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MARTIN MARIETTA

# Development of Advanced Thermal Insulation for Appliances, Progress Report for the Period July 1984 Through June 1985

D. W. Yarbrough
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# DEVELOPMENT OF ADVANCED THERMAL INSULATION FOR APPLIANCES, PROGRESS REPORT FOR THE PERIOD JULY 1984 THROUGH JUNE 1985

D. W. Yarbrough, F. J. Weaver, R. S. Graves, and D. L. McElroy

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# DEVELOPMENT OF ADVANCED THERMAL INSULATION FOR APPLIANCES, PROGRESS REPORT FOR THE PERIOD JULY 1984 THROUGH JUNE 1985*

D. W. Yarbrough, F. J. Weaver, R. S. Graves, and D. L. McElroy

## ABSTRACT

Numerical simulations of the radial heat flow apparatus used to measure the apparent thermal conductivity ($k_a$) of powders with high thermal resistance (R) showed that heat losses from the ends of the cylindrical specimen and core heater cause the $k_a$ of the specimen to be greater than the true value. This effect is large when high-R powders are tested. A radial apparatus 91 cm in length, ORNL-5, was constructed and used to reduce uncertainties introduced by end losses. Numerically derived factors were prepared for use with the relatively short (30 cm) radial heat flow apparatus, ORNL-3, which has vacuum capabilities.

Theoretical considerations suggest that radiative transport in powders of the size range available is by absorption and re-emission rather than by scattering. Consequently, ORNL-5 was used to test mixtures of low-cost coarse fumed-silica particles and relatively uniform, but expensive, fine fumed-silica particles. The mixtures were tested to demonstrate the effect of pore size reduction and reduced radiative transport accomplished by mixing particles of different diameters and properties. R-values per inch (2.54 cm) in air near 7, and hence greater than that for still air without radiative transport, have been measured for pure fumed-silica powders. This R-value is less than anticipated for the pure fumed-silica particle size, perhaps because of particle clustering or an incomplete theory.

The thermal resistances of mixtures of coarse and fine powders were determined in the range 290 to 340 K at atmospheric pressure by using ORNL-5. The results show that R per inch depends on density and that R-values per inch greater than 5 can be achieved with such mixtures. R-values for a mixture of nominal 7-nm fine silica and coarse silica have been measured as a function of pressure near 300 K, and R per inch greater than 40 has been achieved in vacuum (<10 Pa).

Several linear heat flow measurements on evacuated rectangular panels showed that R per inch for the panels dropped from 16.8 to 15.9 during the period March 1983 to April 1985. This aging effect is believed to be due to a pressure increase of 130 Pa in the panels in 39 months. An end-of-life pressure of 1000 Pa is predicted to require at least 94 months.

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

# EXECUTIVE SUMMARY

## BACKGROUND

The need for and value of research to develop insulations with thermal resistances, R-values,* greater than those presently available with commercial products were documented in a 1981 report by Lawrence and Ruccia.[1] A 1984 report[2] introduced a heat transport model that is useful for predicting R-values that can be achieved. Property parameters that give calculated apparent thermal conductivities, $k_a$, less than 0.0072 W/m·K at 300 K and atmospheric pressure were identified. A $k_a$ of less than 0.0072 W/m·K gives an R-value of 3.53 $m^2$·K/W for thickness 2.54 cm (R-value per inch of 20 $ft^2$·h·°F/Btu). At 300 K, the gas and solid conductive components of heat transfer dominate, and it was shown that high thermal resistances are possible if the pore size in the insulation is much less than the mean free path in the gas phase. At atmospheric pressure, this requires particle diameters less than about 5 nm (50 Å). Thermal resistances above R = 20 per inch can be theoretically achieved in vacuum with particles having diameters much larger than 5 nm, and this has been demonstrated.[2] Test results showed that R greater than 20 per inch was achievable in vacuum and that a target of $k_a$ = 0.0144 W/m·K (corresponding to an R-value per inch of 10 $ft^2$·h·°F/Btu) at 300 K and atmospheric pressure was realistic.

## CURRENT RESULTS

Numerical simulations[3] of the radial heat flow apparatus used to measure the $k_a$ of powders with high R showed that heat losses from the ends of the cylindrical specimen and core heater cause the $k_a$ of the specimen to be greater than the true value. This effect is large when high-R powders are tested. A radial apparatus 91 cm in length, ORNL-5, was constructed and used to reduce uncertainties introduced by end losses. Numerically derived factors were prepared for use with the relatively short (30-cm) radial heat flow apparatus, ORNL-3, which has vacuum capabilities.

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*The nomenclature used in this report is defined in Appendix A.

Theoretical considerations[4] suggest that radiative transport in powders of the size range available is by absorption and re-emission rather than by scattering. Consequently, ORNL-5 was used to test mixtures of low-cost coarse fumed-silica particles and relatively uniform, but expensive, fine fumed-silica particles. The mixtures were tested to demonstrate the effect of pore size reduction and reduced radiative transport accomplished by mixing particles of different diameters and properties. R-values per inch in air near 7, and hence greater than the R-value for still air without radiative transport, have been measured for pure fumed-silica powders. This R-value is less than anticipated for the pure fumed-silica particle size, perhaps because of particle clustering or an incomplete theory.

The thermal resistances of mixtures of coarse and fine powders were determined in the range 290 to 340 K at atmospheric pressure by using ORNL-5. The results show that R per inch depends on density and that R-values per inch greater than 5 can be achieved with such mixtures. R-values for a mixture of nominal 7-nm fine silica and coarse silica have been measured as a function of pressure near 300 K, and R per inch greater than 40 (7.06 $m^2 \cdot K/W$ for 2.54 cm) has been achieved in vacuum (<10 Pa).

Several linear heat flow measurements on evacuated rectangular panels showed that R per inch for the panels dropped from 16.8 to 15.9 during the period March 1983 to April 1985. This aging effect is believed to be due to a pressure increase of 130 Pa in the panels in 39 months. An end-of-life pressure of 1000 Pa is predicted to require at least 94 months.

## PLANS

The economical realization of R per inch greater than 10 in air will require a source of particles with very small diameters or an optimization of particle size distribution to achieve the required pore size. The approach of using mixtures with one component that reduces radiative transport and another component that reduces gas conduction is being pursued. The realization of very high R per inch at reduced pressures has been demonstrated, and commercial usage becomes a question of economical packaging and determination of stability with time. A cooperative industry-government program to define this technology has been developed.

# INTRODUCTION

The need for materials with high thermal resistance for both low and high temperature applications has been discussed in reports by Lawrence and Ruccia,[1] McElroy et al.,[2] and Yarbrough et al.[5] The report by Lawrence and Ruccia surveyed methods of attaining high thermal resistances and documented potential savings. The second report in the series[2] included a theoretical model for heat transfer through fine powders. Apparent thermal conductivity, $k_a$, data for 13 materials and evacuated systems were reported. The theoretical model showed that $k_a$ less than 0.0072 W/m·K (R for 2.54 cm = 3.53 $m^2$·K/W, R per inch = 20 $ft^2$·h·°F/Btu) could be achieved with fine powders in air at atmospheric pressure and 300 K. The successful use of fine powders to achieve high thermal resistance depends on decreasing gas-phase conduction and decreasing radiative transport without significantly increasing the solid-phase conduction. The decrease in gas-phase conduction can be accomplished by either reducing the density of the gas-phase material by evacuation or by making the effective pore size in the porous media small compared with the distance traveled by gas-phase molecules between collisions, $\ell_g$. The data for $k_a$ of fine powders obtained by McElroy et al.[2] as a function of pressure included $k_a$ as low as 0.0040 W/m·K and clearly demonstrated the potentially high thermal resistance achievable by using evacuated systems. The experimental research discussed in this report was undertaken to extend the available data base for the apparent thermal conductivity of fine powders.

Fibrous or particulate thermal insulations containing air at atmospheric pressure as the gas phase have the thermal conductivity of air as a limiting value unless the effective pore size can be reduced to less than the mean free path in the gas phase. Unless the gas-phase conductivity is reduced, then the $k_a$ for air at 298 K and one atmosphere pressure of approximately 0.026 W/m·K limits practical R-values to 0.98 $m^2$·K/W for 2.54 cm of material (5.5 $ft^2$·h·°F/Btu per inch of material). The objectives of the present research are to identify thermal insulations that will achieve R-values of 1.75 $m^2$·K/W for 2.54 cm (10.0 $ft^2$·h·°F/Btu per inch) in air at one atmosphere pressure and 3.5 $m^2$·K/W for 2.54 cm (20.0 $ft^2$·h·°F/Btu per inch) at reduced pressures and 300 K.

Heat transport through a system of fine particles can be discussed in terms of the net radiative flux and the conductive flux because convective transport is negligible. If the two heat transfer mechanisms are assumed to be independent, then

$$k_a = k_c + k_r \ . \tag{1}$$

Models for $k_c$ and $k_r$ can then be used as a basis for discussing ways of achieving high thermal resistances or low $k_a$. Equations (2) and (3) were derived in a previous report[2] and are used in discussing the $k_a$ data in this report.

$$k_c = \frac{0.33F_s k_s}{1 + 0.33AF_s} + \frac{(1 + 0.33F_s)k_g{}^\circ}{1 + 1.5F_s(\ell_g/d)} \tag{2}$$

$$k_r = \frac{4F_{\lambda_1-\lambda_2}\sigma T_m{}^3 L^\circ}{1/\varepsilon_H + 1/\varepsilon_C - 1} + \frac{4(1 - F_{\lambda_1-\lambda_2})\sigma T_m{}^3 L^\circ}{3\overline{E}L^\circ/4 + 1/\varepsilon_H + 1/\varepsilon_C - 1} \tag{3}$$

$$T_m = [(T_H{}^4 - T_C{}^4)/4(T_H - T_C)]^{1/3} \tag{4}$$

Equation (2) shows that a large value for $\ell_g/d$ minimizes $k_c$ for a given particle system with fixed values for $A$, $F_s$, and $k_s$.

$$\lim_{(\ell_g/d)\to\infty} (k_c) = \frac{0.33F_s k_s}{1 + 0.33AF_s} \tag{5}$$

The above limiting value can be estimated from $k_a$ measurements at low pressure where $\ell_g$ is large. Equation (5) shows the desirability of small $F_s$ for the reduction of $k_c$. Unfortunately, $k_r$ increases as $F_s$ and $\overline{E}$ become small. There should exist, therefore, a value for $F_s$ or density that minimizes $k_a$ calculated by the above model. The determination of optimum density cannot be done mathematically because $A$ is an unknown function of $F_s$ and particle characteristics. Thus, the density that minimizes $k_a$ for a given type of powder must be determined experimentally.

The apparent thermal conductivity of a powder depends on temperature and pressure. The conductive term, $k_c$, increases with temperature because both $k_g{}^\circ$ and $k_s$ increase with temperature. The quantities $\overline{E}$ and $F_{\lambda_1-\lambda_2}$ in

Eq. (3) also vary with temperature. The radiative term, $k_r$, increases with $T_m^3$, and this is the dominant temperature dependence. The rate of change of $k_c$ with respect to $\ell_g/d$, $\partial k_c/\partial(\ell_g/d)$, obtained from Eq. (2) is negative for all values of $F_s$ and $k_g^\circ$. It follows, therefore, that $k_c$ will decrease as $\ell_g$ increases at constant temperatures for a fixed pore size, $d$. The mean free path, $\ell_g$, varies inversely with the number of molecules per unit volume in the gas phase if intermolecular forces are neglected.[6] The number density of gas molecules for an ideal gas at constant temperature is directly proportional to the pressure, so $\ell_g$ is universally proportional to the pressure and $k_c$ will decrease as the pressure decreases.

Because $k_r$ given by Eq. (3) is independent of pressure, the apparent thermal conductivity given by Eq. (1) will decrease as pressure decreases. The dependence of $k_a$ on pressure, however, depends on the powder as illustrated by Pellaux-Gervais[7] for particles ranging in diameter from 0.0035 μm to 600 μm (Fig. 1 of ref. 2).

Theoretical considerations clearly show that systems with high thermal resistance can be designed by using fine powders and reduced gas-phase pressures. Equation (3) shows the desirability of high extinction coefficients and low boundary emittances. Equations (2) and (3) strictly apply to rectangular geometries or thin annular regions with large internal radii.

Apparent thermal conductivities of powders have been measured by using radial heat flow apparatuses.[2] The steady-state $k_a$ determinations are based on temperature difference measurements and measurements of the energy transferred across a specimen from a centerline core heater. If the heat flow from the central segment of the core heater is in the radial direction, then Fourier's Law can be integrated to obtain Eq. (6) for $k_a$.

$$k_a = q\ln(r_o/r)/2\pi\ L\Delta T) \tag{6}$$

The $k_a$ determination, therefore, requires a measurement of radial heat flow from a given length of specimen, $Q/L$, and the temperature difference across the specimen in the radial direction, $\Delta T$. If axial heat flow in the measurement section of a radial apparatus occurs, then a correction to the $k_a$ calculated from Eq. (6) is necessary. The correction has been

estimated from numerical solutions of the conduction equation that includes radial and axial heat flow.[3] Corrections to Eq. (6) can be significant for very low $k_a$ like those for evacuated powders.

Apparent thermal conductivities for rectangular evacuated panels have been measured by a linear heat flow apparatus (DIET, dynamic insulation efficiency tester) that has been previously described. DIET[2,8,9] was operated as a one-sided experiment for the heat flow measurements across evacuated panels, and $k_a$ was calculated from Eq. (7).

$$k_a = QL^\circ/\Delta T \tag{7}$$

The heat flux, $Q$, in Eq. (7) was the electrical power dissipated per unit area of screen in DIET minus a small calculated correction for heat flow away from the test specimen.

## EQUIPMENT USED TO MEASURE APPARENT THERMAL CONDUCTIVITY

Two radial-heat-flow apparatuses were used to obtain the $k_a$ for powders: ORNL-3, which was described in detail in a previous report,[2] and ORNL-5 (Figs. 1 and 2). The ORNL-3 system was operated without active end guards in the present study. The ORNL-5 system is similar to ORNL-4 (ref. 2) except that it is 91 cm in length; it was used to measure $k_a$ at atmospheric pressure. This longer unguarded radial-heat-flow apparatus was constructed to achieve radial heat flow in the central measurement section. It was constructed from a brass pipe with inside diameter 4.06 cm and length 91.3 cm. Copper tubing was attached to the outside surface of the brass pipe so that the pipe's temperature could be maintained by circulating temperature-controlled coolant. The temperature at the midpoint of the brass pipe was measured by a 36-gauge chromel-constantan thermocouple as shown in Fig. 2. The inside surface temperatures of test specimens were determined from 36-gauge chromel-constantan thermocouples welded to the core heater as shown in the figure.

Electrical power dissipated in either ORNL-3 or ORNL-5 was calculated from voltage drops between thermocouple elements separated by a known distance, and the current was determined from a voltage drop across a

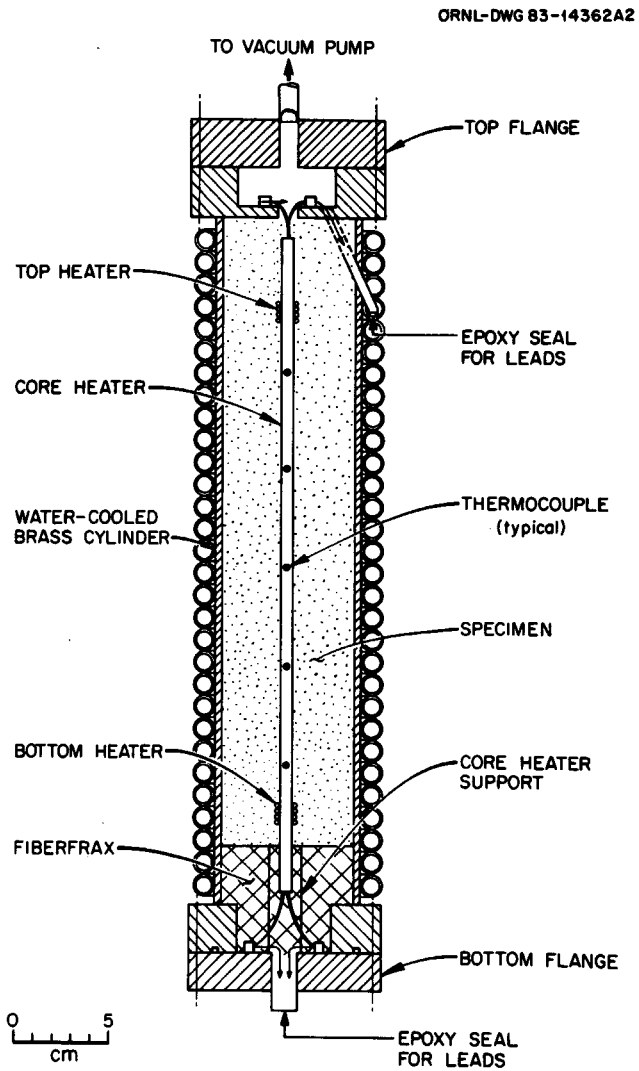


Fig. 1. Diagram of ORNL-3, a radial-heat-flow apparatus with vacuum capability.

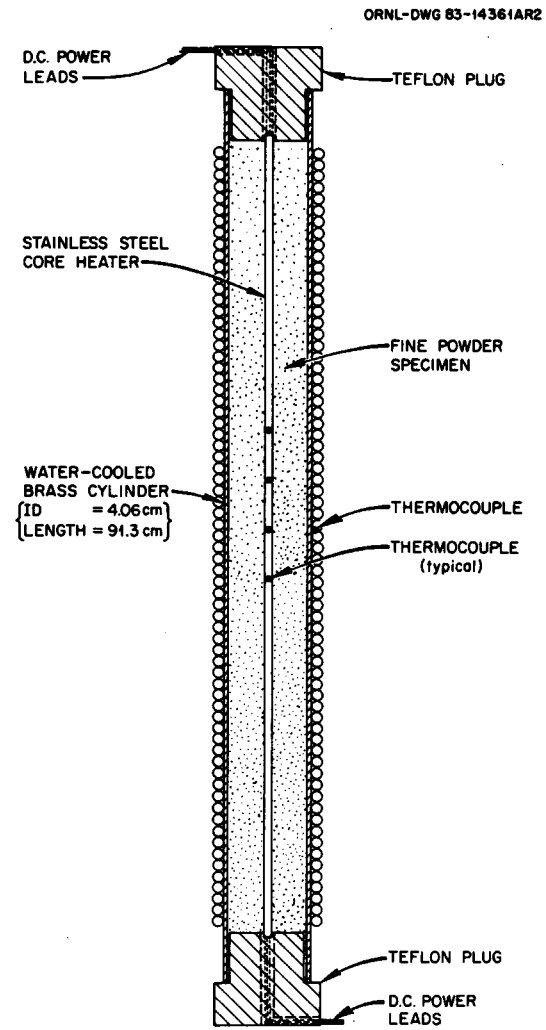


Fig. 2. Diagram of ORNL-5, an unguarded radial-heat-flow apparatus for measurements at atmospheric pressure.

known resistance in series with the core heater. In regions with no axial heat flow, the electrical power is dissipated as radial heat flow across the test specimen, and this is the $Q/L$ in Eq. (6).

The densities of powders tested in ORNL-3 or ORNL-5 were determined by weighing the specimens to ±0.1 g and calculating the volume of the annular space filled by the powder. Densities were increased by either tapping the container as the powder was introduced or by ramming the powder after small amounts of powder were poured into the annular space. A cylindrical block with a hole in the center to slide over the core heater was used as a ram. The volume fraction of solid, $F_s$, was calculated by dividing the measured density by 2200 kg/m$^3$, the density for pure silica.[10]

The linear-heat-flow apparatus was used to determine $k_a$ for silica-filled evacuated panel number 20. These measurements were made to determine the rate at which $k_a$ increases with time as a result of increasing internal pressure.

## COMPUTER MODELING OF ORNL-3 AND ORNL-5

The effect of axial heat flow in an unguarded radial measurement apparatus becomes increasingly important as the specimen apparent thermal conductivity decreases. Previous results[2] from ORNL-3 for evacuated powder showed values for $k_a$ as low as $4 \times 10^{-3}$ W/m·K. Thermal modeling with HEATING5 (ref. 3) was undertaken, therefore, to provide axial heat flow corrections for the $k_a$ calculated by using Eq. (6), which assumes only radial heat flow. The corrections were developed by calculating temperature distributions for the two apparatuses with powders in the annular space between the heater and the outer brass cylinder having $k_a$ from $2 \times 10^{-3}$ W/m·K to $4 \times 10^{-2}$ W/m·K, the $k_a$ range of interest. The data used for the temperature distribution calculations are summarized in Table 1, and the HEATING5 inputs are contained in Appendix B.

Interior temperature distributions were calculated for ORNL-3 and ORNL-5 with the ends and exterior surface at the same constant temperature. The actual apparatuses have a small added resistance at each end

Table 1. Input properties and dimensions for thermal modeling of ORNL-3 and ORNL-5

| Property (dimension) | ORNL-3 | ORNL-5 |
|---|---|---|
| ID of heater (cm) | 0.4988 | 0.50 |
| OD of heater (cm) | 0.5394 | 0.54 |
| ID of specimen (cm) | 0.5394 | 0.54 |
| OD of specimen (cm) | 5.08 | 4.06 |
| Length of specimen (cm) | 14.37 | 45.64 |
| $k_a$ of heater (W/cm·K) | 0.15 | 0.15 |
| $k_a$ of specimen (W/cm·K) | $2 \times 10^{-5}$ to $4 \times 10^{-4}$ | $2 \times 10^{-5}$ to $4 \times 10^{-4}$ |
| Vol. heat generation rate in heater (W/cm$^3$) | 0.10 and 1.0 | 0.10 and 1.0 |
| Program convergence limit | $1 \times 10^{-8}$ | $1 \times 10^{-8}$ |

due to teflon plugs and heat exchange with the surrounding air. The calculated temperatures and input powers were substituted into Eq. (6) to obtain the equivalent of a measured $k_a$. The computer-simulated $k_a$ was then compared with the $k_a$ input to HEATING5. The results can be shown as either a $k_a$ ratio or a $\Delta T$ ratio. From Eq. (6)

$$(\Delta T)_i = (Q/L)\ln(r_o/r)/2\pi k_{a,i} \ , \tag{8}$$

where $i$ denotes either ideal (input) or measured (simulated) values. It follows that

$$\frac{(\Delta T)_{\text{ideal}}}{(\Delta T)_{\text{measured}}} = \frac{k_{a,\text{measured}}}{k_{a,\text{ideal}}} = \frac{1}{C} \ , \tag{9}$$

where "ideal" corresponds to only radial heat flow. The computer simulations were used to determine the relationship between the $k_{a,\text{measured}}$ and

$k_{a,\text{ideal}}$ for the radial-heat-flow systems. The two $k_a$'s are related by Eq. (9) with $C$ for ORNL-3 shown in Fig. 3. This shows a correction of 23% for $k_{a,\text{measured}}$ of $5 \times 10^{-3}$ W/m·K obtained with ORNL-3.

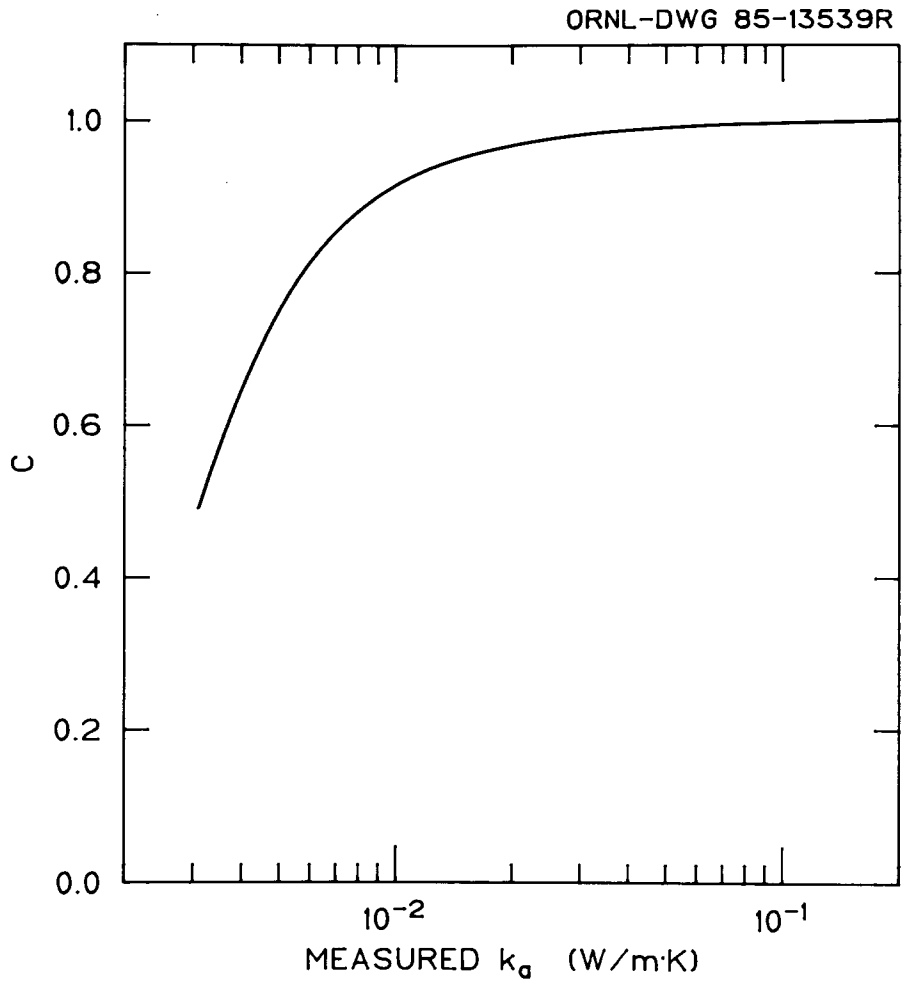


Fig. 3. Factor for the calculation of $k_{a,\text{ideal}}$ from $k_{a,\text{measured}}$ obtained with ORNL-3. $k_{a,\text{ideal}} = C \cdot k_{a,\text{measured}}$.

The difference between $k_{a,\text{measured}}$ and $k_{a,\text{ideal}}$ due to axial heat flow in ORNL-5 is less than 1.0% for $k_a$ above $2 \times 10^{-3}$ W/m·K. Computer simulations for DIET indicated a need for edge-loss corrections for $k_a$ measurements on the evacuated panels because of their high thermal resistance. The calculation of appropriate corrections is in progress.

## APPARENT THERMAL CONDUCTIVITIES WITH ORNL-3

The capability of ORNL-3 to measure in vacuum was applied to two specimens. The apparent thermal conductivities of a powder mixture containing 80 wt % Selma Gray and 20 wt % Cab-O-Sil EH-5* were measured near 300, 331, and 335.5 K for gas-phase pressures from 3 Pa to $1.01 \times 10^5$ Pa. The Selma Gray silica contained particles with diameters from 30 to 300 nm while Cab-O-Sil EH-5 silica has a nominal particle size of 7 nm. The Selma Gray is dark in color, while the EH-5 is white. The mixture, therefore, contains powders with different size distributions and radiative transport properties. The $k_a$ for Cab-O-Sil S-17 was also measured in ORNL-3 in the range 300 to 331 K at atmospheric pressure, $1.01 \times 10^5$ Pa, and under vacuum, 4 to 5 Pa.

The measured quantities used in Eq. (6) to calculate $k_a$ are listed in Appendix C (Tables C.4 and C.5), and materials are identified in Table C.3. The data set for the mixture No. 25 contains 16 points within ±1 K of 300 K, 4 points within ±1 K of 331 K, and 11 points within ±1 K of 335.5 K. Figure 4 shows the three sets of $k_a$ as a function of pressure. A curve has been included on the figure at low pressures that incorporates the correction for axial heat flow.

The mixture data show $dk_a/dP > 0$ over the pressure range 1.0 Pa to $1.0 \times 10^5$ Pa. The transition from the lower pressure segment of the $k_a(P)$ curve to the higher pressure segment occurs in the range $1.0 \times 10^2$ to $1.0 \times 10^3$ Pa (0.75 to 7.5 mm Hg).

The $k_a$ data for S-17 at low and atmospheric pressure and temperatures from 301 to 330 K were used to obtain $k_a$ at 300 K. These results appear as black circles and triangles in Fig. 4. The S-17 data fall below the mixture $k_a$ at atmospheric pressure and above the mixture data at low pressure. The two atmospheric-pressure $k_a$ values for S-17 coincide, while the low-pressure values fall on a line that is roughly parallel to the mixture data curve in Fig. 4.

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*Material sources are listed in Appendix C.

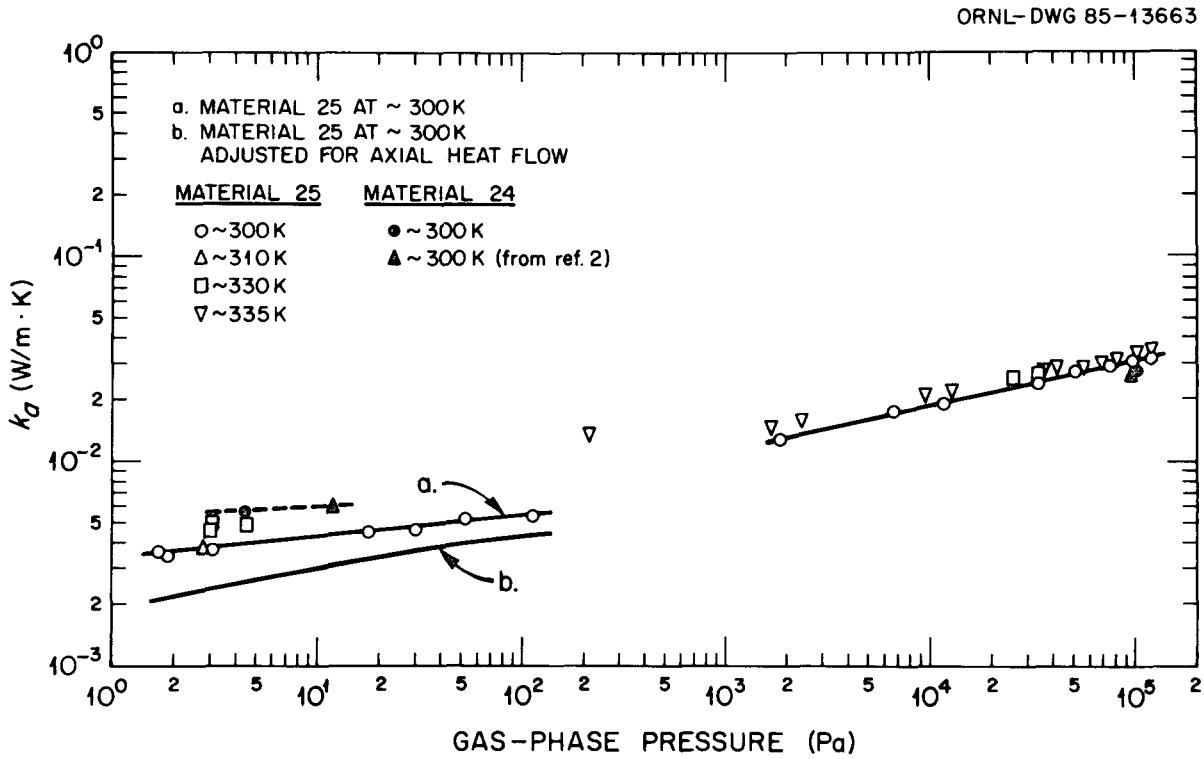


Fig. 4. Apparent thermal conductivity of silica powders as a function of pressure.

## APPARENT THERMAL CONDUCTIVITIES WITH ORNL-5

The radial-heat-flow apparatus ORNL-5 was used to measure $k_a$ for ten powders at atmospheric pressure from 293 to 340 K. The measurements used to calculate $k_a$ are listed in Appendix C (Tables C.4 and C.5). The data set includes $k_a$ for Cab-O-Sil S-17 at 80 kg/m$^3$ and nine mixtures of the fine silica powder with either Reynolds fume or Selma Gray silica.

The $k_a$ for the nine mixtures and S-17 were individually fit by the method of least squares to linear temperature expressions, and the resulting equations (Appendix D) were used to calculate $k_a$ at 300 K. Table 2 contains $k_a$ at 300 K, specimen density, and mass fraction solid, $F_s$, computed with a theoretical density of 2200 kg/m$^3$ for $SiO_2$. Figure 5 shows $k_a$ as a function of $F_s$ or density and demonstrates $dk_a/d\rho$ greater than 0 for the powder mixtures that were tested. An equation formulated from the earlier study[2] is consistent with the current $k_a$ results on Cab-O-Sil S-17 at 80 kg/m$^3$.

Table 2. Apparent thermal conductivities of Cab-O-Sil S-17 and mixtures of Cab-O-Sil S-17 or EH-5 and fumed silica at atmospheric pressure and 300 K

| Composition[a] (wt % fumed silica) | | Density ($kg/m^3$) | $F_s$ | $k_a$ (W/m·K) |
|---|---|---|---|---|
| 0 | (pure S-17) | 80 | 0.036 | 0.0250 |
| 95 | Reynolds fume and S-17 | 357 | 0.162 | 0.0413 |
| 90 | Reynolds fume and S-17 | 325 | 0.148 | 0.0386 |
| 80 | Reynolds fume and S-17 | 251 | 0.114 | 0.0328 |
| 80 | Reynolds fume and S-17 | 313 | 0.142 | 0.0330 |
| 95 | Selma Gray and EH-5 | 297 | 0.135 | 0.0345 |
| 90 | Selma Gray and EH-5 | 249 | 0.113 | 0.0319 |
| 80 | Selma Gray and EH-5 | 162 | 0.074 | 0.0292 |
| 80 | Selma Gray and EH-5 | 201 | 0.091 | 0.0287 |
| 80 | Selma Gray and S-17 | 501 | 0.228 | 0.0515 |
| 100 | Selma Gray | 361 | 0.164 | 0.0369[b] |
| 100 | Reynolds fume | 382 | 0.174 | 0.0415[b] |

[a]Material sources are identified in Appendix C.

[b]Reported by McElroy et al.[2]

## APPARENT THERMAL CONDUCTIVITIES WITH DIET

The linear-heat-flow apparatus DIET was used to measure the $k_a$ of a silica-filled evacuated panel intermittently over a period of 3 years. McElroy et al.[2] reported $k_a$ for evacuated panel No. 20 about 14 months after it was produced. The $k_a$ of the panel has been measured at 25 and 39 months after manufacture to determine the rate of increase of $k_a$ due to pressure increase. Table 3 summarizes the thermal measurements for panel No. 20.

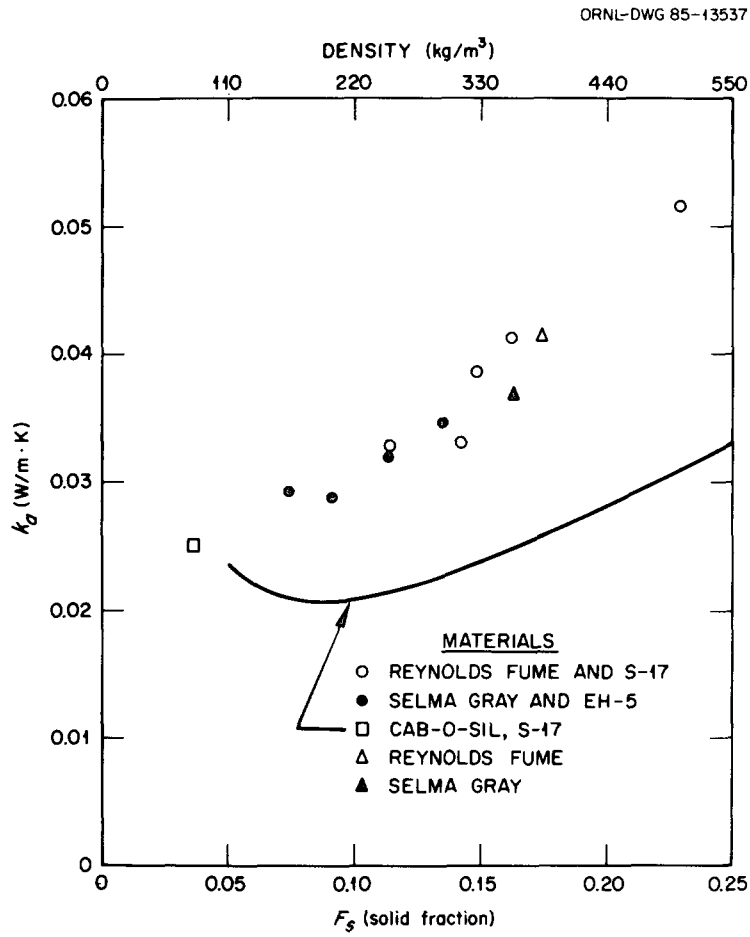


Fig. 5. Apparent thermal conductivity of silica powders at 300 K as a function of fraction solid or density. The curve was calculated from $k_a = 0.1484 \times 10^{-2} + 0.5140 \times 10^{-4}\rho + 1.795/\rho$. (Ref. 2.)

Table 3. Apparent thermal conductivity of L'Air Liquide evacuated panel No. 20 as a function of age

| Panel age (months) | $k_a$ (W/m·K) | R-value (ft²·h·°F/Btu·in.)[a] | Change in R-value[b] (%) | Estimated panel pressure | |
|---|---|---|---|---|---|
| | | | | Uncorrected[c] [Pa (mm Hg)] | Corrected[d] [Pa (mm Hg)] |
| 14 | 0.008589 | 16.79 | | 281 (2.1) | 243 (1.8) |
| 25 | 0.008598 | 16.77 | −0.12 | 284 (2.1) | 244 (1.8) |
| 39 | 0.009108 | 15.84 | −5.66 | 510 (3.8) | 352 (2.6) |

[a]R-value for 2.54 cm (m²·K/W) = 0.1761 × R-value per inch (ft²·h·°F/Btu·in.).

[b]Relative to R-value at 14 months.

[c]Estimate is based on low-pressure $k_a$ obtained with ORNL-3.

[d]Estimate is based on low-pressure $k_a$ corrected for axial heat flow.

The panel pressure estimates in Table 3 were obtained by using the $k_a$ for silica powder mixture 25 to obtain $(\partial \ln k_a/\partial \ln P)_T$ for $P$ less than 150 Pa. The low-pressure segment of the $k_a$ curve in Fig. 4 has a constant slope that approximates the slope of the line segment joining two low-pressure $k_a$ for pure silica powder. The single low-pressure $k_a$ for S-17 at 300 K was combined with the slope number to obtain a predictor for the panel pressure given a $k_a$ value. Equation (10a) is the result if uncorrected low pressure $k_a$ are used, and Eq. (10b) is the result if the $k_a$ are corrected for axial heat flow.

$$(\ln k_a + 5.164)/(\ln P - 1.504) = 0.0984 \tag{10a}$$

$$(\ln k_a + 5.387)/(\ln P - 1.504) = 0.1579 \tag{10b}$$

Equations (10a) and (10b) were rearranged and used to estimate panel pressures on the assumption that the powder measurements made with ORNL-3 represent the silica in the panel. Panel pressure estimates using Eq. (11a) and (11b)

$$P = \mathrm{Exp}\ \{(\ln k_a + 5.312)/0.0984\} \tag{11a}$$

$$P = \mathrm{Exp}\ \{(\ln k_a + 5.624)/0.1579\} \tag{11b}$$

and DIET $k_a$ data versus time are shown in Table 3. A linear least squares fit to each of the two sets of pressure was used to estimate panel pressure at manufacture. Equation (11a) gives 112 Pa (0.8 mm Hg), and Eq. (11b) gives 162 Pa (1.2 mm Hg). Both of these initial pressure estimates are lower than the estimated 1000 Pa (7.5 mm Hg) quoted by the manufacturer.[11]

Equation (10) and the data shown in Fig. 4 can be used to predict future panel performance. The mixture curve in Fig. 4 suggests that transition from the low-pressure regime to the high-pressure regime will occur at about 1000 Pa. The time required to reach 1000 Pa can be estimated from the pressure predictions in Table 3. The result is 94 months after manufacture for the uncorrected estimation and 186 months for the corrected estimation. Additional panel $k_a$ measurements and a determination of the $k_a$ of the silica powder in the panels will permit refinement of the aging prediction.

## DISCUSSION OF THE DATA FOR APPARENT THERMAL CONDUCTIVITIES OF FINE POWDERS

The $k_a$ of fine silica powders measured at atmospheric pressure and 300 K are shown in Fig. 5 as a function of $F_s$ and density. The data clearly show $dk_a/dF_s > 0$ ($dk_a/d\rho > 0$), indicating that further reduction in $k_a$ of these powders is possible. The data show that the pure small-diameter silica powders, S-17 and EH-5, have $k_a$ less than the somewhat larger inexpensive silica powders, Selma Gray and Reynolds fume. Mixtures of the two powders were tested to determine if the thermal resistance of the fume products could be significantly improved by the addition of small amounts of S-17 or EH-5.

The $k_a$ data in Fig. 6 as a function of the amount of fine powder show a sharp decrease in the $k_a$ of mixtures of coarse silica and S-17 or EH-5.

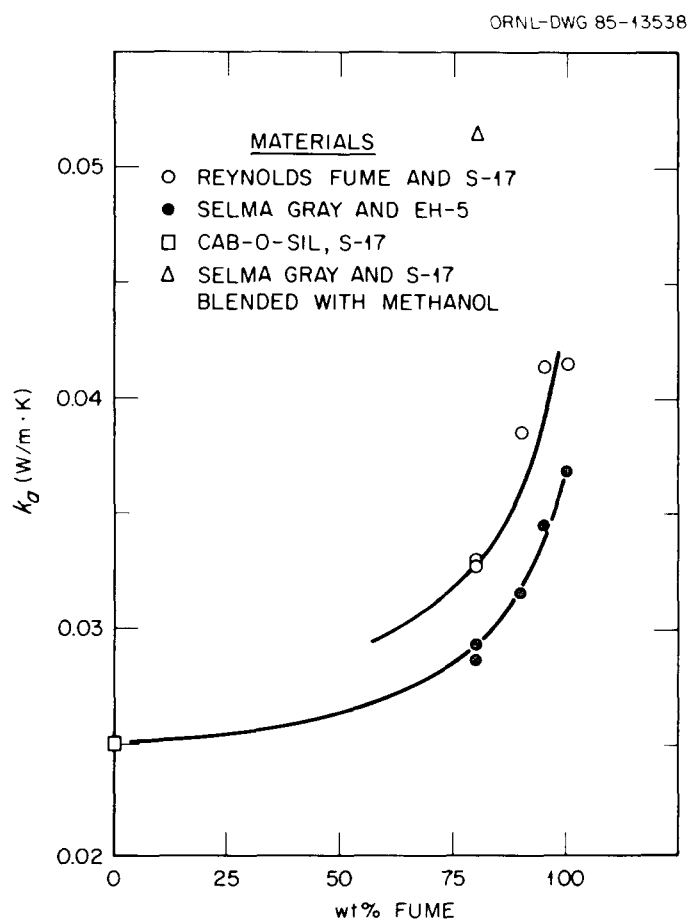


Fig. 6. Apparent thermal conductivity of mixtures of silica powders at atmospheric pressure and 300 K.

The curves in Fig. 6 indicate that mixtures containing 25 wt % S-17 or EH-5 have $k_a$ decreased by 60 to 70% of the difference between the coarse silica and the Cab-O-Sil products.

The data point in Fig. 6 identified as a mixture blended with methanol represents a material with a density of 500 kg/m$^3$. The relatively large $k_a$ is a consequence of the high density and resulting increase in solid-solid contact.

The $k_a$ data at one atmosphere and 300 K have been used to calculate R-values in engineering units, and the results are shown in Fig. 7 as a function of density. The line in the figure represents a linear least squares representation of the data. R-values for these materials would be expected to increase for some range of densities below those tested and decrease for very low densities. An extrapolation of the existing data to the vertical axis gives an upper bound of about 1.1 m$^2$·K/W for 2.54 cm (6 ft$^2$·h·°F/Btu per in.) for silica mixtures like those tested.

If the $k_a$ can be represented by Eq. (1), and Eqs. (2) and (3) are used to represent components, then the parameters $A$ and $d$ can be estimated. The $k_a$ for material No. 25 at $F_s$ = 0.074, 300 K, and atmospheric pressure was 0.02924 W/m·K and at low pressure was determined to be $3.5 \times 10^{-3}$ W/m·K. The smaller number should be representative of $k_r$ and the solid-phase contribution to $k_c$. An estimate of $k_r$ = 0.0005 for a silica powder mixture at $F_s$ = 0.074 can be obtained from Table 9 in ref. 2, and this makes the $k_c$ solid-phase component 0.0030. Substitution of 0.0030 for the limit in Eq. (5), 1.38 W/m·K for $k_s$ and 0.074 for $F_s$, gives $A$ = 419 as an estimate for the structural parameter.

The gas-phase component of the apparent thermal conductivity at atmospheric pressure, 300 K and $F_s$ = 0.074, was estimated by subtracting $3.5 \times 10^{-3}$ W/m·K from $k_a$. The value $k_g^\circ$ = 0.026 W/m·K can then be used to obtain $\ell_g/d$ = 0.3115 from the second term in Eq. (2). The effective pore size for specimen No. 25 is, therefore, 224 nm, and this is consistent with the particle-size range of 30 to 300 nm for the coarse products. Because the pore size is about three times the mean free path in the gas, there is no reduction in gas-phase conductivity.

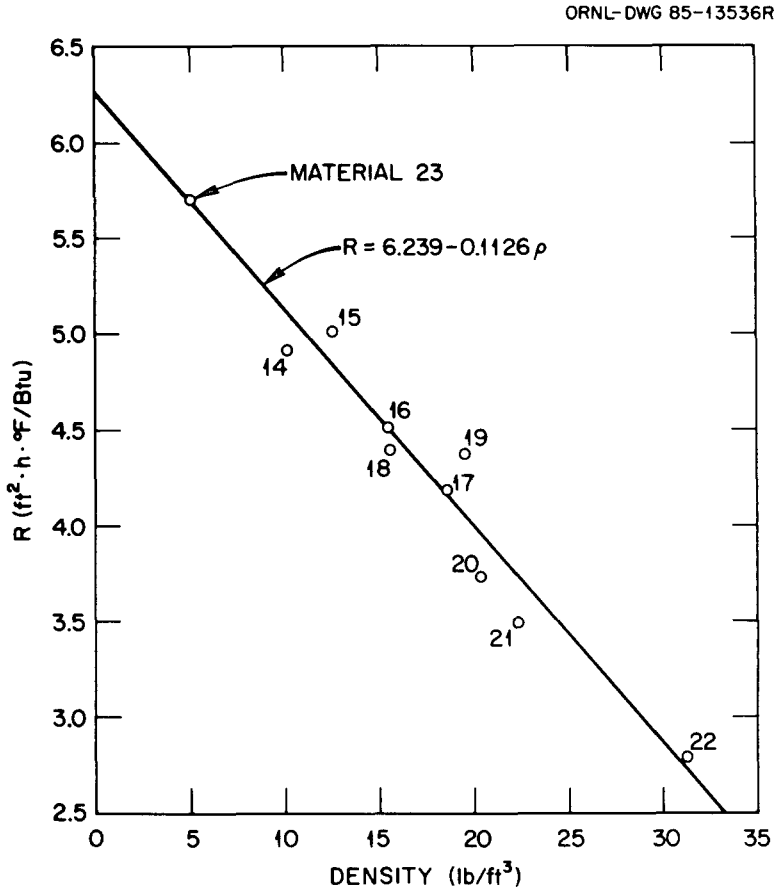


Fig. 7. Thermal resistance per inch for silica powder mixtures as a function of density at 300 K and atmospheric pressure. [R($m^2$·K/W) for 2.54 cm = 0.1762 × R($ft^2$·°F/Btu) for 1.0 in.; density (kg/$m^3$) = density (lb/$ft^3$) × 16.019.]

The measured R-values at atmospheric pressure are less than predicted by McElroy et al.[2] for the *A* and particle sizes given above. Microscopic examination of the fume products and S-17 shown in Figs. 8, 9, and 10 shows that the materials do not necessarily exist as finely divided powders. Figures 8 and 9 show that the fume particles may in fact coalesce to form relatively large particles, while a linked structure for S-17 is evident in Fig. 10. A material structure other than finely divided particles could account for the lower-than-expected R-values.

## CONCLUSIONS AND RECOMMENDATIONS

The thermal resistance of mixtures of fumed silica and fine pure silica powders increases rapidly as the pure silica is added but does not

S-16925

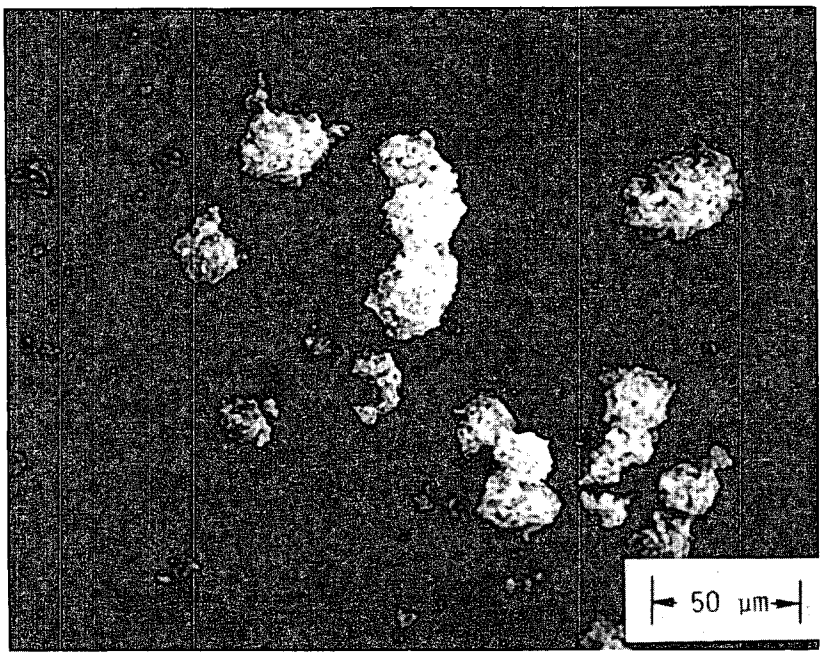


Fig. 8. Photomicrograph of Selma Gray fumed silica.

S-16937

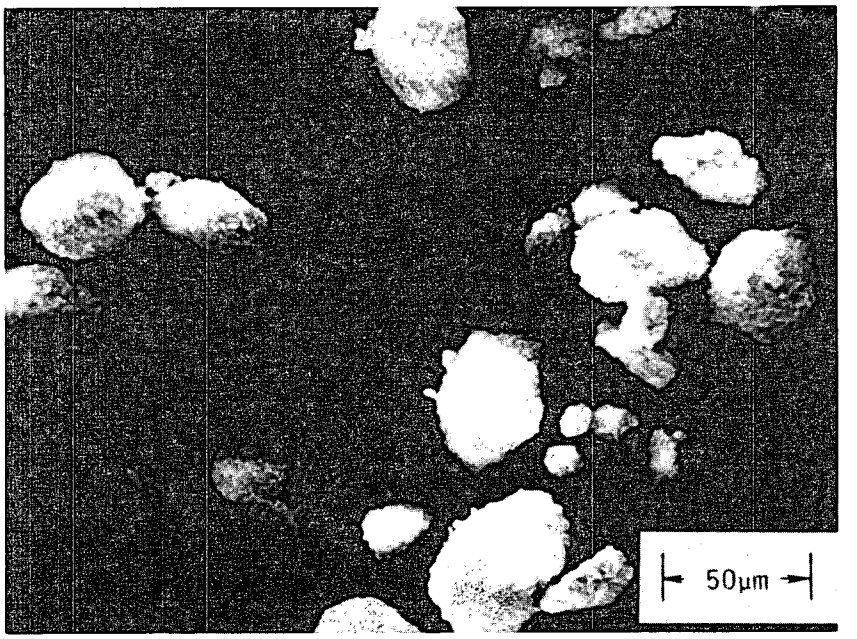


Fig. 9. Photomicrograph of Reynolds fumed silica.

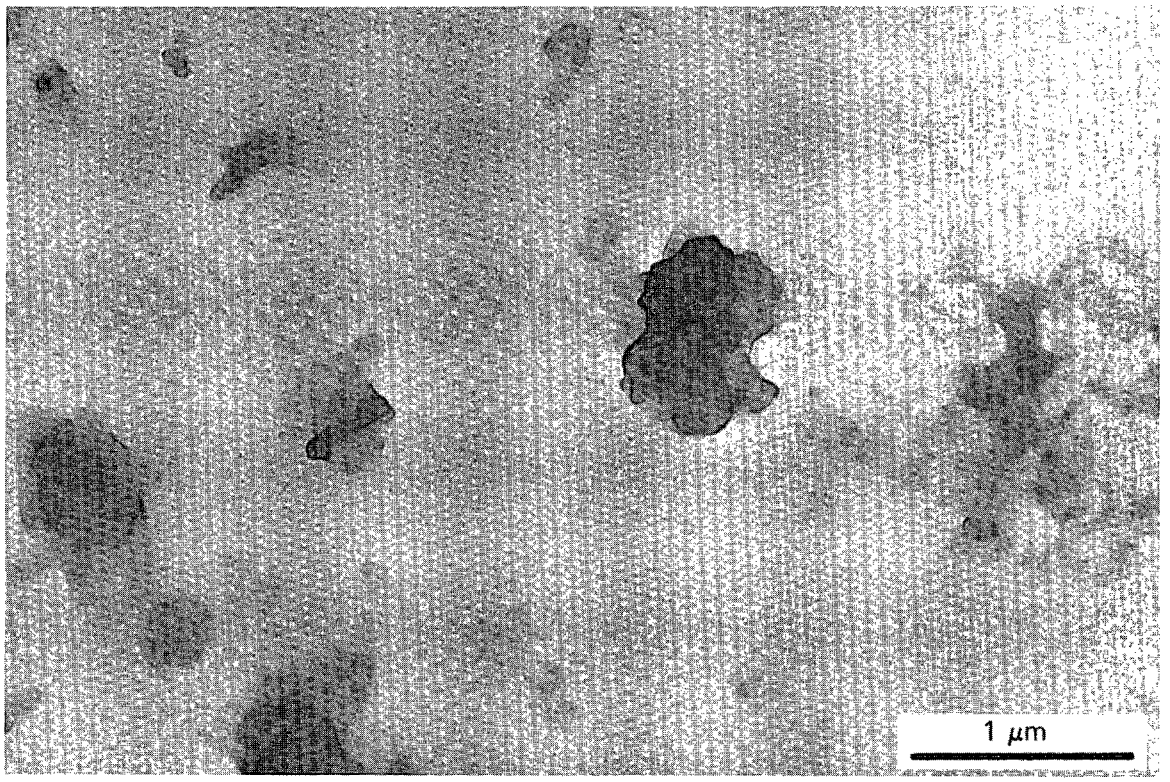


Fig. 10. Photomicrograph of Cab-O-Sil 17 fumed silica.

exceed the value for the pure silica at atmospheric pressure and 300 K. The R-values per inch for the coarse silica—fine silica mixtures that were tested at one atmosphere and 300 K have an upper bound of 6.2 $ft^2 \cdot h \cdot {}^\circ F/Btu$ (1.1 $m^2 \cdot K/W$). The apparent thermal conductivity of the powders increased with temperature in the range 290 to 340 K.

The thermal resistances of powders tested at pressures below 10 Pa and corrected for axial heat flow exceeded 8.46 $m^2 \cdot K/W$ for 2.54 cm (48 $ft^2 \cdot h \cdot {}^\circ F/Btu$ per inch). The structural parameter $A$ = 419 and $d$ = 224 nm were estimated from the low and atmospheric pressure data.

Repeated measurements on L'Air Liquide evacuated panel No. 20 showed a decrease in R-value with time. The evacuated powder $k_a$ measurements from ORNL-3 were used to obtain estimates of the panel pressure. The pressure at time of manufacture was estimated to be about 133 Pa (1 mm Hg), and the transition from a slow decrease in R-value with time to a fast

decrease should occur no sooner than eight years after production. Continued $k_a$ measurements with time will permit refinement of the aging prediction.

The $k_a$ data obtained show that evacuated powders can readily exceed R-values of 3.5 $m^2 \cdot K/W$ for 2.54 cm (20.0 $ft^2 \cdot h \cdot °F/Btu$). The evacuated panel shows that packaging capable of maintaining low pressures for long periods is available. Existing vacuum packaging technology should be used to produce insulators using powders with known $k_a$-$P$ relationships. A sequence of $k_a$ measurements can then be used to determine leak rates and estimate the effective lifetime for candidate systems.

The atmospheric-pressure $k_a$ data obtained for silica powder mixtures give R-values per inch below about 6 $ft^2 \cdot h \cdot °F/Btu$ (1.1 $m^2 \cdot K/W$ for 2.54 cm). The attainment of higher atmospheric-pressure R-values will require finely divided powder that does not form chains or agglomerate. Measurements on unlinked fine-particle specimens should yield atmospheric-pressure R-values above those measured to date.

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## REFERENCES

1. W. T. Lawrence and F. E. Ruccia, *Development of Advanced Insulation for Appliances, Task I Report*, ORNL/Sub-81/1300/1, June 1981.

2. D. L. McElroy et al., *Development of Advanced Thermal Insulation for Appliances*, ORNL/CON-159, July 1984.

3. W. D. Turner, D. L. Elrod, and I. I. Siman-Tov, *HEATING5 — An IBM 360 Heat Conduction Program*, ORNL/CSD/TM-15, March 1977.

4. P. G. Klemens, *Radiative Heat Transfer Under Transient Conditions*, ORNL/SUB/84-89634/1, October 1985.

5. D. W. Yarbrough, T. W. Tong, and D. L. McElroy, "Use of Fine Powders for High Thermal Resistance," *High Temp. Sci.* **19**, 213–225 (1985).

6. Saul Dushman, *Scientific Foundations of Vacuum Technique*, 2nd ed., John Wiley and Sons, Inc., New York, 1962, p. 25.

7. P. Pellaux-Gervais and D. Goumy, "Insulating Material with Low Thermal Conductivity, Formed of a Compacted Granular Structure," U.S. Patent 4,159,359 (assigned to L'Air Liquide, Paris, France), June 26, 1979.

8. D. L. McElroy et al., "A Flat Insulation Tester That Uses an Unguarded Nichrome Screen Wire Heater," pp. 121–39 in *Guarded Hot Plate and Heat Flow Meter Methodology*, ASTM STP 879, C. J. Shirtliffe and R. P. Tye, eds., American Society for Testing and Materials, Philadelphia, 1985.

9. R. S. Graves, D. W. Yarbrough, and D. L. McElroy, "Apparent Thermal Conductivity by an Unguarded Technique," *Thermal Conductivity 18*, Plenum Press, New York, 1985, pp. 339–45.

10. W. D. Kingery, *Property Measurements at High Temperatures*, John Wiley and Sons, Inc., New York, 1959, p. 44.

11. Private communication to D. L. McElroy from J. Y. Faudou, L'Aire Liquide, September 1982.

# Appendix A

## NOMENCLATURE

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | | Material parameter associated with particle contact resistance, Eq. (2) |
| $C$ | | Ratio, $k_{a,\text{ideal}}/k_a$, measured |
| $d$ | | Particle diameter, m |
| $E$ | | Extinction coefficient, $m^{-1}$ |
| | $\overline{E}$ | Average value of $E$, $m^{-1}$ |
| $F$ | | Blackbody function |
| | $F_{\lambda_1-\lambda_2}$ | For wavelength interval $\lambda_1$ to $\lambda_2$ |
| $F_s$ | | Fraction solid |
| $k$ | | Thermal conductivity, W/(m·K) |
| | $k_a$ | Apparent |
| | $k_c$ | Of composite |
| | $k_g$ | Of gas phase |
| | $k_g^\circ$ | Of bulk gas at 101 kPa (1 atm) |
| | $k_r$ | Radiative |
| | $k_s$ | Of solid |
| $\ell_g$ | | Mean free path in gas phase, m |
| $L$ | | Length, m |
| $L^\circ$ | | Specimen thickness, m |
| $P$ | | Pressure, Pa |
| $Q$ | | Heat flux, $W/m^2$ |
| $q$ | | Power, V·I for L, W |
| $r$ | | Radius, m |
| | $r_i$ | Inside |
| | $r_o$ | Outside |
| $R$ | | Thermal resistance, $m^2 \cdot K/W$ or $ft^2 \cdot h \cdot {}^\circ F/Btu$. The R-value per inch is the R-value for one inch of thickness. |

| | | |
|---|---|---|
| $T$ | | Temperature, K |
| | $T_C$ | Cold surface |
| | $T_H$ | Hot surface |
| | $T_m$ | Modified mean $T$ defined by Eq. (4) |
| | $\overline{T}$ | $(T_H + T_C)/2$ |
| $\varepsilon$ | | Emissivity |
| | $\varepsilon_c$ | Of cold surface |
| | $\varepsilon_h$ | Of hot surface |
| $\rho$ | | Density, $kg/m^3$ |
| $\sigma$ | | Stefan-Boltzmann constant, $5.6697 \times 10^{-8}$ $W/(m^2 \cdot K^4)$ |

SI METRIC EQUIVALENTS OF ENGLISH UNITS

| English | SI |
|---|---|
| $ft^2 \cdot h \cdot {}^\circ F/Btu$ | 0.1762 $m^2 \cdot K/W$ |
| Inch | 2.54 cm |

# Appendix B

## INPUT DATA FOR HEATING5 SIMULATIONS OF ORNL-3 AND ORNL-5

HEATING5 Input for the Simulation of ORNL-3

```
L TO D STUDY 1985 LD1 TO LD1F  DAT
     1200        3        2        2                1        2        1
        3                 2

        1     9000    1.E-8
        1        1   0.0500   0.2697                         0.0    14.37
        1        1                                                      1
        2        2   0.2697     2.54                         0.0    14.37
        2                          1                                    1
        1   HEATER  2.25E-2
        2     SPEC    4.E-4
        1    0.030
        1     300.
        2     300.
        1        2     300.

   0.0500   0.2697    2.540
        5       22
      0.0    14.37
       72
```

This simulation was for one-half of the total length of the apparatus and assumes circumferential symmetry. The dimensions of the core heater shown in line 6 were changed from $r_i$ = 0.2494 and $r_o$ = 0.2697 cm to $r_i$ = 0.0500 and $r_o$ = 0.2697 cm to assist numerical convergence. The volumetric heat generation rate, line 12, and the thermal conductivity of the heater, line 10, were adjusted accordingly. The values used with an expanded core heater were 0.0225 for $k$ in line 10 and 0.015 for the volumetric heat generation rate in line 12. The units for this calculation were watts, centimeters, and kelvins.

HEATING5 Input for the Simulation of ORNL-5

```
L TO D STUDY 1985 LD2 TO LD2F  DAT
     1200        3        2        2                1        1        1
        3                 2

        1     9000    1.E-8
        1        1     0.05     0.27                        0.0    45.67
        1        1                                                    1
        2        2     0.27     2.03                        0.0    45.64
        1                          1                                  1
        1   HEATER  0.02216
        2     SPEC    2.E-5
        1    0.015
        1     300.
        1        2     300.

     0.05     0.27    2.030
        5       22
      0.0    45.64
       72
```

This simulation was for one-half the total length of the apparatus and assumes circumferential symmetry. The dimensions of the core heater shown in line 6 were changed from $r_i$ = 0.25 and $r_o$ = 0.27 cm to $r_i$ = 0.05 and $r_o$ = 0.27 cm to assist numerical convergence. The volumetric heat generation rate, line 12, and the thermal conductivity of the heater, line 10, were adjusted accordingly. The values used with an expanded core heater were 0.02216 for $k$ in line 10 and 0.015 for the volumetric heat generation rate in line 12. The units for this calculation were watts, centimeters, and kelvins.

# Appendix C

## IDENTIFICATION OF POWDERS TESTED AND TABULATION OF EXPERIMENTAL DATA

Table C.1. Identification of fine powder specimens that have been tested in ORNL-5 at 101 kPa (1 atmosphere) (air)

| Specimen number | Material description[a] | Test density [kg/m$^3$ (lb/ft$^3$)] |
|---|---|---|
| 14 | 80 wt % Selma Gray fumed silica (B) and 20 wt % Cab-O-Sil fumed silica, EH-5, (C) | 162 (10.11) |
| 15 | 80 wt % Selma Gray fumed silica (B) and 20 wt % Cab-O-Sil fumed silica, EH-5, (C) | 201 (12.55) |
| 16 | 90 wt % Selma Gray fumed silica (B) and 10 wt % Cab-O-Sil fumed silica, EH-5, (C) | 249 (15.54) |
| 17 | 95 wt % Selma Gray fumed silica (B) and 5 wt % Cab-O-Sil fumed silica, EH-5, (C) | 297 (18.54) |
| 18 | 80 wt % Reynolds fumed silica (A) and 20 wt % Cab-O-Sil fumed silica, S-17, (C) | 251 (15.67) |
| 19 | 80 wt % Reynolds fumed silica (A) and 20 wt % Cab-O-Sil fumed silica, S-17, (C) | 313 (19.54) |
| 20 | 90 wt % Reynolds fumed silica (A) and 10 wt % Cab-O-Sil fumed silica, S-17, (C) | 325 (20.29) |
| 21 | 95 wt % Reynolds fumed silica (A) and 5 wt % Cab-O-Sil fumed silica, S-17, (C) | 357 (22.28) |
| 22 | 80 wt % Selma Gray fumed silica (B) and 20 wt % Cab-O-Sil fumed silica, S-17, (C) | 501 (31.27) |
| 23 | Cab-O-Sil fumed silica, S-17, (C) | 80 (4.99) |

[a]Letters in parentheses indicate material source (see Table C.3).

Table C.2. Identification of fine powder specimens that have been tested in ORNL-3

| Specimen number | Material description[a] | Test density [kg/m$^3$ (lb/ft$^3$)] |
|---|---|---|
| 24 | Cab-O-Sil fumed silica, S-17 (C) | 114 (7.12) |
| 25 | 80 wt % Selma Gray fumed silica (B) and 20 wt % Cab-O-Sil fumed silica, EH-5, (C) | 162 (10.11) |

[a]Letters in parentheses indicate material source (see Table C.3).

Table C.3. Sources of powders tested

| Material | Source |
|---|---|
| A | Reynolds Metal Company<br>P.O. Box 191<br>Listerhill, AL 35660 |
| B | Alabama Metallurgical Corporation (ALAMET)<br>P.O. Box 348<br>Selma, AL 36701-0348 |
| C | Cabot Corporation<br>Tuscola, IL 61953 |

Table C.4. Data from ORNL-3 used to calculate apparent thermal conductivity

| Specimen number | $T_H$ (K) | $T_C$ (K) | $\overline{T}$ (K) | $\Delta T_C$ (K)[a] | Power (W/m) | $k_a$ (W/m·K) | $R$ (ft²·h·°F/Btu) | Pressure (Pa) | Medium |
|---|---|---|---|---|---|---|---|---|---|
| 24 | 311.287 | 291.091 | 301.189 | 20.169 | 1.576 | 0.02788 | 5.17 | 101,300 | $N_2$ |
| | 324.602 | 302.626 | 313.614 | 21.674 | 1.780 | 0.02931 | 4.92 | 101,300 | $N_2$ |
| | 341.404 | 322.327 | 331.866 | 18.882 | 1.662 | 0.03140 | 4.59 | 101,300 | $N_2$ |
| | 312.342 | 289.898 | 301.120 | 22.453 | 0.365 | 0.00580 | 24.87 | 4.5 | Air |
| | 328.467 | 304.793 | 316.630 | 23.674 | 0.457 | 0.00688 | 20.96 | 4.9 | Air |
| | 340.080 | 320.571 | 330.325 | 19.551 | 0.428 | 0.00782 | 18.44 | 5.1 | Air |
| 25 | 311.023 | 291.054 | 301.039 | 20.069 | 0.209 | 0.00372 | 38.77 | 3.1 | Air |
| | 320.622 | 300.684 | 310.653 | 20.136 | 0.215 | 0.00380 | 37.96 | 2.8 | Air |
| | 310.105 | 290.338 | 300.221 | 19.972 | 0.187 | 0.00337 | 42.80 | 1.9 | Air |
| | 310.569 | 290.347 | 300.458 | 20.222 | 1.078 | 0.01902 | 7.58 | 11,704 | $N_2$ |
| | 309.224 | 290.348 | 299.786 | 18.876 | 1.276 | 0.02413 | 5.98 | 34,005 | $N_2$ |
| | 309.760 | 290.349 | 300.055 | 19.411 | 0.705 | 0.01295 | 11.14 | 1,880 | $N_2$ |
| | 310.480 | 290.350 | 300.415 | 20.130 | 1.554 | 0.02756 | 5.23 | 51,240 | $N_2$ |
| | 310.797 | 290.354 | 300.576 | 20.443 | 1.666 | 0.02908 | 4.96 | 74,995 | $N_2$ |
| | 309.868 | 290.353 | 300.111 | 19.515 | 1.668 | 0.03050 | 4.73 | 99,175 | $N_2$ |
| | 309.828 | 290.354 | 300.091 | 19.474 | 1.724 | 0.03159 | 4.57 | 128,101 | $N_2$ |
| | 309.582 | 290.353 | 299.968 | 19.229 | 0.962 | 0.01785 | 8.08 | 6,760 | $N_2$ |
| | 309.063 | 290.832 | 299.947 | 18.231 | 0.235 | 0.00460 | 31.36 | 30.7 | $N_2$ |
| | 309.319 | 290.835 | 300.077 | 18.484 | 0.235 | 0.00454 | 31.77 | 18.0 | $N_2$ |
| | 309.898 | 290.343 | 300.121 | 19.555 | 0.296 | 0.00540 | 26.71 | 113.3 | $N_2$ |
| | 310.867 | 290.628 | 300.748 | 20.239 | 0.297 | 0.00523 | 27.58 | 53.3 | $N_2$ |
| | 340.024 | 321.027 | 330.525 | 18.997 | 0.261 | 0.00490 | 29.44 | 4.5 | $N_2$ |
| | 340.791 | 321.027 | 330.909 | 19.764 | 1.143 | 0.02065 | 6.98 | 9,664 | $N_2$ |
| | 341.143 | 321.027 | 331.085 | 20.116 | 1.431 | 0.02539 | 5.68 | 25,514 | $N_2$ |
| | 343.117 | 319.806 | 331.462 | 23.311 | 1.743 | 0.02669 | 5.40 | 33,605 | $N_2$ |
| | 344.940 | 325.440 | 335.190 | 19.500 | 1.530 | 0.02801 | 5.15 | 42,510 | $N_2$ |
| | 344.526 | 325.440 | 334.983 | 19.086 | 1.528 | 0.02857 | 5.05 | 56,186 | $N_2$ |
| | 345.480 | 326.433 | 335.957 | 19.047 | 1.589 | 0.02977 | 4.85 | 70,582 | $N_2$ |
| | 344.872 | 326.436 | 335.654 | 18.436 | 1.594 | 0.03085 | 4.68 | 82,540 | $N_2$ |
| | 344.027 | 326.687 | 335.357 | 17.340 | 1.593 | 0.03279 | 4.40 | 99,375 | $N_2$ |
| | 343.611 | 327.178 | 335.394 | 16.434 | 1.593 | 0.03460 | 4.17 | 128,355 | $N_2$ |
| | 344.450 | 325.488 | 334.969 | 18.962 | 0.822 | 0.01548 | 9.32 | 2,400 | $N_2$ |
| | 344.627 | 325.746 | 335.187 | 18.881 | 1.145 | 0.02165 | 6.66 | 12,997 | $N_2$ |
| | 344.979 | 324.775 | 324.877 | 20.204 | 0.816 | 0.01441 | 10.00 | 1,706 | $N_2$ |
| | 343.279 | 326.479 | 334.879 | 16.800 | 0.644 | 0.01367 | 10.55 | 213.3 | $N_2$ |
| | 345.867 | 326.505 | 336.186 | 19.362 | 0.284 | 0.00524 | 27.53 | 3.1 | Air |
| | 309.022 | 291.270 | 300.146 | 17.752 | 0.177 | 0.00356 | 40.52 | 1.7 | Air |

[a] $\Delta T$ includes a small correction obtained from thermocouple measurements under isothermal conditions.

Table C.5. Data from ORNL-5 used to calculate apparent thermal conductivity

| Specimen number | $T_H$ (K) | $T_C$ (K) | $\overline{T}$ (K) | $\Delta T_C$ (K)[a] | Power (W/m) | $k_a$ (W/m·K) | $R$ (ft²·h·°F/Btu) |
|---|---|---|---|---|---|---|---|
| 14 | 295.306 | 292.100 | 293.703 | 3.208 | 0.2881 | 0.02881 | 5.01 |
| | 312.497 | 302.692 | 307.595 | 9.713 | 0.8982 | 0.02967 | 4.86 |
| | 326.295 | 316.630 | 321.463 | 9.447 | 0.9064 | 0.03079 | 4.69 |
| | 334.269 | 324.664 | 329.467 | 9.282 | 0.9081 | 0.03139 | 4.60 |
| | 305.478 | 295.863 | 300.670 | 9.531 | 0.8714 | 0.02933 | 4.92 |
| 15 | 307.674 | 292.097 | 299.885 | 15.573 | 1.394 | 0.02872 | 5.02 |
| | 317.671 | 301.900 | 309.786 | 15.720 | 1.432 | 0.02924 | 4.93 |
| | 327.323 | 312.504 | 319.914 | 14.721 | 1.372 | 0.02991 | 4.82 |
| | 336.039 | 321.341 | 328.690 | 14.545 | 1.387 | 0.03060 | 4.71 |
| | 347.040 | 332.569 | 339.804 | 14.268 | 1.394 | 0.03134 | 4.60 |
| | 307.541 | 292.550 | 300.045 | 14.987 | 1.338 | 0.02865 | 5.03 |
| 16 | 306.817 | 293.802 | 300.309 | 13.019 | 1.295 | 0.03193 | 4.52 |
| | 319.682 | 301.719 | 310.700 | 17.935 | 1.822 | 0.03260 | 4.42 |
| | 331.615 | 311.525 | 321.570 | 20.015 | 2.078 | 0.03331 | 4.33 |
| | 340.996 | 320.353 | 330.675 | 20.513 | 2.176 | 0.03404 | 4.24 |
| | 313.971 | 292.816 | 303.393 | 21.145 | 2.121 | 0.03219 | 4.48 |
| 17 | 306.757 | 292.810 | 299.784 | 13.929 | 1.499 | 0.03453 | 4.18 |
| | 316.877 | 302.997 | 309.937 | 13.833 | 1.514 | 0.03512 | 4.11 |
| | 326.902 | 313.691 | 320.297 | 13.116 | 1.468 | 0.03591 | 4.02 |
| | 336.484 | 322.800 | 329.642 | 13.543 | 1.543 | 0.03656 | 3.95 |
| | 346.342 | 332.712 | 339.527 | 13.437 | 1.560 | 0.03725 | 3.87 |
| 18 | 306.660 | 291.613 | 299.136 | 15.014 | 1.535 | 0.03281 | 4.40 |
| | 320.501 | 301.420 | 310.961 | 19.005 | 1.996 | 0.03371 | 4.28 |
| | 330.576 | 311.813 | 321.195 | 18.649 | 2.016 | 0.03469 | 4.16 |
| | 337.318 | 321.813 | 329.566 | 15.315 | 1.700 | 0.03561 | 4.05 |
| 19 | 307.686 | 290.947 | 299.317 | 16.705 | 1.714 | 0.03293 | 4.38 |
| | 324.377 | 306.616 | 315.497 | 17.661 | 1.872 | 0.03402 | 4.24 |
| | 340.223 | 322.804 | 331.514 | 17.237 | 1.900 | 0.03534 | 4.08 |
| | 307.973 | 289.976 | 298.974 | 17.964 | 1.846 | 0.03297 | 4.37 |
| 20 | 307.039 | 293.323 | 300.181 | 13.709 | 1.654 | 0.03871 | 3.73 |
| | 316.689 | 302.922 | 309.805 | 13.695 | 1.688 | 0.03955 | 3.65 |
| | 336.539 | 323.038 | 329.788 | 13.321 | 1.699 | 0.04092 | 3.53 |
| | 346.830 | 333.459 | 340.145 | 13.103 | 1.703 | 0.04170 | 3.46 |
| | 307.169 | 293.286 | 300.228 | 13.876 | 1.657 | 0.03833 | 3.76 |
| 21 | 308.175 | 291.236 | 299.706 | 16.914 | 2.178 | 0.04132 | 3.49 |
| | 317.521 | 300.786 | 309.154 | 16.638 | 2.184 | 0.04212 | 3.42 |
| | 327.593 | 311.232 | 319.412 | 16.225 | 2.172 | 0.04296 | 3.36 |
| | 308.126 | 291.140 | 299.633 | 16.961 | 2.175 | 0.04114 | 3.51 |
| 22 | 305.425 | 291.131 | 298.278 | 14.224 | 2.269 | 0.05119 | 2.82 |
| | 318.434 | 302.529 | 310.482 | 15.831 | 2.590 | 0.05249 | 2.75 |
| | 325.783 | 313.452 | 319.618 | 12.207 | 2.068 | 0.05436 | 2.65 |
| | 338.249 | 323.483 | 330.866 | 14.602 | 2.504 | 0.05503 | 2.62 |
| | 308.155 | 291.901 | 300.028 | 16.254 | 2.617 | 0.05166 | 2.79 |
| 23 | 310.638 | 291.122 | 300.880 | 19.438 | 1.525 | 0.02518 | 5.73 |
| | 319.247 | 300.878 | 310.063 | 18.196 | 1.480 | 0.02609 | 5.53 |
| | 329.424 | 310.145 | 319.785 | 19.005 | 1.614 | 0.02725 | 5.29 |
| | 339.268 | 321.305 | 330.287 | 17.577 | 1.565 | 0.02856 | 5.05 |
| | 311.987 | 291.186 | 301.587 | 20.723 | 1.633 | 0.02529 | 5.70 |

[a] $\Delta T$ includes a small correction obtained from thermocouple measurements under isothermal conditions.

# Appendix D

## APPARENT THERMAL CONDUCTIVITY ($k_a$) FOR SILICA POWDERS AS A FUNCTION OF TEMPERATURE

Table D.1. Constants for the equation $k_a = a + bT$ and $k_a$ at 300 K

| Material | Density (kg/m$^3$) | $a$ | $b$ | $k_a$ at 300 K (W/m·K) |
|---|---|---|---|---|
| 23 | 80 | −0.008970 | 0.0001133 | 0.0250 |
| 21 | 357 | 0.01566 | 0.00008546 | 0.0413 |
| 20 | 325 | 0.01494 | 0.00007877 | 0.0386 |
| 18 | 251 | 0.005678 | 0.00009041 | 0.0328 |
| 19 | 313 | 0.01095 | 0.00007336 | 0.0330 |
| 17 | 297 | 0.01369 | 0.00006935 | 0.0345 |
| 16 | 249 | 0.01159 | 0.00006775 | 0.0319 |
| 14 | 162 | 0.007653 | 0.00007195 | 0.0292 |
| 15 | 201 | 0.008591 | 0.00006686 | 0.0286 |
| 22 | 501 | 0.01530 | 0.0001207 | 0.0515 |

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