

# PROPERTIES OF SELECTED MATERIALS AT CRYOGENIC TEMPERATURES

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The design of systems for operation at cryogenic temperatures requires the use of material properties at these low temperatures. The properties at cryogenic temperatures can be much different than the room-temperature values. In addition, some properties can be strong functions of temperature. Property data at cryogenic temperatures are not easy to find. Many measurements were made at the National Institute of Standards and Technology (NIST) and other laboratories about 50 years ago. Some of the results were published in reports that are now out of print, which makes the results unavailable to most researchers. To correct that problem, NIST initiated a program to critically evaluate cryogenic material properties and to curve fit the available data for temperatures in the range of about 4 K to 300 K. The parameters for the curve fit, as well as a graph of the curve, are available on the website [www.cryogenics.nist.gov](http://www.cryogenics.nist.gov). Click on "Material Properties" to find the list of materials. The properties available include thermal conductivity, specific heat, linear thermal expansion, thermal expansion coefficient, and Young's modulus. Not all properties are available for all materials. The materials currently in the database are ones commonly used in the construction of cryogenic hardware.

The tables presented here are the calculated values using the equations given on the website. In general the equations fit a single set of data to within about 1 % to 2 %, but often several sets of data are used in determining the best fit, in which case deviations can be significantly higher, such as 5 %. The website specifies the deviation of the fit relative to the experimental data for each property and each material. Uncertainties in the experimental data usually are in the range of 2 % to 5 %, and variations from sample to sample can also lead to similar uncertainties, especially in thermal conductivity. Some well-characterized materials, such as silicon, are used for standard reference materials. Thus, uncertainties in the experimental data for the thermal expansion coefficient of silicon are usually less than 0.2 %, and the standard deviation of the curve fit to the data is less than about 0.2 % over most of the temperature range

Copper referred to here is of very high purity 99.99% (4N or better) and may be considered oxygen-free (sometimes referred to as OFHC-oxygen free high conductivity). Values are given with respect to the RRR (Residual Resistivity Ratio) which correlates the thermal resistivity and electrical resistivity as the impurity effect and is primarily additive in resistivity. Higher RRR values indicate higher purity and lower electrical and thermal resistance leading to higher thermal conductivity. Standard high-purity copper such as grade 101 or 102 has an RRR value of approximately 100. Higher values may be obtained with considerable effort at minimizing trace impurities by special annealing techniques that can achieve an RRR of about 1000 or greater in some special instances. Specially obtained high RRR value copper is often used only when very low temperatures (< 40 K), and necessarily high thermal conduction at low temperature, are required.

Ti 15-3-3-3 has a nominal composition of 15% V, 3% Cr, 3% Sn, 3% Al, balance Ti. For the specific measurements documented by Canavan and Tuttle (Ref. 29), the exact composition is 14.88% V, 3.13% Cr, 2.88% Sn, 3.01% Al, bal. Ti. The composition for brass is 65% Cu, 32% Zn, 3% Pb which is free machining. The composition for BeCu is 2% Be, 0.3% Co, balance Cu.

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**Thermal Conductivity (in W m<sup>-1</sup> K<sup>-1</sup>)**

Temp. K	Al					Be	Be-Cu	Brass	Cu (OFHC)			G-10		Inconel-718	Invar (Fe-36Ni)	Kevlar-49	
	1100	3003	5083	6061	6063				RRR=50	RRR=100	RRR=300	(norm-dir)	(warp-dir)			Composite	Fiber
1						181.4	0.3161									0.002234	0.003775
2						355.0	0.8999									0.008663	0.01457
3						551.1	1.402									0.01853	0.03077
4	54.11	10.81	3.295	5.347	34.36	741.4	1.879		320.4	642.3		0.07229	0.07322	0.4624	0.2419	0.03089	0.05042
6	83.26	16.77	4.982	8.268	51.64	1082	2.850	3.143	466.8	931.7	2810	0.09112	0.09693	0.8644	0.4001	0.06021	0.09448
8	113.5	22.81	6.685	11.23	69.70	1410	3.877	4.400	622.3	1239	3636	0.1023	0.1179	1.199	0.5630	0.09263	0.1405
10	141.8	28.94	8.427	14.20	86.51	1754	4.955	5.702	778.1	1540	4320	0.1122	0.1361	1.519	0.7339	0.1261	0.1865
12	170.1	35.15	10.19	17.15	103.5	2120	6.069	7.028	927.3	1814	4829	0.1217	0.1518	1.832	0.9114	0.1595	0.2320
14	199.1	41.35	11.97	20.05	121.1	2502	7.207	8.362	1064	2045	5147	0.1309	0.1654	2.136	1.094	0.1920	0.2770
16	228.0	47.49	13.73	22.91	139.2	2887	8.357	9.696	1185	2226	5276	0.1398	0.1775	2.426	1.279	0.2234	0.3213
18	256.2	53.51	15.48	25.70	157.5	3262	9.511	11.02	1287	2352	5234	0.1483	0.1883	2.699	1.465	0.2533	0.3649
20	282.6	59.37	17.21	28.43	175.4	3611	10.66	12.33	1368	2423	5052	0.1565	0.1982	2.956	1.652	0.2819	0.4077
30	371.7	85.21	25.43	41.10	246.3	4685	16.27	18.56	1444	2143	3257	0.1912	0.2393	3.998	2.570	0.4059	0.6122
40	389.5	104.7	32.89	52.23	276.6	4571	21.48	24.12	1163	1485	1833	0.2176	0.2740	4.744	3.437	0.5080	0.8031
50	369.2	118.7	39.66	62.05	277.7	3823	26.20	29.02	863.6	1005	1130	0.2382	0.3061	5.316	4.247	0.5976	0.9841
60	338.0	128.6	45.85	70.76	265.6	2968	30.42	33.36	670.0	741.2	801.8	0.2553	0.3366	5.784	5.005	0.6794	1.157
70	308.1	135.6	51.55	78.55	250.0	2243	34.08	37.26	561.1	603.6	638.5	0.2702	0.3660	6.182	5.717	0.7555	1.323
80	283.3	140.6	56.81	85.56	235.4	1693	37.15	40.84	500.3	529.3	551.0	0.2837	0.3942	6.532	6.386	0.8269	1.482
90	264.1	144.4	61.71	91.91	223.2	1296	39.60	44.21	465.1	487.0	501.0	0.2965	0.4214	6.842	7.016	0.8943	1.634
100	249.7	147.4	66.26	97.70	213.8	1014	41.41	47.45	443.9	461.5	471.1	0.3089	0.4477	7.119	7.611	0.9579	1.779
120	231.5	151.9	74.52	107.9	201.8	670.0	43.12		421.8	434.8	440.6	0.3335	0.4978	7.587	8.702	1.075	2.050
140	222.3	155.5	81.80	116.5	196.6	489.9			411.6	422.1	427.6	0.3586	0.5450	7.962	9.671	1.180	2.297
160	218.2	158.9	88.26	123.9	195.5	390.7			406.0	415.0	421.2	0.3846	0.5899	8.264	10.524	1.274	2.523
180	216.4	162.2	94.04	130.4	196.6	333.3			402.6	410.3	417.5	0.4117	0.6328	8.510	11.270	1.359	2.729
200	215.5	165.5	99.24	136.0	198.6	298.0			400.1	407.0	414.6	0.4399	0.6741	8.720	11.915	1.436	2.917
220	214.8	168.6	104.0	141.0	200.5	274.2			398.2	404.2	411.8	0.4692	0.7141	8.912	12.464	1.507	3.090
240	213.9	171.5	108.3	145.3	201.9	255.5			396.5	401.9	408.8	0.4995	0.7530	9.101	12.925	1.571	3.250
260	213.0	174.1	112.2	149.1	202.3	237.6			395.0	399.9	405.5	0.5307	0.7909	9.301	13.303	1.630	3.398
280	212.1	176.2	115.9	152.4	201.8	217.9			393.6	398.0	401.8	0.5626	0.8278	9.528	13.604	1.685	3.536
300	211.8	177.8	119.3	155.3	200.5	194.9			392.4	396.3	397.9	0.5951	0.8636	9.793	13.835	1.735	3.664

Thermal Conductivity (in  $W m^{-1} K^{-1}$ ), continued

Temp. K	Fe-Ni Alloys						Platinum	Polyamide (Nylon)	Polyethylene Terephthalate (Mylar)	Polyimide (Kapton)	Polystyrene									
	Pb	Mo	Fe-2.25 Ni	Fe-3.5 Ni	Fe-5.0 Ni	Fe-9.0 Ni					12.66 kg m <sup>-3</sup>	32.04 kg m <sup>-3</sup>	49.98 kg m <sup>-3</sup>	99.96 kg m <sup>-3</sup>						
1																				
2									0.03092											
3									0.03610											
4	2682	56.74	1.119	0.9289	0.7754	0.6256	921.7	0.01245	0.03764	0.01079								0.009431		
6	700.1	90.04	1.787	1.455	1.223	0.9814	1210	0.01983	0.03978	0.01309							0.004852	0.008950		
8	313.3	118.4	2.460	1.999	1.679	1.349	1329	0.02880	0.04334	0.01802							0.004842	0.009014		
10	177.1	146.3	3.137	2.535	2.138	1.716	1240	0.03902	0.04791	0.02345							0.004862	0.009055		
12	118.3	175.4	3.809	3.064	2.599	2.080	1053	0.05014	0.05295	0.02883							0.004902	0.009098		
14	89.02	205.3	4.470	3.588	3.061	2.443	856.0	0.06185	0.05816	0.03397							0.004956	0.009155		
16	72.82	234.7	5.121	4.107	3.523	2.804	687.0	0.07388	0.06337	0.03884							0.005018	0.009226		
18	63.12	262.2	5.760	4.624	3.983	3.163	553.5	0.08602	0.06849	0.04345							0.005087	0.009307		
20	56.95	286.9	6.390	5.139	4.442	3.521	451.5	0.09811	0.07349	0.04782							0.005158	0.009393		
30	45.29	353.6	9.423	7.678	6.691	5.293	209.9	0.1543	0.09633	0.06704							0.003803	0.005533	0.009833	
40	41.97	345.0	12.28	10.11	8.825	7.022	137.0	0.1999	0.1158	0.08319							0.005073	0.005905	0.01026	
50	40.10	307.3	14.96	12.40	10.82	8.688	108.3	0.2352	0.1319	0.09706							0.006153	0.006272	0.01071	
60	38.73	267.3	17.42	14.52	12.68	10.28	94.57	0.2619	0.1443	0.1090							0.007232	0.006644	0.01121	
70	37.70	233.7	19.67	16.47	14.39	11.79	87.02	0.2821	0.1526	0.1192							0.008311	0.007031	0.01177	
80	36.98	207.9	21.71	18.25	15.98	13.21	82.32	0.2974	0.1567	0.1280							0.009382	0.007437	0.01239	
90	36.51	188.6	23.56	19.89	17.44	14.55	79.09	0.3091		0.1355							0.01265	0.01045	0.007868	0.01306
100	36.23	174.5	25.23	21.38	18.79	15.81	76.69	0.3179		0.1419							0.01362	0.01151	0.008328	0.01378
120	36.03	156.8	28.14	24.01	21.19	18.09	73.37	0.3298		0.1522							0.01567	0.01368	0.009344	0.01535
140	36.02	147.9	30.56	26.23	23.24	20.07	71.39	0.3367		0.1599							0.01790	0.01594	0.01050	0.01705
160	35.96	143.7	32.62	28.10	24.98	21.77	70.43	0.3405		0.1659							0.02032	0.01829	0.01180	0.01890
180	35.78	142.0	34.36	29.69	26.47	23.23	70.27	0.3424		0.1708							0.02293	0.02072	0.01325	0.02089
200	35.46	141.4	35.84	31.01	27.72	24.46	70.65	0.3431		0.1749							0.02576	0.02320	0.01486	0.02309
220	35.10	141.2	37.06	32.10	28.78	25.49	71.25	0.3428		0.1786							0.02881	0.02572	0.01662	0.02557
240	34.80	140.9	38.01	32.98	29.64	26.32	71.72	0.3420		0.1820							0.03210	0.02826	0.01854	0.02845
260	34.70	140.4	38.70	33.65	30.35	26.98	71.65	0.3406		0.1853							0.03561	0.03082	0.02059	0.03185
280	34.95	139.6	39.09	34.13	30.90	27.48	70.66	0.3389		0.1886							0.03934	0.03343	0.02278	0.03599
300		138.6	39.17	34.43	31.32	27.83	68.42	0.3368		0.1919							0.04323	0.03615	0.02509	0.04112

Thermal Conductivity (in  $W m^{-1} K^{-1}$ ), continued

Temp. K	Polyurethane				Polyvinyl Chloride (PVC)		Stainless Steel					Teflon	Torlon 4203	Ti-6Al-4V	Ti 15-3-3-3
	31.88 kg m <sup>-3</sup>	32.04 kg m <sup>-3</sup>	49.02 kg m <sup>-3</sup>	64.08 kg m <sup>-3</sup>	20.02 kg m <sup>-3</sup>	56.06 kg m <sup>-3</sup>	304	304L	310	316	735				
1											0.4028		0.004330		
2											0.5637		0.008974		0.05608
3											0.7972		0.01145		0.08043
4							0.2724	0.2724	0.2409	0.2724	1.052	0.04599	0.01280		0.1010
6							0.4653	0.4653	0.3960	0.4653	1.315	0.06624	0.01410		0.1450
8							0.6770	0.6770	0.5654	0.6770	1.583	0.08244	0.01467		0.1904
10							0.9039	0.9039	0.7457	0.9039	1.854	0.09545	0.01477		0.2354
12							1.143	1.143	0.9348	1.143	2.126	0.1066	0.01871		0.2796
14							1.391	1.391	1.131	1.391	2.399	0.1166	0.03501		0.3235
16							1.647	1.647	1.331	1.647	3.729	0.1258	0.04760		0.3673
18							1.906	1.906	1.534	1.906	4.937	0.1343	0.05696		0.4114
20							2.169	2.169	1.739	2.169	5.985	0.1422	0.06377	0.8426	0.4559
30			0.01133				3.469	3.469	2.741	3.469	6.872	0.1738	0.07797	1.656	0.6871
40			0.01238				4.670	4.670	3.648	4.670	7.618	0.1953	0.08344	1.905	0.9301
50			0.01352				5.730	5.730	4.430	5.730	8.247	0.2099	0.08884	2.411	1.177
60			0.01465	0.007880			6.647	6.647	5.093	6.647	8.783	0.2203	0.09491	2.917	1.420
70			0.01575	0.008571			7.435	7.435	5.655	7.435	9.245	0.2280	0.1014	3.291	1.655
80	0.01018		0.01684	0.009551			8.114	8.114	6.135	8.114	9.650	0.2341	0.1079	3.531	1.881
90	0.01115		0.01792	0.01065	0.01652		8.705	8.705	6.551	8.705	10.01	0.2391	0.1111	3.685	2.095
100	0.01212	0.01206	0.01900	0.01179	0.01680	0.02844	9.224	9.224	6.917	9.224	10.33	0.2434	0.1143	3.804	2.300
120	0.01399	0.01465	0.02117	0.01407	0.01799	0.02952	10.101	10.10	7.544	10.10	10.91	0.2505	0.1264	4.061	2.687
140	0.01574	0.01736	0.02336	0.01624	0.01931	0.03223	10.834	10.83	8.081	10.83	11.42	0.2562	0.1374	4.412	3.054
160	0.01734	0.02005	0.02554	0.01827	0.02072	0.03503	11.479	11.48	8.568	11.48	11.89	0.2608	0.1477	4.846	3.412
180	0.01881	0.02276	0.02765	0.02015	0.02232	0.03762	12.071	12.07	9.027	12.07	12.34	0.2644	0.1579	5.311	3.770
200	0.02013	0.02550	0.02964	0.02184	0.02416	0.04015	12.633	12.63	9.473	12.63	12.77	0.2672	0.1684	5.750	4.133
220	0.02125	0.02829	0.03144	0.02331	0.02628	0.04291	13.178	13.18	9.912	13.18	13.19	0.2692	0.1800	6.129	4.505
240	0.02210	0.03112	0.03297	0.02452	0.02879	0.04609	13.714	13.71	10.35	13.71	13.61	0.2705	0.1930	6.447	4.885
260	0.02255	0.03401	0.03418	0.02541	0.03184	0.04972	14.247	14.25	10.78	14.25	14.01	0.2715	0.2083	6.740	5.270
280	0.02248	0.03702	0.03500	0.02595	0.03574	0.05366	14.779	14.78	11.21	14.78	14.22	0.2722	0.2263	7.075	5.658
300	0.02181	0.04027	0.03540	0.02608	0.04093	0.05756	15.309	15.31	11.63	15.31	15.01	0.2728	0.2480	7.555	6.041

Specific Heat,  $C_p$  (in  $J\ kg^{-1}\ K^{-1}$ )

Temp. K	Al			Apiezon-N Grease	Be	Cu (OFHC)	G-10	Indium	Invar (Fe-36Ni)	Pb		Fe-Ni Alloys				Platinum
	3003	5083	6061							Normal	Superconducting	Fe-2.25Ni	Fe-3.5Ni	Fe-5.0Ni	Fe-9.0Ni	
1				0.02400							2.570					0.02435
2				0.2118							11.78					0.05529
3				0.8050							32.71					0.09667
4	0.2920	0.292	0.2920	2.031		0.09942	2.016	0.9463	0.9749		75.27					0.1524
6	0.6047	0.605	0.6047	6.761		0.2303	5.463	3.505	1.475		297.0					0.3300
8	1.048	1.048	1.048	14.38		0.4639	10.03	8.387	2.179		764.6					0.6349
10	1.573	1.573	1.573	24.32		0.8558	15.36	15.28	3.130	13.69	1539					1.115
12	2.268	2.268	2.268	35.98	0.5348	1.470	21.20	23.56	4.334	21.43						1.814
14	3.235	3.235	3.235	48.91	0.7169	2.375	27.41	32.62	5.814	29.51						2.770
16	4.581	4.581	4.581	62.76	0.9528	3.640	33.85	42.06	7.621	37.50						4.009
18	6.416	6.416	6.416	77.31	1.249	5.327	40.46	51.61	9.800	45.14						5.544
20	8.854	8.854	8.854	92.37	1.607	7.491	47.17	61.08	12.34	52.25						7.376
30	33.45	33.45	33.45	171.8	4.413	26.40	81.31	104.5		79.06						20.35
40	81.96	81.96	81.96	252.8	9.544	57.63	115.4	138.6		94.45						36.78
50	148.8	148.8	148.8	331.4	18.58	95.84	149.1	163.3		103.4		84.17	84.17	84.17	84.17	52.95
60	223.6	223.6	223.6	405.6	33.66	135.2	182.5	179.9		109.0		90.95	90.95	90.95	90.95	66.88
70	298.3	298.3	298.3	474.9	57.08	171.8	215.9	190.5		112.7		124.8	124.8	124.8	124.8	78.06
80	368.7	368.7	368.7	539.1	90.79	203.8	249.4	196.9		115.3		162.6	162.6	162.6	162.6	86.73
90	433.3	433.3	433.3	598.9	135.9	230.9	283.0	200.7		117.2		196.7	196.7	196.7	196.7	93.40
100	492.2	492.2	492.2	654.9	192.7	253.5	316.9	203.1		118.7		225.6	225.6	225.6	225.6	98.57
120	594.1	594.1	594.1	759.2	336.8	287.6	385.2	206.0		120.9		273.1	273.1	273.1	273.1	106.0
140	677.6	677.6	677.6	858.9	510.4	311.6	454.4	209.1		122.5		312.9	312.9	312.9	312.9	111.4
160	744.5	744.5	744.5	960.6	700.1	329.4	524.3	213.5		123.9		346.9	346.9	346.9	346.9	115.7
180	796.4	796.4	796.4	1070	897.4	343.4	594.4	219.0		125.2		375.1	375.1	375.1	375.1	119.5
200	835.2	835.2	835.2	1194	1097	355.0	664.4	225.0		126.3		397.6	397.6	397.6	397.6	122.9
220	863.7	863.7	863.7	1339	1296	364.7	733.9	230.6		127.4		415.8	415.8	415.8	415.8	125.7
240	885.4	885.4	885.4	1510	1488	372.6	802.5	234.5		128.4		431.0	431.0	431.0	431.0	127.7
260	904.6	904.6	904.6	1717	1661	378.6	869.8	235.7		129.2		443.8	443.8	443.8	443.8	128.8
280	925.8	925.8	925.8	1968	1800	382.5	935.3	233.1		129.8		453.5	453.5	453.5	453.5	128.7
300	953.9	953.9	953.9	2276	1883	384.0	998.7			130.1		457.7	457.7	457.7	457.7	



Specific Heat,  $C_p$  (in  $\text{J kg}^{-1} \text{K}^{-1}$ ), continued

Temp. K	Polyamide (Nylon)	Polyimide (Kapton)	Polystyrene			Polyurethane		Polyvinyl Chloride (PVC)	Stainless Steel				Teflon	
			99.96 $\text{kg m}^{-3}$	9.93 $\text{kg m}^{-3}$	6.07 $\text{kg m}^{-3}$	49.02 $\text{kg m}^{-3}$	389.25 $\text{kg m}^{-3}$		304	304L	310	316		
1														
2														
3														
4	1.560	0.7916							1.849	1.674	2.164	1.977	2.232	
6	4.986	2.708							2.945	2.557	3.166	2.963	3.690	
8	11.01	6.306							4.041	3.525	4.160	4.047	9.104	
10	20.00	11.68						9.335	5.163	4.571	5.226	5.203	18.02	
12	31.89	18.70						13.41	6.394	5.740	6.350	6.494	29.27	
14	46.34	27.10						17.57	7.806	7.004	7.524	7.958	41.50	
16	62.87	36.61						21.52	9.456	8.399	8.780	9.615	53.77	
18	80.98	46.96						25.25	11.39	10.02	10.18	11.49	65.60	
20	100.2	57.92				42.26		28.80	13.65	11.88	11.78	13.61	76.79	
30	201.4	116.2				70.85		46.12	30.70		25.79	29.22	124.3	
40	297.2	172.9				111.9		64.72	58.22		55.98	57.55	164.4	
50	383.5	224.3				158.3		84.66	94.57		98.21	100.2	202.1	
60	461.8	270.4				207.2		105.4	135.7		134.2	141.8	239.0	
70	534.2	311.7				257.8		126.8	177.4		167.7	179.9	275.6	
80	602.2	348.9				310.0		148.9	216.1		197.7	214.7	312.0	
90	667.0	382.8				363.9		171.6	250.2		224.1	245.8	348.4	
100	729.0	413.7	441.8	521.4	472.7	419.6	555.6	195.3	279.0		247.5	273.0	384.6	
120	846.2	468.4	540.4	583.5	535.8	535.9	635.4	246.2	322.3		287.1	317.3	456.7	
140	955.6	515.7	629.9	643.5	602.8	657.9	715.9	302.5	351.7		320.2	351.9	528.4	
160	1058	557.1	719.3	705.6	670.8	783.7	796.3	365.2	373.6		348.8	380.3	599.6	
180	1155	593.8	809.1	769.5	740.2	910.5	877.5	435.3	392.2		373.7	404.5	670.0	
200	1247	626.8	898.5	834.6	811.4	1035	959.0	514.3	410.0		395.0	424.8	738.9	
220	1335	656.6	987.3	900.6	884.2	1155	1039	604.1	428.0		413.2	441.6	805.8	
240	1421	683.9	1076	968.1	958.5	1268	1117	708.2	446.0		428.9	455.1	869.5	
260	1507	709.1	1164	1038	1035	1370	1193	831.5	463.5		443.0	466.5	929.2	
280	1594	732.5	1251	1111	1115	1460	1269	981.0	479.1		457.0	477.4	983.6	
300	1684	754.5	1337	1189	1201	1537	1351	1167	491.3		472.8	490.2	1032	

**Linear Thermal Expansion (in  $10^{-5}$ )**

Temp. K	Al			Be				G-10		Inconel- 718	Invar (Fe-36Ni)	Mo	Nb-Ti
	3003	5083	6061	(//a-axis)	(//c-axis)	Polycrystalline	Be-Cu	(norm-dir)	(warp-dir)				
4	-413.8		-413.8								-40		
6	-414.3		-414.3								-40		
8	-414.6		-414.6								-40		
10	-414.9		-414.9					-714.6			-40		
12	-415.2		-415.2					-713.3	-244.0		-40		
14	-415.3		-415.3					-712.1	-243.4		-40		
16	-415.4		-415.4					-710.7	-242.8		-40		
18	-415.5	-415.5	-415.5					-709.3	-242.2		-40		
20	-415.4	-415.4	-415.4					-707.9	-241.6	-238.9	-40	-92.4	-188.2
30	-414.3	-414.3	-414.3				-316.4	-699.7	-238.0	-238.4	-40	-92.46	-187.1
40	-411.5	-411.5	-411.5				-314.6	-690.1	-233.9	-236.9	-40	-92.04	-184.9
50	-407.3	-407.3	-407.3				-311.3	-679.0	-229.3	-234.5	-40	-91.21	-181.6
60	-401.6	-401.6	-401.6				-306.7	-666.5	-224.2	-231.2	-40	-89.98	-177.4
70	-394.5	-394.5	-394.5				-300.8	-652.6	-218.5	-227.0	-40	-88.39	-172.5
80	-386.1	-386.1	-386.1	-0.1480	-0.0970	-0.1313	-293.8	-637.2	-212.4	-222.1	-40.21	-86.45	-166.9
90	-376.4	-376.4	-376.4	-0.1468	-0.0967	-0.1302	-285.8	-620.5	-205.8	-216.3	-38.20	-84.19	-160.7
100	-365.4	-365.4	-365.4	-0.1450	-0.0960	-0.1287	-276.8	-602.4	-198.8	-209.9	-36.13	-81.64	-154.1
120	-340.2	-340.2	-340.2	-0.1395	-0.0935	-0.1240	-256.2	-562.1	-183.5	-194.9	-31.84	-75.74	-147.1
140	-310.8	-310.8	-310.8	-0.1316	-0.0892	-0.1172	-232.9	-516.4	-166.6	-177.6	-27.45	-68.91	-139.8
160	-277.8	-277.8	-277.8	-0.1213	-0.0832	-0.1083	-207.3	-465.4	-148.4	-158.2	-23.04	-61.31	-132.3
180	-241.5	-241.5	-241.5	-0.1088	-0.0755	-0.0973	-179.9	-409.3	-129.0	-137.0	-18.70	-53.08	-124.7
200	-202.6	-202.6	-202.6	-0.0942	-0.0660	-0.0844	-150.9	-348.2	-108.5	-114.4	-14.53	-44.34	-117.0
220	-161.5	-161.5	-161.5	-0.0774	-0.0547	-0.0696	-120.6	-282.1	-87.16	-90.64	-10.62	-35.22	-109.2
240	-118.6	-118.6	-118.6	-0.0588	-0.0419	-0.0529	-89.16	-211.2	-65.01	-66.17	-7.062	-25.80	-101.3
260	-74.40	-74.40	-74.40	-0.0382	-0.0273	-0.0345	-56.57	-135.6	-42.27	-41.26	-3.941	-16.18	-93.46
280	-29.45	-29.45	-29.45	-0.0160	-0.0113	-0.0144	-22.76	-55.33	-19.08	-16.25	-1.352	-6.431	-85.61
300	15.81	15.81	15.81	0.0079	0.0063	0.0073	12.43	29.44	4.398	8.536	0.6163	3.390	-77.77

Linear Thermal Expansion (in  $10^{-5}$ ), continued

Temp. K	Fe-Ni Alloys				Polyamide (Nylon)	Polystyrene		Polyurethane		Polyvinyl Chloride (PVC)	Sapphire	Stainless Steel			
	Fe-2.25Ni	Fe-3.5Ni	Fe-5.0Ni	Fe-9.0Ni		51.42 kg m <sup>-3</sup>	102.2 kg m <sup>-3</sup>	32.04 kg m <sup>-3</sup>	64.07 kg m <sup>-3</sup>			304	304L	310	316
4	-210.5	-210.5	-210.5	-210.5	-1389	-1697	-1742			-1025		-297.0	-297.0	-297.0	-297.0
6	-210.6	-210.6	-210.6	-210.6	-1389	-1698	-1738			-1020		-297.6	-297.6	-297.6	-297.6
8	-210.5	-210.5	-210.5	-210.5	-1388	-1698	-1735			-1016		-298.1	-298.1	-298.1	-298.1
10	-210.5	-210.5	-210.5	-210.5	-1388	-1697	-1732			-1011		-298.6	-298.6	-298.6	-298.6
12	-210.4	-210.4	-210.4	-210.4	-1387	-1696	-1730			-1006		-299.0	-299.0	-299.0	-299.0
14	-210.2	-210.2	-210.2	-210.2	-1386	-1694	-1727			-1001	-79.13	-299.4	-299.4	-299.4	-299.4
16	-210.1	-210.1	-210.1	-210.1	-1384	-1691	-1724			-996.6	-79.16	-299.6	-299.6	-299.6	-299.6
18	-209.9	-209.9	-209.9	-209.9	-1383	-1688	-1721			-991.7	-79.19	-299.8	-299.8	-299.8	-299.8
20	-209.6	-209.6	-209.6	-209.6	-1381	-1685	-1718	-808.3	-1050	-986.7	-79.21	-300.0	-300.0	-300.0	-300.0
30	-207.9	-207.9	-207.9	-207.9	-1369	-1660	-1702	-803.6	-1036	-961.0	-79.29	-299.7	-299.7	-299.7	-299.7
40	-205.4	-205.4	-205.4	-205.4	-1352	-1624	-1679	-795.4	-1019	-934.0	-79.25	-297.9	-297.9	-297.9	-297.9
50	-202.2	-202.2	-202.2	-202.2	-1331	-1579	-1647	-784.1	-998.9	-905.9	-79.07	-294.7	-294.7	-294.7	-294.7
60	-198.3	-198.3	-198.3	-198.3	-1306	-1525	-1605	-769.9	-975.6	-876.8	-78.73	-290.2	-290.2	-290.2	-290.2
70	-193.8	-193.8	-193.8	-193.8	-1278	-1464	-1551	-752.9	-949.5	-846.9	-78.21	-284.5	-284.5	-284.5	-284.5
80	-188.8	-188.8	-188.8	-188.8	-1246	-1398	-1489	-733.5	-921.0	-816.2	-77.49	-277.7	-277.7	-277.7	-277.7
90	-183.3	-183.3	-183.3	-183.3	-1211	-1329	-1419	-711.8	-890.1	-784.8	-76.54	-269.9	-269.9	-269.9	-269.9
100	-177.3	-177.3	-177.3	-177.3	-1173	-1257	-1346	-688.1	-857.3	-752.7	-75.36	-261.2	-261.2	-261.2	-261.2
120	-164.1	-164.1	-164.1	-164.1	-1090	-1117	-1203	-635.1	-786.3	-686.9	-72.23	-241.3	-241.3	-241.3	-241.3
140	-149.6	-149.6	-149.6	-149.6	-997.9	-979.1	-1059	-575.9	-709.3	-619.1	-68.01	-218.6	-218.6	-218.6	-218.6
160	-133.8	-133.8	-133.8	-133.8	-897.2	-842.6	-916.7	-511.6	-627.6	-549.2	-62.65	-193.7	-193.7	-193.7	-193.7
180	-117.0	-117.0	-117.0	-117.0	-788.5	-706.8	-777.2	-443.1	-542.0	-477.0	-56.12	-167.1	-167.1	-167.1	-167.1
200	-99.05	-99.05	-99.05	-99.05	-671.9	-571.7	-640.6	-371.2	-453.1	-402.2	-48.44	-139.1	-139.1	-139.1	-139.1
220	-80.06	-80.06	-80.06	-80.06	-546.8	-438.1	-506.0	-296.3	-361.3	-324.1	-39.65	-110.2	-110.2	-110.2	-110.2
240	-59.90	-59.90	-59.90	-59.90	-412.3	-307.4	-372.2	-218.9	-266.8	-241.7	-29.84	-80.50	-80.50	-80.50	-80.50
260	-38.39	-38.39	-38.39	-38.39	-266.9	-182.1	-236.6	-138.9	-169.3	-154.0	-19.10	-50.35	-50.35	-50.35	-50.35
280	-15.27	-15.27	-15.27	-15.27	-109.0	-65.04	-96.21	-56.39	-68.57	-59.6	-7.589	-19.87	-19.87	-19.87	-19.87
300	9.770	9.770	9.770	9.770	64.02	39.90	53.03	28.96	36.16	43.09	4.523	10.86	10.86	10.86	10.86

**Linear Thermal Expansion (in  $10^{-5}$ ), continued**

<b>Temp. K</b>	<b>Stycast 2850 FT (Epoxy)</b>	<b>Teflon</b>	<b>Ti-6Al-4V</b>
4	-44.57	-2127	-171.9
6	-44.53	-2127	-172.3
8	-44.48	-2127	-172.5
10	-44.43	-2127	-172.8
12	-44.38	-2126	-173.0
14	-44.32	-2125	-173.2
16	-44.25	-2123	-173.4
18	-44.18	-2121	-173.5
20	-44.11	-2119	-173.6
30	-43.68	-2102	-173.4
40	-43.15	-2077	-172.5
50	-42.53	-2047	-170.7
60	-41.80	-2012	-168.2
70	-40.99	-1972	-165.0
80	-40.08	-1930	-161.1
90	-39.08	-1886	-156.6
100	-37.99	-1839	-151.6
120	-35.55	-1742	-139.9
140	-32.76	-1639	-126.4
160	-29.65	-1529	-111.4
180	-26.20	-1406	-95.39
200	-22.43	-1265	-78.55
220	-18.32	-1095	-61.28
240	-13.87	-883.3	-43.92
260	-9.082	-615.6	-26.82
280	-3.936	-273.8	-10.30
300	1.579	162.2	5.285

Coefficient of Thermal Expansion, CTE

Temp. K	Cu (OFHC) $10^{-6} \text{K}^{-1}$	Sapphire $10^{-6} \text{K}^{-1}$	Si $10^{-8} \text{K}^{-1}$	Phosphor-bronze $10^{-6} \text{K}^{-1}$
0.1			0.0000004800	
0.2			0.000003840	
0.4			0.00003072	
0.6			0.00001037	
0.8			0.00002458	
1			0.0000600	
2			0.00004800	
3			0.0003840	
4	0.002281	0.0001060	0.001296	
6	0.009244	0.0003781	0.003072	
8	0.01893	0.0008953	0.01037	
10	0.03338	0.0016535	0.02458	0.06000
12	0.05522	0.0027127	0.04800	0.1048
14	0.08720	0.0041822	0.08294	0.1657
16	0.1321	0.0061990	0.1331	0.2444
18	0.1927	0.0089156	0.1103	0.3421
20	0.2715	0.01249	-0.04541	0.4599
30	0.9888	0.04771	-0.3407	1.352
40	2.229	0.1152	-5.330	2.667
50	3.790	0.2093	-16.61	4.215
60	5.426	0.3323	-29.23	5.807
70	6.968	0.5154	-40.33	7.309
80	8.335	0.8437	-46.61	8.653
90	9.506		-47.18	9.815
100	10.49		-42.69	10.80
120	12.02		-21.48	12.32
140	13.13		11.13	13.39
160	13.97		49.33	14.17
180	14.65		87.86	14.78
200	15.21		123.6	15.29
220	15.67		156.3	15.73
240	16.05		185.1	16.12
260	16.33		210.8	16.48
280	16.51		233.1	16.78
300	16.58		252.6	17.04

**Youngs Modulus,  $E$  (in GPa)**

Temp. K	Al		Invar (Fe-36Ni)	Fe-Ni Alloys				Stainless Steel		
	5083	6061		Fe-2.25Ni	Fe-3.5Ni	Fe-5.0Ni	Fe-9.0Ni	304	310	316
2	80.85	77.73	141.6	217.7	215.4	209.2	205.4			
4	80.87	77.75	141.7	217.7	215.4	209.2	205.4	210.1	206.7	
6	80.89	77.76	141.7	217.7	215.4	209.3	205.4	210.2	206.7	
8	80.90	77.78	141.7	217.7	215.4	209.3	205.5	210.2	206.7	207.9
10	80.91	77.79	141.7	217.7	215.4	209.3	205.5	210.2	206.7	207.8
12	80.92	77.80	141.7	217.7	215.4	209.4	205.5	210.2	206.7	207.8
14	80.92	77.80	141.7	217.7	215.4	209.4	205.5	210.1	206.7	207.9
16	80.93	77.81	141.7	217.7	215.4	209.4	205.5	210.1	206.7	207.9
18	80.93	77.81	141.7	217.7	215.4	209.4	205.5	210.1	206.6	208.0
20	80.93	77.81	141.7	217.7	215.4	209.4	205.5	210.1	206.6	208.1
30	80.90	77.78	141.6	217.7	215.4	209.5	205.6	210.4	206.5	208.8
40	80.82	77.71	141.4	217.6	215.3	209.5	205.5	211.7	206.3	209.3
50	80.70	77.60	141.1	217.4	215.1	209.5	205.4	213.4	206.0	209.6
60	80.54	77.46	140.8	217.2	214.9	209.4	205.2	214.6	205.7	209.5
70	80.34	77.28	140.5	217.0	214.6	209.3	205.0	214.5	205.3	209.3
80	80.11	77.08	140.1	216.7	214.3	209.1	204.8	214.4	204.9	209.0
90	79.85	76.86	139.9	216.4	214.0	208.9	204.5	214.1	204.5	208.7
100	79.56	76.61	139.7	216.0	213.6	208.7	204.2	213.7	204.0	208.2
120	78.92	76.07	139.5	215.2	212.8	208.1	203.5	212.8	202.9	207.2
140	78.21	75.48	139.7	214.3	211.9	207.3	202.7	211.5	201.7	206.0
160	77.45	74.86	140.3	213.3	211.0	206.4	201.8	210.1	200.4	204.7
180	76.65	74.21	141.3	212.3	210.0	205.4	200.9	208.7	199.1	203.3
200	75.82	73.56	142.8	211.2	208.9	204.3	199.9	207.2	197.7	201.8
220	74.98	72.89	144.6	210.2	207.9	203.1	198.9	205.6	196.3	200.3
240	74.14	72.22	146.7	209.1	206.8	201.9	197.9	204.1	194.8	198.8
260	73.30	71.54	148.8	208.0	205.7	200.6	196.9	202.4	193.4	197.3
280	72.46	70.83	150.8	206.9	204.7	199.4	195.9	200.7	191.9	195.7
300	71.62	70.10	152.4	205.8	203.6	198.2	194.9	198.8	190.3	194.1