OAK RIDGE NATIONAL LABORATORY LIBRARIES
3 4456 0553813 9

179

ORNL/TM-11720

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Interlaboratory Comparison of Four Heat Flow Meter Apparatuses on Planed Polyisocyanurate Boards Foamed with CFC-11

R. S. Graves
D. L. McElroy
R. G. Miller
D. W. Yarbrough
R. R. Zarr

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
CIRCULATION SECTION
4500N ROOM 175
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON.
If you wish someone else to see this report, send in name with report and the library will arrange a loan.
ORNL-118 (6-97)

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-11720

Metals and Ceramics Division

INTERLABORATORY COMPARISON OF FOUR HEAT FLOW METER APPARATUSES ON PLANED POLYISOCYANURATE BOARDS FOAMED WITH CFC-11

R. S. Graves, D. L. McElroy, R. G. Miller,
D. W. Yarbrough, and R. R. Zarr

Date Published: June 1991

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

Prepared for the
U.S. Department of Energy
Office of Buildings Energy Research
EC 01 01 00 0

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6092
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

OAK RIDGE NATIONAL LABORATORY LIBRARIES

3 4456 0553813 9

CONTENTS

LIST OF FIGURES v

LIST OF TABLES vii

ABSTRACT 1

1. INTRODUCTION 2

2. MEASUREMENT PROCEDURE 2

   2.1 TEST SPECIMENS 3

   2.2 TEST RESULTS 5

3. CONCLUSIONS AND RECOMMENDATIONS 16

4. ACKNOWLEDGMENTS 17

5. REFERENCES 17

APPENDIX A: LETTER REPORTS FROM JWRC, NIST, AND TTU 19

APPENDIX B: ORNL UTHA TEST RESULTS 25

LIST OF FIGURES

Figure		Page
1	Interlaboratory comparison test results as a function of test specimen age after planing	7

LIST OF TABLES

Table		Page
1	Calibration factor procedure for heat flow meter apparatuses	4
2	Compilation of 20 test results from JWRC, NIST, ORNL, and TTU	6
3	Results of a least-squares method of fitting 20 thermal conductivity test results to $k = A + Bt$	8
4	Results of a least-squares method of fitting 15 thermal conductivity test results to $k = A + Bt$	10
5	Adjusted values of apparent thermal conductivity at 75°F	12
6	Comparison of least-squares fits of thermal conductivity data sets	13
7	Comparison of thermal conductivity data sets of Board 1, Board 2, and Boards 1 + 2	14
8	Comparison of thermal conductance values for data sets	15

INTERLABORATORY COMPARISON OF FOUR HEAT FLOW METER APPARATUSES ON PLANED POLYISOCYANURATE BOARDS FOAMED WITH CFC-11[1]

R. S. Graves[2], D. L. McElroy[2], R. G. Miller[3],
D. W. Yarbrough[4], and R. R. Zarr[5]

ABSTRACT

This report describes an interlaboratory comparison of apparent thermal conductivity (k) results on planed polyisocyanurate (PIR) boards foamed with chlorofluorocarbon-11 (CFC-11). Sequential tests were conducted at 75°F (24°C) at four facilities on two rigid (PIR) boards, individually and as a pair, using four comparative heat flow meter apparatuses that meet American Society for Testing and Materials (ASTM) C 518. The specimens were shipped from lab to lab, and the testing sequence (Lab 1, 2, 3, 4, and 1) yielded 15 k-values that have a two standard deviation (2 σ) value of 2.2% when described by:

$$k(\text{Btu}\cdot\text{in./h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1365 + 1.15 \times 10^{-4}\ t$$

$$k(\text{W/m}\cdot\text{K}) = 0.0197 + 1.66 \times 10^{-5}\ t\ ,$$

where t is the elapsed time in days after planing of the boards. The 2 σ value for five tests on Board 1 was 2.1% and the 2 σ value for five tests on Boards 1 + 2 was 2.2%; but the 2 σ value for five tests on Board 2 was 2.8%. This may be associated with a larger variation in measured specimen thickness (4.1%) for Board 2 than for Board 1 (1.7%) and Boards 1 + 2 (1.6%).

The 15 thermal conductance (C) values have a 2 σ value of 3.2% when described by:

$$C\ (\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1069 + 1.20 \times 10^{-4}\ t\ .$$

Thus, the 2 σ (k-values) of the interlaboratory comparison is not reduced by comparing C values.

---

[1]Research sponsored by the Office of Buildings Energy Research, Building Systems and Materials Division, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

[2]Oak Ridge National Laboratory, Oak Ridge, TN

[3]Jim Walter Research Corp., St. Petersburg, FL

[4]Tennessee Technological University, Cookeville, TN

[5]The National Institute of Standards and Technology, Gaithersburg, MD

1. INTRODUCTION

This interlaboratory comparison of apparatuses designed to meet American Society for Testing and Materials (ASTM) C 518 (ref. 1) was conducted to help operators establish precision and accuracy statements for results on a material with high thermal resistivity. The selected material was a rigid board of polyisocyanurate (PIR) foamed with CFC-11, and its apparent thermal conductivity is changing with time after final planing.

2. MEASUREMENT PROCEDURE

The interlaboratory comparison involved similar comparative heat flow meter (HFM) apparatuses at four facilities: Jim Walter Research Corp. (JWRC), National Institute of Standards and Technology (NIST), Oak Ridge National Laboratory (ORNL), and Tennessee Technological University (TTU). Each apparatus is designed and operated to meet ASTM C 518 for the testing of homogeneous slab specimens nominally 24 × 24 in. [0.6 × 0.6 m] (ref. 2). Detailed descriptions of the apparatuses are available from the participants.[6] Each participant uses a slightly different procedure to establish the individual quantities to determine the apparent thermal conductivity (k) of the test specimen:

$$k = \frac{Q \cdot L}{A \cdot \Delta T}, \tag{1}$$

where Q is the heat flow, W or Btu/h; A is the area measured on a selected isothermal surface, m^2 or ft^2; L is the thickness of the specimen along a path normal to isothermal surfaces, m or in.; and ΔT is the temperature difference of the two plates, T_h-T_c, °C or °F.

The heat flux (Q/A) is determined from the voltage of a heat flux transducer (HFT) mounted in one of the plates. The calibration factor (N) for the HFT is obtained by use of a Standard Reference Material (SRM) or a transfer standard with a known k:

---

[6]The use of these apparatuses does not imply endorsement of the manufacturer or his product by the authors' organizations.

$$N = \frac{k(T_h - T_c)}{V \cdot L}, \frac{W}{m^2 \cdot mV} \text{ or } \frac{BTU}{h \cdot ft^2 \cdot mV} \tag{2}$$

where V = HFT voltage, mV.

Uncertainty in the k of the calibration materials and the measured parameters, T_h, T_c, Q, and L, produces uncertainty in the measurement of the board thermal conductivity. The procedures used by the four participants to obtain the calibration coefficient (N) are summarized in Table 1. Each 24 X 24 in. (0.6 X 0.6 m) apparatus has a 10 × 10 in. (0.25 × 0.25 m) HFT located in the bottom plate. Table 1 lists the calibration materials, the k of the calibration materials, and the resulting N value obtained by each participant. This shows four different calibration materials are being used and three of the four participants perform calibrations as a function of specimen thickness.

In addition, the ORNL Unguarded Thin-Heater Apparatus (UTHA) was used to measure k of the test specimens prior to and after tests at the four facilities. This apparatus meets ASTM C 1114 (ref. 3) and has a most probable error of about ±1.2% for k.

2.1 TEST SPECIMENS

The test specimens were produced from laminate, rigid boardstock of PIR foamed with CFC-11 for the Cooperative Industry/Government research project sponsored by the Polyisocyanurate Insulation Manufacturers Association (PIMA), Society of the Plastics Industry (SPI), National Roofing Contractors Association (NRCA), Department of Energy (DOE), and the Environmental Protection Agency (EPA) (4). The boardstock was 4 × 8 ft × 1.5 in. (1.2 × 2.4 m × 38 mm) with a black facer (0.025 in. thick) [0.6 mm] on each face. The boardstock was shipped to ORNL in June 1989, and was stored in an unconditioned area at ORNL until June 1990. Boards were planed at ORNL on June 21, 1990, to produce the test specimens for this interlaboratory comparison. For the purposes of these tests, the June 21, 1990, date was designated as t = 0. The test specimens were nominally 24 × 24 × 1.27 in. (0.6 × 0.6 m × 32 mm). Thus, about 0.12 in. (3 mm) of material was planed from each face: the 0.025 in. facer and about 0.09 in. (2.3 mm) of foam. The test specimens for the UTHA, nominally 36 × 60 in. (0.9 × 1.5 m), had a bulk density of

Table 1. Calibration factor procedure for heat flow meter apparatuses

Participant	Calibration material description	Thermal conductivity of calibration material at 75°F (24°C) (Btu·in./h·ft^2·°F) [W/m·K]	Calibration factor, N (W/m^2·mV)
JWRC	Two nominal 2-in. and two nominal 3-in. expanded polystyrene boards (Insulfoam) having a nominal density of 2.5 lb/ft^3 (40 kg/m^3), covering a thickness range of 2 to 6 in., k-values determined at NIST.	2 in.: 0.2319 [0.03344]	10.4347
NIST	High-density, fibrous-glass board similar to SRM 1450, 26.3 mm, 138.4 kg/m^3	0.2281 [0.03290]	9.2326
ORNL	SRM 1451, six 1-in. pieces to make 1-, 3-, and 6-in. stacks. Fit N vs Δx	k[a] k(1 in.): 0.2827 [0.04077] k(3 in.): 0.2841 [0.04098] k(6 in.): 0.2829 [0.04080]	1 in.: 13.715 3 in.: 13.356 6 in.: 13.335
TTU	Three 1-in. pieces of SRM 1450b (A, B, C) used as one-, two-, and three-board combinations. Fit N vs Δx	A: 0.2411 [0.03477] B: 0.2416 [0.03485] C: 0.2400 [0.03462]	PIR 1[b]: 10.357 PIR 2: 10.357 PIR 1-2: 10.184

[a]k: from SRM 1451 certificate k(T, density) equation
[b]PIR: polyisocyanurate

1.882 lb/ft^3 (30.15 kg/m^3) and a density corrected for the buoyancy of air of 1.96 lb/ft^3 (31.40 kg/m^3). Test board 1 and test board 2 were cut from the center of the UTHA specimens. Test board 1 had a bulk density of 1.865 lb/ft^3 (29.89 kg/m^3) and a density corrected for the buoyancy of air of 1.94 lb/ft^3 (31.08 kg/m^3). Test board 2 had a bulk density of 1.860 lb/ft^3 (29.80 kg/m^3) and a density corrected for the buoyancy of air of 1.934 lb/ft^3 (30.98 kg/m^3).

2.2 TEST RESULTS

The specimens were tested sequentially at ORNL, JWRC, NIST, TTU, and again at ORNL. The specimens were carefully packaged by each laboratory and shipped air freight to the next laboratory to minimize the effect of aging on the k-value. Each facility tested Board 1, Board 2, and Boards 1 and 2 together. JWRC made duplicate runs. Table 2 is a compilation of the 20 test results reported by the facilities. Appendix A contains letter reports from JWRC, NIST, and TTU that were used to produce Table 2. Two laboratories submitted data in SI units and small errors occurred in converting to the IP units in Table 2 for these labs.

Appendix B summarizes the ORNL UTHA test results that were fitted by a least-squares method to provide the k (75) value in Table 2. The ORNL UTHA tests at 15 d age were conducted with Board 1 and Board 2 on each side of the thin-heater (i.e., an average was obtained). Then the individual boards were tested in a one-sided mode of operation. The ORNL UTHA tests at 111 d age were conducted at 75°F in a one-sided heat flow mode of operation on Board 1, Board 2, and a stack of Boards 1 and 2. These results show k (111 d) is 5% greater than k (15 d), which supports use of a time-dependent equation to describe the HFM test results.

Table 2 (Data Set I) indicates the foam age from the time (t) of specimen planing when the test was conducted, temperature data, the instrument indicated specimen thickness (x), the heat flux (q), the specimen conductance ($C = q/\Delta T$), and the apparent thermal conductivity (k), Eq. (1). Figure 1 shows the test results as a function of foam age. Table 3 (Data Set I) contains the results of fitting the 20 k-values by a least squares method and shows that the following equation,

$$k(\text{Btu}\cdot\text{in./h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1373 + 9.43 \times 10^{-5}\ t \tag{3a}$$

$$k(\text{W/m}\cdot\text{K}) = 0.01981 + 1.36 \times 10^{-5}\ t \tag{3b}$$

Table 2. Compilation of 20 test results from JWRC, NIST, ORNL, and TTU

ORNL/JWRC/NIST/TTU Interlaboratory Comparison; CFC-11 Foam Boards; Manufactured: May 31, 1989
Planed: June 21, 1990 (Age = 0)

Specimen (ID)	t Age (d)	T(h) (°F)	T(c) (°F)	Delta T (°F)	T(m) (°F)	x (inch)	q (Btu/h ft^2)	C[a] (Btu/h ft^2·°F)	k[a] (Btu in./ h ft^2·°F)
ORNL #1/2 (UTHA)	15	--	--	--	75	--	--	--	0.1408
ORNL #1	18	94.94	55.38	39.56	75.16	1.260	4.353	0.1100	0.1387
ORNL #2	18	94.95	55.40	39.55	75.17	1.280	4.298	0.1087	0.1391
ORNL #1/#2	15	94.97	55.18	39.78	75.08	2.535	2.134	0.0536	0.1360
JWRC #1	20	94.7	55.1	39.6	74.9	1.248	4.44	0.112	0.140
#1	21	94.9	55.1	39.8	75.0	1.246	4.46	0.112	0.140
#2	21	94.9	55.1	39.8	75.0	1.312	4.34	0.109	0.143
#2	22	95.2	55.0	40.2	75.1	1.296	4.38	0.109	0.141
#1/#2	21	95.1	55.0	40.1	75.0	2.516	2.21	0.055	0.139
#1/#2	21	95.1	55.0	40.1	75.0	2.516	2.21	0.055	0.139
NIST #1	25	--	--	39.42	75.74	1.268	4.297	0.1090	0.1382
#2	26	--	--	39.42	75.74	1.280	4.238	0.1075	0.1376
#1/#2	26	--	--	39.96	75.74	2.543	2.169	0.0543	0.1381
TTU #1	30	96.30	53.65	42.64	74.97	1.2536	4.8229	0.1131	0.1418
#2	31	96.37	53.56	42.80	74.97	1.2521	4.7965	0.1121	0.1404
#1/#2	31	96.76	53.64	43.13	75.20	2.5027	2.4325	0.0564	0.1412
ORNL #1	34	94.74	55.58	39.16	75.16	1.264	4.356	0.1112	0.1406
#2	34	94.76	55.57	39.19	75.17	1.280	4.284	0.1093	0.1399
#1/#2	33	94.95	55.40	39.55	75.18	2.547	2.152	0.0544	0.1386
ORNL #1/2 (UTHA)	111				75				0.1481

[a]Calculated property (see text).

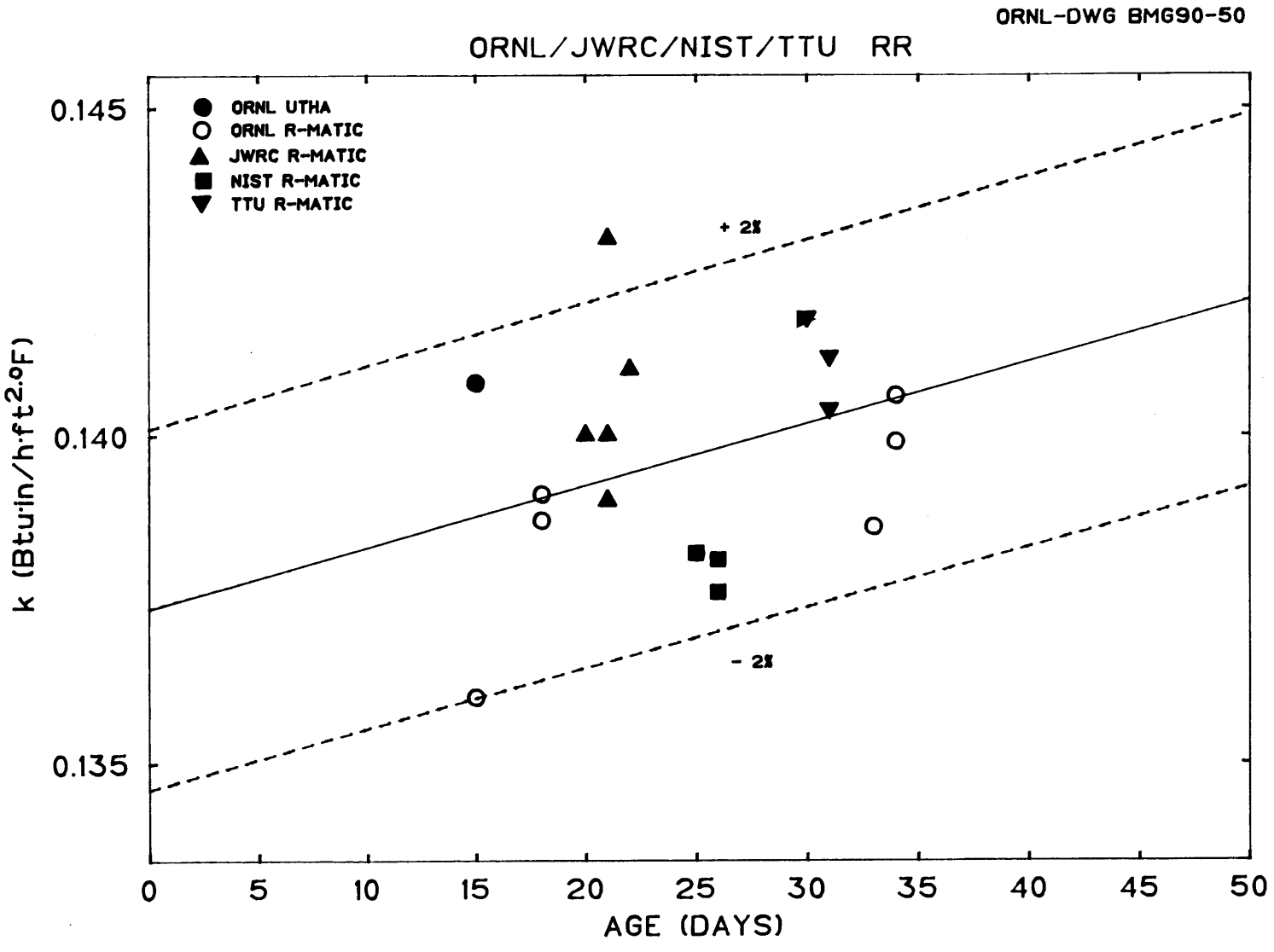


Fig 1. Interlaboratory comparison test results as a function of test specimen age after planing.

Table 3. Results of a least-squares method of fitting 20 thermal conductivity test results to k = A + Bt

ORNL/JWRC/NIST/TTU Foam Interlaboratory Comparison 1990
The parameters for k = A + Bt are: A = 1.373524×10^{-1}; B = 9.433543×10^{-5}

	t (d)	k[a]	k[a] Calc	% Diff[b]	Diff
1	15	0.1408	0.1388	1.44	0.0020
2	18	0.1387	0.1391	0.25	-0.0004
3	18	0.1391	0.1391	0.04	0.0000
4	15	0.1360	0.1388	2.03	-0.0028
5	20	0.1400	0.1392	0.54	0.0008
6	21	0.1400	0.1393	0.48	0.0007
7	21	0.1430	0.1393	2.56	0.0037
8	22	0.1410	0.1394	1.12	0.0016
9	21	0.1390	0.1393	0.24	-0.0003
10	21	0.1390	0.1393	0.24	-0.0003
11	25	0.1382	0.1397	1.09	-0.0015
12	26	0.1376	0.1398	1.60	-0.0022
13	26	0.1381	0.1398	1.23	-0.0017
14	30	0.1418	0.1402	1.14	0.0016
15	31	0.1404	0.1403	0.09	0.0001
16	31	0.1412	0.1403	0.65	0.0009
17	34	0.1406	0.1406	0.03	0.0000
18	34	0.1399	0.1406	0.47	-0.0007
19	33	0.1386	0.1405	1.35	-0.0019
20	111	0.1481	0.1478	0.19	0.0003

[a]Btu·in./h·ft^2·°F.
[b]Absolute value.
Variance: 2.589×10^{-6}.
Avg % dev: 8.39×10^{-1}.

where t is the elapsed time in days after planing the boards, describes the results with an average percent deviation of 0.84% and a variance of 2.589×10^{-6}. One standard deviation is the $(\text{variance})^{1/2}$ and is 0.001609 Btu·in./h·ft^2·°F (0.000232 W/m·K). The average k for the 20 measurements given in Table 3 is 0.14005 Btu·in./h·ft^2·°F (0.02020 W/m·K), so one standard deviation is 1.15% and two standard deviations are 2.30%. Only one of the 20 results is outside two standard deviations. This is a very encouraging result and indicates that each participant is exercising procedures to meet ASTM C 518 with his particular apparatus.

The first alternate analysis removed the ORNL UTHA results and averaged the JWRC repeat values to yield three test results per facility, or a total of 15 test results. Table 4 (Data Set II) includes the first and last ORNL data sets. This shows that

$$k(\text{Btu·in./h·ft}^2\text{·°F}) = 0.1365 + 1.15 \times 10^{-4}\ t \tag{4a}$$

$$k(\text{W/m·K}) = 0.0197 + 1.66 \times 10^{-5}\ t \tag{4b}$$

describes the 15 test results with an average percent deviation of 0.83%, a variance of 2.353×10^{-6}, and one standard deviation of 0.001534 or 1.10%, since the average k(15 d) is 0.1394 Btu·in./h·ft^2·°F (0.02011 W/m·K). Thus, two standard deviations are 2.20% and all test results are within two standard deviations. The ORNL UTHA k (15 d) value of 0.1408 Btu·in./h·ft^2·°F (0.02031 W/m·K) is 0.74% above the 15-d k-value predicted by Eq. (3) and 0.53% above the average k. Since the UTHA is an absolute determination of k, this provides a check on the values from the comparative heat flow meter apparatuses.

The next alternate analysis was to correct all of the k-values in Table 4 to 75°F using the temperature dependency of k measured by the UTHA. The UTHA k-values are described by

$$k(\text{Btu·in./h·ft}^2\text{·°F}) = 0.1123 + 3.80 \times 10^{-4}\ T\ (\text{°F}) \tag{5a}$$

$$k(\text{W/m·K}) = 0.01794 + 9.90 \times 10^{-5}\ T\ (\text{°C}) \tag{5b}$$

with an average percent deviation of 0.29% and a 2 σ value of 1.04%. This equation predicts a change in k of 0.27%/°F near 75°F. The maximum change in k was -0.21% for the NIST values that were reported at 75.74°F. Table 5 (Data Set III) contains the 75°F k-values which are reported to six figures to show the correction. The JWRC duplicate

Table 4. Results of a least-squares method of fitting 15 thermal conductivity test results to k = A + Bt

The parameters for k = A + Bt are:
A = 1.364613×10^{-1}
B = 1.153153×10^{-4}

	t(d)	k[a]	k[a] Calc	% Diff[b]	Diff
1	15	0.1360	0.1382	1.61	-0.0022
2	18	0.1387	0.1385	0.12	0.0002
3	18	0.1391	0.1385	0.40	0.0006
4	20	0.1400	0.1388	0.84	0.0012
5	21	0.1420	0.1389	2.15	0.0031
6	21	0.1390	0.1389	0.08	0.0001
7	25	0.1382	0.1393	0.83	-0.0011
8	26	0.1376	0.1395	1.35	-0.0019
9	26	0.1381	0.1395	0.98	-0.0014
10	30	0.1418	0.1399	1.33	0.0019
11	31	0.1404	0.1400	0.26	0.0004
12	31	0.1412	0.1400	0.82	0.0012
13	33	0.1386	0.1404	1.20	-0.0017
14	34	0.1406	0.1404	0.16	0.0002
15	34	0.1399	0.1403	0.34	-0.0005

[a]Btu·in./h·ft^2·°F.
[b]Absolute value.
Variance: 2.353×10^{-6}.
Avg % Dev: 8.32×10^{-1}.

values were averaged. The results in Table 5 are described by

$$k(\text{Btu}\cdot\text{in./h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1364 + 1.14 \times 10^{-4}\, t \qquad (6)$$

with an average percent deviation of 0.88%, a variance of 2.56219×10^{-6}, and with an average k-value of 0.1393 Btu·in./h·ft^2·°F (0.02009 W/m·K) yielding a 2 σ value of 2.30%. This result is very similar to that of the previous data fits.

Two additional data fits were completed. These excluded either the first or the second set of tests by ORNL. The results of all five data fits are shown in Table 6. The 2 σ value is increased if either ORNL data set is eliminated. Thus, either the treatment of Set II or Set III is a satisfactory description of the test results, and the authors choose to use Set II since it yields the lowest 2 σ value (2.20%).

The sets of five data for Board 1, Board 2, and Boards 1 plus 2 were fitted by a least-squares method, and the results given in Table 7 were obtained. The 2 σ value for Board 2 (2.84%) is 1.3 times the 2 σ value for Board 1 and Boards 1 + 2. Table 7 contains the average thickness for the five tests, the range, and the range percent for the specimens. The large value of range percent for Board 2 may be the cause for the large 2 σ value for the Board 2 test results.

Table 7 shows the average value for k and the intercept A, which is the projected value for k at zero time (the time when the specimens were planed). These two k-values for Boards 1 + 2 are less than the corresponding values for Board 1 and Board 2. Thus, the A value for Boards 1 + 2 (0.13400) is less than the average A value for Board 1 and Board 2 (0.13850) by about 3.2%; and the k (average) for Boards 1 + 2 (0.13849) is less than the k (average) for Board 1 and Board 2 (0.13978) by 0.9%. This suggests that an interfacial resistance exists in the tests for Boards 1 + 2 that yields a lower k for the pair. This was observed by two of the four test facilities (see Table 2).

Table 8 shows that a least-squares fit to the thermal conductance, $C = q/\Delta T$, for Data Set II yields a 2 σ of ±3.2%. The 2 σ value for the Set II k results is 2.2%. The C value comparisons should reduce the influence of thickness errors. The 2 σ values given in Table 8 for the other C data sets are greater than those given in Table 7 for the corresponding k data sets. Thus, based on 2 σ values, the C values appear to contain the major differences in the data sets.

Table 5. Adjusted values of apparent thermal conductivity at 75°F

	Age (d)	T_m (°F)	k	k(75)
ORNL-1	18	75.159	0.1387	0.138639
2	18	75.173	0.1391	0.139034
1/2	15	75.078	0.1360	0.135970
JWRC 1	20.5	74.95	0.140	0.140019
2	21.5	75.05	0.142	0.141981
1/2	21.0	75.0	0.139	0.139000
NIST 1	25	74.74	0.1382	0.137918
2	26	75.74	0.1376	0.137318
1/2	26	75.74	0.1381	0.137818
TTU 1	30	74.975	0.1418	0.141810
2	31	74.966	0.1404	0.140415
1/2	31	75.200	0.1412	0.141124
ORNL 1	34	75.150	0.1406	0.140539
2	34	75.167	0.1399	0.139836
1/2	33	75.176	0.1386	0.138533

Table 6. Comparison of least-squares fits of thermal conductivity data sets

	Data sets				
	I	II	III	IV	V
Number of values	20	15	15 (75°F)	12 (75°F) w/o O-2[a]	12 (75°F) w/o O-1[b]
A	0.13735	0.13646	0.13641	0.13527	0.13850
B	9.4335×10^{-5}	1.15315×10^{-4}	1.14214×10^{-4}	1.68956×10^{-4}	4.30937×10^{-5}
k (avg)	0.14005	0.13941	0.13930	0.13925	0.13969
Avg % Dev	0.84	0.83	0.88	0.92	0.91
$(\text{Variance})^{1/2}$	1.6091×10^{-3}	1.5339×10^{-3}	1.6007×10^{-3}	1.7057×10^{-3}	1.6351×10^{-3}
$2\ \sigma$, %	2.30	2.20	2.30	2.45	2.34

[a]w/o O-2 means without ORNL data set 2.
[b]w/o O-1 means without ORNL data set 1.

Table 7. Comparison of thermal conductivity data sets for Board 1, Board 2, and Boards 1 + 2

	Board 1	Board 2	Boards 1 + 2
Number of values	5	5	5
A	0.13653	0.13976	0.13400
B	0.13724×10^{-4}	-1.6276×10^{-6}	1.7821×10^{-4}
k[a] (average)	0.13985	0.13972	0.13849
Avg % Dev	0.67	0.89	0.82
$(\text{Variance})^{1/2}$	1.4429×10^{-3}	1.9873×10^{-3}	1.5401×10^{-3}
2σ	2.06	2.84	2.22
Thickness (in.)			
Average	1.2585	1.2792	2.5287
Range	0.021	0.052	0.0443
Percent	1.67	4.06	1.75

[a]Btu·in./h·ft^2·°F.

Table 8. Comparison of thermal conductance values for data sets

		Board 1	Board 2	Twice C of Boards 1 + 2	Boards 1 + 2
Number of values	15	5	5	5	5
A	0.10688	0.10891	0.10628	0.10549	0.05274
B	1.1998×10^{-4}	8.4195×10^{-5}	1.1628×10^{-4}	1.5830×10^{-4}	7.9151×10^{-5}
C average	0.10995	0.11106	0.10932	0.10948	0.05474
Avg % Dev	1.30	1.09	1.00	1.30	1.30
$(\text{Variance})^{1/2}$	1.7713×10^{-3}	1.7510×10^{-3}	1.7599×10^{-3}	2.0244×10^{-3}	1.01222×10^{-3}
$2\ \sigma$, %	3.22	3.15	3.20	3.70	3.70

3. CONCLUSIONS AND RECOMMENDATIONS

The 15 k-values have a two standard deviation (2 σ) value of 2.2% when described by:

$$k(\text{Btu}\cdot\text{in./h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1365 + 1.15 \times 10^{-4}\ t$$

$$k(\text{W/m}\cdot\text{K}) = 0.0197 + 1.66 \times 10^{-5}\ t\ ,$$

where t is the elapsed time in days after planing the boards. This result on high thermal resistivity test specimens is less than the 2 σ value (imprecision) of 3.0% found for test results on glass-fiber blanket by nine laboratories in the 1987 ASTM C 687 Round Robin (5). The plate-to-plate thermal resistance for the C 687 test was about 24 $\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F/Btu}$ and for these tests was 18 $\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F/Btu}$ or less. This suggests that future tests should include test specimens with greater thickness to see if the 2 σ level changes with increased plate-to-plate thickness or thermal resistance.

The 2 σ value for Board 2 (2.8%) is 1.3 times the 2 σ value for Board 1 and Boards 1 + 2. This larger 2 σ value is associated with the larger test thickness range (4.1%) for Board 2 than for Board 1 and Boards 1 + 2 (1.7%). A lower test thickness range might reduce the 2 σ value for all tests to 2.0% or less.

Three of the five data sets yielded lower k-values for Boards 1 + 2 than found for Board 1 and Board 2. This suggests that an interfacial resistance exists in the tests on Boards 1 + 2. This could impact results obtained by testing stacks of thin boards, which is used to accelerate the aging process in foam boards.

This suggests that future tests include boards and stacks of boards to evaluate the interfacial resistance effect and determine an approach for corrections. It might be useful to test very compressible materials as interfacial layers to correct for this and to seek a way to address test specimens that contain surface undulations (waves).

Fifteen C values have a precision, 2 σ, value of 3.2% when described by:

$$C\ (\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}) = 0.1069 + 1.20 \times 10^{-4}\ t\ .$$

This suggests that the thickness differences noted above are contained in the C values.

4. ACKNOWLEDGMENTS

The authors of this paper appreciate the reviews and comments provided by T. G. Kollie, J. P. Moore, and K. E. Wilkes of the Oak Ridge National Laboratory. We thank F. J. Weaver for preparing the figures and helping record the results. Finally, we thank Ms. Gabrielle Burn for preparing the manuscript.

5. REFERENCES

1. "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission by Means of the Heat Flow Meter Apparatus," ASTM C 518-85, pp. 150-62, in *1989 Annual Book of ASTM Standards*, Vol. 04.06, American Society for Testing and Materials, 1989.

2. Each heat flow meter apparatus was manufactured by Holometrix, Inc. (formerly Dynatech R/D Company), 33 Erie Street, Cambridge, MA 02139.

3. "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus," ASTM C 1114-89, pp. 600-606 in *1989 Annual Book ASTM of Standards*, Vol. 04.06, American Society for Testing and Materials, 1989.

4. The laminate, rigid boardstock was manufactured by Atlas Roofing Corporation at their plant in East Moline, Ill., on May 31, 1989.

5. "Standard Practice for Determination of the Thermal Resistance of Loose-Fill Building Insulation," ASTM C 687-88, pp. 327-32, in *1989 Annual Book of ASTM Standards*, Vol. 04.05, American Society for Testing and Materials, 1989.

APPENDIX A

LETTER REPORTS FROM JWRC, NIST, AND TTU

jim walter research corp.

July 18, 1990

Mr. Ron Graves
Oak Ridge National Laboratory
Bldg. 4508, MS 6092
P.O. Box 2008
Oak Ridge, TN 37831-6092

Dear Ron:

Summarized below are the results of the R-Matic heat flow meter tests. Duplicate tests were run on the single samples and the stacked sample.

Sample ID	Th (°F)	Tc (°F)	q (Btu/hft²)	t (inch)	Tm (°F)	C (Btu/hft²F)	k (Btu-in/hft²F)
#1	94.7	55.1	4.44	1.248	74.9	0.112	0.140
#1	94.9	55.1	4.46	1.246	75.0	0.112	0.140
#2	94.9	55.1	4.34	1.312	75.0	0.109	0.143
#2	95.2	55.0	4.38	1.296	75.1	0.109	0.142
#1/#2	95.1	55.0	2.21	2.516	75.0	0.055	0.139
#1/#2	95.1	55.0	2.21	2.516	75.0	0.055	0.139

If you have any questions, please give me a call.

Sincerely,

Gerry

R. Gerry Miller
Research Associate

/ec

cc: J. Hagan

10301 NINTH STREET NORTH • ST. PETERSBURG, FLORIDA 33716 • PHONE (813) 576-4171

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

July 23, 1990

Mr. Ron Graves
Oak Ridge National Laboratory
P.O. 2008
Oak Ridge, Tennessee 37831-6092

Letter Report: July 23, 1990

Dear Ron:

Summarized below are NIST's measurements of thermal conductivity for polyisocyanurate specimens (CFC-11, #1 & #2) supplied by Oak Ridge National Laboratory. All measurements were conducted with our 610 mm Heat-Flow-Meter (HFM) Apparatus (ASTM C518).

Test #	Specimen ID	Δl (mm)	ρ (kg/m^3)	k-factor mW/(m•K)	Mean (°C)	ΔT (°C)
R900716A	#1	32.2	29.5	19.87	24.3	21.9
R900717A	#2	32.5	29.4	19.82	24.3	21.9
R900717B	#1,#2*	64.6	29.4	19.96	24.3	22.2

*Stacked: Hot face, #2, #1, Cold face

The HFM was calibrated on 6 July 1990 using a specimen of 26.2 mm thick, high-density fibrous glass board, similar to SRM-1450. The thermal conductivity of the specimen was calculated using a regression equation from Siu[1]. Test conditions for calibration were 24.1°C and 21.5°C for the mean specimen temperature and temperature difference, respectively. The calibration coefficient for all three tests reported above was 9.2326 W/mV/m^2.

[1] Siu, M.C.I. "Comparison of Results of Measurements Made On a Line-Heat-Source and a Distributed-Heat-Source Guarded-Hot-Plate Apparatus", Thermal Conductivity 17, pp.413-426.

Ron, if you need additional information, please contact me at 1-301-975-6436.

Sincerely,

Robert R. Zarr
Mechanical Engineer
Heat Transfer Group
Building Environment Division

cc. A.H. Fanney, NIST
J.E. Hill, NIST
R.G. Miller, JWRC

Tennessee Technological University
College of Engineering • *Department of Chemical Engineering*
Box 5013 • Cookeville, TN 38505 • 615-372-3297

MEMORANDUM

TO: R.S. Graves

FROM: D.W. Yarbrough

DATE: July 23, 1990

SUBJECT: Round-Robin Foamboard Data.

Board No. 1 Mass 352 grams.

T_H = 35.72°C T_C = 12.03°C $\bar{T}$ = 23.875°C
k_a = 0.02045 W/m•K Q = 4.8229 Btu/hr•ft^2
Age 30 days. Test Thickness 3.1842 cm
Measurement Date 7/21/90 @2300
Time in R-Matic 11 hours

Board No. 2 Mass 356 grams.

T_H = 35.76°C T_C = 11.98°C $\bar{T}$ = 23.870°C
k_a = 0.02025 W/m•K Q = 4.7966 Btu/hr•ft^2
Age 31 days Test Thickness 3.1803 cm
Measurement Date 7/22/90 @1040
Time in R-Matic 10 hours

Stack of Two Boards - No. 1 on top

T_H = 35.98°C T_C = 12.02°C $\bar{T}$ = 24.00°C
k_a = 0.02037 W/m•K Q = 2.4325 Btu/hr•ft^2
Age 31 days. Test Thickness 6.3569 cm
Measurement Date 7/22/90 @1545
Time in R-Matic 5 hours

APPENDIX B

ORNL UTHA TEST RESULTS

CFC11 EXPERIMENTAL BOARDS (T3B9);AGE=395-401 DAYS
ALTERNATIVE BLOWING AGENT PROJECT (ABAP)
ORNL/NIST/JWRC RR TESTS
MATERIAL MANUFACTURED:MAY 31, 1989
PP 157-172 Book #9;UTHA
SAVED AS (CFC11RR)

	Hours	t (c)	T (K)	k(a) (W/m.K)	t (F)	k(a) (Btu-in/h.ft^2.F)	density (lb/ft^3)
Test #1,DATA #1	24.0	27.3100	300.460	0.02068	81.1580	0.1434	1.882
,DATA #2	22.0	39.9804	313.130	0.02191	103.9647	0.1519	
,DATA #3	17.0	50.1350	323.285	0.02295	122.2430	0.1591	
,DATA #4(HFU)	19.0	39.8283	312.978	0.02196	103.6909	0.1522	
,DATA #5(HFD)	66.0	39.9567	313.107	0.02174	103.9221	0.1507	

UTHA DATA;ORNL/NIST/JWRC/TTU RR;CFC-11

THE PARAMATERS FOR :

Y = A + B*X

ARE :

A = 1.794110D-02
B = 9.905408D-05

	X	Y	YCALC	% DIFF	DIFF
1)	27.3100	0.0207	0.0206	0.1631	0.0000
2)	39.9804	0.0219	0.0219	0.0396	0.0000
3)	50.1350	0.0230	0.0229	0.1866	0.0000
4)	39.8283	0.0220	0.0219	0.3358	0.0001
5)	39.9567	0.0217	0.0219	0.7313	-0.0002

VARIANCE : 1.125271D-08
AVG % DEV. : 2.912747D-01

THE PARAMATERS FOR :

Y = A + B*X

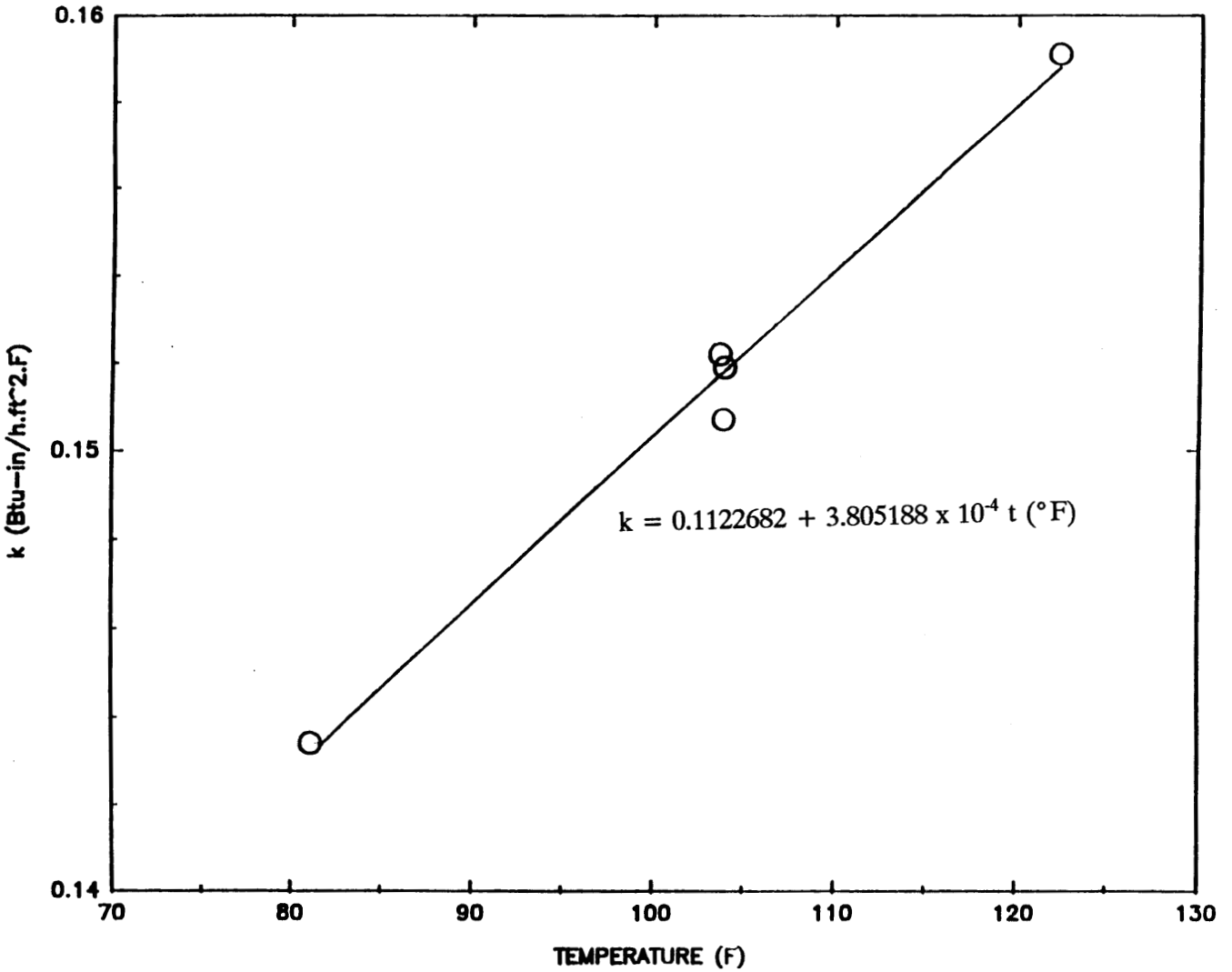
ARE :

A = 1.122682D-01
B = 3.805188D-04

	X	Y	YCALC	% DIFF	DIFF
1)	81.1580	0.1434	0.1432	0.1741	0.0002
2)	103.9647	0.1519	0.1518	0.0469	0.0001
3)	122.2430	0.1591	0.1588	0.1987	0.0003
4)	103.6909	0.1522	0.1517	0.3124	0.0005
5)	103.9221	0.1507	0.1518	0.7382	-0.0011

VARIANCE : 5.436799D-07
AVG % DEV. : 2.940635D-01

CFC11 RR


0.16
0.15
0.14
k (Btu-in/h.ft^2.F)
70
80
90
100
110
120
130
TEMPERATURE (F)
k = 0.1122682 + 3.805188 x 10^-4 t (°F)

INTERNAL DISTRIBUTION

1-2. Central Research Library
3. Document Reference Section
4-5. Laboratory Records Department
6. Laboratory Records, ORNL RC
7. ORNL Patent Section
8. M&C Records Office
9-18. G. L. Burn
19. R. S. Carlsmith
20. P. W. Childs
21. J. E. Christian
22. G. E. Courville
23. D. F. Craig
24-28. R. S. Graves
29. T. G. Kollie
30. M. A. Kuliasha
31-35. D. L. McElroy
36. R. B. Shelton
37. K. E. Wilkes
38-42. D. W. Yarbrough
43. A. D. Brailsford (Consultant)
44. Y. A. Chang (Consultant)
45. H. W. Foglesong (Consultant)
46. J. J. Hren (Consultant)
47. M. L. Savitz (Consultant)
48. J. B. Wachtman, Jr. (Consultant)

EXTERNAL DISTRIBUTION

49. Alumbaugh, R. L., Naval Civil Eng. Lab, Port Hueneme, CA
50. Anderson, J., Foam Enterprises, Minneapolis, MN
51. Bankvall, C., Swedish National Testing and Research Institute, Boras, Sweden
52. Beck, J., Michigan State University, East Lansing, MI
53. Bomberg, M., National Research Council of Canada, Ontario, Canada
54. Boulin, J. J., DOE/HQ, Washington, DC
55. Braun, S., MIMA, Alexandria, VA
56. Clinton, J. L., NRG Barriers, Inc., Saco, ME
57. Desjarlais, A. O., Holometrix, Inc., Cambridge, MA
58. Ellis, W. P., 754 Bob-Bea Lane, Harleysville, PA
59. Fairey, P., Florida Solar Energy Center, Cape Canaveral, FL
60-64. Fine, H. A., University of Kentucky, Lexington, KY
65. Flynn, D. R., DRF R&D, Millwood, VA
66. Gilbo, C. F., Journal of Thermal Insulation, Lancaster, PA
67. Glicksman, L. R., Massachusetts Institute of Technology, Cambridge, MA
68. Goldsmith, J. C., DOE/HQ, Washington, DC
69. Gorham, F. C., Roofing Services, Inc., Springfield, VA
70. Goss, W. P., University of Massachusetts, Amherst, MA
71. Hagan, J. R., Jim Walter Research Corp., St. Petersburg, FL
72. Harris, T., BASF Canada, Inc., Toronto, Canada
73. Harshaw, B. D., Central Fiber Corp., Wellsville, KS

74. Jonsson, B., Swedish National Testing and Research Institute, Boras, Sweden
75. Kifer, E. W., Thermal Products International, Pittsburgh, PA
76. Kochhar, G. S., University of West Indies, Trinidad, West Indies
77. LaCosse, R. A., 207 Withorn Lane, Mt. Prospect, IL
78. Leger, G., Leger Designs, New Boston, NH
79. Lichtenberg, F. W. , The Society of the Plastics Industry, New York, NY
80. R. F. Martin, Roof Maintenance Systems, Farmingdale, NJ
81. Martynowicz, L., Huntsman Chemical Corp., Chesapeake, VA
82. McBride, M. F., Owens-Corning Fiberglas, Granville, OH
83. McGillvary, D. R., Firestone Building Products Co., Carmel, IN
84. McGuire, D., Regal Industries, Inc., Crothersville, IN
85-89. Miller, R. G., Jim Walter Research Corp., St. Petersburg, FL
90. Mumaw, J. R., Owens-Corning Fiberglas, Granville, OH
91. Ober, D. G., Manville Corp., Denver, CO
92. Poppendiek, H. F., Geoscience, Ltd., Solana Beach, CA
93. Portfolio, D. C., Tremco, Inc., Cleveland, OH
94. Ray, R. J., Manville Sales Corp., Denver, CO
95. Rynd, J. P., U.C. Industries, Tallmadge, OH
96. Sherman, M., 6723 14th Avenue, N., St. Petersburg, FL
97. Shirtliffe, C. J., NRCC Ottawa, Canada
98. Shu, L. S., W. R. Grace & Co., Cambridge, MA
99. Skinner, A., Roofing Service Associates, Inc., Knoxville, TN
100. Smith, D. R., NIST, Boulder, CO
101. Smith, J. A., NAHB, Washington, DC
102. Smith, S. E., Yankee Scientific, Ashland, MA
103. Stern, E., Expertech CMSC, Montreal, Canada
104. Strzepek, B., Dow Chemical, Granville, OH
105. Stumpf, F. M., Dalen Corp., Netcong, NJ
106. Sullivan, R., National Center for Appropriate Technology, Butte, MT
107. Szoke, S., National Concrete Masonry Assoc., Herndon, VA
108. Tewes, S., Small Homes Council - Building Research Council, Champaign, IL
109. Thomas, J. R., Virginia Polytechnic Institute, Blacksburg, VA
110. Tong, T. W., Arizona State University, Tempe, AZ
111. Tsongas, G., Portland State University, Portland, OR
112. Tuluca, A., Steven Winter Associates, Inc., Norwalk, CT
113. Tye, R. P., 292 Jerusalem Road, Cohasset, MA
114. Vander Linden, C. R., Vander Linden & Associates, Littleton, CO
115. Warner, J., 6427 Forest Road, Cheverly, MD
116. Whelan, B. J., Sarnafil, Inc., Canton, MA
117. Wysocki, D. C., Mobay Corp., Pittsburgh, PA
118-137. Zarr, R. R., NIST, Gaithersburg, MD
138. Zenor, G. N., JPS Elastomerics Corp., Northampton, MA
139. U.S. Department of Energy, Oak Ridge Operations Office, P.O. Box 2008, Oak Ridge, TN 37831-8600
140-149. U.S. Department of Energy, Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831