ORNL/TM-7266

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OAK RIDGE NATIONAL LABORATORY

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An Experimental Study of Thermal Resistance Values (R-Values) of Low-Density Mineral-Fiber Building Insulation Batts Commercially Available in 1977

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

PREPARED FOR THE DEPARTMENT OF ENERGY
CONSERVATION AND SOLAR ENERGY
OFFICE OF BUILDINGS AND COMMUNITY SYSTEMS
BUILDINGS DIVISION

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-7266
Distribution
Category UC-95d

Contract No. W-7405-eng-26

AN EXPERIMENTAL STUDY OF THERMAL RESISTANCE VALUES (R-VALUES) OF LOW-DENSITY MINERAL-FIBER BUILDING INSULATION BATTS COMMERCIALLY AVAILABLE IN 1977

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Part of
The National Program
for
Building Thermal Envelope Systems and Insulating Materials
Research Sponsored by the
Office of Buildings and Community Systems

Date Published: April 1980

NOTICE: This document contains information of preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

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FOREWORD

This experimental study is part of a continuing effort to evaluate and insure accurate reporting of insulation product performance data. The relative accuracy of alternate test methods and the degree to which their results represent current industry production is of crucial importance. DOE considers the test data reported to be of technical importance to this objective. A more comprehensive program of continued sampling and testing involving multiple laboratories is under consideration.

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Insulating Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy waste in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

Other reports in this series include the following, which are available from NTIS:

1. DOE/CS-0059: *The National Program Plan for Building Thermal Envelope Systems and Insulating Materials* (January 1979);
2. ORNL/SUB-7556/1: *Assessment of the Corrosiveness of Cellulosic Insulating Materials* (June 1979).
3. ORNL/SUB-7504/3: *Recessed Light Fixture Test Facility* (July 1979).
4. ORNL/SUB-7559/1: *Problems Associated with the Use of Urea-Formaldehyde Foam for Residential Insulation* (September 1979).
5. ORNL/SUB-7551/1: *Interim Progress Report on an Investigation of Energy Transport in Porous Insulator Systems* (October 1979).
6. ORNL/TM-6494: *A Technique for Measuring the Apparent Conductivity of Flat Insulations* (October 1979).
7. ORNL/SUB-79/13660/1: *Minnesota Retrofit Insulation In Situ Test Program Extension and Review* (February 1980).

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EDITOR'S NOTE

Although ORNL has a policy of reporting its work in SI metric units, this report uses English units. The justification is that the insulation industry at present operates completely with English units, and reporting otherwise would lose meaning to the intended readership. To assist the reader in obtaining the SI equivalents, these are listed below for the units occurring in this report.

Property	Unit Used	SI Equivalent
Dimension	in.	25.4 mm
Dimension	ft	0.3048 m
Density	lb/ft^3	$16.02\ kg/m^3$
Power	Btu/h	0.2929 W
Thermal conductivity	Btu in./h ft^2 °F	0.1441 W/m K
Thermal resistance	h ft^2 °F/Btu	0.1762 K m^2/W
Temperature	°F	°C = (5/9)(°F − 32)
Temperature difference	°F	°C = (5/9)°F

ACKNOWLEDGMENTS

The authors are grateful for the assistance with the analysis sections of this report that was provided by T. L. Hebble of the Computer Science Division at the Oak Ridge National Laboratory. The report was also greatly improved by the meaningful reviews of the draft report that were performed by T. G. Godfrey and J. P. Moore of the Metals and Ceramics Division. It is a pleasure to acknowledge the help of a number of people who assisted the authors in preparing this report: Sharon Buhl for her careful typing of several drafts of the report, S. Peterson for his technical editing efforts, and the Reports Office Staff of the Metals and Ceramics Division for expediting the report. The authors thank the external reviewers for their careful review of this report. Their comments improved the report and are reproduced in Appendix H.

EXECUTIVE SUMMARY

This study was initiated in June 1977 to obtain and evaluate full-thickness thermal performance data on mineral fiber batt-type insulations. The mineral fiber industry at that time and currently determines the thermal resis-tance (R-value) of these products on specimens usually 1.5 in. thick. Thermal test specimens are sliced from the marketed products, which are usually 3.5 or 6 in. thick, and tested to determine apparent thermal conductivity. The measured apparent thermal conductivity is then used in a manner prescribed in ASTM recommended practice to provide the R-value at full thickness by a linear extrapolation.

The study aimed to obtain full-thickness thermal performance data and to assess other properties of mineral fiber building insulations. The physical property measurements discussed in this report provide a measure of the range of values for density, thickness, and R-value based on a sampling of low-density mineral-fiber building insulation batts purchased in the marketplace in 1977. The experimental data were used to establish mean R-values at nominal (label) thickness of R-11 and R-19 fiberglass batts and R-11 rock wool batts.

The guarded hot plate apparatus used to obtain full-thickness thermal performance data was estimated to be accurate to ±3% by a determinate error analysis and from measurements on specimens studied by others. This apparatus was also used to measure the apparent thermal conductivity of sliced batt materials in order to compare the two methods. The results obtained by using sliced materials indicated mean nominal-thickness R-values consistent with the manufacturers' label value. The full-thickness tests showed mean nominal-thickness R-values below (but within 10% of) the manufacturers' label value. The mean R-values obtained with slicing were greater than the full-thickness R-values by approximately 0.9 R-units for R-11 fiberglass insulations and by approximately 1.2 R-units for R-19 fiberglass insulations both of which exceed the apparatus error estimate.

The full-thickness and sliced testing techniques provided a set of R-values on the purchased samples that were converted to R-values at label thickness by using a particular correlation of apparent thermal

conductivity and density. The following table lists the product type tested, the number of tests, the percentage found to be below the labeled R-value, and the percentage found to be below 90% of the labeled R-value:

Experimental (Full Thickness) Data Summary[a]

Product Type	Number of Tests	Percentage Below Label Value	Percentage Below 90% of Label Value[a]
R-11 Fiberglass	48	85	19
R-19 Fiberglass	30	93	23
R-11 Rock wool 3 in. thick	12	100	67
R-11 Rock wool 3.5 in. thick	15	53	0

[a]Nine measurements made using test specimens sliced from fiberglass batts (the current practice) showed R-values above 90% of the label value.

The full thickness results indicate surprisingly large percentages below labeled R-value for these four types of mineral fiber insulation. This report includes a statistical analysis of these data based on the assumption of normally distributed properties, which yielded estimates of similar magnitude for the population from which the samples were purchased.

Recovered thickness data are available that are in conflict with the values obtained in this study. Measurements on R-19 fiberglass batts obtained as part of the certification program operated by the National Association of Home Builders Research Foundation show recovered thicknesses that are greater than those listed in this report. The conflicting data and comments from reviewers have been included in this report in appendices.

This report identifies an urgency for continued sampling and further testing of mineral fiber insulations by many laboratories. The differences between results obtained with the sliced technique and results obtained with full-thickness testing must be thoroughly understood and documented so that adjustment factors for the thickness effect can be accurately established.

This experimental study, which has generated a data base on full-thickness testing and the thickness effect by using a single guarded hot plate, should be viewed as part of a continuing effort to assess the effectiveness of available thermal insulating materials and associated test methods. Both ASTM and NBS view the accuracy of full-thickness testing as unresolved and recommend continued use of the sliced testing technique until full-thickness calibration standards are available. Mineral fiber insulating materials are a major contribution to conservation and a continuing test program on the thermal effectiveness is being planned.

1. INTRODUCTION

After the impact of the 1973 oil embargo, increased energy conservation in buildings by more and better use of thermal insulation became an obvious area of study. In 1975, as part of its overall interests in energy conservation, the newly formed Energy Research and Development Administration (ERDA) established a materials group having a scope that included the evaluation of thermal performance and other properties of the current building insulation materials. A number of significant events have occurred since this project was conceived. A brief summary of these events has been included in Appendix A.

In mid-1977 ERDA initiated an investigation of the properties of the various mineral fiber batt and blanket products that were then available. Mineral fiber products are the most widely used insulation materials, particularly in the residential sector. The products are being sold on the basis of having a specified thermal resistance (R-value). Furthermore, a certification program* has been ongoing for a number of years within the mineral fiber manufacturing industry to certify that the products do, in fact, conform to the stated level of performance. It was anticipated that manufacturers of other thermal insulation products would follow the lead of the mineral fiber industry, and it was anticipated that there could be overall product improvements that would encourage the increased use of insulation for energy conservation in buildings.

Thermal insulations, by their nature, are heterogenous, and their performance characteristics, especially thermal performance, can vary markedly with relatively small changes in density and thickness. The mineral fiber products as manufactured are compacted before transportation to the installation site. These products are designed for a specified level of thermal performance, which depends upon recovered thickness and apparent thermal conductivity (apparent thermal conductivity varies with density). The extent to which these products recover from compaction is examined in this report.

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*Program operated by The National Association of Home Builders Research Foundation (NAHBRF), Inc., a wholly owned subsidiary of the National Association of Home Builders.

The purpose of this investigation was to evaluate R-11 and R-19 products from each plant of each major manufacturer. Samples were purchased directly from retail sources in different geographical areas such that every manufacturing plant was represented. These samples were shipped directly to the test laboratory, where recovered thickness, density, and thermal resistance were measured.

The investigation was initiated in June 1977 with Dynatech R/D Company being selected to obtain the sample materials and investigate thermal performance. Dynatech had a 24-in.-square hot plate apparatus and was one of the few organizations in a position to evaluate the insulation products in accordance with ASTM C 177-76,* "Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate."[1] This measurement procedure was chosen because it is an absolute test method, which does not rely on a calibration factor derived from evaluating standard reference materials.

The first phase of the investigation included the determination of recovered thickness, density, and thermal resistance at a mean temperature of 75°F on all the sample materials obtained and additional measurements of thermal resistance as a function of temperature and temperature difference on a limited number of sample materials. Thermal performance measurements were undertaken at the recovered thickness with subsequent calculation of the R-value at nominal (label) thickness. Nominal-thickness R-values were calculated and reported to provide a basis for comparing the materials that were tested.

The second phase of the investigation addressed the question of full-thickness testing versus testing of sliced samples. The previously mentioned certification program requires that these products be evaluated on specimens sliced from the product in accordance with ASTM C 653-70, "Determination of the Thermal Resistance of Low-Density Mineral Fiber Blanket-Type Building Insulation." Thus, the present work included measurements intended to provide a comparison between the two different experimental techniques. This second phase of the investigation was undertaken in 1978, and involved a limited number of samples from a

*American Society for Testing and Materials, approved June 11, 1976.

single manufacturer. Test specimens were removed from the same rolls of material that were used in the first phase and were evaluated in an identical fashion to that performed for the certification program for mineral wool batts and blankets. In this way differences in the two different measurement techniques could be evaluated quantitatively.

A diagrammatic representation of the sample distribution and testing sequence is shown in Fig. 1 for the two phases of this study. A statistical analysis was completed at Oak Ridge National Laboratory (ORNL) after the experimental results were reported by Dynatech. Details of the procedures, experimental results, and the resultant analysis are presented in the following sections.

REFERENCE

1. *1977 Annual Book of ASTM Standards, Part 18, Thermal and Cryogenic Insulating Materials; Building Seals and Sealants; Fire Tests; Building Constructions; Environmental Acoustics.* American Society for Testing and Materials, Philadelphia.

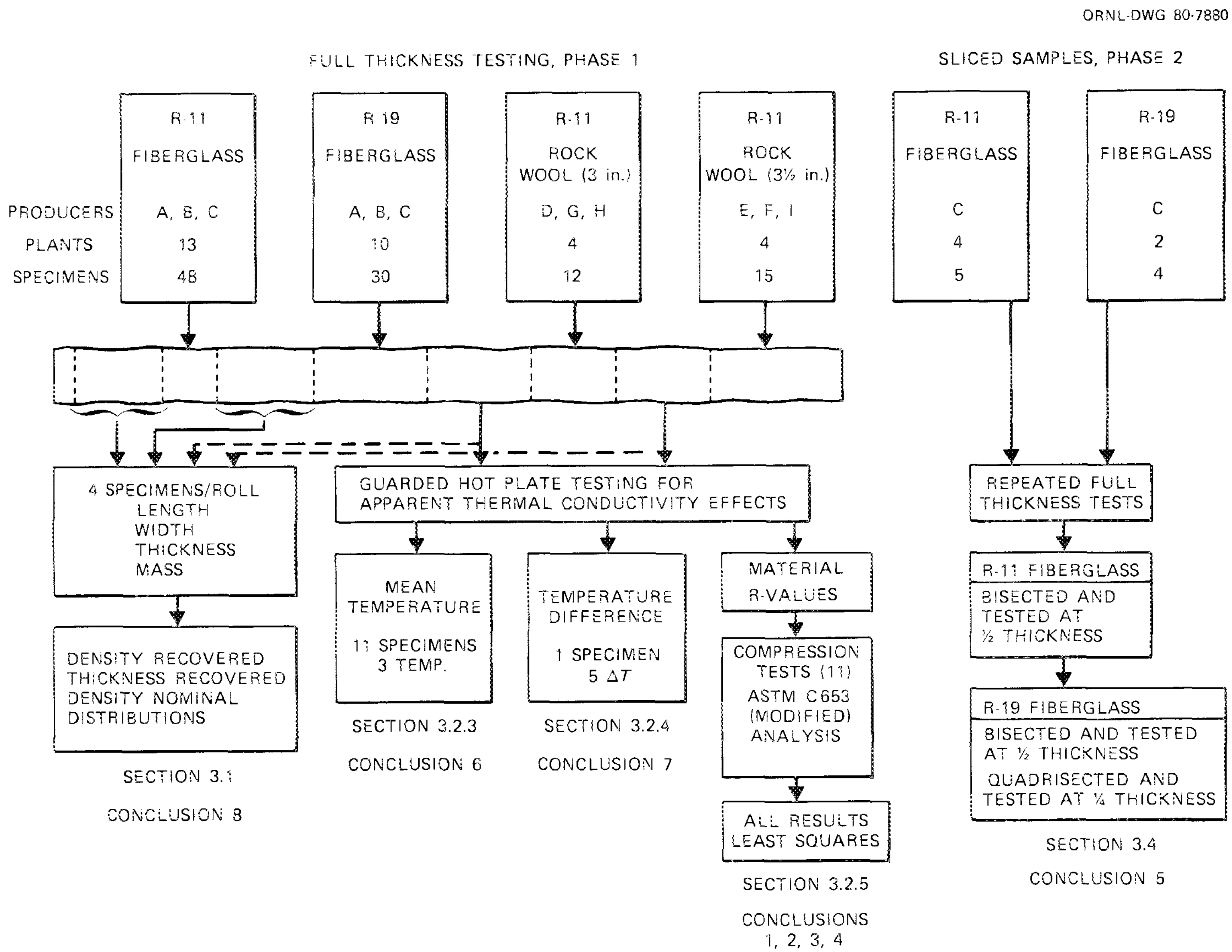

Fig. 1. Flow Diagram of Sampling and Testing Procedure.

2. SAMPLE PROCUREMENT

2.1 Phase 1

In an attempt to eliminate questions concerning the validity of this investigation concerning the representativeness of the sample materials evaluated in this test program, it was decided that Dynatech would be responsible for the procurement of the test samples. A total of 99 packages of mineral fiber batt insulation materials were purchased from retail sources across the country. These materials fell into three major categories: R-11 unfaced low-density fiberglass, R-19 unfaced low-density fiberglass, and R-11 paper faced rook wool insulation materials.

The material sources were randomly selected retail insulation and building supply outlets in major metropolitan areas that were geographically close to the manufacturing plants.

Dynatech purchased 42 packages of R-11 fiberglass. From information supplied by the retail source or deduced from package markings it was possible to identify the manufacturing facility that supplied the insulation materials. The intention was to procure 3 sample lots from 15 different production plants, divided equally among the 3 major manufacturers. Samples with different shift numbers or dates of manufacture were sought to provide adequate product representation. Because of shortages in supply at the time of sampling, it was possible to procure sample material from only 13 plants.

A five-digit code number was assigned to each sample of insulation material as it was received. The codes identify manufacturers and production plants and permit proper grouping of the data. The codes are listed in Appendix B.

Similarly, 30 packages of R-19 low-density fiberglass and 27 packages of rock wool insulations were also identified and purchased. Ten manufacturing plants were identified in connection with the R-19 low-density fiberglass materials and eight manufacturing plants were represented in the rock wool products that were obtained. This conformed with the original request for distribution of samples for these two material types. As with the R-11 fiberglass materials, a code was assigned to each sample of R-19 fiberglass insulation and R-11 rock wool insulation.

Upon receipt of each sample material, two specimens approximately 48 in. in length were cut from the sample roll for the determination of density. Two specimens approximately 24 in. in length were cut from the sample roll for the determination of apparent thermal conductivity and thermal resistance. In cases where the roll width was less than 24 in., additional specimen pieces were cut to fabricate test specimens 24 in. square. This was achieved by cutting two additional specimen pieces and sandwiching them on either side of the original specimen piece such that there were no joints in the actual metering section. All remaining sample materials were sent to ORNL.

The only criteron applied in the selection of test specimens from the sample was that they be from the middle portion of the sample to minimize transportation damage in the actual test specimens. The pair of apparent thermal conductivity specimens was cut from approximately the same location along the batt length, while the density specimens were cut from two locations to determine the variability of density within a single roll or bag.

Two additional test specimens were removed from one randomly chosen roll of each manufacturer to determine apparent thermal conductivity and thermal resistance as a function of temperature and density. These two specimens were also removed from the same location along the length of the batt but not necessarily from the same location as the original pair of apparent thermal conductivity specimens.

2.2 Phase 2

For the purpose of determining experimentally the difference between R-values obtained by measuring full-thickness batts and those obtained by using ASTM C 653-70, five pairs of R-11 and four pairs of R-19 low-density fiberglass samples were submitted to Dynatech by ORNL. These specimens were removed from the same rolls or batts as those in Phase 1. They were labeled with the identical coding from the previous phase and were from a single manufacturer.

3. EXPERIMENTAL PROCEDURES AND DISCUSSION OF RESULTS

3.1 Thickness and Density

3.1.1 Procedure for Thickness and Density Measurements

Thickness and density measurements were made in accordance with ASTM C 167-64, "Thickness and Density of Blanket or Batt-Type Thermal Insulating Materials." In general, the procedure for thickness and density measurements involved selection of two density specimens (ρ_1 and ρ_2) about 48 in. in length, which were cut from each roll or batt of sample material. Each specimen was held at two points about 30 in. apart along the long edge, suspended with the long edge horizontal, and shaken vigorously in a horizontal plane for 5 s. Each test specimen was then placed on a horizontal flat surface and allowed to expand freely for at least 4 h to recovered thickness.

Each specimen was ruled off into four equal areas along its length, and the thickness was measured as specified in ASTM C 167-64. For insulations with paper facing, the facing was cut and peeled back to expose the surface of the insulation material. The thickness measurement was performed in the center of each of the four areas. Lengths and widths of the test specimens were measured with a steel rule to ±1/16 in. at three positions along the specimen. Each specimen was weighed to within ±0.1 g. Specimens having paper facings were weighed with as much of the facing material removed as possible without damaging the specimen. Thus, each density measurement set involved thickness measurements (four), length measurements (three), width measurements (three), and a weight determination. In some cases (20 of the 105 measurements) the density specimen was less than 48 in. in length, but it was always greater than 23 in. in length.

The density of a specimen at recovered thickness, ρ_R, was calculated by using

$$\rho_R = 3.81\ M/LWT_R\ , \qquad (1)$$

where

ρ_R = density at recovered thickness, pounds per foot cubed;

M = mass of specimen, grams;

L = average length of specimen, inches;

W = average width of specimen, inches;

T_R = average recovered thickness of specimen, inches.

The density of a specimen at its nominal thickness, ρ_N, was calculated by

$$\rho_N = \rho_R T_R / T_N \ , \tag{2}$$

with T_N = nominal thickness, inches (stated on label).

Recovered thickness and density were measured on a total of four specimens from each roll or batt of material tested. A measurement was made on each of the specimens taken from two different locations on the batt specifically for density determination, and a density measurement was made on each of the pair of specimens taken from a single roll location for apparent thermal conductivity measurement. The single value reported for the density of the thermal conductivity specimens represents an average of two measurements taken at a location different from the two density specimens.

3.1.2 Discussion of Thickness and Density Results

The experimental results obtained for thickness and density are tabulated in Appendix C. The data are summarized in Table 1. The data shown in Appendix C were analyzed to determine the distribution of thicknesses and densities present in the sampling. The three entries for each specimen were weighted equally in the calculation of averages since they come from three locations. Results are shown for each of the three fiberglass manufacturers represented in the sample as well as composite results for a given type product. In the case of the rock wool data, only composite statistics are reported since the sample size for a given manufacturer was relatively small.

Table 1. The Calculated Mean, Sample Standard Deviation, Predicted Range, and Observed Range of Densities and Thicknesses of Low Density-Fiberglass and Rock Wool Insulation Materials

Product and Nominal Thickness	Manu-facturer	Number of Measure-ments	Physical Property[a]	Value of Property		
				Sample Mean	Sample Std. Dev.	Observed Range
Fiberglass						
R-11 (3.5 in.)	A	47	ρ_R	0.596	0.0683	0.478–0.775
			ρ_N	0.613	0.0907	0.417–0.775
			T_R	3.60	0.357	2.85–4.22
R-11 (3.5 in.)	B	19	ρ_R	0.419	0.0338	0.378–0.460
			ρ_N	0.484	0.033	0.439–0.565
			T_R	4.06	0.321	3.54–4.52
R-11 (4.0 in.)	B	19	ρ_R	0.406	0.054	0.332–0.537
			ρ_N	0.380	0.059	0.304–0.460
			T_R	3.76	0.487	3.12–4.71
R-11 (3.5 in.)	C	47	ρ_R	0.576	0.0642	0.474–0.765
			ρ_N	0.596	0.0444	0.532–0.681
			T_R	3.65	0.336	2.79–4.33
R-11 Composite (3.5 in.)		113	ρ_R	0.558	0.0886	0.378–0.775
			ρ_N	0.584	0.0805	0.417–0.775
			T_R	3.69	0.378	2.79–4.52
R-19 (6.0 in.)	A	33	ρ_R	0.678	0.0826	0.529–0.828
			ρ_N	0.639	0.0818	0.501–0.880
			T_R	5.71	0.804	4.30–7.22
R-19 (6.5 in.)	B	27	ρ_R	0.442	0.121	0.291–0.745
			ρ_N	0.414	0.092	0.307–0.588
			T_R	6.16	0.5175	5.11–6.93
R-19 (6.0 in.)	C	30	ρ_R	0.637	0.0505	0.563–0.784
			ρ_N	0.613	0.0524	0.548–0.750
			T_R	5.78	0.434	4.53–6.56
R-19 Composite (6.0 in.)		63	ρ_R	0.658	0.072	0.529–0.828
			ρ_N	0.626	0.070	0.501–0.880
			T_R	5.75	0.651	4.30–7.22
Rock Wool						
R-11 (3.0 in.)	D,G,H	36	ρ_R	2.203	0.278	1.788–2.936
			ρ_N	2.165	0.297	1.720–2.650
			T_R	2.98	0.488	2.31–4.32
R-11 (3.5 in.)	E,F,I	45	ρ_R	1.927	0.247	1.441–2.448
			ρ_N	1.666	0.247	1.066–2.153
			T_R	3.03	0.396	1.90–3.67

[a] ρ_R is the density at recovered thickness and ρ_N is the density at nominal thickness, calculated by Eq. (2); both are in pounds per cubic foot. T_R is the average recovered thickness in inches.

In each case two parameters are used to describe the distribution of the property under discussion. The sample mean computed with

$$\overline{X} = (\sum_{i=1}^{N} X_i)/N \tag{3}$$

was taken as an estimate of the population mean, while

$$s^2 = \sum_{i=1}^{N} (X_i - \overline{X})^2/(N - 1) \tag{4}$$

was used to obtain an estimate of the population variance. In these equations

X_i = an experimental value for property X,
$\overline{X}$ = the estimated mean of property X,
N = the number of experimental values available for property X, and
s^2 = the estimated variance of the X population.

The property values are assumed to be normally distributed about their respective means. Figures that show the experimentally determined property distribution have been included to provide some insight into the validity of the assumption. Figures 2 through 5 show the distributions for the composite data for T_R. Distributions for the data from individual manufacturers and the thickness and density measurements can be found in Appendix C.

In addition to the analysis that leads to a description of the property distributions, the 99% confidence interval for the means of the property distributions was determined by using

$$|\overline{P} - \overline{X}| \leqslant ts/\sqrt{N} \; , \tag{5}$$

where

$\overline{P}$ = the true mean of property X, and
t = value obtained from t distribution table for $\alpha = 0.01$ (99% confidence level) and $(N - 1)$ degrees of freedom.

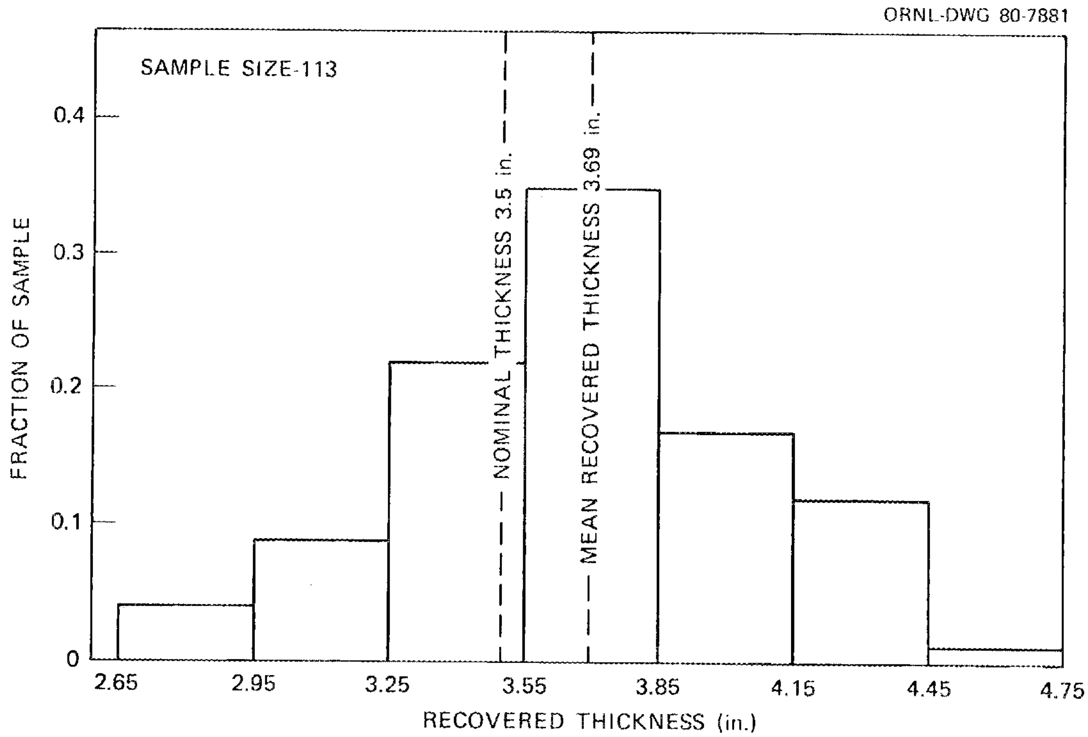

Fig. 2. Observed Distribution about the Mean Recovered Thickness of R-11 Fiberglass Batts.

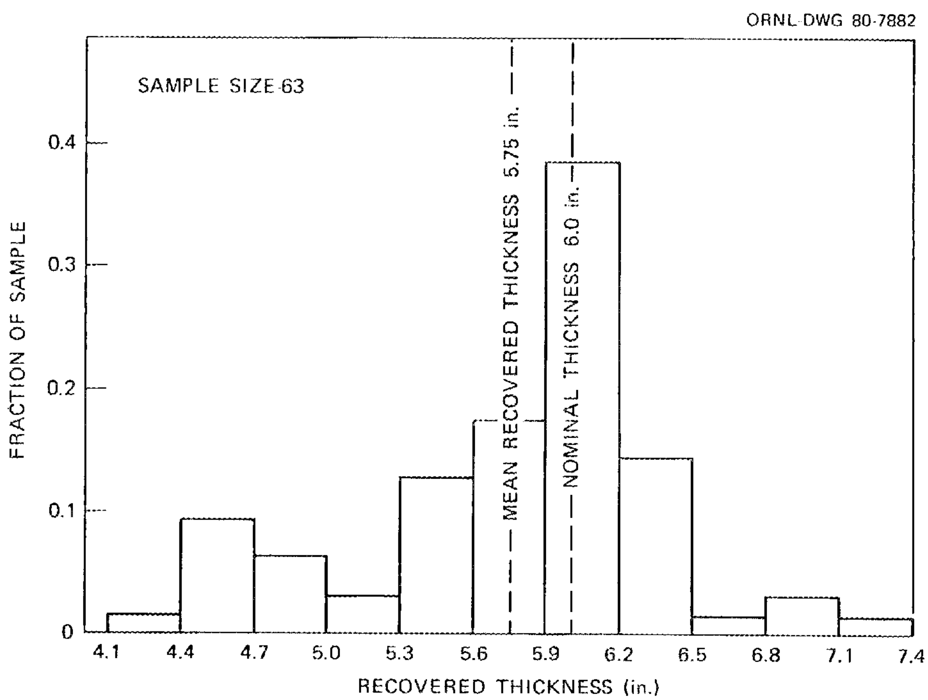

Fig. 3. Observed Distribution about the Mean Recovered Thickness of R-19 Fiberglass Batts.

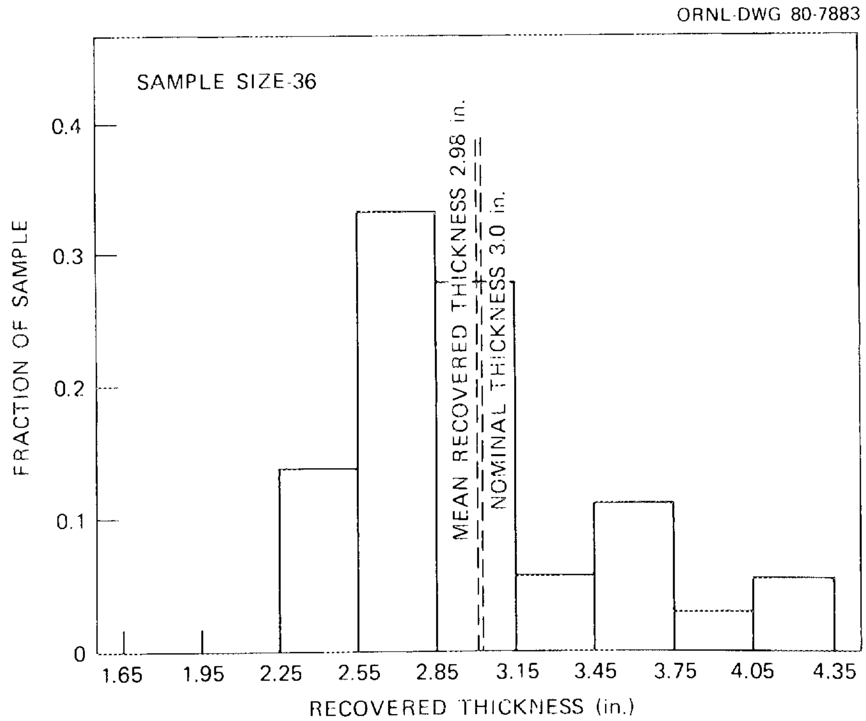

Fig. 4. Observed Distribution about the Mean Recovered Thickness of R-11 Nominally 3-in.-Thick Rock Wool Batts.

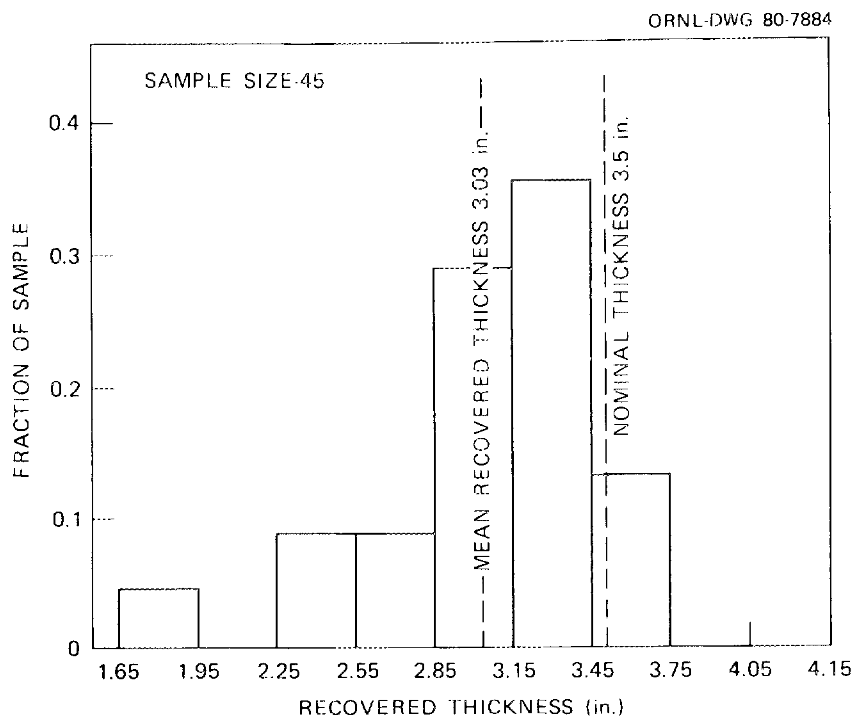

Fig. 5. Observed Distribution about the Mean Recovered Thickness of R-11 Nominally 3.5-in.-Thick Rock Wool Batts.

Table 1 contains the results of the analysis described above. For each of the three properties — ρ_R, ρ_N and T_R — values are shown for the mean of the experimental property measurements, which are the population mean estimates; an estimate of the standard deviations, s, of the property value population; and the observed range of the property. Table 2 shows for each class of material an interval in which with 99% confidence the true property mean will be located. Table 2 also lists the observed property ranges expressed as a percentage of the mean.

The following observations are made regarding the results in Table 1.

- The mean recovered thicknesses for all of the R-11 fiberglass sets exceed the nominal thickness except for the nominally 4-in.-thick material.
- In the case of the R-19 fiberglass data the mean recovered thicknesses for the manufacturers represented and the composite value fall below the nominal thickness.
- The mean T_R for nominally 3-in. R-11 rock wool samples is very close to the nominal thickness. The mean for the 3.5-in. R-11 rock wool samples is significantly below the nominal value.

The density distributions are of interest because of the strong relationship between density and apparent thermal conductivity. The entries in the last column of Table 1 are a measure of the variability of the products examined. Table 1 contains entries by manufacturer and entries for product composites. No attempt was made to discuss data from individual manufacturers' plants since the objective was to measure marketplace variability.

The last column in Table 2 contains an additional indicator of the variability of densities and thicknesses of the materials studied. The percentages shown in Table 2 are one-half of the observed range expressed as a percentage of the mean. In the case of the fiberglass materials the numbers shown for individual manufacturers are an indicator of the product variability. For the R-11 fiberglass, for example, the observed densities at recovered thickness vary about the mean by approximately ±25%. Variation of the density at recovered thickness for the R-19 fiberglass is more difficult to characterize, ranging from ±17.3% for manufacturer C to

Table 2. The Predicted Interval for the Density and Thickness Means and Property Ranges Expressed as Percentages

Product and Nominal Thickness	Manu-facturer	Physical Property[a]	Sample Mean	99% Confidence Interval for the Population Mean	Observed Range[b] (% of Mean)
Fiberglass					
R-11 (3.5 in.)	A	ρ_R	0.596	0.571–0.622	±24.9
		ρ_N	0.613	0.579–0.647	29.2
		T_R	3.60	3.46–3.73	19.0
R-11 (3.5 in.)	B	ρ_R	0.419	0.397–0.442	9.8
		ρ_N	0.484	0.462–0.506	13.0
		T_R	4.06	3.847–4.273	12.1
R-11 (4.0 in.)	B	ρ_R	0.406	0.371–0.441	25.2
		ρ_N	0.380	0.342–0.419	20.5
		T_R	3.76	3.44–4.08	21.1
R-11 (3.5 in.)	C	ρ_R	0.576	0.553–0.601	25.3
		ρ_N	0.596	0.579–0.613	12.5
		T_R	3.65	3.52–3.77	21.1
R-11 Composite (3.5 in.)		ρ_R	0.558	0.513–0.559	35.6
		ρ_N	0.584	0.540–0.584	30.6
		T_R	3.69	3.60–3.78	23.4
R-19 (6.0 in.)	A	ρ_R	0.678	0.641–0.715	22.1
		ρ_N	0.639	0.602–0.676	29.7
		T_R	5.71	5.35–6.07	25.6
R-19 (6.5 in.)	B	ρ_R	0.442	0.378–0.507	51.4
		ρ_N	0.414	0.365–0.463	33.9
		T_R	6.16	5.88–6.44	14.8
R-19 (6.0 in.)	C	ρ_R	0.637	0.613–0.660	17.3
		ρ_N	0.613	0.587–0.637	16.5
		T_R	5.78	5.58–5.99	17.6
R-19 Composite (6.0 in.)		ρ_R	0.658	0.634–0.682	22.7
		ρ_N	0.626	0.603–0.650	30.3
		T_R	5.75	5.53–5.96	25.4
Rock Wool					
R-11 (3.0 in.)	D,G,H	ρ_R	2.203	2.083–2.323	26.1
		ρ_N	2.165	2.037–2.293	21.5
		T_R	2.98	2.77–3.19	33.7
R-11 (3.5 in.)	E,F,I	ρ_R	1.927	1.832–2.022	26.1
		ρ_N	1.666	1.571–1.761	32.6
		T_R	3.03	2.87–3.18	29.2

[a] ρ_R is the density at recovered thickness and ρ_N is the density at nominal thickness, calculated by Eq. (2); both are in pounds per cubic foot. T_R is the average recovered thickness in inches.

[b] 0.5(range × 100)/mean.

±51.4% for manufacturer B. The density at recovered thickness for the rock wools tested shows variations of ±26%. A scan of the last column in Table 2 shows that the recovered thickness of the fiberglass materials varies at about the ±20% level, while the rock wools vary at about the ±30% level.

3.2 Apparent Thermal Conductivity and R-Values

All measurements of apparent thermal conductivity of the commercial insulations were performed in accordance with ASTM C 177-76. A detailed discussion of the guarded hot plate apparatus is given in Sect. 3.2.1, and a schematic of the apparatus is given in Fig. 6. Three sets of apparent thermal conductivity measurements were obtained. The first set of measurements to be considered shows the variation of apparent thermal conductivity with mean sample temperature and the temperature difference

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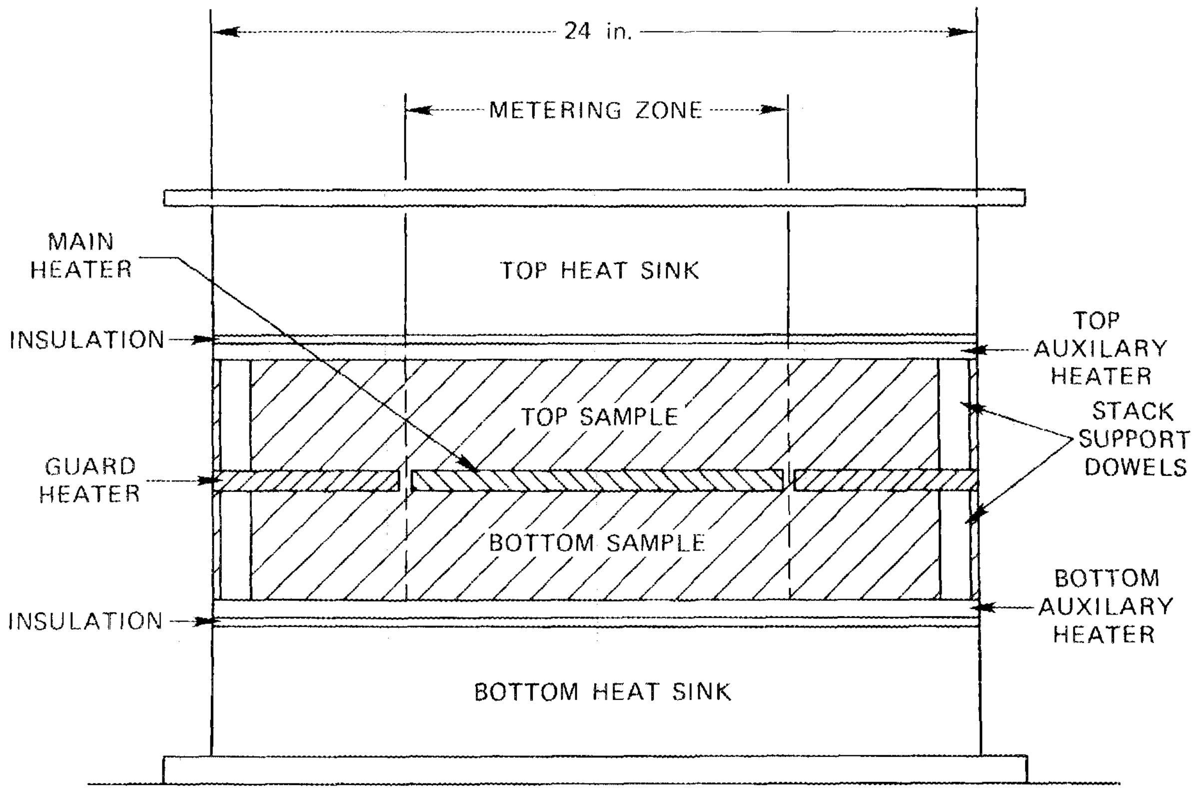


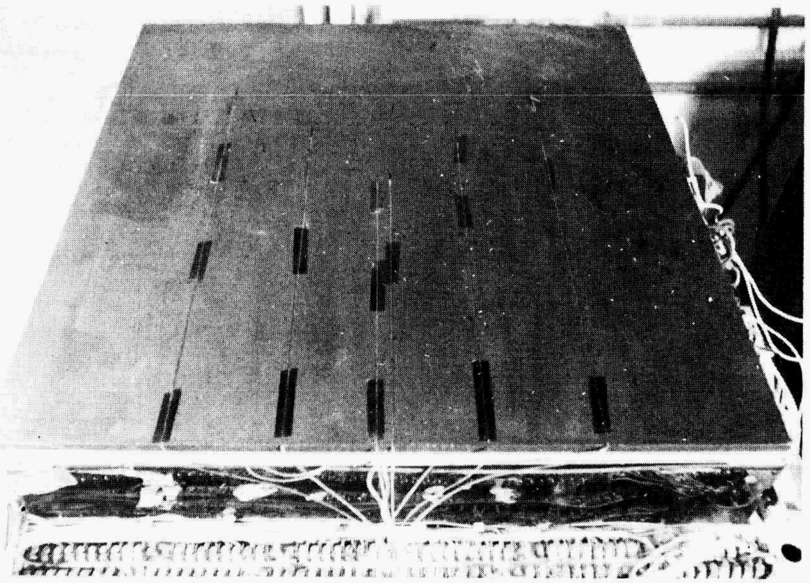
Fig. 6. Schematic of Guarded Hot Plate Apparatus.

across the specimen. The second and largest set of data involves apparent thermal conductivity measurements completed on full-thickness samples from which R-values at recovered thickness and R-values at nominal thickness are computed. The second set of data forms a basis for discussing the distribution of R-values indicated by the nationwide sample. A third set of measurements was undertaken to determine if slicing of batts to provide thin samples for an apparent thermal conductivity measurement has an effect on the R-value determined for a full-thickness sample. This third set is described separately in Sect. 3.4.

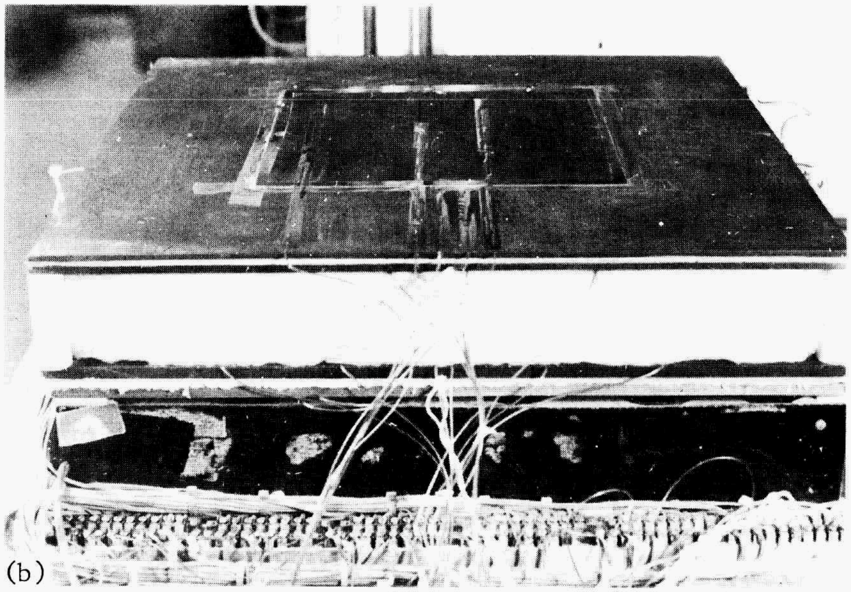
3.2.1 Guarded Hot Plate Apparatus

The instrument that was used to perform all the thermal performance measurements was a 24-in.-square horizontal guarded hot plate built and maintained by Dynatech. A heating unit, which consisted of a central metering section and a guard section, was sandwiched between two insulation specimens. This composite stack was mounted between two cooling units and surrounded with edge insulation. A schematic diagram of the guarded hot plate apparatus is shown in Fig. 6. The apparatus at three stages of assembly is shown in Fig. 7. The metering section consisted of a metering area heater and metering area surface plates, and the guard section consisted of a single guard heater and guard surface plates. The cooling units consisted of a cooling plate, a cooling unit heater, and a cooling surface plate. All surface plates were fabricated of 3/8-in.-thick black anodized aluminum. The surfaces of these plates had a measured total hemispherical emittance of 0.82 at 75°F.

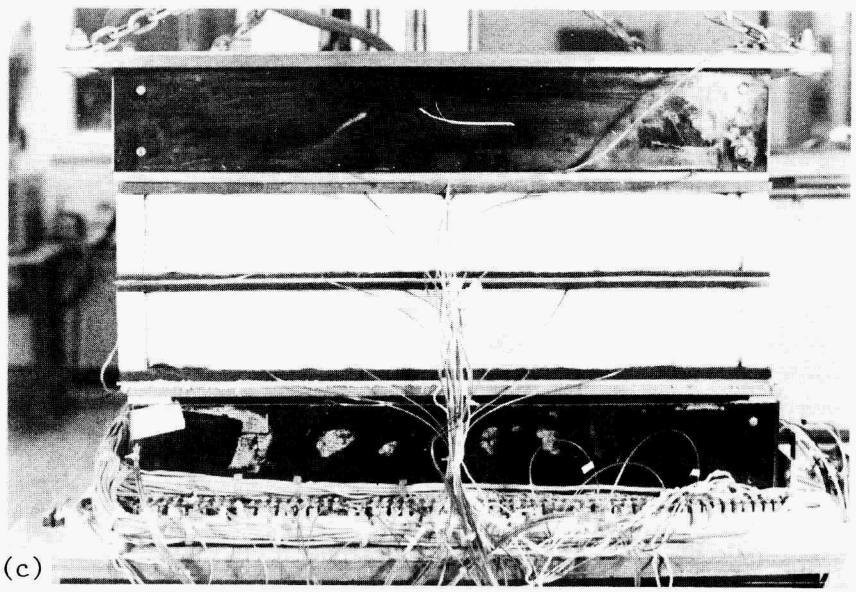
Each heating unit was fabricated by sandwiching a two-heater silicone rubber unit between two thin sheets of Teflon paper and two surface plates. The overall geometry of the heating unit was 24 in. square, with the metering section being the central 12 in. square. The unit was bolted together at six points, two being in the metering section. The two sections of the heater unit were separated by a 0.125-in. gap around the perimeter of the metering section. The area of the gap represented 4.2% of the total metering section area. The area of the metering section was determined by measurements to the centers of the gap. A 48-junction



(a)



(b)



(c)

Fig. 7. The Guarded Hot Plate Assembly. (a) Bottom heat sink. (b) Bottom heat sink, bottom sample, and main heater. (c) Complete assembly less edge insulation. Dynatech photographs.

differential thermopile fabricated of 32-gage Chromel-Alumel type K wire was installed between the silicone rubber heating unit and the Teflon sheets such that alternate junctions were in the metering and guard sections, respectively, and close to the gap between the sections. The sensitivity of this thermopile was approximately 0.55 mV/°F at 75°F.

The metering area heater was connected to a Lamda model LK 342FM dc power supply. A 0.001-Ω precision resistor was connected in series with the heater, and the voltage drop across this resistor was measured to determine the current through the heater. A 1000 to 1 precision voltage divider was attached in parallel with the metering area heater, and the voltage drop across this divider (0.001 times the voltage drop across metering heater) was measured. The three resistors used in the power measurement circuit were routinely checked against a precision resistor traceable to the National Bureau of Standards (NBS).

The output of the differential thermopile and guard heater were connected to a Leeds and Northrup Electromax III differential controller, which supplied power to the heater such that the thermopile output was minimized.

The cooling units consisted of a 3/8-in. copper plate of the same size as the heating unit with a series of interconnected 1/2-in.-diam copper tubes soldered to the plate and insulated in place with a spray urethane foam, a silicone-rubber-covered heater unit, and a surface plate. A temperature-controlled chiller unit circulated coolant through the copper tubes. A control thermocouple from a Leeds and Northrup Electromax III temperature controller was attached to the backside of each surface plate. Temperature stability was attained by chilling the fluid and trimming to the control temperature with the electric heater. Temperature measurements were made with the following arrangement. A total of eight 30-gage type T copper vs constantan thermocouples were cemented into 1/16-in.-square grooves machine cut into the surface plates, six in the metering section and two in the guard section. The thermocouples were connected to copper wire in an isothermal block, and all wire connections after the isothermal block were copper to copper. The individual thermocouple leads were then run to a selector switch whose output was connected to a referencing switch, which allowed the individual temperature readouts to be measured with or without referencing. The reference used with this instrument was an Acromag model 320 electronic ice reference. The setpoint accuracy for the reference was ±0.9°F with a 0.2°F stability for an 8-h period. The output of the reference was connected to a Newport model 2400 A/S digital millivolt meter with a range of ±0 to 39.999 mV. The resolution of the meter is 1 μV with a maximum error of 0.01% of the output ±2 μV over an 8-h period. In addition to monitoring the temperature levels of the working plates, the instrument was modified so that the differential thermopile output could be checked by unreferencing the readout system.

Since the upper cooling unit weighed 200 lb (91 kg), spacers were needed to prevent compression of each of the individual test specimens. Four 3/8-in.-diam balsa wood dowels were machined to ±0.002 in. of each of the individual test specimen thicknesses and placed between the corners of the guard heater and cooling unit plates. The surface pressure on the insulation was very close to zero. There may have been as a result air gaps between the specimen and the plates. Such air gaps would add to the R-value of the insulation, but data were not obtained to assess the magnitude of the effect.

Heat losses from the outer edges of the guard section and test specimens were reduced with edge insulation. Two nominal R-19 low-density fiberglass batts were wrapped around the test system for this purpose. These losses were monitored by attaching a thermocouple to the center of the test specimen edge with aluminized tape. Under test conditions the edge loss ratio, defined as the difference in edge and mean temperatures divided by the temperature difference through the specimen, was maintained at less than 0.04 but typically was less than 0.02. In general, higher edge loss ratios were measured when the test temperature was 150°F. A summary of the determinate error parameters affecting the accuracy of measurement for this guarded hot plate apparatus is as follows:

power ±0.1%

dimensions ±0.2% for most cases

temperature difference ±1%
(thermocouple)

electronic measurement circuits ±0.1%

An analysis shown in Appendix D was carried out by using the tables in the Appendix of ASTM C 177-76 with the appropriate parameters for the present plate to determine the maximum specimen thickness that can be used. The results of the analysis show that the guarded hot plate used in this study can be used to measure to better than ±2% the apparent thermal conductivity of samples up to 8.6 in. in thickness. Table D1 also contains data that were obtained to demonstrate the absence of bias due to heat flow up and down.

In order to establish limits of measurement accuracy, various samples of known apparent thermal conductivity have been measured in the present plate at various times before, during, and after the present investigation. These included samples of reference materials from National Bureau of Standards (NBS) and Laboratoire D'Essais (LDE), a sample from the National Mineral Wool Insulation Association (NMWIA) C16 Round Robin, and a sample of 16-year old, very stable, high-density polystyrene, which had been measured a number of times in different absolute apparatuses. The results of the various measurements are summarized in Table 3. Consideration of the above factors results in the conclusion that the overall accuracy of apparent thermal conductivity measurements of the Dynatech guarded hot plate is better than ±3%.

3.2.2 Procedure for Determining Apparent Thermal Conductivity

Steady-state conditions were established in the test system 6 to 8 h after the specimen was installed. The temperatures on the cooling surface plates were controlled to within ±0.2°F of each other and allowed to fluctuate by no more than ±0.15°F. A temperature difference of approximately 50°F was maintained across each test specimen by adjustment of the power to the metering area heater. The differential output was checked and adjusted such that the thermopile output was maintained between ±0.01 mV. Equilibrium or steady state was defined as being established when four regular sets of data taken 15 min apart gave values of the apparent thermal conductivity data with only random variations of less than 1%. This constancy satisfies the usual requirement for the attainment of steady state. The power to the metering area heater was measured

Table 3. Summary of Measurements on Samples of Known Properties

Material Description	Year[a]	Density (lb/ft^3)	Thickness (in.)	Apparent Thermal Conductivity Btu in./h ft^2 ° F	
				Measured	Accepted
NBS A	1977	7.49	0.987	0.225	0.223
NBS A (stacked)[b]	1977	7.49	1.97	0.227	
NBS B	1977	7.67	1.03	0.230	0.230
NBS B (stacked)	1977	7.67	2.00	0.234	
NBS A and B	1977	7.58	1.985	0.228	
LDE	1977	5.49	1.44	0.230	0.230
LDE	1977	5.49	2.87	0.225	0.230
LDE (stacked)	1979	5.49	2.87	0.228	0.230
NMWIA-C16, 8 and 9	1977	0.802	3.5	0.292	0.284[c]
NMWIA-C16, 10 and 11	1977	0.759	3.5	0.294	0.287[c]
NMWIA-C16, 8+9 and 10+11	1977	0.786	7.0	0.289	
NMWIA-C16, 8 and 9	1979	0.806	3.5	0.286	0.284[c]
NMWIA-C16, 8+9 and 10+11	1979	0.788	7.0	0.287	
Aged polystyrene	1977	3.1	3.5	0.316	0.317 ± 0.003
Aged polystyrene	1977	3.1	7.0	0.319	

[a]The year of measurement distinguishes measurements made before and after the apparatus was moved to a different location.

[b]Operated single sided.

[c]Data obtained with 18-in. guarded hot plate (horizontal heat flow) by National Research Council in Canada. Average value in 1977–78 of all results on same sample by different methods was 0.289 ± 0.006 Btu in./h ft^2 °F.

with the precision resistor network, and the temperatures of the working surfaces were evaluated from the thermocouple readings at steady state. Spacings between the hot and cold surfaces, ΔX, were maintained by 3/8-in. balsa wood dowels (Sect. 3.2.1).

The apparent thermal conductivity (λ) was calculated from:

$$\lambda = \frac{q}{A} \left|\frac{\Delta X}{\Delta T}\right| , \tag{6}$$

where

q is one-half of the power supplied to the central metering section, Btu/h;

ΔX is the average thickness of the two samples between the hot and cold surfaces, in.;

ΔT is the average temperature difference between the hot and cold surfaces, °F; and

A is the area of one side of the central metering section and one-half the gap area, ft^2.

3.2.3 Variation of Apparent Thermal Conductivity with Mean Sample Temperature

Apparent thermal conductivity measurements at three different mean sample temperatures but with constant temperature differences were completed by using the apparatus and procedure already discussed. By controlling the surface temperature of the cooling units at different temperatures the apparent thermal conductivity can be measured at various mean sample temperatures. Apparent thermal conductivity values at mean sample temperatures of 0, 75, and 150°F and temperature difference of 50°F are shown in Fig. 8 for ten samples. The test density at which the measurements were made was determined from thickness and density measurements given in Appendix C except for the entry coded 1206-4a, which is from Appendix E. The apparent thermal conductivites shown in Fig. 8 are for the listed test thicknesses. The data are tabulated in Appendix E.

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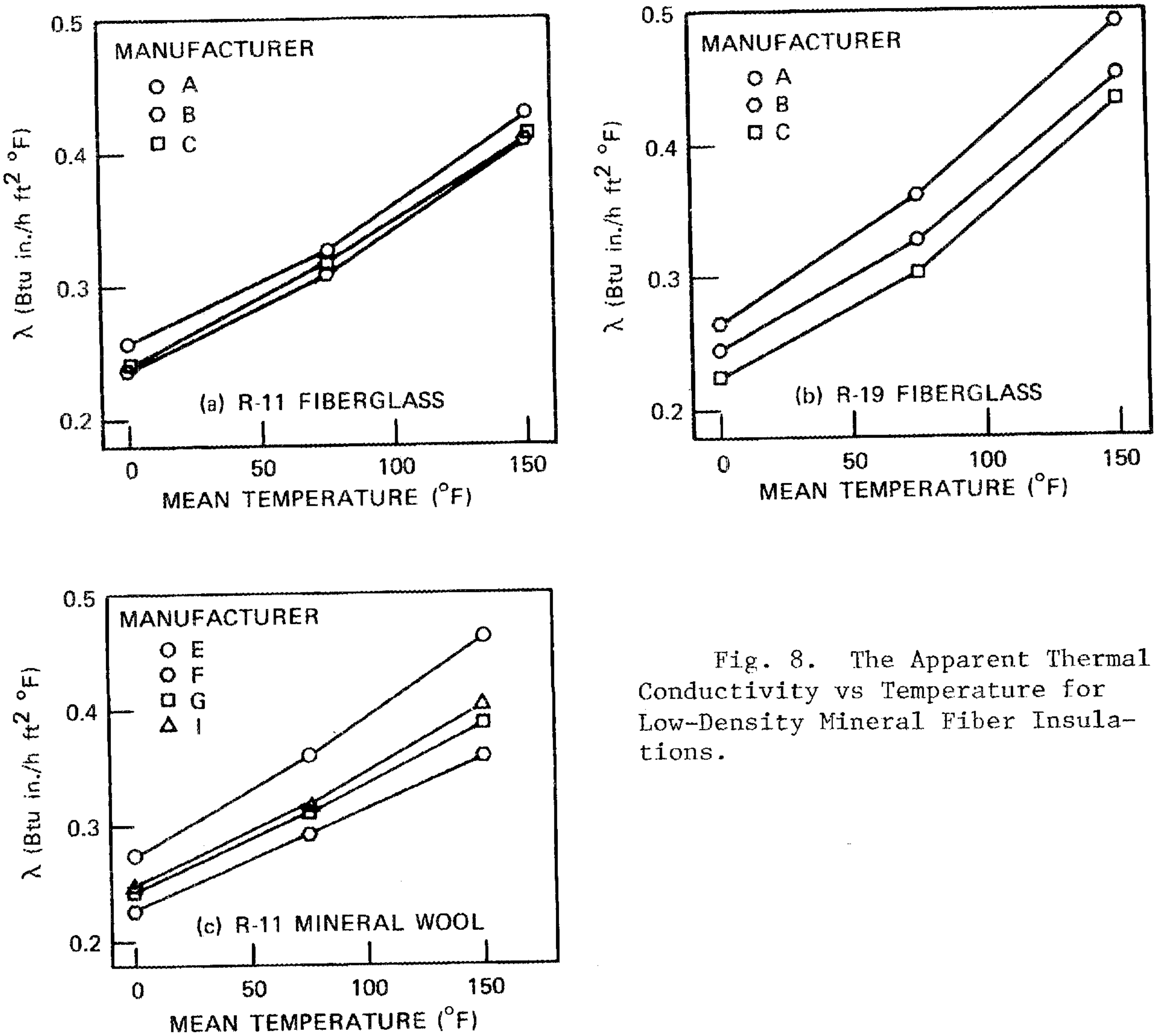

Fig. 8. The Apparent Thermal Conductivity vs Temperature for Low-Density Mineral Fiber Insulations.

In all cases the insulation showed a regular increase in λ (decrease in R-value) with increase in mean temperature or, alternatively, an increase in R per inch with a decrease in the mean temperature. In each case the data indicate an increase in R-value per inch of approximately 0.12 units for a 10°F decrease in mean temperature.

3.2.4 Variation of Apparent Thermal Conductivity with Temperature Difference Across Sample

A series of experiments was undertaken to determine the effect of the temperature difference, ΔT, maintained across a sample of insulation on the resulting apparent thermal conductivity value. By varying the surface temperature of the cooling units, the experiments could be performed at any temperature level and different ΔT values. Insulation specimens that were used in the density studies were used in this phase of the project. The results of the experimental work are given in Table 4.

The data show that for the entire range of ΔT employed, 6 to 106°F, the apparent thermal conductivity determined in the guarded hot plate apparatus varied less than 2%. Variations of a few degrees about the ΔT of 50°F produced negligible changes in the apparent thermal conductivity value.

Table 4. The Apparent Thermal Conductivity and Thermal Resistance of a Low-Density Fiberglass Insulation Material as a Function of Temperature Difference[a]

Temperature, °F[b]		Power (Btu/h)	Apparent Thermal Conductivity (Btu in./h ft^2 °F)	Thermal Resistance (h ft^2 °F/Btu)
Mean	Difference			
76.5	106.59	23.82	0.315	9.14
75.2	71.69	15.97	0.314	9.17
75.1	49.90	11.01	0.311	9.26
75.4	17.01	3.74	0.310	9.29
75.9	6.48	1.43	0.311	9.26

[a]Specimen code 1204-3, test density 0.659 lb/ft^3, test thickness 2.88 in. (bisected specimen).

[b]The temperature variation on the hot plate was less than 0.2°F while the temperature variation on the cold plates was less than 0.6°F.

3.2.5 Apparent Thermal Conductivity and R-Value at 75°F

A primary objective of this study was the determination of the distribution of R-values for mineral fiber batt insulations commercially available in 1977. Toward that end a series of apparent thermal conductivity measurements was made by using the specimen identified by "λ" in the Appendix C listing. A total of 105 measurements are reported for the apparent thermal conductivity and R-value determined on full-thickness samples. These measurements are at the specimen densities listed in Appendix C.

The full-thickness measurements were supplemented by 33 measurements of apparent thermal conductivity made on samples compressed to 90, 80, and 70% of nominal thickness. This additional set of data, reported in Table 5, was obtained to provide the relationship between apparent thermal conductivity and density, ρ. The constants a, b and c in

$$\lambda = a + b\rho + c/\rho \tag{7}$$

were determined from the apparent thermal conductivity measurements made on compressed samples. Equation (7) was then used to calculate the apparent thermal conductivity of a specimen at a density corresponding to nominal thickness. According to ASTM C 653-70, Eq. (7) can be used to calculate λ at densities up to 150% of the density at full recovered thickness. One set of thermal conductivity measurements at reduced thickness was made for each of the fiberglass manufacturers represented in the sample and four of the rock wool manufacturers. The results obtained for the parameters a, b, and c are given in Table 6.

Thermal resistance, R-values, at nominal thickness were computed by using the parameters from Table 6 in the following way. Apparent thermal conductivity at full recovered thickness was measured as indicated in Sect. 3.2.2. For the specimens of insulations represented in Table 6 the thermal conductivity was calculated from the given parameters and the density at nominal thickness. The R-value was then computed with

$$R = T_N/\lambda_N \ . \tag{8}$$

Table 5. Apparent Thermal Conductivity Versus Density for 11 Samples of Low-Density Fiberglass and Rock Wool Insulation Materials

Specimen Code	Compression (% of Nominal Thickness)	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$
			Fiberglass			
1101-1	90	0.721	3.15	49.3	9.85	0.308
	80	0.811	2.80	50.7	10.84	0.293
	70	0.927	2.45	50.6	11.65	0.276
1107-1	90	0.601	3.15	50.5	10.42	0.318
	80	0.676	2.80	49.1	10.89	0.304
	70	0.773	2.45	49.4	11.82	0.287
1107-2B[a]	100	0.656	1.44	50.0	21.21	0.299
	90	0.729	1.30	49.4	22.51	0.290
	80	0.820	1.15	50.0	24.60	0.277
	70	0.937	1.01	50.8	27.02	0.263
1111-1	90	0.534	3.15	49.3	9.85	0.308
	80	0.601	2.80	51.0	10.94	0.294
	70	0.687	2.45	48.4	11.30	0.280
1202-1	90	0.651	5.40	49.4	6.11	0.327
	80	0.732	4.80	51.1	6.81	0.313
	70	0.837	4.20	49.6	7.21	0.299
1204-2	90	0.649	5.40	50.5	5.67	0.297
	80	0.730	4.80	50.5	6.13	0.285
	70	0.834	4.20	49.4	6.56	0.273
1207-2	90	0.483	5.40	49.0	6.43	0.347
	80	0.544	4.80	50.5	7.18	0.334
	70	0.621	4.20	51.5	8.07	0.322
			Rock Wool			
1302-1	90	1.753	3.15	50.9	11.22	0.340
	80	1.972	2.80	50.6	12.04	0.326
	70	2.254	2.45	49.3	12.58	0.306
1304-1	90	2.153	3.15	50.6	9.45	0.288
	80	2.422	2.80	50.6	10.19	0.276
	70	2.769	2.45	49.1	10.85	0.265
1306-1	90	2.247	2.70	50.0	10.97	0.290
	80	2.528	2.40	49.4	11.69	0.278
	70	2.889	2.10	49.3	12.71	0.265
1309-2	90	1.813	3.15	50.0	9.79	0.302
	80	2.040	2.80	50.8	10.71	0.289
	70	2.331	2.45	50.2	11.68	0.279

[a]This specimen is from package identified by the code 1107-2.

Table 6. The Calculated Constants of 11 Samples of Low-Density Fiberglass and Rock Wool Insulation Materials in Accordance with ASTM C 653-70[a]

Material	Specimen Code	Constants		
		a[b]	*b*	*c*
Fiberglass	1101-1	0.2895	−0.07615	0.05293
	1107-1	0.3647	−0.1354	0.02083
	1107-2B	0.3542	−0.11065	0.01158
	1111-1	0.1843	−0.00167	0.06653
	1202-1	0.1937	0.00494	0.08472
	1204-2	0.1895	−0.000447	0.06998
	1207-2	0.1853	0.04460	0.06772
Rock Wool	1302-1	0.5693	−0.09540	−0.10879
	1304-1	0.1186	0.01342	0.30260
	1306-1	0.2421	−0.01258	0.17110
	1309-2	0.00870	0.04580	0.38121

[a]Constants of Eq. (7).

[b]These constants give thermal conductivity in Btu·in./$ft^2 \cdot h \cdot {}^\circ F$.

For a fiberglass specimen not listed in Table 6 a modified ASTM calculation procedure was followed, in which the measured apparent thermal conductivity at recovered thickness was used to calculate the constant a of Eq. (7) with b and c fixed at values from Table 6. For rock wool specimens not listed in Table 6, b and c were made equal to those for one of the listed specimens chosen to match as closely as possible the nominal thickness, density, and measured apparent thermal conductivity.

A relationship between apparent thermal conductivity and density can also be obtained by estimating a, b, and c in Eq. (7) by the method of least squares by using all the 75°F thermal conductivity data in Tables 5, 7, 8, and 9. Estimates of the constants in Eq. (7) have been obtained by using data for R-11 and for R-19 fiberglass for the individual manufacturers and for the 3- and 3.5-in.-thick rock wool insulations. Estimates were also obtained for the complete sets of R-11 and R-19 fiberglass.

Table 7. The Apparent Thermal Conductivity and Thermal Resistance of 48 Samples of R-11 Low-Density Fiberglass Insulation Materials at 75°F and Full Thickness

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	Thermal Resistance $\left(\frac{h\ ft^2\ °F}{Btu}\right)$
1101-1	0.550	4.13	49.8	8.52	0.346	11.94
1101-2	0.571	4.03	50.1	9.80	0.386	10.44
1101-3	0.610	4.02	50.9	9.05	0.350	11.49
1102-1	0.612	3.81	49.6	8.96	0.337	11.31
1102-1a	0.660	4.20	50.1	7.85	0.322	13.04
1102-2	0.593	3.92	50.7	9.30	0.352	11.14
1102-3	0.775	3.50	49.9	9.82	0.337	10.39
1103-1	0.745	3.50	50.9	9.27	0.312	11.22
1103-2	0.706	3.38	50.7	9.65	0.315	10.73
1103-3	0.489	3.11	49.2	11.54	0.357	8.71
1103-3a	0.512	2.85	49.8	13.03	0.365	7.81
1104-1	0.637	3.30	51.0	10.42	0.330	10.00
1104-2	0.478	3.69	49.7	10.51	0.382	9.66
1104-3	0.526	4.17	50.9	9.08	0.364	11.46
1105-1	0.521	3.85	50.6	10.18	0.379	10.16
1105-2	0.530	3.54	49.7	10.35	0.361	9.81
1105-3	0.582	3.76	50.9	9.71	0.351	10.71
1106-1	0.694	3.30	50.6	10.24	0.327	10.09
1106-2	0.474	4.17	50.3	9.29	0.377	11.06
1106-3	0.510	3.91	50.6	9.02	0.341	11.47
1106-3a	0.565	4.10	50.1	8.64	0.346	11.85
1107-1	0.531	3.57	50.9	9.73	0.334	10.69
1107-1a	0.551	3.80	49.4	9.06	0.341	11.14
1107-2	0.765	2.79	49.2	10.63	0.295	9.46
1107-3	0.615	3.83	49.6	8.97	0.339	11.30
1108-1	0.484	4.33	49.7	8.79	0.375	11.55
1108-2	0.545	3.53	50.0	10.42	0.360	9.81
1108-3	0.512	3.79	49.7	10.05	0.375	10.11
1109-1	0.588	3.21	50.8	11.54	0.357	8.99
1109-2	0.557	3.78	50.8	9.61	0.350	10.80
1109-3	0.554	4.12	49.7	8.60	0.349	11.81
1110-1	0.564	4.23	50.5	8.61	0.353	11.98
1110-2	0.502	3.72	50.7	8.35	0.300	12.40
1110-3	0.501	3.72	49.1	9.20	0.341	10.91
1111-1	0.377	4.46	50.3	8.32	0.361	12.35
1111-3	0.391	4.11	49.2	9.10	0.372	11.05
1112-1	0.380	3.30	49.7	11.94	0.388	8.51
1112-2	0.377	3.88	49.8	10.33	0.394	9.85
1112-3	0.332	3.69	50.0	12.01	0.434	8.50
1113-1	0.460	4.30	48.4	8.28	0.360	11.94
1113-2	0.389	4.37	49.5	8.86	0.383	11.41
1113-3	0.378	4.31	49.4	8.38	0.358	12.04
1114-2	0.406	4.71	51.3	8.19	0.368	12.80
1114-3	0.418	4.39	50.7	8.56	0.363	12.09
1115-1	0.407	4.14	50.6	9.11	0.365	11.34
1115-1a	0.435	3.84	48.9	9.39	0.361	10.64
1115-2	0.438	4.20	49.3	8.42	0.351	11.97
1115-2a	0.432	3.72	49.8	9.68	0.354	10.51

Table 8. The Apparent Thermal Conductivity and Thermal Resistance of 30 Samples of R-19 Low-Density Fiberglass Insulation Materials at 75°F and Full Thickness

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	Thermal Resistance $\left(\frac{h\ ft^2\ °F}{Btu}\right)$
1201-1	0.652	6.44	49.4	5.34	0.341	18.89
1201-2	0.732	7.22	49.1	4.32	0.311	23.22
1201-3	0.763	4.98	50.0	6.50	0.317	15.71
1202-1	0.651	5.40	49.4	6.11	0.327	16.51
1202-2	0.655	6.11	49.4	5.93	0.359	17.02
1202-3	0.529	6.41	49.3	5.80	0.369	17.37
1202-4	0.647	6.22	49.7	5.62	0.344	18.08
1202-5	0.597	6.46	50.2	5.43	0.342	18.89
1203-1	0.552	6.01	50.0	6.83	0.402	14.95
1203-2	0.729	4.93	50.5	6.82	0.326	15.12
1203-3	0.817	4.30	50.5	7.25	0.302	14.24
1204-1	0.574	6.06	49.7	5.81	0.347	17.46
1204-2	0.610	5.74	49.4	5.29	0.301	19.07
1204-3	0.596	6.00	49.1	5.62	0.336	17.86
1205-1	0.671	6.00	50.1	5.49	0.322	18.63
1205-2	0.641	5.78	50.6	5.69	0.318	18.18
1205-3	0.563	5.99	50.6	6.02	0.349	17.16
1206-1	0.630	6.01	50.3	5.76	0.337	17.83
1206-2	0.744	6.05	50.6	5.43	0.318	19.03
1206-3	0.685	4.84	49.6	6.66	0.318	15.22
1206-4	0.651	5.62	50.7	6.14	0.333	16.88
1207-1	0.365	6.93	49.4	5.65	0.388	17.86
1207-2	0.405	6.43	49.3	5.67	0.362	17.76
1207-3	0.323	6.63	49.5	6.22	0.408	16.25
1208-1	0.405	6.32	50.7	6.47	0.395	16.00
1208-2	0.366	6.21	50.3	7.41	0.448	13.86
1208-3	0.378	6.60	50.1	6.17	0.398	16.58
1209-1	0.419	5.50	50.9	7.70	0.407	13.51
1209-2	0.541	6.88	49.5	5.23	0.356	19.33
1209-3	0.655	5.44	50.6	6.12	0.322	16.89

Table 9. The Apparent Thermal Conductivity and Thermal Resistance of 27 Samples of R-11 Rock Wool Insulation Materials at 75°F and Full Thickness

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ °\text{F}}\right)$	Thermal Resistance $\left(\frac{\text{h ft}^2\ °\text{F}}{\text{Btu}}\right)$
1301-1	2.163	2.72	49.5	12.19	0.328	8.29
1301-2	1.981	2.83	49.3	10.61	0.298	9.50
1301-3	2.723	2.87	49.3	10.39	0.296	9.70
1302-1	1.578	3.50	50.3	10.54	0.359	9.75
1302-2	1.967	3.22	49.6	9.66	0.307	10.49
1302-3	1.751	2.36	49.5	13.76	0.321	7.35
1303-1	2.344	2.99	50.7	11.71	0.338	8.85
1303-2	1.598	3.20	50.2	10.48	0.327	9.79
1303-3	1.687	3.67	50.5	8.88	0.316	11.61
1304-1	2.068	3.28	49.4	9.05	0.294	11.16
1304-2	2.084	2.91	49.8	9.51	0.272	10.70
1304-3	1.834	2.97	50.8	10.16	0.291	10.21
1305-1	2.010	2.91	49.7	10.29	0.295	9.86
1305-2	2.223	2.76	49.3	10.44	0.286	9.65
1305-3	2.084	2.85	50.6	10.87	0.300	9.50
1306-1	1.932	3.14	49.7	10.06	0.311	10.10
1306-2	1.978	4.11	50.0	7.56	0.304	13.52
1306-3	1.788	4.32	50.7	7.50	0.313	13.80
1307-1	2.061	2.87	49.9	10.97	0.309	9.29
1307-2	1.811	2.97	50.4	11.44	0.330	9.00
1307-3	2.688	2.46	50.5	12.28	0.293	8.40
1308-1	1.750	3.27	49.3	9.58	0.311	10.51
1308-2	2.126	3.46	49.9	8.28	0.281	12.31
1308-3	1.602	3.32	49.1	9.37	0.310	10.71
1309-1	1.441	3.16	49.6	10.55	0.329	9.60
1309-2	1.646	3.47	50.4	9.44	0.318	10.91
1309-3	2.051	3.03	50.1	10.00	0.296	10.24

This approach of using all the available data to produce relationships between the apparent thermal conductivity and the density has the advantage of providing a measure of error variance. Apparent thermal conductivities and R-values at nominal thickness were computed from these equations and are reported along with the values obtained by the modified procedure that was described in preceding paragraphs.

The apparent thermal conductivity results are organized as follows. Tables 7 through 9 contain the apparent thermal conductivities measured at full recovered thickness and the corresponding R-value at full recovered thickness. Tables 10 through 12 contain apparent thermal conductivities at nominal thickness calculated from the measured values by means of Eq. (7). Three sets of numbers are reported for the fiberglass insulation. The column headed with "ASTM Modified Method" refers to calculations involving the adjustment of parameter a in Eq. (7). The column headed "Single-Manufacturer Data" refers to least squares determination of the constants in Eq. (7) by using data from a single manufacturer. The column headed "Composite Data" contains values obtained by using all the data for R-11 or R-19 fiberglass to determine the constants in Eq. (7). Two sets of numbers are shown for the rock wool data. One column contains thermal conductivities at nominal thickness obtained by the modified method. The second set of thermal conductivity values was obtained by using constants estimated from all the 3-in. or all the 3.5-in. rock wool data. A complete tabulation of the least squares parameter estimates is contained in Appendix F. Plots of the apparent thermal conductivity at 75°F vs density have been included in Appendix F.

3.3 Analysis of the Thermal Resistance Results

The major findings of the study are based on the data contained in Tables 7 through 12, which contain R-values for the mineral fiber insulations that were tested. The thermal resistance values reported in Tables 7 through 9 were obtained directly from guarded hot plate measurements. Since the apparent thermal conductivity, λ, was measured at approximately full recovered thickness (test thickness), it was necessary

Table 10. Apparent Thermal Conductivities and R-Values of 48 Samples of R-11 Low-Density Fiberglass Insulation Materials at Nominal Thickness

Specimen Code	Nominal Density (lb/ft^3)	Nominal Thickness (in.)	Properties Adjusted to Nominal Thickness by Different Methods: ASTM Modified Method, Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ {}^\circ\text{F}}\right)$	ASTM Modified Method, R-Value $\left(\frac{\text{h ft}^2\ {}^\circ\text{F}}{\text{Btu}}\right)$	Single-Manufacturer Data[a], Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ {}^\circ\text{F}}\right)$	Single-Manufacturer Data[a], R-Value $\left(\frac{\text{h ft}^2\ {}^\circ\text{F}}{\text{Btu}}\right)$	Composite Data[b], Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ {}^\circ\text{F}}\right)$	Composite Data[b], R-Value $\left(\frac{\text{h ft}^2\ {}^\circ\text{F}}{\text{Btu}}\right)$
1101-1	0.650	3.50	0.324	10.80	0.335	10.44	0.324	10.82
1101-2	0.658	3.50	0.367	9.54	0.333	10.50	0.322	10.87
1101-3	0.701	3.50	0.332	10.54	0.324	10.81	0.313	11.17
1102-1	0.666	3.50	0.326	10.74	0.332	10.56	0.320	10.93
1102-1a	0.792	3.50	0.299	11.71	0.304	11.50	0.295	11.86
1102-2	0.665	3.50	0.336	10.42	0.332	10.55	0.321	10.92
1102-3	0.775	3.50	0.337	10.39	0.308	11.37	0.299	11.72
1103-1	0.745	3.50	0.312	11.22	0.314	11.13	0.305	11.49
1103-2	0.682	3.50	0.319	10.97	0.328	10.67	0.317	11.04
1103-3	0.435	3.50	0.375	9.33	0.388	9.02	0.369	9.48
1103-3a	0.417	3.50	0.396	8.84	0.393	8.90	0.373	9.38
1104-1	0.601	3.50	0.338	10.36	0.346	10.11	0.334	10.49
1104-2	0.503	3.50	0.375	9.33	0.370	9.46	0.354	9.88
1104-3	0.627	3.50	0.340	10.29	0.340	10.28	0.328	10.66
1105-1	0.573	3.50	0.366	9.56	0.353	9.92	0.339	10.31
1105-2	0.536	3.50	0.359	9.75	0.362	9.67	0.347	10.09
1105-3	0.626	3.50	0.341	10.26	0.341	10.28	0.328	10.66
1106-1	0.655	3.50	0.334	10.48	0.319	10.98	0.323	10.85
1106-2	0.565	3.50	0.358	9.78	0.340	10.30	0.341	10.26
1106-3	0.570	3.50	0.329	10.64	0.339	10.34	0.340	10.29
1106-3a	0.662	3.50	0.327	10.70	0.317	11.04	0.321	10.90
1107-1	0.541	3.50	0.332	10.54	0.346	10.13	0.346	10.11
1107-1a	0.599	3.50	0.331	10.57	0.332	10.55	0.334	10.48
1107-2	0.610	3.50	0.323	10.84	0.329	10.64	0.332	10.55
1107-3	0.672	3.50	0.329	10.64	0.315	11.12	0.319	10.97
1108-1	0.599	3.50	0.351	9.97	0.332	10.55	0.334	10.48
1108-2	0.550	3.50	0.359	9.75	0.343	10.19	0.344	10.17
1108-3	0.554	3.50	0.366	9.56	0.342	10.22	0.343	10.19
1109-1	0.539	3.50	0.366	9.56	0.346	10.12	0.346	10.12
1109-2	0.602	3.50	0.341	10.26	0.331	10.57	0.333	10.51
1109-3	0.652	3.50	0.330	10.61	0.319	10.96	0.323	10.84
1110-1	0.681	3.50	0.331	10.57	0.313	11.19	0.317	11.04
1110-2	0.534	3.50	0.293	11.95	0.347	10.08	0.348	10.06
1110-3	0.532	3.50	0.334	10.48	0.348	10.07	0.348	10.06
1111-1	0.481	3.50	0.323	10.84	0.333	10.53	0.359	9.75
1111-3	0.459	3.50	0.347	10.09	0.341	10.25	0.364	9.62
1112-1	0.314	4.00	0.425	9.41	0.435	9.19	0.398	10.05
1112-2	0.366	4.00	0.399	10.03	0.392	10.19	0.385	10.39
1112-3	0.306	4.00	0.451	8.87	0.443	9.03	0.400	10.00
1113-1	0.565	3.50	0.333	10.51	0.305	11.46	0.341	10.26
1113-2	0.486	3.50	0.349	10.03	0.331	10.59	0.358	9.78
1113-3	0.465	3.50	0.325	10.77	0.339	10.33	0.362	9.67
1114-2	0.478	4.00	0.343	11.66	0.334	11.99	0.360	11.11
1114-3	0.459	4.00	0.349	11.46	0.341	11.71	0.364	10.99
1115-1	0.481	3.50	0.340	10.29	0.333	10.53	0.359	9.75
1115-1a	0.478	3.50	0.347	10.09	0.334	10.49	0.360	9.72
1115-2	0.460	4.00	0.344	11.63	0.341	11.73	0.364	10.99
1115-2a	0.402	4.00	0.366	10.93	0.370	10.82	0.377	10.61

[a]Constants of Eq. (7) obtained by least squares fit of data on a single manufacturer's product.

[b]Constants of Eq. (7) obtained by least squares fit of composite data.

Table 11. Apparent Thermal Conductivities and R-Values of 30 Samples of R-19 Low-Density Fiberglass Insulation Materials at Nominal Thickness

Specimen Code	Nominal Density (lb/ft^3)	Nominal Thickness (in.)	Properties Adjusted to Nominal Thickness by Different Methods					
			ASTM Modified Method		Single-Manufacturer Data[a]		Composite Data[b]	
			Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	R-Value $\left(\frac{h\ ft^2\ °F}{Btu}\right)$	Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	R-Value $\left(\frac{h\ ft^2\ °F}{Btu}\right)$	Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	R-Value $\left(\frac{h\ ft^2\ °F}{Btu}\right)$
1201-1	0.700	6.00	0.332	18.07	0.326	18.41	0.318	18.88
1201-2	0.880	6.00	0.292	20.55	0.293	20.48	0.282	21.27
1201-3	0.633	6.00	0.339	17.70	0.344	17.42	0.332	18.06
1202-1	0.586	6.00	0.341	17.60	0.361	16.64	0.343	17.50
1202-2	0.667	6.00	0.357	16.81	0.334	17.94	0.325	18.47
1202-3	0.566	6.00	0.359	16.71	0.368	16.29	0.348	17.26
1202-4	0.671	6.00	0.339	17.70	0.333	18.00	0.324	18.52
1202-5	0.643	6.00	0.332	18.07	0.341	17.58	0.330	18.18
1203-1	0.553	6.00	0.402	14.93	0.374	16.05	0.351	17.11
1203-2	0.599	6.00	0.351	17.09	0.356	16.87	0.340	17.66
1203-3	0.585	6.00	0.342	17.54	0.361	16.63	0.343	17.49
1204-1	0.580	6.00	0.346	17.34	0.338	17.73	0.344	17.43
1204-2	0.584	6.00	0.306	19.61	0.337	17.79	0.343	17.48
1204-3	0.596	6.00	0.336	17.86	0.334	17.97	0.341	17.62
1205-1	0.671	6.00	0.332	18.63	0.314	19.09	0.324	18.52
1205-2	0.618	6.00	0.322	18.63	0.328	18.30	0.336	17.88
1205-3	0.562	6.00	0.349	17.19	0.344	17.46	0.348	17.22
1206-1	0.631	6.00	0.337	17.80	0.324	18.50	0.333	18.04
1206-2	0.750	6.00	0.317	18.93	0.296	20.27	0.307	19.51
1206-3	0.552	6.00	0.343	17.49	0.347	17.31	0.351	17.10
1206-4	0.610	6.00	0.340	17.65	0.330	18.18	0.337	17.79
1207-1	0.389	6.50	0.378	17.20	0.395	16.45	0.396	16.41
1207-2	0.401	6.50	0.363	17.91	0.391	16.64	0.392	16.57
1207-3	0.329	6.50	0.404	16.09	0.419	15.51	0.418	15.56
1208-1	0.394	6.50	0.399	16.29	0.393	16.53	0.395	16.48
1208-2	0.350	6.50	0.456	14.25	0.410	15.84	0.410	15.87
1208-3	0.384	6.50	0.395	16.46	0.397	16.38	0.398	16.34
1209-1	0.355	6.50	0.433	15.01	0.408	15.92	0.408	15.94
1209-2	0.573	6.50	0.350	18.57	0.337	19.27	0.346	18.79
1209-3	0.548	6.50	0.337	19.29	0.344	18.88	0.352	18.47

[a]Constants of Eq. (7) obtained by least squares fit of data on a single manufacturer's product.

[b]Constants of Eq. (7) obtained by least squares fit of composite data.

Table 12. Apparent Thermal Conductivities and R-Values of 27 Samples of R-11 Rock Wool Insulation Materials at Nominal Thickness

Specimen Code	Nominal Density (lb/ft^3)	Nominal Thickness (in.)	Properties Adjusted to Nominal Thickness by Different Methods			
			ASTM Modified Method		Composite Data[a]	
			Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	R-Value $\left(\frac{h\ ft^2\ °F}{Btu}\right)$	Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	R-Value $\left(\frac{h\ ft^2\ °F}{Btu}\right)$
1301-1	1.962	3.00	0.339	8.85	0.309	9.72
1301-2	1.870	3.00	0.304	9.87	0.312	9.62
1301-3	2.605	3.00	0.300	10.00	0.285	10.51
1305-1	1.950	3.00	0.298	10.07	0.309	9.71
1305-2	2.045	3.00	0.295	10.17	0.306	9.82
1305-3	1.980	3.00	0.306	9.80	0.308	9.74
1306-1	2.022	3.00	0.306	9.80	0.306	9.79
1306-2	2.710	3.00	0.271	11.07	0.282	10.65
1306-3	2.575	3.00	0.274	10.95	0.287	10.47
1307-1	1.972	3.00	0.314	9.55	0.308	9.74
1307-2	1.793	3.00	0.331	9.06	0.315	9.54
1307-3	2.204	3.00	0.313	9.58	0.300	10.01
1302-1	1.578	3.50	0.359	9.75	0.325	10.78
1302-2	1.810	3.50	0.318	11.00	0.313	11.17
1302-3	1.180	3.50	0.346	10.12	0.344	10.17
1303-1	2.003	3.50	0.363	9.64	0.304	11.52
1303-2	1.461	3.50	0.333	10.51	0.330	10.59
1303-3	1.769	3.50	0.311	11.25	0.315	11.10
1304-1	1.938	3.50	0.302	11.59	0.307	11.40
1304-2	1.732	3.50	0.297	11.78	0.317	11.04
1304-3	1.556	3.50	0.317	11.04	0.326	10.74
1308-1	1.635	3.50	0.321	10.90	0.322	10.87
1308-2	2.102	3.50	0.282	12.41	0.299	11.71
1308-3	1.519	3.50	0.319	10.97	0.328	10.68
1309-1	1.301	3.50	0.351	9.97	0.338	10.35
1309-2	1.632	3.50	0.319	10.97	0.322	10.87
1309-3	1.776	3.50	0.312	11.22	0.315	11.11

[a]Constants of Eq. (7) obtained by least squares fit of composite data.

to use a relationship between density, ρ, and λ to calculate apparent thermal conductivities and R-values at densities corresponding to nominal (label) thickness.

The method outlined in ASTM C 653-70 for calculating $\lambda(\rho)$ is not well suited for this since λ at varying ρ values was not obtained for every product line represented in the data set. It was necessary, therefore, to modify the ASTM C 653-70 procedure. Three calculational schemes for obtaining $\lambda(\rho)$ were discussed in Sect. 3.2.5, and tabular results were given. A number of additional schemes could be used. For example, the parameter c in Eq. (7) could be used to adjust between product lines rather than the parameter a used in the present study. The results of such a calculation fall within the pattern of R-values included in the report.

The calculated R-values in Tables 10 through 12 show variations that depend on the calculation method used. The differences between the methods decrease when statistics for groups of measurements are examined. Since one objective of the study was a sampling of the marketplace to address the question of R-values of available insulation materials, the particular choice of method of adjusting λ with ρ is of diminished importance. This report does not contain a recommendation for a procedure for adjusting with confidence the λ value for a particular insulation sample.

The analysis of the data reported starts with a determination of sample means and standard deviations using Eqs. (3) and (4). The statistics for various subsets of the data collection are listed in Table 13. The discussion of the data that follows is in terms of R-values since insulation materials are commonly marketed this way.

The mean R-values in Table 13 represent one measure of the thermal resistance value to be expected for a random sample from the population studied. The sampling plan did not consider the relative market share of the various manufacturers or of their different processes. All mean R-values at nominal thickness by manufacturer were within 10% of the manufacturers' stated R-values of either 11 or 19. All the means calculated were below the claimed R-value with the value for 3-in. R-11 rock wool obtained for a relatively small sample being significantly lower than the advertised value.

Table 13. Sample Means and Standard Deviations for R-Values at Nominal Thickness[a]

Sample Description	Number of Measurements in the sample	Values Based on ASTM Modified Method		Values Based on Single-Manufacturer Data		Values Based on Composite Data	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
R-11 Fiberglass							
Manufacturer A	17	10.24	0.758	10.30	0.739	10.69	0.706
B	14	10.47	0.812	10.63	0.879	10.19	0.544
C	17	10.41	0.579	10.53	0.394	10.46	0.342
Composite	48	10.36	0.708	10.48	0.687	10.47	0.576
R-19 Fiberglass							
Manufacturer A	11	17.52	1.34	17.48	1.25	18.22	1.16
B	9	16.79	1.63	16.82	1.33	16.71	1.14
C	10	18.11	0.793	18.26	0.877	17.86	0.713
Composite	30	17.50	1.35	17.54	1.27	17.65	1.18
R-11 Rock Wool							
3-in. batts	12	9.90	0.649			9.94	0.381
3.5-in. batts	15	10.87	0.771			10.94	0.420

[a]The numbers in this table were computed from a nationwide sampling of insulations. No attempt has been made to weight the individual data elements to account, for example, for the fact that the fraction of the market commanded by a given manufacturer varies.

Table 14 contains numbers that specify intervals in which with 99% confidence it can be stated that the means from additional samples of the same size will fall. These values are viewed as one estimate of an interval in which the population mean of R-value at nominal thickness resides. The entries in the last column in Table 14 show that the 99% confidence intervals about the mean do not include the label R-value for three of the four classes of insulation tested. Two entries showing data for a single manufacturer show intervals that include the label R-value, while three entries are for intervals that include values below the minimum acceptable value (90% of label R-value). Intervals in which the population mean is anticipated have been constructed for each of the three calculation methods used in the study in order to demonstrate the conclusion that the position of the mean population R-value at nominal thickness is relatively insensitive to the calculation method chosen.

Table 14. Estimates of 99% Confidence Intervals for the Population Means of the R-Value at Nominal Thickness[a]

	ASTM Modified Method	Single-Manufacturer Data	Intervals Based on Composite Data
R-11 Fiberglass			
Manufacturer A	9.70–10.78	9.77–10.82	10.19–11.19
B	9.79–11.14	9.90–11.36	9.73–10.64
C	10.00–10.82	10.25–10.81	10.21–10.70
Composite	10.09–10.63	10.21–10.75	10.25–10.69
R-19 Fiberglass			
Manufacturer A	16.24–18.80	16.29–18.67	17.11–19.33
B	14.97–18.61	15.16–18.48	15.44–17.98
C	17.30–18.93	17.36–19.16	17.13–18.59
Composite	16.82–18.17	16.90–18.18	17.06–18.24
R-11 Rock Wool			
3-in. batts	9.32–10.48		9.60–10.28
3.5-in. batts	10.28–11.46		10.69–11.19

[a]Estimates of either (1) additional sampling of the same size or (2) the true population mean.

The R-values at nominal thickness as determined by the "Composite Calculation" have been used to discuss the distribution of R-values for a given type of insulating material. The following observations about the distribution of R-values for the composite R-11 fiberglass, R-19 fiberglass, R-11 rock wool (3 in. thick), and R-11 rock wool (3.5 in. thick) are based on the assumption that the R-value data for each type of insulation are normally distributed. The R-value data were tested for normality by using a procedure outlined by Hahn and Shapiro.[1] Figure 9 contains probability plots for the four sets of data being discussed. A straight line indicates normality. The assumption that the four sets of

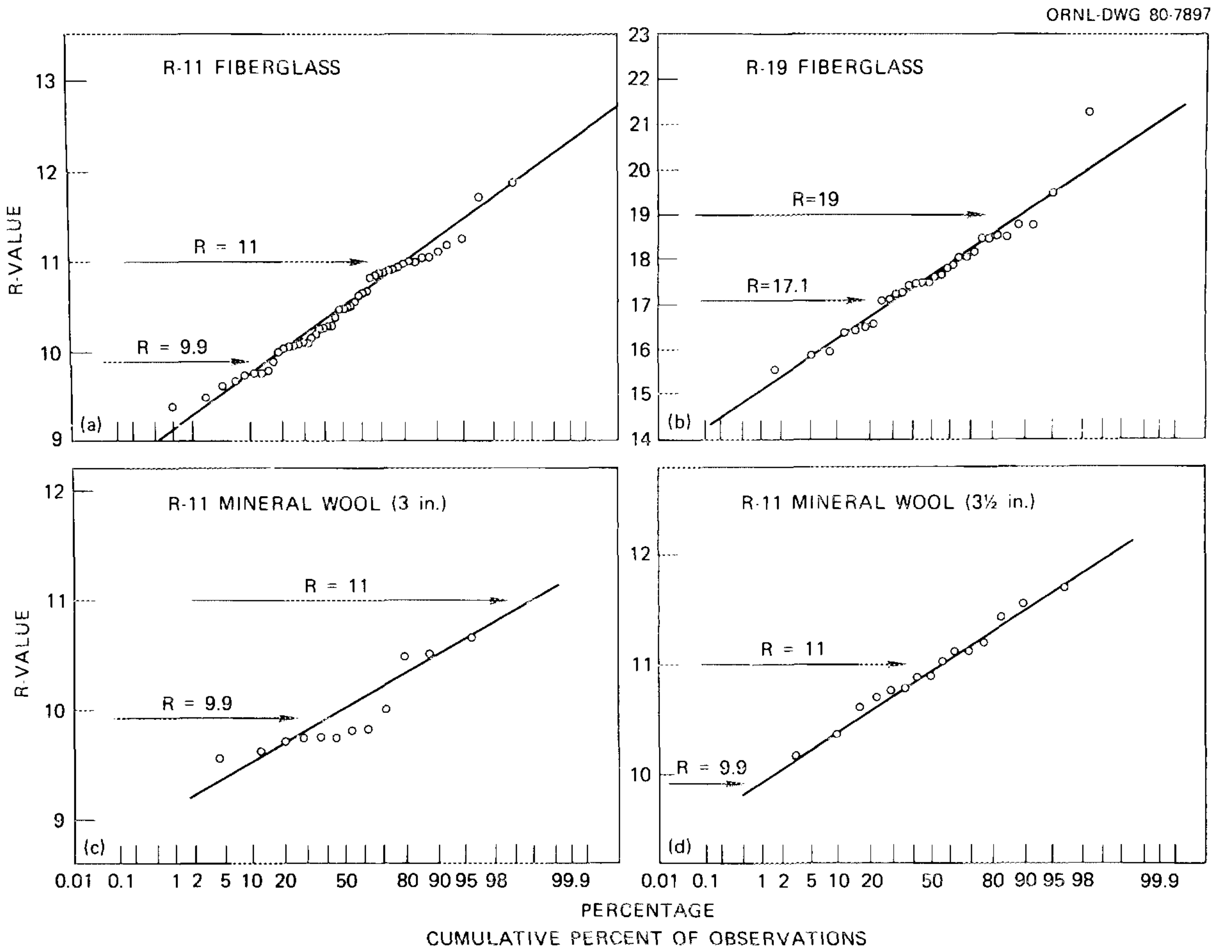

Fig. 9. Normality Test for the Apparent Thermal Conductivity Data.

R-values are normally distributed is supported by the plots in Fig. 9. The relatively small sample of 3-in.-thick rock wool insulations tends to make the normality test less conclusive for that material.

Each of the four composite data sets was treated as a random sample of a population of R-values for the type of insulation represented by the data. It is then possible to determine fractions of each given population falling above or below a particular value. A table of "Tolerance Factors for Normal Distributions" given by Bowker and Lieberman[2] was used.

The results of the analysis along with corresponding fractions of the sampling are given in Tables 15 and 16. The entries in Table 15 are for a confidence of 99%. The first column gives a lower bound on the fraction of the indicated population that will fall below the nominal R-value of 11 or 19. The second column gives a lower bound on the fraction of the population that will be above 90% of the nominal R-value, while the third column gives an upper bound on the fraction of the population falling below 90% of nominal R.

The significance of the entries in Table 15 can be discussed as follows. The number 0.71 in Column 2 for R-11 fiberglass is a lower bound on the probability of randomly picking an R-11 insulation with a value of 9.9 or greater for the R-value at nominal thickness. A nominally R-11 insulation is judged satisfactory if the measured R-value at nominal thickness is 9.9 or greater as specified by ASTM C 665. The entries in Table 16 follow directly from the data presented in the last column of Table 10.

The probability that a sample of size N contains only satisfactory material (passing) could be as low as X^N, where X is an appropriate entry from the second column of numbers in Table 15. This means, for example, that if $N = 4$ the probability of failure $(1 - X^N)$ based on the present study could be as high as 0.75 for R-11 fiberglass, 0.92 for R-19 fiberglass, 0.98 for 3-in.-thick R-11 rock wool, and 0.34 for 3.5-in.-thick R-11 rock wool. The reader must understand that the preceding listed failure probabilities are upper bounds, and that the data being tested are the results of full-thickness testing.

Table 15. Fractions of Population in Specific R-Value Intervals

Type Material	1. Lower Bound on Fraction of Population Below Nominal R-Value (99% Confidence)	2. Lower Bound on Fraction of Population Above 0.9 of Nominal R-Value (99% Confidence)	3. Upper Bound on Fraction of Population Below 0.9 of Nominal R-Value (99% Confidence)
R-11 Fiberglass	0.69	0.71	0.29
R-19 Fiberglass	0.72	0.53	0.47
R-11 Rock Wool (3 in.)	0.90	0.39	0.61
R-11 Rock Wool (3.5 in.)	0.40	0.90	0.10

Table 16. Fractions of Sampling in Specific R-Value Intervals

Type Material	Fraction Below Nominal R-Value	Fraction Above 0.9 of Nominal R-Value	Fraction Below 0.9 of Nominal R-Value
R-11 Fiberglass	0.85	0.81	0.19
R-19 Fiberglass	0.93	0.77	0.23
R-11 Rock Wool (3 in.)	1.00	0.33	0.67
R-11 Rock Wool (3.5 in.)	0.53	1.00	0.00

3.4 Determination of Full-Thickness R-Values from Thin Sample Measurements

The primary purpose of the work reported in this section was to determine whether measurement techniques used for certification would yield results that are consistent with full-thickness testing. Nine specimen pairs of low-density fiberglass produced by manufacturer C were submitted to Dynatech by ORNL to make the required measurements. These specimens were removed by ORNL personnel from the original samples purchased by Dynatech for the measurements already discussed and were identified by the same code numbers. Recovered thickness and density were measured in accordance with ASTM C 167-64 along with measurements of thermal performance at 75°F. The results are presented in Tables 17 and 18. Using the modified ASTM calculation procedure outlined in Sect. 3.3, we calculated the R-values at nominal thickness, and the results are presented in Table 19.

Upon completion of the full-thickness testing, one specimen from each pair was sliced in a fashion similar to those materials submitted for certification purposes. A Dynatech representative accompanied the

Table 17. Physical Properties of Nine Samples of Low-Density Fiberglass Insulation Materials

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Test Thickness		Test Thickness	Nominal Thickness
1106-2	24.2	15.1	3.46	197.8	0.596	0.589
1106-3	24.0	16.5	3.92	236.3	0.580	0.650
1107-2	23.9	15.05	3.68	191.5	0.551	0.581
1108-1	24.85	15.15	3.75	192.3	0.519	0.556
1109-3	24.1	23.05	3.22	304.7	0.649	0.597
1204-3	23.2	23.25	6.00	541.2	0.637	0.637
1205-3	21.45	14.95	6.00	277.3	0.549	0.549
1206-3	22.05	15.2	5.10	321.3	0.716	0.609
1206-4	24.4	15.35	5.64	326.6	0.589	0.553

Table 18. Apparent Thermal Conductivity and Thermal Resistance of Nine Samples of Low-Density Fiberglass Insulation Materials Before Slicing

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ \text{°F}}\right)$	Thermal Resistance (h ft^2 °F/Btu)
1106-2	0.596	3.46	50.1	9.64	0.326	10.6
1106-3	0.580	3.92	50.2	8.58	0.328	11.9
1107-2	0.551	3.22	49.9	10.86	0.343	9.4
1108-1	0.519	3.75	49.8	9.50	0.350	10.7
1109-3	0.649	3.68	49.6	9.53	0.346	10.6
1204-3	0.637	6.00	50.5	5.61	0.326	18.4
1205-3	0.549	6.00	50.2	6.03	0.353	17.0
1206-3	0.716	5.10	50.2	6.41	0.319	16.0
1206-4	0.589	5.64	50.3	5.9	0.324	17.4

Table 19. Apparent Thermal Conductivity and Thermal Resistance of Nine Samples of Low-Density Fiberglass Insulation Materials at Nominal Thickness Calculated by the Modified Method

Specimen Code	Nominal Density (lb/ft^3)	Nominal Thickness (in.)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ \text{°F}}\right)$	Thermal Resistance (h ft^2 °F/Btu)
1106-2	0.589	3.50	0.327	10.7
1106-3	0.650	3.50	0.318	11.0
1107-2	0.581	3.50	0.339	10.3
1108-1	0.556	3.50	0.344	10.2
1109-3	0.597	3.50	0.354	9.90
1204-3	0.637	6.00	0.326	18.4
1205-3	0.549	6.00	0.353	17.0
1206-3	0.609	6.00	0.334	17.98
1206-4	0.553	6.00	0.329	18.2

materials to NAHBRF* and witnessed all the specimen slicing. The specimens were cut into sections approximately 1.5 in. thick with a horizontal hand-driven band saw. The R-11 specimen materials were bisected and the R-19 specimen materials quadrisected. This was accomplished for all sliced specimens with less than a 1% change in weight.

Each bisected specimen was tested for thermal performance at 75°F. The thermal performance of the bisected specimens was calculated at nominal thickness, and these results are presented in Tables 20 and 21. Bisected R-19 specimens were separated into four individual thicknesses, and each test pair was tested individually. By following the same procedure as described earlier, the thermal performance of the R-19 fiberglass batts was calculated at nominal thickness. These two series of experimental results are presented in Tables 22 and 23.

The R-values at nominal thickness that were measured in this phase of the project will be divided into two groups for discussion. Group 1 consists of five samples of R-11 fiberglass insulation, while group 2 consists of four samples of R-19 fiberglass insulation. Several R-value determinations are available for each group. Table 24 contains values for the statistics used in the discussion.

We determined R-values for the R-11 samples based on full-thickness testing and reported them in Sect. 3.2. A second series of full-thickness apparent thermal conductivity determinations was completed on companion specimens as part of this phase of the study and used to calculate R-values at nominal thickness. Also, R-values at nominal thickness were determined from measurements performed on the bisected samples taken from one of the companion specimen pairs. The three sets of five values were regarded as samples from populations of R-11 insulation, and a "*t* test" described by Bryant[3] was used to determine if the materials were from different populations. From the statistical analysis we concluded that the two sets of R-values obtained for R-11 fiberglass specimens by full-thickness testing are equal because rejection of the hypothesis that they are equal

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*The National Association of Home Builders Research Foundation, Inc., a wholly owned subsidiary of the National Association of Home Builders.

Table 20. Apparent Measured Thermal Conductivity and Thermal Resistance of Nine Bisected Samples of Low-Density Fiberglass Insulation Materials

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ \text{°F}}\right)$	Thermal Resistance (h ft^2 °F/Btu)
1106-2	0.717	1.44	49.2	20.45	0.293	4.92
1106-3	0.852	1.35	49.2	20.10	0.270	5.00
1107-2	0.703	1.44	49.1	20.13	0.289	4.98
1108-1	0.675	1.44	49.2	20.80	0.298	4.83
1109-3	0.727	1.44	47.6	20.66	0.306	4.71
1204-3	0.659	2.88	49.9	11.01	0.311	9.26
1205-3	0.572	2.88	49.3	12.10	0.346	8.32
1206-3	0.710	2.52	49.7	12.17	0.302	8.34
1206-4	0.623	2.80	49.8	11.26	0.310	9.04

Table 21. Thermal Conductivity and Thermal Resistance of Nine Bisected Samples of Low-Density Fiberglass Insulation at Nominal Thickness Calculated by Modified Method

Specimen Code	Nominal Density (lb/ft^3)	Nominal Thickness (in.)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ \text{°F}}\right)$	Thermal Resistance (h ft^2 °F/Btu)
1106-2	0.590	3.50	0.311	11.3
1106-3	0.657	3.50	0.296	11.8
1107-2	0.578	3.50	0.306	11.4
1108-1	0.555	3.50	0.315	11.1
1109-3	0.598	3.50	0.323	10.8
1204-3	0.632	6.00	0.315	19.0
1205-3	0.549	6.00	0.350	17.2
1206-3	0.596	6.00	0.318	18.9
1206-4	0.581	6.00	0.316	19.0

Table 22. Apparent Thermal Conductivity and Thermal Resistance of Four Quardrisected Samples of Low-Density Fiberglass Insulation Materials

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature Difference (°F)	Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	Thermal Resistance ($h\ ft^2\ °F/Btu$)
1204-3 I	0.600	1.44	50.8	22.99	0.319	4.51
1204-3 II	0.716	1.44	50.0	21.42	0.302	4.77
1205-3 I	0.499	1.44	50.3	22.84	0.320	4.50
1205-3 II	0.645	1.44	49.8	22.96	0.325	4.43
1206-3 I	0.709	1.44	50.1	20.83	0.293	4.91
1206-3 II	0.667	1.08	49.4	26.82	0.287	3.76
1206-4 I	0.626	1.44	50.5	21.49	0.300	4.80
1206-4 II	0.613	1.36	49.3	22.44	0.303	4.49

Table 23. Calculated Thermal Conductivity and Thermal Resistance of Four Quadrisected Samples of Low-Density Fiberglass Insulation Materials at 6.00-in. Nominal Thickness

Specimen Code	Nominal Density (lb/ft^3)	Apparent Thermal Conductivity $\left(\frac{Btu\ in.}{h\ ft^2\ °F}\right)$	Thermal Resistance ($h\ ft^2\ °F/Btu$)
1204-3	0.632	0.314	19.1
1205-3	0.549	0.326	18.4
1206-3	0.580	0.307	19.5
1206-4	0.579	0.307	19.5

Table 24. Sample Means and Standard Deviations for the Materials Used in the Study of the Effect of Slicing on Reported R-Values

Data Set	Source of R-Values	Mean R-Value at Nominal Thickness	Sample Standard Deviation	Number of Measurements in Sample
1	reported in Sect. 3.2, R-11 fiberglass	10.37	0.4174	5
2	obtained in this section-full thickness, R-11 fiberglass	10.42	0.3916	5
3	obtained from bisected samples, R-11 fiberglass	11.29	0.3319	5
4	reported in Sect. 3.2, R-19 fiberglass	17.55	0.2445	4
5	obtained in this section-full thickness, R-19	17.91	0.5376	4
6	obtained from bisected samples	18.53	0.7892	4
7	obtained from quadrisected samples	19.15	0.4683	4

would require a level of significance greater than 0.8. Thus the mean R-value for the bisected R-11 fiberglass insulations is different from the full-thickness mean R-value because the hypothesis that they are equal is rejected at a level of significance less than 0.01.

We measured R-values for the R-19 samples examined in this section and reported them in Sect. 3.2. Companion specimens from the same sample packages were measured at full thickness as part of this phase of the study. Thermal conductivity measurements were also made on bisected specimens (about 3 in. thick) and on quadrisected specimens (about 1.5 in. thick) taken from one piece of the companion specimen pair. The results of the analysis of the data obtained for the R-19 materials can be summarized as follows. We conclude that the mean R-values from the two sets of full-thickness testing come from different populations because the hypothesis that they are equal is rejected at a level of significance greater than 0.2. The bisected and quadrisected R-19 specimens will, therefore, be compared only with the R-value data given in Table 18. We conclude that the *mean* R-value for the bisected R-19 fiberglass insulations is different from the full-thickness *mean* R-value because the hypothesis that they are equal is rejected at a level of significance greater than 0.2. We conclude that the *mean* R-value for the quadrisected R-19 insulations is different from the *mean* R-value obtained with full-thickness testing because the hypothesis that they are equal is rejected at a level of significance less than 0.02.

The overall conclusion for both the sliced R-11 and sliced R-19 insulations is that the measurement of apparent thermal conductivity made by using thin specimens yields higher R-values than those measured by using full-thickness testing. The observed increase was approximately 8% (0.9 R-value) for the bisected R-11 fiberglass insulation tested and approximately 7% (1.2 R-value) for the quadrisected R-19 fiberglass insulations tested. This phase-2 study has not resulted in a satisfactory explanation for the change in measured R-value with sample thickness. A detailed study of the observed thickness effect should include consideration of several factors:

- tendency toward high densities in sliced samples
- thermal radiation effects
- edge losses
- contact resistance
- damage due to slicing

In principle, the density effect is taken into account by measuring the apparent thermal conductivity as a function of density. Thermal radiation and edge losses would appear to decrease the apparent R-value as a sample thickness increases. The question of the magnitude of the contact resistance at the sample boundary has not been addressed in this work. The existence of a contact resistance would change the reported R-value in the observed direction. The mechanical properties of the insulations resulting from the slicing operation have changed as recognized by incomplete thickness recovery of the sliced samples, but the effect of this change on thermal resistance is uncertain.

3.5 References

1. G. J. Hahn and S. S. Shapiro, *Statistical Models in Engineering,* Wiley, New York, 1968.
2. A. H. Bowker and G. J. Lieberman, *Engineering Statistics,* Prentice-Hall, Englewood Cliffs, N. J., 1960.
3. E. C. Bryant, *Statistical Analysis,* McGraw-Hill, New York, 1966.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusions

The results of this study on full-thickness determination of R-values to ±3% using a Dynatech horizontally guarded hot plate on a sampling of 99 low-density mineral-fiber thermal insulation batts that were commercially available in 1977 support the conclusions that follow. The observations made in this study are based on a modest sample size in comparison with the magnitude of the production of the insulation industry. Sample size, however, is taken into account in the calculations of standard deviations, confidence intervals, and levels of significance. In general, the products sampled showed considerable variability in all the properties tested: dimensions, density, thermal resistance, and apparent thermal conductivity.

1. Analysis indicates that the mean R-value at nominal (label) thickness for a composite of manufacturers of R-11 and R-19 fiberglass samples and R-11 rock wool samples are below the labeled R-value. The mean R-value at nominal thickness for the four types of insulations tested (as composites) — R-11 fiberglass, R-19 fiberglass, R-11 rock wool (3 in.), and R-11 rock wool (3.5 in.) — were within 10% of the labeled R-value. The mean R-value at nominal thickness for R-19 fiberglass batts produced by one manufacturer, however, was below the minimum acceptable value of 17.1. The preceding conclusions hold for three different methods of computing the R-value at nominal thickness.

2. Analysis of the R-values at nominal thicknesses shows that the 99% confidence interval for the population mean for three of the four classes of insulation tested (as composite) does not include the label R-value. The predicted interval of the R-value mean for the R-11 rock wool (3.5-in. batts) did include the label value. The R-values from one manufacturer's insulation (treated separately) resulted in a 99% confidence interval that included the label value for both the R-11 and R-19 fiberglass products. It was also observed that the composite R-19 fiberglass mean R-value interval includes values below the minimum

acceptable values. The R-11 rock wool (3 in.) and one manufacturer's fiberglass insulation also had mean R-value prediction intervals that include numbers below 0.9 of the label value.

3. A statistical analysis of the distribution of R-values at nominal thickness showed that significant fractions of each type of material tested were below 0.9 of the label value. At the 99% confidence level the upper bounds for the population fractions below 0.9 of the label value were: 0.10 for 3.5-in. R-11 rock wool, 0.29 for R-11 fiberglass, 0.49 for R-19 fiberglass, and 0.61 for 3.0-in. R-11 rock wool.

4. An extension to ASTM C 653-70 for obtaining a relationship between apparent thermal conductivity and density, which uses a least squares fit to all of the collected data, was tested. The results using the least squares calculation shift upward from 0 to 1.2% the calculated sample means for R-value at nominal thickness for the four classes of materials tested. The use of the larger set of data, however, reduces the chance of a single faulty measurement seriously affecting the results.

5. A comparison of R-values at nominal thickness obtained with full-thickness samples with R-values at nominal thickness obtained from thin samples sliced from the insulation showed that the results obtained on thin samples yielded higher R-values. A statistical analysis of the results showed that the differences in mean R-value for nominal R-11 fiberglass are significant at the 19% level of significance, while the R-value difference for R-19 fiberglass, quadrisected versus full, is significant at the 2% level of significance.

The mean R-values obtained with slicing were increased by about 0.9 R-units on the average for R-11 fiberglass insulations and by about 1.2 R-units on the average for R-19 fiberglass insulations.

6. Experimental results for the variation of R-value with mean temperature showed an increase in R-value with decrease in temperature for mineral fiber insulations.

7. A series of tests to determine the effect of the magnitude of the temperature difference, ΔT, on the experimental results for apparent thermal conductivity resulted in the conclusion that the variation for mineral fiber insulations is less than 2% for a range of ΔT values from 6 to 107°F.

8. From the data for recovered thickness that was accumulated in this study, the mean of observed recovered thickness was seen to lie below the nominal thickness (label value) for three of the four sets of composite data examined. The range of recovered thicknesses of the fiberglass insulations tested extended about the respective mean values by approximately ±20%, while the rock wool variation was approximately ±30%. Recovered thickness data obtained by NAHBRF for R-19 fiberglass batts do not agree with the values reported as a result of this study. The NAHBRF data have been included in Appendix G.

4.2 Recommendations

1. The results of this study suggest that additional tasks should be undertaken. Sufficient testing should be completed to determine possible shifts in insulation properties since the 1977 sampling. If a small sample of current products indicates that the distribution of R-values has shifted, then a complete sampling must be undertaken to determine the current status of the marketplace. Attention should be directed toward maximum utilization of the correlations established from the 1977 data.

2. A study should be undertaken to confirm the observation that R-values obtained from measurements on thin samples of insulation are greater than R-values obtained by full-thickness testing. If the observed R-value increase is substantiated, then the certification process* currently being conducted by NAHBRF should be reexamined.

3. Every effort should be made to establish a reliable pool of insulation property data, which includes input from the insulation manufacturers.

4. The manufacturing sector should be encouraged to target production at label values and increase quality control measures.

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*Program operated by The National Association of Home Builders Research Foundation (NAHBRF), Inc., a wholly owned subsidiary of the National Association of Home Builders.

APPENDIX A

Project History and Background

Summary of Project History

	Approximate Date	Event
1.	Spring 1977	Phase 1 of project initiated at Dynatech R/D Co.
2.	January 1978	Phase 2 of project initiated at Dynatech R/D Co.
3.	Spring 1978	Dynatech R/D Co. provided initial set of Phase 1 data to ORNL
4.	July 1979	Dynatech R/D Co. provided complete set of Phase 1 and Phase 2 data to ORNL
5.	September 1979	Dynatech R/D Co. provided Draft 1 of project report to ORNL
6.	October 1979	ORNL review of Draft 1 completed. Modifications suggested in Draft 2 supplied by ORNL to Dynatech R/D Co.
7.	November 1979	Dynatech R/D Co. accepted suggested modifications. ORNL initiated internal and external review of Draft 3.
8.	December 1979	Review process initiated. Comments to be included in final report or reproduced in Appendix H.
9.	January 1980	Discussions with reviewers and additional material provided to reviewers.
10.	February 1980	Reviewer's comments received and considered.
11.	March 1980	Review process completed.
12.	April 1980	Report distributed.

Some Background on Full-Thickness Testing

Several significant events since 1976 have focused attention on the need for additional experimental and theoretical analyses of heat transfer in insulation. Some of these events are outlined below.

First, in 1976 the American Society for Testing and Materials (ASTM) approved a significant change in the ASTM C 177 specification for the standard guarded hot plate test method.[1] Among the changes, ASTM C 177-76 noted that the thermal properties of a specimen may change with specimen thickness and provided a new method to estimate the maximum thickness of specimens that can be tested in a guarded hot plate apparatus. Before this change, the maximum thickness was limited to one-third of the lateral dimension of the central section of the apparatus. Since most central sections were less than 6 in., most tests were conducted at a specimen thickness of less than 2 in. Thus, before 1976 few studies provided data sets on the specimen thickness effect, and a linear extrapolation of any available data to design thickness was employed. The C 177-76 specification, however, indicated the need for measurements on insulations at their design or full or actual-use or representative thickness. Since 1976, a number of laboratories have increased the central section dimension to 12 in. or more, which by the old specification would allow sample thickness of 6 in. or more. These devices should provide direct experimental data on the effect of thickness on measured apparent thermal conductivity.

While ASTM has endorsed the philosophy of full-thickness testing, a cautionary statement was included in C 177-76 and a position statement issued.[2] Both suggest that identification of measurement accuracy and the full-thickness effect require calibration standards, which do not exist.

Third, in 1979, the Federal Trade Commission issued a final rule on labeling and advertising of home insulation that includes prescribed standardized test methods for determining R-values of home insulation materials.[3] It states that all tests must be done at a representative thickness, which means a thickness at which the R-value per unit thickness will vary no more than ±2% with increases in thickness. The effective date of this rule was to be November 30, 1979, but this has been delayed.

This delay prompted a reexamination of the options available to industry and federal agencies that would provide an acceptable interim testing procedure. This effort was conducted by the National Bureau of Standards at the request of the Federal Trade Commission and included representatives of the thermal insulation manufacturing industry and the thermal insulation property measuring community. The NBS recommended to the FTC that the current techniques be continued until calibration standards for full thickness test techniques were available from NBS.[4]

Late in 1979, the Department of Energy Residential Conservation Service (RCS) program issued a final rule,[5] which became effective

December 7, 1979 and would recognize the FTC final rule as including requirements for thermal resistance testing. Since the RCS program is a major federal effort to encourage energy conservation measures, such as application of home insulation, this makes full-thickness testing and understanding it an important part of national energy conservation.

This recounting is far from complete but is included to indicate some of the changing background in this field.

REFERENCES

1. ASTM C 177-76, *1979 Annual Book of ASTM Standards*, Part 18, American Society for Testing and Materials, Philadelphia, pp. 19–52.
2. "C-16 Statement on Thermal Resistance of Thick, Low Density Insulations (October 25, 1978)," *ASTM Standardization News*, 7(3): 37 (March 1979).
3. Federal Trade Commission, "Trade Regulations: Labeling and Advertising of Home Insulation," Title 16, *Code of Federal Regulations*, Part 460; *Federal Register* 44(167) Part III: 50218–45 (Aug. 27, 1979).
4. E. Ambler, Director, National Bureau of Standards, official communication to M. Pertschuk, chairman, Federal Trade Commission, Nov. 19, 1979.
5. Department of Energy, "Residential Conservation Service Program," Title 10, *Code of Federal Regulations*, Part 456; *Federal Register* 44(217) Part II: 64602–727 (Nov. 7, 1979).

APPENDIX B

Specimen Code by Manufacturer and Plant

Table B1. Identification of 48 Samples of R-11 Low-Density Fiberglass Insulation Materials

Specimen Code[a]	Manufacturer	Plant	Specimen Code[a]	Manufacturer	Plant
1101-1	A	1	1107-3	C	6
1101-2	A	1	1108-1	C	6
1101-3	A	1	1108-2	C	6
1102-1	A	2	1108-3	C	6
1102-1a	A	2	1109-1	C	8
1102-2	A	2	1109-2	C	8
1102-3	A	2	1109-3	C	8
1103-1	A	3	1110-1	C	8
1103-2	A	3	1110-2	C	9
1103-3	A	2	1110-3	C	6
1103-3a	A	2	1111-1	B	10
1104-1	A	4	1111-3	B	10
1104-2	A	4	1112-1	B	11
1104-3	A	4	1112-2	B	11
1105-1	A	4	1112-3	B	11
1105-2	A	4	1113-1	B	12
1105-3	A	2	1113-2	B	12
1106-1	C	5	1113-3	B	12
1106-2	C	5	1114-2	B	13
1106-3	C	6	1114-3	B	13
1106-3a	C	6	1115-1	B	12
1107-1	C	7	1115-1a	B	12
1107-1a	C	7	1115-2	B	12
1107-2	C	7	1115-2a	B	12

[a]The codes ending with "a" are duplicate specimens from the package identified by the same numerical code without the "a."

Table B2. Identification of 30 Samples of R-19 Low-Density Fiberglass Insulation Materials

Specimen Code	Manufacturer	Plant
1201-1	A	1
1201-2	A	1
1201-3	A	4
1202-1	A	2
1202-2	A	2
1202-3	A	2
1202-4	A	2
1202-5	A	2
1203-1	A	4
1203-2	A	4
1203-3	A	4
1204-1	C	5
1204-2	C	5
1204-3	C	6
1205-1	C	7
1205-2	C	7
1205-3	C	9
1206-1	C	9
1206-2	C	9
1206-3	C	9
1206-4	C	6
1207-1	B	10
1207-2	B	10
1207-3	B	10
1208-1	B	11
1208-2	B	11
1208-3	B	11
1209-1	B	11
1209-2	B	13
1209-3	B	13

Table B3. Identification of 27 Samples of R-11 Rock Wool Insulation Materials

Specimen Code	Manufacturer	Plant
1301-1	D	14
1301-2	D	14
1301-3	D	14
1302-1	E	16
1302-2	E	16
1302-3	E	16
1303-1	E	17
1303-2	E	17
1303-3	E	17
1304-1	F	18
1304-2	F	18
1304-3	F	18
1305-1	D	15
1305-2	D	15
1305-3	D	15
1306-1	G	19
1306-2	G	19
1306-3	G	19
1307-1	H	20
1307-2	H	20
1307-3	H	20
1308-1	I	21
1308-2	I	21
1308-3	I	21
1309-1	I	21
1309-2	I	21
1309-3	I	21

APPENDIX C

Results of Thickness and Density Measurements

The results given in this appendix are reported along with the manufacturing code number listed in Appendix B. Thickness and density values are reported for four samples from a given batt. The lines in Tables C-1, C-2, and C-3 identified with a λ contain the average of two thickness and density measurements made on the thermal measurement samples.

Table C1. Results of Thickness and Density Measurements on R-11 Low-Density Fiberglass Insulation Materials

Specimen Code		Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
		Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1101-1	λ	23.9	22.4	4.13	319.5	0.550	0.650
	ρ1	24.2	24.0	3.97	339.1	0.560	0.635
	ρ2	24.0	24.0	3.86	324.9	0.557	0.614
1101-2	λ	23.65	23.8	4.03	340.5	0.571	0.658
	ρ1	24.2	24.2	3.65	332.1	0.592	0.617
	ρ2	25.2	24.0	3.59	333.9	0.586	0.601
1101-3	λ	14.75	24.0	4.02	227.7	0.610	0.701
	ρ1	48.8	14.95	3.62	429.4	0.619	0.641
	ρ2	48.25	14.95	3.69	445.3	0.637	0.672
1102-1	λ	24.4	24.0	3.81	358.6	0.612	0.666
	ρ1	24.4	24.0	4.07	367.1	0.597	0.694
	ρ2	23.8	23.6	4.22	363.4	0.584	0.704
1102-1a	λ	23.8	23.6	4.20	408.7	0.660	0.792
1102-2	λ	24.0	15.15	3.92	222.1	0.593	0.665
	ρ1	49.0	15.35	3.75	431.1	0.582	0.624
	ρ2	49.2	15.35	3.44	424.8	0.623	0.612
1102-3	λ	24.0	15.55	3.50	266.0	0.775	0.775
	ρ1	48.0	15.5	3.44	466.0	0.694	0.682
	ρ2	48.4	15.55	3.36	484.4	0.730	0.700

Table C1. (Continued)

Specimen Code		Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
		Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1103-1	λ	24.1	15.05	3.50	248.3	0.745	0.745
	ρ1	48.45	15.15	3.71	449.6	0.629	0.667
	ρ2	46.05	15.15	4.15	487.2	0.641	0.760
1103-2	λ	23.4	14.95	3.38	219.2	0.706	0.682
	ρ1	45.3	14.95	3.47	408.4	0.662	0.656
	ρ2	50.4	14.95	3.69	488.1	0.668	0.705
1103-3	λ	24.6	23.8	3.11	234.1	0.489	0.435
	ρ1	47.25	23.8	2.93	467.0	0.540	0.452
	ρ2	49.2	24.0	3.04	514.5	0.546	0.474
1103-3a	λ	23.9	24.0	2.85	220.0	0.512	0.417
1104-1	λ	22.25	14.35	3.30	176.5	0.637	0.601
	ρ1	23.45	14.35	3.26	175.6	0.610	0.568
	ρ2	23.45	14.55	3.29	169.9	0.577	0.542
1104-2	λ	22.85	14.9	3.69	157.3	0.478	0.503
	ρ1	44.55	14.95	3.49	330.4	0.541	0.540
	ρ2	48.8	15.0	3.12	348.1	0.581	0.518
1104-3	λ	24.55	14.9	4.17	210.7	0.526	0.627
	ρ1	48.5	14.85	3.75	400.6	0.565	0.605
	ρ2	49.0	14.75	3.65	384.6	0.555	0.579
1105-1	λ	25.85	14.85	3.85	201.9	0.521	0.573
	ρ1	24.4	14.95	3.22	167.9	0.543	0.499
	ρ2	23.8	15.15	2.87	153.3	0.564	0.463
1105-2	λ	24.2	14.75	3.54	176.0	0.530	0.536
	ρ1	48.85	14.75	3.57	337.6	0.500	0.510
	ρ2	48.8	14.9	3.65	350.9	0.504	0.525
1105-3	λ	23.95	15.15	3.76	208.8	0.582	0.626
	ρ1	48.05	15.05	3.32	430.3	0.683	0.648
	ρ2	49.6	15.05	3.41	439.7	0.658	0.641
1106-1	λ	23.7	14.8	3.30	210.5	0.694	0.655
	ρ1	47.45	14.95	3.75	417.7	0.598	0.641
	ρ2	48.2	15.0	3.87	448.7	0.611	0.676

Table C1. (Continued)

Specimen Code	Dimensions, in. Length	Width	Recovered Thickness	Weight (g)	Density, lb/ft^3, at Recovered Thickness	Nominal Thickness
1106-2 λ	24.1	14.75	4.17	184.5	0.474	0.565
ρ1	48.65	15.3	3.72	382.6	0.526	0.559
ρ2	48.25	15.2	3.89	411.5	0.549	0.611
1106-3 λ	25.1	16.45	3.91	216.1	0.510	0.570
ρ1	48.8	16.55	3.31	457.7	0.652	0.617
ρ2	48.85	16.55	3.25	478.3	0.693	0.644
1106-3a λ	25.45	16.15	4.10	250.0	0.565	0.662
1107-1 λ	23.8	14.95	3.57	176.9	0.531	0.541
ρ1	47.8	15.25	3.56	411.7	0.604	0.615
ρ2	49.0	15.15	3.54	404.3	0.586	0.593
1107-1a λ	23.95	14.85	3.80	195.6	0.551	0.599
1107-2 λ	23.6	14.95	2.79	197.6	0.765	0.610
ρ1	47.65	15.35	3.51	390.9	0.580	0.582
ρ2	45.3	15.3	3.45	364.9	0.581	0.573
1107-3 λ	24.5	16.45	3.83	249.0	0.615	0.672
ρ1	47.65	16.55	3.61	469.4	0.628	0.648
ρ2	48.8	16.5	3.65	496.3	0.643	0.671
1108-1 λ	23.2	15.15	4.33	193.4	0.484	0.599
ρ1	46.85	15.35	3.58	374.1	0.554	0.566
ρ2	46.6	15.35	3.68	374.0	0.541	0.569
1108-2 λ	25.0	14.85	3.53	187.5	0.545	0.550
ρ1	44.7	14.95	3.19	331.6	0.593	0.540
ρ2	45.85	14.95	3.07	344.9	0.624	0.548
1108-3 λ	23.4	15.1	3.79	180.0	0.512	0.554
ρ1	49.6	15.3	3.66	392.9	0.539	0.563
ρ2	48.8	15.35	3.65	370.2	0.516	0.538
1109-1 λ	23.25	23.55	3.21	271.0	0.588	0.539
ρ1	49.6	24.0	3.91	618.2	0.506	0.565
ρ2	48.1	24.0	3.67	577.7	0.519	0.545
1109-2 λ	24.6	24.0	3.78	326.5	0.557	0.602
ρ1	49.6	24.0	3.53	719.3	0.652	0.658
ρ2	46.4	24.0	3.37	606.5	0.616	0.593

Table Cl. (Continued)

Specimen Code		Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
		Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1109-3	λ	24.0	23.8	4.12	342.3	0.554	0.652
	ρ1	51.2	23.7	3.25	668.6	0.646	0.600
	ρ2	45.05	23.8	3.00	599.7	0.710	0.609
1110-1	λ	23.6	24.0	4.23	354.6	0.564	0.681
	ρ1	48.1	24.0	3.41	625.5	0.605	0.590
	ρ2	48.25	24.0	3.44	596.7	0.571	0.561
1110-2	λ	24.6	15.05	3.72	181.5	0.502	0.534
	ρ1	49.8	15.0	3.96	377.3	0.486	0.550
	ρ2	46.45	14.7	4.28	381.9	0.498	0.609
1110-3	λ	23.6	15.85	3.72	183.0	0.501	0.532
	ρ1	50.0	15.75	3.82	446.3	0.565	0.617
	ρ2	48.4	15.7	3.86	441.8	0.574	0.633
1111-1	λ	24.4	15.15	4.46	163.4	0.377	0.481
	ρ1	46.05	15.55	3.76	288.5	0.408	0.439
	ρ2	49.4	15.45	3.69	332.9	0.450	0.475
1111-3	λ	24.3	15.2	4.11	155.8	0.391	0.459
	ρ1	46.85	15.75	3.83	303.3	0.409	0.447
	ρ2	45.65	15.85	3.71	293.5	0.417	0.442
1112-1	λ	24.0	24.5	3.30	193.6	0.380	0.358
	ρ1	48.4	24.8	3.57	409.0	0.364	0.371
	ρ2	48.3	23.6	3.33	373.4	0.375	0.357
1112-2	λ	24.2	24.0	3.88	223.2	0.377	0.418
	ρ1	46.75	24.0	3.25	430.1	0.449	0.417
	ρ2	48.1	23.9	3.30	375.0	0.377	0.355
1112-3	λ	24.6	24.0	3.69	189.9	0.332	0.350
	ρ1	45.65	25.0	3.43	363.5	0.354	0.347
	ρ2	46.1	24.05	3.67	391.3	0.366	0.384
1113-1	λ	24.25	15.55	4.30	195.8	0.460	0.565
	ρ1	48.0	15.55	4.52	376.3	0.424	0.549
	ρ2	47.9	15.6	4.44	347.1	0.399	0.506
1113-2	λ	24.1	15.4	4.37	165.7	0.389	0.486
	ρ1	48.0	15.4	4.25	320.7	0.389	0.472
	ρ2	48.05	16.15	4.40	348.3	0.389	0.489

Table Cl. (Continued)

Specimen Code		Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
		Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1113-3	λ	27.45	15.45	4.31	181.2	0.378	0.465
	ρ1	47.25	15.75	3.67	327.2	0.456	0.479
	ρ2	47.3	15.1	3.54	338.7	0.510	0.516
1114-2	λ	22.85	23.55	4.71	270.0	0.406	0.546
	ρ1	48.45	23.65	4.30	473.1	0.366	0.449
	ρ2	48.7	23.75	4.67	506.9	0.358	0.477
1114-3	λ	23.8	22.45	4.39	257.2	0.418	0.524
	ρ1	48.4	23.45	3.79	475.4	0.421	0.456
	ρ2	48.4	23.55	3.81	529.6	0.465	0.506
1115-1	λ	23.9	15.55	4.14	164.2	0.407	0.481
	ρ1	47.6	15.6	3.79	320.8	0.434	0.470
	ρ2	47.8	15.55	3.96	332.5	0.430	0.487
1115-1a	λ	23.9	15.15	3.84	159.0	0.435	0.478
1115-2	λ	24.05	24.2	4.20	281.0	0.438	0.525
	ρ1	47.85	23.6	3.12	496.5	0.537	0.478
	ρ2	47.7	23.6	3.31	487.0	0.498	0.471
1115-2a	λ	23.2	23.6	3.72	231.0	0.432	0.459

Table C2. Results of Thickness and Density Measurements on 30 Specimens of R-19 Low-Density Fiberglass Insulation Materials

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1201-1 λ	23.8	23.25	6.44	610.5	0.652	0.700
ρ1	24.4	23.2	5.99	568.8	0.639	0.638
ρ2	24.55	23.5	5.89	636.9	0.714	0.701
1201-2 λ	24.05	15.05	7.22	501.5	0.732	0.880
ρ1	48.05	15.15	6.93	989.9	0.748	0.863
ρ2	49.6	15.1	6.92	926.2	0.681	0.785
1201-3 λ	25.5	14.85	4.98	377.4	0.763	0.633
ρ1	36.8	15.0	4.50	539.8	0.828	0.621
ρ2	38.2	14.8	4.61	541.5	0.791	0.608
1202-1 λ	24.6	15.25	5.40	346.5	0.651	0.586
ρ1	48.4	15.3	5.42	668.6	0.635	0.573
ρ2	48.3	15.35	5.74	750.6	0.672	0.643
1202-2 λ	24.0	23.35	6.11	587.8	0.655	0.667
ρ1	24.05	23.25	6.27	582.9	0.633	0.662
ρ2	24.85	23.4	6.03	582.5	0.633	0.636
1202-3 λ	23.8	15.35	6.41	325.7	0.529	0.566
ρ1	48.65	15.35	6.22	706.0	0.579	0.600
ρ2	47.8	15.35	6.09	767.3	0.654	0.664
1202-4 λ	23.95	14.9	6.22	377.0	0.647	0.671
ρ1	48.6	15.0	5.85	758.9	0.678	0.661
ρ2	48.2	15.15	6.15	748.3	0.635	0.651
1202-5 λ	23.6	15.1	6.46	361.1	0.597	0.643
ρ1	48.8	15.1	6.38	777.3	0.630	0.670
ρ2	48.7	15.3	6.11	727.3	0.609	0.620
1203-1 λ	24.0	14.05	6.01	312.8	0.552	0.553
ρ1	48.0	15.0	5.15	572.8	0.588	0.505
ρ2	50.8	14.95	5.35	599.1	0.562	0.501
1203-2 λ	23.35	15.25	4.93	336.0	0.729	0.599
ρ1	35.85	15.35	4.53	491.0	0.750	0.567
ρ2	36.2	15.35	4.74	538.2	0.778	0.615

Table C2. (Continued)

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1203-3 λ	25.4	14.95	4.30	350.0	0.817	0.585
ρ1	37.0	14.95	4.49	530.8	0.814	0.609
ρ2	36.9	14.95	4.54	527.0	0.802	0.607
1204-1 λ	24.2	15.75	6.06	348.2	0.574	0.580
ρ1	47.65	15.55	5.91	732.6	0.637	0.628
ρ2	47.9	15.45	5.98	751.7	0.647	0.645
1204-2 λ	24.0	15.05	5.74	332.0	0.610	0.584
ρ1	48.85	15.0	6.12	734.1	0.624	0.636
ρ2	47.85	15.0	6.48	804.2	0.659	0.711
1204-3 λ	22.15	23.45	6.00	487.1	0.596	0.596
ρ1	26.2	23.65	5.89	575.7	0.601	0.590
ρ2	24.45	23.4	5.79	505.1	0.581	0.561
1205-1 λ	23.65	23.25	6.00	581.1	0.671	0.671
ρ1	48.4	23.2	6.56	1127.7	0.583	0.638
ρ2	49.0	23.45	6.34	1113.5	0.582	0.615
1205-2 λ	24.5	15.25	5.78	363.4	0.641	0.618
ρ1	48.35	15.35	6.05	732.1	0.621	0.626
ρ2	48.8	15.25	5.89	721.5	0.627	0.616
1205-3 λ	24.55	14.5	5.99	315.0	0.563	0.562
ρ1	37.0	15.0	4.53	478.6	0.725	0.548
ρ2	36.8	14.95	5.40	489.6	0.627	0.565
1206-1 λ	22.6	15.25	6.01	342.5	0.630	0.631
ρ1	48.4	15.3	5.78	681.7	0.607	0.584
ρ2	48.8	15.3	5.94	697.3	0.599	0.593
1206-2 λ	22.35	15.1	6.05	398.5	0.744	0.750
ρ1	35.65	15.15	5.82	571.9	0.693	0.672
ρ2	36.2	15.1	5.56	625.5	0.784	0.727
1206-3 λ	23.05	14.95	4.84	299.5	0.685	0.552
ρ1	35.45	15.1	5.24	473.7	0.643	0.562
ρ2	36.6	15.2	5.47	496.5	0.622	0.567
1206-4 λ	23.25	15.1	5.62	337.4	0.651	0.610
ρ1	30.9	15.3	5.42	436.0	0.648	0.586
ρ2	28.0	15.25	5.30	371.9	0.626	0.553

Table C2. (Continued)

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1207-1 λ	23.35	15.75	6.93	244.0	0.365	0.422
ρ1	48.0	16.55	6.86	416.9	0.291	0.333
ρ2	47.45	15.0	6.17	522.6	0.453	0.466
1207-2 λ	22.25	15.5	6.43	235.4	0.405	0.435
ρ1	48.05	15.55	6.33	444.3	0.358	0.378
ρ2	47.5	15.5	6.46	469.5	0.376	0.405
1207-3 λ	25.1	15.8	6.63	222.7	0.323	0.356
ρ1	48.8	15.8	6.27	435.9	0.343	0.359
ρ2	48.25	15.8	5.97	398.0	0.333	0.331
1208-1 λ	23.25	24.0	6.32	375.6	0.405	0.427
ρ1	47.35	24.0	5.76	745.6	0.434	0.417
ρ2	46.25	23.9	5.43	669.7	0.425	0.385
1208-2 λ	23.8	23.9	6.21	339.2	0.366	0.378
ρ1	47.15	24.65	6.13	738.3	0.395	0.403
ρ2	47.1	23.9	5.78	716.8	0.420	0.404
1208-3 λ	23.35	24.2	6.60	370.2	0.378	0.416
ρ1	47.25	24.0	6.57	750.4	0.384	0.420
ρ2	47.3	23.75	6.37	738.8	0.393	0.418
1209-1 λ	22.2	24.7	5.50	331.5	0.419	0.384
ρ1	46.8	24.75	6.10	755.8	0.408	0.414
ρ2	47.3	24.75	6.02	745.0	0.403	0.404
1209-2 λ	25.35	23.45	6.88	580.8	0.541	0.621
ρ1	23.85	23.45	6.33	561.2	0.604	0.637
ρ2	25.75	23.35	6.63	602.6	0.576	0.636
1209-3 λ	25.1	23.3	5.44	546.8	0.655	0.594
ρ1	23.7	23.45	5.02	545.4	0.745	0.623
ρ2	24.3	23.45	5.11	562.7	0.736	0.627

Table C3. Results of Thickness and Density Measurements on 27 Samples of R-11 Rock Wool Insulation Materials

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1301-1 λ	23.8	14.75	2.72	542.7	2.163	1.962
ρ1	47.85	14.75	2.95	1200.4	2.196	2.160
ρ2	48.2	14.8	2.57	966.3	2.008	1.720
1301-2 λ	24.0	15.0	2.83	530.0	1.981	1.870
ρ1	48.8	14.95	2.61	1139.4	2.280	1.983
ρ2	48.7	14.8	2.74	1115.0	2.151	1.964
1301-3 λ	23.3	14.8	2.87	707.0	2.723	2.605
ρ1	48.45	14.9	2.44	1274.0	2.755	2.241
ρ2	48.45	14.8	2.47	1365.2	2.936	2.418
1302-1 λ	23.4	15.0	3.50	509.0	1.578	1.578
ρ1	46.6	15.2	2.76	985.4	1.922	1.516
ρ2	46.05	14.95	2.93	998.8	1.886	1.579
1302-2 λ	23.2	15.1	3.22	582.5	1.967	1.810
ρ1	46.25	15.15	1.90	746.6	2.136	1.160
ρ2	46.55	15.2	2.00	692.9	1.865	1.066
1302-3 λ	23.85	14.8	2.36	382.5	1.751	1.180
ρ1	48.05	14.95	2.61	921.5	1.872	1.396
ρ2	48.0	14.8	3.50	1405.5	2.153	2.153
1303-1 λ	23.6	14.95	2.99	649.8	2.344	2.003
ρ1	48.7	15.0	2.94	1215.8	2.157	1.811
ρ2	49.6	14.95	2.76	1063.3	1.979	1.561
1303-2 λ	24.6	14.85	3.20	490.5	1.598	1.461
ρ1	49.25	14.95	3.11	960.3	1.598	1.420
ρ2	48.8	14.95	3.04	979.9	1.683	1.462
1303-3 λ	24.4	14.95	3.67	593.2	1.687	1.769
ρ1	48.75	15.0	3.16	988.1	1.629	1.471
ρ2	48.75	14.85	3.28	960.6	1.541	1.444
1304-1 λ	24.4	14.95	3.28	649.8	2.068	1.938
ρ1	44.1	14.75	3.29	1079.4	1.921	1.806
ρ2	50.15	14.8	3.15	1172.7	1.911	1.720
1304-2 λ	23.6	14.55	2.91	546.5	2.084	1.732
ρ1	45.5	14.35	3.12	1234.1	2.308	2.057
ρ2	44.7	14.2	2.89	1178.6	2.448	2.021

Table C3. (Continued)

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1304-3 λ	24.4	14.85	2.97	518.3	1.834	1.556
ρ1	51.95	14.75	3.15	1129.8	1.783	1.605
ρ2	42.5	14.55	3.13	846.4	1.666	1.490
1305-1 λ	25.0	14.75	2.91	566.3	2.010	1.950
ρ1	44.9	14.75	2.80	1196.7	2.458	2.295
ρ2	47.8	14.85	2.74	1194.1	2.338	2.135
1305-2 λ	24.6	14.95	2.76	592.3	2.223	2.045
ρ1	46.45	15.15	3.31	1345.9	2.201	2.429
ρ2	47.25	15.05	2.81	1058.7	2.018	1.891
1305-3 λ	24.8	14.95	2.85	578.1	2.084	1.980
ρ1	47.65	15.0	2.80	1025.5	1.952	1.822
ρ2	47.5	15.0	2.49	920.7	1.977	1.641
1306-1 λ	24.2	15.1	3.14	581.9	1.932	2.022
ρ1	49.2	15.15	2.72	1269.5	2.385	2.163
ρ2	48.4	15.0	2.87	1165.2	2.130	2.038
1306-2 λ	23.85	14.7	4.11	748.6	1.978	2.710
ρ1	48.05	14.95	3.60	1304.4	1.922	2.306
ρ2	47.85	14.8	3.74	1315.2	1.892	2.358
1306-3 λ	24.55	14.95	4.32	744.0	1.788	2.575
ρ1	48.0	14.95	3.87	1440.8	1.976	2.550
ρ2	47.95	15.0	3.72	1499.1	2.134	2.647
1307-1 λ	24.1	23.25	2.87	870.0	2.061	1.972
ρ1	22.85	23.2	3.20	1076.8	2.418	2.579
ρ2	24.0	23.3	3.48	1166.9	2.284	2.650
1307-2 λ	23.5	23.25	2.97	771.5	1.811	1.793
ρ1	24.45	23.25	2.31	823.1	2.388	1.839
ρ2	24.4	23.25	2.60	822.6	2.125	1.841
1307-3 λ	22.95	23.15	2.46	922.1	2.688	2.204
ρ1	24.0	23.45	2.68	982.6	2.482	2.217
ρ2	24.0	23.25	2.87	1035.6	2.463	2.357
1308-1 λ	24.0	15.0	3.27	541.0	1.750	1.635
ρ1	48.45	14.8	2.91	1085.9	1.982	1.648
ρ2	48.1	14.9	3.08	1122.4	1.937	1.705

Table C3. (Continued)

Specimen Code	Dimensions, in.			Weight (g)	Density, lb/ft^3, at	
	Length	Width	Recovered Thickness		Recovered Thickness	Nominal Thickness
1308-2 λ	23.9	15.0	3.46	692.3	2.126	2.102
ρ1	45.65	14.95	3.22	1133.1	1.963	1.806
ρ2	49.6	15.0	2.26	1136.7	1.966	1.663
1308-3 λ	24.4	14.85	3.32	506.0	1.602	1.519
ρ1	47.85	15.0	2.26	1004.0	2.358	1.522
ρ2	48.45	14.75	3.23	1233.2	2.035	1.878
1309-1 λ	24.8	14.85	3.16	440.4	1.441	1.301
ρ1	48.7	14.75	3.22	1184.1	1.950	1.794
ρ2	46.05	14.4	3.22	1171.8	2.091	1.923
1309-2 λ	25.25	14.75	3.47	559.1	1.646	1.632
ρ1	48.8	14.55	3.31	1174.1	1.903	1.800
ρ2	48.85	14.7	3.56	1281.1	1.909	1.941
1309-3 λ	24.3	14.95	3.03	593.0	2.051	1.776
ρ1	49.2	14.85	2.83	1217.0	2.242	1.813
ρ2	48.8	14.95	2.52	1158.0	2.400	1.728

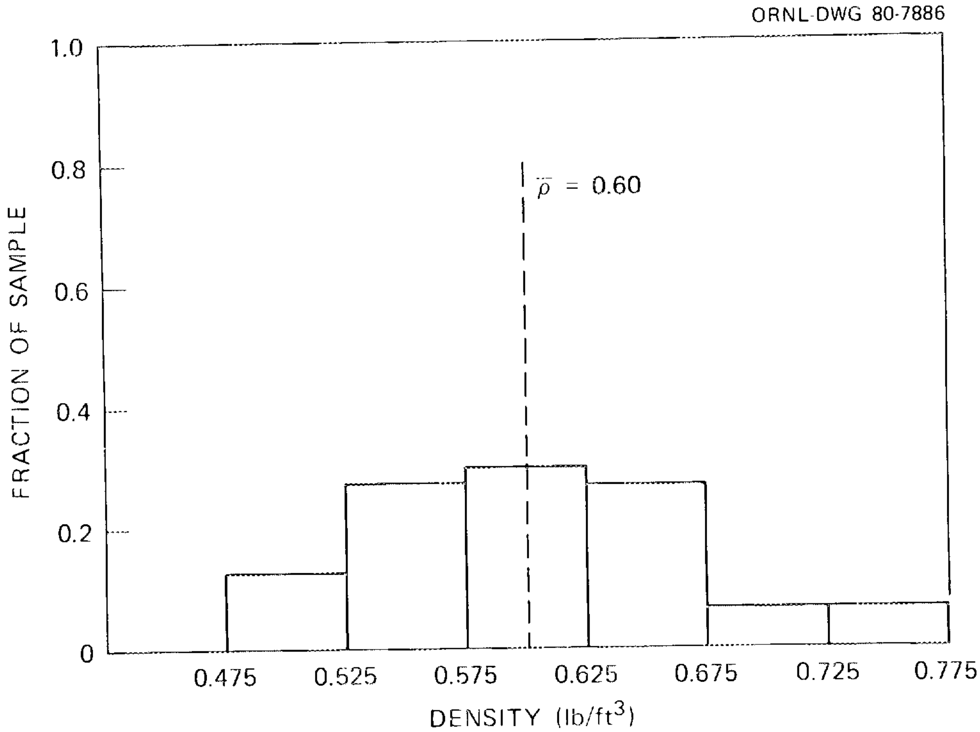

Fig. C1. The Distribution of Recovered Density of R-11 Low-Density Fiberglass Produced by Manufacturer A.

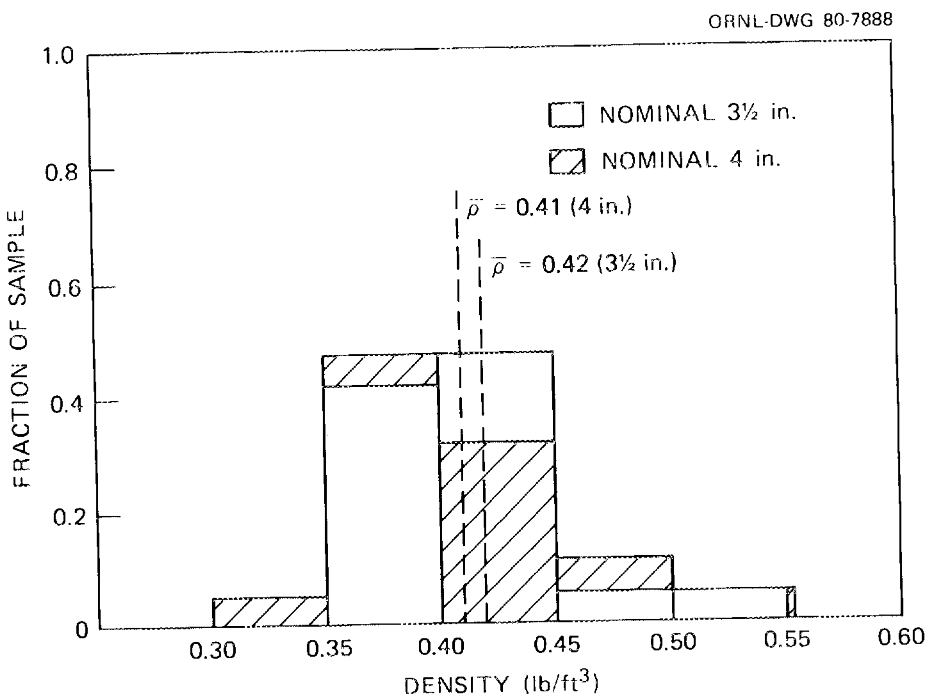

Fig. C2. The Distribution of Recovered Density of R-11 Low-Density Fiberglass Produced by Manufacturer B.

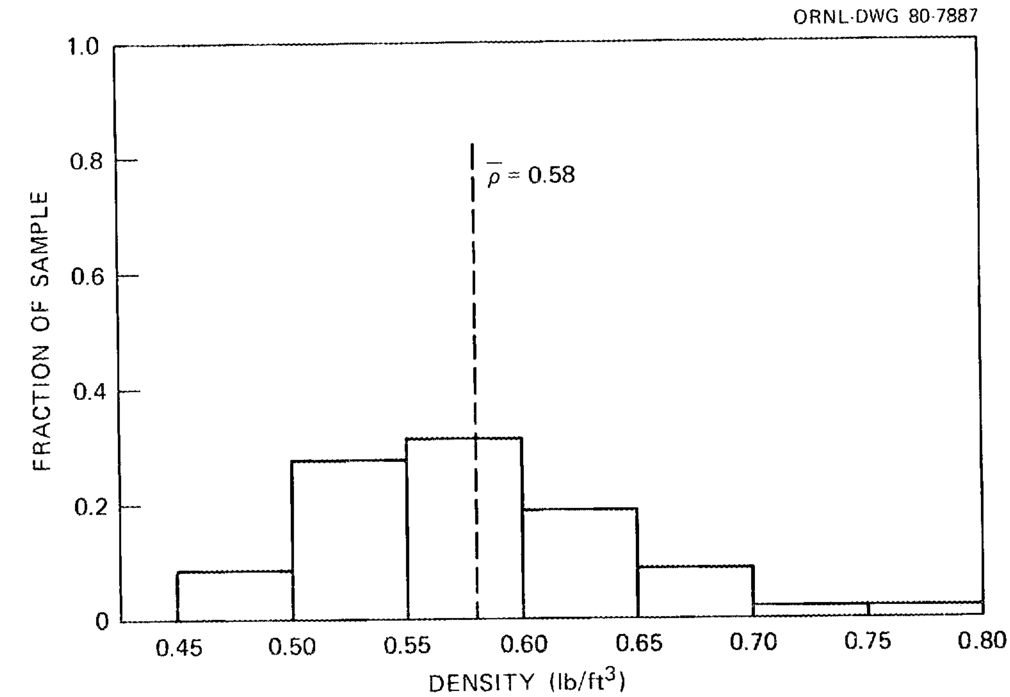

Fig. C3. The Distribution of Recovered Density of R-11 Low-Density Fiberglass Produced by Manufacturer C.

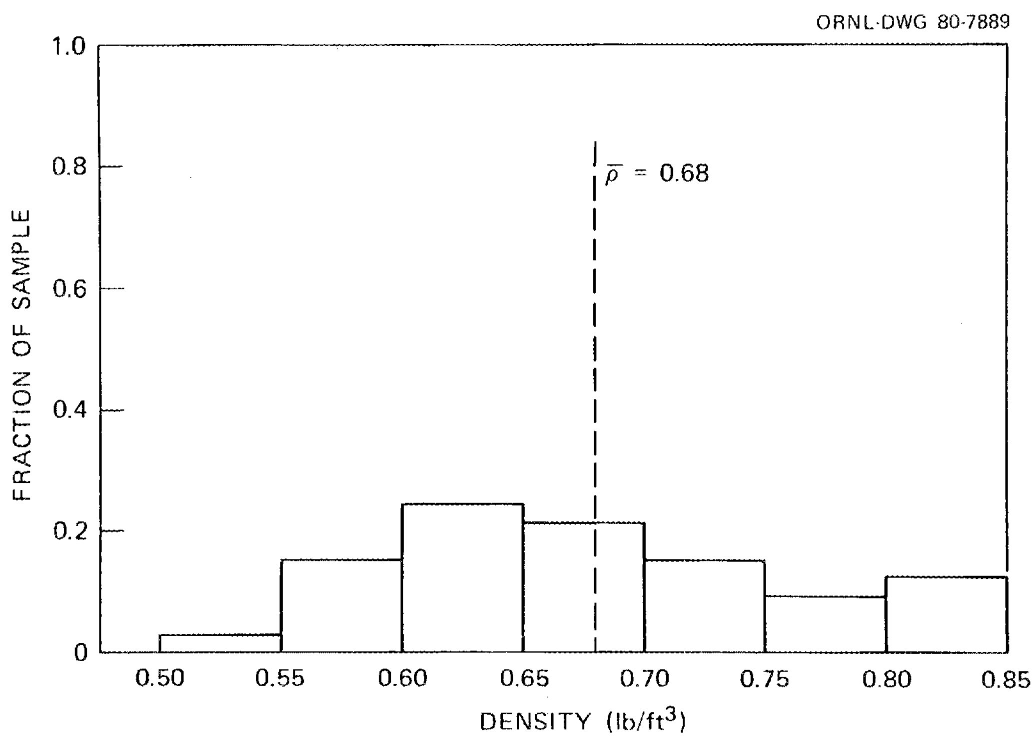

Fig. C4. The Distribution of Recovered Density of R-19 Low-Density Fiberglass Produced by Manufacturer A.

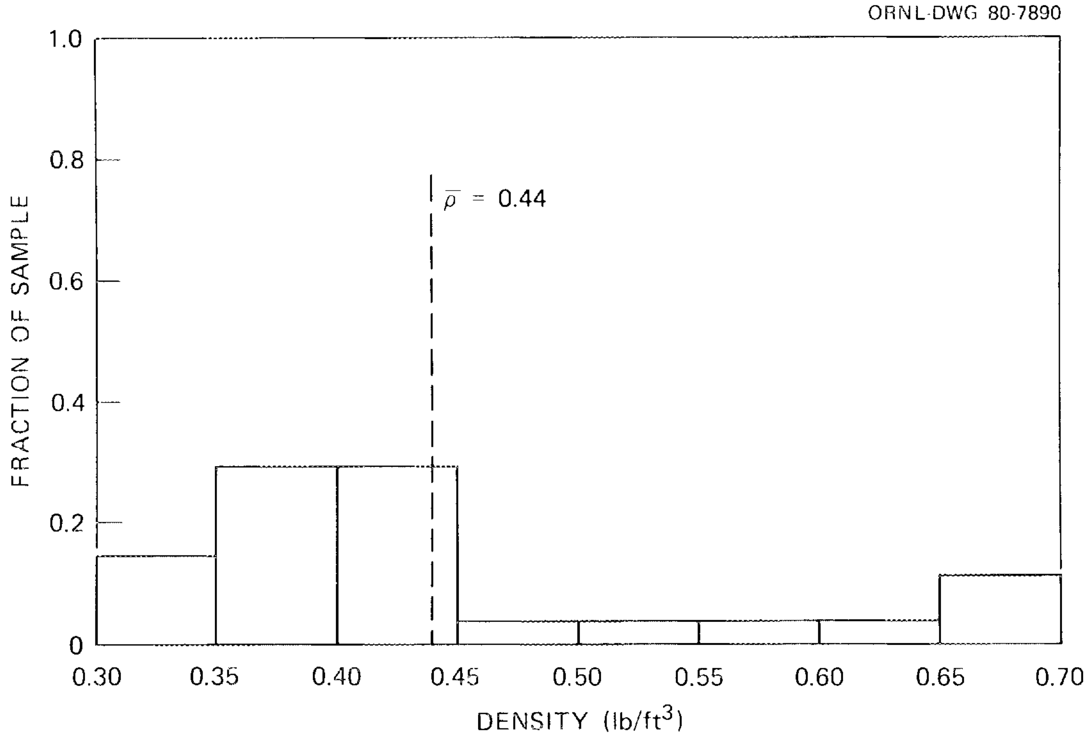

Fig. C5. The Distribution of Recovered Density of R-19 Low-Density Fiberglass Produced by Manufacturer B.

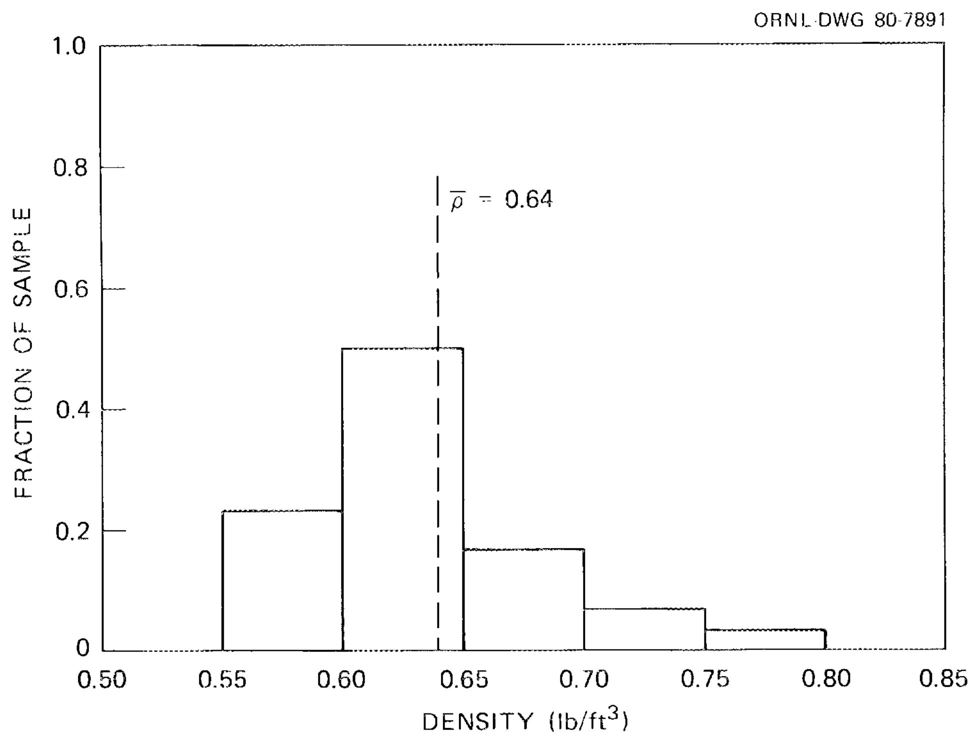

Fig. C6. The Distribution of Recovered Density of R-19 Low-Density Fiberglass Produced by Manufacturer C.

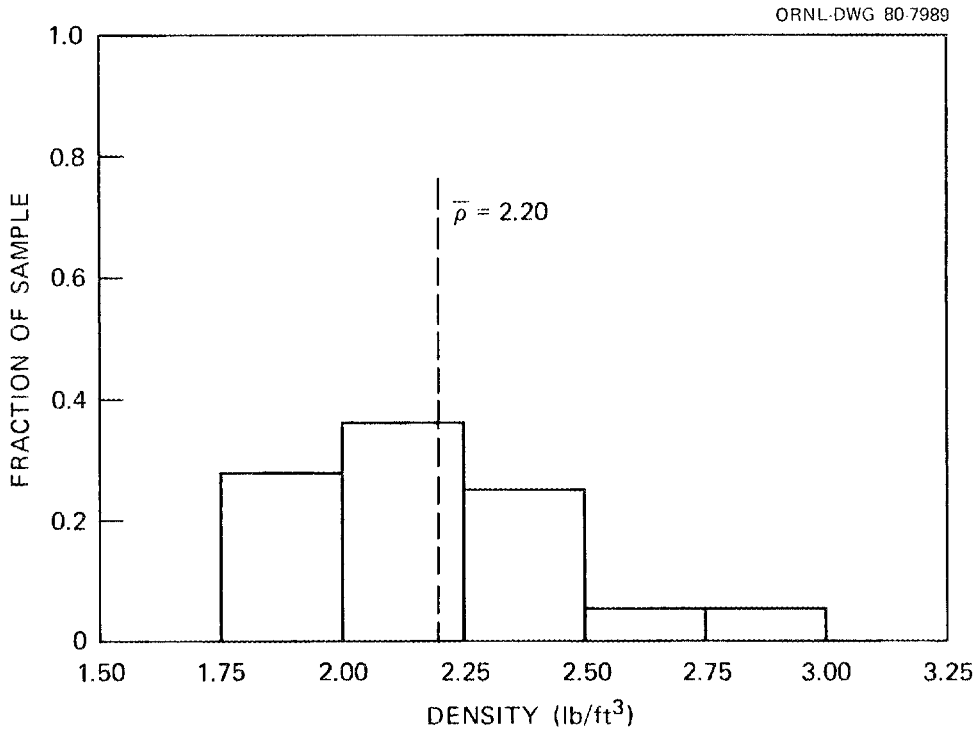

Fig. C7. The Distribution of Recovered Density of R-11 Rock Wool Produced by Manufacturers D, G, and H.

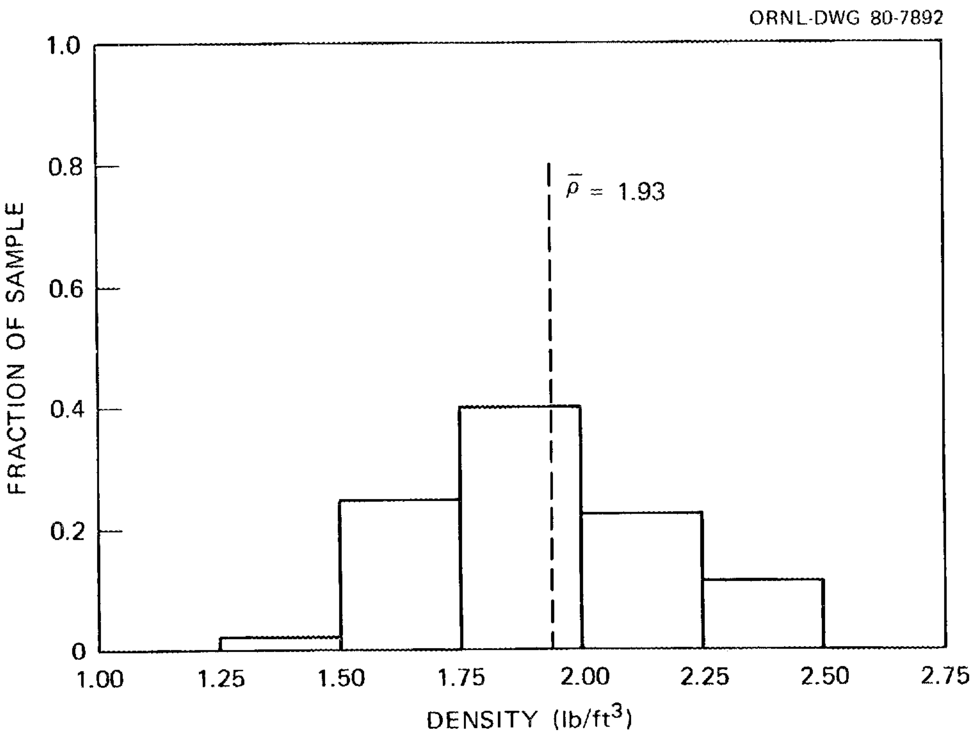

Fig. C8. The Distribution of Recovered Density of R-11 Rock Wool Produced by Manufacturers E, F, and I.

APPENDIX D

Estimate of Edge Effect and Vertical Heat Flow Measurements

Theoretical Estimate of the Maximum Thickness of Specimens that can be Used in the Guarded Hot Plate Apparatus

The tables in the Appendix of ASTM C 177-76 were used in the following analysis. The key parameters for the Dynatech 24-in.-square guarded hot plate are given below. Definitions for the symbols can be found in ASTM C 177-76.

E = 0.5

RATIO T = 0.0004

RATIO K = 8775

T/C K = 0.5

GAP = 3.17 mm (0.125 in.)

PLATE = 610 mm (24.0 in.)

GUARD = 152 mm (6.0 in.)

To obtain a "worst case" value for the maximum specimen thickness that can be used in the apparatus conservative values for RATIO T, RATIO K, and T/C K have been used. For a 2% bound on error in apparent thermal conductivity due to edge losses the maximum specimen thickness exceeds 219 mm (8.6 in.).

Vertical Heat Flow Measurements

The guarded hot plate was operated in such a way that measured apparent thermal conductivity values obtained with upward heat flow can be compared with apparent thermal conductivity values obtained with downward heat flow. See Table D1.

Table D1. Orientation Effect on Heat Flow

Direction of Heat Flow	Test Thickness (in.)	Temp. Diff. (°F)	Power (Btu/h)	Apparent Thermal Conductivity (Btu in./h ft^2 °F)
Up	2.874	36.09	4.165	0.325
Down	2.882	35.73	4.079	0.322
Up	5.760	35.55	2.035	0.323
Down	5.760	36.09	2.055	0.321

APPENDIX E

Variation of Apparent Thermal Conductivity with Temperature for Eleven Mineral Fiber Insulations

Specimen Code	Test Density (lb/ft^3)	Test Thickness (in.)	Temperature, °F		Power (Btu/h)	Apparent Thermal Conductivity $\left(\frac{\text{Btu in.}}{\text{h ft}^2\ ^\circ\text{F}}\right)$	Thermal Resistance $\left(\frac{\text{h ft}^2\ ^\circ\text{F}}{\text{Btu}}\right)$
			Mean	Difference			
1101-1	0.638	3.56	0	50.1	7.36	0.256	13.91
			75	50.9	9.49	0.325	10.96
			150	49.4	12.13	0.428	8.32
1107-1	0.604	3.14	0	50.1	7.82	0.240	13.09
			75	49.9	10.29	0.317	9.91
			150	50.7	13.43	0.407	7.71
1111-1	0.532	3.16	0	49.8	7.63	0.237	13.33
			75	49.6	9.88	0.308	10.26
			150	49.8	13.14	0.408	7.74
1202-1	0.651	5.40	0	50.0	4.62	0.244	22.11
			75	49.4	6.11	0.327	16.52
			150	49.3	8.41	0.451	11.98
1204-2	0.601	5.83	0	50.7	4.00	0.225	25.90
			75	49.1	5.21	0.303	19.25
			150	50.4	7.65	0.433	13.46
1206-4a	0.623	2.80	0	50.0	8.43	0.231	12.12
			75	49.8	11.26	0.310	9.04
			150	50.0	16.13	0.442	6.33
1207-2	0.425	6.13	0	49.5	4.37	0.265	23.14
			75	49.6	5.97	0.361	16.97
			150	50.8	8.31	0.491	12.49
1302-1	1.578	3.50	0	49.4	7.87	0.273	12.82
			75	50.3	10.54	0.359	9.75
			150	49.5	13.38	0.463	7.56
1304-1	2.068	3.28	0	49.3	7.03	0.229	14.33
			75	49.4	9.05	0.294	11.15
			150	49.9	11.19	0.360	9.11
1306-1	1.932	3.14	0	49.4	7.78	0.242	12.97
			75	49.7	10.06	0.311	10.09
			150	49.7	12.58	0.389	8.07
1309-2	1.646	3.47	0	50.6	7.39	0.248	13.99
			75	50.4	9.44	0.318	10.91
			150	49.9	11.87	0.404	8.59

APPENDIX F

Results of the Least Squares Calculations for Apparent Thermal Conductivity as a Function of Density

Table F1 gives values for the constants a, b, and c in

$$\lambda = a + b\rho + c/\rho \qquad \text{(F-1)}$$

estimated by the method of least squares from appropriate sets of data given in Tables 4, 6, 7, and 8. For each of the data sets studied the variance and the average deviation are given. A composite fit of Eq. (F-1) to the R-11 rock wool data was discarded because the variance of c was large compared with c. In this latter case Eq. (F-1) was replaced by

$$\lambda = a + b\rho \; . \qquad \text{(F-2)}$$

Table F1. Summary of Least Squares Parameters for Apparent Thermal Conductivity as a Function of Density

Material	Manufacturer	*a*	*b*	*c*	Variance	Average Deviation (%)
Fiberglass	A	0.423058	−0.179984	0.018910	0.000182	2.6
R-11	B	0.103995	0.044556	0.099619	0.000153	2.1
	C	0.435165	−0.204016	0.011221	0.000330	4.1
	Composite	0.431763	−0.184631	0.007683	0.000379	4.4
Fiberglass	A	0.071943	0.058813	0.148908	0.000194	2.7
R-19	B	0.403006	−0.195358	0.026479	0.000471	3.8
	C	0.310747	−0.119931	0.056370	0.000260	3.8
	Composite	0.389984	−0.156311	0.026055	0.000360	3.8
Rock Wool	D	0.987940	−0.148624	−0.784045	0.000318	2.7
R-11	E	−0.743371	0.264104	1.058679	0.000239	3.6
	F	0.416651	−0.043790	−0.083792	0.000089	1.6
	G	0.298825	−0.024969	0.108943	0.0000078	0.5
	H	−0.211917	0.095246	0.669030		[a]
	I	0.288235	−0.024767	0.109011	0.000025	1.2
3-in. Composite Data		0.378824	−0.035837	0.	0.000157	3.3
3.5-in. Composite Data		0.402418	−0.0492678	0.	0.000333	4.1

[a]Sample size of three.

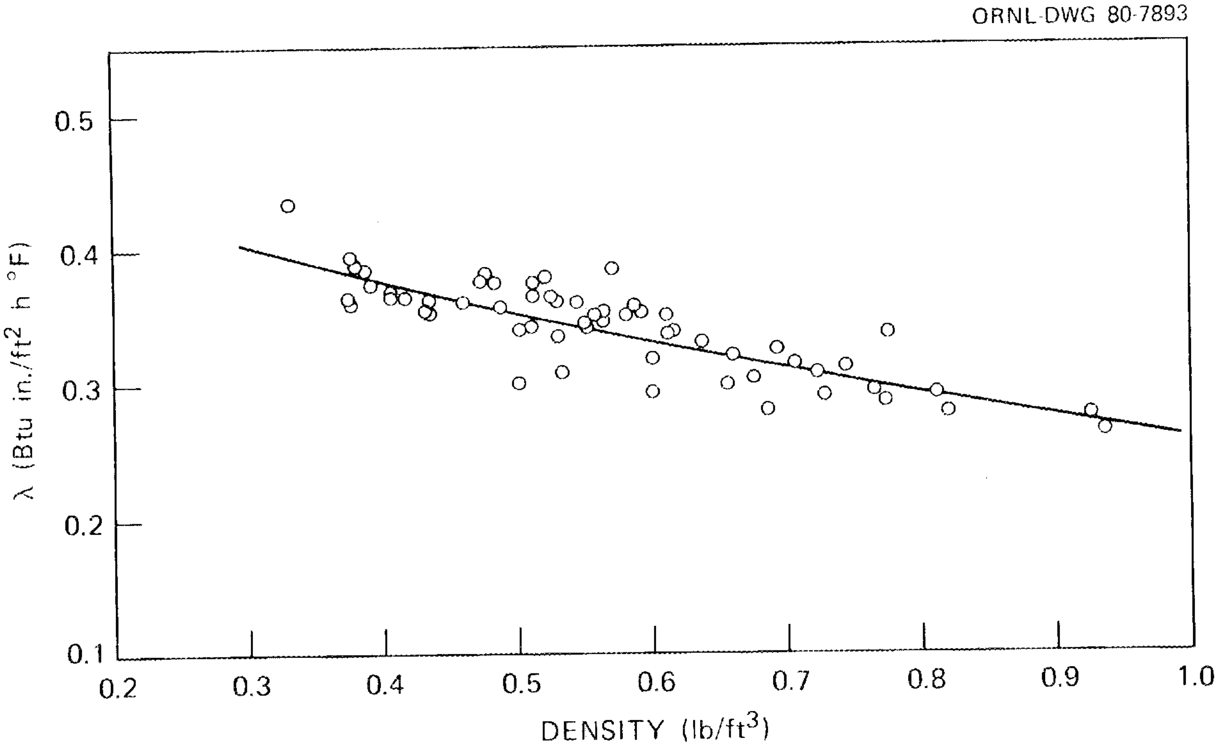

Fig. F1. Apparent Thermal Conductivity at 75°F Versus Density for R-11 Fiberglass.

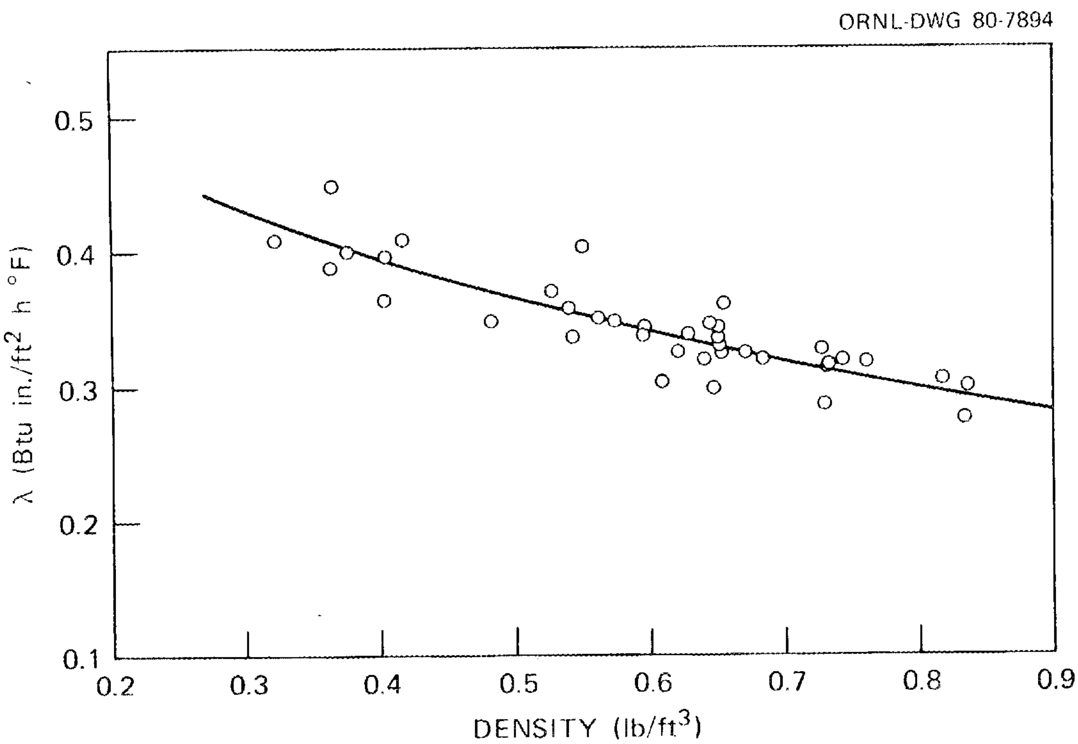

Fig. F2. Apparent Thermal Conductivity at 75°F Versus Density for R-19 Fiberglass.

ORNL-DWG 80-7895

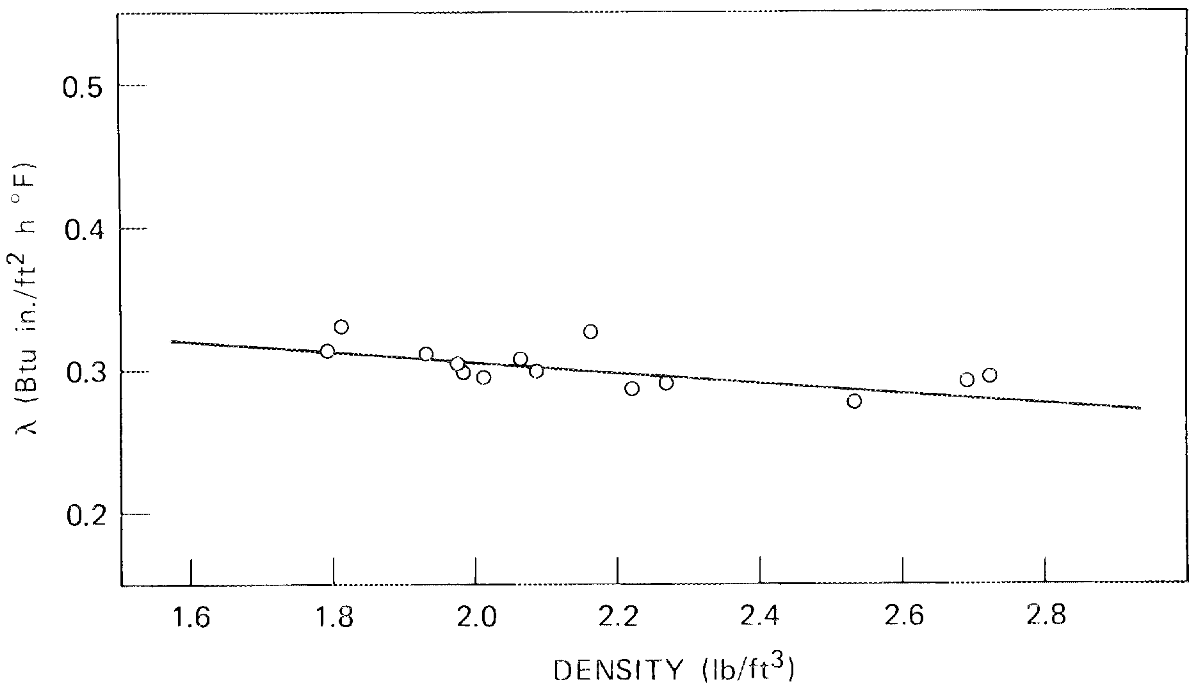

Fig. F3. Apparent Thermal Conductivity at 75°F Versus Density for R-11 Rock Wool (3 in.).

ORNL-DWG 80-7896

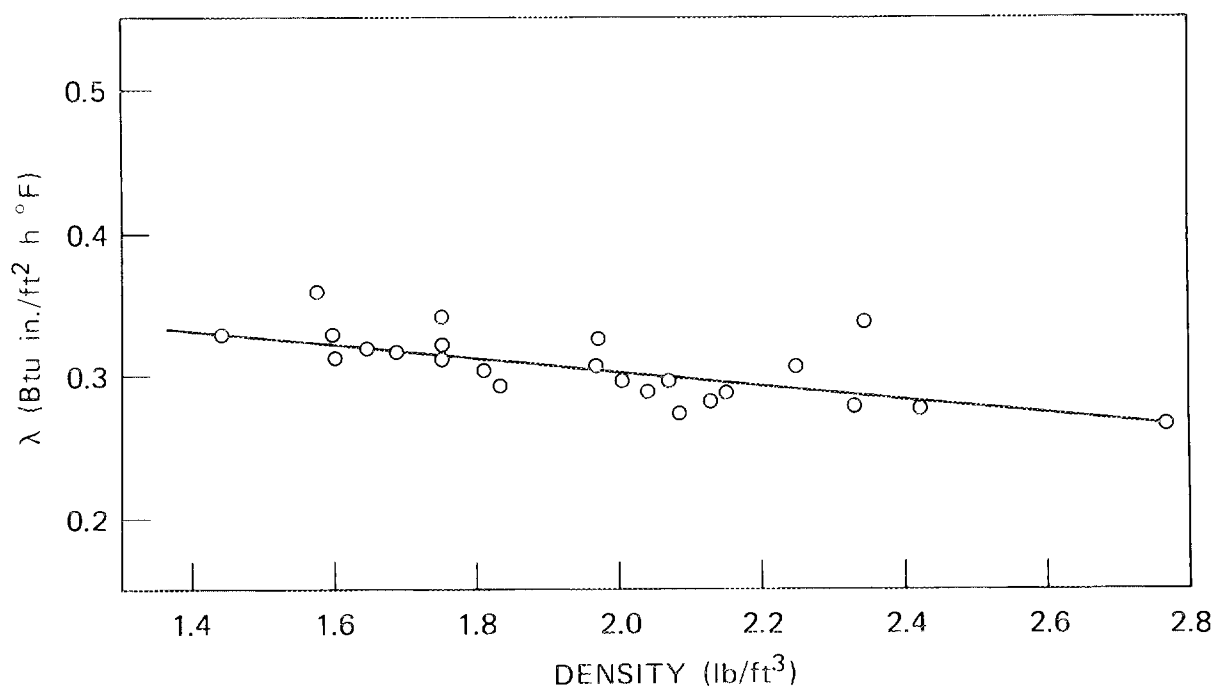

Fig. F4. Apparent Thermal Conductivity at 75°F Versus Density for R-11 Rock Wool (3.5 in.).

APPENDIX G

Recovered Thickness Data from the National Association of Home Builders Research Foundation*

Manufacturer	Plant	Mean Thickness (in.)	Std. Dev.	Std. Dev. of the Mean
1	A	6.358	0.431	0.102
	B	6.692	0.396	0.093
	C	6.849	0.433	0.102
	D	6.739	0.353	0.083
	E	6.359	0.244	0.058
	Grand Average	6.599		
2	A	7.051	0.234	0.055
	B	7.726	0.392	0.092
	C	7.056	0.216	0.051
	D	6.933	0.284	0.067
	Grand Average	7.192		
3	A	6.496	0.096	0.023
	B	6.400	0.230	0.054
	Grand Average	6.448		

*These data were obtained under NAHBRF supervision at the manufacturing site. Each of the mean values is the result of 270 thickness measurements.

APPENDIX H

Comments from External Reviewers

Reviews of this report were requested from 13 individuals and the Mineral Insulation Manufacturers Association (MIMA) in addition to ORNL reviews. These reviewers are listed in Table H1. Eight of the requests resulted in modification or additions to the report, as listed below. The review prepared by MIMA represented a composite of inputs from many sources within the mineral fiber industry. In several cases a written summary of comments that was prepared by the reviewers is included in this appendix.

Contributing Reviewer	Written Summary or Statement Included
R. W. Anderson	X
E. L. Bales	
E. C. Freeman	
D. M. Greason	X
F. J. Powell	X
B. G. Rennex	X
C. J. Shirtliffe	
MIMA	X
John Mandel	X
A. J. Duncan	X

Table H1. List of Report Reviewers

		Organization	Reason
		Internal Reviewers	
1.	T. G. Godfrey	ORNL	Experience in Measurements
2.	J. P. Moore	ORNL	Experience in Measurements
3.	T. L. Hebble	ORNL	Experience in Statistics
		External Reviewers	
1.	Mineral Insulation Association	Manufacturers	DOE agreed to MIMA review request
2.	R. W. Anderson	Diversified Insulation Co.	Program Manager, ERDA, at project initiation
3.	E. L. Bales	Stevens Institute of Technology	Program Manager, DOE, during project
4.	E. C. Freeman	Office of Building and Community Systems	Program Manager, DOE, during project
5.	F. J. Powell	NBS	Experience in measurements
6.	C. J. Shirtliffe	NRC-Canada	Experience in measurements
7.	D. M. Greason	Dow Chemical USA	Experience in measurements, co-worker ASTM C16 Position Paper on Insulations
8.	J. F. Kimpflen	CertainTeed Products Corp.	Experience in measurements, co-worker ASTM C16 Position Paper on Insulations
9.	M. Hollingsworth,	Owens-Corning Fiberglass Corp.	Experience in measurements, active input to ASTM C16 Position Paper on insulations
10.	B. G. Rennex	NAHB Research Foundation, Inc.	Experience in measurements
11.	J. Tyler	U.S. Fiber Co.	DOE agreed to review request
12.	John Mandel	NBS	E-11 Statistical Analysis
13.	Acheson Duncan	John Hopkins University	E-11 Statistical Analysis
14.	Jack Snell	NBS	DOE request

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Northern Cellulose Products, Inc.
Beverly MA
(617) 922-8206

Robinson Insulation Co.
Great Falls MT
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Therma-Coustics, Inc.
Colton CA
(714) 783-0462

December 14, 1979

DEC 17 7 35 AM '79

Dr. Ted S. Lundy
Program Manager
Building Thermal Envelope Systems
and Insulating Materials
Oak Ridge National Laboratory
Post Office Box X
Oak Ridge, Tennessee 37830

Dear Ted:

Thank you for the opportunity to review the draft report "Thermal Resistance Values of Low-Density Mineral Fiber Building Insulation Batts Commercially Available in 1977". The enclosed copy of the report contains my specific comments, as marked in red, for your consideration.

Additional comments, of a more general nature are given below:

1) The report is very well documented with respect to procedures, testing and analyses methods, and support data. Whereas this level of detail may seem excessive to some, such detail is needed as a basis for subsequent evaluation and follow-on studies. Also, since it is likely that some sectors of industry may challenge the results of the report, the detailed data presented will form the basis for common understanding.

2) Because of the level of detail in the body of the report, I recommend that the Executive Summary be carefully rewritten in laymen's language. It is doubtful that most readers would wade through the detailed data or would comprehend the meanings of the statistical analyses and technical jargon. The Executive Summary should clearly state the major findings and recommendations in an interpretive manner.

3) I believe there are several major benefits and conclusions that can be drawn from the data that had not been specifically identified or highlighted in the Executive Summary and Conclusion/Recommendation sections:

   a) The data demonstrate the need for more rigorous or improved testing procedures, e.g. sampling and sample preparation.

b) The data provide an understanding of the precision of various test and methods of analyses required for realistic setting of property standards and the tolerances on such standards. This, of course, leads to improved standards.

c) The data provide needed information relative to the expected precision of "performance" data of building envelope components. This becomes particularly important with the adoption of ASHRAE 90 and the pending BEPS. Any tolerance limits placed on envelope performance must consider the variability of the respective components.

4) The data demonstrate the need for similar evaluation of other building envelope components, including other insulation materials.

As a final note, I wish to commend the authors for their excellent research work and their evaluation of the complex data. I look forward to the publication of the test report so that serious consideration of the "Recommendations" can be addressed by DOE and the industry as a whole.

Robert Anderson

Robert W. Anderson

kj

enc

DOW CHEMICAL U.S.A.

GRANVILLE RESEARCH CENTER
P.O. BOX 515
GRANVILLE, OHIO 43023

December 17, 1979

Dr. T. S. Lundy
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

Dear Ted:

COMMENTS ON THE DRAFT REPORT "THERMAL RESISTANCE VALUES (R-VALUES OF LOW DENSITY MINERAL FIBER BUILDING INSULATION BATTS COMMERCIALLY AVAILABLE IN 1977"

This is an impressive piece of work, but other competent investigators have failed to find such large differences in thermal performance attributable to "thickness effects." Thermal measurements on stacked, bisected and quadrasected samples, with and without paper septa, would have been most valuable for comparison with tests on the individual bisected and quadrasected specimens and with full thickness tests on the same samples before slicing. This might have made it possible to separate the "thickness effects" from other possible changes in the samples produced by slicing and subsequent handling; e.g. the observed loss in thickness of samples after slicing is surprising.

Where $T_R \geq T_N$, it might have been simpler and more desirable to make thermal measurements directly on samples at nominal thickness rather than calculating these values. The authors have been kind in not emphasizing the fact that in the many cases where $T_R < T_N$, actual R-values realized would be even lower than those calculated for nominal thickness. It is certainly clear that there was a thickness recovery problem with these materials in 1977.

In some recent working documents, Brian G. Rennex of the NAHB Research Foundation points out the physical significance of the constants "a, b, and c" in the expression for apparent thermal conductivity given in ASTM Practice C 653-70:

$$k = a + bD + (c/D)$$

where k = thermal conductivity,
a,b,c = constants related to the particular product, and
D = density

Dr. T. S. Lundy
December 17, 1979
Page Two

As Rennex shows, "a" corresponds to the thermal conductivity of air, "b" times "D" corresponds to the thermal conductivity of the solid material, and the "c/D" term corresponds to the radiant thermal transmission. The constant "a", therefore, must be 0.18, and "b" should be positive and $\leq$ 0.01 in U.S. customary units. Most of the values for these constants given in Table 7 and Table D-1 are "unphysical" and artificial, and affect the accuracy of extrapolation adversely.

This study raises valid questions about the accuracy of extrapolating the thermal performance of thick, low density insulations from tests on relatively thin specimens. It also points out the need for improved control of thickness recovery. I'm sure these issues are not being taken lightly, and this work will spur further efforts to answer important questions and improve existing ASTM test methods and practices. Despite sincere differences in opinion regarding the magnitude of "thickness effects" at this time, this work represents a contribution to improvement of our technology, and as our technology improves, everyone should benefit. Thank you for the opportunity to review and comment on this important work.

Yours very sincerely,

D M Greason

D. M. Greason

ldz

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

F. J. Powell of the National Bureau of Standards has asked that the following precede his letter reproduced here:

January 14, 1980

The following comments were the result of an early draft of the present report. Several of the reviewer's comments resulted in additions to the report or modifications of the draft that was reviewed.

Dr. Ted S. Lundy
Program Manager, Building Thermal Envelope
Systems and Insulating Materials
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

Dear Ted:

This is in response to your request for review of draft No. 2, "Thermal Resistance Values (R-values) of Low-Density Mineral Fiber Building Insulation Batts Commercially Available in 1977," enclosed.

Rather than detail here in this letter comment that is of an editorial nature, I am returning the manuscript with red ink markings for perusal by the authors. The draft, in my view, could be much improved editorially.

I shall comment only on what I consider to be substantive technical matters as follows.

Executive Summary - Many people read only the Executive Summary, and I think the purpose and results of the paper are not clearly set forth in this Executive Summary. It is assumed, for example, that readers know the difference between "recovered" thickness and "nominal" thickness when in fact in this paper they have very specific meanings not evident in the Executive Summary. Similarly, results should be given first in terms of the items given in the title, such as R-values measured versus R-values claimed on the label. Initially, terms such as apparent thermal conductivity tend to confuse the reader because from the title of the paper a reader would look for thermal resistance information.

Introduction - Page 2 says that Dynatech obtained samples for thermal performance and, in the first phase, evaluated recovered thickness, density, and thermal resistance at 75°F, and then did a second-phase on thinner specimens sliced from the product. The last paragraph says the samples were shipped to ORNL after phase 1 and returned to Dynatech for phase 2. It would be helpful to the reader to have in the introduction the involvement of ORNL and its contribution to the paper. I suspect that an independent coordinated analysis of the data and results was done, and perhaps some statistical work, at ORNL. If this is so, I would suggest that a statement to that effect be added to the Introduction.

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Sample Procurement, pages 5, 6, and 7 - I suggest a sketch be used to illustrate where the various samples were taken from the rolls.

Table 1, pages 12-13; Table 2, pages 14-15 - Some of the nominal thicknesses in parenthesis are not shown in Tables 1 and 2 or identified as nominal thicknesses. Yet on page 11, paragraph 2 observations comparing recovered thicknesses and nominal thickness are made. In Tables 1 and 2 for manufacturer B, are the results reversed, e.g., does T_R 4.06 in. truly apply to nominal 3.5 in., or should it be opposite 4.0 in.?

Conclusion No. 8, page 65 - The first sentence says, "A large body of data of recovered thicknesses was accumulated in this study." Statistically, in my view, the paper does not present a large body of data. NAHB is known to have much more data than shown in this report. I suggest deleting the first sentence.

The second sentence should be changed to read, "The mean of observed recovered thickness lies below the nominal thickness (label value) for three of the four sets of composite data examined." Table 1 for R-11 composite (3.5 in. nom.) shows T_R = 3.69.

The third sentence cannot be verified in Table 1 because nominal thicknesses for R-11 for manufacturers A and C are not given in the table. If the nominal values of A and C are 3.5 inches, the third sentence is incorrect. The third sentence is a poor sentence as a conclusion, and I would suggest deletion of it as the conclusion drawn in the fourth sentence is much more meaningful and understandable.

3.2.1 Guarded Hot Plate Apparatus and Figure 6 - The apparatus used for measurements, Dynatech Model TCFG-R-4-6 Horizontal Guarded Hot Plate, is such that heat energy from the metering plate flows simultaneously upward through the top specimen and downward through the bottom specimen. Normally, when the paired specimens are of the same thickness and are of high enough density so that convection of air within the material is not a factor, a horizontal or vertical hot plate of the C-177 type allows the relationship $R = x/\lambda$ to be valid. For low-density materials, such as used in this study, convection may be occuring in the top specimen (heat flow up) and may be a minimum in the bottom specimen because of stratification for the heat flow down configuration. Therefore, the heat flow being measured is the result of the larger heat flow upward necessary to maintain a fixed temperature difference and a smaller heat flow down to maintain the same fixed temperature difference. In other words, the bottom specimen may indicate a higher R-value than the top specimen because of convection effects, and the R-values and apparent thermal conductivities as given in this paper are an automatic average of the two. An average of the two R-values does not reflect the R-value that would be expected of the same material in service. One way to determine experimentally if this effect is present in these tests is to place on the bottom a high-density glass fiber board with a known R-value, such as that available from NBS, with the low-density board on top. From the test results the heat flow through the top specimen and hence its R-value can

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be deduced by subtracting the difference from the total heat flow through the high-density board as calculated from the known resistance and measured temperature difference. The reverse procedure would be followed for a heat flow down determination in the low-density material. I would strongly recommend that these additional tests be performed, reported, and discussed in this paper before the present results are published.

3.2.2 Procedure for Determining Apparent Thermal Conductivity, page 29 - I suggest that a short description on how Δx was measured be added here.

3.2.3 Variation of Apparent Thermal Conductivity with Mean Sample Temperature and Appendix C, Table C-1 - Fourth sentence, "The test density at which the measurements were made were determined from thickness and density measurements given in Appendix B except for . . . "

The hot plate tests were apparently made at a material density from Table B-- the column density at nominal thickness. For example, the specimen 1101-λ in B-1 lists a nominal thickness density of 0.650, and Table C-1 density is given as 0.638, from which the thickness 3.56 inches was calculated using the data of Table B-1 in Formula (1). Table B-1 lists a recovered thickness of 4.13 inches and a recovered density of 0.550. It would seem to me that the recovered thickness and density should have been used to determine experimentally the apparent conductivity and the measured thermal resistance of the sample which is calculated from the test thickness used. Why wasn't the recovered thickness used?

3.3 Analysis of the Thermal Conductivity Results - I suggest that it would be useful to the reader to receive a discussion of the basic results of the measurements. For example, in Table 8 the thermal resistance was calculated from the measured values of the area times the temperature difference divided by the heat flux. The apparent thermal conductivity can then be calculated from the measured thickness divided by the specimen thermal resistance. The tabular results in Tables 8, 9, and 10 should be discussed. Then, say why the data as given in Table 14 is presented in terms of nominal thickness and resistance and discuss the significance of the results presented.

The last paragraph should be deleted as it only can be substantively understood by statisticians.

4.1 Conclusions - I suggest a conclusion be drawn concerning the mean R-value of the insulations based on the actual measured recovered thickness, as these were the measurements made. Then it should be stated that these data were used to derive mean R-values at nominal thicknesses and define nominal in the conclusions.

Conclusion 1 - See marked copy. I suggest the following sentence to follow the second sentence in this conclusion. "The results will meet the requirements of ANSI/ASTM C 665-78, Standard Specification for Mineral Fiber Blanket Thermal Insulation for Wood Frame and Light Construction Buildings."

4

Conclusion 2 - I suggest the practical meaning of "99% confidence interval" be included as part of this conclusion.

Conclusion 8 - I suggest deleting the first sentence. What is a large body of data? Sentence 2 is not accurate. Table 1 shows 3 out of 4, with R-11 composite mean greater than (3.69) this nominal (3.5). All other composites do show nominal greater than mean. Delete the third sentence if "three out of four" change is made.

Add, "See Table 2" at the end.

Conclusion 9 - Suggest a conclusion 9 as follows. "The desirability of specifying required performance by R-value and not by thickness was verified in this investigation.

Sincerely,

Frank J. Powell, Manager
Thermal Insulation Program
Office of Energy Programs

Enclosure

cc:
J. Snell/A. Paladino
R. Jones/B. Peavy/C. Siu
E. Freeman, DOE

"Summary Evaluation" from submission by Brian G. Rennex, NAHB Research Foundation, Inc.

A good way to summarize the evaluation of this report is to comment on how well the goal of comparing a full-thickness test method with a sliced-batt test method is met. At the onset, I should say that this goal and the corollary goal of determining what R-values are actually to be found on the marketplace are extremely laudable. The catch is that it is very difficult or, to put it another way, it would require a considerable effort to arrive at statistically well-substantiated conclusions. The general reason for this difficulty is that fibrous insulation products are variable from plant-to-plant, manufacturer-to-manufacturer, product-to-product and producing machine-to-producing machine.

In fact, there are two comparisons going on between the full-thickness and the spliced-batt test methods. One comparison is between the determination of an R-per-unit-thickness value based on a full-thickness measurement and the determination based on a smaller-thickness measurement. With certain reservations, it is certainly most likely that the best R-per-unit value will result from measurements at a greater thickness. However, the reservations are very important. These deal with the uncertainty in measurement values of thermal conductivity at larger thicknesses. That is, there are at least two likely factors involved in the measurement uncertainty: namely, thickness effects and edge effects. In order to really establish whether the smaller-thickness values are not as good as the full-thickness values, one should really know the accuracy of the apparatus. In fact, the accuracies of large-scale guarded hot plates are not well-known. The comment on Table 24 notes a 5% discrepancy in the data within this report for a comparison between 1-1/2" measurements and 3" measurements. My conclusion is, then, that it is not possible at this time to make a well-substantiated comparison between measurements at smaller-thicknesses and at thicknesses of 3" or more.

A second part of this comparison between the so-called full-thickness and sliced-batt test method is, in fact, a comparison between a measurement at one thickness to determine a K-value and a measurement at three thicknesses to determine a K-value by means of a K vs. density curve. The inadequacy of making a single thickness measurement is that it involves a good chance that there will be significant voids at the sample boundary, in which case, there will be additional errors in the K-value measurement. A second difficulty is that a measurement at a single thickness or density does not permit the determination of a K vs. density curve. This in turn results in a less representative characterization of an insulation product, because thermal conductivity measurements must be made for each data point. The alternative is to determine an average density of a product based on measurements of a much larger volume of insulation. The second part of the alternative is to then determine a K vs. density product curve and to determine the K-value at the nominal density that was determined in the first part. In conclusion, the use of the ASTM C653 test method avoids a boundary-void source of error and results in a more representative sampling of an insulation product.

An additional consideration in comparing the two methods is the identical treatment of samples. The questions that arose in the comments were the following. Was the test density determined only in the metered area or was it assumed to be the same for the entire insulation sample? Did the full-thickness measurement result in boundary voids? The samples that were sliced by the Research Foundation seemed to have been more compressed than the typical samples measured at the Research Foundation. The determination of the average density is different. Sample age may have been a factor, and it would be useful to know the sample age of the samples used in this report. An additional consideration is related to statistics. My overall impression is that the number of samples was too small to be representative of the industry. There are several examples that support this opinion. One was that a comparison of nominal density, which should have been the same, showed that values in which the Research Foundation had a great deal of confidence were significantly outside of the 99% interval quoted for the same properties in the report. In addition, the use of the "t" test and the percentage interval range must assume a uniform population. In fact, the population of insulation prodcuts vary from plant to plant. Perhaps, this is the reason that the 99% interval comparisons do not correspond with common-sense comparisons with well established average values. An additional indication of whether or not the statistics in the report are characteristic of the insulation product is found in the a, b and c coefficient values. If the statistics were adequate, these values should converge to physically reasonable values. This was not the case, even for the composite values.

On the basis of the above considerations, I would like to make the following recommendation. This recommendation is that the authors examine with care whether or not the statistics in the report are misleading. Any statistics that are considered to be misleading should not be included in the report. That is, any dressing up of the data to make it seem more certain is not helpful to the investigation of the thermal properties of insulation. I think that the investigation should be considered a preliminary investigation based on a small and not-representative sampling of the insulation industry. A result of this preliminary investigation would certainly be that the report goals should be investigated in a more thorough manner. My recommendation for such an investigation would be that it should be carried out by more than one laboratory to insure that there are not systematic differences between different testing laboratories. In addition, I would recommend that a very precise appratus be used in such an investigation, for example a large-scale heat flow meter, and that the values of this apparatus be tied to some national standard. This would help to eliminate uncertainties due to systematic errors between large-scale heat flow apparatuses.

In my opinion, this study has served the very valuable purpose of establishing the complexity and the overall difficulty associated with a study of, "What R-values are actually out there on the marketplace." I think the authors should emphasize this valuable accomplishment.

GEORGE A. HOFFMANN President
JOSEPH D. MURPHY Vice President
THOMAS E. CAVANAUGH III Treasurer

SHELDON H. CADY Executive Vice President
KENNETH D. MENTZER Director Materials & Standards

mima
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March 21, 1980

MIMA STATEMENT ON ORNL/DYNATECH R-VALUE REPORT

During 1977 when this study was conducted, the Mineral Insulation industry was manufacturing and testing insulation products under procedures that represented the state of the art at that time. The participants relying on these procedures included not only the companies that manufacture materials, but the regulatory and procurement agencies of the federal government, model code bodies, independent testing laboratories, the National Bureau of Standards, and ASTM. The thermal test procedures employed then are the same as those currently in use. The basic testing method is to obtain representative material specimens 1-1½" thick; test for thermal conductivity (k) in apparatus which has been calibrated with the available one-inch standard reference material from the NBS; then extrapolate this data to the product's full thickness R-value using procedures developed by ASTM. These test methods and procedures have been recently reaffirmed by ASTM and NBS as the most appropriate for batt-type mineral fiber building insulation.

This study was initiated to conduct experimental tests for R-value at full product thickness (3½" and 6") and to obtain data for comparison with the conventional test methods. It should be understood that the thermal tests were performed by the only laboratory in the United States which at that time had a guarded hot plate equipment capable of testing material at greater than 2 inches thick. Equipment of this type is subject to errors which increase with test thickness and, indeed, the relative accuracy of this apparatus, testing at full thickness, (versus the conventional method) will not be known until thick specimen calibration standards are produced by the NBS in 1981.

Another possible source of error in the R-values reported in this study is associated with the measurement of recovered thickness. Data available from an independent source, the National Association of Home Builders Research Foundation (NAHBRF), taken from a much larger and comprehensive sampling program, directly refutes the low recovered thickness data represented by a limited sampling in this report and the subsequently understated R-values which are the products of such measurement. Since the report data and NAHBRF data relative to thickness recovery were derived utilizing the same test methods (ASTM C167) it raises questions about other physical property test results reported in the study. For example, densities reported in this study were measured on the entire 24" x 24" specimen (including pieces added to make up the guard area) instead of the generally accepted method of using the 12" x 12" heat flow measurement as practiced within the NAHBRF program. By so doing the study introduced variations into the K/density relationship that are not substantiated by the participanting manufacturers' quality control records.

Other questions have been raised concerning the validity of the data and conclusions represented in the study. For example, the sample size is considered inadequate; some of the material was not representative; and the method of statistically extending the relatively small sample to the entire production of mineral fiber batt and blanket insulation is at best questionable. Statisticians clearly disagree with the treatment of the data in this study as being representative of the population of insulation produced during the study period in 1977.

Thermal data contained in the study represent measurements obtained from an experimental procedure that has not as of this date been validated through experience or accepted as to accuracy by the federal government, ASTM, private and commercial testing laboratories, or members of the insulation industry. Any attempt to portray the thermal data as representative of actual product R-value in 1977 is unjustified.

Finally, the only conclusions that should be drawn from this early experimental study and other related studies are:

* That full thickness testing, as conducted, produced lower R-values than conventional slice testing.
* That the differences in R-values reported in this study are more than twice as large as those reported in recent technical seminars where efforts to specifically quantify the so-called thickness effect were detailed.
* That the experimental and unproven apparatus used was unique in 1977 and had not been either calibrated at these thicknesses by the Natioanl Bureau of Standards or checked by a round-robin test program as is the common practice in the industry. The

known errors which contribute to and exacerbate the apparent thickness effect (such as edge loss and thermal contact resistance) were not identified and quantified and therefore, are still reflected in the data and the resulting conclusions.

* That the relative impact of the so-called thickness effect has not been, and still needs to be, quantified.
* That the relative accuracy of testing at full thickness without calibration standards versus the accuracy of slice testing with NBS calibration standards has not been established by this study and remains a need.
* That industry recognizes existence of the thickness effect, but that the current lack of calibration capability might inject more error than could be attributed to the thickness effect alone. (See footnotes to ASTM C177 and C518).
* That when full thickness calibration stancards are available from the NBS, establishing absolute values for certification purposes, an adjustment factor should be developed for slice testing and extrapolation to full thickness R-values.
* That this study and report with their acknowledged limitations, should be superceded by a new study which utilizes a number of labs (at least three) and a far larger sampling of products from current production.

In conclusion, MIMA does not object to the concept of full thickness testing, and indeed advocates its use, but only when the possible errors can be reliably assessed by comparison testing using NBS low density calibration standards of thickness equal to the thickness of the products to be measured. Until such standards are available, full thickness testing must be regarded as a tentative experimental procedure and not used for product evaluation. NBS has indicated that in the future, (estimated to be early 1981), calibrated standards from NBS will help resolve this situation.

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

March 21, 1980

Mr. D. L. McElroy
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

Dear Mr. McElroy:

In view of the very limited time I had to examine the draft report entitled "An Experimental Study of Thermal Resistance Values of Low-Density Mineral-Fiber Building Insulation Batts Commercially Available in 1977", I can only give you comments based on a very cursory examination of this report.

The statistical treatment of the data, on the whole, appears to be fairly adequate, but shows a number of weaknesses of which the following are examples:

1. In Table 1, the data for any given manufacturer were pooled for all plants from this manufacturer. If there is an additional component due to plant-to-plant variability, the standard deviation resulting from this pooling will generally be an underestimate of the true standard deviation and the length of the confidence interval for the mean will likewise be underestimated.

2. The half-ranges, expressed as percent of the means (last column of Table 2) are poor measures, expecially when used to compare manufacturers, since different manufacturers were represented by different sample sizes.

3. In Table 7, the values of a, b, and c were each obtained by solving 3 equations in 3 unknowns. This does not allow for an evaluation of the uncertainties of these calculated values.

4. Page 45: It is not correct to state that in a probability plot "A straight line indicates normality". First of all, it is hard to judge the linearity of a cumulative probability plot. Secondly, even a test of significance (such as Hahn and Shapiro) can never prove normality. It can only indicate that there is no conclusive evidence against it. To use this as a basis for calculating tolerance intervals, especially when sample sizes are not large, is a risky procedure, since tolerance intervals are quite sensitive to the nature of the underlying distribution.

These comments are not exhaustive. I would recommend that if a final draft of this report is prepared for publication, a closer look should be taken at the statistical treatment of the data. While not seriously wrong, it could be improved.

Sincerely yours,

John Mandel
Statistical Consultant
National Measurement Laboratory

COMMITTEE E-11
ON
STATISTICAL METHODS

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March 24, 1980

Mr. D. L. McElroy
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

Dear Mr. McElroy:

Re: DOE report on thermal resistance values of insulation materials

Although your letter of March 6 and the report on insulation materials arrived the very next day after you phoned, deadlines on two other projects on which I was working prevented me at the time from making more than a cursory review of the report. As you probably know, I called Mr. Yarbrough on the 14th and indicated my reservations with respect to the statistical analysis in view of the manner in which the sampling of the insulation material was carried out, hoping that this would at least give you some input from me prior to the meeting on March 19. I now have had time to study the report in depth and would like to make the following comments.

1. It is unfortunate that the sampling procedure was not statistically designed for the study of the distribution of R-values for mineral fiber batt insulations commercially available in 1977, which was one of the primary objectives of the report. All that can be done now in this regard is to proceed as if certain sets of data are random samples from specific populations in which you are interested, checking this assumption against possible evidence of nonrandomness. I will discuss this further below. It is desirable that the report make very clear the hypothetical nature of its findings.

2. In view of Comment 1, the report should give more information than it does on just how the sample units of insulation material were obtained. The geographical locations should be specified. It is stated that retail outlets were "randomly" selected at each location, but just what does that mean? Were the various outlets listed and a table of random numbers used to choose those that went into the sample or does it simply mean that no particular rule was followed in selecting the outlets. I gather that units of material from a given outlet were not randomly chosen but were purposely selected so as to meet a quota with respect to five plants each for

three given manufacturers and also that an effort was made to get units from different shifts or dates of manufacture. It would be informative if the report could give full historical details of just how the units of at least one of the insulation materials were selected. For a reader such as myself who has little knowledge of insulation material, it would also be helpful to describe the sampling unit for each material. Is it a roll? What are its dimensions?

3. I found the coding of the sampling units somewhat puzzling. The fourth digit from the left generally indicates the manufacturing facility and the manufacturer. I note, however, that the R-11 package coded 1103-3 comes from facility 2 of manufacturer A. Does this have any significance? Also why is it numbered 1103-3 and included in the set in which other packages are numbered 1103-1 and 1103-2? There are other cases of this kind in Tables A-1 and A-2.

4. A fuller explanation should be given as to how specimens were selected from the various sampling units. It is stated that all specimens come from the middle portion of a sampling unit. The pair of apparent thermal conductivity specimens are stated to be "cut from approximately the same location" which I presume means that they were approximately contiguous. The density specimens are said to come from "different locations". Was the distance between them generally about the same and if so, can information be given on this? Also were the locations from which subsequent specimens for Phase 2 of the study were taken as far from the locations from which the density specimens for Phase 1 were taken as the two latter locations were from each other?

5. In view of the manner in which the sample units were obtained it is well to look at the test results for possible evidence of lack of homogeneity. Toward this end I have prepared three charts, copies of which are enclosed. Figure 1 is a plot of the absolute difference between two measurements for the same batt of the test density of R-11 fiberglass. Looking upon Figure 1 as a range "control chart" for a sample of 2, we note that none of the points fall above the upper "control limit." The set of three small differences for manufacturing factury A-1 suggests that it might be worthwhile studying within-batt variability further, but the reported data do not show a striking lack of homogeneity with respect to within-batt variability of test density.

Figure 2, which is a plot of average test densities, does show a definite lack of homogeneity. I have been told that the obvious difference between the test densities for Manufacturers A and C on the one hand and those for Manufacturer B on the other is due to the difference in the process of manufacture and was to be expected. It casts doubt, however, on the usefulness of any composite analysis of the variation in test densities between facilities. Variability within a facility does not show the same striking difference between manufacturers. Figure 2 signals the need for being generally cautious in merging data for Manufacturer B with data for other manufacturers.

Figure 3, which gives R-values for R-11 fiberglass for recovered thickness, shows little difference in the averages of the three manufacturers. It is possible that numerical analysis might show significant differences between the means of the different manufacturing facilities and/or the variability of facility output.

6. I hesitate to comment on the procedure for going from R-values at recovered thickness to R-values at nominal thickness since I know little about the properties of insulation material nor the physical relationships that underlie the form of equation (7). I gather that the values of the constants a, b, and c that are considered appropriate for a given material are a function of the properties of that particular material. Since Manufacturer B uses a different manufacturing process than manufacturers A and C, I would think that values of a, b, and c derived by least squares for each separate manufacturer would be a more appropriate set to use than the least squares values of a, b. and c derived from the composite results. This presumption appears to be supported by enclosed Figures 4 and 5. Figure 4, which displays the R-values at T_N computed from composite least squares values for a, b, and c, shows a greater variation in the median values for each manufacturer than does Figure 5, which displays the R-values at T_N computed from least squares values for a, b, and c derived for each manufacturer separately.

7. I have not checked to see whether the R-values at T_N derived from separate manufacturer least squares estimates of a, b, and c follow a normal distribution as Figure 9 of the report shows for the R-values at T_N derived from composite least squares estimates of a, b, and c. I do not believe that this is a particularly relevant consideration. Evidence that a set of data plots along a straight line on normal probability paper is not "proof" that the data are random. A time series that follows a logistic type of growth similar to the ogive of a cummulative normal distribution would plot linearly on normal probability paper. For the case in hand, enclosed Figure 4 indicates that R-values for Manufacturer B are predominant on the lower tail of the distribution and R-values for Manufacturer A are predominant on the upper tail, which is not what you would expect from purely random data.

8. In line with the above argument, I believe it would be desirable to delete the presentation of confidence limits for the composite mean. Confidence limits for the mean output of each manufactuere could be presented if it is clearly stated that these are based on the not definitively verified assumption that in each case the data are a random sample from a normal distribution.

9. With respect to the percentage of R-values below the nominal value or below .9 of the nominal value, I believe, for reasons I have indicated, that it would be better to work with the R-values at T_N derived from least squares estimates of a, b, and c for each separate manufacturer rather than with the R-values derived from the composite estimates of a, b, and c, i.e. it would be better to work with data of enclosed Figure 5 instead of enclosed Figure 4. The argument could be made that if the data of enclosed Figure 5 could be viewed as a random sample from each manufacturer's output and if the proportion of the total output turned out by each manu-

facturer is the same as the proportion indicated in the sample, then using the binomial distribution, a lower .99 confidence limit can be derived for the percentage of the combined output that falls below the nominal R or .9 of the nominal R. Thus, in the enclosed Figure 5, 10 out of 42 or approximately 24% of the points plot above an R-value of 11. From the enclosed copy of a page from the National Bureau of Standards Tables of the Binomial Probability Distribution, we note that the proportion of R-values in the population that are equal to or above 11 would have to be approximately 40% to have a probability of 99% of getting 10 or more R-values above 11 in a random sample of 42. Thus the lower .99 confidence limit for the population proportion of R-values below 11 would be approximately 1 - .40 or 60%. [Compare this with the 69% lower limit given in the report.] A similar procedure could be used to find the lower .99 confidence limit for the population proportion of R-values below 9.9. I am skipping over some of the niceties involved in this type of analysis, but I believe the procedure is good enough for your purposes. I would like to note, however, that the proper form for a confidence interval statement is to say that there is a probability of .99 that the interval .60 - 1.00 brackets the population proportion p.

10. In the above analysis no use is made of the assumption of a normal distribution. The Bowker-Lieberman reference on p. 50 of the report is not pertinent to the analysis. What the Bowker-Lieberman table gives is a list of the k-factors that could be used in making a statement that there is .99 confidence that 95%, or $(1 - \alpha)$ in general, of the population values will be covered by the interval 0 to $\bar{X} + ks$. This is a tolerance interval statement dependent on the assumption of normality. It is not a confidence interval statement for the population proportion p and does not involve the nominal value 11.

11. The analysis of the effect of splicing appears to be straightforward. The only comment I have is to note that if 0.9 is added to the R-values at T_N shown in enclosed Figure 5 for Manufacturer C, all but one will be raised to values either above 11 or very close to 11.

12. A general comment is that it would be very helpful to a reader like myself who is not knowledgeable in the area to present at the beginning a concise statement of the logic of determining R-values at nominal thickness. I presume emphasis is put on R-values at nominal thickness rather than on R-values at recovered thickness because this is the way a product is described in the market and the report is interested in showing how well product sold complies with the manufacturer's certification. If there are other reasons for being interested in R-values at nominal thickness, they should be stated. It would also be helpful if all the tables and charts were annotated so that the contents are fully explained or referenced.

I am sending copies of this letter to John Mandel, since he is a fellow member of Committee E-11 who was asked to review the report and to B. G. Rennex who appears to have considerable interest in it. I hope this review will reach you in

Mr. McElroy
March 24, 1980
Page 5

time to be of use to you. If you have any questions or if I can be of any further assistance, please let me know. The report is a very significant undertaking and deserves all the attention that can be given it.

Sincerely yours,

Acheson J. Duncan

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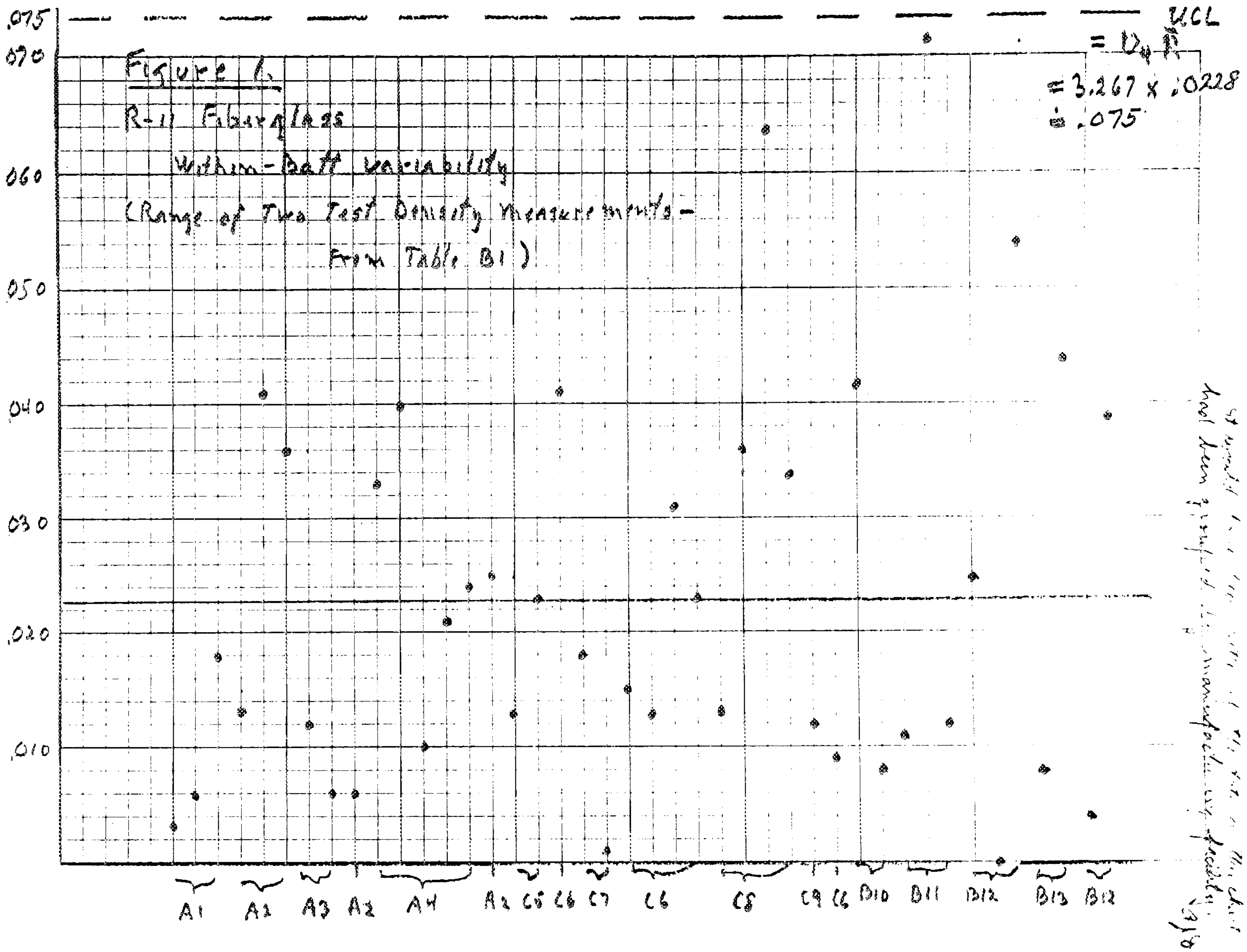
Department of Mathematical Sciences
The Johns Hopkins University
Baltimore, Md. 21218

AJD/djm

ENCLOSURES

cc: J. Mandel
B. G. Rennex

P.S. An analysis similar to that developed above for R-11 fiberglass can also be applied to the other insulation materials.



.075
.070
.060
.050
.040
.030
.020
.010
UCL
= D4 R̄
= 3.267 x .0228
≐ .075
Figure 6
R-11 Fiberglass
Within-Batt Variability
(Range of Two Test Density measurements -
From Table B1)
A1
A2
A3
A2
A4
A2
C5
C6
C7
C6
C8
C9
C6
B10
B11
B12
B13
B12

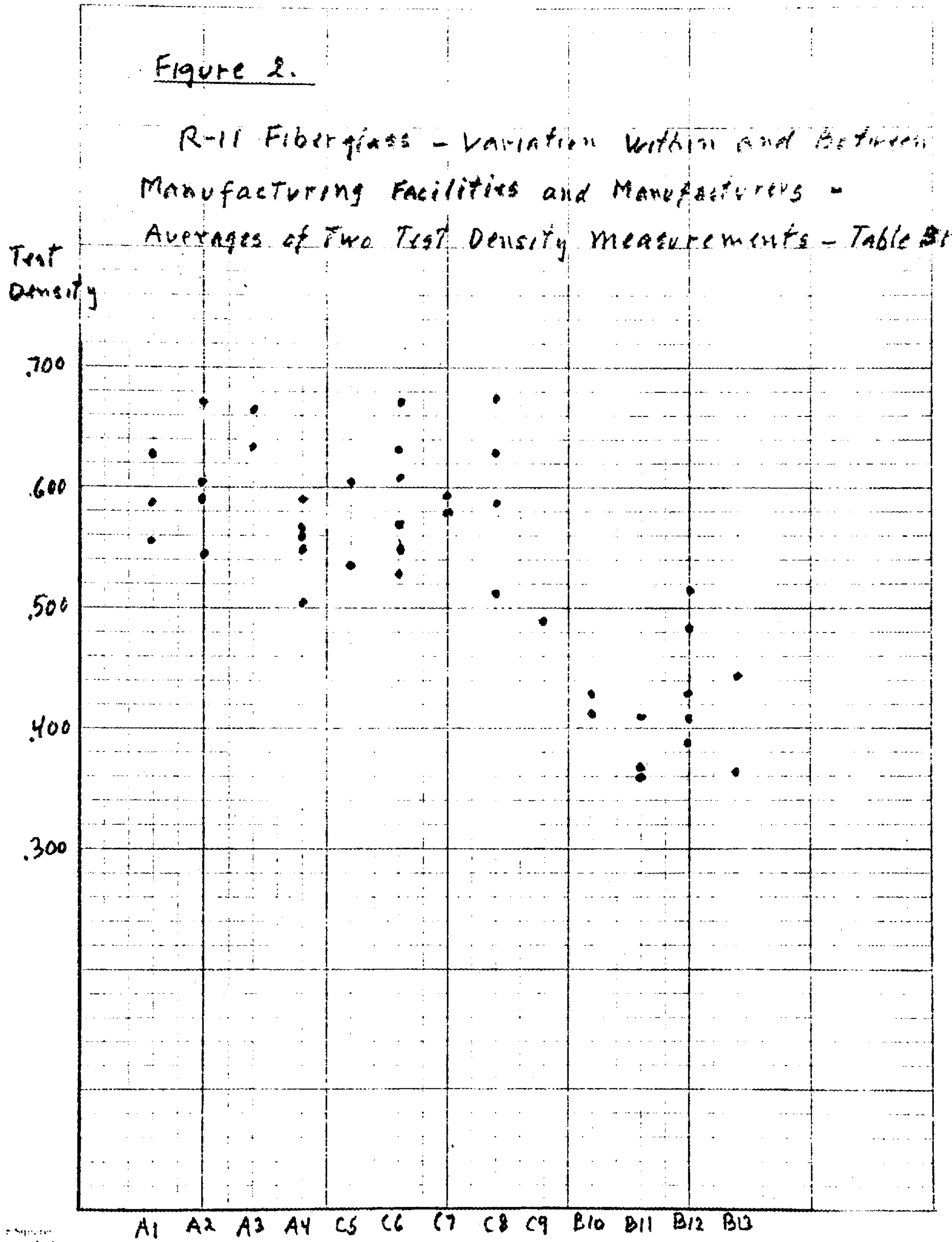


Figure 2.
R-11 Fiberglass - Variation Within and Between Manufacturing Facilities and Manufacturers - Averages of Two Test Density Measurements - Table B1
Test Density
.700
.600
.500
.400
.300
A1 A2 A3 A4 C5 C6 C7 C8 C9 B10 B11 B12 B13

Figure 5

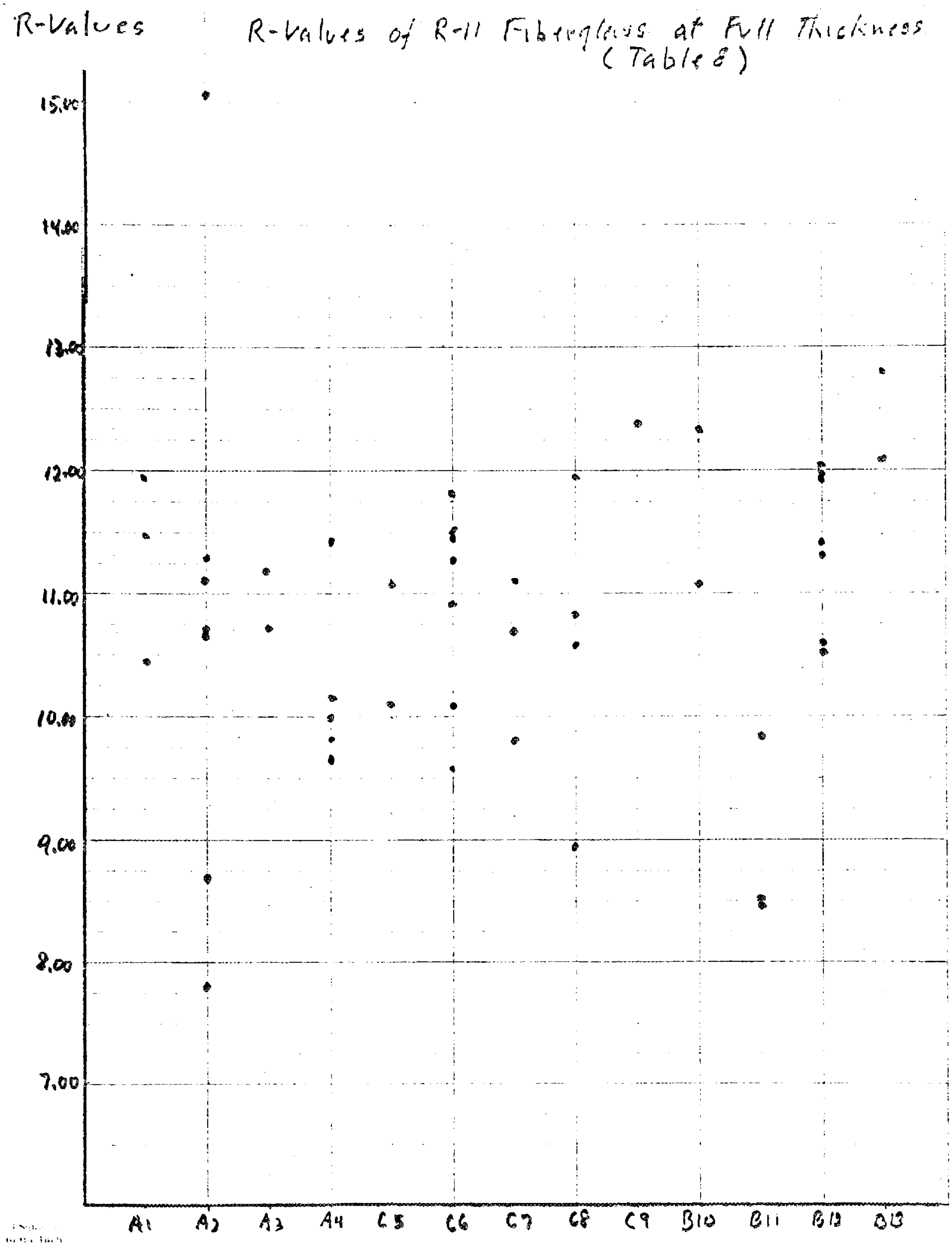

R-Values
R-Values of R-11 Fiberglass at Full Thickness (Table 8)
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
A1
A2
A3
A4
C5
C6
C7
C8
C9
B10
B11
B12
B13

Figure 4

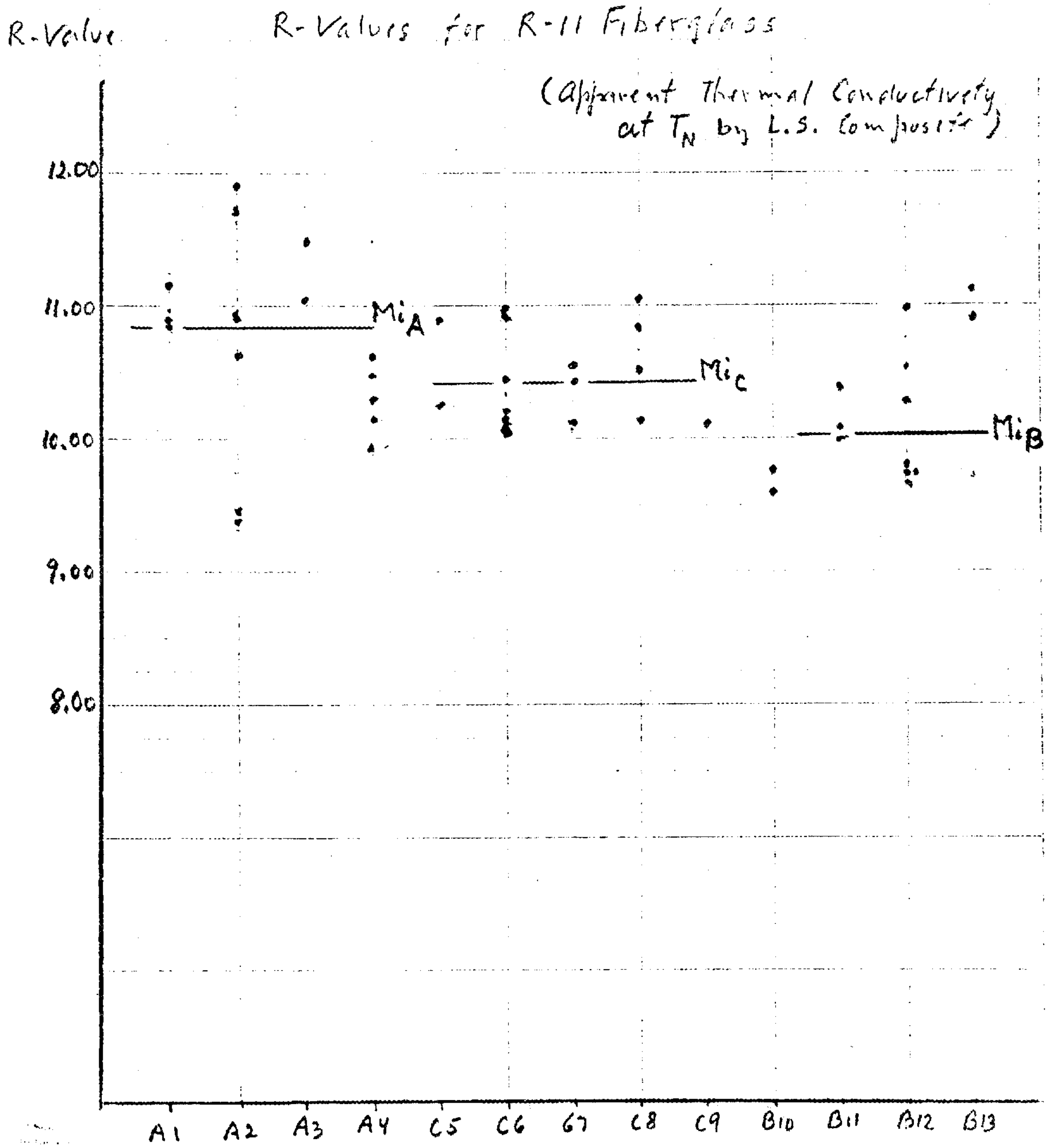
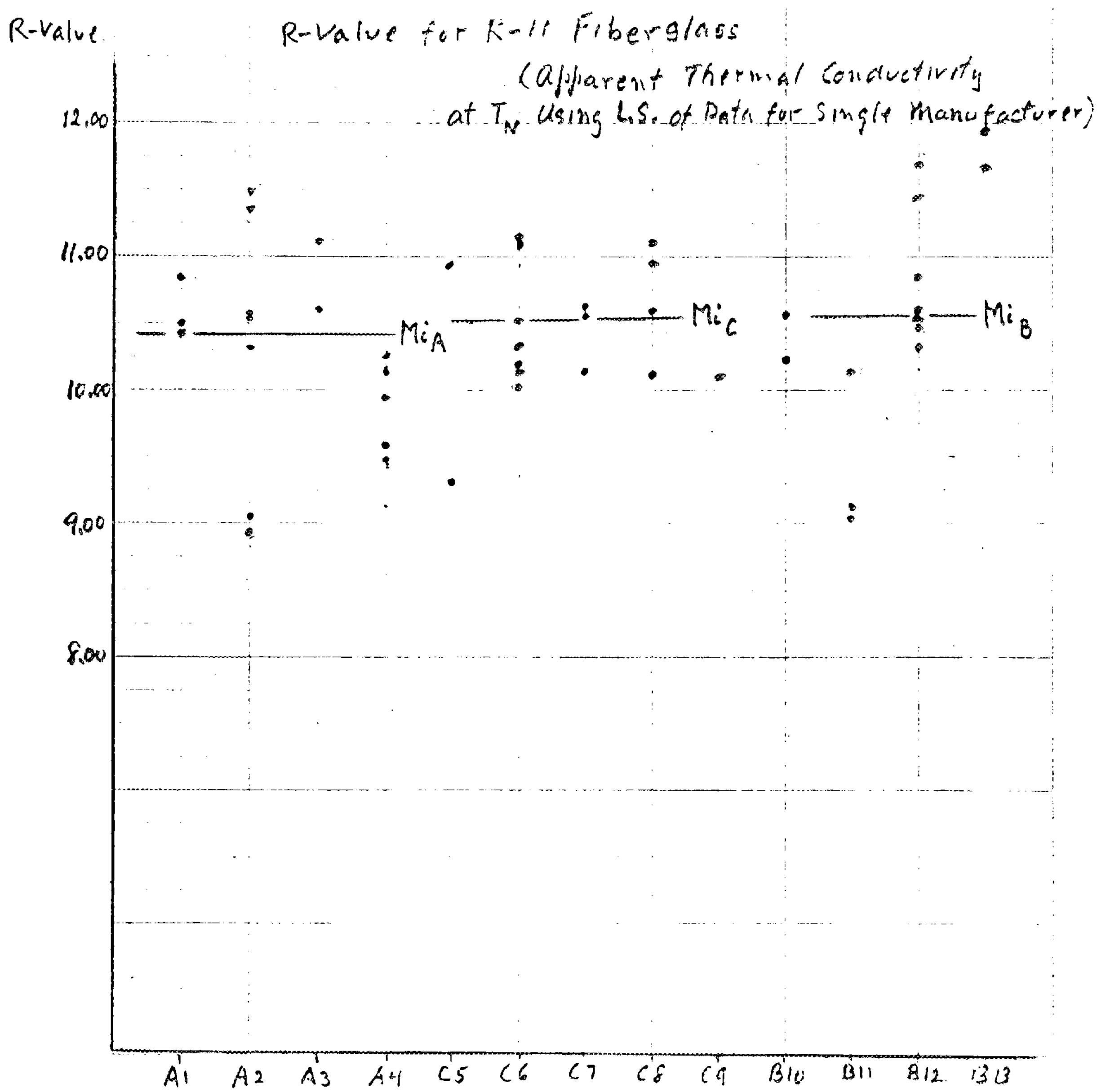

R-Value
R-Values for R-11 Fiberglass
(Apparent Thermal Conductivity at T_N by L.S. Composite)
12.00
11.00
10.00
9.00
8.00
Mi_A
Mi_C
Mi_B
A1
A2
A3
A4
C5
C6
C7
C8
C9
B10
B11
B12
B13

Figure 5


R-Value
R-Value for R-11 Fiberglass
(Apparent Thermal Conductivity
at T_N Using L.S. of Data for Single Manufacturer)
12.00
11.00
10.00
9.00
8.00
Mi_A
Mi_C
Mi_B
A1
A2
A3
A4
C5
C6
C7
C8
C9
B10
B11
B12
B13

BINOMIAL DISTRIBUTION

Table 2 - Partial Sums

$$\sum_{s=r}^{n} \binom{n}{s} p^s q^{n-s}$$

p	n=42 r=10	n=42 r= 9	n=42 r= 8	n=42 r= 7	n=42 r= 6	n=42 r= 5	p
.01	.0000000	.0000000	.0000000	.0000002	.0000038	.0000625,	.01
.02	.0000000	.0000001	.0000016	.0000187	.0001809	.0014700	.02
.03	.0000004	.0000036	.0000311	.0002342	.0015116	.0082092	.03
.04	.0000047	.0000351	.0002282	.0012873	.0062296	.0254648	.04
.05	.0000328	.0001930	.0009991	.0044996	.0174320	.0572779	.05
.06	.0001501	.0007332	.0031518	.0118124	.0381952	.1052217	.06
.07	.0005177	.0021585-	.0079288	.0254516	.0707189	.1682447	.07
.08	.0014509	.0052706	.0168985-	.0474631	.1158089	.2432648	.08
.09	.0034679	.0111552	.0317303	.0792815-	.1727694	.3260560	.09
.10	.0073092	.0210887	.0539163	.1214472	.2396264	.4121041	.10
.11	.0139122	.0363838	.0845114	.1735164	.3135418	.4972607	.11
.12	.0243379	.0582058	.1239495-	.2341484	.3912839	.5781477	.12
.13	.0396608	.0873978	.1719635-	.3013212	.4696521	.6523313	.13
.14	.0608387	.1243470	.2276148	.3726111	.5458012	.7183226	.14
.15	.0885857	.1689152	.2894096	.4454784	.6174432	.7754648	.15
.16	.1232691	.2204377	.3554734	.5175163	.6829350,	.8237645,	.16
.17	.1648469	.2777866	.4237486	.5866372	.7412749	.8637067	.17
.18	.2128517	.3394824	.4921842	.6511880	.7920339	.8960823	.18
.19	.2664226	.4038323	.5588969	.7099974	.8352518	.9218430	.19
.20	.3243761	.4690763	.6222882	.7623677	.8713184	.9419892	.20
.21	.3853048	.5335215-	.6811154	.8080261	.9008590	.9574906	.21
.22	.4476890	.5956528	.7345172	.8470515,	.9246320	.9692360	.22
.23	.5100087	.6542116	.7820026	.8797906	.9434472	.9780058	.23
.24	.5708430	.7082407	.8234122	.9067745-	.9581040	.9844624	.24
.25	.6289497	.7570975-	.8588619	.9286433	.9693491	.9891519	.25
.26	.6833194	.8004408	.8886794	.9460829	.9778511	.9925133	.26
.27	.7332053	.8381977	.9133393	.9597760	.9841887	.9948922	.27
.28	.7781278	.8705176	.9334048	.9703671	.9888482	.9965546	.28
.29	.8178598	.8977212	.9494772	.9784402	.9922281	.9977022	.29
.30	.8523972	.9202482	.9621562	.9845071	.9946478	.9984848	.30
.31	.8819199	.9386096	.9720104	.9890032	.9963576	.9990121	.31
.32	.9067480	.9533467	.9795584	.9922898	.9975504	.9993632	.32
.33	.9272992	.9649976	.9852580	.9946602	.9983720	.9995941	.33
.34	.9440478	.9740733	.9895016	.9963471	.9989309	.9997443	.34
.35	.9574910	.9810406	.9926174	.9975317	.9993063	.9998407	.35
.36	.9681203	.9863128	.9948739	.9983527	.9995553	.9999020	.36
.37	.9764011	.9902458	.9964858	.9989143	.9997184	.9999404	.37
.38	.9827582	.9931384	.9976215,	.9992934	.9998238	.9999642	.38
.39	.9875678	.9952361	.9984109	.9995460	.9998912	.9999787	.39
.40	.9911543	.9967359	.9989521	.9997120	.9999336	.9999875,	.40
.41	.9937901	.9977933	.9993181	.9998197	.9999600	.9999928	.41
.42	.9956994	.9985282	.9995622	.9998886	.9999762	.9999959	.42
.43	.9970624	.9990317	.9997227	.9999321	.9999861	.9999977	.43
.44	.9980213	.9993718	.9998268	.9999592	.9999919	.9999987	.44
.45	.9986860	.9995982	.9998934	.9999758	.9999954	.9999993	.45
.46	.9991399	.9997467	.9999353	.9999859	.9999974	.9999996	.46
.47	.9994453	.9998427	.9999613	.9999919	.9999986	.9999998	.47
.48	.9996476	.9999037	.9999772	.9999954	.9999992	.9999999	.48
.49	.9997795,	.9999420	.9999868	.9999974	.9999996	.9999999	.49
.50	.9998642	.9999656	.9999925-	.9999986	.9999998	1.0000000	.50

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