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STEADY-STATE AND TRANSIENT RESULTS ON INSULATION MATERIALS

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ABSTRACT: The Unguarded Thin-Heater Apparatus (UTHA, ASTM C 1114) was used to determine the thermal conductivity (k), specific heat (C), and thermal diffusivity (α) of selected building materials from 24 to 50°C. Steady-state and transient measurements yielded data on four types of material: gypsum wall board containing 0, 15, and 30 wt% wax; calcium silicate insulations with densities (ρ) of 307, 444, and 605 kg/m^3; three wood products: southern yellow pine flooring (575 kg/m^3), Douglas fir plywood (501 kg/m^3), and white spruce flooring (452 kg/m^3); and two cellular plastic foams: extruded polystyrene (30 kg/m^3) blown with HCFC-142b and polyisocyanurate rigid board (30.2 kg/m^3) blown with CFC-11. The extruded polystyrene was measured several times after production (25 days, 45 days, 74 days, 131 days, and 227 days). The UTHA is an absolute technique that yields k with an uncertainty of less than ±2% as determined by modeling, by determinate error analyses, and by use of Standard Reference Materials SRM-1450b and SRM-1451.

In the transient mode of operation, a step-change in heat flux was applied to specimens that were initially isothermal or that had a steady, imposed temperature gradient. Analysis of the temperature response of the thin heater for short times predicts a temperature rise that is a linear function of the square-root of time. This behavior was observed for materials with densities above 300 kg/m^3 and the slope of this relation provided experimental values for the product $k \cdot \rho \cdot C$. The overall error in determining the product $k \cdot \rho \cdot C$ is less than 1%. Values of C were calculated from experimental values of k, ρ, and the product of $k \cdot \rho \cdot C$.

However, for the 30 kg/m^3 foams, the thermal mass of the thin heater delayed the onset of the linear temperature rise with the square-root of time. This effect negated the use of the short-time transient analysis for low density materials. A finite difference program that described this observation provided an alternate method to obtain values for the product $k \cdot \rho \cdot C$ from the experimental data.

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KEYWORDS: thermal conductivity, thermal diffusivity, specific heat, thin-heater apparatus, gypsum containing wax, wood products, calcium silicate, plastic foams, extruded polystyrene, polyisocyanurate

INTRODUCTION

This paper describes the use of the ORNL Unguarded Thin-Heater Apparatus (UTHA) in the steady-state and transient modes of operation to determine thermophysical properties of building materials from 24 to 50°C (75 to 120°F). The thermophysical properties determined were thermal conductivity (k), specific heat (C), and thermal diffusivity (α). These properties were determined for gypsum wall board with and without wax, calcium silicate insulations, three wood products, and two cellular plastic foams.

The need for transient analysis of buildings has increased interest in measuring the nonsteady-state thermal behavior of building materials. Transient analysis is possible with the ORNL UTHA because the heat capacity of the screen heater is small relative to that of commonly used measurement systems and can be small relative to that of many test specimens of building materials.

The use of the UTHA in the steady-state and transient modes of operation was initially prompted by the need to test gypsum board specimens containing 0, 15, or 30 weight percent wax ($C_{18}H_{38}$, n-octadecane) in the temperature range 20 to 50°C. These tests were part of an effort to develop a gypsum wall board with enhanced thermal storage capacity.

These transient tests showed the potential value of applying this technique to other building materials to develop a thermophysical-property data base.

EQUIPMENT

The UTHA is an absolute, longitudinal heat flow technique with less than 2% uncertainty for steady-state thermal resistance tests at mean temperatures from 20 to 50°C. This technique has been described extensively in the literature (1-9).

Transient tests can be performed in the UTHA as a two-sided test by applying a step-change in heat flux to an initially isothermal specimen, or to a specimen with a steady-state temperature gradient. The resulting temperature-time behavior of the heater can be analyzed to obtain specimen properties (3,7).

A Hewlett-Packard (HP) 9121 computer was used to control the test and data was logged by a HP 3497A data acquisition system (10). The average heater temperatures were determined from the readings of five thermocouples located in the central area of the heater. The emf of each thermocouple was measured to 1 μV and converted to temperature by use of a calibration table (11). Data were recorded every 12 seconds from 10 minutes prior to changing the power until 60 minutes after the power was changed, then every 120 seconds for the next 300 minutes, and then every 300 seconds until steady-state was achieved. The software allows 1000 points to be recorded. For each specimen, the first transient test was conducted on an isothermal specimen with the initial temperature difference between the plates and the screen less than 0.05 K for plate temperatures between 25 and 50°C. At the conclusion of the first transient test, a steady-state measurement was made of the specimen k. The second transient test was initiated with a temperature gradient on the specimen and was followed by a steady-state measurement of the specimen k. This procedure was repeated to obtain three or four heating transient tests on most specimens. Finally, a cooling transient test was conducted by a step-change in the heat flux to zero.

ANALYSIS OF TRANSIENT TESTS

Method 1

A solution of the heat conduction equation is given by Carslaw and Jaeger (12) for the case of a semi-infinite solid that is initially at constant temperature, T°, and which is subjected to a constant heat flux, F, at the surface x = 0 for time (t) ≥ t_o. The temperature-time relationship at x = 0 (the heater) is:

$$T = T^{o} + \frac{2F}{k}\left[\frac{\alpha}{\pi} \cdot (t-t_{o})\right]^{1/2} \quad . \qquad (1)$$

For a short time interval this equation for a semi-infinite material is applicable to a material of finite thickness (L), such as the specimens in the UTHA. The short time interval for the denser materials of interest is about 1800 s. In the current work, the temperature versus time and the heat flux are measured, so Eq. 1 allows the quantity kρC to be determined from the slope of a least-squares fit of the temperature versus $(t-t_o)^{1/2}$ data.

Equation 1 can be arranged as follows:

$$T = T^{o} + \frac{2F}{(\pi k \rho C)^{1/2}}\,(t - t_{o})^{1/2} = A + B\,(t - t_{o})^{1/2} \quad . \qquad (2)$$

Thus, a linear-least-squares fit of the heater temperature as a function of $(t-t_o)^{1/2}$ can be performed.

The principle of superposition allows the Eq. 2 to be extended to a material which has an initial temperature gradient. In the determination of kρC using Eq. 2 with a temperature gradient, F equals the change in heat flux applied at time t_0. For a two-sided test, the change in heat flux is F/2.

Figure 1 shows that the experimentally determined heater temperature is a linear function of $(\mathrm{time})^{½}$ after the heat flux was changed at 877 s for a transient test (T1R) on a gypsum board. A least-squares fit of 151 points between 877 and 2689 seconds yielded

$$T = 20.96 + 0.06446\ (t-877)^{½} \qquad (3)$$

with an average percent deviation of less than 0.06%. The T^o value of 20.96°C is within 0.01°C of the average cold plate temperature of 20.97°C. The slope term and the heat flux change of 41.281 W/m^2 yield a $k\rho C$ value of 130560 $W^2 \cdot s/m^4\ K^2$, which yields a C of 1055 J/kgK for this specimen with a k of 0.178 W/m·K and ρ of 695.1 kg/m^3. This procedure for data analysis was called Method 1.1 and used the complete data set for times from 200 to 1800 seconds after the heat flux change. Method 1.2 used only 10 data points selected in uniform increments from the complete data set for the same time period. Method 1.2 used less data but yielded coefficients within 1% of those of Method 1.1.

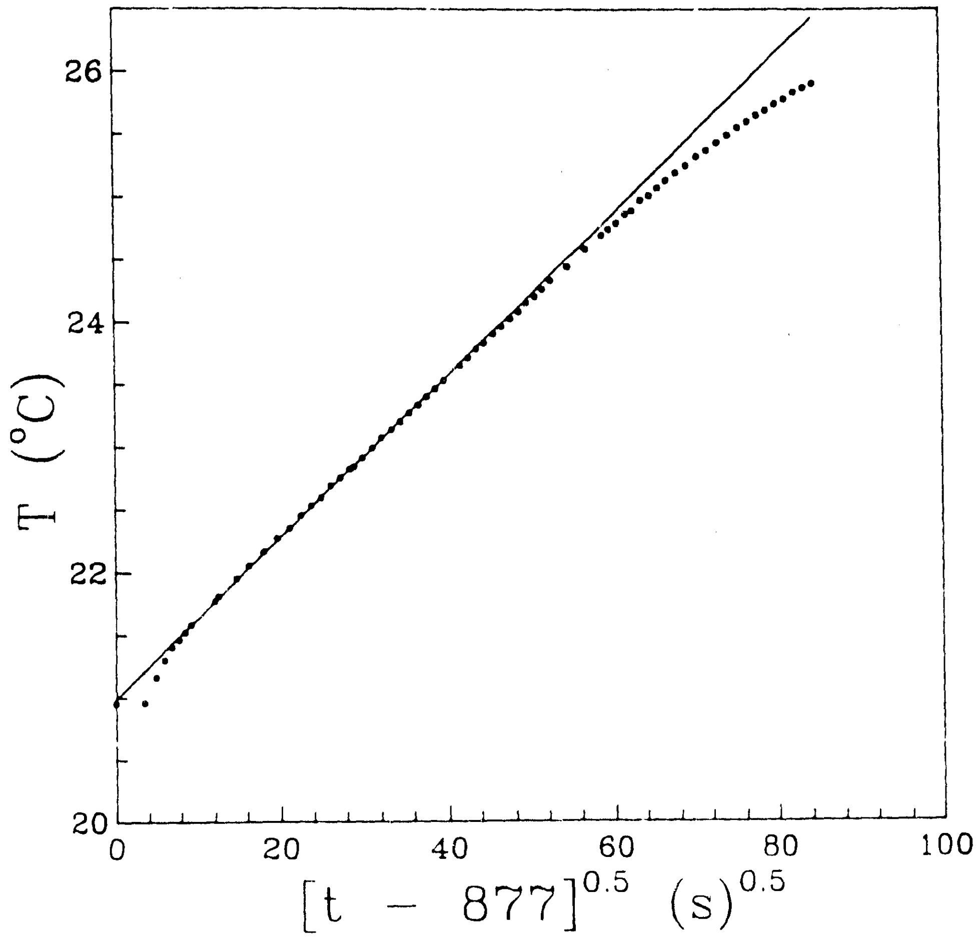

FIG. 1 -- Temperature of the thin heater as a function of √time for run T1R on a gypsum board (695 kg/m^3).

Several indeterminate errors arise in the analysis of the transient tests. The development of Eq. 2 assumes that the heat flux is constant. During the early stage of a transient, however, the thin heater of the experimental apparatus undergoes a significant temperature change, since this heater has a small thermal mass. This was illustrated in the results as an offset of approximately 0.03°C between the known initial temperature and that resulting from the least-squares analysis (see Fig. 1). This effect has been discussed by Domingos and Voelker (13).

Figure 1 shows that deviations of the temperature rise of the heater from a straight line begins to occur near 1800 s. Comparisons of the complete solution to the short-time solution at 1800 s show the short-time solution is 1 mK too low and the slope of the line through the origin is 0.9999 (7, 8). To minimize this error, the limit of applicability of the short-time solution was taken as 1800 s. In general, the results of the transient experiments show very good internal agreement for the values of kρC for dense materials. Thus, overall error in kρC is less than ±1%.

Method 2

This method of analyzing transient data was used after tests on low density (30 kg/m³) extruded polystyrene yielded a temperature response of the thin heater that was delayed in time. This time lag was associated with the thermal mass of the heater. To reduce the effect of this time lag, the step change in heat flux was reduced.

$$\begin{aligned} F(reduced) &= F-F_1 = F-\frac{dT}{dt}\left[\frac{x}{2}\cdot\rho\cdot C\right] \\ &= F-303.79\cdot\frac{dT}{dt} \end{aligned} \qquad (4)$$

where dT/dt is the rate of temperature change of the heater,
ρ is the heater density, 2115 kg/m³,
C is the heater specific heat, 435 J/kg K, and
x/2 is half the heater thickness, 330×10^{-6} m.

Method 3

This method of analyzing the transient data evolved from Method 2 and is described in detail in Ref. 8. It is based on a finite difference model of the transient behavior of an infinite slab of thickness L and a thin heater of thickness 0.5 t_{sc}. The boundary of the slab at x = L is maintained at constant temperature T(0). The boundary at x = zero is in intimate contact with the thin heater. The heater has a finite thermal mass, 0.5 $t_{sc}\cdot\rho_{sc}\cdot C_{sc}$, per unit area and high thermal conductivity relative to the slab. The slab may initially be isothermal or have a temperature profile. The model yields the heater temperature versus time for a given step change in the power to the heater.

The model involves dimensionless position, X = x/L, Fourier Number (or dimensionless time), $N_{Fo} = \alpha t/L^2$, dimensionless temperature, and thermal mass ratio, TMR = 0.5 $t_{sc} \cdot \rho_{sc} \cdot C_{sc}/L \cdot \rho \cdot C$. The zero-heater-thermal-mass case, i.e. TMR equal zero, corresponds to Method 1.

As the thermal mass ratio increases, a nonlinear regime in the relationship between temperature and the square root of time occurs at short times. The length of this regime increases as TMR increases. In all cases, the nonlinear regime is followed by a linear region. The linear region is then followed by curvature in the time-temperature relationship, as was the case for TMR equal zero. For TMR less than or equal to 1, however, the linear region occurs for *dimensionless temperatures* between 0.3 and 0.5.

The slopes of the dimensionless heater temperatures versus the square root of Fourier number, N_{Fo}, are a function of the TMR and N_{Fo}. In the linear region between dimensionless temperatures of 0.3 and 0.5, the slope is solely a function of TMR and can be expressed as a polynomial in TMR:

$$\frac{S(TMR)}{S(0)} = 1 + a\,TMR + b\,(TMR)^2 + \cdots\cdots \qquad (5)$$

S(TMR) is measured in a test. S(o) is given in Eq 2. Since C appears on both sides of Eq. 5 an iterative technique is used to solve for C.

SPECIMENS

Two-sided and one-sided steady-state tests and two-sided transient tests were conducted on the specimens described in this section. The heater was positioned at the mid-plane of each test specimen, and the entire heater was covered by the specimen or by perimeter materials of similar properties. Table 1 lists the materials tested, the test specimen density and thickness, and the values of k, C, and α at 24°C estimated from published data (14-23) as described below and in Ref. 7 and 8. This paper does not describe results on the gypsum with and without wax test specimens, since this has been published elsewhere (7,8).

The calcium silicate board test specimens were duplicate slabs, each nominally 0.9 m x 1.5 m x 0.038 m, of three densities (307, 444, and 605 kg/m^3) that were conditioned in the Building Materials laboratory prior to testing (24). Calcium silicate insulation is a reacted hydrous calcium silicate material made using uncalcined diatomaceous earth and lime blended with reinforcing fibers (25). ASTM Standards (26, 27) and literature (16) give k as a function of density for calcium silicate and yielded the estimates of k given in Table 1. Specific heat values of 836 - 878 J/kg·K and 1045 - 1170 J/kg·K are listed for hydrous calcium silicate (16), and yield an average C of about 1000 J/kg·K. Table 1 shows that the estimated thermal diffusivity decreases as the specimen density increases.

The southern yellow pine flooring and white spruce flooring test specimens were made by gluing individual tongue-in-groove boards together and planing their surfaces to produce 0.9 m x 1.5 m slabs of uniform thickness. The Douglas fir plywood test specimen was made from 1.2 m x 2.5 m plywood boardstock by cutting a 0.9 m x 1.5 m slabs and sanding one surface to produce a uniform thickness. Tests were conducted with heat flowing perpendicular to the board face, as would be the case for a flooring application (30). Test specimens were conditioned in the Building Materials laboratory for several weeks prior to testing, and the average moisture content did not change significantly as a result of the thermal tests. Some moisture redistribution from warm to cold regions was noted. The estimated properties given in Table 1 were obtained from an assessment of the thermal conductivity and specific heat of wood and wood products by TenWolde, McNatt, and Krahn (31).

Thermal test specimens, 0.9 m x 1.5 m, were prepared from 1.2 m x 2.4 m boardstock of extruded polystyrene and polyisocyanurate plastic cellular foam. Each polystyrene test specimen was nominally 0.051 m thick, had a density of 30 kg/m^3, and was tested with the as-produced surfaces (32). The polystyrene was foamed with HCFC-142b. The polyisocyanurate test specimen was prepared by planing a rigid foam boardstock blown with CFC-11. The density of the test specimen was 30.2 kg/m^3 and each specimen was nominally 0.032 m thick (33). Table 1 contains typical thermal properties given by Strzepek (34), Sparks (35), and Luikov, et al (36). The estimated α for both increase with time and the value for extruded polystyrene is about 60% greater than that of the polyisocyanurate foam.

TABLE 1 -- Estimated properties for building materials for steady-state and transient tests in the UTHA

Code	Material	Density kg/m^3	Total Thickness, m	Estimated Properties at 24°C k W/m·K	 C J/kg·K	 α m^2/s·10^7
GOW	Gypsum Board	695.1	0.1002	0.142	1079	1.893
G15W	Gypsum Board - 14.1 wt/o wax	816.9	0.1011	0.161	1262	1.562
G30W	Gypsum board - 30 wt/o wax	1000	0.1006	0.194	1465	1.324
CS1	Calcium silicate 1	307.4	0.077	0.081	1000	2.635
CS2	Calcium silicate 2	443.9	0.077	0.093	1000	2.095
CS3	Calcium silicate 3	605.1	0.077	0.121	1000	2.000
WSF	White spruce flooring[a]	451.5	0.097	0.127	1627	1.729
DFP	Douglas fir plywood[a]	500.9	0.073	0.115	1554	1.477
SYPF	Southern yellow pine flooring[a]	575.2	0.098	0.151 0.020	1548	1.696
PS	Polystyrene (HCFC-142b)[b]	30.0	0.101	0.020	1150	5.797
	After 100 days			0.0288	1150	8.348
PIR	Polyisocyanurate (CFC-11)[b]	30.2	0.064	0.017	1525	3.691
	After 1 year			0.024	1525	5.211

[a] Moisture contents: WSF, 11.5%; DFP, 9.0%; SYPF, 8.8%.

[b] Initial value.

THERMAL CONDUCTIVITY RESULTS

This section describes the k-values as a function of temperature that were determined for the building materials from steady-state tests and those determined before and at the end of the transient tests. The k-values found for the test specimens G0W, G15W, and G30W were independent of temperature and found to be: G0W, 0.1786 W/m·K from 24 to 45°C, G15W (liquid wax), 0.1919 W/m·K from 29 to 34°C; and G30W (liquid wax), 0.2325 W/m·K from 29 to 32°C. The k-values increase with wax content and the average k-value for G0W is 25% greater than the estimated value given in Table 1. This value and the data given in Ref. 16 are described to 2% by

$$k = 0.1076 + 9.8344 \cdot 10^{-5}\,\rho \qquad (6)$$

This equation predicts k-values that are about 17% greater than those given in the ASHRAE Handbook (17).

Table 2 contains equations that describe the measured k-values as a function of temperature for calcium silicate test specimens: CS1, CS2, and CS3. The k-values increase with temperature and density. The data on each specimen are described by a linear equation in temperature and the average deviation of the data from the equation 0.26% or less. The k at 24°C and published values (16, 26, 28, and 29) are described by an equation with an average deviation of less than 2%

$$k = 0.03620 + 9.2316 \times 10^{-5}\,\rho - 9.505 \times 10^{-9}\,\rho^2 \quad . \qquad (7)$$

Equation 7 yields k-values at 24°C that are 23 to 36% less than those given in Table 1.

TABLE 2 -- Equations for the thermal conductivity values for three calcium silicate specimens as measured in the ORNL Unguarded Thin-Heater Apparatus

CS1, 307 kg/m^3	$k = 6.3842 \times 10^{-2} + 6.3009 \times 10^{-5}\,t$, ±0.26%[a]
CS2, 444 kg/m^3	$k = 7.2640 \times 10^{-2} + 7.9893 \times 10^{-5}\,t$, ±0.077%
CS3, 605 kg/m^3	$k = 8.7021 \times 10^{-2} + 7.9729 \times 10^{-5}\,t$, ±0.20%

[a] Average deviation.

Equations for the k results for the wood products are given in Table 3. The k-values increase with temperature for the three products and were fit by a least-squares method to a linear function of temperature. The resulting equations show that an average deviation of the results from the equations is less than 0.3% The measured k-values at 24°C are within 3% of the estimated k-values for 0% moisture content: WSF (2.9%), DFP (2.2%), and SYPF (2.5%) (8). However, the measured k-values at 24°C are significantly lower than the estimated k-values for the measured moisture content of the test specimens: WSF (-19%), DFP (-11.7%), and SYPF (-15.9%). This result suggests that the equations used to estimate the k-values (31) should be modified.

TABLE 3 -- Equations for the thermal conductivity values for three wood products

WSF	$k = 0.09920 + 1.5537 \times 10^{-4}\ t$, ±0.28%[a]
DFP	$k = 0.09786 + 1.6039 \times 10^{-4}\ t$, ±0.18%[a]
SYPF	$K = 0.1234 + 1.16153 \times 10^{-4}\ t$, ±0.11%[a]

[a] Average deviation

Equations for the k-values as a function of temperature and time after manufacture for extruded polystyrene foamed with HCFC 142b and the results 398 days after manufacture on the polyisocyanurate foamed with CFC-11 are given in Table 4. The average percent deviation is less than ±0.15% for the five data sets for the extruded polystyrene and is ±0.3% for the polyisocyanurate. Figure 2 shows that the k-values increase with temperature and increase with time after manufacture for the extruded polystyrene and the polyisocyanurate.

TABLE 4 -- Equations for the thermal conductivity as a function of temperature and time after production for extruded polystyrene foamed with HCFC 142b and polyisocyanurate foamed with CFC-11

PS (HCFC-142b): 25 days	$k = 0.02302 + 1.1653 \times 10^{-4}\ t$, ±0.15%[a]
PS (HCFC-142b): 45 days[b]	$k = 0.02368 + 1.2618 \times 10^{-4}\ t$, ±0.014%
PS (HCFC-142b): 74 days	$k = 0.02480 + 1.1841 \times 10^{-4}\ t$, ±0.081%
PS (HCFC-142b): 131 days[b]	$k = 0.02567 + 1.1834 \times 10^{-4}\ t$, ±0.085%
PS (HCFC-142b): 227 days[b]	$k = 0.02602 + 1.2181 \times 10^{-4}\ t$, ±0.012%
PIR (CFC-11): 398 days[b]	$k = 0.01794 + 9.9032 \times 10^{-5}\ t$, ±0.29%

[a] Average deviation
[b] Transient tests were conducted at these times.

The equations given in Table 4 for extruded polystyrene were used to obtain the values of k at 24°C, and these values show the initial k (24°C) value, 0.02492, is about 25% greater than the initial value estimated in Table 1, but the 100 day value, 0.0281, is within 3% of the estimated 100 day value. The k at 24°C for the polyisocyanurate is within the predicted range.

In a study on the aging of thin specimens planed from polyisocyanurate roof insulation boards (37), we have noted that ℓn 100 k is a linear function of $(\text{time})^{\frac{1}{2}}$/thickness. The first three extruded polystyrene data points are described by

$$\ell n\ 100\ k = 2.7896 + 10.81 \times 10^{-8}\ t^{\frac{1}{2}}/h \quad , \qquad (8)$$

where h is 5.08 cm, and t is time in seconds. The coefficient for the variable, 10.81×10^{-8} cm^2/sec, is an apparent diffusion coefficient for air components in this polystyrene foam.

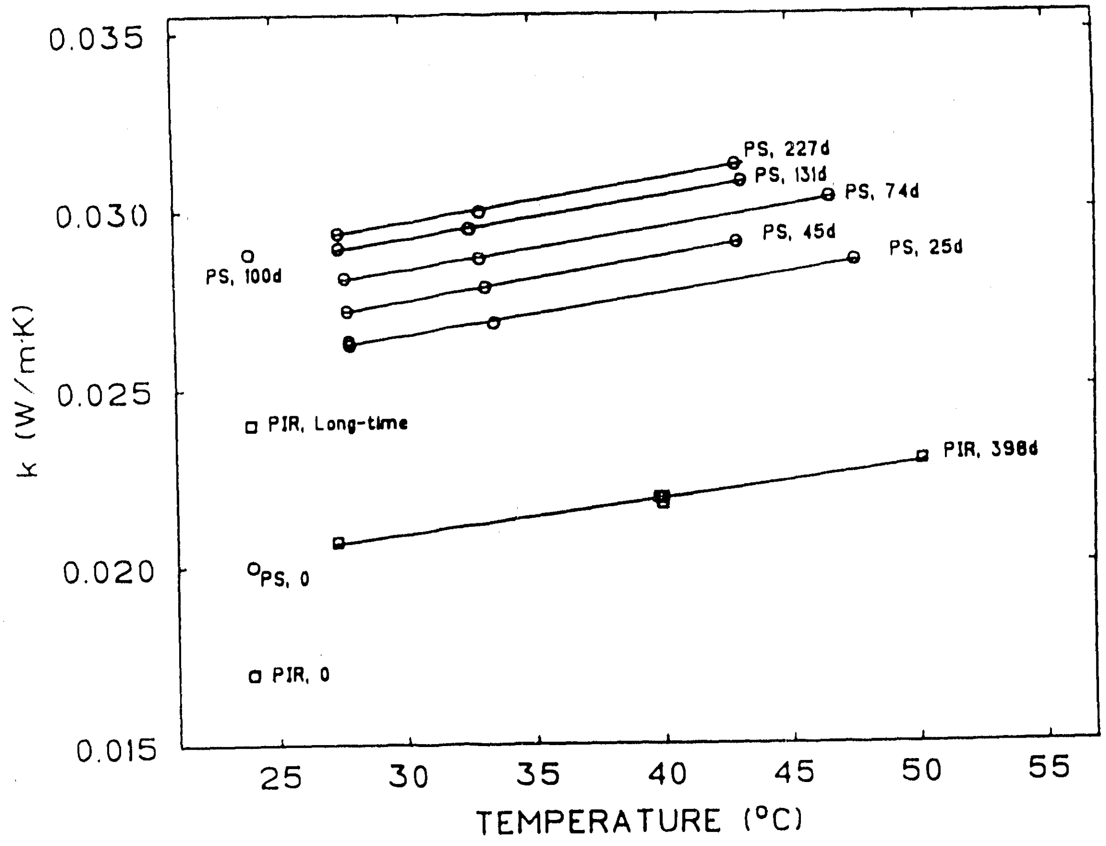

FIG. 2 -- Thermal conductivity as a function of temperature and time after manufacture for extruded polystyrene (HCFC-142b) and polyisocyanurate (CFC-11).

TRANSIENT DATA ANALYSIS RESULTS

This section presents the results of analyzing the transient temperature response of the thin heater. Table 5 lists the results obtained by analyzing the transient data for the G0W, G15W, and G30W specimens using Method 1.1. Each specimen was subjected to positive and negative step changes in heat flux. The slope was determined from data that spanned the first 1.8 ks of each transient.

The five C values for G0W increase with temperature and are described to 1% by

$$C(J/kg \cdot K) = 159.5 + 3.0070\ T\ (K) \tag{9}$$

and are about 2.5% below the value given in Table 1. Three of the five C values for G15W are very large and indicate that a phase change was occurring during the transient. The other two C values average 1285 J/kg·K, which is 2% above the value in Table 1. Four of the eight values for G30W are large and are indicative of a phase change. The other four C values average 1527 J/kg·K, which is 4% above the value in Table 1. These four C values apply for gypsum containing liquid wax between 28 and 38°C. The large apparent specific heat values were derived using the short-time solution. This equation is for determining the specific heat only, and does not apply for cases where a phase change is occurring. An analysis that includes the latent heat of fusion is needed to treat these cases.

TABLE 5 -- Specific heat values obtained by Methods 1 or 2, and 3

Material (TMR)	Temperature (°C)	C-M3 (J/kg K)	C-M1 or M2 (J/kg K)
GOW (0.0075)	23.3	1089	1048
	29.3	1121	1056
	34.8	1136	1078
	31.0	1115	1092
	23.6	1111	1055
G15W (0.0055)	22.8	3021	2461
	23.9	2923	2098
	29.0	1428	1425
	36.1	1301	1296
	35.2	1295	1274
G30W (0.0038)	23.9	7155	4116
	30.1	9336	5891
	29.2	1549	1534
	24.5	9270	6012
	25.0	4507**	1942
	28.6	1503	1528
	34.3	1502	1520
	33.6	1491	1526
CS-1 (0.0231)	25.8	1100	1003
	28.3	1065	1005
	33.1	1050	1026
	41.0	1101	1050
	50.8	1123	1069
	43.9	1061	1021
CS-2 (0.0164)	26.8	1008	1027
	36.2	1074	1052
	50.5	1120	1078
	44.3	1024	1008
CS-3 (0.0121)	26.6	1041	1028
	34.0	1070	1052
	45.5	1094	1075
	40.4	1004	1000
WSF (0.00777)	23.7	1672	1656
	28.8	1704	1668
	39.5	1748	1712
	37.3	1720	1723
DFP (0.0105)	23.3	1438	1400
	31.8	1487	1411
	44.2	1533	1421
	35.8	1492	1412
SYPF (0.0065)	23.4	1544	1576
	27.6	1596	1642
	36.3	1600	1676
	34.9	1601	1669

PIR+CFC-11 (0.237)	26.7	1218	1530*
	40.0	1327	1640*
	43.6	1300	1680*
PS@45 d (0.132)	27.2	1359	1250*
	35.2	1397	1309*
	49.7	1552	1441*
	46.5	1485	1381*
PS@127 d (0.144)	26.9	1275	1157*
	34.4	1323	1226*
	49.0	1349	1239*
	46.8	1364	1283*
PS@227 d (0.145)	27.1	1308	1168*
	34.2	1270	1165*
	48.7	1350	1245*
	46.6	1353	1266*

*C-M2.

**Based on slope for T equal 0.3 to 0.4.

Table 6 contains α values from 20 to 40°C that were calculated from the experimental values of ρ, k, and C for the three specimens. The α values for the gypsum without wax decrease with increasing temperature due to C increasing with temperature. The α values for the composites decrease with increasing wax content and the α (solid wax) values are 3 to 5% larger than the α (liquid wax) values. The experimental α values (Table 6) are 15 to 25% larger than the α values estimated from the literature (Table 1).

Table 5 lists the results obtained by analyzing the 14 transient tests for the CS-1, CS-2, and CS-3 specimens using Method 2. Each specimen was subjected to positive and negative step changes in heat flux.

The slope was determined using the data that spanned the range 200 to 1800 seconds of each transient. The heat flux correction for the screen thermal mass was less than 2% for all 14 cases. The specific heat (C) was calculated using the k-values calculated from the equations given in Table 2.

TABLE 6 -- Calculated thermal diffusivity for three gypsum-wax

	GOW	G15W	G30W
Percent Wax	0	14.1	30
Density kg/m^3	695.1	816.9	1000.0
C, J/kg·K	a	1285	1527
k, W/m·K	0.1780	0.1919[b]	0.2325[b]
	α, m^2/s x 10^7		
t, °C 20	2.460	(1.919)[c]	(1.565)
25	2.425	1.919	1.565
30	2.391	1.828	1.523
40	2.264	(1.828)	(1.523)

[a] Eq. 8

[b] k of liquid-wax gypsum composite

[c] Extrapolated.

The 14 values of C for the calcium silicate test specimens are plotted in Fig. 3 and increase with temperature. Each of the transient tests with negative step changes in heat flux yielded low C values. If these are excluded, the remaining 11 values are described with an average deviation of 1.0% by

$$C = 951.5 + 2.556\ t\ . \tag{10}$$

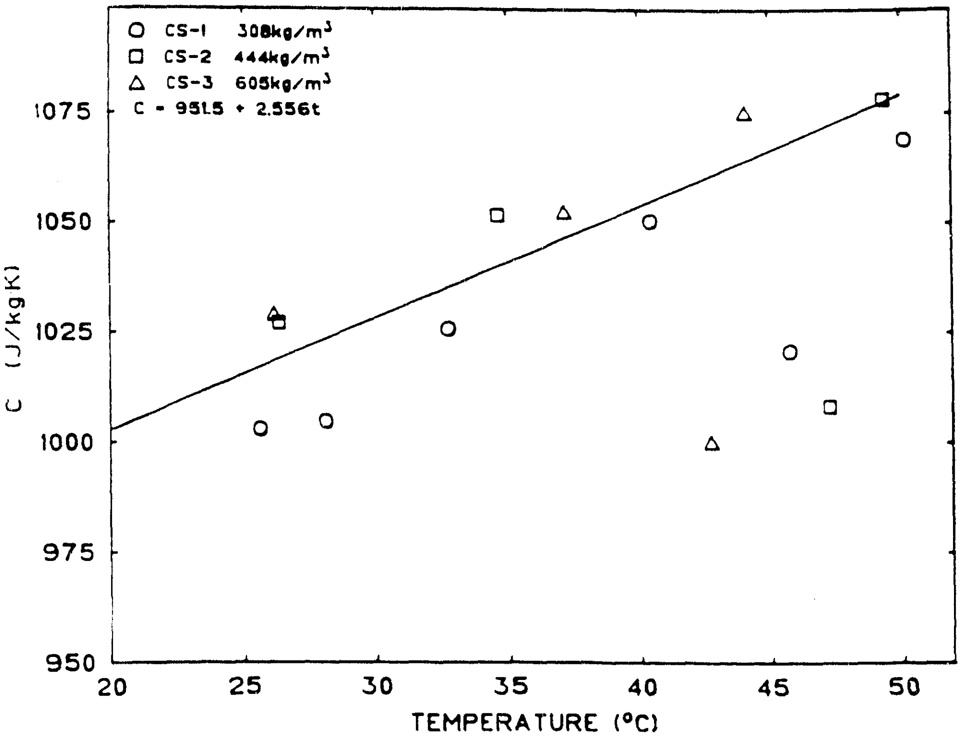

FIG. 3 -- Specific heat as a function of temperature for three calcium silicate insulations.

Equation 10 yields a C (24°C) of 1012.6 J/kg·K, which is 1.3% above the estimated value for C given in Table 1. Table 7 contains thermal diffusivity values calculated from the experimental values of ρ and C and the k-values calculated from the equations in Table 2.

TABLE 7 -- Calculated thermal diffusivity for three calcium silicate specimens

(α x 10^7, m^2/s)

		CS-1	CS-2	CS-3
Density, kg/m^3		307.4	443.95	605.1
t, °C	20	2.145	1.712	1.441
	24	2.130	1.639	1.432
	30	2.107	1.629	1.419
	50	2.031	1.596	1.377

The α values decrease with temperature and with increasing density. The α values are 19 to 28% lower than the estimated α values given in Table 1.

Table 5 contains the results obtained by analyzing the 12 transient tests conducted on the wood products using Method 2. Each specimen was subjected to three positive and one negative step change in heat flux. The slope was determined using data that spanned the range 200 to 1800 seconds for each transient. The heat flux correction for the screen thermal mass was -1.03% for the WSF specimens, -1.09% for the DFP specimens, and -0.85% for the SYPF specimens. The specific heat was calculated using the k-values calculated from the equations in Table 3.

The C values for each wood specimen are plotted in Fig. 4, and span the range 1400 J/kg·K to 1725 J/kg·K. Each wood product has a different temperature dependence, with C increasing from DFP to SYPF to WSF.

The WSF specimen, yielded a C (24°C) of 1658 J/kg·K, which is 1.9% above the estimated C given in Table 1. The SYPF has a lower moisture content than the WSF specimen and has a lower C value. The SYPF, has a C (24°C) of 1604 J/kg·K, which is 3.6% above the estimated C given in Table 1. The DFP specimen showed the lowest C values and a C (24°C) of 1402 J/kg·K, which is 9.8% lower than the estimated C given in Table 1. Table 8 contains α values for the three wood product test specimens. The α values for the WSF and SYPF are about 20% lower and the DFP is 2% lower than the estimated α in Table 1.

Table 5 contains the results obtained by analyzing three transient tests conducted on the polyisocyanurate (CFC-11) and 12 transient tests conducted on the extruded polystyrene (HCFC-142b). This analysis used Method 2. Each specimen was subjected to positiveand negative step changes in heat flux. The heat flux corrections for the heater thermal mass were large. The slope was determined using data that spanned the range 200 to 1800 seconds for the polyisocyanurate and 100 to 900 seconds for the extruded polystyrene.

The C values obtained from each test of the cellular plastic foams is plotted in Fig. 5 and span the range 1140 J/kg·K to 1680 J/kg·K. The C values for the polyisocyanurate are highest and yield a C (24) of 1496 J/kg·K, and this is 1.9% above the estimated C given in Table 1. The C values for the extruded polystyrene specimen decrease as aging time increases.

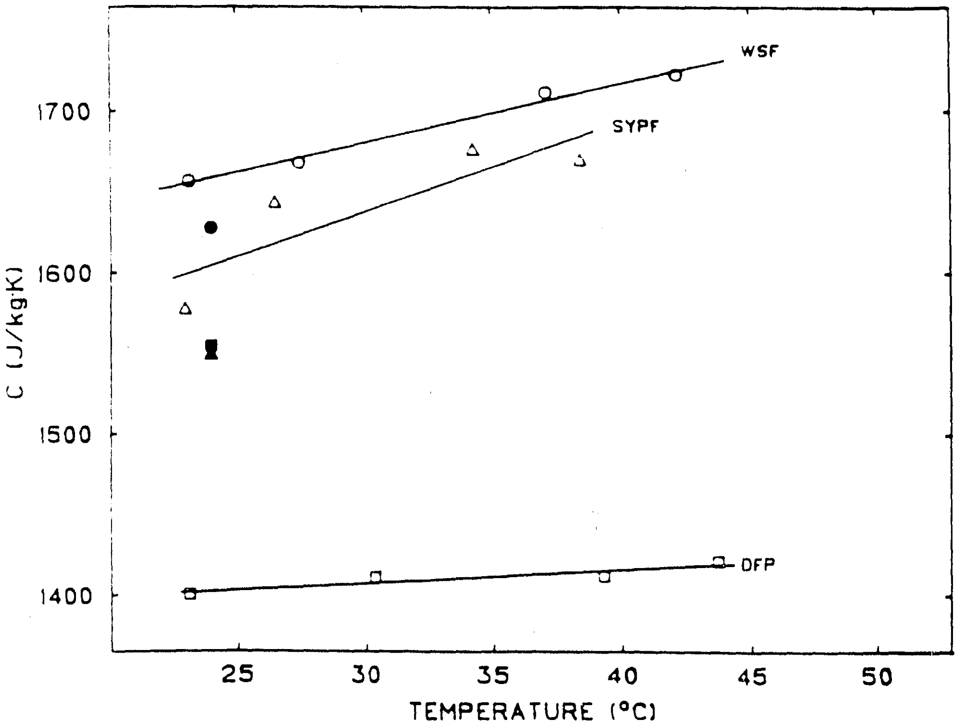

FIG. 4 -- Specific heat as a function of temperature for three wood products.

TABLE 8 -- Calculated thermal diffusivity for three wood product specimens
$\alpha \times 10^7$, m^2/s

		WSF	SYPF	DFP
Density, kg/m^3		451.5	575.2	500.9
t°, C	20	1.3773	1.3876	1.4430
	24	1.3735	1.3756	1.4485
	30	1.3676	1.3578	1.4567
	50	1.3482	1.2982	1.4841

The PS (227 d) has a C (24) of 1147 J/kg·K, which is 0.25% less than the estimate of C given in Table 1. It is noteworthy that C (45 days) is greater than C (227 days) and this may be due to inward diffusion of air and outward diffusion of HCFC-142b, with the higher C being associated with the HCFC blowing agent.

Table 9 contains thermal diffusivity values calculated from the experimental ρ and C values and the k-values calculated from the Equations in Table 5.

The α values for PIR (CFC-11) are between the values estimated in Table 1. The α values for the PS (HCFC-142b) started out greater than the initial α estimated in Table 1 and exceed the α (beyond 100 days) value by 2.7%.

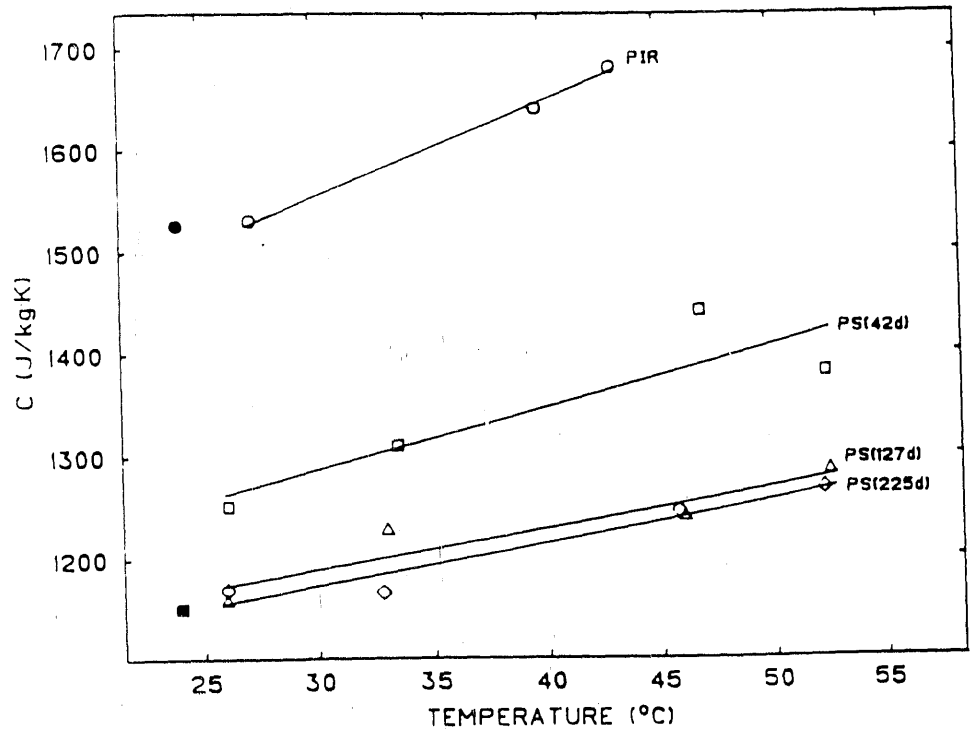

FIG. 5 -- Specific heat as a function of temperature for cellular plastic foams.

TABLE 9 -- Calculated thermal diffusivity for cellular plastic foams $\alpha \times 10^7$ m^2/sec

	PIR (CFC-11)	PS (HCFC-142b)		
Density, kg/m^3	30.2	30.0	30.0	30.0
Age, days	398	45	131	227
t, °C 20	4.516	6.891	8.181	8.415
24	4.495	6.888	8.170	8.421
30	4.463	6.875	8.206	8.447
50	4.356	6.833	8.311	8.529

Because of the high thermal mass ratios for these materials, Method 2 was used to find their specific heats. Method 2 has no fundamental basis and large differences in C resulted: PIR (CFC-11), -21% or -335 J/kg K; PS@45 d, +7.7% or 103 J/kg K; PS@131 d, +8.3% or 102 J/kg K; and PS@227 d, +9.1% or 109 J/kg K. The thermal mass ratios for these materials were approximately 0.14 for the PS and 0.24 for the PIR. If the C values for the plastic foams from Method 3 were used to compute the α values, then the α (PIR) would increase by about 25% and the α (PS) would decrease by about 10%. Table 10 summarizes the materials with the highest TMR studied.

TABLE 10 -- Summary of differences between calculation methods

Material	TMR	Methods	Delta C[*]	% Difference
GOW	0.0075	3 & 1	49	4.6
G15W	0.0055[**]	3 & 1	13[**]	1.0[**]
G30W	0.0038[**]	3 & 1	-16[**]	-1.0[**]
CS-I	0.0231	3 & 1	54	5.3
CS-II	0.0164	3 & 1	15	1.4
CS-III	0.0121	3 & 1	14	1.3
WSF	0.0077	3 & 1	21	1.3
DFP	0.0105	3 & 1	77	5.4
SYP	0.0065	3 & 1	-56	-3.4
PIR-CFC	0.237	3 & 2	-335	-20.7
PS@45	0.132	3 & 2	103	7.7
PS@130	0.144	3 & 2	102	8.3
PS@230	0.145	3 & 2	109	9.1

[*] C for M3 minus C for M1 or M2.
[**] Gypsum plus liquid wax only.

CONCLUSIONS

(1) Steady-state and transient modes of operation of the UTHA yielded thermophysical properties (k, C, and α) of four types of building materials (gypsum containing wax, calcium silicate insulations, wood products, and cellular plastic foams) from 24 to 50°C; (2) A procedure was developed to operate the UTHA in a transient mode by applying a step change in heat flux to specimens that were initially isothermal or that had a steady imposed temperature gradient. The procedure used a computer to control the test and to record the temperature-time behavior of the thin-heater; and (3) Experimental values for the product $k\rho C$ were determined from the temperature change of the thin-heater that is a linear function of the square root of time after the step change in heat flux. The error in the product $k\rho C$ was less than 1% for building materials with $(k\rho C)^{-1/2}$ values below 10 $m^2K/W\sqrt{s}$ (densities above 300 kg/m^3, and low values of TMR). However, for the cellular plastic foams with $(k\rho C)^{-1/2}$ values above 30 $m^2K/W\sqrt{s}$ (densities near 30 kg/m^3 and large TMR values), alternative analyses were required due to the large relative thermal mass of the heater and larger differences were found for $k\rho C$.

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