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Models For Heat Transport Through Assemblies of Uniform-Diameter Hollow Spheres

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NOMENCLATURE

A	fraction of heat transport along parallel path
ACS	coefficient in solid conduction expression [see Eq. (15)]
$\bar{A}_L$	log-mean area
A_p	parameter defined by Eq. (13)
B_p	parameter defined by Eq. (13)
B_R	coefficient in expression for k_r [see Eq. (21)]
D_s	diameter of sphere
E	extinction coefficient
f_g	fraction gas
f_s	fraction solid
k_a	apparent thermal conductivity
k_g	apparent thermal conductivity of gas phase
k_{og}	apparent thermal conductivity of gas phase at atmospheric pressure
k_{gc}	apparent thermal conductivity of gas component in the system
k_{gr}	apparent thermal conductivity of hollow "granular" solid
k_p	apparent thermal conductivity of parallel elements
k_r	radiative transport written as a conductivity
k_s	thermal conductivity of solid
k_{sc}	apparent thermal conductivity of solid component in the system
k_{s1}	apparent thermal conductivity of series elements
q	heat flux
ℓ	thickness
ℓ_g	molecular mean free path
ℓ_s	characteristic length in the interstitial gas space
m	void fraction
n	pressure exponent [see Eq. (15)]
N	refractive index
P	pressure
P_r	Prandtl number
r	radial coordinate
R	sphere radius
T	temperature

v	$= k_s/k_g$ [see Eq. (20)]
V_s	volume solid
W	sphere wall thickness
X	$= [2\theta/(\theta + 1)]\cdot(2 - \alpha)/(\alpha\cdot P_r)$
α	accommodation coefficient
β	extinction coefficient
σ	Stefan-Boltzman constant
Θ	T_{hot}/T_{cold}
δ	average distance between surfaces
γ	C_p/C_v

MODELS FOR HEAT TRANSPORT THROUGH ASSEMBLIES OF UNIFORM-DIAMETER HOLLOW SPHERES*

D. W. Yarbrough, D. L. McElroy, and F. J. Weaver

ABSTRACT

Uniform-diameter thin-wall hollow ceramic spheres are being developed as a thermal insulating material. The radial heat flow across test beds of the hollow spheres has been measured as a function of interstitial gas pressure and temperature for specimens with either nitrogen or helium as the interstitial gas. This report covers the development of equations used to model the heat flow process. The primary modes of heat transfer in this case are conduction and radiation. Convective transport is a minor but apparently not a negligible part of the overall transport.

Three models have been used to describe 17 experimental data sets obtained for combinations of sphere sizes, sphere material, and interstitial gas type and pressure. In each case, the experimental data have been used to determine parameters appearing in the models. In general, the experimental thermal conductivity data for a given bed of spheres can be described to better than 10% over the pressure range investigated. One of the models which includes a pressure explicit function describes the data set to better than 5%.

FORTRAN programs have been written to expedite use of the models to describe the data. These programs can be easily modified to produce thermal conductivity predictions for untested combinations of, for example, sphere size, interstitial gas type and pressure, and solid conductivity. The programs have been included in this report.

INTRODUCTION

A novel process for producing thin-wall gas-filled hollow spheres from a suspension of ceramic powder in liquid has been developed by

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Chapman et al.[1] at the Georgia Institute of Technology. The process provides uniform-diameter spheres from bulk materials such as Al_2O_3, partially stabilized ZrO_2, SiO_2, or Al_2O_3-Cr_2O_3 alloys. Sufficient quantities of spheres with outside diameters in the range 2100 to 3500 μm and wall thicknesses near 100 μm have been produced to provide specimens for thermal testing.

Apparent thermal conductivity data for eight combinations of sphere diameter, wall thickness, and sphere shell material with interstitial gas of either nitrogen or helium have been reported by Shapiro.[2] These data were obtained at mean specimen temperatures near 300 K and a temperature difference across the test specimens of about 10 K in a radial-heat-flow apparatus identified as ORNL-7 and described by McElroy et al.[3] Predecessors to ORNL-7 have been reported by Yarbrough et al.,[4] and by Copeland et al.[5] This apparatus was designed specifically for the measurement of the apparent thermal conductivity (k_a) of fine powders or materials like hollow spheres as a function of the interstitial gas pressures at temperatures near 300 K.

A radial-heat-flow apparatus, identified as ORNL-8, can be used to measure the k_a of powders or spheres in the temperature range 300 to 800 K at interstitial gas pressure near 1.0 atm. A cylindrical nichrome-screen heater provides the outside boundary for test specimens in ORNL-8. The outside boundary can be maintained at temperatures in the 300 to 800 K range by dc power and thus provides for mean specimen temperatures near 800 K.

Thin-wall ceramic spheres are candidates for high-temperature thermal insulation applications. The combination of thin walls and relatively low solid-phase thermal conductivity should result in a low composite k_a. In addition, heat transport across the composite can be varied by changing the interstitial gas species. In this work, for example, heat transport data were obtained for both helium and nitrogen as the interstitial gas.

The k_a measurements presented in this report have been determined using a one-dimensional form of Fourier's Law in cylindrical coordinates:

$$q = 2\pi \ell k_a (T_1 - T_2)/\ln(r_2/r_1) \quad . \tag{1}$$

The quantities of q/ℓ and $(T_1 - T_2)$ are measured for an annular space with inside radius r_1 and outside radius r_2 that is filled with the hollow spheres making up the test specimen. The apparent thermal conductivity, k_a, is obtained from Eq. (1) by an algebraic rearrangement:

$$k_a = (q/\ell)\ell n(r_2/r_1)/(2\pi[T_1 - T_2]) \quad . \tag{2}$$

We have, in general, assumed that the overall heat flow per unit length (q/ℓ) can be separated into convective, conduction, and radiative components:

$$\frac{q}{\ell} = \left(\frac{q}{\ell}\right)_{conv} + \left(\frac{q}{\ell}\right)_{cond} + \left(\frac{q}{\ell}\right)_{rad} \quad . \tag{3}$$

Equation (3) can be approximated by Eq. (4) if $(q/\ell)_{\rm conv}$ is neglected:

$$\frac{q}{\ell} = (k)\overline{A_L}\left|\frac{\Delta T}{\Delta r}\right| + k_r\overline{A_L}\left|\frac{\Delta T}{\Delta r}\right| \quad . \tag{4}$$

The thermal conductivity, k, in Eq. (4) includes both solid and gas conduction terms. The gas-phase conduction can be considered as two components in the case of hollow spheres. If the spherical shells are impervious to the gas, then there will be an "interior" gas phase and an "interstitial" gas phase. In this case only the "interstitial" gas would be affected by evacuation of the bed of spheres. The calculations that are reported here assume the same gas type and pressure inside and outside of the hollow spheres.

The radiative conductivity, k_r, in Eq. (4) is given by

$$k_r = 16N^2\delta\overline{T}^3/3\beta \quad , \tag{5}$$

if the radiation is viewed as a diffusive process.[6] The apparent thermal conductivity obtained with ORNL-7 is based on constant $\bar{A}_L$ and $\Delta T/\Delta r$. In addition, the ORNL-7 data were obtained at a fixed value for $\bar{T}$. As a result, the k_a is composed of a conductive term and a constant radiative term.

The modeling of the heat transport through the hollow spheres was undertaken for two reasons. First, the equations developed can be used to reduce the tabular data to analytical form and provide for interpolations and graphical display of trends. Equations that describe the experimental data can be used to assess sensitivities of the heat transport to quantities such as interstitial gas type and pressure, sphere size, and sphere-shell material. Three distinctly different mathematical models have been utilized in efforts to describe the measured apparent thermal conductivity data. Each of the three models contains adjustable parameters that are characteristic of the sphere-gas system.

SERIES-PARALLEL MODEL

The series-parallel model has been used by Pawel et al. to describe the apparent thermal conductivity data for carbon-bonded carbon-fiber insulation of all[7,8] and fibrous alumina insulation.[9] This model neglects convective transport and assumes that conductive and radiative heat transport are additive as shown in Eq. (6). The key feature of the model is a simplifying assumption that conduction through the solid and gas phases can be described by a combination of gas and solid elements in series and gas and solid elements in parallel. The gas inside the hollow spheres is taken to be the same composition and pressure as the gas outside the spheres. The two modes of heat transfer, series or parallel, are taken to be additive with A representing the fraction of conductive transport in the parallel model as shown in Eq. (7):

$$k = k_c + k_r \ , \tag{6}$$

$$k_c = Ak_p + (1 - A)k_{s\ell} \ . \tag{7}$$

The term $k_{s\ell}$ is obtained by adding thermal resistances for the gas phase fraction, f_g, and solid phase fraction, f_s, spanning the thickness (ℓ) of the specimen:

$$\frac{1}{k_{s\ell}} = \frac{f_s}{k_s} + \frac{f_g}{k_g} \ , \tag{8a}$$

$$k_{s\ell} = \frac{k_g k_s}{f_s k_g + f_g k_s} \ . \tag{8b}$$

The term k_p is for conductive transport along parallel conductive paths that are either gas or solid. Taking the overall cross-sectional area and temperature gradient to be the same for both paths yields Eq. (9) for the parallel path contribution to the thermal conductivity:

$$k_p = f_s k_s + f_g k_g \ . \tag{9}$$

A combination of Eqs. (6), (7), (8b), and (9) yields a working expression for the apparent thermal conductivity of the composite material:

$$k_a = A(f_s k_s + f_g k_g) + (1 - A)\ (k_g k_s)/(f_s k_g + f_g k_s) + k_r \ . \tag{10}$$

The dependence of k_a on temperature comes from the temperature dependence of k_s, k_g, and k_r. The dependence of k_a on interstitial gas pressure comes from the dependence of k_g on pressure:

$$k_g = k_g^o \frac{\ell_s}{\ell_s + \ell_g} \ . \tag{11}$$

The parameters ℓ_g and ℓ_s in Eq. (11) are characteristic lengths; ℓ_g is the molecular mean free path in the gas phase while ℓ_s is a characteristic length for the space between particles. The molecular mean free path for a given chemical species varies inversely with pressure at constant temperature. At 300 K the ℓ_g for helium is 0.1936/*P* (μm), 0.0694/*P* (μm) for *A*, and for nitrogen it is 0.0654/*P* (μm) where *P* is the pressure in atmospheres. If we take the radius of the spheres comprising a test specimen to be ℓ_s and calculate the pressure reduction required to achieve a 10% decrease in k_g, then extremely low pressures are indicated for sphere sizes like those used in this project. Calculated results for helium, nitrogen, and argon are shown in Table 1 for the pressure that will decrease the gas phase thermal conductivity by 10% at 300 K.

The calculations summarized in Table 1 show that for a fixed value of ℓ_s, the effect of a given pressure decrease on *k* will be greater for helium than for nitrogen or *A*.

Table 1. Pressure to give a 10% reduction in k_g at 300 K

ℓ_s (μm)	Helium pressure (atm)	Nitrogen pressure (atm)	Argon pressure (atm)
1000	1.74×10^{-3}	5.89×10^{-4}	6.25×10^{-4}
500	3.48×10^{-3}	1.18×10^{-3}	1.25×10^{-3}
100	1.74×10^{-2}	5.89×10^{-3}	6.25×10^{-3}
50	3.48×10^{-2}	1.18×10^{-2}	1.25×10^{-2}
10	1.74×10^{-1}	5.89×10^{-2}	6.25×10^{-2}

Table 2 contains thermal conductivity ratios calculated for beds of spheres with either helium or nitrogen as the interstitial gas. The ratios are experimental k_a values at a gas pressure of about 2.0 atm (k_{high}) divided by k_a values at gas pressure of about 0.06 atm (k_{low}) for the same sphere diameter. The ratios in Table 2 qualitatively support the observation that the reduction in k_a due to reduced pressure will be greater for a helium-filled system than a nitrogen-filled system. Equation (11) and values for ℓ_g, however, suggest that the helium pressure effect should be about three times as large as the nitrogen pressure effect on k_g. The experimental data in Table 2 show the helium pressure effect to be 1.05 to 1.20 times the nitrogen pressure effect. This indicates that either the gas phase conduction is not the dominant transport mechanism, or that ℓ_s is small enough compared to ℓ_g to give $k_g < k_g^{\circ}$. The parameter ℓ_s has been treated as an adjustable parameter in this work.

Table 2. Measured effect of pressure on k at 300 K

Sphere radius (μm)	Helium $(k_{high}/k_{low})^a$	Nitrogen (k_{high}/k_{low})
1724	1.18	1.12
1115	1.46	1.22
1145	1.42	1.20
1426	1.24	1.17

[a] k_{high} are values near 2.0 atm; k_{low} are values in the range 0.045 to 0.065 atm.

The fraction solid, f_s, used in this model is taken to be the fraction of the total volume that is occupied by sphere wall material. If V_s is the volume fraction occupied by spheres, then Eq. (12) gives f_s:

$$f_s = V_s \left[\frac{4\pi}{3} (D_s/2)^3 - \frac{4\pi}{3} (D_s/2 - W)^3\right] / \left[\frac{4\pi}{3} (D_s/2)^3\right] ,$$

$$= V_s \left[(D_s/2)^3 - (D_s/2 - W)^3\right] / \left[(D_s/2)^3\right] . \tag{12}$$

The series-parallel model described by Eqs. (10) and (11) has been used to correlate experimental k_a data with interstitial gas pressure. The experimental data that were used are tabulated in Appendix B. The two FORTRAN programs used for analysis with the series-parallel model are contained in Appendix C. The first program, PMODA.FOR, allowed the parameters A, k_r, ℓ_s, and f_s to be determined by least squares. The second program, PMODB.FOR, uses a modification of PMODA.FOR that contains the series conductive term but not the parallel conductive term.

Table 3 contains the parameters determined for the 17 data sets in Appendix B using PMODA.FOR. The table also contains the average absolute percent differences between the experimental and calculated apparent thermal conductivities. The calculation carried out by PMODA forces the parameters A and k_r to be non-negative. If either parameter is determined from the least-squares calculation to be negative, the program overrides the calculation and sets the parameter equal to zero. As shown in Table 3, the least-squares estimate for the parameter A is zero for all but one of the 17 cases. A comparison of calculated with experimental k_a for this model is contained in Appendix C.

The consistently zero value for the least-squares estimate for A in Eq. (10) suggests that the parallel term is not needed. As a result of the output shown in Table 3, the parallel heat transfer term in Eq. (7) was dropped, and code PMODB.FOR resulted. This modification gives a result that is different from the previous case where $A \leq 0$ is taken to be $A = 0$. A listing of PMODB.FOR and tables containing calculated and experimental k_a are contained in Appendix C.

Table 3. Parameters for the description of hollow sphere thermal conductivity data using PMODA.FOR

Data set	Internal gas	A	k_r	ℓ_s	f_s	Average % derivation[a]
10	N_2	0.00	0.135	3.600	0.07781	2.10
11	He	0.00	0.231	14.90	0.07781	3.39
12	N_2	0.00	0.218	0.400	0.1237	5.37
13	He	0.00	0.480	3.600	0.1237	4.09
14	N_2	0.00	0.219	0.300	0.1367	1.25
15	He	0.00	0.445	20.30	0.1367	8.54
16	N_2	0.00	0.226	0.400	0.1846	1.22
17	He	0.00	0.520	5.800	0.1846	6.94
18	He	0.00	0.580	1.700	0.1959	9.31
19	N_2	0.00	0.160	3.10	0.1077	2.94
20	H_e	0.00	0.263	13.00	0.1077	4.23
21	N_2	0.00	0.126	7.10	0.0692	2.55
22	He	0.00	0.150	26.00	0.0692	2.81
23	N_2	0.00	0.106	6.80	0.1697	1.51
24	He	0.00	0.0163	32.50	0.1697	5.22
25	N_2	0.00	0.252	0.200	0.1959	3.87
26	N_2	0.08	0.143	0.500	0.1846	1.10

[a]Average value for $| k_{calc} - k_{exp} | \bullet 100/k_{exp}$

A summary of the results obtained with PMODB is contained in Table 4. The quality of the description of the experimental data afforded by PMODB is about the same as that for PMODA. The observed decrease in k_a with decrease in pressure is not predicted quantitatively with the gas phase thermal conductivity expression in Eq. (11).

Table 4. Parameters for the description of hollow sphere thermal conductivity data using PMODB.FOR

Data set	Interstitial gas	k_r	ℓ_s	f_s	Average % derivation[a]
10	N_2	0.174	9.300	0.07781	2.54
11	He	0.458	32.50	0.07781	3.83
12	N_2	0.213	11.60	0.1237	6.77
13	He	0.704	3.80	0.0467	2.33
14	N_2	0.227	5.30	0.1367	3.97
15	He	0.604	13.60	0.1367	11.13
16	N_2	0.238	32.50	0.1846	5.85
17	He	0.751	0.500	0.1849	10.23
18	He	0.716	19.80	0.1959	14.80
19	N_2	0.188	3.700	0.1077	4.85
20	He	0.488	32.40	0.1077	3.51
21	N_2	0.165	32.50	0.0692	3.69
22	He	0.377	32.50	0.0692	3.13
23	N_2	0.146	3.40	0.1697	0.76
24	He	0.237	32.50	0.1697	1.33
25	N_2	0.244	1.300	0.1959	4.05
26	N_2	0.231	1.600	0.1849	2.53

[a]Average value for $| k_{calc} - k_{exp} | \bullet 100/k_{exp}$

Figure 1 is a deviation plot for model PMODB for the entire data set. This is an obvious skew of the k_a data as gas pressure is lowered. The k_a data for nitrogen are within ±10% of the calculated values with the exception of four values obtained at very low pressures. The helium k_a data, however, are described to only ±20% by the model. In the case of nitrogen or helium as the interstitial gas, the measured k_a is consistently less than the calculated k_a at low pressure. This is demonstrated by the upturn at low pressure of the deviations in Fig. 1.

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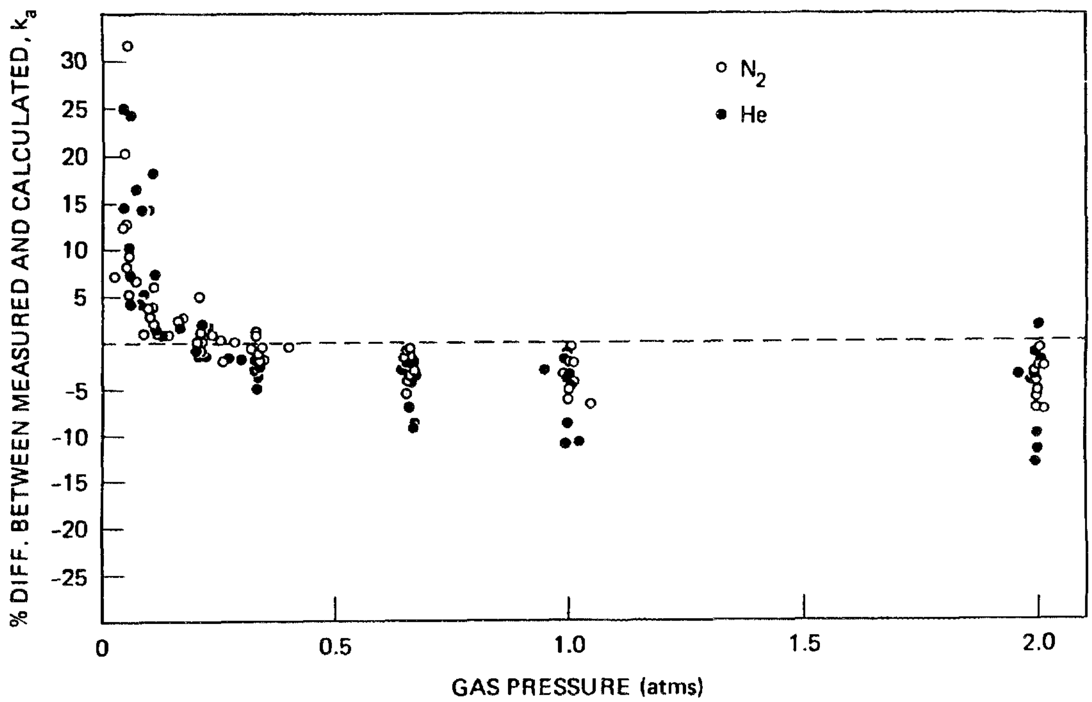

Fig. 1. A comparison of k_a calculated with PMODB.FOR and the experimental k_a.

A pressure-dependent term was added to PMODB in order to reduce the deviations shown in Fig. 1. The resulting program is called PMODC.FOR. PMODC uses Eq. (10) with the parallel term dropped with the expression shown below as an additive term:

$$k_{pr} = A_p + B_p \sqrt{P} \ . \qquad (13)$$

The parameters A_p and B_p were obtained for each data set using the method of least-squares applied to the residuals shown in Fig. 1. A listing of the program PMODC.FOR is contained in Appendix C along with output for the 17 data sets. Table 5 contains parameters obtained for each data set along with the average percent difference between measured and calculated k_a. A comparison of the results in Tables 4 and 5 show that the addition of k_{pr} as described by Eq. (12) reduces the overall average deviation between

Table 5. Parameters for the description of hollow sphere thermal conductivity data using PMODC.FOR

Data set	Interstitial gas	k_r	ℓ_s	f_s	A_p	B_p	Average % derivation[a]
10	N_2	0.176	3.26	0.07781	-0.8009E-2	0.1142E-1	1.00
11	He	0.574	0.02	0.07781	-0.3363E-1	0.4606E-1	2.90
12	N_2	0.223	3.26	0.1237	-0.2883E-1	0.4160E-1	3.83
13	He	0.831	0.02	0.1237	0.9016E-1	0.9898E-1	3.07
14	N_2	0.234	3.26	0.1367	-0.2120E-1	0.3027E-1	2.31
15	He	0.810	0.02	0.1367	-0.2120E-1	0.2103	5.07
16	N_2	0.241	3.26	0.1846	-0.2178E-1	0.3344E-1	1.86
17	He	0.880	0.02	0.1846	-0.1435	0.2138	4.98
18	He	0.926	0.02	0.1959	-0.2016	0.2921	6.25
19	N_2	0.200	3.26	0.1077	-0.1352E-1	0.1961E-1	1.79
20	He	0.626	0.02	0.1077	-0.5118E-1	0.7501E-1	3.36
21	N_2	0.168	3.26	0.0692	-0.8097E-2	0.1189E-1	1.45
22	He	0.514	0.02	0.0692	-0.2111E-1	0.3083E-1	2.46
23	N_2	0.146	3.26	0.1697	-0.2425E-2	0.3279E-2	0.35
24	He	0.374	0.02	0.1697	-0.7938E-3	0.1155E-2	1.63
25	N_2	0.251	3.26	0.1959	-0.2527E-1	0.3675E-1	2.56
26	N_2	0.234	3.26	0.1846	-0.575E-1	0.1852E-1	1.16
						Average	2.71

[a]Average value for $| k_{calc} - k_{exp} | \cdot 100/k_{exp}$

calculated and experimental k_a from 5.02 to 2.71%. The scatter of the differences for PMODC is less than that of PMODB. Figure 2, which shows the differences between experimental and calculated k_a for PMODC, demonstrates the improved description of the data provided by PMODC.

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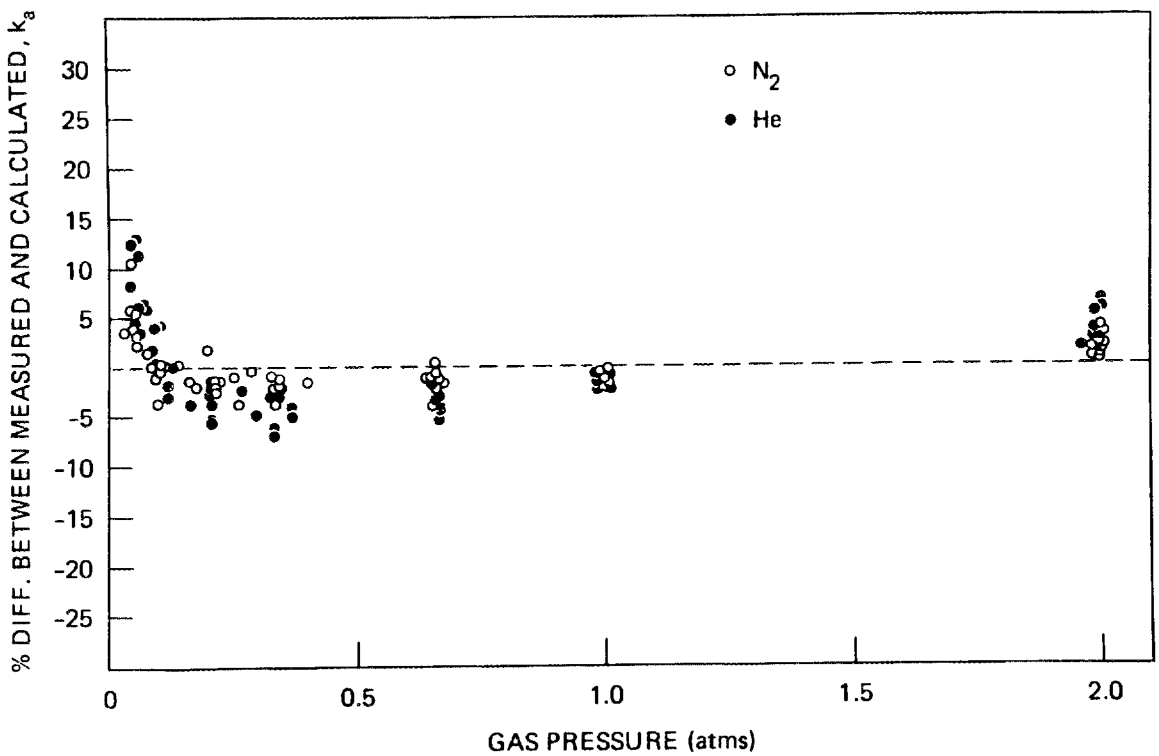

Fig. 2. A comparison of k_a calculated with PMODC.FOR and the experimental data.

GEOMETRIC MODEL

A computational technique that uses combinations of solid and gas elements in either series or parallel is referred to here as the geometric model. This type of model was described in detail by Moore et al.[9] and used to analyze heat flow through UO_2 or ThO_2 powders. Yang[10] extended the model and included provisions for mixtures of spheres of different diameters. Both Moore and Yang considered solid spheres that were stacked to form a regular lattice.

The geometric model neglects convective transport and assumes that the radiation across gas-filled interstices and conduction across the spaces are independent. An accommodation coefficient α is included to account for heat transfer at solid-gas interfaces. Gas phase thermal conductivity includes a term $\alpha/(\alpha - 2)$ that results in a reduction in k_g for $\alpha < 1$. Heat transport through opaque solid elements is by conduction only. The model is one-dimensional in the sense that heat flows successively across gas-filled spaces or through solid elements. The heat flow across a bed of spheres is characterized by a unit cell shown in Fig. 3(*a*) taken from ref. 8. A typical element in the unit cell is shown in Fig. 3(*b*).

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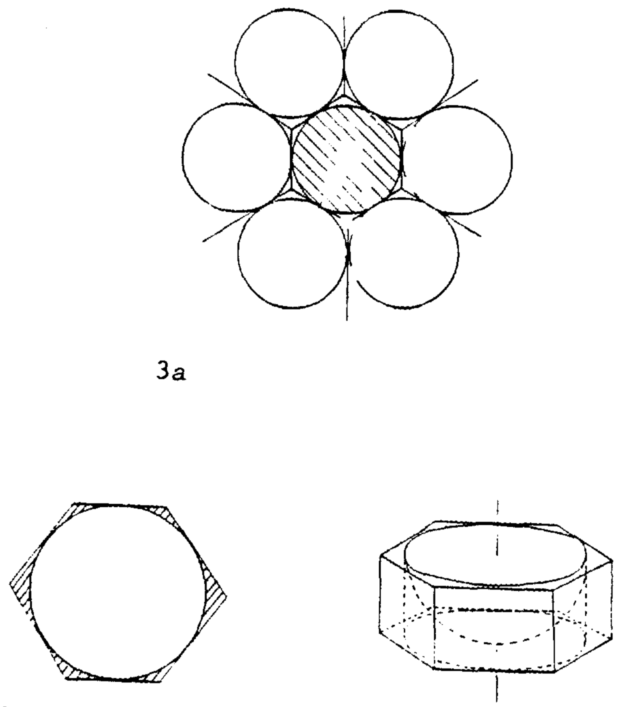

3a

3b 3c

Fig. 3. Diagrams showing unit cell for geometric model. (*a*) Shaded region is top plant of unit cell. (*b*) Shaded region is hexagonal component. (*c*) Cylindrical component shown by dashed lines inside the unit cell.

The cross-hatched rectangular strip in Fig. 4 represents one heat flow path across the gas and solid elements in series for a solid spheres. In the case of a hollow sphere, the cross-hatched rectangle in the "solid" region is replaced by two rectangles in series, one of which is for the solid shell and the second for the gas in the sphere. A number of such elements in parallel can be used to describe the heat flow across the unit cell. Heat flow across the gas elements consists of conduction and radiation in parallel.

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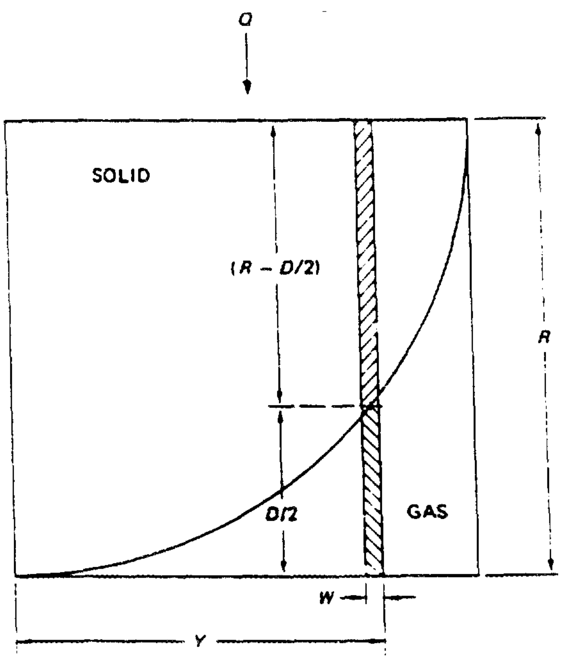

Fig. 4. Heat flow across the cylindrical component is represented by cylindrical shells in parallel. The shaded region is the cross-section of a single cylindrical shell.

The cross section shown in Fig. 3(*b*) shows that some paths between the upper and lower planes bounding the unit cell are totally gas-filled. These paths belong to the hexagonal component of the unit cell. Paths containing both solid and gas elements belong to the cylindrical component of the unit cell. The hexagonal component can be treated as a single path joining the bounding planes. The fraction of the unit cell occupied by the hexagonal component is 0.0931, while the cylindrical component occupies 0.9069 of the volume. The fraction of the unit cell occupied by spheres is 0.6046. Heat flow across the unit cell is described using cylindrical shells in parallel with the single hexagonal component through which heat is transferred by radiation and conduction in parallel. Heat flow across each cylindrical shell involves the gas and solid elements in series as illustrated in Fig. 4. Heat flow across the gas elements consists of radiation and conduction in parallel. This combination of series and parallel elements can be illustrated by means of the electrical analog using reciprocals of radiative or conductive conductances.

The heat flow analog shown in Fig. 5 is the basis for the program DYPOW3.FOR, listed in Appendix D. DYPOW3 is a translation of Moore's original [Fig. 3(*a*), (*b*), (*c*)] program[9] into FORTRAN. A calculation of the heat transfer without radiation has been added. In order to use DYPOW3 for hollow spheres, it is necessary to adjust the input value for the solid sphere to simulate the combined conductive-radiative transport.

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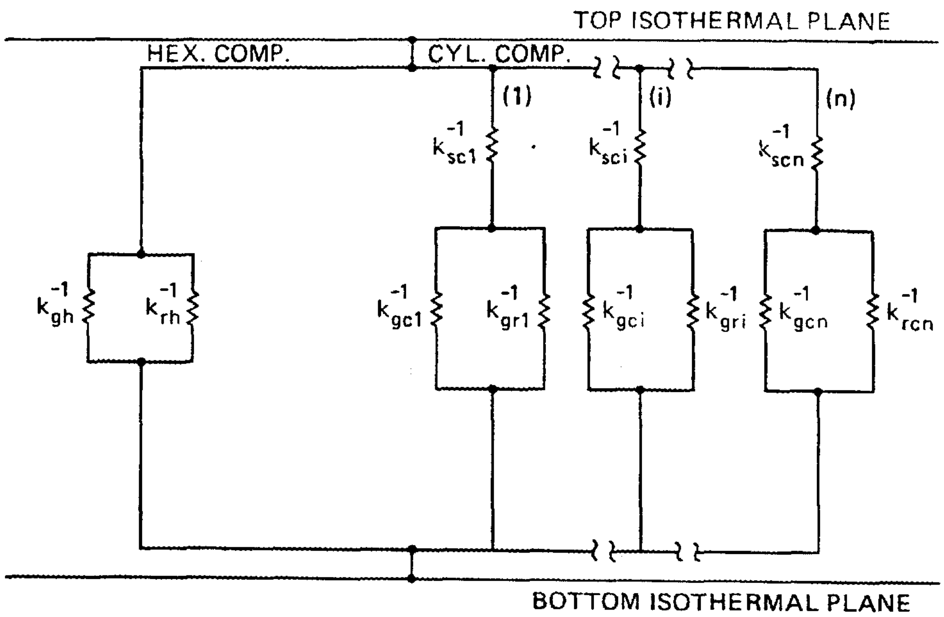

Fig. 5. Electrical analog for heat flow across a unit cell.

The program DYPOW4.FOR listed in Appendix D is an extension of DYPOW3.FOR. The term for the conductance through the solid part of the cylindrical component is replaced by a series of concentric cylindrical shells. The cylindrical shells have a gas component for the interior of the sphere and a solid element for the sphere wall in series. The electrical analog in Fig. 6 is for a typical element that replaces k^{-1}_{sci} in Fig. 5. The subroutine "SOLID" in DYPOW4.FOR replaces the constant used in DYPOW3 for the thermal conductivity of the solid. DYPOW4 had the capability of performing computations with different gas species and gas pressure on the inside of the sphere and outside of the sphere.

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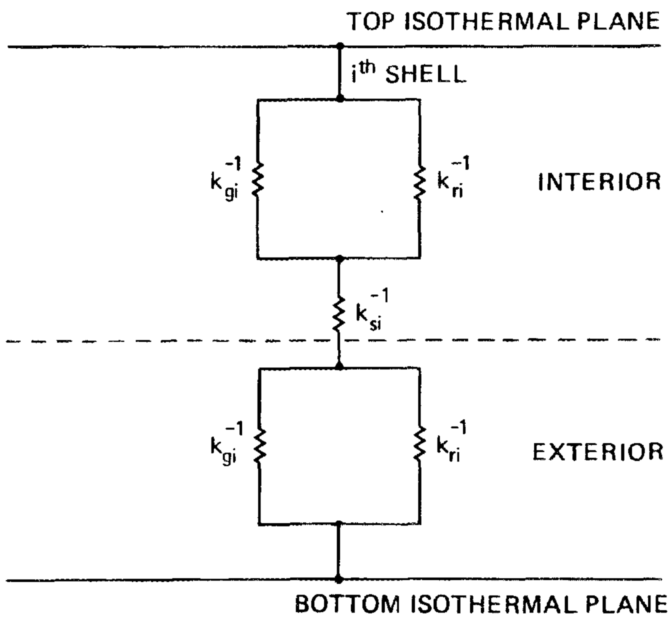

Fig. 6. Electrical analog showing components representing the hollow sphere above the dashed line.

Table 6 lists 19 sets of calculations completed with DYPOW4. Numerical results for these calculation sets are contained in Tables D-8 through D-12 in Appendix D. Figure 7 shows calculated k_a values for a bed of 2502-μm-diam Al_2O_3 spheres with wall thicknesses of 112 μm for

Table 6. Identification of properties used for calculations of *k* using DYPOW3.FOR or DYPOW4.FOR with Al_2O_3 as the solid phase

Particle diameter (μm)	Gas	Temperature range (K)	Accomodation coefficients	Interstitial gas pressure (atm)	Results in table
			DYPOW3.FOR		
40.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-1A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-1B
80.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-2A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-2B
400.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-3A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-3B
500.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-4A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-4B
1200.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-5A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-5B
2502.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-6A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-6B
3169.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-7A
	He	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-7B
			DYPOW4.FOR		
500.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-8
1000.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-9
2502.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-10
3169.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-11
6000.0	N_2	300-900	0.1, 0.5, 1.0	0.1, 0.5, 1.0	D-12

temperatures from 300 to 900 K and pressures from 0.1 to 1.0 atm. Figure 8 shows similar results for a bed of 3169-μm-diam Al_2O_3 spheres with wall thicknesses of 56 μm.

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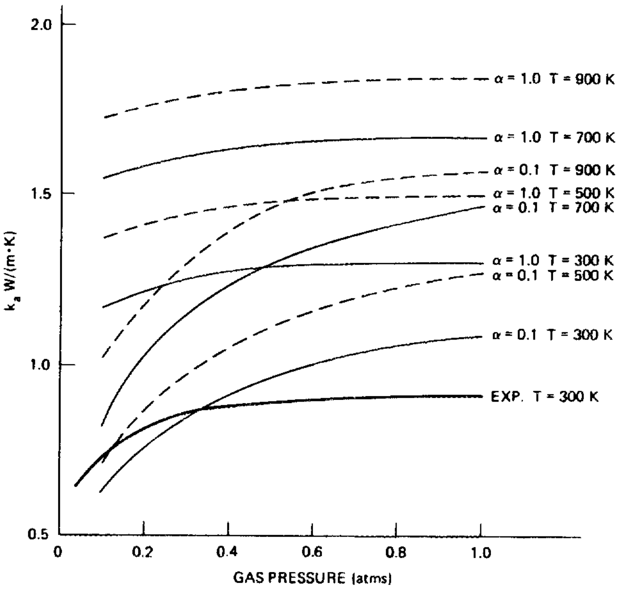

Fig. 7. k_a as a function of T, P, and α for 2502-μm-diam hollow Al_2O_3 spheres with He as the interstitial gas.

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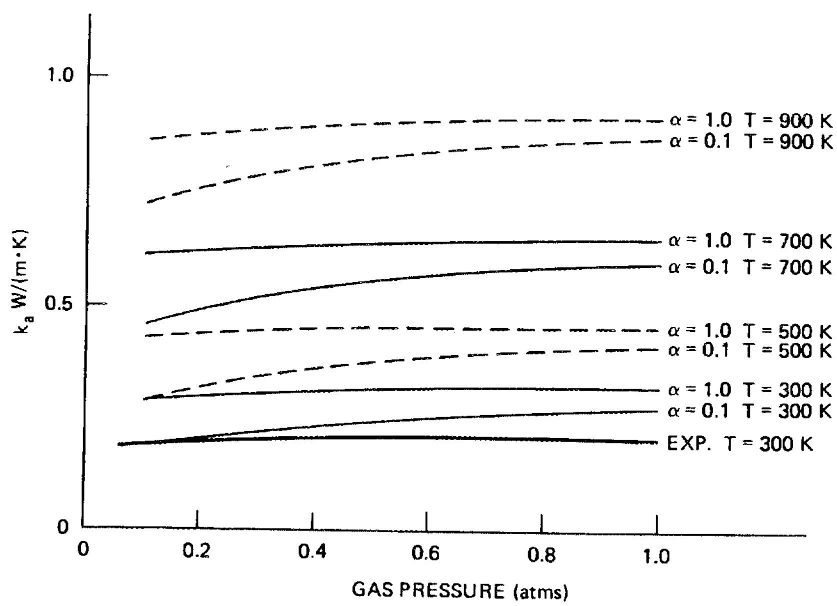

Fig. 8. k_a as a function of T, P, and α for 3169-μm-diam hollow Al_2O_3 spheres with N_2 as the interstitial gas.

The results in Figs. 7 and 8 show the dependence of k on the accommodation coefficient α. The accommodation coefficient has a greater effect on the calculated k_a when helium is the interstitial gas than when nitrogen is the interstitial gas. This is consistent with the concept that the accommodation coefficient deviates most from unity when the molecular weight difference between the solid and the gas is large. A single set of data obtained at 300 K is shown in both figures. These data indicate that the model is providing reasonable estimates of k_a if the accommodation coefficient is taken to be around 0.1. This suggests that the model is useful for predicting trends in k_a with T, P, or sphere diameter.

MODIFIED CUNNINGTON-TIEN MODEL

Cunnington and Tien[11,12] have developed equations to describe the transport of heat through an optically thick assembly of hollow spheres. This approach assumes that conductive and radiative terms are additive, and convection in the interstitial space between spheres is absent. Conduction occurs through the gas phase and across the contacting surfaces of the spheres. Conductive transport at the points of contact includes gas-phase conduction near the contact points, thus reducing the contact resistance.

The Cunnington-Tien model can be summarized by the following nine equations:

$$k = k_{sc} + k_{gc} + k_r \ , \qquad (14)$$

$$k_{sc} = ASC \cdot P^n \cdot k_s \ , \qquad (15)$$

$$k_{gc} = k_g \left\{ \frac{5.8(1-m)^2}{K} \left[\frac{1}{k} \ln(k_{gr}/k_g) - 1 - K/2 \right] + 1 \right\} \ , \qquad (16)$$

$$k_g = k_g^0 / (1 + 2 \cdot X \cdot \ell_g / \delta) \ , \qquad (17)$$

$$K = 1 - k_g / k_{gr} \ , \qquad (18)$$

$$k_{gr} = k_s \{1 + [2m(1-v)/(2v+1)]/[1 - m(1-v)/(2v+1)]\} \ , \qquad (19)$$

$$v = k_s / k_g \ , \qquad (20)$$

$$k_r = BR \cdot \sigma \cdot \ell \cdot \overline{T}^3 \cdot (1 + \theta)(1 + \theta^2) \ , \tag{21}$$

$$\theta = T_C / T_H \ . \tag{22}$$

The coefficient in Eq. (21) must be determined empirically and this represents a modification to the original model. The Knudsen number, ℓ_g/δ, in Eq. (17) controls the change in the gas phase thermal conductivity with pressure since ℓ_g, the mean free path in the gas phase, increases as pressure deceases. The model has been further modified by the pressure term P^n in Eq. (15). The parameter *ASC* is a measure of the contact resistance area and the factor P^n introduces a mechanical pressure dependence on the contact area between spheres.

The inputs required for the calculation of k_a are sphere diameter, sphere shell thickness, interstitial gas type, gas and solid thermal conductivities, the gas-solid accommodation coefficient, the void fraction, and values for *BR*, *ASC*, and n. The accommodation coefficient was taken to be 1 and the gases inside and outside the sphere are the same. The pressure exponent was taken to be in the range 0.25 to 0.50. The parameters *BR* and *ASC* were chosen to produce the best agreement between calculated and experimental k values.

Appendix E contains a printout of the computer program used to calculate k from the input listed above. Figures 9 through 19 show calculated k as a function of pressure compared with the measured values. The agreement between calculated and experimental values can be ±10% over the pressure range tested by judicious choice of the adjustable parameters. The calculated curves have the correct variation with pressure but the calculated change in k_a with reduced pressure is less than that obtained without the pressure terms in Eq. (15).

Table 7 is a listing of the parameter combinations used to calculate k_a as a function of pressure. In some cases several parameter combinations were used with the results shown in comparison with the experimental results in a single figure. Increasing the value for *ASC* increases the calculated k_a. Increasing the pressure exponent n results in increased pressure dependence for k_a and increased concavity in the k_a vs pressure curves.

ORNL-DWG 89-14484

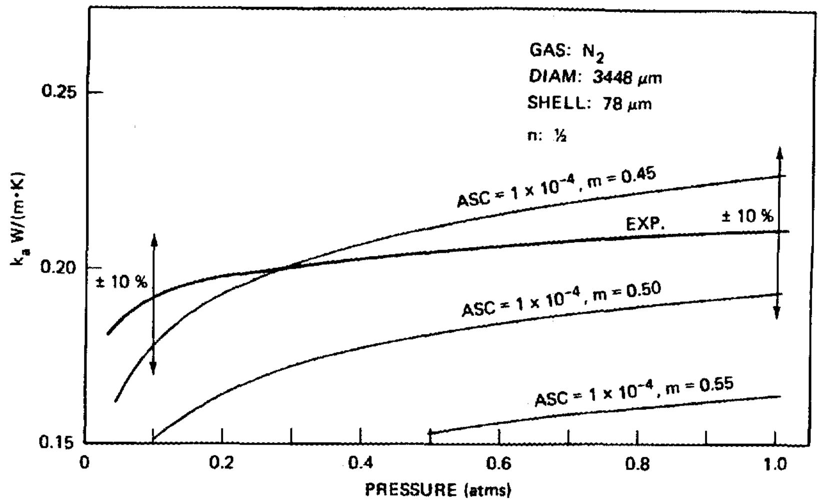

Fig. 9. A comparison of calculated and experimental *k* values for 3448-μm-diam hollow spheres with wall thicknesses of 78 μm. The interstitial gas is nitrogen. The pressure exponent is 1/2 and the experimental data set is number 10.

ORNL-DWG 89-14485

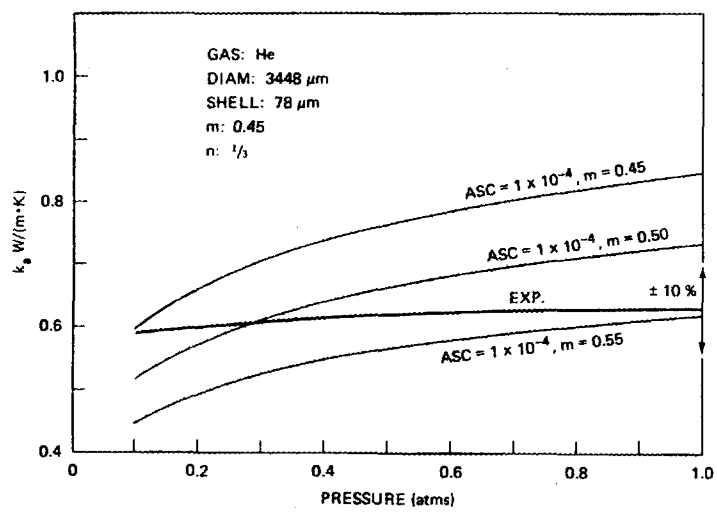

Fig. 10. A comparison of calculated and experimental *k* values for 3448-μm-diam hollow spheres with wall thicknesses of 78 μm. The interstitial gas is helium. The pressure exponent is 1/3 and the experimental data set is number 11.

ORNL-DWG 89-14486

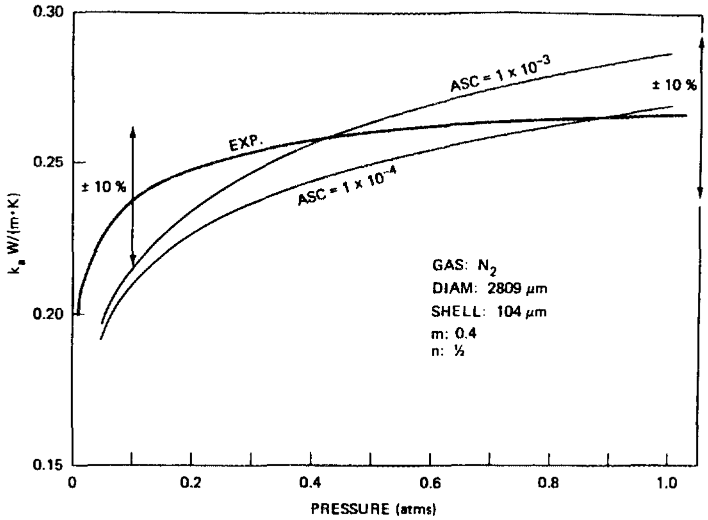

Fig. 11. A comparison of calculated and experimental k values for 2809-μm-diam hollow spheres with wall thicknesses of 104 μm. The interstitial gas is nitrogen. The pressure exponent is 1/2 and the experimental data set is number 12.

ORNL-DWG 89-14487

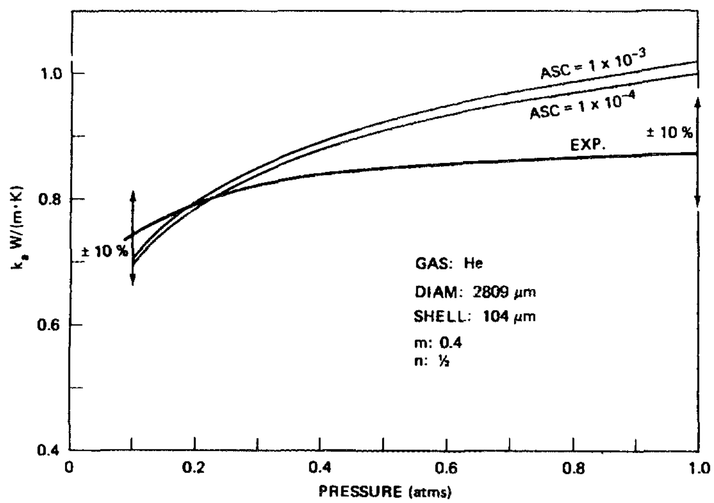

Fig. 12. A comparison of calculated and experimental k values for 2809-μm-diam hollow spheres with wall thicknesses of 104 μm. The interstitial gas is helium. The pressure exponent is 1/2 and the experimental data set is number 13.

ORNL-DWG 89-14488

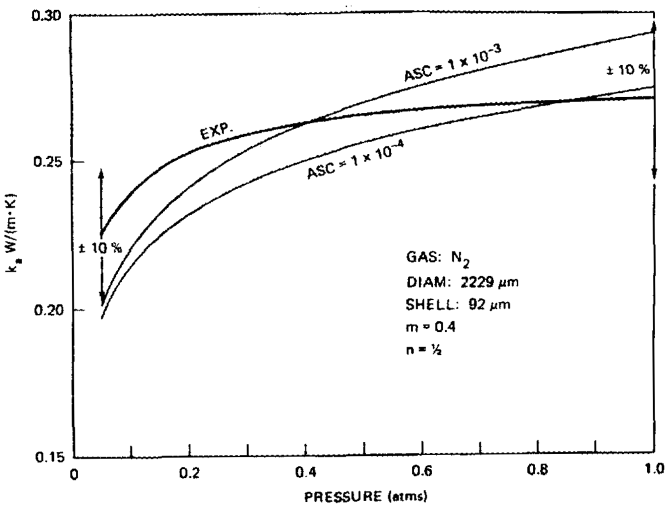

Fig. 13. A comparison of calculated and experimental k values for 2229-μm-diam hollow spheres with wall thicknesses of 126 μm. The interstitial gas is nitrogen. The pressure exponent is 1/2 and the experimental data set is number 14.

ORNL-DWG 89-14489

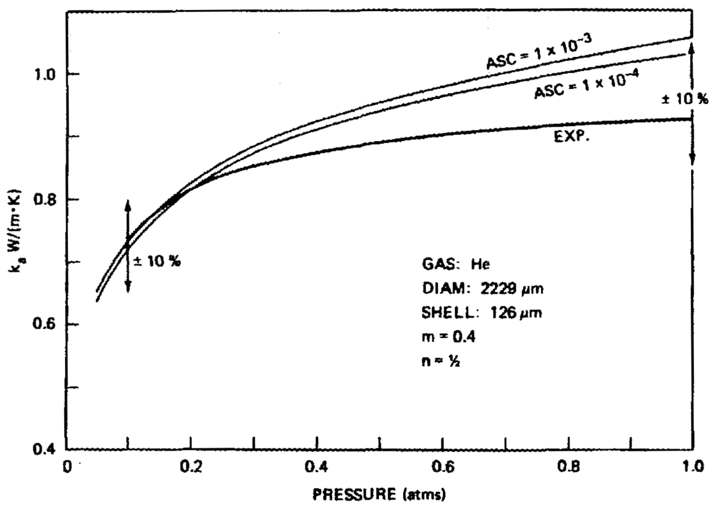

Fig. 14. A comparison of calculated and experimental k values for 2229-μm-diam hollow spheres with wall thicknesses of 126 μm. The interstitial gas is helium. The pressure exponent is 1/2 and the experimental data set is number 15.

ORNL-DWG 89-14490

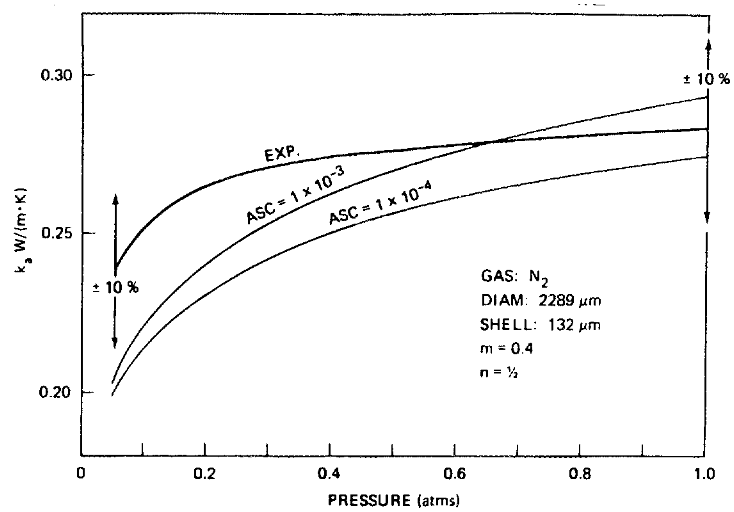

Fig. 15. A comparison of calculated and experimental k values for 2289-μm-diam hollow spheres with wall thicknesses of 132 μm. The experimental data set is 16.

ORNL-DWG 89-14491

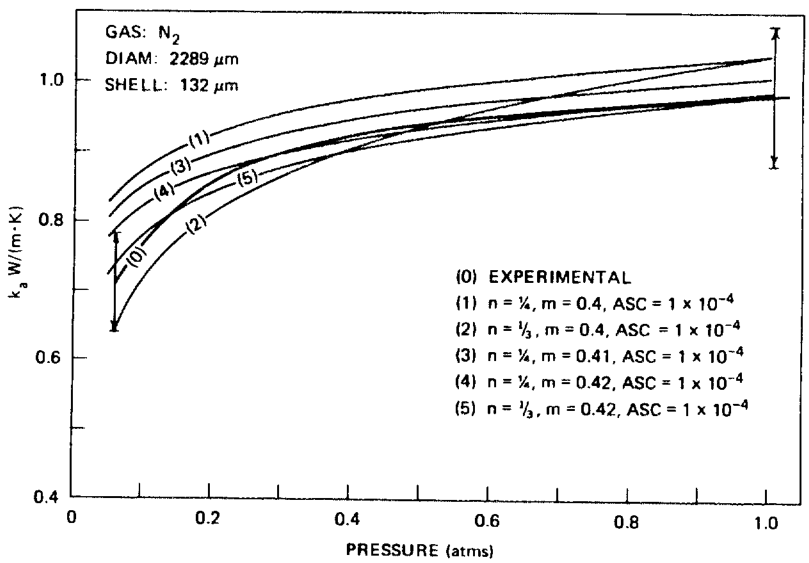

Fig. 16. A comparison of calculated and experimental k values for 2289-μm-diam hollow spheres with wall thicknesses of 132 μm. The experimental data set is 17.

ORNL-DWG 89-14492

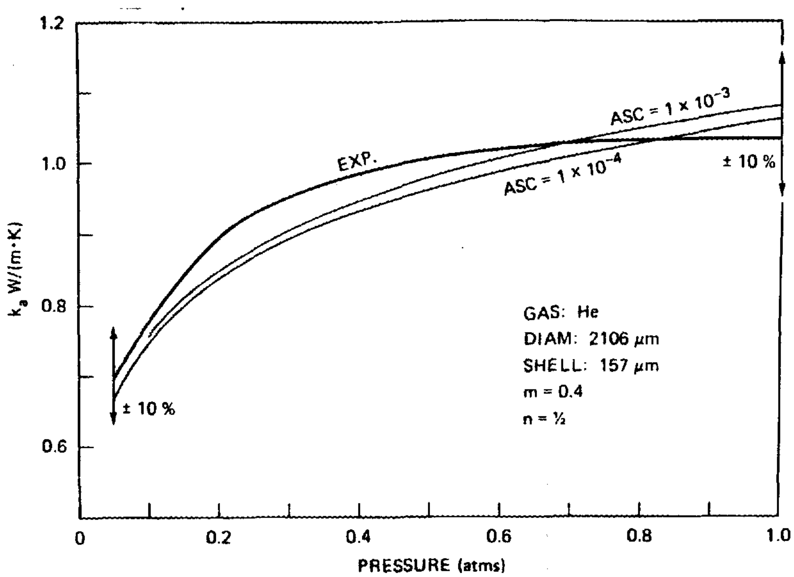

Fig. 17. A comparison of calculated and experimental *k* values for 2106-μm-diam hollow spheres with wall thicknesses of 157 μm. The experimental data set is 18.

ORNL-DWG 89-14493

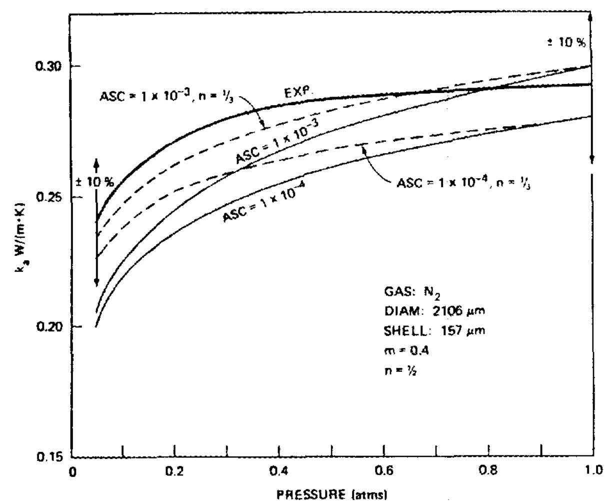

Fig. 18. A comparison of calculated and experimental *k* values for 2106-μm-diam hollow spheres with wall thicknesses of 157 μm. The experimental data set is 25.

ORNL-DWG 89-14494

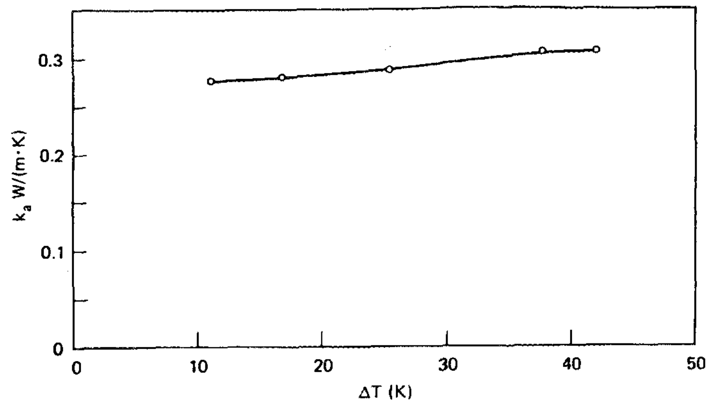

Fig. 19. The apparent thermal conductivity of 2200-μm-diam hollow Al_2O_3 spheres at 300 *K* and nitrogen pressure of 1 atm as a function of the temperature difference across the test specimen.

Figures 9 through 18 contain the results for k_a calculated with the modified Cunnington-Tien model for the parameter combinations in Table 7. The numerical values for k_a obtained with this model are given in Tables E-1 through E-10 in Appendix E. The calculation of k_a requires input of values for the void fraction in the spherical bed (m), the solid contact factor (*ASC*), and the exponent for the pressure multiplier for solid conduction (n). The figures were constructed to show the dependence of k_a on these input values.

Figures 9, 10, and 16 show the strong dependence of k on m. The curves in these figures show that, as expected, k decreases as m increases. Figure 9, which gives results for nitrogen as the interstitial gas; and Fig. 10, which gives results for helium as the interstitial gas, show that a change from $m = 0.45$ to $m = 0.50$ decreases the calculated k by about 20%. Precise void fraction determinations have not been made for the sphere beds tested and this means that m must be treated as an adjustable parameter.

Figures 11 through 15, 17, and 18 show k calculated with $ACS = 1 \cdot 10^{-3}$ and $ASC = 1 \cdot 10^{-4}$. This solid contact factor must be treated as an adjustable parameter since it is not part of the experimental determination. The change in k_a with *ASC* is much greater for nitrogen than for helium. Figures 11, 13, 15, and 18 show that increasing *ACS* from

Table 7. Parameter combinations for which *k* values have been computed using the modified Cunnington-Tien model

Data set	Gas	Sphere diameter (μm)	Shell thickness (μm)	*ASC*	*n*	Void fraction	Figure
10	N_2	3448	78	1×10^{-4}	0.500	0.45	9
10	N_2	3448	78	1×10^{-4}	0.500	0.50	9
10	N_2	3448	78	1×10^{-4}	0.500	0.55	9
11	He	3448	78	1×10^{-4}	0.500	0.45	10
11	He	3448	78	1×10^{-4}	0.500	0.50	10
11	He	3448	78	1×10^{-4}	0.500	0.55	10
12	N_2	2809	104	1×10^{-4}	0.500	0.40	11
12	N_2	2809	104	1×10^{-3}	0.500	0.40	11
13	He	2809	104	1×10^{-4}	0.500	0.40	12
13	He	2809	104	1×10^{-3}	0.500	0.40	12
14	N_2	2229	126	1×10^{-4}	0.500	0.40	13
14	N_2	2229	126	1×10^{-3}	0.500	0.40	13
15	He	2229	126	1×10^{-5}	0.500	0.40	14
15	He	2229	126	1×10^{-4}	0.500	0.40	14
15	He	2229	126	1×10^{-3}	0.500	0.40	14
16	N_2	2289	132	1×10^{-4}	0.500	0.40	15
16	N_2	2289	132	1×10^{-3}	0.500	0.40	15
17	He	2289	132	1×10^{-4}	0.250	0.41	16
17	He	2289	132	1×10^{-4}	0.250	0.42	16
17	He	2289	132	1×10^{-4}	0.250	0.43	16
17	He	2289	132	1×10^{-4}	0.333	0.41	16
17	He	2289	132	1×10^{-4}	0.333	0.42	16
17	He	2289	132	1×10^{-4}	0.500	0.40	16
18	He	2106	157	1×10^{-4}	0.500	0.40	17
18	He	2106	157	1×10^{-3}	0.500	0.40	17
25	N_2	2106	157	1×10^{-4}	0.500	0.40	18
25	N_2	2106	157	1×10^{-3}	0.500	0.40	18
25	N_2	2106	157	1×10^{-4}	0.333	0.40	18
25	N_2	2106	157	1×10^{-3}	0.333	0.40	18

$1 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ increases the k_a by 8 to 10% for nitrogen at 1.0 atm. The effect of changing *ASC* is reduced to the 1 to 2% range at a pressure of 0.1 atm of nitrogen. Figures 12, 14, and 17 show the change in k_a with *ACS* with helium as the interstitial gas. The increase in k_a as *ACS* is increased from $1 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ is in the range 2 to 3% when the helium pressure is 1 atm. The effect on k_a of the same change in *ASC* is less than 1% at 0.1 atm of helium. Figures 16 and 18 show the effect of changing the exponent on the pressure multiplier of the solid conduction term on calculated k_a values. Figure 16 shows calculated k_a values for spheres with helium as the interstitial gas, while Fig. 18 shows a similar type result for nitrogen. A change from $n = 0.25$ to $n = 0.333$ increases the calculated k_a for helium by about 20% at 0.05 atm. A change from $n = 0.333$ to $n = 0.50$ increases the calculated k_a for nitrogen by about 15% at 0.05 atm. The pressure exponent has no effect at atmospheric pressure.

Trends in k_a with pressure, contact resistance, and void fraction can be determined with this model. Quantitative predictions require accurate values for n, m, and *ACS*. At the present, these three parameters must be treated as adjustable parameters.

A void fraction of 0.40, a solid contact factor of $1 \cdot 10^{-4}$, and a pressure exponent of 1/2 generally give calculated k values near the measured k values. This set of parameters can be used if sufficient data are not available. Calculated k values are also dependent on the lead coefficient for the radiative term (*BR*). The value for *BR* depends on the extinction coefficient for the spheres, the emittance of the boundaries, and the refractive index n of the material. Ozizik has derived an expression[13] for k_r for an absorbing and isotopically scattering planar media of thickness ℓ. Ozizik's equation for k_r was written as shown below on the assumption that the emittances of the inside surfaces of the radial heat flow apparatus were one:[13]

$$k_r = \frac{n^2 \sigma T_1^3 \ell \ (1 + \theta)\ (1 + \theta^2)}{(3/4 E\ell + 1)} \ . \qquad (23)$$

An average E value of 1200^{m-1} obtained by Shapiro[2] and refractive index (n) of one gives $BR = 0.0306$ from Eqs. (21) and (22). The *BR* value 0.0306 was used in the calculations done with DMODEL.FOR.

The need to include pressure-dependent terms in the preceding models to obtain agreement between experimental and calculated k_a suggests the presence of a convective heat transfer component. This hypothesis was tested by measuring k_a for 2200-μm Al_2O_3 spheres as a function of the temperature difference across the vertically oriented test specimen. Figure 19 shows k_a obtained with a series of values for the temperature difference across the test specimen (ΔT) ranging from 10 to 42°C. These measurements were obtained for 2200-μm-diam hollow Al_2O_3 spheres at $\bar{T}$ = 300 K. The interstitial gas was nitrogen at 1 atm. The measured k_a by over 10% when ΔT was increased from 10 to 40°C. These data suggest the existence of a convective component and support the use of pressure-dependent terms in the analysis.

CONCLUSIONS AND RECOMMENDATIONS

Three models have been used to correlate experimental k_a data for hollow ceramic spheres as a function of pressure at constant temperature. All three models contain adjustable parameters that must be fixed by measuring k_a. The series-parallel model with an additive pressure term is the easiest to understand. This model can describe a given set of k_a data to better than 5%. The Cunnington-Tien model as modified can be used to describe data sets to about the same accuracy as the series-parallel model with a few adjustable parameters. This is especially true if the void fraction and fraction solid for the test specimen are determined independently. The geometric model is the most difficult to use and produces results for k_a that are strongly dependent on the accommodation coefficient.

All three models can be used to demonstrate the decrease in k_a as interstitial gas pressure is decreased. The models clearly demonstrate the strong dependence of k_a on the thermal conductivity of the gas phase.

The series-parallel or the modified Cunnington-Tien model are found to be best for calculating the effect on k_a of pressure, sphere characteristics, or interstitial gas type. The geometric model requires data for a system being considered to fix the accommodation coefficient.

All three models can be used to predict k_a as a function of temperature. A calculation of $k_a(T)$ requires data for the thermal conductivity of the solid and gas components. A serious weakness exists in that the radiative transport term is constant for the data sets examined, and this means that a determination of the extinction coefficient has not been made. A precise calculation of $k_a(T)$ will require characterization of the optical properties of sphere materials.

Continued experimental work at temperatures from 300 to 1000 K would be useful. A separate measurement of the extinction coefficient or other optical properties of the sphere materials would give added insight into the high-temperature performance of the spheres. It is possible that radiative properties could be measured using thin, flat sections of the materials used to generate spheres.

A direct determination of gas permeability of the spheres is needed. This information would address a question of long-term stability and whether higher resistance sphere beds can be generated by the use of low conductivity gas inside the spheres or perhaps a low pressure gas inside the spheres.

A test sequence on spheres of mixed sizes would be useful in determining the extent to which internal convection can be suppressed. Mixtures of spheres and particles could give an opportunity for suppressing convection provided that solid conduction does not increase to an unacceptable level.

Mechanical properties of the spheres need to be determined before the material will find significant application. Stability under compression and vibration needs to be determined.

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APPENDIX A

PHYSICAL PROPERTY DATA

PHYSICAL PROPERTY DATA

The gas phase thermal conductivity data used in this report were taken from the compilation published by Y. S. Touloukian et al.[A-1] The recommended thermal conductivity values were used to obtain $k_g^o(T)$ at one atmosphere of pressure that are linear in temperature. Equations (A.1) and (A.2) are for N_2 and He, respectively.

$$k_g^o(T) = 4.3018 \times 10^{-3} + 7.2018 \times 10^{-5}\ T \tag{A.1}$$

$$k_g^o(T) = 5.6809 \times 10^{-2} + 3.0964 \times 10^{-4}\ T \tag{A.2}$$

Mean free path lengths have been calculated as a function of temperature and pressure using an expression from Hirschfelder et al.[A-2]:

$$\ell_g = kT/\xi' P\pi\sigma^2 \tag{A.3}$$

Equation (A.3) can be simplified to the following form which requires P in atmospheres, T in K, and the collision diameter σ in centimeters to obtain ℓ_g in centimeters. The "k" in Equation (A.3) is Boltzmann's constant.

$$\ell_g = 3.065 \times 10^{-23}\ T/\sigma^2 P \tag{A.4}$$

Values for σ given by Hirschfelder et al.[A-3] complete the information required to evaluate ℓ_g at a given temperature and pressure. Table A1 gives example ℓ_g values for He and N_2.

The thermal conductivity data used for the solid part of the spheres in calculations in this report are given in Table A.1.

Table A.1. Mean free path lengths for helium and nitrogen

Species	σ (cm)	P (atm)	T (K)	ℓ_g (cm)
He	2.18×10^{-8}	1.0	100	6.45×10^{-6}
			300	1.93×10^{-5}
		0.1	100	6.45×10^{-5}
			300	1.93×10^{-4}
N_2	3.75×10^{-8}	1.0	100	2.18×10^{-6}
			300	6.54×10^{-6}
		0.1	100	2.18×10^{-5}
			300	6.54×10^{-5}

Table A.2. Solid phase thermal conductivity data

Species	Thermal conductivity (W/mK) at 300 K
Al_2O_3	21.4
$Al_2O_3 \cdot 7\% Cr_2O_3$	10.8
P.S. ZrO_2[a]	2.5

[a]Partially stabilized with MgO.

REFERENCES

A-1. Y. S. Touloukian, P. E. Liley, and S. C. Saxena, *Thermophysical Properties of Matter, Volume 3, Thermal Conductivity, Nonmetallic Liquids and Gases*, Plenum Press, New York (1970) pp. 33, 69.

A-2. J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, *Molecular Theory of Gases and Liquids*, John Wiley and Sons, New York (1954) p. 10.

A-3. J. O. Hirschfelder, F. Curtiss, and R. B. Bird, *Molecular Theory of Gases and Liquids*, John Wiley and Sons, New York (1954) p. 15.

APPENDIX B

EXPERIMENTAL DATA FOR APPARENT THERMAL CONDUCTIVITY OF UNIFORM-DIAMETER HOLLOW SPHERES

This appendix contains a series of input data files containing information about the spheres, the solid phase conductivity, gas species, and k_a as a function of pressure. The data files are organized as follows.

Line 1. Number of data points, mean temp. (K), sphere diameter (μm), sphere shell thickness (μm), parameter m, solid conductivity (W/mK), gas type (1 + N_2, 2 - He).

Remaining Lines: Pressure (atms), apparent thermal conductivity (W/mK0.

```
.TYPE FOR10.DAT
7,300.,3448.0,78.0,0.6,21.4,1
0.058,.1853
0.119,0.1939
0.254,0.1992
0.345,0.2011
0.652,0.2039
1.012,.2054
2.016,0.2070
```

```
.TYPE FOR11.DAT
6,300.0,3448.0,78.0,0.6,21.4,2
0.059,0.5389
0.113,0.5882
0.327,0.6093
0.644,0.6217
1.014,0.6281
2.017,0.6336
```

```
.TYPE FOR12.DAT
7,300.0,2809.0,104.0,0.6,21.4,1
0.048,0.2004
0.102,0.2377
0.178,0.2397
0.402,0.2487
0.654,0.2625
1.047,0.2661
2.029,0.2685
```

```
.TYPE FOR13.DAT
6,300.0,2809.0,104.0,0.6,21.4,2
0.087,0.7282
0.333,0.8303
0.654,0.8582
0.947,0.8711
1.995,0.8901
1.958,0.8886

.TYPE FOR14.DAT
7,300.0,2229.0,92.0,0.6,21.4,1
0.048,0.2243
0.166,0.2512
0.219,0.2551
0.325,0.2599
0.668,0.2674
1.009,0.2706
2.004,0.2743

.TYPE FOR15.DAT
9,300.0,2229.0,92.0,0.6,21.4,2
0.048,0.6473
0.073,0.6959
0.119,0.7575
0.168,0.7989
0.210,0.8216
0.334,0.8590
0.673,0.9032
1.023,0.9227
2.009,0.9477

.TYPE FOR16.DAT
7,300.0,2289.0,132.0,0.6,21.4,1
0.057,0.2389
0.073,0.2448
0.097,0.2528
0.264,0.2697
0.656,0.2697
1.003,0.2833
1.997,0.2866

.TYPE FOR17.DAT
8,300.0,2289.0,132.0,0.6,21.4,2
0.060,0.7083
0.101,0.7724
0.208,0.8647
0.297,0.8996
0.336,0.9092
0.658,0.9578
1.004,0.9807
2.000,1.008
```

```
.TYPE FOR18.DAT
7,300.0,2106.0,130.0,0.6,21.4,2
0.054,0.7024
0.103,0.7845
0.211,0.9087
0.335,0.9659
0.669,1.0288
0.997,1.0557
1.997,1.0929

.TYPE FOR19.DAT
7,300.0,2852.0,91.0,0.6,10.8,1
0.052,0.2020
0.102,0.2138
0.214,0.2237
0.338,0.2273
0.659,0.2317
1.017,0.2334
2.004,0.2354

.TYPE FOR20.DAT
7,300.0,2852.0,91.0,0.6,10.8,2
0.048,0.5475
0.090,0.5961
0.204,0.6341
0.336,0.6480
0.658,0.6638
1.004,0.6713
1.996,0.6809

.TYPE FOR21.DAT
7,300.0,3498.0,70.0,0.6,10.8,1
0.027,0.1704
0.106,0.1856
0.217,0.1913
0.338,0.1946
0.667,0.1966
1.000,0.1976
2.001,0.1985

.TYPE FOR22.DAT
7,300.0,3498.0,70.0,0.6,10.8,2
0.056,0.4797
0.078,0.4946
0.212,0.5221
0.336,0.5316
0.669,0.5393
1.011,0.5427
2.000,0.5463
```

```
.TYPE FOR23.DAT
6,300.0,2250.0,118.0,0.6,2.5,1
0.089,0.1653
0.140,0.1670
0.286,0.1703
0.662,0.1722
0.996,0.1728
2.009,0.1733

.TYPE FOR24.DAT
7,300.0,2250.0,118.0,0.6,2.5,2
0.061,0.3605
0.130,0.3758
0.209,0.3829
0.270,0.3846
0.662,0.3900
1.001,0.3916
1.997,0.3931

.TYPE FOR25.DAT
7,300.0,2106.0,130.0,0.6,21.4,1
0.051,0.2397
0.106,0.2582
0.210,0.2718
0.335,0.2809
0.656,0.2880
1.000,0.2916
2.003,0.2949

.TYPE FOR26.DAT
5,300.0,2289.0,132.0,0.6,21.4,1
0.203,0.2458
0.330,0.2563
0.655,0.2611
1.014,0.2652
1.994,0.2678
```

APPENDIX C

FORTRAN PROGRAMS FOR THE ANALYSIS OF HOLLOW SPHERE THERMAL CONDUCTIVITY DATA USING THE SERIES-PARALLEL MODEL

A listing of PMODA.FOR is contained on pages 46 and 47. This program accepts input from the data files shown in Appendix B and calculates least square values for the parameters A, k_r, LS, and F_s. Pages 48 through 53 contain a comparison of experimental and calculated k_a for each of the 17 data sets. In some cases the calculated k_a are biased from the experimental values. This is the result of the requirement in the program that the parameter "A" be non-negative.

A listing for PMODB.FOR is contained on pages 54 and 55. PMODB differs from PMODA is the elimination of the parallel conductive component of heat transfer. The parameters for PMODB and comparisons of experimental and calculated k_a are given on pages 56 through 61.

A listing for PMODC.FOR is contained on pages 62, 63, and 64. PMODC uses the output from PMODB to generate a set of residuals that are fit by the method of least squares to a linear expression in $\sqrt{P}$. The output from PMODC is listed on pages 65 through 73. The output includes results for PMODB and PMODC so that a comparison can be made. The PMODB output on pages 56 through 61 is different from that on pages 65 through 73 because different intervals were searched for the optimum parameter values.

```
...TYPE PMODA.FOR
C       PMODA.FOR     11/88     DWY
C       A AND KRAD ARE THE PARAMETERS TO BE DETERMINED
        IMPLICIT REAL ( A-H,K-L,O-Z)
        DIMENSION KT(50),P(50),X(50),Z(50),KTC(50),DK(50)
        DIMENSION SIG(4),G1(4),G2(4)
        DATA SIG/3.75E-8,2.18E-8,3.64E-8,3.75E-8/,G1/4.3018E-3,
     &  5.6809E-2,2.7264E-3,5.4818E-3/,G2/7.2018E-5,3.0964E-4,
     &  4.9873E-5,6.9073E-5/
        DO 333  MM=10,26
        WRITE(5,884) MM
884     FORMAT(2X,/////,2X,'INPUT FILE NUMBER',I4,/)
        READ(MM,*) N,T,DS,W,FS,KS,JJ
        FSC=FS*((.5*DS)**3-(.5*DS-W)**3)/(.5*DS)**3
        FG=1-FS
C       WRITE(5,13)
C       READ(5,*) JJ
        IF ( JJ .EQ. 1 ) WRITE(5,200)
        IF ( JJ .EQ. 2 ) WRITE(5,201)
        IF ( JJ .EQ. 3 ) WRITE(5,202)
        IF ( JJ .EQ. 4 ) WRITE(5,203)
        DO 2 J=1,N
999     READ(MM,*) P(J),KT(J)
2       CONTINUE
        CLOSE(UNIT=MM)
C       WRITE(5,4)
C       READ(5,*) LS1,LS2
        KGO = G1(JJ) + G2(JJ)*T
        PMAX=1.E5
        LSF =1.E5
        FSF =1.E5
        ABEST=1.E5
        BBEST=1.E5
        DO 3 KK=1,325
        LS=0.1*KK
        DO 3 KKK=1,800,5
        FS=FSC*(1.+(KKK-1.)/10.0)/40.0
        PC=0.0
        S1=0.0
        S2=0.0
        S3=0.0
        S4=0.0
        DO 5 I = 1,N
        LG=3.065E-19*T/(SIG(JJ)**2*P(I))
        KG=KGO*LS/(LS+LG)
        X(I) = FS*KS + FG*KG - KS*KG/(FG*KS + FS*KG)
        Z(I) = KT(I) - KS*KG/(FG*KS + FS*KG)
        S1 = S1 + X(I)
        S2 = S2 + X(I)**2
        S3 = S3 + Z(I)
        S4 = S4 + X(I)*Z(I)
5       CONTINUE
```

```
            A = (S1*S3-N*S4)/(S1**2 - N*S2)
            B = (S1*S4-S3*S2)/(S1**2-N*S2)
            IF ( B .LT. 0.0 ) B = 0.0
            IF ( A .LT. 0.0 ) A = 0.0
            DO 6 I = 1,N
            KTC(I) = A*X(I) + B +KS*KG/(FG*KS+FS*KG)
            DK(I)  = (KTC(I) - KT(I))**2
            PC=PC+(DK(I))
6           CONTINUE
            IF ( PC .GT. PMAX ) GO TO 3
            PMAX=PC
            ABEST=A
            BBEST=B
            LSF=LS
            FSF=FS
            FGF=1-FS
3           CONTINUE
            WRITE(5,7)
C           WRITE(5,8) (P(I),KT(I), I=1,N)
            WRITE(5,9) ABEST,BBEST
            WRITE(5,10)
            SDK=0.0
            DO 16 K=1,N
            LG=3.065E-19*T/(SIG(JJ)**2*P(K))
            KG=KG0*LSF/(LSF+LG)
            X(K)=FSF*KS+FGF*KG-KS*KG/(FGF*KS+FSF*KG)
            KTC(K)=ABEST*X(K)+BBEST+KS*KG/(FG*KS+FS*KG)
            DK(K)=(KTC(K)-KT(K))*100.0/KT(K)
            SDK=SDK+ABS(DK(K))
16          CONTINUE
            SDK=SDK/N
            WRITE(5,11) (P(I),KT(I),KTC(I),DK(I),I=1,N)
            WRITE(5,15)SDK,LSF,FSF,FSC
333         CONTINUE
4           FORMAT(2X,'INPUT LS1,LS2')
7           FORMAT(5X,'PRESSURE   KTOTAL')
9           FORMAT(2X,'A=',E10.3,'  B=',E10.3)
8           FORMAT(2X,2E10.4)
10          FORMAT(6X,'PRESSURE KEXP       KCALC      DK(%)')
11          FORMAT(2X,F10.3,2E10.4,F10.2)
12          FORMAT(2X,'N2=1  HE=2  A=3')
13          FORMAT(2X,'INPUT GAS TYPE,1=N2,2=HE,3=A,4=AIR')
14          FORMAT(2X,'KS=',E10.4)
15          FORMAT(2X,'AVERAGE ERROR=',E10.4,' LS=',E10.4,' FS=',E10.4,
         &  ' FSC=',E10.4)
200         FORMAT(2X,'GAS IS N2')
201         FORMAT(2X,'GAS IS HE')
202         FORMAT(2X,'GAS IS A')
203         FORMAT(2X,'GAS IS AIR')
            END
```

INPUT FILE NUMBER 10

GAS IS N2

PRESSURE KTOTAL
A= 0.000E+00 B= 0.135E+00

PRESSURE	KEXP	KCALC	DK(%)
0.058	.1853E+00	.1847E+00	-0.32
0.119	.1939E+00	.1916E+00	-1.20
0.254	.1992E+00	.1958E+00	-1.69
0.345	.2011E+00	.1969E+00	-2.09
0.652	.2039E+00	.1984E+00	-2.70
1.012	.2054E+00	.1990E+00	-3.11
2.016	.2070E+00	.1996E+00	-3.59

AVERAGE ERROR= .2101E+01 LS= .3600E+01 FS= .1945E-02 FSC= .7781E-01

INPUT FILE NUMBER 11

GAS IS HE

PRESSURE KTOTAL
A= 0.000E+00 B= 0.231E+00

PRESSURE	KEXP	KCALC	DK(%)
0.059	.5389E+00	.5376E+00	-0.25
0.113	.5882E+00	.5664E+00	-3.71
0.327	.6093E+00	.5905E+00	-3.08
0.644	.6217E+00	.5974E+00	-3.91
1.014	.6281E+00	.6000E+00	-4.47
2.017	.6336E+00	.6023E+00	-4.93

AVERAGE ERROR= .3394E+01 LS= .1490E+02 FS= .1167E-01 FSC= .7781E-01

INPUT FILE NUMBER 12

GAS IS N2

PRESSURE KTOTAL
A= 0.000E+00 B= 0.218E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.2004E+00	.2323E+00	15.92
0.102	.2377E+00	.2425E+00	2.01
0.178	.2397E+00	.2513E+00	4.86
0.402	.2487E+00	.2636E+00	6.00
0.654	.2625E+00	.2694E+00	2.62
1.047	.2661E+00	.2736E+00	2.81
2.029	.2685E+00	.2775E+00	3.35

AVERAGE ERROR= .5366E+01 LS= .4000E+00 FS= .3091E-02 FSC= .1237E+00

INPUT FILE NUMBER 13

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.480E+00

PRESSURE	KEXP	KCALC	DK(%)
0.087	.7282E+00	.7110E+00	-2.37
0.333	.8303E+00	.8013E+00	-3.49
0.654	.8582E+00	.8247E+00	-3.90
0.947	.8711E+00	.8330E+00	-4.38
1.995	.8901E+00	.8432E+00	-5.27
1.958	.8886E+00	.8430E+00	-5.13

AVERAGE ERROR= .4092E+01 LS= .3600E+01 FS= .6183E-02 FSC= .1237E+00

INPUT FILE NUMBER 14

GAS IS N2

PRESSURE KTOTAL

A= 0.000E+00 B= 0.219E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.2243E+00	.2309E+00	2.95
0.166	.2512E+00	.2472E+00	-1.58
0.219	.2551E+00	.2517E+00	-1.34
0.325	.2599E+00	.2580E+00	-0.74
0.668	.2674E+00	.2680E+00	0.24
1.009	.2706E+00	.2725E+00	0.69
2.004	.2743E+00	.2776E+00	1.20

AVERAGE ERROR= .1249E+01 LS= .3000E+00 FS= .3416E-02 FSC= .1367E+00

INPUT FILE NUMBER 15

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.445E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.6473E+00	.7558E+00	16.76
0.073	.6959E+00	.7744E+00	11.29
0.119	.7575E+00	.7898E+00	4.26
0.168	.7989E+00	.7974E+00	-0.19
0.210	.8216E+00	.8012E+00	-2.49
0.334	.8590E+00	.8070E+00	-6.06
0.673	.9032E+00	.8121E+00	-10.09
1.023	.9227E+00	.8138E+00	-11.80
2.009	.9477E+00	.8155E+00	-13.95

AVERAGE ERROR= .8542E+01 LS= .2030E+02 FS= .1367E-01 FSC= .1367E+00

INPUT FILE NUMBER 16

GAS IS N2

PRESSURE KTOTAL

A= 0.000E+00 B= 0.226E+00

PRESSURE	KEXP	KCALC	DK(%)
0.057	.2389E+00	.2424E+00	1.45
0.073	.2448E+00	.2456E+00	0.33
0.097	.2528E+00	.2497E+00	-1.21
0.264	.2697E+00	.2656E+00	-1.52
0.656	.2697E+00	.2774E+00	2.87
1.003	.2833E+00	.2813E+00	-0.72
1.997	.2866E+00	.2854E+00	-0.41

AVERAGE ERROR= .1215E+01 LS= .4000E+00 FS= .4614E-02 FSC= .1846E+00

INPUT FILE NUMBER 17

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.520E+00

PRESSURE	KEXP	KCALC	DK(%)
0.060	.7083E+00	.7591E+00	7.17
0.101	.7724E+00	.7995E+00	3.51
0.208	.8647E+00	.8403E+00	-2.82
0.297	.8996E+00	.8541E+00	-5.06
0.336	.9092E+00	.8580E+00	-5.63
0.658	.9578E+00	.8736E+00	-8.80
1.004	.9807E+00	.8795E+00	-10.32
2.000	.1008E+01	.8853E+00	-12.17

AVERAGE ERROR= .6935E+01 LS= .5800E+01 FS= .1154E-01 FSC= .1846E+00

INPUT FILE NUMBER 18

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.580E+00

PRESSURE	KEXP	KCALC	DK(%)
0.054	.7024E+00	.7005E+00	-0.28
0.103	.7845E+00	.7575E+00	-3.44
0.211	.9087E+00	.8223E+00	-9.51
0.335	.9659E+00	.8582E+00	-11.15
0.669	.1029E+01	.8983E+00	-12.69
0.997	.1056E+01	.9141E+00	-13.41
1.997	.1093E+01	.9321E+00	-14.72

AVERAGE ERROR= .9313E+01 LS= .1700E+01 FS= .4898E-02 FSC= .1959E+00

INPUT FILE NUMBER 19

GAS IS N2
PRESSURE KTOTAL
A= 0.000E+00 B= 0.160E+00

PRESSURE	KEXP	KCALC	DK(%)
0.052	.2020E+00	.2058E+00	1.88
0.102	.2138E+00	.2134E+00	-0.19
0.214	.2237E+00	.2187E+00	-2.25
0.338	.2273E+00	.2207E+00	-2.92
0.659	.2317E+00	.2225E+00	-3.99
1.017	.2334E+00	.2231E+00	-4.39
2.004	.2354E+00	.2238E+00	-4.94

AVERAGE ERROR= .2939E+01 LS= .3100E+01 FS= .4038E-02 FSC= .1077E+00

INPUT FILE NUMBER 20

GAS IS HE
PRESSURE KTOTAL
A= 0.000E+00 B= 0.263E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.5475E+00	.5474E+00	-0.02
0.090	.5961E+00	.5824E+00	-2.29
0.204	.6341E+00	.6097E+00	-3.85
0.336	.6480E+00	.6192E+00	-4.45
0.658	.6638E+00	.6266E+00	-5.60
1.004	.6713E+00	.6294E+00	-6.24
1.996	.6809E+00	.6321E+00	-7.17

AVERAGE ERROR= .4232E+01 LS= .1300E+02 FS= .2288E-01 FSC= .1077E+00

INPUT FILE NUMBER 21

GAS IS N2
PRESSURE KTOTAL
A= 0.000E+00 B= 0.126E+00

PRESSURE	KEXP	KCALC	DK(%)
0.027	.1704E+00	.1745E+00	2.38
0.106	.1856E+00	.1857E+00	0.07
0.217	.1913E+00	.1883E+00	-1.58
0.338	.1946E+00	.1892E+00	-2.78
0.667	.1966E+00	.1900E+00	-3.35
1.000	.1976E+00	.1903E+00	-3.69
2.001	.1985E+00	.1906E+00	-3.98

AVERAGE ERROR= .2547E+01 LS= .7100E+01 FS= .4325E-02 FSC= .6920E-01

INPUT FILE NUMBER 22

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.150E+00

PRESSURE	KEXP	KCALC	DK(%)
0.056	.4797E+00	.4787E+00	-0.20
0.078	.4946E+00	.4899E+00	-0.94
0.212	.5221E+00	.5097E+00	-2.38
0.336	.5316E+00	.5142E+00	-3.27
0.669	.5393E+00	.5182E+00	-3.92
1.011	.5427E+00	.5195E+00	-4.27
2.000	.5463E+00	.5209E+00	-4.66

AVERAGE ERROR= .2805E+01 LS= .2600E+02 FS= .2595E-01 FSC= .6920E-01

INPUT FILE NUMBER 23

GAS IS N2

PRESSURE KTOTAL

A= 0.000E+00 B= 0.106E+00

PRESSURE	KEXP	KCALC	DK(%)
0.089	.1653E+00	.1637E+00	-0.96
0.140	.1670E+00	.1658E+00	-0.70
0.286	.1703E+00	.1679E+00	-1.43
0.662	.1722E+00	.1690E+00	-1.85
0.996	.1728E+00	.1693E+00	-2.01
2.009	.1733E+00	.1696E+00	-2.12

AVERAGE ERROR= .1512E+01 LS= .6800E+01 FS= .1909E-01 FSC= .1697E+00

INPUT FILE NUMBER 24

GAS IS HE

PRESSURE KTOTAL

A= 0.000E+00 B= 0.163E-01

PRESSURE	KEXP	KCALC	DK(%)
0.061	.3605E+00	.3421E+00	-5.10
0.130	.3758E+00	.3575E+00	-4.87
0.209	.3829E+00	.3630E+00	-5.21
0.270	.3846E+00	.3650E+00	-5.09
0.662	.3900E+00	.3693E+00	-5.30
1.001	.3916E+00	.3704E+00	-5.43
1.997	.3931E+00	.3713E+00	-5.53

AVERAGE ERROR= .5218E+01 LS= .3250E+02 FS= .4454E-01 FSC= .1697E+00

```
INPUT FILE NUMBER  25

GAS IS N2
   PRESSURE   KTOTAL
A= 0.000E+00  B= 0.252E+00
    PRESSURE KEXP       KCALC      DK(%)
      0.051 .2397E+00 .2612E+00       8.97
      0.106 .2582E+00 .2683E+00       3.92
      0.210 .2718E+00 .2778E+00       2.20
      0.335 .2809E+00 .2852E+00       1.54
      0.656 .2880E+00 .2957E+00       2.66
      1.000 .2916E+00 .3012E+00       3.30
      2.003 .2949E+00 .3081E+00       4.47
AVERAGE ERROR= .3865E+01 LS= .2000E+00 FS= .4898E-02 FSC= .1959E+00
```

```
INPUT FILE NUMBER  26

GAS IS N2
   PRESSURE   KTOTAL
A= 0.848E-02  B= 0.143E+00
    PRESSURE KEXP       KCALC      DK(%)
      0.203 .2458E+00 .2442E+00      -0.65
      0.330 .2563E+00 .2512E+00      -1.99
      0.655 .2611E+00 .2588E+00      -0.89
      1.014 .2652E+00 .2622E+00      -1.15
      1.994 .2678E+00 .2656E+00      -0.84
AVERAGE ERROR= .1104E+01 LS= .5000E+00 FS= .3415E+00 FSC= .1846E+00
```

```
C       PMODB.FOR      11/88       DWY
C       A AND KRAD ARE THE PARAMETERS TO BE DETERMINED
        IMPLICIT REAL ( A-H,K-L,O-Z)
        DIMENSION KT(50),P(50),X(50),Z(50),KTC(50),DK(50)
        DIMENSION SIG(4),G1(4),G2(4)
        DIMENSION CP(50),RP(50)
        DATA SIG/3.75E-8,2.18E-8,3.64E-8,3.75E-8/,G1/4.3018E-3,
     &  5.6809E-2,2.7264E-3,5.4818E-3/,G2/7.2018E-5,3.0964E-4,
     &  4.9873E-5,6.9073E-5/
        DO 333  MM=10,26
        WRITE(5,884) MM
884     FORMAT(2X,/////,2X,'INPUT FILE NUMBER',I4,/)
        READ(MM,*) N,T,DS,W,FS,KS,JJ
        FSC=FS*((.5*DS)**3-(.5*DS-W)**3)/(.5*DS)**3
        FG=1-FS
C       WRITE(5,13)
C       READ(5,*) JJ
        IF ( JJ .EQ. 1 ) WRITE(5,200)
        IF ( JJ .EQ. 2 ) WRITE(5,201)
        IF ( JJ .EQ. 3 ) WRITE(5,202)
        IF ( JJ .EQ. 4 ) WRITE(5,203)
        DO 2 J=1,N
999     READ(MM,*) P(J),KT(J)
2       CONTINUE
        CLOSE(UNIT=MM)
C       WRITE(5,4)
C       READ(5,*) LS1,LS2
        KG0 = G1(JJ) + G2(JJ)*T
        PMAX=1.E5
        LSF =1.E5
        FSF =1.E5
        ABEST=1.E5
        DO 3 KK=1,325
        LS=0.1*KK
        DO 3 KKK=1,800,5
        FS=FSC*(1.+(KKK-1.)/10.0)/40.0
        FG=1-FS
        PC=0.0
        S1=0.0
        DO 5 I = 1,N
        LG=3.065E-19*T/(SIG(JJ)**2*P(I))
        KG=KG0*LS/(LS+LG)
        X(I)=KT(I)-KS*KG/(FG*KS+FS*KG)
        S1 = S1 + X(I)
5       CONTINUE
```

```
              A=S1/N
              DO 6 I = 1,N
              KTC(I)=KS*KG/(FG*KS+FS*KG)+A
              DK(I)  = (KTC(I) - KT(I))**2
              PC=PC+(DK(I))
      6       CONTINUE
              IF ( PC .GT. PMAX ) GO TO 3
              PMAX=PC
              ABEST=A
              LSF=LS
              FSF=FS
              FGF=1-FSF
      3       CONTINUE

              WRITE(5,7)
      C       WRITE(5,8) (P(I),KT(I), I=1,N)
              WRITE(5,9) ABEST
              WRITE(5,10)
              SDK=0.0
              DO 16 K=1,N
              LG=3.065E-19*T/(SIG(JJ)**2*P(K))
              KG=KG0*LSF/(LSF+LG)
              X(K)=KS*KG/(FGF*KS+FSF*KG)
              KTC(K)=X(K)+ABEST
              CP(K)=X(K)*100.0/KTC(K)
              RP(K)=ABEST*100.0/KTC(K)
              DK(K)=(KTC(K)-KT(K))*100.0/KT(K)
              SDK=SDK+ABS(DK(K))
      16      CONTINUE
              SDK=SDK/N
              WRITE(5,11) (P(I),KT(I),KTC(I),DK(I),CP(I),RP(I),I=1,N)

              WRITE(5,15)SDK,LSF,FSF,FSC
      333     CONTINUE
      4       FORMAT(2X,'INPUT LS1,LS2')
      7       FORMAT(5X,'PRESSURE   KTOTAL')
      9       FORMAT(2X,'A=',E10.3)
      8       FORMAT(2X,2E10.4)
      10      FORMAT(6X,'PRESS    KEXP       KC ',12X,'DK(%)     %C      %R')
      11      FORMAT(2X,F10.3,2E10.4,F10.2,2F10.2)
      12      FORMAT(2X,'N2=1  HE=2  A=3')
      13      FORMAT(2X,'INPUT GAS TYPE,1=N2,2=HE,3=A,4=AIR')
      14      FORMAT(2X,'KS=',E10.4)
      15      FORMAT(2X,'AVERAGE ERROR=',E10.4,' LS=',E10.4,' FS=',E10.4,
            & ' FSC=',E10.4)
      200     FORMAT(2X,'GAS IS N2')
      201     FORMAT(2X,'GAS IS HE')
      202     FORMAT(2X,'GAS IS A')
      203     FORMAT(2X,'GAS IS AIR')
              END
```

INPUT FILE NUMBER 10

GAS IS N2

PRESSURE KTOTAL

A= 0.174E+00

PRESSURE	KEXP	KCALC	DK(%)
0.058	.1853E+00	.1975E+00	6.56
0.119	.1939E+00	.1988E+00	2.53
0.254	.1992E+00	.1996E+00	0.18
0.345	.2011E+00	.1997E+00	-0.68
0.652	.2039E+00	.2000E+00	-1.92
1.012	.2054E+00	.2001E+00	-2.59
2.016	.2070E+00	.2002E+00	-3.30

AVERAGE ERROR= .2537E+01 LS= .9300E+01 FS= .1945E-02 FSC= .7781E-01

INPUT FILE NUMBER 11

GAS IS HE

PRESSURE KTOTAL

A= 0.458E+00

PRESSURE	KEXP	KCALC	DK(%)
0.059	.5389E+00	.5940E+00	10.22
0.113	.5882E+00	.6002E+00	2.05
0.327	.6093E+00	.6051E+00	-0.70
0.644	.6217E+00	.6064E+00	-2.47
1.014	.6281E+00	.6069E+00	-3.38
2.017	.6336E+00	.6073E+00	-4.15

AVERAGE ERROR= .3827E+01 LS= .3250E+02 FS= .1945E-02 FSC= .7781E-01

INPUT FILE NUMBER 12

GAS IS N2

PRESSURE KTOTAL

A= 0.213E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.2004E+00	.2437E+00	21.61
0.102	.2377E+00	.2455E+00	3.28
0.178	.2397E+00	.2463E+00	2.74
0.402	.2487E+00	.2468E+00	-0.82
0.654	.2625E+00	.2470E+00	-5.90
1.047	.2661E+00	.2471E+00	-7.13
2.029	.2685E+00	.2472E+00	-7.93

AVERAGE ERROR= .6773E+01 LS= .1160E+02 FS= .1509E+00 FSC= .1237E+00

INPUT FILE NUMBER 13

GAS IS HE

PRESSURE KTOTAL

A= 0.704E+00

PRESSURE	KEXP	KCALC	DK(%)
0.087	.7282E+00	.8078E+00	2.34
0.333	.8303E+00	.8406E+00	1.23
0.654	.8582E+00	.8497E+00	-0.99
0.947	.8711E+00	.8534E+00	-2.25
1.995	.8901E+00	.8575E+00	-3.67
1.958	.8886E+00	.8574E+00	-3.51

AVERAGE ERROR= .2333E+01 LS= .3800E+01 FS= .4668E-01 FSC= .1237E+00

INPUT FILE NUMBER 14

GAS IS N2

PRESSURE KTOTAL

A= 0.227E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.2243E+00	.2523E+00	12.50
0.166	.2512E+00	.2567E+00	2.19
0.219	.2551E+00	.2571E+00	0.77
0.325	.2599E+00	.2578E+00	-0.81
0.668	.2674E+00	.2584E+00	-3.38
1.009	.2706E+00	.2586E+00	-4.45
2.004	.2743E+00	.2588E+00	-5.67

AVERAGE ERROR= .3968E+01 LS= .5300E+01 FS= .1999E+00 FSC= .1367E+00

INPUT FILE NUMBER 15

GAS IS HE

PRESSURE KTOTAL

A= 0.604E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.6473E+00	.7768E+00	20.01
0.073	.6959E+00	.7916E+00	13.76
0.119	.7575E+00	.8042E+00	5.51
0.168	.7989E+00	.8102E+00	-6.41
0.210	.8216E+00	.7510E+00	-9.51
0.334	.8590E+00	.7564E+00	-11.94
0.673	.9032E+00	.8234E+00	-9.66
1.023	.9227E+00	.8250E+00	-10.59
2.009	.9477E+00	.8265E+00	-12.79

AVERAGE ERROR= .1113E+02 LS= .1360E+02 FS= .2392E+00 FSC= .1367E+00

INPUT FILE NUMBER 16

GAS IS N2
PRESSURE KTOTAL
A= 0.238E+00

PRESSURE	KEXP	KCALC	DK(%)
0.057	.2389E+00	.2632E+00	10.15
0.073	.2448E+00	.2633E+00	7.57
0.097	.2528E+00	.2635E+00	4.24
0.264	.2697E+00	.2638E+00	-2.17
0.656	.2697E+00	.2640E+00	-2.13
1.003	.2833E+00	.2640E+00	-6.82
1.997	.2866E+00	.2640E+00	-7.88

AVERAGE ERROR= .5852E+01 LS= .3250E+02 FS= .4614E-02 FSC= .1846E+00

INPUT FILE NUMBER 17

GAS IS HE
PRESSURE KTOTAL
A= 0.751E+00

PRESSURE	KEXP	KCALC	DK(%)
0.060	.7083E+00	.7720E+00	8.99
0.101	.7724E+00	.7834E+00	1.42
0.208	.8647E+00	.8058E+00	-14.04
0.297	.8996E+00	.8191E+00	-8.95
0.336	.9092E+00	.8237E+00	-9.40
0.658	.9578E+00	.8498E+00	-11.28
1.004	.9807E+00	.8641E+00	-18.27
2.000	.1008E+01	.8824E+00	-12.46

AVERAGE ERROR= .1023E+02 LS= .5000E+00 FS= .4669E-01 FSC= .1849E+00

INPUT FILE NUMBER 18

GAS IS HE
PRESSURE KTOTAL
A= 0.716E+00

PRESSURE	KEXP	KCALC	DK(%)
0.054	.7024E+00	.8713E+00	24.04
0.103	.7845E+00	.8808E+00	12.27
0.211	.9087E+00	.9100E+00	-6.73
0.335	.9659E+00	.9136E+00	-5.41
0.669	.1029E+01	.9167E+00	-24.99
0.997	.1056E+01	.8976E+00	-16.40
1.997	.1093E+01	.8985E+00	-17.78

AVERAGE ERROR= .1480E+02 LS= .1980E+02 FS= .2106E+00 FSC= .1959E+00

INPUT FILE NUMBER 19

GAS IS N2

PRESSURE KTOTAL

A= 0.188E+00

PRESSURE	KEXP	KCALC	DK(%)
0.052	.2020E+00	.2100E+00	3.96
0.102	.2138E+00	.2132E+00	-0.29
0.214	.2237E+00	.2153E+00	-3.74
0.338	.2273E+00	.2161E+00	-4.91
0.659	.2317E+00	.2168E+00	-6.41
1.017	.2334E+00	.2171E+00	-6.98
2.004	.2354E+00	.2174E+00	-7.66

AVERAGE ERROR= .4850E+01 LS= .3700E+01 FS= .1403E+00 FSC= .1077E+00

INPUT FILE NUMBER 20

GAS IS HE

PRESSURE KTOTAL

A= 0.488E+00

PRESSURE	KEXP	KCALC	DK(%)
0.048	.5475E+00	.6229E+00	2.35
0.090	.5961E+00	.6290E+00	5.53
0.204	.6341E+00	.6353E+00	0.20
0.336	.6480E+00	.6370E+00	-1.65
0.658	.6638E+00	.6383E+00	-3.84
1.004	.6713E+00	.6388E+00	-4.85
1.996	.6809E+00	.6392E+00	-6.12

AVERAGE ERROR= .3505E+01 LS= .3240E+02 FS= .1481E-01 FSC= .1077E+00

INPUT FILE NUMBER 21

GAS IS N2

PRESSURE KTOTAL

A= 0.165E+00

PRESSURE	KEXP	KCALC	DK(%)
0.027	.1704E+00	.1893E+00	11.07
0.106	.1856E+00	.1906E+00	2.68
0.217	.1913E+00	.1908E+00	-0.25
0.338	.1946E+00	.1909E+00	-1.90
0.667	.1966E+00	.1910E+00	-2.86
1.000	.1976E+00	.1910E+00	-3.34
2.001	.1985E+00	.1910E+00	-3.76

AVERAGE ERROR= .3693E+01 LS= .3250E+02 FS= .1730E-02 FSC= .6920E-01

INPUT FILE NUMBER 22

GAS IS HE

PRESSURE KTOTAL

A= 0.377E+00

PRESSURE	KEXP	KCALC	DK(%)
0.056	.4797E+00	.5128E+00	6.91
0.078	.4946E+00	.5166E+00	4.45
0.212	.5221E+00	.5231E+00	0.20
0.336	.5316E+00	.5246E+00	-1.31
0.669	.5393E+00	.5259E+00	-2.48
1.011	.5427E+00	.5264E+00	-3.01
2.000	.5463E+00	.5268E+00	-3.57

AVERAGE ERROR= .3133E+01 LS= .3250E+02 FS= .1730E-02 FSC= .6920E-01

INPUT FILE NUMBER 23

GAS IS N2

PRESSURE KTOTAL

A= 0.146E+00

PRESSURE	KEXP	KCALC	DK(%)
0.089	.1653E+00	.1673E+00	1.24
0.140	.1670E+00	.1688E+00	1.09
0.286	.1703E+00	.1703E+00	0.02
0.662	.1722E+00	.1712E+00	-0.56
0.996	.1728E+00	.1715E+00	-0.77
2.009	.1733E+00	.1717E+00	-0.91

AVERAGE ERROR= .7644E+00 LS= .3400E+01 FS= .4242E-02 FSC= .1697E+00

INPUT FILE NUMBER 24

GAS IS HE

PRESSURE KTOTAL

A= 0.237E+00

PRESSURE	KEXP	KCALC	DK(%)
0.061	.3605E+00	.3736E+00	3.63
0.130	.3758E+00	.3804E+00	1.21
0.209	.3829E+00	.3828E+00	-0.03
0.270	.3846E+00	.3837E+00	-0.24
0.662	.3900E+00	.3856E+00	-1.13
1.001	.3916E+00	.3860E+00	-1.42
1.997	.3931E+00	.3865E+00	-1.68

AVERAGE ERROR= .1334E+01 LS= .3250E+02 FS= .4242E-02 FSC= .1697E+00

INPUT FILE NUMBER 25

GAS IS N2

PRESSURE KTOTAL

A= 0.244E+00

PRESSURE	KEXP	KCALC	DK(%)
0.051	.2397E+00	.2628E+00	9.63
0.106	.2582E+00	.2695E+00	4.36
0.210	.2718E+00	.2744E+00	0.95
0.335	.2809E+00	.2768E+00	-1.47
0.656	.2880E+00	.2790E+00	-3.12
1.000	.2916E+00	.2799E+00	-4.01
2.003	.2949E+00	.2808E+00	-4.78

AVERAGE ERROR= .4045E+01 LS= .1300E+01 FS= .3218E+00 FSC= .1959E+00

INPUT FILE NUMBER 26

GAS IS N2

PRESSURE KTOTAL

A= 0.231E+00

PRESSURE	KEXP	KCALC	DK(%)
0.203	.2458E+00	.2533E+00	3.06
0.330	.2563E+00	.2548E+00	-0.57
0.655	.2611E+00	.2562E+00	-1.87
1.014	.2652E+00	.2567E+00	-3.19
1.994	.2678E+00	.2572E+00	-3.94

AVERAGE ERROR= .2525E+01 LS= .1600E+01 FS= .2542E-01 FSC= .1849E+00

```
C       PMODC.FOR      11/88      DWY
C       A AND KRAD ARE THE PARAMETERS TO BE DETERMINED
        IMPLICIT REAL ( A-H,K-L,O-Z)
        DIMENSION KT(50),P(50),X(50),Z(50),KTC(50),DK(50)
        DIMENSION SIG(4),G1(4),G2(4)
        DIMENSION DK1(50),KTC2(50),DK2(50)
        DIMENSION  CP(50),RP(50)
        DATA SIG/3.75E-8,2.18E-8,3.64E-8,3.75E-8/,G1/4.3018E-3,
     &  5.6809E-2,2.7264E-3,5.4818E-3/,G2/7.2018E-5,3.0964E-4,
     &  4.9873E-5,6.9073E-5/
        DO 333  MM=10,26
        WRITE(5,884) MM
884     FORMAT(2X,/////,2X,'INPUT FILE NUMBER',I4,/)
        READ(MM,*) N,T,DS,W,FS,KS,JJ
        FSC=FS*((.5*DS)**3-(.5*DS-W)**3)/(.5*DS)**3
        FG=1-FS
C       WRITE(5,13)
C       READ(5,*) JJ
        IF ( JJ .EQ. 1 ) WRITE(5,200)
        IF ( JJ .EQ. 2 ) WRITE(5,201)
        IF ( JJ .EQ. 3 ) WRITE(5,202)
        IF ( JJ .EQ. 4 ) WRITE(5,203)
        DO 2 J=1,N
999     READ(MM,*) P(J),KT(J)
2       CONTINUE
        CLOSE(UNIT=MM)
C       WRITE(5,4)
C       READ(5,*) LS1,LS2
        KG0 = G1(JJ) + G2(JJ)*T
        PMAX=1.E5
        LSF =1.E5
        FSF =1.E5
        ABEST=1.E5
        DO 3 KK=1,325
        LS=0.01+.01*KK
        DO 3 KKK=1,200,5
        FS=FSC*(1.+(KKK-1.)/10.0)/200.0
        FG=1-FS
        PC=0.0
        S1=0.0
        DO 5 I = 1,N
        LG=3.065E-19*T/(SIG(JJ)**2*P(I))
        KG=KG0*LS/(LS+LG)
        X(I)=KT(I)-KS*KG/(FG*KS+FS*KG)
        S1 = S1 + X(I)
5       CONTINUE
```

```
      A=S1/N
      DO 6 I = 1,N
      KTC(I)=KS*KG/(FG*KS+FS*KG)+A
      DK(I)  = (KTC(I) - KT(I))**2
      PC=PC+(DK(I))
    6 CONTINUE
      IF ( PC .GT. PMAX ) GO TO 3
      PMAX=PC
      ABEST=A
      LSF=LS
      FSF=FS
      FGF=1-FSF
    3 CONTINUE
      WRITE(5,7)
C     WRITE(5,8) (P(I),KT(I), I=1,N)
      WRITE(5,9) ABEST
      WRITE(5,10)
      SDK=0.0
      SK1=0.0
      SK2=0.0
      SK3 = 0.0
      SK4 = 0.0
      DO 16 K=1,N
      LG=3.065E-19*T/(SIG(JJ)**2*P(K))
      KG=KG0*LSF/(LSF+LG)
      X(K)=KS*KG/(FGF*KS+FSF*KG)
      KTC(K)=X(K)+ABEST
      CP(K)=X(K)*100.0/KTC(K)
      RP(K)=ABEST*100.0/KTC(K)
      DK(K)=(KTC(K)-KT(K))*100.0/KT(K)
      DK1(K)=(KT(K)-KTC(K))
      SK1 = SK1+DK1(K)*SQRT(P(K))
      SK2 = SK2 + P(K)
      SK3 = SK3 + DK1(K)
      SK4=SK4 + SQRT(P(K))
      SDK=SDK+ABS(DK(K))
   16 CONTINUE
      SDK=SDK/N
      WRITE(5,11)(P(I),KT(I),KTC(I),DK(I),CP(I),RP(I),I=1,N)
```

```
          WRITE(5,15)SDK,LSF,FSF,FSC
          BP=(N*SK1-SK3*SK4)/(N*SK2-SK4**2)
          AP=SK3/N-BP*SK4/N
          SDK2=0.0
          DO 17 K=1,N
          KTC2(K)=KTC(K)+AP+BP*SQRT(P(K))
          DK2(K)=(KTC2(K)-KT(K))*100.0/KT(K)
          SDK2=SDK2+ABS(DK2(K))
17        CONTINUE
          SDK2=SDK2/N
          WRITE(5,20) (P(I),KT(I),KTC2(I),DK2(I),I=1,N)
          WRITE(5,18) SDK2,AP,BP
18        FORMAT(2X,'AVE ERR=',E10.4,' P COEFFS=',E10.4,E10.4)
333       CONTINUE
4         FORMAT(2X,'INPUT LS1,LS2')
7         FORMAT(5X,'PRESSURE   KTOTAL')
9         FORMAT(2X,'A=',E10.3)
8         FORMAT(2X,2E10.4)
10        FORMAT(6X,'PRESSURE KEXP       KCALC      DK(%)')
11        FORMAT(2X,F10.3,2E10.4,3F10.2)
12        FORMAT(2X,'N2=1  HE=2  A=3')
13        FORMAT(2X,'INPUT GAS TYPE,1=N2,2=HE,3=A,4=AIR')
14        FORMAT(2X,'KS=',E10.4)
15        FORMAT(2X,'AVERAGE ERROR=',E10.4,' LS=',E10.4,' FS=',E10.4,
     &    ' FSC=',E10.4)
20        FORMAT(2X,F10.3,2E10.4,F10.2)
200       FORMAT(2X,'GAS IS N2')
201       FORMAT(2X,'GAS IS HE')
202       FORMAT(2X,'GAS IS A')
203       FORMAT(2X,'GAS IS AIR')
          END
```

INPUT FILE NUMBER 10

GAS IS N2

PRESSURE KTOTAL

A= 0.176E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.058	.1853E+00	.1949E+00	5.19	9.88	90.12
0.119	.1939E+00	.1978E+00	2.03	11.21	88.79
0.254	.1992E+00	.1997E+00	0.24	12.03	87.97
0.345	.2011E+00	.2002E+00	-0.47	12.24	87.76
0.652	.2039E+00	.2008E+00	-1.52	12.52	87.48
1.012	.2054E+00	.2011E+00	-2.11	12.64	87.36
2.016	.2070E+00	.2013E+00	-2.74	12.75	87.25

AVERAGE ERROR= .2043E+01 LS= .3260E+01 FS= .3890E-03 FSC= .7781E-01

0.058	.1853E+00	.1897E+00	2.35
0.119	.1939E+00	.1938E+00	-0.07
0.254	.1992E+00	.1974E+00	-0.89
0.345	.2011E+00	.1989E+00	-1.12
0.652	.2039E+00	.2020E+00	-0.92
1.012	.2054E+00	.2046E+00	-0.41
2.016	.2070E+00	.2095E+00	1.22

AVE ERR= .9979E+00 P COEFFS=-.8009E-02 .1142E-01

INPUT FILE NUMBER 11

GAS IS HE

PRESSURE KTOTAL

A= 0.594E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.059	.5389E+00	.5947E+00	10.36	0.15	99.85
0.113	.5882E+00	.5955E+00	1.25	0.29	99.71
0.327	.6093E+00	.5987E+00	-1.74	0.82	99.18
0.644	.6217E+00	.6032E+00	-2.98	1.55	98.45
1.014	.6281E+00	.6080E+00	-3.20	2.34	97.66
2.017	.6336E+00	.6196E+00	-2.20	4.17	95.83

AVERAGE ERROR= .3621E+01 LS= .2000E-01 FS= .3890E-03 FSC= .7781E-01

0.059	.5389E+00	.5723E+00	6.19
0.113	.5882E+00	.5774E+00	-1.84
0.327	.6093E+00	.5914E+00	-2.93
0.644	.6217E+00	.6065E+00	-2.45
1.014	.6281E+00	.6208E+00	-1.17
2.017	.6336E+00	.6514E+00	2.81

AVE ERR= .2899E+01 P COEFFS=-.3363E-01 .4606E-01

INPUT FILE NUMBER 12

GAS IS N2

PRESSURE KTOTAL

A= 0.223E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.048	.2004E+00	.2411E+00	20.29	7.58	92.42
0.102	.2377E+00	.2444E+00	2.83	8.86	91.14
0.178	.2397E+00	.2461E+00	2.66	9.47	90.53
0.402	.2487E+00	.2475E+00	-0.50	9.98	90.02
0.654	.2625E+00	.2479E+00	-5.55	10.14	89.86
1.047	.2661E+00	.2482E+00	-6.72	10.25	89.75
2.029	.2685E+00	.2484E+00	-7.47	10.33	89.67

AVERAGE ERROR= .6575E+01 LS= .3260E+01 FS= .6183E-03 FSC= .1237E+00

0.048	.2004E+00	.2213E+00	10.45
0.102	.2377E+00	.2289E+00	-3.70
0.178	.2397E+00	.2348E+00	-2.05
0.402	.2487E+00	.2450E+00	-1.48
0.654	.2625E+00	.2527E+00	-3.72
1.047	.2661E+00	.2619E+00	-1.56
2.029	.2685E+00	.2789E+00	3.86

AVE ERR= .3832E+01 P COEFFS=-.2883E-01 .4160E-01

INPUT FILE NUMBER 13

GAS IS HE

PRESSURE KTOTAL

A= 0.831E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.087	.7282E+00	.8324E+00	14.31	0.16	99.84
0.333	.8303E+00	.8361E+00	0.69	0.60	99.40
0.654	.8582E+00	.8406E+00	-2.05	1.13	98.87
0.947	.8711E+00	.8444E+00	-3.06	1.58	98.42
1.995	.8901E+00	.8567E+00	-3.75	2.99	97.01
1.958	.8886E+00	.8563E+00	-3.63	2.94	97.06

AVERAGE ERROR= .4585E+01 LS= .2000E-01 FS= .6183E-03 FSC= .1237E+00

0.087	.7282E+00	.7715E+00	5.94
0.333	.8303E+00	.8030E+00	-3.29
0.654	.8582E+00	.8305E+00	-3.23
0.947	.8711E+00	.8506E+00	-2.35
1.995	.8901E+00	.9063E+00	1.82
1.958	.8886E+00	.9046E+00	1.80

AVE ERR= .3073E+01 P COEFFS=-.9016E-01 .9898E-01

```
INPUT FILE NUMBER  14

GAS IS N2
     PRESSURE   KTOTAL
A= 0.234E+00
        PRESSURE KEXP       KCALC     DK(%)
          0.048 .2243E+00 .2521E+00    12.41        7.25       92.75
          0.166 .2512E+00 .2570E+00     2.30        9.00       91.00
          0.219 .2551E+00 .2576E+00     0.98        9.22       90.78
          0.325 .2599E+00 .2583E+00    -0.63        9.45       90.55
          0.668 .2674E+00 .2590E+00    -3.13        9.72       90.28
          1.009 .2706E+00 .2593E+00    -4.19        9.80       90.20
          2.004 .2743E+00 .2595E+00    -5.39        9.89       90.11
AVERAGE ERROR= .4147E+01 LS= .3260E+01 FS= .6833E-03 FSC= .1367E+00
          0.048 .2243E+00 .2376E+00     5.92
          0.166 .2512E+00 .2481E+00    -1.23
          0.219 .2551E+00 .2506E+00    -1.78
          0.325 .2599E+00 .2543E+00    -2.14
          0.668 .2674E+00 .2626E+00    -1.81
          1.009 .2706E+00 .2685E+00    -0.78
          2.004 .2743E+00 .2812E+00     2.51
AVE ERR= .2309E+01 P COEFFS=-.2120E-01 .3027E-01


INPUT FILE NUMBER  15

GAS IS HE
     PRESSURE   KTOTAL
A= 0.810E+00
        PRESSURE KEXP       KCALC     DK(%)
          0.048 .6473E+00 .8107E+00    25.24        0.09       99.91
          0.073 .6959E+00 .8111E+00    16.55        0.14       99.86
          0.119 .7575E+00 .8118E+00     7.16        0.22       99.78
          0.168 .7989E+00 .8125E+00     1.70        0.31       99.69
          0.210 .8216E+00 .8131E+00    -1.03        0.39       99.61
          0.334 .8590E+00 .8149E+00    -5.13        0.61       99.39
          0.673 .9032E+00 .8197E+00    -9.25        1.19       98.81
          1.023 .9227E+00 .8243E+00   -10.67        1.74       98.26
          2.009 .9477E+00 .8357E+00   -11.82        3.08       96.92
AVERAGE ERROR= .9839E+01 LS= .2000E-01 FS= .6833E-03 FSC= .1367E+00
          0.048 .6473E+00 .7276E+00    12.40
          0.073 .6959E+00 .7387E+00     6.15
          0.119 .7575E+00 .7551E+00    -0.32
          0.168 .7989E+00 .7695E+00    -3.68
          0.210 .8216E+00 .7803E+00    -5.03
          0.334 .8590E+00 .8073E+00    -6.02
          0.673 .9032E+00 .8630E+00    -4.45
          1.023 .9227E+00 .9078E+00    -1.62
          2.009 .9477E+00 .1005E+01     6.00
AVE ERR= .5073E+01 P COEFFS=-.1292E+00 .2103E+00
```

INPUT FILE NUMBER 16

GAS IS N2

PRESSURE KTOTAL

A= 0.241E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.057	.2389E+00	.2598E+00	8.75	7.38	92.62
0.073	.2448E+00	.2610E+00	6.61	7.79	92.21
0.097	.2528E+00	.2621E+00	3.69	8.20	91.80
0.264	.2697E+00	.2647E+00	-1.84	9.10	90.90
0.656	.2697E+00	.2658E+00	-1.45	9.47	90.53
1.003	.2833E+00	.2661E+00	-6.09	9.56	90.44
1.997	.2866E+00	.2663E+00	-7.08	9.64	90.36

AVERAGE ERROR= .5072E+01 LS= .3260E+01 FS= .9229E-03 FSC= .1846E+00

0.057	.2389E+00	.2460E+00	2.98
0.073	.2448E+00	.2482E+00	1.40
0.097	.2528E+00	.2508E+00	-0.81
0.264	.2697E+00	.2601E+00	-3.55
0.656	.2697E+00	.2711E+00	0.52
1.003	.2833E+00	.2778E+00	-1.95
1.997	.2866E+00	.2918E+00	1.81

AVE ERR= .1860E+01 P COEFFS=-.2178E-01 .3344E-01

INPUT FILE NUMBER 17

GAS IS HE

PRESSURE KTOTAL

A= 0.880E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.060	.7083E+00	.8805E+00	24.31	0.10	99.90
0.101	.7724E+00	.8811E+00	14.07	0.18	99.82
0.208	.8647E+00	.8827E+00	2.08	0.36	99.64
0.297	.8996E+00	.8840E+00	-1.73	0.50	99.50
0.336	.9092E+00	.8846E+00	-2.71	0.57	99.43
0.658	.9578E+00	.8891E+00	-7.18	1.07	98.93
1.004	.9807E+00	.8936E+00	-8.88	1.58	98.42
2.000	.1008E+01	.9052E+00	-10.20	2.84	97.16

AVERAGE ERROR= .8894E+01 LS= .2000E-01 FS= .9229E-03 FSC= .1846E+00

0.060	.7083E+00	.7893E+00	11.44
0.101	.7724E+00	.8055E+00	4.29
0.208	.8647E+00	.8367E+00	-3.24
0.297	.8996E+00	.8570E+00	-4.74
0.336	.9092E+00	.8650E+00	-4.87
0.658	.9578E+00	.9190E+00	-4.05
1.004	.9807E+00	.9643E+00	-1.67
2.000	.1008E+01	.1064E+01	5.56

AVE ERR= .4981E+01 P COEFFS=-.1435E+00 .2138E+00

INPUT FILE NUMBER 18

GAS IS HE

PRESSURE KTOTAL

A= 0.926E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.054	.7024E+00	.9264E+00	31.89	0.09	99.91
0.103	.7845E+00	.9271E+00	18.18	0.17	99.83
0.211	.9087E+00	.9288E+00	2.21	0.34	99.66
0.335	.9659E+00	.9306E+00	-3.66	0.54	99.46
0.669	.1029E+01	.9353E+00	-9.09	1.04	98.96
0.997	.1056E+01	.9396E+00	-11.00	1.49	98.51
1.997	.1093E+01	.9512E+00	-12.97	2.70	97.30

AVERAGE ERROR= .1271E+02 LS= .2000E-01 FS= .9796E-03 FSC= .1959E+00

0.054	.7024E+00	.7928E+00	12.87
0.103	.7845E+00	.8195E+00	4.46
0.211	.9087E+00	.8616E+00	-5.18
0.335	.9659E+00	.8984E+00	-6.99
0.669	.1029E+01	.9731E+00	-5.42
0.997	.1056E+01	.1030E+01	-2.41
1.997	.1093E+01	.1163E+01	6.44

AVE ERR= .6252E+01 P COEFFS=-.2016E+00 .2927E+00

INPUT FILE NUMBER 19

GAS IS N2

PRESSURE KTOTAL

A= 0.200E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.052	.2020E+00	.2191E+00	8.45	8.54	91.46
0.102	.2138E+00	.2220E+00	3.85	9.76	90.24
0.214	.2237E+00	.2241E+00	0.16	10.58	89.42
0.338	.2273E+00	.2248E+00	-1.09	10.88	89.12
0.659	.2317E+00	.2255E+00	-2.67	11.15	88.85
1.017	.2334E+00	.2258E+00	-3.26	11.26	88.74
2.004	.2354E+00	.2260E+00	-3.98	11.35	88.65

AVERAGE ERROR= .3351E+01 LS= .3260E+01 FS= .5385E-03 FSC= .1077E+00

0.052	.2020E+00	.2100E+00	3.97
0.102	.2138E+00	.2148E+00	0.45
0.214	.2237E+00	.2196E+00	-1.83
0.338	.2273E+00	.2227E+00	-2.02
0.659	.2317E+00	.2279E+00	-1.63
1.017	.2334E+00	.2320E+00	-0.59
2.004	.2354E+00	.2403E+00	2.07

AVE ERR= .1793E+01 P COEFFS=-.1352E-01 .1961E-01

```
INPUT FILE NUMBER  20

GAS IS HE
    PRESSURE    KTOTAL
A= 0.626E+00
     PRESSURE KEXP       KCALC      DK(%)
       0.048 .5475E+00 .6268E+00     14.48       0.12       99.88
       0.090 .5961E+00 .6274E+00      5.25       0.22       99.78
       0.204 .6341E+00 .6291E+00     -0.78       0.49       99.51
       0.336 .6480E+00 .6311E+00     -2.61       0.80       99.20
       0.658 .6638E+00 .6356E+00     -4.25       1.50       98.50
       1.004 .6713E+00 .6401E+00     -4.65       2.20       97.80
       1.996 .6809E+00 .6516E+00     -4.30       3.93       96.07
AVERAGE ERROR= .5189E+01 LS= .2000E-01 FS= .5385E-03 FSC= .1077E+00
       0.048 .5475E+00 .5920E+00      8.13
       0.090 .5961E+00 .5987E+00      0.44
       0.204 .6341E+00 .6118E+00     -3.51
       0.336 .6480E+00 .6234E+00     -3.80
       0.658 .6638E+00 .6452E+00     -2.80
       1.004 .6713E+00 .6641E+00     -1.07
       1.996 .6809E+00 .7064E+00      3.75
AVE ERR= .3359E+01 P COEFFS=-.5118E-01 .7501E-01


INPUT FILE NUMBER  21

GAS IS N2
    PRESSURE    KTOTAL
A= 0.168E+00
     PRESSURE KEXP       KCALC      DK(%)
       0.027 .1704E+00 .1825E+00      7.11       8.15       91.85
       0.106 .1856E+00 .1894E+00      2.07      11.50       88.50
       0.217 .1913E+00 .1914E+00      0.04      12.40       87.60
       0.338 .1946E+00 .1921E+00     -1.28      12.73       87.27
       0.667 .1966E+00 .1928E+00     -1.93      13.05       86.95
       1.000 .1976E+00 .1931E+00     -2.30      13.16       86.84
       2.001 .1985E+00 .1933E+00     -2.62      13.27       86.73
AVERAGE ERROR= .2477E+01 LS= .3260E+01 FS= .3460E-03 FSC= .6920E-01
       0.027 .1704E+00 .1764E+00      3.50
       0.106 .1856E+00 .1852E+00     -0.21
       0.217 .1913E+00 .1888E+00     -1.30
       0.338 .1946E+00 .1909E+00     -1.89
       0.667 .1966E+00 .1944E+00     -1.11
       1.000 .1976E+00 .1968E+00     -0.38
       2.001 .1985E+00 .2020E+00      1.77
AVE ERR= .1453E+01 P COEFFS=-.8097E-02 .1189E-01
```

INPUT FILE NUMBER 22

GAS IS HE

PRESSURE KTOTAL

A= 0.514E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.056	.4797E+00	.5146E+00	7.29	0.17	99.83
0.078	.4946E+00	.5150E+00	4.12	0.23	99.77
0.212	.5221E+00	.5170E+00	-0.98	0.62	99.38
0.336	.5316E+00	.5188E+00	-2.41	0.97	99.03
0.669	.5393E+00	.5235E+00	-2.94	1.85	98.15
1.011	.5427E+00	.5280E+00	-2.72	2.68	97.32
2.000	.5463E+00	.5394E+00	-1.26	4.76	95.24

AVERAGE ERROR= .3100E+01 LS= .2000E-01 FS= .3460E-03 FSC= .6920E-01

0.056	.4797E+00	.5008E+00	4.40
0.078	.4946E+00	.5025E+00	1.59
0.212	.5221E+00	.5101E+00	-2.30
0.336	.5316E+00	.5156E+00	-3.02
0.669	.5393E+00	.5276E+00	-2.17
1.011	.5427E+00	.5378E+00	-0.90
2.000	.5463E+00	.5619E+00	2.86

AVE ERR= .2464E+01 P COEFFS=-.2111E-01 .3083E-01

INPUT FILE NUMBER 23

GAS IS N2

PRESSURE KTOTAL

A= 0.146E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.089	.1653E+00	.1673E+00	1.18	12.65	87.35
0.140	.1670E+00	.1688E+00	1.06	13.44	86.56
0.286	.1703E+00	.1703E+00	0.01	14.23	85.77
0.662	.1722E+00	.1713E+00	-0.54	14.69	85.31
0.996	.1728E+00	.1715E+00	-0.74	14.82	85.18
2.009	.1733E+00	.1718E+00	-0.88	14.95	85.05

AVERAGE ERROR= .7391E+00 LS= .3260E+01 FS= .8484E-03 FSC= .1697E+00

0.089	.1653E+00	.1658E+00	0.31
0.140	.1670E+00	.1676E+00	0.35
0.286	.1703E+00	.1697E+00	-0.38
0.662	.1722E+00	.1715E+00	-0.40
0.996	.1728E+00	.1724E+00	-0.25
2.009	.1733E+00	.1740E+00	0.40

AVE ERR= .3483E+00 P COEFFS=-.2425E-02 .3279E-02

INPUT FILE NUMBER 24

GAS IS HE

PRESSURE KTOTAL

A= 0.374E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.061	.3605E+00	.3751E+00	4.05	0.25	99.75
0.130	.3758E+00	.3761E+00	0.09	0.53	99.47
0.209	.3829E+00	.3773E+00	-1.46	0.84	99.16
0.270	.3846E+00	.3782E+00	-1.66	1.08	98.92
0.662	.3900E+00	.3837E+00	-1.60	2.50	97.50
1.001	.3916E+00	.3882E+00	-0.87	3.62	96.38
1.997	.3931E+00	.3998E+00	1.70	6.41	93.59

AVERAGE ERROR= .1632E+01 LS= .2000E-01 FS= .8484E-03 FSC= .1697E+00

0.061	.3605E+00	.3746E+00	3.91
0.130	.3758E+00	.3758E+00	-0.01
0.209	.3829E+00	.3771E+00	-1.53
0.270	.3846E+00	.3780E+00	-1.71
0.662	.3900E+00	.3839E+00	-1.57
1.001	.3916E+00	.3886E+00	-0.78
1.997	.3931E+00	.4006E+00	1.91

AVE ERR= .1630E+01 P COEFFS=-.7938E-03 .1155E-02

INPUT FILE NUMBER 25

GAS IS N2

PRESSURE KTOTAL

A= 0.251E+00

PRESSURE	KEXP	KCALC	DK(%)		
0.051	.2397E+00	.2701E+00	12.67	6.89	93.11
0.106	.2582E+00	.2733E+00	5.84	7.98	92.02
0.210	.2718E+00	.2751E+00	1.23	8.60	91.40
0.335	.2809E+00	.2759E+00	-1.77	8.87	91.13
0.656	.2880E+00	.2766E+00	-3.95	9.10	90.90
1.000	.2916E+00	.2769E+00	-5.04	9.18	90.82
2.003	.2949E+00	.2771E+00	-6.02	9.26	90.74

AVERAGE ERROR= .5217E+01 LS= .3260E+01 FS= .9796E-03 FSC= .1959E+00

0.051	.2397E+00	.2531E+00	5.59
0.106	.2582E+00	.2600E+00	0.68
0.210	.2718E+00	.2667E+00	-1.87
0.335	.2809E+00	.2719E+00	-3.19
0.656	.2880E+00	.2811E+00	-2.39
1.000	.2916E+00	.2884E+00	-1.11
2.003	.2949E+00	.3039E+00	3.05

AVE ERR= .2555E+01 P COEFFS=-.2527E-01 .3675E-01

```
INPUT FILE NUMBER  26

GAS IS N2
   PRESSURE   KTOTAL
A= 0.234E+00
    PRESSURE KEXP       KCALC       DK(%)
     0.203 .2458E+00 .2580E+00       4.95        9.15       90.85
     0.330 .2563E+00 .2588E+00       0.98        9.44       90.56
     0.655 .2611E+00 .2595E+00      -0.60        9.69       90.31
     1.014 .2652E+00 .2598E+00      -2.03        9.79       90.21
     1.994 .2678E+00 .2601E+00      -2.89        9.87       90.13
AVERAGE ERROR= .2293E+01 LS= .3260E+01 FS= .9229E-03 FSC= .1846E+00
     0.203 .2458E+00 .2506E+00       1.94
     0.330 .2563E+00 .2537E+00      -1.01
     0.655 .2611E+00 .2588E+00      -0.89
     1.014 .2652E+00 .2627E+00      -0.94
     1.994 .2678E+00 .2704E+00       0.99
AVE ERR= .1155E+01 P COEFFS=-.1575E-01 .1852E-01
```

APPENDIX D

FORTRAN PROGRAMS FOR THE ANALYSIS OF HOLLOW SPHERE THERMAL CONDUCTIVITY DATA USING THE GEOMETRIC MODEL

```
.TYPE DYPOW3.FOR
C        THERMAL CONDUCTIVITY OF MONO SIZE MICROSPHERE
C        POWDER.  MOORE 1981  .TAKEN FROM APPENDIX G
C        OF ORNL/TM-8196 AND MODIFIED BY D.W.YARBROUGH
C        JAN 87
C        UNITS: THERMAL CONDUCTIVITY IN W/MK
C               PRESSURE             IN ATMOS
C               PARTICLE DIAMETER    IN MICRO-METERS
C        DATA:  V = 13.54E-6  FOR HE
C                   43.0E-6   FOR AR
C                   21.9E-6 FOR N2
C               C2= 0.970  FOR HE
C                   0.077  FOR AR
C                   0.150  FOR N2
         IMPLICIT REAL*8 (A-H,O-Z)
         REAL*8 KFR
         DIMENSION VA(3),C2A(3)
         DATA VA/13.54E-6,43.0E-6,21.9E-6/,C2A/.97,.077,.15/
999      CONTINUE
         WRITE(5,100)
100      FORMAT(2X,'INPUT PARTICLE DIA.,SHELL THICK, AND EMITTANCE')
         READ(5,*) RP,ST,E1
         WRITE(5,106) RP
106      FORMAT(2X,' PARTICLE DIAMETER IN MICRO-METERS',F10.2)
         RP = RP*.5
         N = 0.34*SQRT(2.0*RP)
         WRITE(5,101) N
101      FORMAT(2X,'NUMBER OF INTERVALS WITH SMALL GAPS',I4)
         WRITE(5,102)
102      FORMAT(2X,'INPUT 1=HE 2=AR 3=N2  AND PRESSURE')
         READ(5,*) JG,PR
         V = VA(JG)
         C2=C2A(JG)
         WRITE(5,103)
103      FORMAT(2X,'INPUT TEMP,K SOLID, K GAS')
         READ(5,*)X,SC,BGC
         SC = SC+ 22.68E-10*E1*.7854*(RP-ST)*X**3
888      CONTINUE
         A =  0.1
         AF = 1.0
         WRITE(5,110)
110      FORMAT(2X,///)
         WRITE(5,111)
111      FORMAT(2X,'PARAMETERS FOR THIS TABLE')
         IF ( JG.EQ.1) WRITE(5,120)
         IF ( JG.EQ.2) WRITE(5,121)
         IF ( JG.EQ.3) WRITE(5,122)
120      FORMAT(2X,'GAS IS HELIUM  ')
121      FORMAT(2X,'GAS IS ARGON   ')
122      FORMAT(2X,'GAS IS NITROGEN')
```

```
      WRITE(5,112) RP,E1
112   FORMAT(2X,'PART. RADIUS = ',F10.2,' EMITTANCE = ',F10.2)
      WRITE(5,113) V,C2,PR
113   FORMAT(2X,'V = ',E12.3,' C2 = ',E12.3,' PRESSURE =',F10.2)
      WRITE(5,114) X,SC,BGC
114   FORMAT(2X,'TEMP =',F10.1,' K SOLID =',F10.4,' K GAS =',F10.4)
      WRITE(5,110)
      WRITE(5,109)
109   FORMAT(4X,'ACCOM.',4X,'COND.',7X,'COND.(NR)',5X,'RAD FR',/)
222   CONTINUE
      G = (V*((2.-A)/A)*BGC*(SQRT(X)))/PR
      W = 1*0.0001
      R = RP*0.0001
      C = 0.0
      TH = 0.0
      THNR = 0.0
      DO 3 I =1,RP
      Y = C+W
      C = Y
      H = Y-W
      KFR = (C**2-H**2)/R**2
      D   = 2.*(R-SQRT(ABS(R**2-Y**2)))
      GFR =  0.5*D/R
      SFR = 1.0 - GFR
      IF (I-N) 382,382,384
382   GC = ((C2*(A/(2.0-A))*PR)/(SQRT(X)))+22.68E-10*E1*D*X**3
      GCNR = ((C2*(A/(2.0-A))*PR)/(SQRT(X)))
      GO TO 385
384   HC = BGC/(1.0+(2.0*G)/D)
      GC = BGC/(1.0+(2.*G)/D)+22.68E-10*E1*D*X**3
      GCNR = BGC/(1.0+(2.0*G)/D)
385   CC = (GC*SC)/(SC*GFR+GC*SFR)
      CCNR = (GCNR*SC)/(SC*GFR+GCNR*SFR)
      ETCNR = CCNR*KFR
      ETCNR = ETCNR+THNR
      THNR = ETCNR
      ETC = CC*KFR
      ETC = ETC+TH
      TH = ETC
3     CONTINUE
      P = TH*0.907+0.093*(HC+22.68E-10*2.0*E1*R*X**3)
      PNR = THNR*.907+.093*HC
      FRAD = 1.0- PNR/P
      WRITE(5,105) A,P,PNR,FRAD
105   FORMAT(2X,E10.3,E12.5,E12.5,F10.3)
      A = A+0.1
      IF ( A.LE.(AF+0.01)) GO TO 222
      WRITE(5,110)
      WRITE(5,110)
      WRITE(5,107)
```

```
107     FORMAT(2X,'IF NEW DATA SET TYPE 1, TYPE 0 IF NO')
        READ(5,*) JJ
        IF ( JJ .EQ. 1 ) GO TO 999
        WRITE(5,108)
108     FORMAT(2X,' INPUT NEW PRESSURE ')
        READ(5,*) PR
        GO TO 888
        END
```

```
.TYPE DYPOW4.FOR
C         THERMAL CONDUCTIVITY OF MONO SIZE MICROSPHERE
C         POWDER.  MOORE 1981  .TAKEN FROM APPENDIX G
C         OF ORNL/TM-8196 AND MODIFIED BY D.W.YARBROUGH
C         JAN 87
C         UNITS: THERMAL CONDUCTIVITY IN W/MK
C                PRESSURE              IN ATMOS
C                PARTICLE DIAMETER     IN MICRO-METERS
C         DATA:  V = 13.54E-6   FOR HE
C                    43.0E-6    FOR AR
C                    21.9E-6 FOR N2
C                C2= 0.970  FOR HE
C                    0.077  FOR AR
C                    0.150  FOR N2
          REAL KFR
          DIMENSION PRESS(5),PRESI(5)
          COMMON VA(3),C2A(3),T1,T2,GI,SC1,SC2,BGCI,E1I,X
          DATA VA/13.54E-6,43.0E-6,21.9E-6/,C2A/.97,.077,.15/
          DATA PRESS/0.1,0.5,1.0,5.0,10.0/
          DATA PRESI/0.1,0.5,1.0,5.0,10.0/
 999      CONTINUE
          WRITE(5,100)
 100      FORMAT(2X,'INPUT DIA(MICR) , OUT. EMIT.,INNER EMIT')
          READ(5,*) RP,E1,E1I
          WRITE(5,115)
 115      FORMAT(2X,'INPUT OUTER LAYER, IN. LAYER(MICRONS)')
          READ(5,*) T1,T2
C         WRITE(5,106) RP
 106      FORMAT(2X,' PARTICLE DIAMETER IN MICRO-METERS',F10.2)
          RP = RP*.5
          N = 0.34*SQRT(2.0*RP)
C         WRITE(5,101) N
 101      FORMAT(2X,'NUMBER OF INTERVALS WITH SMALL GAPS',I4)
          WRITE(5,102)
 102      FORMAT(2X,'INPUT 1=HE 2=AR 3=N2 FOR OUTER GAS  ')
          READ(5,*) JG
          V = VA(JG)
          WRITE(5,116)
 116      FORMAT(2X,'INPUT INTERIOR GAS TYPE ')
          READ(5,*) JGI
          VI = VA(JGI)
          C2I = C2A(JGI)
          C2=C2A(JG)
          WRITE(5,103)
 103      FORMAT(2X,'INPUT TEMP,K SOLID ONE, K SOLID TWO')
          READ(5,*)X,SC1,SC2
          WRITE(5,117)
 117      FORMAT(2X,'INPUT K OUTER GAS, K INNER GAS')
          READ(5,*) BGC.BGCI
 888      CONTINUE
          DO 890 JPR = 1,5
          DO 889 JPRI= 1,5
```

```
          PR = PRESS(JPR)
          PRI= PRESI(JPRI)
          A =  0.1
          AF = 1.0
          WRITE(5,110)
110       FORMAT(2X,///)
          WRITE(5,111)
111       FORMAT(2X,'PARAMETERS FOR THIS TABLE',/)
          IF ( JG.EQ.1) WRITE(5,120)
          IF ( JG.EQ.2) WRITE(5,121)
          IF ( JG.EQ.3) WRITE(5,122)
          IF (JGI.EQ.1 ) WRITE(5,123)
          IF (JGI.EQ.2 ) WRITE(5,124)
          IF (JGI.EQ.3 ) WRITE(5,125)
120       FORMAT(2X,'OUTER GAS IS HELIUM ')
121       FORMAT(2X,'OUTER GAS IS ARGON  ')
122       FORMAT(2X,'OUTER GAS IS NITROGEN')
123       FORMAT(2X,'INNER GAS IS HELIUM')
124       FORMAT(2X,'INNER GAS IN ARGON')
125       FORMAT(2X,'INNER GAS IS NITROGEN')
          WRITE(5,112) RP,E1,E1I
112       FORMAT(2X,'RADIUS=',F7.1,'  OUT E=',F4.1,' IN E=',F4.1)
          WRITE(5,126) T1,T2
126       FORMAT(2X,'T1(OUT)=',F7.1,'     T2(IN)=',F7.1)
          WRITE(5,113) PR,PRI
113       FORMAT(2X,'OUTER PRESS=';F7.2,'    INNER PRESS=',F7.2)
          WRITE(5,114) X,SC1,SC2
114       FORMAT(2X,'T=',F7.1,'    K S1=',F7.2,'      K S2=',F7.2)
          WRITE(5,127) BGC,BGCI
127       FORMAT(2X,'K OUTER GAS= 'F8.4,'    K INNER GAS=',F8.4)
          WRITE(5,110)
          WRITE(5,109)
109       FORMAT(4X,'ACCOM.',4X,'COND.',7X,'COND.(NR)',5X,'RAD FR',/)
222       CONTINUE
          G = (V*((2.-A)/A)*BGC*(SQRT(X)))/PR
          GI = (VI*((2.-A)/A)*BGCI*(SQRT(X)))/PRI
          W = 1*0.0001
          R = RP*0.0001
          C = 0.0
          TH = 0.0
          THNR = 0.0
          DO 3 I =1,NN
          Y = C+W
          C = Y
          H = Y-W
          KFR = (C**2-H**2)/R**2
          D   = 2.*(R-SQRT(ABS(R**2-Y**2)))
          GFR =  0.5*D/R
          SFR = 1.0 - GFR
          IF (I-N) 382,382,384
382       GC = ((C2*(A/(2.0-A))*PR)/(SQRT(X)))+22.68E-10*E1*D*X**3
          GCNR = ((C2*(A/(2.0-A))*PR)/(SQRT(X)))
          GO TO 385
```

```
384     HC = BGC/(1.Ø+(2.Ø*G)/D)
        GC = BGC/(1.Ø+(2.*G)/D)+22.68E-1Ø*E1*D*X**3
        GCNR = BGC/(1.Ø+(2.Ø*G)/D)
        CALL SOLID(RP,D,SC,SCNR)
385     CC = (GC*SC)/(SC*GFR+GC*SFR)
        CCNR = (GCNR*SCNR)/(SCNR*GFR+GCNR*SFR)
        ETCNR = CCNR*KFR
        ETCNR = ETCNR+THNR
        THNR = ETCNR
        ETC = CC*KFR
        ETC = ETC+TH
        TH = ETC
3       CONTINUE
        P = TH*Ø.9Ø7+Ø.Ø93*(HC+22.68E-1Ø*2.Ø*E1*R*X**3)
        PNR = THNR*.9Ø7+.Ø93*HC
        FRAD = 1.Ø- PNR/P
        WRITE(5,1Ø5) A,P,PNR,FRAD
1Ø5     FORMAT(2X,E1Ø.3,E12.5,E12.5,F1Ø.3)
        A = A+Ø.1
        IF ( A.LE.(AF+Ø.Ø1)) GO TO 222
        WRITE(5,11Ø)
        WRITE(5,11Ø)
889     CONTINUE
89Ø     CONTINUE
        WRITE(5,1Ø7)
1Ø7     FORMAT(2X,'IF NEW DATA SET TYPE 1, TYPE Ø IF NO')
        READ(5,*) JJ
        IF ( JJ .EQ. 1 ) GO TO 999
        WRITE(5,1Ø8)
1Ø8     FORMAT(2X,' INPUT NEW OUT EMIT & INNER EMIT ')
        READ(5,*) E1,E1I
        GO TO 888
        END
```

```
      SUBROUTINE SOLID(RP,D,SC,SCNR)
      COMMON VA(3),C2A(3),T1,T2,GI,SC1,SC2,BGCI,E1I,X
      RI = RP-D*5000.   - T1 - T2
      IF ( RI .EQ. 0.0 ) GO TO 40
      IF ( RI .GT. -T1 .AND. RI .LT. -(T1+T2)) GO TO 50
      IF ( RI .LE. -T1 ) GO TO 60
      GCI = BGCI/(1.0+(GI)/RI)+4.536E-13*E1I*RI*X**3
      RGCI = RI/GCI
      GCINR = BGCI/(1.+(GI)/RI)
      RS = T1/SC1 + T2/SC2
      RGCINR = RI/GCINR
      RT = RGCI + RS
      RTNR = RGCINR + RS
      SC = (RP-D)/RT
      SCNR = (RP-D)/RTNR
      RETURN
40    RS = T1/SC1 + T2/SC2
      SC = (T1+T2)/RS
      SCNR = SC
      RETURN
50    RES1 = T1/SC1
      RES2 = (T2+RI)/SC2
      SC   = (T1+T2+RI)/(RES1+RES2)
      SCNR = SC
      RETURN
60    SC = SC1
      SCNR = SC1
      RETURN
      END
```

Table D-1A. DYPOW3 output for k_a of 40.0-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.026	0.1	0.2008 E-1
				0.5	0.6192 E-1
				1.0	0.9677 E-1
	0.5	36.0	0.026	0.1	0.5511 E-1
				0.5	0.1137 E-1
				1.0	0.1496 E-1
	1.0	36.0	0.026	0.1	0.7591 E-1
				0.5	0.1365 E-1
				1.0	0.1731 E-1
500.0	0.1	20.2	0.0386	0.1	0.1868 E-1
				0.5	0.6607 E-1
				1.0	0.1125 E-1
	0.5	20.2	0.0386	0.1	0.5763 E-1
				0.5	0.1367 E-1
				1.0	0.1887 E-1
	1.0	20.2	0.0386	0.1	0.8413 E-1
				0.5	0.1698
				1.0	0.2197
700.0	0.1	12.6	0.0493	0.1	0.1884 E-1
				0.5	0.6762 E-1
				1.0	0.1209
	0.5	12.6	0.0493	0.1	0.5842 E-1
				0.5	0.1500
				1.0	0.2143
	1.0	12.6	0.0493	0.1	0.8785 E-1
				0.5	0.1908
				1.0	0.2520
900.0	0.1	8.9	0.0587	0.1	0.2093 E-1
				0.5	0.6951 E-1
				1.0	0.1270
	0.5	8.9	0.0587	0.1	0.5998 E-1
				0.5	0.1595
				1.0	0.2331
	1.0	8.9	0.0587	0.1	0.9091 E-1
				0.5	0.2061
				1.0	0.2762

Table D-1B. DYPOW3 output for k_a of 40.0-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.4099 E-1
				0.5	0.1797
				1.0	0.3469
	0.5	36.0	0.160	0.1	0.1524
				0.5	0.4442
				1.0	0.6766
	1.0	36.0	0.160	0.1	0.2414
				0.5	0.5889
				1.0	0.8236
500.0	0.1	20.2	0.220	0.1	0.3410 E-1
				0.5	0.1634
				1.0	0.3430
	0.5	20.2	0.220	0.1	0.1362
				0.5	0.4546
				1.0	0.7301
	1.0	20.2	0.220	0.1	0.2273
				0.5	0.6256
				1.0	0.9032
700.0	0.1	12.6	0.280	0.1	0.3153 E-1
				0.5	0.1520
				1.0	0.3357
	0.5	12.6	0.280	0.1	0.2157
				0.5	0.4558
				1.0	0.7613
	1.0	12.6	0.280	0.1	0.2157
				0.5	0.6446
				1.0	0.9538
900.0	0.1	8.9	0.334	0.1	0.3193 E-1
				0.5	0.1443
				1.0	0.3264
	0.5	8.9	0.334	0.1	0.1191
				0.5	0.4501
				1.0	0.7726
	1.0	8.9	0.334	0.1	0.2062
				0.5	0.6487
				1.0	0.9769

Table D-2A. DYPOW3 output for k_a of 80-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.3343 E-1
				0.5	0.8726 E-1
				1.0	0.1271
	0.5	36.0	0.0260	0.1	0.7912
				0.5	0.1458
				1.0	0.1846
	1.0	36.0	0.0260	0.1	0.1036
				0.5	0.1706
				1.0	0.2086
500.0	0.1	20.2	0.0386	0.1	0.3312 E-1
				0.5	0.9852
				1.0	0.1535
	0.5	20.2	0.0386	0.1	0.8783 E-1
				0.5	0.1804
				1.0	0.2356
	1.0	20.2	0.0386	0.1	0.1205
				0.5	0.2160
				1.0	0.2664
700.0	0.1	12.6	0.0493	0.1	0.3473 E-1
				0.5	0.1053
				1.0	0.1703
	0.5	12.6	0.0493	0.1	0.9316
				0.5	0.2030
				1.0	0.2705
	1.0	12.6	0.0493	0.1	0.1309
				0.5	0.2466
				1.0	0.3067
900.0	0.1	8.9	0.0587	0.1	0.3966 E-1
				0.5	0.1124
				1.0	0.1842
	0.5	8.9	0.0587	0.1	0.9939
				0.5	0.2212
				1.0	0.2977
	1.0	8.9	0.0587	0.1	0.1404
				0.5	0.2707
				1.0	0.3380

Table D-2B. DYPOW3 output for k_a of 80-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.7533
				0.5	0.2820
				1.0	0.4904
	0.5	36.0	0.160	0.1	0.2448
				0.5	0.6006
				1.0	0.8395
	1.0	36.0	0.160	0.1	0.3623
				0.5	0.7532
				1.0	0.9728
500.0	0.1	20.2	0.220	0.1	0.6463 E-1
				0.5	0.2705
				1.0	0.5074
	0.5	20.2	0.220	0.1	0.2307
				0.5	0.6388
				1.0	0.9268
	1.0	20.2	0.220	0.1	0.3594
				0.5	0.8231
				1.0	0.1084 E1
700.0	0.1	12.6	0.280	0.1	0.6078 E-1
				0.5	0.2608
				1.0	0.5136
	0.5	12.6	0.280	0.1	0.2203
				0.5	0.6591
				1.0	0.9807
	1.0	12.6	0.280	0.1	0.3537
				0.5	0.8651
				1.0	0.1153 E1
900.0	0.1	8.9	0.334	0.1	0.6218 E-1
				0.5	0.2537
				1.0	0.5122
	0.5	8.9	0.334	0.1	0.2136
				0.5	0.6653
				1.0	0.1006 E1
	1.0	8.9	0.334	0.1	0.3471
				0.5	0.8839
				1.0	0.1186 E1

Table D-3A. DYPOW3 output for k_a of 400-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.8354 E-1
				0.5	0.1564
				1.0	0.2005
	0.5	36.0	0.0260	0.1	0.1467
				0.5	0.2194
				1.0	0.2530
	1.0	36.0	0.0260	0.1	0.1751
				0.5	0.2419
				1.0	0.2686
500.0	0.1	20.2	0.0386	0.1	0.9895 E-1
				0.5	0.1978
				1.0	0.2597
	0.5	20.2	0.0386	0.1	0.1841
				0.5	0.2859
				1.0	0.3307
	1.0	20.2	0.0386	0.1	0.2240
				0.5	0.3163
				1.0	0.3496
700.0	0.1	12.6	0.0493	0.1	0.1196
				0.5	0.2352
				1.0	0.3092
	0.5	12.6	0.0493	0.1	0.2189
				0.5	0.3398
				1.0	0.3904
	1.0	12.6	0.0493	0.1	0.2666
				0.5	0.3745
				1.0	0.4103
900.0	0.1	8.9	0.0587	0.1	0.1529
				0.5	0.2792
				1.0	0.3616
	0.5	8.9	0.0587	0.1	0.2611
				0.5	0.3951
				1.0	0.4487
	1.0	8.9	0.0587	0.1	0.3143
				0.5	0.4321
				1.0	0.4689

Table D-3B. DYPOW3 output for k_a of 400-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.2480
				0.5	0.6083
				1.0	0.8522
	0.5	36.0	0.160	0.1	0.5559
				0.5	0.9559
				1.0	0.1130 E1
	1.0	36.0	0.160	0.1	0.7109
				0.5	0.1075 E1
				1.0	0.1200 E1
500.0	0.1	20.2	0.220	0.1	0.2404
				0.5	0.6548
				1.0	0.9520
	0.5	20.2	0.220	0.1	0.5916
				0.5	0.1077 E1
				1.0	0.1280 E1
	1.0	20.2	0.220	0.1	0.7796
				0.5	0.1217 E1
				1.0	0.1356 E1
700.0	0.1	12.6	0.280	0.1	0.2450
				0.5	0.6898
				1.0	0.1021 E1
	0.5	12.6	0.280	0.1	0.6196
				0.5	0.1158 E1
				1.0	0.1371 E1
	1.0	12.6	0.280	0.1	0.8292
				0.5	0.1306 E1
				1.0	0.1447 E1
900.0	0.1	8.9	0.334	0.1	0.2650
				0.5	0.7199
				1.0	0.1068 E1
	0.5	8.9	0.334	0.1	0.6463
				0.5	0.1210 E1
				1.0	0.1425 E1
	1.0	8.9	0.334	0.1	0.8668
				0.5	0.1361 E1
				1.0	0.1499 E1

Table D-4A. DYPOW3 output for k_a of 500-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.9240 E-1
				0.5	0.1665
				1.0	0.2101
	0.5	36.0	0.0260	0.1	0.1568
				0.5	0.2283
				1.0	0.2598
	1.0	36.0	0.0260	0.1	0.1851
				0.5	0.2495
				1.0	0.2739
500.0	0.1	20.2	0.0386	0.1	0.1124
				0.5	0.2137
				1.0	0.2748
	0.5	20.2	0.0386	0.1	0.2001
				0.5	0.2999
				1.0	0.3414
	1.0	20.2	0.0386	0.1	0.2399
				0.5	0.3282
				1.0	0.3581
700.0	0.1	12.6	0.0493	0.1	0.1392
				0.5	0.2584
				1.0	0.3311
	0.5	12.6	0.0493	0.1	0.2421
				0.5	0.3602
				1.0	0.4062
	1.0	12.6	0.0493	0.1	0.2897
				0.5	0.3920
				1.0	0.4235
900.0	0.1	8.9	0.0587	0.1	0.1816
				0.5	0.3125
				1.0	0.3928
	0.5	8.9	0.0587	0.1	0.2943
				0.5	0.4243
				1.0	0.4725
	1.0	8.9	0.0587	0.1	0.3472
				0.5	0.4579
				1.0	0.4898

Table D-4B. DYPOW3 output for k_a of 400-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.2841
				0.5	0.6591
				1.0	0.9000
	0.5	36.0	0.160	0.1	0.6061
				0.5	0.9989
				1.0	0.1159 E1
	1.0	36.0	0.160	0.1	0.7617
				0.5	0.1109 E1
				1.0	0.1219 E1
500.0	0.1	20.2	0.220	0.1	0.2811
				0.5	0.7186
				1.0	0.1012 E1
	0.5	20.2	0.220	0.1	0.6542
				0.5	0.1130 E1
				1.0	0.1313 E1
	1.0	20.2	0.220	0.1	0.8438
				0.5	0.1258 E1
				1.0	0.1379 E1
700.0	0.1	12.6	0.280	0.1	0.2909
				0.5	0.7651
				1.0	0.1091 E1
	0.5	12.6	0.280	0.1	0.6933
				0.5	0.1219 E1
				1.0	0.1408 E1
	1.0	12.6	0.280	0.1	0.9049
				0.5	0.1352 E1
				1.0	0.1473 E1
900.0	0.1	8.9	0.334	0.1	0.3184
				0.5	0.8061
				1.0	0.1148 E1
	0.5	8.9	0.334	0.1	0.7307
				0.5	0.1279 E1
				1.0	0.1468 E1
	1.0	8.9	0.334	0.1	0.9533
				0.5	0.1413 E1
				1.0	0.1530 E1

Table D-5A. DYPOW3 output for k_a of 1200-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.1314
				0.5	0.2074
				1.0	0.2467
	0.5	36.0	0.0260	0.1	0.1980
				0.5	0.2614
				1.0	0.2836
	1.0	36.0	0.0260	0.1	0.2248
				0.5	0.2769
				1.0	0.2917
500.0	0.1	20.2	0.0386	0.1	0.1783
				0.5	0.2840
				1.0	0.3376
	0.5	20.2	0.0386	0.1	0.2709
				0.5	0.3568
				1.0	0.3840
	1.0	20.2	0.0386	0.1	0.3080
				0.5	0.3761
				1.0	0.3932
700.0	0.1	12.6	0.0493	0.1	0.2459
				0.5	0.3709
				1.0	0.4323
	0.5	12.6	0.0493	0.1	0.3555
				0.5	0.4532
				1.0	0.4814
	1.0	12.6	0.0493	0.1	0.3988
				0.5	0.4733
				1.0	0.4903
900.0	0.1	8.9	0.0587	0.1	0.3502
				0.5	0.4866
				1.0	0.5519
	0.5	8.9	0.0587	0.1	0.4699
				0.5	0.5734
				1.0	0.6013
	1.0	8.9	0.0587	0.1	0.5166
				0.5	0.5935
				1.0	0.6099

Table D–5B. DYPOW3 output for k_a of 1200–μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.4518
				0.5	0.8582
				1.0	0.1068
	0.5	36.0	0.160	0.1	0.8067
				0.5	0.1141 E1
				1.0	0.1241 E1
	1.0	36.0	0.160	0.1	0.9523
				0.5	0.1212 E1
				1.0	0.1273 E1
500.0	0.1	20.2	0.220	0.1	0.5260
				0.5	0.1074 E1
				1.0	0.1326 E1
	0.5	20.2	0.220	0.1	0.1007 E1
				0.5	0.1403 E1
				1.0	0.1496 E1
	1.0	20.2	0.220	0.1	0.1192 E1
				0.5	0.1471 E1
				1.0	0.1523 E1
700.0	0.1	12.6	0.280	0.1	0.5372
				0.5	0.1079 E1
				1.0	0.1345 E1
	0.5	12.6	0.280	0.1	0.1010 E-1
				0.5	0.1430 E-1
				1.0	0.1536 E-1
	1.0	12.6	0.280	0.1	0.1202 E1
				0.5	0.1507 E1
				1.0	0.1568 E1
900.0	0.1	8.9	0.334	0.1	0.6210
				0.5	0.1181 E1
				1.0	0.1450 E1
	0.5	8.9	0.334	0.1	0.1109 E1
				0.5	0.1534 E1
				1.0	0.1635 E1
	1.0	8.9	0.334	0.1	0.1307 E1
				0.5	0.1608 E1
				1.0	0.1665 E1

Table D-6A. DYPOW3 output for k_a of 2502-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.1700
				0.5	0.2433
				1.0	0.2760
	0.5	36.0	0.0260	0.1	0.2348
				0.5	0.2867
				1.0	0.3011
	1.0	36.0	0.0260	0.1	0.2584
				0.5	0.2970
				1.0	0.3056
500.0	0.1	20.2	0.0386	0.1	0.2569
				0.5	0.3580
				1.0	0.4004
	0.5	20.2	0.0386	0.1	0.3465
				0.5	0.4135
				1.0	0.4300
	1.0	20.2	0.0386	0.1	0.3779
				0.5	0.4254
				1.0	0.4349
700.0	0.1	12.6	0.0493	0.1	0.3932
				0.5	0.5107
				1.0	0.5569
	0.5	12.6	0.0493	0.1	0.4977
				0.5	0.5705
				1.0	0.5868
	1.0	12.6	0.0493	0.1	0.5328
				0.5	0.5824
				1.0	0.5914
900.0	0.1	8.9	0.0587	0.1	0.6039
				0.5	0.7280
				1.0	0.7746
	0.5	8.9	0.0587	0.1	0.7146
				0.5	0.7878
				1.0	0.8033
	1.0	8.9	0.0587	0.1	0.7506
				0.5	0.7992
				1.0	0.8076

Table D-6B. DYPOW3 output for k_a of 2502-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.6183
				0.5	0.1013 E1
				1.0	0.1177 E1
	0.5	36.0	0.160	0.1	0.9686
				0.5	0.1226 E1
				1.0	0.1285 E1
	1.0	36.0	0.160	0.1	0.1091 E1
				0.5	0.1269 E1
				1.0	0.1302 E1
500.0	0.1	20.2	0.220	0.1	0.7089
				0.5	0.1186 E1
				1.0	0.1372 E1
	0.5	20.2	0.220	0.1	0.1133 E1
				0.5	0.1424 E1
				1.0	0.1486 E1
	1.0	20.2	0.220	0.1	0.1276 E1
				0.5	0.1469 E1
				1.0	0.1503 E1
700.0	0.1	12.6	0.280	0.1	0.8369
				0.5	0.1356 E1
				1.0	0.1545 E1
	0.5	12.6	0.280	0.1	0.1300 E1
				0.5	0.1597 E1
				1.0	0.1655 E1
	1.0	12.6	0.280	0.1	0.1449 E1
				0.5	0.1640 E1
				1.0	0.1671 E1
900.0	0.1	8.9	0.334	0.1	0.1020 E1
				0.5	0.1544 E1
				1.0	0.1727 E1
	0.5	8.9	0.334	0.1	0.1489 E1
				0.5	0.1775 E1
				1.0	0.1829 E1
	1.0	8.9	0.334	0.1	0.1635 E1
				0.5	0.1815 E1
				1.0	0.1844 E1

Table D-7A. DYPOW3 output for k_a of 3169-μm Al_2O_3 spheres with N_2 as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.1840
				0.5	0.2556
				1.0	0.2856
	0.5	36.0	0.0260	0.1	0.2475
				0.5	0.2951
				1.0	0.3072
	1.0	36.0	0.0260	0.1	0.2696
				0.5	0.3038
				1.0	0.3109
500.0	0.1	20.2	0.0386	0.1	0.2892
				0.5	0.3874
				1.0	0.4259
	0.5	20.2	0.0386	0.1	0.3767
				0.5	0.4373
				1.0	0.4511
	1.0	20.2	0.0386	0.1	0.4058
				0.5	0.4474
				1.0	0.4551
700.0	0.1	12.6	0.0493	0.1	0.4587
				0.5	0.5713
				1.0	0.6123
	0.5	12.6	0.0493	0.1	0.5594
				0.5	0.6237
				1.0	0.6371
	1.0	12.6	0.0493	0.1	0.5912
				0.5	0.6335
				1.0	0.6405
900.0	0.1	8.9	0.0587	0.1	0.7205
				0.5	0.8375
				1.0	0.8780
	0.5	8.9	0.0587	0.1	0.8254
				0.5	0.8889
				1.0	0.9014
	1.0	8.9	0.0587	0.1	0.8574
				0.5	0.8981
				1.0	0.9048

Table D-7B. DYPOW3 output for k_a of 3169-μm Al_2O_3 spheres with He as the interstitial gas

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.160	0.1	0.6752
				0.5	0.1059 E1
				1.0	0.1205 E1
	0.5	36.0	0.160	0.1	0.1017 E1
				0.5	0.1247 E1
				1.0	0.1297 E1
	1.0	36.0	0.160	0.1	0.1130 E1
				0.5	0.1283 E1
				1.0	0.1310 E1
500.0	0.1	20.2	0.220	0.1	0.7909
				0.5	0.1251 E1
				1.0	0.1415 E1
	0.5	20.2	0.220	0.1	0.1203 E1
				0.5	0.1460 E1
				1.0	0.1510 E1
	1.0	20.2	0.220	0.1	0.1332 E1
				0.5	0.1497 E1
				1.0	0.1524 E1
700.0	0.1	12.6	0.280	0.1	0.9539
				0.5	0.1451 E1
				1.0	0.1615 E1
	0.5	12.6	0.280	0.1	0.1400 E1
				0.5	0.1660 E1
				1.0	0.1704 E1
	1.0	12.6	0.280	0.1	0.1533 E1
				0.5	0.1692 E1
				1.0	0.1717 E1
900.0	0.1	8.9	0.334	0.1	0.1184 E1
				0.5	0.1678 E1
				1.0	0.1834 E1
	0.5	8.9	0.334	0.1	0.1629 E1
				0.5	0.1873 E1
				1.0	0.1917 E1
	1.0	8.9	0.334	0.1	0.1757 E1
				0.5	0.1905 E1
				1.0	0.1928 E1

Table D-8. DYPOW4 output for k_a of 500-μm Al_2O_3 spheres with N_2 as the interior and interstitial gas. Inside gas pressure equals interstitial gas pressure. Wall thickness 15 μm.

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.3184 E-1
				0.5	0.3578 E-1
				1.0	0.3822 E-1
	0.5	36.0	0.0260	0.1	0.3537 E-1
				0.5	0.3988 E-1
				1.0	0.4491 E-1
	1.0	36.0	0.0260	0.1	0.3665 E-1
				0.5	0.4283 E-1
				1.0	0.4879 E-1
500.0	0.1	20.2	0.0386	0.1	0.5087 E-1
				0.5	0.5878 E-1
				1.0	0.6126 E-1
	0.5	20.2	0.0386	0.1	0.5818 E-1
				0.5	0.6253 E-1
				1.0	0.6581 E-1
	1.0	20.2	0.0386	0.1	0.5982 E-1
				0.5	0.6452 E-1
				1.0	0.6805 E-1
700.0	0.1	12.6	0.0493	0.1	0.7547 E-1
				0.5	0.8921 E-1
				1.0	0.9254 E-1
	0.5	12.6	0.0493	0.1	0.8821 E-1
				0.5	0.9377 E-1
				1.0	0.9629 E-1
	1.0	12.6	0.0493	0.1	0.9079 E-1
				0.5	0.9538 E-1
				1.0	0.9774 E-1
900.0	0.1	8.9	0.0587	0.1	0.1099
				0.5	0.1310
				1.0	0.1361
	0.5	8.9	0.0587	0.1	0.1294
				0.5	0.1376
				1.0	0.1400
	1.0	8.9	0.0587	0.1	0.1336
				0.5	0.1392
				1.0	0.1411

Table D-9. DYPOW4 output for k_a of 1000-μm Al_2O_3 spheres with N_2 as the interior and interstitial gas. Inside gas pressure equals interstitial gas pressure. Wall thickness 30 μm.

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.3560 E-1
				0.5	0.3838 E-1
				1.0	0.4024 E-1
	0.5	36.0	0.0260	0.1	0.3807 E-1
				0.5	0.4142 E-1
				1.0	0.4447 E-1
	1.0	36.0	0.0260	0.1	0.3905 E-1
				0.5	0.4330 E-1
				1.0	0.4637 E-1
500.0	0.1	20.2	0.0386	0.1	0.6504 E-1
				0.5	0.7037 E-1
				1.0	0.7209 E-1
	0.5	20.2	0.0386	0.1	0.6997 E-1
				0.5	0.7293 E-1
				1.0	0.7479 E-1
	1.0	20.2	0.0386	0.1	0.7110 E-1
				0.5	0.7412 E-1
				1.0	0.7580 E-1
700.0	0.1	12.6	0.0493	0.1	0.1096
				0.5	0.1197
				1.0	0.1220
	0.5	12.6	0.0493	0.1	0.1190
				0.5	0.1228
				1.0	0.1242
	1.0	12.6	0.0493	0.1	0.1208
				0.5	0.1237
				1.0	0.1248
900.0	0.1	8.9	0.0587	0.1	0.1760
				0.5	0.1934
				1.0	0.1972
	0.5	8.9	0.0587	0.1	0.1922
				0.5	0.1982
				1.0	0.1996
	1.0	8.9	0.0587	0.1	0.1954
				0.5	0.1992
				1.0	0.2001

Table D-10. DYPOW4 output for k_a of 2502-μm Al_2O_3 spheres with N_2 as the interior and interstitial gas. Inside gas pressure equals interstitial gas pressure. Wall thickness 112 μm.

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.4436 E-1
				0.5	0.4625 E-1
				1.0	0.4746 E-1
	0.5	36.0	0.0260	0.1	0.4603 E-1
				0.5	0.4813 E-1
				1.0	0.4953 E-1
	1.0	36.0	0.0260	0.1	0.4671 E-1
				0.5	0.4904 E-1
				1.0	0.5019 E-1
500.0	0.1	20.2	0.0386	0.1	0.1005
				0.5	0.1037
				1.0	0.1048
	0.5	20.2	0.0386	0.1	0.1035
				0.5	0.1052
				1.0	0.1060
	1.0	20.2	0.0386	0.1	0.1042
				0.5	0.1058
				1.0	0.1064
700.0	0.1	12.6	0.0493	0.1	0.1989
				0.5	0.2064
				1.0	0.2079
	0.5	12.6	0.0493	0.1	0.2059
				0.5	0.2084
				1.0	0.2090
	1.0	12.6	0.0493	0.1	0.2059
				0.5	0.2084
				1.0	0.2090
900.0	0.1	8.9	0.0587	0.1	0.3559
				0.5	0.3707
				1.0	0.3735
	0.5	8.9	0.0587	0.1	0.3697
				0.5	0.3742
				1.0	0.3750
	1.0	8.9	0.0587	0.1	0.3722
				0.5	0.3748
				1.0	0.3753

Table D-11. DYPOW4 output for k_a of 3169-μm Al_2O_3 spheres with N_2 as the interior and interstitial gas. Inside gas pressure equals interstitial gas pressure. Wall thickness 56 μm.

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.4636 E-1
				0.5	0.4639 E-1
				1.0	0.4660 E-1
	0.5	36.0	0.0260	0.1	0.4623 E-1
				0.5	0.4663 E-1
				1.0	0.4666 E-1
	1.0	36.0	0.0260	0.1	0.4652 E-1
				0.5	0.4665 E-1
				1.0	0.4667 E-1
500.0	0.1	20.2	0.0386	0.1	0.1129
				0.5	0.1100
				1.0	0.1147
	0.5	20.2	0.0386	0.1	0.1105
				0.5	0.1148
				1.0	0.1149
	1.0	20.2	0.0386	0.1	0.1143
				0.5	0.1149
				1.0	0.1149
700.0	0.1	12.6	0.0493	0.1	0.2338
				0.5	0.2375
				1.0	0.2402
	0.5	12.6	0.0493	0.1	0.2396
				0.5	0.2405
				1.0	0.2408
	1.0	12.6	0.0493	0.1	0.2139
				0.5	0.2408
				1.0	0.2409
900.0	0.1	8.9	0.0587	0.1	0.4299
				0.5	0.4438
				1.0	0.4445
	0.5	8.9	0.0587	0.1	0.4400
				0.5	0.4453
				1.0	0.4460
	1.0	8.9	0.0587	0.1	0.4395
				0.5	0.4458
				1.0	0.4461

Table D-12. DYPOW4 output for k_a of 6000-μm Al_2O_3 spheres with N_2 as the interior and interstitial gas. Inside gas pressure equals interstitial gas pressure. Wall thickness 100 μm.

Temperature (K)	Pressure (atms)	k solid (W/mk)	k gas (W/mK)	Accomodation coefficient	k_a (W/mK)
300.0	0.1	36.0	0.0260	0.1	0.4627 E-1
				0.5	0.4796 E-1
				1.0	0.4899 E-1
	0.5	36.0	0.0260	0.1	0.4777 E-1
				0.5	0.4953 E-1
				1.0	0.5056 E-1
	1.0	36.0	0.0260	0.1	0.4836 E-1
				0.5	0.5022 E-1
				1.0	0.5101 E-1

APPENDIX E

FORTRAN PROGRAM FOR THE ANALYSIS OF HOLLOW SPHERE THERMAL CONDUCTIVITY USING THE MODIFIED CUNNINGTON-TIEN MODEL

The FORTRAN program DMODEL.FOR is listed in this appendix. This program uses the modified Cunnington-Tien model for heat transport through a bed of hollow spheres to calculate the apparent thermal conductivity through the spheres as a function of pressure. This appendix contains a series of input data files containing information about the spheres, the solid phase conductivity, gas species, and k_a as a function of pressure. The data files are organized as follows.

Line 1. Number of data points, mean temp. (K), sphere diameter (μm), sphere shell thickness (μm), parameter m, solid conductivity (W/mK), gas type (1 = N_2, 2 = He).

Remaining lines: Pressure (atm), apparent thermal conductivity (W/mK).

Program DMODEL.FOR

```
C       DMODEL.FOR
        FUNCTION KRAD(BR,THV,TCV,XL)
        IMPLICIT REAL (A-Z)
        THETA = TCV/THV
        KRAD = BR*5.668E-8*XL*THV**3*(1.+THETA)*(1.+THETA**2)
        RETURN
        END
        FUNCTION KGC(M,VKG,VKGR,VKS)
        IMPLICIT REAL (A-Z)
        VK = 1.-VKG/VKS
        VL = 1. - VKG/VKGR
        KGC = (5.8*(1.-M)**2)/VL
        KGC = KGC*(ALOG(VKGR/VKG)/VL-1.-.5*VK)+1.0
        KGC=KGC*VKG
        RETURN
        END
        FUNCTION KGR(SC,GC,MP,PV)
        IMPLICIT REAL (A-Z)
        V=SC/GC
        W=MP*(1-V)/(2.*V+1.0)
        KGR = SC*(1.+2.*W/(1.-W))
        RETURN
        END
        IMPLICIT REAL (A-H,K-Z)
        DIMENSION A(2),B0(2),B1(2),PR(2),GAMMA(2),SIG(2)
        XF(ALPHA)=2.*(2.-ALPHA)/((GAMMA(IGAS)+1.)*PR(IGAS)*ALPHA)
        KS(TM)=A(1)*TM+A(2)*TM**2
        KG0(TM)=B0(IGAS)+B1(IGAS)*TM
        DELA(M,DGR)=2.*M*DGR/(3.*(1-M))
        L(TM,PV,SIGMA)=1.E4*(3.065E-23*TM/(PV*SIGMA**2))
        KG(TM)=KG0(TM)/(1.+2.*XF(ALPHA)*L(TM,PV,SIG(IGAS))/DELA(M,DGR))
333     CONTINUE
        XL =0.0352
        WRITE(5,110)
110     FORMAT(2X,' INPUT 1 FOR N2  INPUT 2 FOR HE',//)
        READ(5,*) IGAS
        SIGMA=SIG(IGAS)
        WRITE(5,128)
128     FORMAT(2X,'INPUT DGR')
        READ(5,*) DGR
        WRITE(5,129)
129     FORMAT(2X,'INPUT WT')
        READ(5,*) WT
        MP=((DGR-2.0*WT)/DGR)**3
        A(1)=.070
        A(2)=0.00
        B0(1)=0.05054
        B0(1)=0.00164
```

```
      B1(2)=3.2?1E-4
      B1(1)=6.4?4E-5
      PR(1)=0.70
      PR(2)=0.71
      GAMMA(1)=1.4
      GAMMA(2)=1.67
      SIG(1)=3.75E-8
      SIG(2)=2.18E-8
      WRITE(5,103)
103   FORMAT(2X,'INPUT ACCOMMODATION COEFFICIENT')
      READ(5,*) ALPHA
      WRITE(5,104)
104   FORMAT(2X,'INPUT KRAD CONSTANT')
      READ(5,*) BR
      WRITE(5,118)
118   FORMAT(2X,' INPUT VOID FRACTION ',/)
      READ(5,*) M
101   FORMAT(7X,'PRESSURE        K CALC                    ',/)
335   CONTINUE
      WRITE(5,100)
100   FORMAT(2X,'INPUT ASC')
      READ(5,*) ASC
      WRITE(5,131)
131   FORMAT(2X,'INPUT THE PRESSURE EXPONENT')
      READ(5,*) PEX
      WRITE(5,137)
      IF(IGAS.EQ.1) WRITE(5,135)
      IF(IGAS.EQ.2) WRITE(5,136)
135   FORMAT(2X,'THIS TABLE IS FOR NITROGEN')
136   FORMAT(2X,'THIS TABLE IS FOR HELIUM')
      WRITE(5,101)
      PJ=1.05
      DO 60 J=1,20
      PJ=PJ-.05
      TM=300.0
      IF(PJ.LT.1.0) VKS=KS(TM)*PJ**PEX
      IF(PJ.GE.1.0) VKS=KS(TM)
      VKG = KG(TM)
      VKGR = KGR(VKS,VKG,MF,PJ)
      THV=310.0
      TCV=290.0
      KCALC = ASC*VKS+KGC(M,VKG,VKGR,VKS)+KRAD(BR,THV,TCV,XL)
      PRAD=KRAD(BR,THV,TCV,XL)*100/KCALC
      PSC=ASC*VKS*100.0/KCALC
      PGC=KGC(M,VKG,VKGR,VKS)*100/KCALC
      CONTINUE
      WRITE(5,105) PJ,KCALC
105 x FORMAT(5X,2E12.4,3E12.2)
```

```
60      CONTINUE
        WRITE(5,106) A(1),A(2)
106     FORMAT(2X,///,2X,'SOLID K CONSTANTS',2E10.4)
        WRITE(5,107) BO(IGAS),B1(IGAS)
107     FORMAT(2X,'GAS K CONSTANTS',2E10.4)
        WRITE(5,108)ASC,BR,ALPHA,M,WT
108     FORMAT(2X,'ASC',E10.4,/,2X,'BR',E10.4,/,'
     &   ALPHA',E12.4,/,2X,'M',E12.4,/,2X,'WT',E12.4)
        WRITE(5,132) PEX
132     FORMAT(2X,'PRESSURE EXPONENT',F12.4)
        WRITE(5,137)
        WRITE(5,130)
130     FORMAT(2X,'IF NEW ASC TYPE 1')
        READ(5,*) IFLAG
        IF(IFLAG.EQ.1) GO TO 335
        GO TO 333
137     FORMAT(2X,'*******************************************',/)
        END
```

Table E-1A. Calculated *k* with pressure exponent n = 1/2
(Parameters for data set 10, m = 0.45)

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.45
 INPUT ASC
1.0E-4
 INPUT THE PRESSURE EXPONENT
.5
 ******************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2270E+00
      0.9500E+00  0.2258E+00
      0.9000E+00  0.2246E+00
      0.8500E+00  0.2233E+00
      0.8000E+00  0.2219E+00
      0.7500E+00  0.2205E+00
      0.7000E+00  0.2189E+00
      0.6500E+00  0.2172E+00
      0.6000E+00  0.2155E+00
      0.5500E+00  0.2135E+00
      0.5000E+00  0.2114E+00
      0.4500E+00  0.2090E+00
      0.4000E+00  0.2064E+00
      0.3500E+00  0.2035E+00
      0.3000E+00  0.2001E+00
      0.2500E+00  0.1961E+00
      0.2000E+00  0.1912E+00
      0.1500E+00  0.1850E+00
      0.1000E+00  0.1763E+00
      0.5000E-01  0.1617E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 E  0.4500E+00
 WT  0.7800E+02
 PRESSURE EXPONENT        0.5000
 ******************************************
```

Table E-1B. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 10, m = 0.50)

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
.0306
  INPUT VOID FRACTION

0.5
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE         K CALC

      0.1000E+01  0.1935E+00
      0.9500E+00  0.1926E+00
      0.9000E+00  0.1915E+00
      0.8500E+00  0.1905E+00
      0.8000E+00  0.1893E+00
      0.7500E+00  0.1881E+00
      0.7000E+00  0.1868E+00
      0.6500E+00  0.1854E+00
      0.6000E+00  0.1839E+00
      0.5500E+00  0.1823E+00
      0.5000E+00  0.1805E+00
      0.4500E+00  0.1786E+00
      0.4000E+00  0.1764E+00
      0.3500E+00  0.1739E+00
      0.3000E+00  0.1711E+00
      0.2500E+00  0.1678E+00
      0.2000E+00  0.1638E+00
      0.1500E+00  0.1586E+00
      0.1000E+00  0.1514E+00
      0.5000E-01  0.1393E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 GR .3060E-01
 ALPHA  0.1000E+01
 M  0.5000E+00
 WT  0.7800E+02
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-1C. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 10, m = 0.55)

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
.0306
  INPUT VOID FRACTION

0.55
 INPUT ASC
1.0E-4
 INPUT THE PRESSURE EXPONENT
.5
 *****************************************
```

THIS TABLE IS FOR NITROGEN

PRESSURE	K CALC
0.1000E+01	0.1633E+00
0.9500E+00	0.1625E+00
0.9000E+00	0.1616E+00
0.8500E+00	0.1607E+00
0.8000E+00	0.1598E+00
0.7500E+00	0.1588E+00
0.7000E+00	0.1577E+00
0.6500E+00	0.1566E+00
0.6000E+00	0.1554E+00
0.5500E+00	0.1540E+00
0.5000E+00	0.1526E+00
0.4500E+00	0.1510E+00
0.4000E+00	0.1492E+00
0.3500E+00	0.1472E+00
0.3000E+00	0.1449E+00
0.2500E+00	0.1422E+00
0.2000E+00	0.1389E+00
0.1500E+00	0.1347E+00
0.1000E+00	0.1289E+00
0.5000E-01	0.1190E+00

```
 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.5500E+00
 WT  0.7800E+02
 PRESSURE EXPONENT      0.5000
 *****************************************
```

Table E-2A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 11, m = 0.45)

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.45
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ***************************************

 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.8468E+00
      0.9500E+00$ 0.8408E+00
  $   0.9040E-00  4.8344E+00
      0.8500E+00  0.8277E+00
      0.8000E+00  0.8206E+00
      0.7500E+00  0.8131E+00
      0.7000E+00  0.8051E+00
      0.6500E+00  0.7965E+00
      0.6000E+00  0.7872E+00
      0.5500E+00  0.7772E+00
      0.5000E+00  0.7663E+00
      0.4500E+00  0.7543E+00
      0.4000E+00  0.7409E+00
      0.3500E+00  0.7259E+00
      0.3000E+00  0.7086E+00
      0.2500E+00  0.6884E+00
      0.2000E+00  0.6640E+00
      0.1500E+00  0.6330E+00
      0.1000E+00  0.5902E+00
      0.5000E-01  0.5199E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 KR .3060E-01
 ALPHA  0.1000E+01
 M  0.4500E+00
 WT  0.7800E+02
 PRESSURE EXPONENT       0.5000
 ***************************************
```

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.45
 INPUT ASC
1.0E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ******************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.8468E+00
      0.9500E+00  0.8408E+00
      0.9000E+00  0.8344E+00
      0.8500E+00  0.8277E+00
      0.8000E+00  0.8206E+00
      0.7500E+00  0.8131E+00
      0.7000E+00  0.8051E+00
      0.6500E+00  0.7965E+00
      0.6000E+00  0.7872E+00
      0.5500E+00  0.7772E+00
      0.5000E+00  0.7663E+00
      0.4500E+00  0.7543E+00
      0.4000E+00  0.7407E+00
      0.3500E+00  0.7259E+00
      0.3000E+00  0.7086E+00
      0.2500E+00  0.6884E+00
      0.2000E+00  0.6640E+00
      0.1500E+00  0.6330E+00
      0.1000E+00  0.5902E+00
      0.5000E-01  0.5199E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4500E+00
 WT  0.7800E+02
 PRESSURE EXPONENT       0.5000
 ******************************************
```

Table E-2B. Calculated *k* with pressure exponent n = 1/2
(Parameters for data set 11, m = 0.50)

```
 INPUT SSA
3446.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0\0\0.5
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ********************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.7271E+00
      0.9500E+00  0.7221E+00
      0.9000E+00  0.7168E+00
      0.8500E+00  0.7113E+00
      0.8000E+00  0.7054E+00
      0.7500E+00  0.6992E+00
      0.7000E+00  0.6925E+00
      0.6500E+00  0.6854E+00
      0.6000E+00  0.6777E+00
      0.5500E+00  0.6695E+00
      0.5000E+00  0.6604E+00
      0.4500E+00  0.6505E+00
      0.4000E+00  0.6394E+00
      0.3500E+00  0.6270E+00
      0.3000E+00  0.6127E+00
      0.2500E+00  0.5960E+00
      0.2000E+00  0.5758E+00
      0.1500E+00  0.5501E+00
      0.1000E+00  0.5148E+00
      0.5000E-01  0.4567E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 KR .3060E-01
 ALPHA  0.1000E+01
 M  0.5000E+00
 WT  0.7800E+02
 PRESSURE EXPONENT        0.5000
 ********************************************
```

Table E-2C. Calculated *k* with pressure exponent n = 1/2
(Parameters for data set 11, m = 0.55)

```
 INPUT DGR
3448.0
 INPUT WT
78.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.55
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 *****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.6187E+00
      0.9500E+00  0.6147E+00
      0.9000E+00  0.6104E+00
      0.8500E+00  0.6059E+00
      0.8000E+00  0.6011E+00
      0.7500E+00  0.5961E+00
      0.7000E+00  0.5907E+00
      0.6500E+00  0.5849E+00
      0.6000E+00  0.5787E+00
      0.5500E+00  0.5720E+00
      0.5000E+00  0.5646E+00
      0.4500E+00  0.5566E+00
      0.4000E+00  0.5476E+00
      0.3500E+00  0.5375E+00
      0.3000E+00  0.5259E+00
      0.2500E+00  0.5124E+00
      0.2000E+00  0.4960E+00
      0.1500E+00  0.4752E+00
      0.1000E+00  0.4466E+00
      0.5000E-01  0.3995E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.5500E+00
 WT  0.7800E+02
 PRESSURE EXPONENT       0.5000
 *****************************************
```

Table E-3A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 12, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DUR
2809.0
 INPUT WT
104.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.0E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2684E+00
      0.9500E+00  0.2670E+00
      0.9000E+00  0.2656E+00
      0.8500E+00  0.2641E+00
      0.8000E+00  0.2624E+00
      0.7500E+00  0.2607E+00
      0.7000E+00  0.2589E+00
      0.6500E+00  0.2569E+00
      0.6000E+00  0.2547E+00
      0.5500E+00  0.2524E+00
      0.5000E+00  0.2499E+00
      0.4500E+00  0.2471E+00
      0.4000E+00  0.2440E+00
      0.3500E+00  0.2405E+00
      0.3000E+00  0.2365E+00
      0.2500E+00  0.2317E+00
      0.2000E+00  0.2259E+00
      0.1500E+00  0.2185E+00
      0.1000E+00  0.2081E+00
      0.5000E-01  0.1906E+00



 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 m  0.4000E+00
 WT  0.1040E+03
 PRESSURE EXPONENT      0.5000
 ****************************************
```

Table E-3B. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 12, m = 0.4 and ASC = 1 × 10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************

 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2873E+00
      0.9500E+00  0.2855E+00
      0.9000E+00  0.2835E+00
      0.8500E+00  0.2815E+00
      0.8000E+00  0.2793E+00
      0.7500E+00  0.2771E+00
      0.7000E+00  0.2747E+00
      0.6500E+00  0.2721E+00
      0.6000E+00  0.2694E+00
      0.5500E+00  0.2664E+00
      0.5000E+00  0.2633E+00
      0.4500E+00  0.2598E+00
      0.4000E+00  0.2560E+00
      0.3500E+00  0.2517E+00
      0.3000E+00  0.2468E+00
      0.2500E+00  0.2412E+00
      0.2000E+00  0.2344E+00
      0.1500E+00  0.2258E+00
      0.1000E+00  0.2141E+00
      0.5000E-01  0.1949E+00

 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-02
 BP .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1040E+03
 PRESSURE EXPONENT       0.5000
 ******************************************
```

Table E-4A. Calculated k with pressure exponent n = 1/2 (Parameters for data set 13, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2809.0
 INPUT WT
104.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************

 THIS TABLE IS FOR HELIUM
```

PRESSURE	K CALC
0.1000E+01	0.1004E+01
0.9500E+00	0.9965E+00
0.9000E+00	0.9888E+00
0.8500E+00	0.9808E+00
0.8000E+00	0.9723E+00
0.7500E+00	0.9633E+00
0.7000E+00	0.9537E+00
0.6500E+00	0.9434E+00
0.6000E+00	0.9323E+00
0.5500E+00	0.9203E+00
0.5000E+00	0.9072E+00
0.4500E+00	0.8928E+00
0.4000E+00	0.8767E+00
0.3500E+00	0.8586E+00
0.3000E+00	0.8379E+00
0.2500E+00	0.8136E+00
0.2000E+00	0.7842E+00
0.1500E+00	0.7468E+00
0.1000E+00	0.6952E+00
0.5000E-01	0.6101E+00

```
 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1040E+03
 PRESSURE EXPONENT        0.5000
 ****************************************
```

Table E-4B. Calculated *k* with pressure exponent n = 1/2
(Parameters for data set 13)

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1023E+01
      0.9500E-00  0.1015E+01
      0.9000E+00  0.1007E+01
     00.8500E+00  0.9982E+00
      0.8000E+00  0.9892E+00
      0.7500E+00  0.9797E+00
      0.7000E+00  0.9695E+00
      0.6500E+00  0.9586E+00
      0.6000E+00  0.9469E+00
      0.5500E+00  0.9343E+00
      0.5000E+00  0.9205E+00
      0.4500E+00  0.9054E+00
      0.4000E+00  0.8887E+00
      0.3500E+00  0.8698E+00
      0.3000E+00  0.8483E+00
      0.2500E+00  0.8231E+00
      0.2000E+00  0.7927E+00
      0.1500E-00  0.7541E+00
      0.1000E+00  0.7012E+00
      0.5000E-01  0.6144E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1040E+03
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-5A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 14, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DOR
2229.0
 INPUT WT
92.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE         K CALC

      0.1000E+01  0.2697E+00
      0.9500E-00  0.2684E+00
      0.9000E+00  0.2669E+00
      0.8500E+00  0.2654E+00
      0.8000E+00  0.2637E+00
      0.7500E+00  0.2620E+00
      0.7000E+00  0.2602E+00
      0.6500E+00  0.2582E+00
      0.6000E+00  0.2560E+00
      0.5500E+00  0.2537E+00
      0.5000E+00  0.2512E+00
      0.4500E-00  0.2484E+00
      0.4000E+00  0.2453E+00
      0.3500E+00  0.2418E+00
      0.3000E+00  0.2378E+00
      0.2500E+00  0.2330E+00
      0.2000E+00  0.2272E+00
      0.1500E+00  0.2198E+00
      0.1000E+00  0.2094E+00
      0.5000E-01  0.1918E+00



 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.9200E+02
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-5B. Calculated k with pressure exponent n = 1/2 (Parameters for data set 14, m = 0.4 and ASC = 1×10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2886E+00
      0.9500E+00  0.2868E+00
      0.9000E+00  0.2848E+00
      0.8500E+00  0.2828E+00
      0.8000E+00  0.2806E+00
      0.7500E+00  0.2784E+00
      0.7000E+00  0.2760E+00
      0.6500E+00  0.2734E+00
      0.6000E+00  0.2707E+00
      0.5500E+00  0.2678E+00
      0.5000E+00  0.2646E+00
      0.4500E+00  0.2611E+00
      0.4000E+00  0.2573E+00
      0.3500E+00  0.2530E+00
      0.3000E+00  0.2481E+00
      0.2500E+00  0.2424E+00
      0.2000E+00  0.2356E+00
      0.1500E+00  0.2271E+00
      0.1000E+00  0.2153E+00
      0.5000E-01  0.1960E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.9200E+02
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-6A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 15, m = 0.4 and ASC = 1 × 10^{-5})

```
 INPUT DGR
2229.0
 INPUT WT
92.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-5
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1009E+01
      0.9500E+00  0.1002E+01
      0.9000E+00  0.9941E+00
      0.8500E+00  0.9861E+00
      0.8000E+00  0.9777E+00
      0.7500E+00  0.9687E+00
      0.7000E+00  0.9591E+00
      0.6500E+00  0.9488E+00
      0.6000E+00  0.9378E+00
      0.5500E+00  0.9258E+00
      0.5000E+00  0.9127E+00
      0.4500E+00  0.8983E+00
      0.4000E+00  0.8823E+00
      0.3500E+00  0.8642E+00
      0.3000E+00  0.8435E+00
      0.2500E+00  0.8192E+00
      0.2000E+00  0.7898E+00
      0.1500E+00  0.7523E+00
      0.1000E+00  0.7006E+00
      0.5000E-01  0.6151E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-04
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.9200E+02
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-6B. Calculated k with pressure exponent n = 1/2 (Parameters for data set 15, m = 0.4 and ASC = 1×10^{-4})

```
 INPUT DGR
2229.0
 INPUT WT
92.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ******************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1011E+01
      0.9500E+00  0.1004E+01
      0.9000E+00  0.9959E+00
      0.8500E+00  0.9879E+00
      0.8000E+00  0.9793E+00
      0.7500E+00  0.9703E+00
      0.7000E+00  0.9607E+00
      0.6500E+00  0.9503E+00
      0.6000E+00  0.9392E+00
      0.5500E+00  0.9272E+00
      0.5000E+00  0.9140E+00
      0.4500E+00  0.8996E+00
      0.4000E+00  0.8835E+00
      0.3500E+00  0.8653E+00
      0.3000E+00  0.8446E+00
      0.2500E+00  0.8202E+00
      0.2000E+00  0.7906E+00
      0.1500E+00  0.7531E+00
      0.1000E+00  0.7012E+00
      0.5000E-01  0.6155E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.9200E+02
 PRESSURE EXPONENT       0.5000
 ******************************************
```

Table E-6C. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 15, m = 0.4 and ASC = 1 × 10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1030E-01
      0.9500E+00  0.1022E+01
      0.9000E+00  0.1014E+01
      0.8500E+00  0.1005E+01
      0.8000E+00  0.9963E+00
      0.7500E+00  0.9867E+00
      0.7000E+00  0.9765E+00
      0.6500E+00  0.9656E+00
      0.6000E+00  0.9539E+00
      0.5500E+00  0.9412E+00
      0.5000E+00  0.9274E+00
      0.4500E+00  0.9122E+00
      0.4000E+00  0.8954E+00
      0.3500E+00  0.8765E+00
      0.3000E+00  0.8549E+00
      0.2500E+00  0.8296E+00
      0.2000E+00  0.7991E+00
      0.1500E+00  0.7604E+00
      0.1000E+00  0.7072E+00
      0.5000E-01  0.6197E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.9200E+02
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-7A. Calculated k with pressure exponent n = 1/4 (Parameters for data set 17, m = 0.41 and ASC = 1×10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.41
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.25
 *****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1008E+01
      0.9500E+00  0.1004E+01
      0.9000E+00  0.1000E+01
      0.8500E+00  0.9964E+00
      0.8000E+00  0.9923E+00
      0.7500E+00  0.9878E+00
      0.7000E+00  0.9831E+00
      0.6500E+00  0.9780E+00
      0.6000E+00  0.9725E+00
      0.5500E+00  0.9666E+00
      0.5000E+00  0.9601E+00
      0.4500E+00  0.9529E+00
      0.4000E+00  0.9448E+00
      0.3500E+00  0.9357E+00
      0.3000E+00  0.9253E+00
      0.2500E+00  0.9129E+00
      0.2000E+00  0.8978E+00
      0.1500E+00  0.8784E+00
      0.1000E+00  0.8510E+00
      0.5000E-01  0.8041E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4100E+00
 WT  0.1320E+03
 PRESSURE EXPONENT      0.2500
 *****************************************
```

Table E-7B. Calculated *k* with pressure exponent n = 1/4 (Parameters for data set 17, m = 0.42 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.42
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.25
 ******************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.9791E+00
      0.9500E+00  0.9756E+00
      0.9000E+00  0.9720E+00
      0.8500E+00  0.9682E+00
      0.8000E+00  0.9642E+00
      0.7500E+00  0.9599E+00
      0.7000E+00  0.9553E+00
      0.6500E+00  0.9504E+00
      0.6000E+00  0.9451E+00
      0.5500E+00  0.9394E+00
      0.5000E+00  0.9331E+00
      0.4500E+00  0.9261E+00
      0.4000E+00  0.9183E+00
      0.3500E+00  0.9096E+00
      0.3000E+00  0.8994E+00
      0.2500E+00  0.8875E+00
      0.2000E+00  0.8729E+00
      0.1500E+00  0.8541E+00
      0.1000E+00  0.8277E+00
      0.5000E-01  0.7825E+00


 SOLID K CONSTANTS .7008E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4200E+00
 WT  0.1320E+03
 PRESSURE EXPONENT       0.2500
 ******************************************
```

Table E-7C. Calculated *k* with pressure exponent n = 1/4 (Parameters for data set 17, m = 0.43 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.43
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.25
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.9510E+00
      0.9500E+00  0.9476E+00
      0.9000E+00  0.9442E+00
      0.8500E+00  0.9405E+00
      0.8000E+00  0.9366E+00
      0.7500E+00  0.9325E+00
      0.7000E+00  0.9280E+00
      0.6500E+00  0.9233E+00
      0.6000E+00  0.9182E+00
      0.5500E+00  0.9126E+00
      0.5000E+00  0.9065E+00
      0.4500E+00  0.8998E+00
      0.4000E+00  0.8923E+00
      0.3500E+00  0.8838E+00
      0.3000E+00  0.8741E+00
      0.2500E+00  0.8625E+00
      0.2000E+00  0.8484E+00
      0.1500E+00  0.8303E+00
      0.1000E+00  0.8048E+00
      0.5000E-01  0.7612E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4300E+00
 WT  0.1320E+03
 PRESSURE EXPONENT      0.2500
 ****************************************
```

Table E-7D. Calculated *k* with pressure exponent n = 1/3 (Parameters for data set 17, m = 0.41 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
   INPUT VOID FRACTION

0.41
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.333
 ******************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1008E+01
      0.9500E+00  0.1003E+01
      0.9000E+00  0.9980E+00
      0.8500E+00  0.9927E+00
      0.8000E+00  0.9872E+00
      0.7500E+00  0.9813E+00
      0.7000E+00  0.9750E+00
      0.6500E+00  0.9683E+00
      0.6000E+00  0.9610E+00
      0.5500E+00  0.9531E+00
      0.5000E+00  0.9445E+00
      0.4500E+00  0.9350E+00
      0.4000E+00  0.9244E+00
      0.3500E+00  0.9124E+00
      0.3000E+00  0.8986E+00
      0.2500E+00  0.8823E+00
      0.2000E+00  0.8625E+00
      0.1500E+00  0.8372E+00
      0.1000E+00  0.8016E+00
      0.5000E-01  0.7415E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BK .3060E-01
 ALPHA  0.1000E+01
 M  0.4100E+00
 WT  0.1320E+03
 PRESSURE EXPONENT        0.3330
 ******************************************
```

Table E-7E. Calculated *k* with pressure exponent n = 1/3 (Parameters for data set 17, m = 0.42 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.42
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.333
 ****************************************
```

THIS TABLE IS FOR HELIUM

PRESSURE	K CALC
0.1000E+01	0.9791E+00
0.9500E+00	0.9745E+00
0.9000E+00	0.9697E+00
0.8500E+00	0.9647E+00
0.8000E+00	0.9593E+00
0.7500E+00	0.9536E+00
0.7000E+00	0.9475E+00
0.6500E+00	0.9410E+00
0.6000E+00	0.9340E+00
0.5500E+00	0.9264E+00
0.5000E+00	0.9180E+00
0.4500E+00	0.9088E+00
0.4000E+00	0.8986E+00
0.3500E+00	0.8870E+00
0.3000E+00	0.8737E+00
0.2500E+00	0.8579E+00
0.2000E+00	0.8388E+00
0.1500E+00	0.8143E+00
0.1000E+00	0.7800E+00
0.5000E-01	0.7219E+00

```
SOLID K CONSTANTS .7000E-01 .0000E+00
GAS K CONSTANTS .5054E-01 .72[illegible]
ASC .1000E-03
PR .3060E-01
ALPHA  0.1000E+01
M  0.4200E+00
WT  0.1320E+03
PRESSURE EXPONENT          0.3330
****************************************
```

Table E-7F. Calculated *k* with pressure exponent n = 1/2
(Parameters for data set 17, m = 0.40 and ASC = 1 × 10^{-4})

```
 IN UT DGR
2289.0
 INPUT WT
152.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ***************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1037E+01
      0.9500E+00  0.1029E+01
      0.9000E+00  0.1022E+01
      0.8500E+00  0.1014E+01
      0.8000E+00  0.1005E+01
      0.7500E+00  0.9960E+00
      0.7000E+00  0.9863E+00
      0.6500E+00  0.9758E+00
      0.6000E+00  0.9646E+00
      0.5500E+00  0.9525E+00
      0.5000E+00  0.9393E+00
      0.4500E+00  0.9247E+00
      0.4000E+00  0.9085E+00
      0.3500E+00  0.8902E+00
      0.3000E+00  0.8692E+00
      0.2500E+00  0.8446E+00
      0.2000E+00  0.8147E+00
      0.1500E+00  0.7768E+00
      0.1000E+00  0.7243E+00
      0.5000E-01  0.6374E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1520E+03
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-8A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 16, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2289.0
 INPUT WT
132.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.0E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ******************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2745E+00
      0.9500E+00  0.2731E+00
      0.9000E+00  0.2717E+00
      0.8500E+00  0.2701E+00
      0.8000E+00  0.2685E+00
      0.7500E+00  0.2668E+00
      0.7000E+00  0.2649E+00
      0.6500E+00  0.2629E+00
      0.6000E+00  0.2608E+00
      0.5500E+00  0.2585E+00
      0.5000E+00  0.2560E+00
      0.4500E+00  0.2532E+00
      0.4000E+00  0.2500E+00
      0.3500E+00  0.2465E+00
      0.3000E+00  0.2425E+00
      0.2500E+00  0.2377E+00
      0.2000E+00  0.2319E+00
      0.1500E+00  0.2244E+00
      0.1000E+00  0.2140E+00
      0.5000E-01  0.1963E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1320E+03
 PRESSURE EXPONENT       0.5000
 ******************************************
```

Table E-8B. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 16, m = 0.4 and ASC = 1 × 10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE          K CALC

      0.1000E+01   0.2934E+00
      0.9500E+00   0.2916E+00
      0.9000E+00   0.2896E+00
      0.8500E+00   0.2876E+00
      0.8000E+00   0.2854E+00
      0.7500E+00   0.2831E+00
      0.7000E+00   0.2807E+00
      0.6500E+00   0.2782E+00
      0.6000E+00   0.2754E+00
      0.5500E+00   0.2725E+00
      0.5000E+00   0.2693E+00
      0.4500E+00   0.2658E+00
      0.4000E+00   0.2620E+00
      0.3500E+00   0.2577E+00
      0.3000E+00   0.2528E+00
      0.2500E+00   0.2471E+00
      0.2000E+00   0.2403E+00
      0.1500E+00   0.2317E+00
      0.1000E+00   0.2200E+00
      0.5000E-01   0.2006E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .4034E-04
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 NT  0.1320E+02
 PRESSURE EXPONENT        0.5000
 ****************************************************
```

Table E-9A. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 18, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2106.0
 INPUT WT
130.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1043E+01
      0.9500E+00  0.1035E+01
      0.9000E+00  0.1028E+01
      0.8500E+00  0.1020E+01
      0.8000E+00  0.1011E+01
      0.7500E+00  0.1002E+01
      0.7000E+00  0.9922E+00
      0.6500E+00  0.9817E+00
      0.6000E+00  0.9705E+00
      0.5500E+00  0.9584E+00
      0.5000E+00  0.9451E+00
      0.4500E+00  0.9305E+00
      0.4000E+00  0.9142E+00
      0.3500E+00  0.8959E+00
      0.3000E+00  0.8749E+00
      0.2500E+00  0.8502E+00
      0.2000E+00  0.8203E+00
      0.1500E+00  0.7822E+00
      0.1000E+00  0.7295E+00
      0.5000E-01  0.6422E+00



 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1300E+03
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-9B. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 18, m = 0.4 and ASC = 1 × 10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
.5
 ****************************************


 THIS TABLE IS FOR HELIUM
      PRESSURE        K CALC

      0.1000E+01  0.1062E+01
      0.9500E+00  0.1054E+01
      0.9000E+00  0.1046E+01
      0.8500E+00  0.1037E+01
      0.8000E+00  0.1028E+01
      0.7500E+00  0.1018E+01
      0.7000E+00  0.1008E+01
      0.6500E+00  0.9970E+00
      0.6000E+00  0.9852E+00
      0.5500E+00  0.9724E+00
      0.5000E+00  0.9585E+00
      0.4500E+00  0.9432E+00
      0.4000E+00  0.9262E+00
      0.3500E+00  0.9071E+00
      0.3000E+00  0.8852E+00
      0.2500E+00  0.8596E+00
      0.2000E+00  0.8287E+00
      0.1500E+00  0.7895E+00
      0.1000E+00  0.7355E+00
      0.5000E-01  0.6465E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .5054E-01 .3251E-03
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1300E+03
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-10A. Calculated *k* with pressure exponent n = 1/3 (Parameters for data set 25, m = 0.4 and ASC = 1 × 10^{-4})

```
 INPUT DGR
2106.0
 INPUT WT
130.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
0.333
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2945E+00
      0.9500E+00  0.2933E+00
      0.9000E+00  0.2920E+00
      0.8500E+00  0.2906E+00
      0.8000E+00  0.2892E+00
      0.7500E+00  0.2876E+00
      0.7000E+00  0.2860E+00
      0.6500E+00  0.2843E+00
      0.6000E+00  0.2824E+00
      0.5500E+00  0.2804E+00
      0.5000E+00  0.2782E+00
      0.4500E+00  0.2758E+00
      0.4000E+00  0.2732E+00
      0.3500E+00  0.2702E+00
      0.3000E+00  0.2668E+00
      0.2500E+00  0.2628E+00
      0.2000E+00  0.2580E+00
      0.1500E+00  0.2519E+00
      0.1000E+00  0.2435E+00
      0.5000E-01  0.2296E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-02
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1300E+03
 PRESSURE EXPONENT      0.3330
 ****************************************
```

Table E-10B. Calculated *k* with pressure exponent n = 1/2 (Parameters for data set 25, m = 0.4 and ASC = 1 × 10^{-3})

```
 INPUT DGR
2156.0
 INPUT WT
130.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.330
 *************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2756E+00
      0.9500E+00  0.2747E+00
      0.9000E+00  0.2737E+00
      0.8500E+00  0.2727E+00
      0.8000E+00  0.2716E+00
      0.7500E+00  0.2705E+00
      0.7000E+00  0.2692E+00
      0.6500E+00  0.2679E+00
      0.6000E+00  0.2665E+00
      0.5500E+00  0.2649E+00
      0.5000E+00  0.2632E+00
      0.4500E+00  0.2613E+00
      0.4000E+00  0.2592E+00
      0.3500E+00  0.2569E+00
      0.3000E+00  0.2541E+00
      0.2500E+00  0.2509E+00
      0.2000E+00  0.2470E+00
      0.1500E+00  0.2419E+00
      0.1000E+00  0.2348E+00
      0.5000E-01  0.2226E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1300E+03
 PRESSURE EXPONENT       0.3350
 *************************************
```

Table E-10C. Calculated k with pressure exponent n = 1/2 (Parameters for data set 25, m = 0.4 and ASC = 1×10^{-4})

```
 INPUT DGR
2106.0
 INPUT WT
130.0
 INPUT ACCOMMODATION COEFFICIENT
1.0
 INPUT KRAD CONSTANT
0.0306
  INPUT VOID FRACTION

0.4
 INPUT ASC
1.E-4
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE        K CALC

      0.1000E+01  0.2756E+00
      0.9500E+00  0.2743E+00
      0.9000E+00  0.2728E+00
      0.8500E+00  0.2713E+00
      0.8000E+00  0.2696E+00
      0.7500E+00  0.2679E+00
      0.7000E+00  0.2660E+00
      0.6500E+00  0.2640E+00
      0.6000E+00  0.2619E+00
      0.5500E+00  0.2596E+00
      0.5000E+00  0.2571E+00
      0.4500E+00  0.2543E+00
      0.4000E+00  0.2511E+00
      0.3500E+00  0.2476E+00
      0.3000E+00  0.2436E+00
      0.2500E+00  0.2388E+00
      0.2000E+00  0.2329E+00
      0.1500E+00  0.2255E+00
      0.1000E+00  0.2150E+00
      0.5000E-01  0.1974E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-03
 BR .3060E-01
 ALPHA  0.1000E+01
 M  0.4000E+00
 WT  0.1300E+03
 PRESSURE EXPONENT       0.5000
 ****************************************
```

Table E-10D. Calculated k with pressure exponent n = 1/2 (Parameters for data set 25, m = 0.4 and ASC = 1 × 10^{-3})

```
 IF NEW ASC TYPE 1
1
 INPUT ASC
1.E-3
 INPUT THE PRESSURE EXPONENT
0.5
 ****************************************


 THIS TABLE IS FOR NITROGEN
      PRESSURE          K CALC

      0.1000E+01   0.2945E+00
      0.9500E+00   0.2927E+00
      0.9000E+00   0.2907E+00
      0.8500E+00   0.2887E+00
      0.8000E+00   0.2865E+00
      0.7500E+00   0.2843E+00
      0.7000E+00   0.2818E+00
      0.6500E+00   0.2793E+00
      0.6000E+00   0.2765E+00
      0.5500E+00   0.2736E+00
      0.5000E+00   0.2704E+00
      0.4500E+00   0.2669E+00
      0.4000E+00   0.2631E+00
      0.3500E+00   0.2588E+00
      0.3000E+00   0.2539E+00
      0.2500E+00   0.2482E+00
      0.2000E+00   0.2414E+00
      0.1500E+00   0.2328E+00
      0.1000E+00   0.2210E+00
      0.5000E-01   0.2016E+00


 SOLID K CONSTANTS .7000E-01 .0000E+00
 GAS K CONSTANTS .6164E-02 .6434E-04
 ASC .1000E-02
 RP .5000E-01
 E.PHW  0.1000E+01
 M  0.4000E+00
 RT  0.1300E-03
 PRESSURE EXPONENT        0.5000
 ****************************************
```

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