4g. Thermal Conductivity

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Symbols and Units

A	cross-sectional area, meters^2
c_p	specific heat at constant pressure, joules/kilogram · kelvin
c_v	specific heat at constant volume, joules/kilogram · kelvin
J	heat current density, watts/meter^2
L	Lorenz ratio $\equiv \lambda/\sigma T$, volts^2/kelvin^2
l	mean free path, meters

M	molecular weight, kilograms/mole
$\dot{Q}$	heat current, watts
R	gas constant per mole, 8.3143 joule/kelvin · mole
T	temperature, kelvins
t	time, seconds
v	velocity, meters/second
x	space coordinate, meters
α	thermal diffusivity, meters^2/second
λ	thermal conductivity, watts/meter · kelvin
μ	dynamic viscosity, Newton · second/meter^2, (= 10 poise)
ρ	density, kilograms/meter^3
σ	electrical conductivity, 1/ohm · meter

4g-1. General Definitions and Units. The thermal conductivity is a nonequilibrium property usually determined in a steady-state experiment utilizing the Fourier law for linear heat flow in a homogeneous, isotropic substance:

$$\dot{Q} = -\lambda A \frac{dT}{dx}$$

where $\dot{Q}$ is the thermal energy current, A is the cross-sectional area, dT/dx is the temperature gradient, and λ is the thermal conductivity coefficient. Commonly used units and their conversion factors are given in Table 4g-1. For nonisotropic bodies such as some dielectric crystals the basic differential equation is modified to

$$J = -\lambda \operatorname{grad} T$$

where J is the vector thermal current density, and λ is a symmetric tensor of second order. Heat-conduction equations and their solutions for nonhomogeneous and nonlinear systems are discussed at length by McAdams [38], Schneider [62], and Carslaw and Jaeger [10].

In general, the total heat *transport* is affected by radiation, convection, and conduction mechanisms and may depend on temperature, pressure, density, material, and temperature gradient, etc. However, the coefficient λ, as defined by the above equations, refers only to heat transport by conduction mechanisms. It is usually assumed that the thermal conductivity is not a function of the temperature gradient, but is a function of the temperature, composition, purity, perfection, and other similar intensive parameters of the system. It is also assumed that the conductivity is not size- or shape-dependent, though this is not always true. Size and shape effects become significant whenever the size of the conductor is comparable to the mean free path for motion of the particles (or quasi-particles) that transport the thermal energy. These effects have been observed for conduction by molecules in rarefied gases and for conduction by phonons (quantized normal modes of lattice vibration) in small, high-purity dielectric crystals at low temperatures.

Representative values for the temperature dependence of several substances are given in Fig. 4g-1. They are typical curves for a high-purity metal (copper), high-purity crystalline dielectric (sapphire), nonferrous alloy (aluminum alloy), ferrous alloy (stainless steel), disordered dielectric (glass), fluid (helium), and water.

The Thermophysical Properties Research Center at Purdue University has published a large compilation of thermal conductivity data and graphs over large temperature ranges for many solids and fluids [72]. A general survey of the experimental and theoretical aspects of thermal conductivity is given in the book edited by Tye [73]. Proceedings of the annual conferences on thermal conductivity [71] are usually available from the sponsoring agency; sometimes they are formally published.

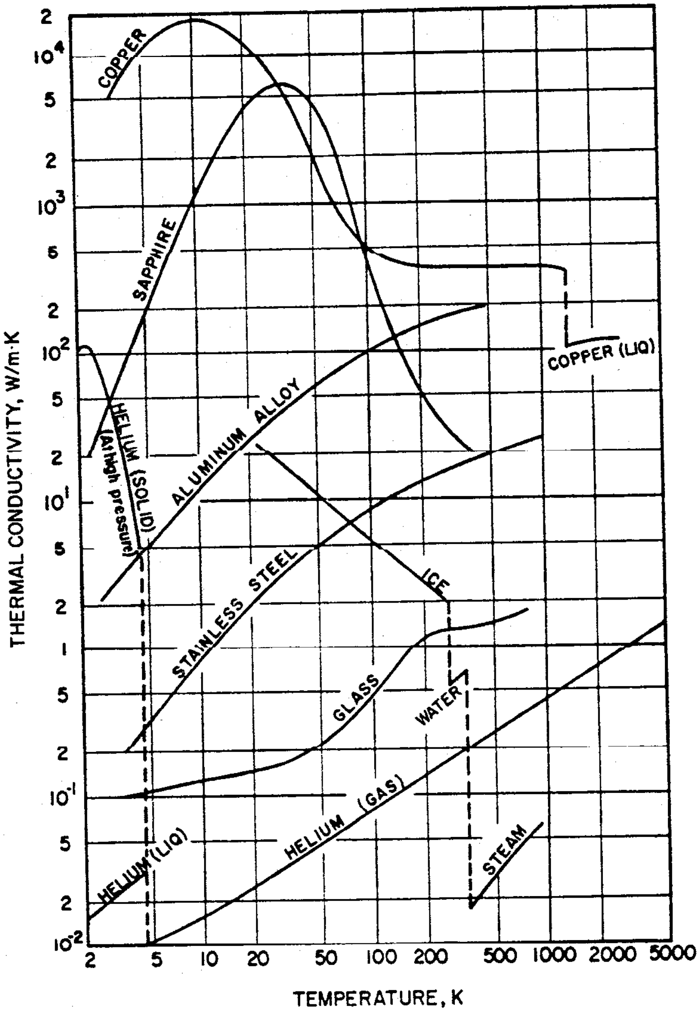

Fig. 4g-1. Typical curves showing temperature dependence of thermal conductivity.

A similar coefficient useful in *transient* heat-flow problems is the thermal diffusivity α defined by

$$\alpha \equiv \frac{\lambda}{\rho c_p}$$

where ρ is the density, and c_p is the specific heat at constant pressure. For an isotropic, homogeneous body without local heat sources or sinks, the basic partial differential equation for transient heat conduction is

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

The more complicated equations and their solutions are discussed by Jakob [29], Schneider [62], and Carslaw and Jaeger [10]. Values of the diffusivity α are not tabulated, but may be calculated, using conductivity values from this section, densities from Sec. 2b, and specific heats from Sec. 4e.

4g-2. Heat Transport in Fluids. In fluids three types of heat transport can occur: radiation, convection, and conduction. Thermal radiation becomes more important as the temperature of a system is increased. For most systems above about 1000 K it becomes a significant contribution to the total heat transfer. Radiative heat transfer is also significant, however, in low-temperature apparatus if any of the critical components are exposed to room-temperature radiation. Radiative constants are given in Sec. 6g of this Handbook. Convection is particularly important in systems with fluid density inversions, heated vertical surfaces, or forced fluid flow. Convection is not actually a separate mode of heat transfer, but rather a complex combination of fluid conduction, solid-to-fluid boundary conduction, and fluid flow. Therefore it is not surprising that solutions for realistic convective heat-transfer problems are complicated but inexact. The physical parameters entering the equations are complex, for they depend not only on the temperature and pressure but also on the shape, position, material, and roughness of the surfaces; the composition and density of the fluids; and the velocity and the type of fluid flow, whether laminar or turbulent, forced, or free. Convective heat transfer is discussed in detail by McAdams [38]; Bird, Stewart, and Lightfoot [6]; and Rohsenow and Choi [58].

For a dilute gas, the thermal conductivity increases slowly with temperature ($\sim T^{0.6}$), and is in principle independent of density or pressure. A definition of "diluteness" is given by Childs and Hanley [12]. A gas is essentially dilute up to about 10 atm at room temperatures and about 40 atm at 1000 K.

A convenient equation for estimating the thermal conductivity of a dilute monatomic gas is

$$\lambda = \frac{15}{4}\frac{R}{M}\mu$$

where R is the gas constant, M the molecular weight, and μ the viscosity. For dilute polyatomic gases a correction factor is needed. The simplest is the Eucken formula,

$$\lambda = \frac{15}{4}\frac{R}{M}\mu\left(\frac{3}{5} + \frac{4}{15}\frac{c_v}{R}\right)$$

where c_v is the specific heat at constant volume. A survey of more sophisticated corrections and of the theories and equations for thermal conductivities of gases is given by Hirschfelder, Curtiss, and Bird [25]. More recent work on dense gas theories is discussed by Sengers [64]. The thermal conductivities for dilute inorganic gases are given in Table 4g-2; for dilute organic gases in Table 4g-3.

Near the critical or condensation region, the thermal conductivity of a fluid is very density- and pressure-dependent, as is shown by the typical set of curves in Fig. 4g-2. Most classical fluids show a similar behavior. Water, however, is an exception. Its conductivity along the liquidus curve above the dome has a broad maximum near 140°C. Green and Sengers [19] review recent work on the anomalous behavior of the thermal conductivity of fluids near the critical point.

The conductivity of a gas is also density- and pressure-dependent at high pressures. Data on the effect of pressure on the conductivity of four gases are given in Table 4g-4. Rough estimates for the conductivity of other gases at high pressures can be made, using the principle of corresponding states as explained by Hirschfelder, Curtiss, and Bird [25].

At low pressures where the effective mean free path of the molecule is limited by the dimensions of the container (below about 10^{-4} atm for many systems), heat conduction through a gas is directly proportional to the pressure. Conduction is then not a property of the gas alone, but also depends upon the gas-wall interactions as represented by the accommodation coefficients or temperature discontinuities at the walls. The conductivity values listed in Tables 4g-2 to 4g-4 do not apply under the above conditions. This transport phenomenon at low pressures is called *free-molecule* or *Knudsen gas conduction.* Formulas, discussions, and coefficients for this effect have been given by Kennard [32] and, more recently, by Corruccini [14], von Ubisch [74], and Devienne [15]. Corruccini also discusses the transition region between free-molecule and regular gas conduction.

The thermal conductivity of classical liquids decreases with increasing temperatures, although water is again an exception. Data for the conductivities of normal liquids near room temperature and at atmospheric pressure are given in Table 4g-5; of cryogenic liquids at saturation pressures in Table 4g-6; and of liquid metals in Table 4g-7. Liquid conductivities at very high pressures are given by Bridgman [7]. For most substances, the conductivity is about 10 times larger in the liquid phase than in the gaseous phase. Similarly, solid conductivity near the melting point is considerably larger than liquid conductivity, liquid bismuth and tellurium being exceptions.

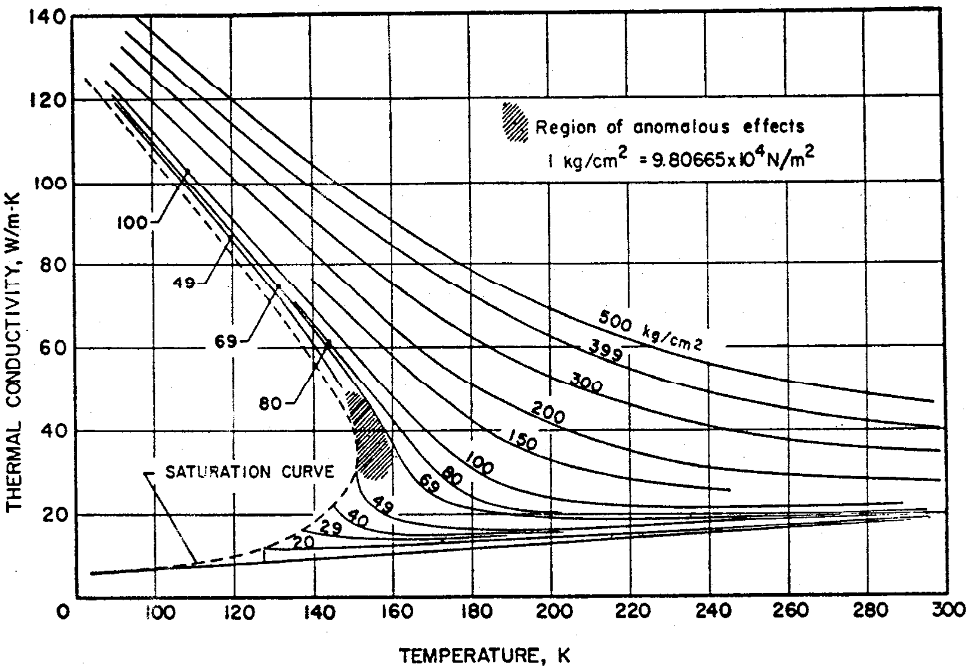

FIG. 4g-2. Effect of pressure on the thermal conductivity of argon. [*B. J. Bailey and K. Kellner, Physica* **39**, 444 (1968).]

4g-3. Heat Transport in Solids. Two principal mechanisms are responsible for the transport of heat energy in a solid. The first is the drift motion of conduction electrons; the second is the directional cooperative vibration of interacting lattice ions, represented by the quasi-particle concept, phonons. Other mechanisms such as internal radiation or excitons may be important in some materials. Electron conduction is predominant in metals and alloys; phonon conduction in dielectrics and some highly disordered alloys. Both electron and phonon conductions are limited at low temperatures by impurity and imperfection scattering. Therefore the thermal conductivity at low temperatures is critically dependent on the exact amount and types of impurities and imperfections. At high temperatures electron conduction is limited by phonon or lattice scattering primarily and therefore is not critically dependent on the impurities. The conductivities of various metals or alloys of approximately the same composition tend to converge at high temperatures. Phonon conduction in crystalline dielectrics is limited at high temperatures by phonon-phonon scattering. Therefore the thermal conductivities of crystalline dielectrics also tend to converge to common values at high temperatures. Phonon conduction in disordered dielectrics is highly limited at most temperatures by imperfection scattering.

TABLE 4g-1. CONVERSION FACTORS FOR THERMAL CONDUCTIVITY*

		$\frac{\text{Watt cm}}{\text{cm}^2\ °\text{K}}$	$\frac{\text{Watt m}}{\text{m}^2\ °\text{K}}$	$\frac{\text{Watt in.}}{\text{in.}^2\ °\text{R}}$	$\frac{\text{Cal cm}}{\text{cm}^2\ \text{sec}\ °\text{K}}$	$\frac{\text{Kcal m}}{\text{m}^2\ \text{hr}\ °\text{K}}$	$\frac{\text{Cal in.}}{\text{in.}^2\ \text{sec}\ °\text{R}}$	$\frac{\text{Btu in.}}{\text{in.}^2\ \text{sec}\ °\text{R}}$	$\frac{\text{Btu in.}}{\text{in.}^2\ \text{hr}\ °\text{R}}$	$\frac{\text{Btu ft}}{\text{ft}^2\ \text{hr}\ °\text{R}}$	$\frac{\text{Btu in.}}{\text{ft}^2\ \text{hr}\ °\text{R}}$
$\frac{\text{Watt cm}}{\text{cm}^2\ °\text{K}}$	=	1.000	100.0	1.411	0.2390	86.04	0.3373	1.338×10^{-3}	4.818	57.82	693.8
$\frac{\text{Watt m}}{\text{m}^2\ °\text{K}}$	=	1.000×10^{-2}	1.000	1.411×10^{-2}	2.390×10^{-3}	0.8604	3.373×10^{-3}	1.338×10^{-5}	4.818×10^{-2}	0.5782	6.938
$\frac{\text{Watt in.}}{\text{in.}^2\ °\text{R}}$	=	0.7087	70.87	1.000	0.1694	60.97	0.2390	9.485×10^{-4}	3.414	40.97	491.7
$\frac{\text{Cal cm}}{\text{cm}^2\ \text{sec}\ °\text{K}}$	=	4.184	418.4	5.904	1.000	360.0	1.411	5.600×10^{-3}	20.16	241.9	2.903
$\frac{\text{Kcal m}}{\text{m}^2\ \text{hr}\ °\text{K}}$	=	1.162×10^{-2}	1.162	1.640×10^{-2}	2.778×10^{-3}	1.000	3.920×10^{-3}	1.555×10^{-5}	5.600×10^{-2}	0.6720	8.064
$\frac{\text{Cal in.}}{\text{in.}^2\ \text{sec}\ °\text{R}}$	=	2.965	296.5	4.184	0.7087	255.1	1.000	3.968×10^{-3}	14.29	171.4	2.057
$\frac{\text{Btu in.}}{\text{in.}^2\ \text{sec}\ °\text{R}}$	=	747.2	7.472×10^{-4}	1054	178.6	6.429×10^{-4}	252.0	1.000	3600	4.320×10^{-4}	5.184×10^{-5}
$\frac{\text{Btu in.}}{\text{in.}^2\ \text{hr}\ °\text{R}}$	=	0.2075	20.75	0.2929	4.961×10^{-2}	17.86	7.000×10^{-2}	2.778×10^{-4}	1.000	12.00	144.0
$\frac{\text{Btu ft}}{\text{ft}^2\ \text{hr}\ °\text{R}}$	=	1.730×10^{-2}	1.730	2.441×10^{-2}	4.134×10^{-3}	1.488	5.833×10^{-3}	2.315×10^{-5}	8.333×10^{-2}	1.000	12.00
$\frac{\text{Btu in.}}{\text{ft}^2\ \text{hr}\ °\text{R}}$	=	1.441×10^{-3}	0.1441	2.034×10^{-3}	3.445×10^{-4}	0.1240	4.861×10^{-4}	1.929×10^{-6}	6.944×10^{-3}	8.333×10^{-2}	1.000

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* Units are given in terms of (1) the absolute joule per second or watt, (2) the defined thermochemical calorie = 4.184 joules, or (3) the defined British thermal unit (Btu) where 1.8 Btu/lb = 1 cal/g and therefore 1 Btu = 1,054.35 joules.

Therefore the thermal conductivity of disordered dielectrics is very low compared with that of metals or crystalline dielectrics. A review of the phenomena and various mechanisms for metals at low temperatures was given by Powell [44], and a more detailed study of the theories and concepts for solids by Rosenberg [60]. The book edited by Tye [73] also contains reviews of both the theoretical and experimental aspects for solids.

The thermal conductivity of a metal or alloy can be estimated by using the Wiedemann-Franz-Lorenz law,

$$\lambda = L\sigma T$$

where σ is the electrical conductivity, λ is the thermal conductivity, T is temperature, and L is the Lorenz ratio whose Sommerfeld classical value is

$$L \approx 2.45 \times 10^{-8} \text{ (volt/kelvin)}^2$$

For both pure metals and alloys the Lorenz ratio generally approaches the Sommerfeld value at high and very low temperatures. For pure metals L is lower than the above number at temperatures below the ice point; for alloys it is higher, as much as 10 times greater (near 20 K) for very disordered, multicomponent alloys.

Data for the conductivity of metals are given in Table 4g-8. It should be noted that the values quoted at 4.2 K, and often at 20 K, are for the most pure specimen that has been measured at the present. Future measurements on more pure metals may give substantially higher conductivites. Above 20 K the quoted values should not change substantially (more than 5 per cent) as more pure metals are measured with more refined techniques. Data for the conductivity of some commercial alloys are given in Table 4g-9; of semiconductors in Table 4g-10; of crystalline dielectrics and optical materials in Table 4g-11; and of disordered materials in Table 4g-12.

A few selected values for solids below 1 K are given in Table 4g-13. The conductivity of normal metals varies linearly with temperature at temperatures below their conductivity maximum. In superconductors the electrons do not contribute significantly to the transport of heat. Therefore their conductivity is governed by phonon processes and usually varies as T^3. The conductivity of crystalline solids is usually size-dependent below 1 K and therefore depends on the exact specimen configuration.

A recent review of the literature by Childs et al. [46] includes data, tables, and graphs on most solids for temperatures at and below 300 K.

TABLE 4g-2. THERMAL CONDUCTIVITY OF DILUTE INORGANIC GASES
(In milliwatts/meter · kelvin)

Gas	Ref.	20 K	60 K	80 K	100 K	200 K	300 K	400 K	600 K	800 K	1000 K
Ar...........	21	....	....	.....	6.44	12.5	17.7	22.3	29.7	36.1	41.8
Air...........	24	....	....	.....	9.22	18.2	26.1	33.0	45.6	56.9	67.2
Br_2...........	72	....	....	.....	.....	......	5.7*				
Cl_2...........	72	....	....	.....	.....	......	8.89	12.4	19.0		
CO...........	24, 72	....	....	.....	8.75	17.4	25.2	32.3	44.4	54.9	64.4
CO_2...........	24, 72	....	....	.....	.....	0.53	16.6	24.6	38.0	54.0	67.0
D_2...........	72	....	36.0	47.5	57.7	101	141	176			
F_2...........	72	....	....	.....	8.60	18.3	27.9	37.1	52.7	61.8	
Freon-12......	72	....	....	.....	.....	......	9.70	15.1			
H_2 (normal)...	72	15.5	42.6	55.2	67.6	128	182	228	291	360	428
H_2 (para).....	30	15.5	43.0	57.8	75.0	146	187				
He...........	52	25.8	52.1	63.1	73.0	115	150	180	247	307	363
Hg...........	72	....	....	.....	.....	......	......	7.7†			
Kr...........	22	....	....	.....	.....	6.48	9.48	12.2	16.8	20.7	
N_2...........	12	....	....	7.62	9.76	18.7	26.1	32.4	43.9	55.2	66.0
Ne...........	22	....	14.8	18.6	21.7	37.0	48.9	59.1	76.7	92.0	105
NH_3...........	52	....	....	.....	.....	15.3	24.6	36.4	65.6	97.9	
O_2...........	12	....	....	.....	9.04	18.3	26.6	34.1	47.4	59.4	71.8
Steam........	28	....	....	.....	.....	......	18.1	26.4	46.4	68.0	
Xe...........	22	....	....	.....	.....	3.82	5.52	7.17	10.2	12.8	15.1

* At 350 K.
† At 476 K.
Various authors differ from 2 to 10 % on the experimental results for the conductivities of gases.

TABLE 4g-3. THERMAL CONDUCTIVITY OF DILUTE ORGANIC GASES
(In milliwatts/meter · kelvin)

Gas	Formula	200 K	300 K	400K	500 K	1000 K
Acetone..............	$(CH_3)_2CO$	.....	11.5	20.1	31.0	
Benzene..............	C_6H_6	.....	10.4	19.5	33.5	
Carbon tetrachloride...	CCl_4	.....	6.73	9.89	12.6	
Ethane...............	C_2H_6	10.2	21.8	36.0	51.6	164
Ethyl alcohol.........	C_2H_5OH	.....	.....	24.5	32.7	
Ethylene.............	C_2H_4	8.80	20.4	35.0		
Ethyl ether...........	$C_4H_{10}O$	.....	.....	25.0	37.1	
Methane..............	CH_4	21.8	34.3	48.4	67.1	169
Methyl alcohol........	CH_3OH	.....	.....	24.9	35.1	
Propane..............	C_3H_8	.....	18.3	29.5	41.7	

Various authors differ from 2 to 10 % on the experimental results for the conductivities of gases.
Values quoted are from ref. 72.

TABLE 4g-4. PRESSURE EFFECT ON THERMAL CONDUCTIVITY OF GASES
(In milliwatts/meter · kelvin)

Gas	Ref.	*T*, K	Pressure, atm†			
			1	10	100	300
Ar..........	3, 24, 70	90	5.19	119*	124	136
		100	6.44	106*	113	126
		120	7.70	.....	91.5	108
		140	8.95	.....	70.1	90.5
		160	10.2	.....	48.4	75.4
		180	11.4	11.7	30.0	62.9
		200	12.5	13.0	23.9	53.1
		300	17.7	18.1	22.4	34.0
N_2..........	24, 79	80	7.62	131*	139	154
		100	9.76	95*	110	129
		120	11.3	13.4	82	107
		140	13.0	14.2	58	88
		160	14.7	15.9	41	75
		180	16.7	17.6	34	64
		200	18.7	19.3	30	58
		300	26.1	.....	32	
		400	32.4	.....	37	
		600	43.9	.....	48	
		800	55.2	.....	59	
O_2..........	24, 79	80	163*	164*	170	
		90	8.4	151*	158	
		100	9.04	137*	146	
		120	11.3	13.4	121	
		140	13.0	15.1	95	
		160	15.1	16.7	66	
		180	16.7	18.0	42	
		200	18.3	19.7	33	
Steam.......	14, 28	380	24.5	680*	690*	700
		400	26.4	680*	690*	710
		420	28.2	680*	690*	710
		440	30.0	670*	690*	700
		460	31.7	33.3	680*	700
		480	33.7	34.4	670*	690
		500	35.0	35.6	660*	670
		550	41.1	39.1	590*	620
		600	46.4	42.9	61.6	530
		650	51.8	46.9	57.0	212
		700	57.2	51.0	57.2	113
		750	63.0	55.1	59.3	85.5
		800	68.0	59.3	62.2	76.7

* Indicates a liquid below its critical pressure.

† 1 atm = 1.01325 × 10^5 N/m^2.

Various authors differ from 2 to 10% on the experimental results for the conductivities of gases.

TABLE 4g-5. THERMAL CONDUCTIVITY OF LIQUIDS NEAR ROOM TEMPERATURE
(In milliwatts/meter · kelvin)

Liquid	−20°C	0°C	20°C	40°C	60°C	Ref.
Acetone	177	169	162	155	.....	72
Benzene	...	...	146	141	136	72
Benzene (ortho-dichloro)	...	...	...	127	122	51
Carbon tetrachloride	113	109	105	101	97.2	72
Ethyl alcohol	179	174	168	162	156	72
Glycerol	...	...	287	290	292	57
Kerosene	...	...	...	147	142	61
Methyl alcohol	216	210	204	198	193	72
Oil, mineral	...	...	131	129	127	57
Oil, petroleum	...	...	150	...	.....	61
Oil, silicone (mol. wt. 162)	...	...	...	...	99.3	61
Oil, silicone (mol. wt. 1,200)	...	...	...	...	132	61
Oil, silicone (mol. wt. 15,800)	...	...	...	...	160	61
Oil, transformer	...	136	134	132	131	61
Toluene	146	141	136	131	126	72
Water	...	562	597	627	652	72
Water, heavy	...	554	579	600	620	51

Various authors differ from 2 to 15 % on the experimental results for the conductivities of liquids near room temperature.

For additional results on liquids see refs. 28, 51, and 61.

TABLE 4g-6. THERMAL CONDUCTIVITY OF CRYOGENIC LIQUIDS AT SATURATION PRESSURE

(In milliwatts/meter · kelvin)

Liquid	Ref.	T, K	Conductivity
Ar..........	3	85	125
		90	117
		95	111
		100	105
		105	100
		110	93.0
		115	88.5
		120	80.9
		125	74.5
		130	69.5
		135	62.9
		140	56.8
		145	50.0
D_2..........	55	21	128
		22	130
		23	132
H_2..........	30	16	109
		18	113
		20	118
		22	123
		24	127
		26	132
He^3.........	36	1.2	10.5
		1.4	11.2
		1.6	12.2
		1.8	13.0
		2.0	13.5
		2.1	13.8
He^4(I)*.....	36	2.4	19.0
		2.8	19.5
		3.2	20.8
		3.6	23.3
		4.0	26.8
N_2........	79	70	150
		72	147
		74	144
		76	142
		78	139
		80	136
		82	134
		84	131
		86	128
		88	125
Ne........	37	25	117
		26	116
		27	114
		28	112
		29	106
O_2........	79	80	163
		85	157
		90	150
		95	144
		100	137
		105	129
		110	122
		115	115
		120	109
		125	103
		130	96.7
		135	89.1
		140	79.1

* Heat conduction in liquid helium II is not governed by the usual heat-conduction mechanisms and equations.

Various authors differ from 2 to 8% on the experimental results for the conductivities of liquids at saturation pressure.

TABLE 4g-7. THERMAL CONDUCTIVITY OF LIQUID METALS
(In watts/meter · kelvin)

Metal	Ref.	t, °C	Conductivity
Al	54	700	90.0
		750	91.6
		800	93.2
		850	94.8
		900	96.4
		950	98.0
		1000	98.8
Bi	43	300	11.3
		350	11.8
		400	12.3
		450	12.8
		500	13.3
		550	13.9
Bi-Pb eutectic (44.5 wt. % Pb)	53	150	9.3
		200	10.1
		250	10.9
		300	11.7
		350	12.4
		400	13.1
		450	13.7
		500	14.2
Cu	72	1100	160
		1500	172
		1700	176
		2000	177
Ga	8	50	33.1
		100	42.5
		150	53.8
		200	54.5
		250	57.3
Hg	17	0	8.4
		100	9.5
		200	10.7
		300	11.8
		400	12.6
		500	13.3
K	16	200	45
		300	42
		400	40
		500	38
		600	35
K-Na (23 wt. % Na)	17	150	24
		200	25
		300	26
		400	26
		500	26
		600	26
		700	25
K-Na (43.5 wt. % Na)	17	150	24
		200	25
		300	26
		400	27
		500	27
Li	72	250	44
		300	43
		400	40
		500	34
Na	16	200	82
		300	76
		400	71
		500	67
Na-Hg (6.3 wt. % Hg)	53	100	22
		150	25
Na-Hg (30 wt. % Hg)	53	100	9
		150	11
Pb	53	350	16.0
		400	16.9
		450	17.6
		500	18.1
		550	18.4
		600	18.7
Sb	72	700	22
Sn	43	300	34
		400	33
		500	33
Sn-Pb (38 wt. % Pb)	72	250	24
		300	26
		400	29
Te	1	460	20
		500	13
Zn	72	450	59
		500	59
		600	58
		700	57

Various authors differ from 5 to 75% on the experimental results for the conductivities of liquid metals.
See the article by R. W. Powell (ref. 47) for a review.

TABLE 4g-8. THERMAL CONDUCTIVITY OF SOLID ELEMENTS
(In watts/meter · kelvin)

Element*	4.2 K†	20 K†	77 K	194 K	273 K	373 K	573 K	973 K‡
Ag	14,500	5,100	481	430	428	422	407	376
Al	17,000	11,500	440	238	235	234	233	
Au	2,190	1,570	354	328	318	313	306	279
B	40	350	270	54	32	22	17	
Be	....	3,500	1,800	318	220	172	134	96
Bi (⊥*c*)	1,590	100	27	13	11	9		
Cd	9,500	226	107	99	98	95	89	
Ce	0.5	1.9	5.0	......	11			
Co	95	450	205	130	100	85		
Cr	165	575	192	112	95	87	81	66
Cs	110	61						
Cu	11,800	10,500	610	419	401	393	384	359
Dy	2.8	15	12	9	11			
Er	5	12	11	14	14			
Fe	8,500	15,000	218	95	83.5	71.9	56.3	33.9
Ga (‖*b*)	16,000	630	105	90	85			
Gd	16	32	16	13	14			
Ge	900	1,500	330	98	67	47	29	18
Hf	3.6	18	26	......	22	22	21	
Hg	180	....	41.5	34				
Ho	5.8	18	7.7	9	10.5			
In	850	183	....	100	87			
Ir	550	1,800	230	162	160	157	152	
K	650	150	114	112	109			
La	9							
Li	256	720	152	90	82	80		
Lu (‖*c*)	20	40	28	25	23			
Mg	510	1,390	200	156	153	150	146	
Mn	0.94	2.4	5.5	7.0	7.7			
Mo	66	277	215	138	135	132	130	113
Na	4,750	590	137	128	125			
Nb	27	85	56	51	51	53	55	60
Nd	....	....	....	......	16			
Ni	300	800	195	110	91	81	67	71
Os	125	540	135	91	88	85	85	
P	0.6	27	35	18	13			
Pb	2,100	59	41	37	35	34	32	
Pd	800	600	82	76	76	76		
Pr	....	....	6.8	11	12.5			
Pt	910	490	87	75	73	72	72	74
Pu	....	....	2.8	4.6	6.2	8.8		
Rb	185	70	61	60	60			
Re	700	840	64	51	49	47	44	44
Rh	1,110	3,800	250	155	151	147	137	
Ru	660	2,300	190	120	117	117	117	
S	11	2.4	0.67	0.37	0.29	0.15		
Sb	200	220	58	31	26	21	19	
Sc	2.8	12	14	18	22			
Se (‖*c*)	150	59	14					
Si	260	4,900	1,400	270	170	108	65	32
Sm	4.8	6.9	7.1	11	13			
Sn	7,500	230	89	73	67	63		
Ta	48	147	60	57	57	57	59	61
Tb	6.0	20	12	10	13			
Tc	....	....	....	......	51	50	50	
Te (⊥*c*)	850	90	15	6.2	4.4	3.2	2.4	
Th	17	54	50	39	37	37	37	38
Ti	5.8	28	33	25	22	21	19	20
Tl	1,800	80	58	49	47			
Tm	9.0	18	12	16	17			
U	4.6	15	21	25	27	28	30	40
V	2.3	12	23	27	30	32	34	
W	4,000	5,400	264	180	170	166	141	122
Y	2.2	10	....	......	15	15	15	15
Zn	970	690	138	124	119	113	103	
Zr	40	105	37	25	22	20	19	21

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* Solid A, H_2, and He are in Table 4g-11. Symbols in parentheses indicate heat flow parallel or perpendicular to *b* or *c* axes. For other elements the results are for isotropic or polycrystalline elements.

† The low-temperature conductivity depends critically on the exact amount and types of impurities and imperfections. The values quoted are for the most pure specimen that has been measured at the present.

‡ For temperatures greater than 973 K see reviews by refs. 46 and 52.

Values quoted are from the reviews and compilations by R. L. Powell and Blanpied (ref. 46) and R. W. Powell et al. (ref. 52). The values are generally for the highest-purity metals tested. Disagreements among different modern authors are caused primarily by differences in sample purity and preparation.

TABLE 4g-9. THERMAL CONDUCTIVITY OF SELECTED COMMERCIAL ALLOYS
(In watts/meter · kelvin)

Alloy*†	Ref.	4.2 K	20 K	77 K	194 K	273 K	373 K	573 K	973 K
Aluminum:									
1100	45	50	240	270	220	220			
2024	45	3.2	17	56	95	130			
3003	45	11	58	140	150	160			
5052	45	4.8	25	77	120	140			
5083, 5086	45	3.0	17	55	95	120			
Duralumin	72	5.5	30	91	140	160	180		
Bismuth:									
Rose metal	46	......	5.5	8.3	14	16			
Wood's metal	72	4	17	23					
Copper:									
Electrolytic tough pitch	45	330	1,300	550	400	390	380	370	350
Free cutting, leaded	45	200	800	460	380	380			
Phosphorus deoxidized	45	7.5	42	120	190	220			
Brass, leaded	45	2.3	12	39	70	120			
Beryllium	72	2.0	17	36	70	90	113	172	
German silver	46, 72	0.75	7.5	17	20	23	25	30	40
Silicon bronze, A	45	......	3.4	11	23	30			
Manganin	46	0.48	3.2	14	17	22			
Constantan	46	0.9	8.6	17	19	22			
Ferrous:									
Commercial pure iron	46, 48	15	72	106	82	76	66	54	34
SAE 1020	46	13	20	58	65	65			
SAE 1095	46	......	8.5	31	41	45			
3 Ni, 0.7 Cr, 0.6 Mo	48	......	6	22	.....	33	35	36	30
4 Si	48	......	......	.....	.....	20	24	28	26
Stainless	11	0.3	2	8	13	14	16	19	25
27 Ni, 15 Cr	48	......	1.7	55	.....	11	12	16	21
Gold:									
Gold-cobalt thermocouple	45	1.2	8.6	20					
Lead:									
60 Pb, 40 Sn	72	......	28	44					
Nickel:									
80 Ni, 20 Cr	48	......	......	.....	.....	12	14	17	23
Contracid	46	0.2	2	7.3	9.5	13			
Inconel	27, 48	0.5	4.2	12.5	13	15	16	19	26
Monel	46	0.9	7.1	15	20	21	24	30	43
Platinum:									
10 Ir	46	......	......	.....	.....	31	31.4		
10 Rh	46	......	......	.....	.....	30.1	30.5		
Silver:									
Silver solder	46	......	12	34	58				
Normal Ag thermocouple	46	48	230	310					
Tin (60 Sn, 40 Pb)	72	16	55	51					
Titanium:									
5.5 Al, 2.5 Sn, 0.2 Fe	27	......	1.8	4.3	6.4	7.8	8.4	10.8	
4.7 Mn, 3.99 Al, 0.14 C	46	......	1.7	4.5	6.5	8.5			

* Commercial alloys of the same nominal composition may vary in conductivity from 5 to 25% because of differences in heat treatment and uncontrolled impurities. Contracid, Inconel, and Monel are registered trade names for nickel alloys. See ref. 46 for additional data.

† When composition is given, it is by weight percent.

TABLE 4g-10. THERMAL CONDUCTIVITY OF SEMICONDUCTORS*
(In watts/meter · kelvin)

Substance	Ref.	Dopant	Electrical conductivity at room temp., ohm-m	Type	Carriers at room temp., no./m³	Temperature					
						4K	20K	77K	194K	273K	373K
Graphite . . .	50	. . . .	9.8×10^{-6}	⊥ C	. . . .	0.25	15	190	300	250	
	50	. . . .	4.1×10^{-5}	∥ C	. . . .	0.2	7.4	68	84	80	
	50, 72	. . . .	2.4×10^{-5}	Ext.	. . . .	0.02	0.7	15			
	50, 72	. . . .	5.7×10^{-5}	Molded	. . . .	. . . .	0.08	1.2	4	5	
	70	. . . .	1.2×10^{-6}	Natural	. . . .	6	150	610	270	160	
	50, 72	. . . .	2.4×10^{-4}	Deposit	. . . .	. . . .	. . . .	. . . .	. . . .	580	540
	50, 72	. . . .	2.1×10^{-3}	Coke	. . . .	. . . .	. . . .	. . . .	. . . .	28	28
Ge.	70	Cu	. . . .	*p*,*n*	10^{20}	1000	1500	300	90	70	50
	9	In	3×10^{-2}	*p*	10^{21}	290	1300	310			
	9	Ga	3×10^{-5}	*p*	10^{25}	8.5	270	200			
Si.	56	O_2	5.5×10^{-2}	*n*	7.8×10^{20}	310	1900	900	270	150	
	66	P	4.6×10^{-1}	*p*	4×10^{20}	200	4200	1500	270	150	
	9	Au	2.2×10^{-1}	*p*	10^{26}	87	1300	840	250	150	
	66	B	4.5×10^{-2}	*p*	4×10^{21}	140	3500	1500	270	150	
Bi_2Te_3	72	. . . .	. . . .	*n*	3×10^{23}	. . . .	. . . .	6	3	3	4.9
GaAs	26	. . . .	. . . .	. . . .	7×10^{15}	1000	1900	300	80	50	
InAs.	72	. . . .	. . . .	*n*	10^{25}	. . . .	. . . .	. . . .	. . . .	6.7	5.0
				n	3×10^{22}	. . . .	. . . .	. . . .	. . . .	6.7	5.2
InSb.	26	. . . .	. . . .	*p*	10^{22}	. . . .	1000	110	. . . .	17	12
				n	10^{23}	. . . .	. . . .	. . . .	. . . .	18	14
PbS.	20	. . . .	. . . .	*p*	2×10^{24}	17	46	8			
				n	8×10^{23}	0.7	2.8	3.9			
PbSe.	20, 56	. . . .	. . . .	*p*	5×10^{24}	24	33	5.5			
PbTe	20	. . . .	. . . .	*p*	2×10^{24}	11	31	7	4	2.4	1.7
				n	6×10^{24}	. . . .	. . . .	8	1.3	2.3	2.4
SiC.	66	N	10×10^{-2}	*n*	10^{23}	30	2000	3000	1000	500	
	66	Al	6×10^{-3}	*p*	4×10^{25}	0.08	1.5	50	150	140	

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* Pure Ge and Si are in Table 4g-8.

Various authors differ from 5 to 10 % on the experimental results for the conductivities of semiconductors.

See also the review by E. F. Steigmeier in vol. 2, pp. 203–251, of ref. 73.

TABLE 4g-11. THERMAL CONDUCTIVITY OF CRYSTALLINE DIELECTRICS AND OPTICAL MATERIALS
(In watts/meter · kelvin)

Material	Ref.	*T*, K	Conductivity
Ar	52	8	6.0
		10	3.7
		20	1.4
		77	0.31
AgCl	39	223	1.3
		273	1.2
		323	1.1
		373	1.1
Al_2O_3 (sapphire) 36 deg to *c* axis	46	4.2	110
		20	3,500
		35	6,000
		77	1,100
Al_2O_3 (sapphire) ⊥ to *c* axis	48, 72	373	2.6
		523	3.9
		773	5.8
Al_2O_3 (sintered)	46, 48	4.2	0.5
		20	23
		77	150
		194	48
		273	35
		373	26
		973	8
As_2S_3 (glass)	72	283	0.16
		323	0.21
		373	0.27
BaF_2	39	225	20
		260	13.4
		305	10.9
		370	10.5
BeO	46, 48	4.2	0.3
		20	16
		77	270
		373	210
		573	120
		1,273	29
C (diamond)	46	4.2	75
		20	1,600
		77	3,400
		194	870
		273	660
$CaCO_3$ ∥ to *c* axis	72	83	25
		273	5.5
$CaCO_3$ ⊥ to *c* axis	72	83	17
		194	6.5
		273	4.6
		373	3.6
CaF_2	39	83	39
		223	18
		273	10
		323	9.2
		373	9.0
CsBr	39	223	1.2
		273	0.94
		323	0.81
		373	0.77
CsI	39	223	1.4
		273	1.2
		323	1.0
		373	0.95
Glass (phoenix)	46	4.2	0.095
		20	0.13
		77	0.37
Glass (plastic perspex)	46	4.2	0.058
		20	0.074
Glass (Pyrex)	46	77	0.44
		194	0.88
		273	1.0
H_2 (para + 0.5 % ortho)	46	2.5	100
		3.0	150
		4.0	200
		6.0	30
		10	3
H_2O (ice)	72	173	3.5
		223	2.8
		273	2.2
He^3	52	0.6	25
		1.0	2
		1.5	0.57
		2.0	0.21
He^4	52	0.5	42
		0.8	120
		1.0	24
		2.0	0.18
I	52	300	0.45
		325	0.42
		350	0.40
KBr	39, 75	2	150
		4.2	360
		100	12
		273	5.0
		323	4.8
		373	4.8
KCl	39, 75	4.2	500
		25	140
		80	35
		194	10
		273	7.0
		323	6.5
		373	6.3
KI	75	4.2	700
		80	13
		194	4.6
		273	3.1
Kr	52	4.2	0.48
		10	1.7
		20	1.2
		77	0.36
LiF	5, 72	4.2	620
		20	1,800
		77	150
$MgO{\cdot}Al_2O_3$ (spinel)	48, 68	373	13
		773	8.5
MnO	72	4.2	0.25
		40	55
		120	8.0
		573	3.5
NaCl	39, 77	4.2	440
		20	300
		77	30
		273	6.4
		323	5.6
		373	5.4
NaF	69, 75	5	1,100
		50	250
		100	90

TABLE 4g-11. THERMAL CONDUCTIVITY OF CRYSTALLINE DIELECTRICS AND OPTICAL MATERIALS (*Continued*)

(In watts/meter · kelvin)

Material	Ref.	T, K	Conductivity	Material	Ref.	T, K	Conductivity
Ne	52	2	3.0	SiO_2 (quartz) ⊥ to c axis	72	20	370
		3	4.6			194	10
		4.2	4.2			273	6.8
		10	0.8	SiO_2 (fused)	72	4.2	0.25
		20	0.3			20	0.7
NH_4Cl	46	77	17			77	0.8
		194	23			194	1.2
		230	38			273	1.4
		273	27			373	1.6
$NH_4H_2PO_4$ ∥ to optic axis	72	315	0.71			673	1.8
		339	0.71	TlBr	72	316	0.59
				TlCl	72	311	0.75
$NH_4H_2PO_4$ ⊥ to optic axis	72	313	1.26				
		342	1.34	TiO_2 (rutile) ∥ to optic axis	72	4.2	200
NiO	72	4.2	5.9			20	1,000
		10	100			273	13
		194	82				
SiO_2 (quartz) ∥ to c axis	72	20	720	TiO_2 (rutile) ⊥ to optic axis	72	4.2	160
		194	20			20	690
		273	12			273	9

Various authors differ from 5 to 25 % on the experimental results for the conductivities of crystalline dielectrics and optical materials.

See ref. 46 for additional data.

TABLE 4g-12. THERMAL CONDUCTIVITY OF DISORDERED DIELECTRICS, CERAMICS, REFRACTORY OXIDES, AND INSULATING MATERIALS
(In watts/meter · kelvin)

Material	Density g/cc	t, °C	Conductivity
Alumina	3.8	100	30
		400	13
		1,300	6
		1,800	7.4
	3.5	100	17
		800	7.6
Alumina + MgO	....	100	15
		400	10
		1,000	5.6
Asbestos	0.4	−100	0.07
		0	0.09
		100	0.1
Asbestos + 85 % MgO	0.3	30	0.08
Barium titanate	....	50	3
		100	2.8
		150	2.6
		200	2.4
Beryllia	2.8	100	210
		400	90
		1,000	20
		1,800	15
	1.85	50	64
		200	40
		600	23
Brick, dry	1.54	0	0.04
Brick refractory:			
Aloxite	....	1,000	1.3
Aluminous	1.99	400	1.2
		1,000	1.3
Diatomaceous	0.77	100	0.20
		500	0.24
	0.40	100	0.08
		500	0.10
Fireclay	2.0	400	1
		1,000	1.2
Silicon carbide	2	200	2
		600	2.4
Vermiculite	0.77	200	0.26
		600	0.31
Calcium oxide	....	100	16
		400	9
		1,000	7.5
Cement mortar	2.0	90	0.55
Charcoal	0.2	20	0.055
Concrete	1.6	0	0.8
Cork	0.05	0	0.03
		100	0.04
	0.35	0	0.06
		100	0.08
Cotton wool	0.08	30	0.04
Diatomite	0.2	0	0.05
		400	0.09
	0.5	0	0.09
		400	0.16
Ebonite	1.2	0	0.16
Felt, flax	0.2	30	0.05
	0.3	30	0.04
	0.3	30	0.05
Fuller's earth	0.53	30	0.10
Glass wool	0.2	−200 to 20	0.005
		50	0.04
		100	0.05
		300	0.08
Graphite, 100 mesh	0.48	40	0.18
20–40 mesh	0.70	40	1.29
Linoleum, cork	0.54	20	0.08

Material	Density g/cc	t, °C	Conductivity
Magnesium oxide	....	100	36
		400	18
		1,200	5.8
		1,700	9.2
Magnesium + SiO_2	....	100	5.3
		400	3.5
		1,500	2.3
Mica, muscovite	....	100	0.72
		300	0.65
		600	0.69
Phlogopite	....	100	0.66
Canadian	....	300	0.19
		600	0.20
Micanite	....	30	0.3
Mineral wool	0.15	30	0.04
Paper, fiber glass and Al foil layers	0.1	−200 to 20	0.0001
Perlite, expanded	0.1	−200 to 20	0.002
Plastic:			
Celluloid	1.4	30	0.02
Polystyrene foam	0.05	−200 to 20	0.033
Aluminized Mylar foil	0.05	−200 to 20	0.0001
Porcelain	....	90	1
Rock, basalt	....	20	2
Chalk	....	20	0.92
Granite	2.8	20	2.2
Limestone	2.0	20	1
Sandstone	2.2	20	1.3
Slate, ⊥	....	95	1.4
Slate, ∥	....	95	2.5
Rubber, sponge	0.2	20	0.05
Rubber, 92 %	....	25	0.16
Sawdust	0.2	30	0.06
Shellac	....	20	0.23
Silica aerogel	0.1	−200 to 20	0.003
Silica aerogel + 50 % Al	0.1	−200 to 20	0.003
Snow	0.25	0	0.16
Steel wool	0.1	55	0.09
Thoria	....	100	10
		400	5.8
		1,500	2.4
Titanium dioxide	....	100	6.5
		400	3.8
		1,200	3.3
Uranium dioxide	....	100	9.8
		400	5.5
		1,000	3.4
Wood, balsa, ⊥	0.11	30	0.04
Fir, ⊥	0.54	20	0.14
Fir, ∥	0.54	20	0.35
Pine, ⊥	0.45	60	0.11
Pine, ∥	0.45	60	0.26
Walnut, ⊥	0.65	20	0.14
Wool	0.09	30	0.04
Zinc oxide	....	200	17
		800	5.3
Zirconia	....	100	2
		400	2
		1,500	2.5
Zirconia + SiO_2	....	200	5.6
		600	4.6
		1,500	3.7

Values quoted are from W. D. Kingery et al. (ref. 33), R. W. Powell (ref. 48), and "International Critical Tables" (ref. 42).

Various authors differ from 10 to 50 % on the experimental results for the conductivities of disordered dielectrics, ceramics, refractory oxides, and insulating materials.

TABLE 4g-13. THERMAL CONDUCTIVITY OF SOME MATERIALS BELOW 1 K†
(In watts/meter · kelvin)

Material	Ref.	Temperature				
		0.2 K	0.4 K	0.6 K	0.8 K	1.0 K
Cr K Alum	72	0.05	0.3*	0.8*	2*	3.2
Epibond 104‡	2	0.00018	0.001	0.0025	0.0048	0.006*
In (superconducting)	18, 72	0.1*	1.2	7	15	23
KCl	4, 65	0.2*	1.6	5	16	30
KI	65	1.5*	6	22	50	100
Kel-F‡	2	0.00029	0.0012	0.0027	0.0045	0.006*
LiF	23	0.09	0.8	2	6.5	10
Nb (normal, superconducting)	13, 72	4.5*	9*	12*	20*	25
	13	0.1*	0.5	1.5	3.5	6
Nylon‡	2	0.00018	0.0006	0.0011	0.0015*	0.002*
Pyrex	2	0.001	0.003	0.0065	0.011	0.016*
Rubber (hard)	2	0.0025	0.007	0.015	0.02*	0.03*
Sn (normal, superconducting)	52, 78	100*	2000*	4500	6000	7000
	52, 35	0.4	2.5	15	80	150
Ta (normal, superconducting)	13, 72	3*	6*	8*	10*	11
	13	0.15*	0.9	3	9	10
Teflon‡	2	0.00008	0.0004	0.0013	0.0022*	0.0035*
Tl (normal, superconducting)	52, 78	2000*	4000*	6000*	7000*	8500*
	52, 78	0.06	5	120	600	1200

The conductivities of materials below 1 K are strongly dependent upon their chemical purity and physical perfection and, for small specimens, depend on the actual dimensions and surfaces. The values quoted are typical for these materials. See ref. 46 for additional data.

* Extrapolated values.

† The thermal conductivity of normal metals in the impurity range varies as $\lambda = aT$.

‡ Epibond is a diglycidal ether of bisphenol which is a fluid mixed in a ratio of 4:1 with powdered Bentonite clay. Kel-F is a polychlorotrifluorethylene. Nylon is a polyamide. Teflon is a polytetrafluorethylene.

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