	2.41
Insulation in unit 15B after transport	2.76	2.38

[a]Material conditioned for 16 d at 69°F and 49% RH.

[b]Average of four measurements.

With the exception of the dry material blown into a box, the measured densities are greater than the label. The measured densities in units 15A and 15B after transport are lower than those in units 14A and 14B. Units 15A and 15B had 16 d to dry, while units 14A and 14B had 9 d to dry.

An effort has been made to reconcile the apparently high densities with the insulated area and amount of insulation that was installed. This required a determination of the volume and mass of the installed insulation. The volume of insulation was determined from the area of the attic

floor, the heel height, the slope of the roof deck, and an estimate of volumes occupied by air-handling ducts and trusses. The mass of insulation was determined from the number of 30-lb bags that were installed, and the amount of water added was determined from the installation time. The results of this calculation are given in Table 3. The calculations do not include a correction for the angle of the attic floor.

The measured densities reported in Table 2 and the calculated densities reported in Table 3 are all greater than the label density of 2.0 lb/ft^3. The densities measured in units 15A and 15B after transport indicate a loss in moisture content after a relatively longer drying period. There seems to be little correspondence between observed densities and label density.

Table 3. Installed insulation densities calculated from the mass of installed insulation

	Units 14A and 14B	Units 15A and 15B
Nominal length (ft)	40.0	52.0
Nominal width (ft)	13.2	13.2
Full-thickness depth of insulation (ft)	0.717	0.717
Volume insulation, full-thickness region (ft^3)	459.0	581.0
Volume insulation, reduced-thickness region (ft^3)	208.3	281.7
Estimated duct volume (ft^3)	26.0	68.8
Estimated volume of buried trusses (ft^3)	25.1	32.4
Net insulation volume (ft^3)	616.2	761.5
Bags of insulation	47	60
Mass of insulation (lb)	1410.0	1800.0
Mass of water (lb)	220.5	324.5
Calculated density with water (lb/ft^3)	2.65	2.79
Calculated density without water (lb/ft^3)	2.29	2.36

The increased densities that were observed have a minor impact on thermal resistance. Equation (4) can be used to calculate the R-value for $t = 8.6$ in. and $\rho > 2.0$ lb/ft^3: if $\rho = 2.0$ lb/ft^3, then Eq. (4) yields an R-value of 30.2; if $\rho = 2.5$ lb/ft^3, then Eq. (4) yields an R-value of 29.9; and if $\rho = 3.0$ lb/ft^3, then Eq. (4) yields an R-value of 29.7. These calculations show that R-value is not significantly reduced by the increased density as long as the specified thickness is achieved.

THICKNESS MEASUREMENTS

The primary objective of this project was to determine the amount, if any, of insulation settling due to vibrations and impacts after the insulation was installed. Thickness measurements were used to determine the amount of settling. Each thickness measurement that is reported is the average of five measurements in an area of ~1 ft^2. Three sets of measurements are reported for each of the four units that were monitored. Table 4 contains the thickness measurements for units 14A and 14B, while Table 5 contains the thickness measurements for units 15A and 15B. Tables 4 and 5 also contain average thicknesses ($\bar{t}$) from which changes can be calculated. All thicknesses reported in Table 4 and 5 are for the part of the attic space where the thickness of insulation is not limited by the roof deck.

The averages shown in Tables 4 and 5 have been used to calculate the percentage reductions, P, in thickness using Eq. (5):

$$P = \left| \bar{t} - \bar{t}_{initial} \right| \times 100/\bar{t}_{initial} \qquad (5)$$

Two percentage reductions are shown in Table 6 for each unit. The first percentage reduction in thickness occurs as construction of the unit proceeds, while the second percentage reduction is a result of construction and over-the-road transport.

The average of the four overall reductions in thickness is 5.04%. The thickness reductions in the manufacturing plant accounted for 81% of the settling. This is in contrast to an earlier study on loose-fill rock wool[1] where the overall thickness reduction was about evenly divided between in-plant and over-the-road effects.

Table 4. Thickness measurements for manufactured home units 14A and 14B

Bay	Initial [in. (mm)]	End of manufacture [in. (mm)]	After transport [in. (mm)]
		Unit 14A	
3	(219.0)*	(206.2)	(213.6)
5	(204.2)	(203.4)	(203.8)
9	(198.8)	(198.0)	(195.6)
13	(198.2)	(194.2)	(189.6)
17	(226.4)	(208.8)	(208.0)
21	(234.0)	(242.2)	(235.4)
24	(222.2)	(202.0)	(201.4)
26	(205.6)	(180.2)	(175.0)
28	(215.4)	(207.8)	(197.2)
30	(203.2)	(194.2)	(184.8)
Average	8.374 (212.7)	8.020 (203.7)	7.890 (200.4)
Standard deviation	(11.8)	(15.2)	(15.8)
		Unit 14B	
3	(209.4)	(208.0)	(201.4)
5	(219.2)	(211.2)	(209.8)
9	(213.8)	(204.4)	(196.2)
13	(191.2)	(177.8)	(187.2)
17	(198.6)	(198.4)	(191.8)
21	(260.2)	(249.4)	(250.0)
24	(303.0)	(277.6)	(284.2)
26	(279.4)	(275.6)	(263.8)
28	(311.2)	(297.0)	(282.0)
30	(228.0)	(217.4)	(207.6)
Average	9.504 (241.4)	9.122 (231.7)	8.953 (227.4)
Standard deviation	(41.6)	(38.2)	(36.4)

*Thicknesses are shown in millimeters since this unit was used in collecting data.

Table 5. Thickness measurements for manufactured home units 15A and 15B

Bay	Initial [in. (mm)]	End of manufacture [in. (mm)]	After transport [in. (mm)]
		Unit 15A	
1	(236.4)*	(229.4)	(221.6)
3	(228.8)	(227.4)	(217.2)
5	(217.6)	(210.8)	(219.4)
9	(242.0)	(224.4)	(234.8)
13	(272.2)	(254.0)	(248.0)
17	(230.0)	(217.6)	(215.2)
21	(261.4)	(251.6)	(250.6)
25	(245.6)	(234.4)	(240.8)
27	(227.2)	(224.4)	(235.4)
31	(217.4)	(214.6)	(231.2)
35	(197.4)	(204.0)	(200.4)
37	(275.8)	(265.4)	(262.4)
39	(231.8)	(214.8)	(212.4)
Average	9.339 (237.2)	9.004 (228.7)	9.055 (230.0)
Standard deviation	(21.5)	(17.6)	(16.9)
		Unit 15B	
1	(228.4)	(209.8)	(204.0)
3	(229.8)	(198.8)	(201.6)
5	(148.4)	(141.6)	(148.8)
9	(210.4)	(197.2)	(205.8)
13	(237.2)	(224.6)	(217.0)
19	(211.2)	(216.6)	(212.6)
21	(182.0)	(182.6)	(174.6)
23	(173.4)	(166.6)	(162.0)
27	(200.8)	(193.2)	(200.2)
31	(191.2)	(191.8)	(188.2)
35	(210.4)	(201.6)	(196.2)
37	(191.8)	(182.4)	(177.0)
39	(206.8)	(195.6)	(188.6)
Average	7.941 (201.7)	7.579 (192.5)	7.500 (190.5)
Standard deviation	(23.6)	(20.6)	(19.3)

*Thicknesses are shown in millimeters since this unit was used in collecting data.

Table 6. Attic insulation thickness reductions from installation to delivery

	Unit				Average
	14A	14B	15A	15B	
Initial thickness (in.)	8.374	9.504	9.339	7.941	8.790
Thickness at end of manufacturing (in.)	8.020	9.122	9.004	7.579	8.431
Thickness reduction due to manufacturing (in.)	0.354	0.382	0.335	0.362	0.358
Percentage reduction in thickness due to manufacturing	4.23	4.02	3.59	4.56	4.07
Thickness at end of transport (in.)	7.890	8.953	9.055	7.500	8.350
Thickness reduction due to transport (in.)	0.130	0.169	-0.051	0.079	0.082
Overall percentage reduction in thickness (P-value)	5.78	5.80	3.04	5.55	5.04

The small thickness reductions due to transport are likely a result of "curing" of the adhesive during the time from installation to the time of transport. It is interesting to note that units 15A and 15B with a curing time of 16 d before transport showed a much smaller insulation thickness change than units 14A and 14B with a curing time of 9 d before transport.

THE EFFECT OF THICKNESS REDUCTION ON THERMAL PERFORMANCE

The change in R-value resulting from the measured 5% thickness reduction can be estimated using Eq. (4). The calculation of R-value is done by taking the full-thickness region to be in parallel with the region with insulation thickness restricted by the roof deck. The insulation in the

restricted region is assumed not to settle in Case 1 and taken to settle 5% in Case 2. The thermal resistance is calculated from the log-mean thickness in both cases. A derivation of the equation used to calculate R-value is contained in Appendix B. The calculation will be based on a starting dry-density of 2.5 lb/ft^3. This number is a compromise between the measured densities in the four units and the calculated densities shown in Table 3. The calculated thermal resistance is based on the isothermal planes model in the *ASHRAE Handbook of Fundamentals*[4] and does not include the effect of trusses. The calculations are summarized in Table 7.

Table 7. Reduction in material R-value due to attic insulation thickness reduction in a manufactured home unit

	Full-thickness region	Varying-thickness region	
		Case 1	Case 2
Initial thickness (in.)	8.60	5.67[a]	5.67
Initial density (lb/ft^3)	2.50	2.50	2.50
Initial R-value ($ft^2 \cdot h \cdot {}^\circ F/Btu$)	29.9	19.7	19.7
Area fraction[b]	0.608	0.392	0.392
Initial R-value overall[c] ($ft^2 \cdot h \cdot {}^\circ F/Btu$)		24.86	24.86
Final thickness (in.)	8.17	5.67	5.39
Final density (lb/ft^3)	2.63	2.50	2.63
Final R-value ($ft^2 \cdot h \cdot {}^\circ F/Btu$)	28.3	19.7	18.7
Final R-value overall ($ft^2 \cdot h \cdot {}^\circ F/Btu$)		24.2	23.6
Percent reduction in R-value		2.65	5.1

[a] $\bar{y}_{ln} = (y_1 - y_0)/\ln(y_1/y_0)$.

[b] Region between trusses.

[c] Case 1 assumes no settling in this region. Case 2 assumes 5% settling in the varying thickness region.

The R-value reductions shown in Table 7 for Cases 1 and 2 are 2.65 and 5.1%, respectively. The conditions chosen for the calculation are believed to be representative of the stabilized cellulosic product. The final R-values of 24.2 and 23.6 for Cases 1 and 2 are well below the target value of R-30 for the material, but this is a result of the attic section design that limits the thickness of insulation that can be installed. The space limitation between the ceiling and roof of these manufactured home units has a more significant impact on the installed thermal resistance than the modest amount of settling. The system R-value would be further reduced by including the attic trusses in the calculation, but this effect should be associated with the design of the unit rather than the insulating material.

CONCLUSIONS

The average attic insulation thickness decrease observed for stabilized cellulose in four units of manufactured housing was 5%. About 80% of this thickness decrease occurred in the manufacturing plant. The overall decrease in R-value due to thickness decreases for the material across a typical section of attic not containing trusses was calculated to be in the range 2.65 to 5.1%. An overall R-value decrease from 24.86 to 23.6 $ft^2 \cdot h \cdot {}^\circ F/Btu$ shown in Table 7 gives the 5.1% value. The smaller value assumes no settling for the insulation initially in contact with the roof deck, while the larger percentage assumes 5% settling in all regions.

The overall thermal resistance that can be provided in the attic space is limited by the depth of the attic along the outside wall of the unit. If this "heel" depth is less than the thickness required to achieve a given R-value, the overall R-value will be reduced. This factor is the responsibility of the manufactured home designer.

RECOMMENDATIONS

This report represents the second in a series of manufactured home projects. Two insulation products used in the attics of manufactured homes have been examined. The type of study reported here should be repeated for the range of loose-fill insulation products used in the manufactured homes that are currently being produced.

The calculated R-values for the attic systems of low-heel and low-slope roof designs show the need for improved designs. From an energy conservation viewpoint, there is a need for additional attic space for the installation of ceiling insulation.

An agreed-upon model for calculating U-values or system R-values for the roof sections of manufactured homes should be developed. A model is needed to rationally compare the performance of competing insulation products. The model should take settling and the design of the ceiling-attic-roof part of the manufactured home envelope into account.

ACKNOWLEDGMENTS

This project was made possible by the cooperation of Suncoast Insulation Manufacturing Company of Tampa, Florida, and Fleetline Homes, Inc., of Lady Lake, Florida. The authors appreciate the assistance and participation in the project of Fred Vincelli, Louie Kovach, and Brad Alburtus of SunCoast and Rick Murray of Fleetline. The report was improved by the reviews and suggestions provided by Kenneth E. Wilkes and Edwin I. Griggs. Appreciation is extended to Glenda R. Carter for preparation of the manuscript.

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NOMENCLATURE

k_a	apparent thermal conductivity, Btu·in./ft^2·h·°F
P	percent reduction, defined by Eq. (5)
R	thermal resistance, ft^2·h·°F/Btu
t	thickness, in.
$\bar{t}$	average thickness, in.
$\bar{T}$	average temperature, °F
ρ	density, lb/ft^3

APPENDIX A

SI EQUIVALENTS OF CUSTOMARY UNITS USED IN THIS REPORT

Property	Customary unit	SI equivalent
Dimension	in.	25.4 mm
Dimension	ft	0.3048 m
Density	lb/ft^3	16.02 kg/m^3
Mass	lb	453.6 g
Thermal conductivity	$Btu \cdot in./ft^2 \cdot h \cdot {}^\circ F$	0.144 W/m K
Thermal resistance	$ft^2 \cdot h \cdot {}^\circ F/Btu$	0.1762 K m^2/W
Temperature	$^\circ F$	$^\circ C = (5/9)(^\circ F - 32)$
Temperature difference	$^\circ F$	$^\circ C = (5/9)^\circ F$
Distance	mile	1.6 km

APPENDIX B

DERIVATION OF EQUATION FOR THE R-VALUE OF CONSTANT DENSITY THERMAL INSULATION WITH VARIABLE THICKNESS

An equation is derived in this appendix for the thermal resistance of a constant density thermal insulation installed with variable thickness. The derivation is based on parallel heat flow elements between isothermal surfaces. The thickness, y, which is the distance between the bottom of the insulation (attic floor) and the top of the insulation (bottom of roof deck or top of insulation bounded by air), varies with coordinate x. Figure B-1 shows the coordinate system used in the derivation and identifies the factors used to describe the insulated region. Equation (B-1) represents the overall thermal resistance for a material extending from $x = 0$ to $x = L$ with thickness described by $y(x)$ and k_a constant.

$$R^{-1} = \frac{1}{L} \int_0^L \frac{k_a dx}{y(x)} \tag{B-1}$$

The region [0,L] may include a segment that is constant thickness. This is the case in the attics of some manufactured home units where full thickness insulation can be installed in a central region of the attic.

$$R^{-1} = \frac{k_a}{L} \left(\int_0^{x_1} \frac{dx}{y(x)} + \int_{x_1}^{L} \frac{dx}{y_1} \right) \tag{B-2}$$

The value x_1 is the distance from the edge of the attic to the point where full thickness insulation can be achieved.

If $y(x) = y_0 + mx$ where y_0 is the "heel" depth and m is the slope of the roof deck, then Eq. (B-2) can be evaluated using

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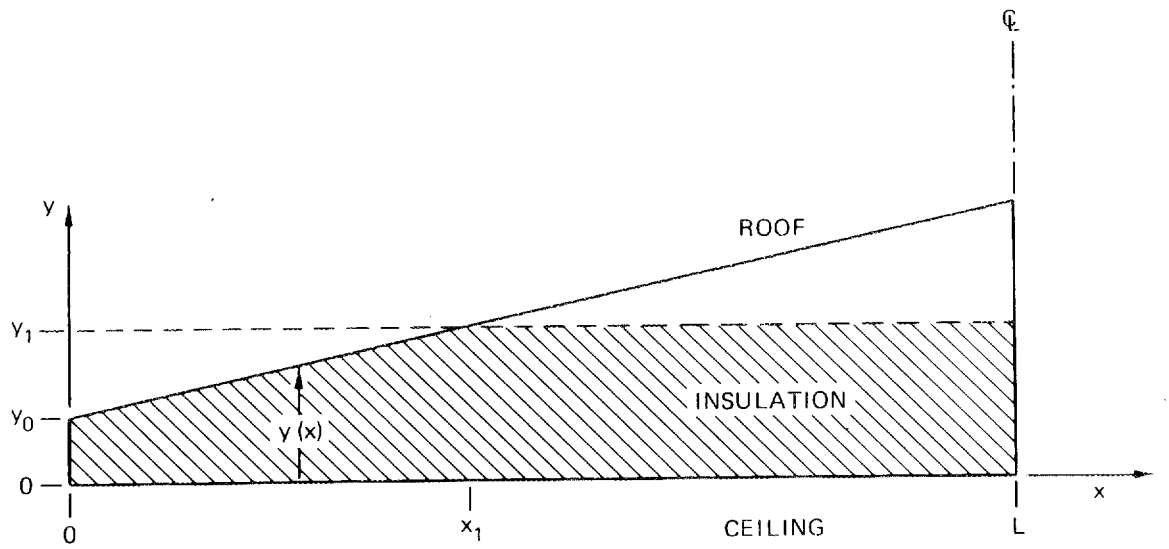

Fig. B.1. Diagram showing variables used to calculate R-values.

$$R^{-1} = \frac{k_a}{L}\left(\int_0^{x_1} \frac{dx}{y_0 + mx} + \frac{L - x_1}{y_1}\right) \tag{B-3}$$

$$R^{-1} = \frac{k_a}{L}\left(\frac{1}{m}\ln\frac{y_0 + mx_1}{y_0} + \frac{L - x_1}{y_1}\right) \tag{B-4}$$

$$R = \left(\frac{f_1}{\bar{y}_1 R^*} + \frac{f_2}{y_1 R^*}\right)^{-1} \tag{B-5}$$

where R is the thermal resistance for the region [0,L]. The term R^* is k_a^{-1}. The area fractions f_1 and f_2 are for the reduced-thickness and full-thickness regions, respectively.

EXAMPLE CALCULATION USING DATA FROM TABLE 7, CASE 1

Input: $y_0 = 3.50$ in., $y_1 = 8.60$ in., $f_1 = 0.392$, $f_2 = 0.608$, $R^* = 3.477$.

Calculations: $\bar{y}_{ln} = (8.60 - 3.50)/\ln(8.60/3.50) = 5.67$ in.

$$R = \left(\frac{0.392}{(5.67)(3.477)} + \frac{0.608}{(8.60)(3.477)} \right)^{-1} = 24.86$$

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