Cryogenic Design References

Rev 1

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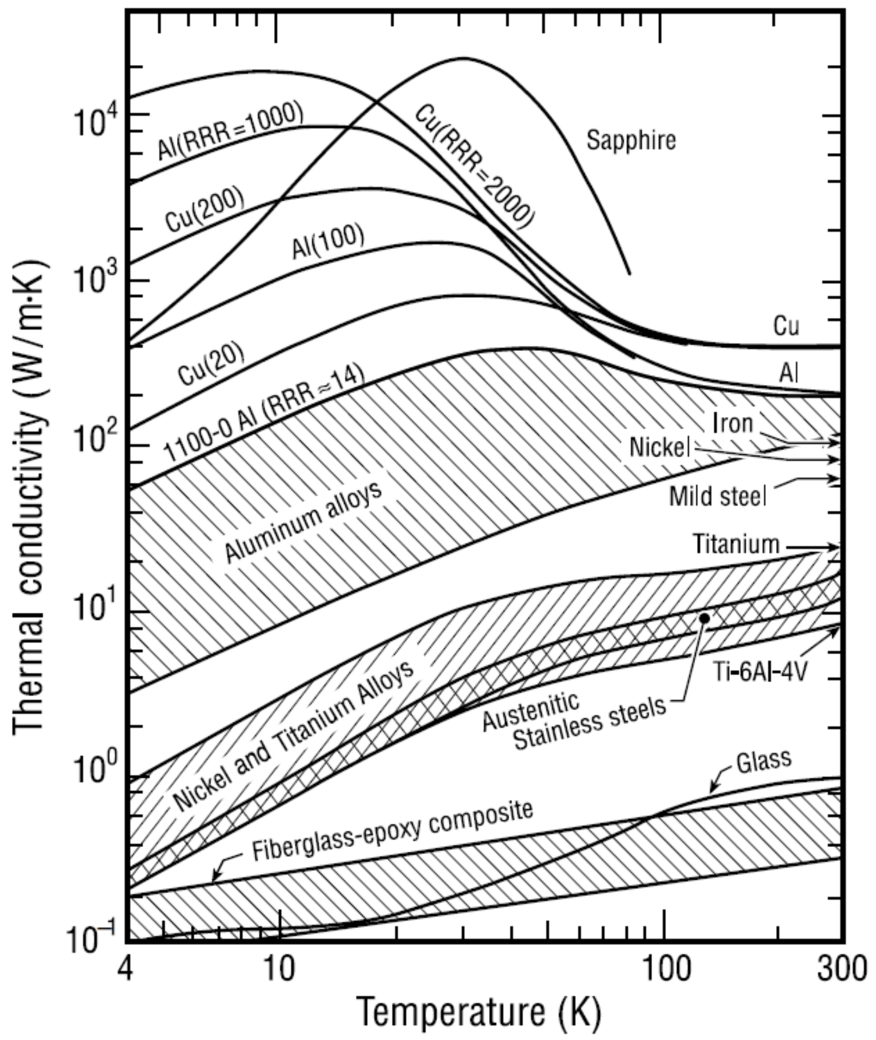
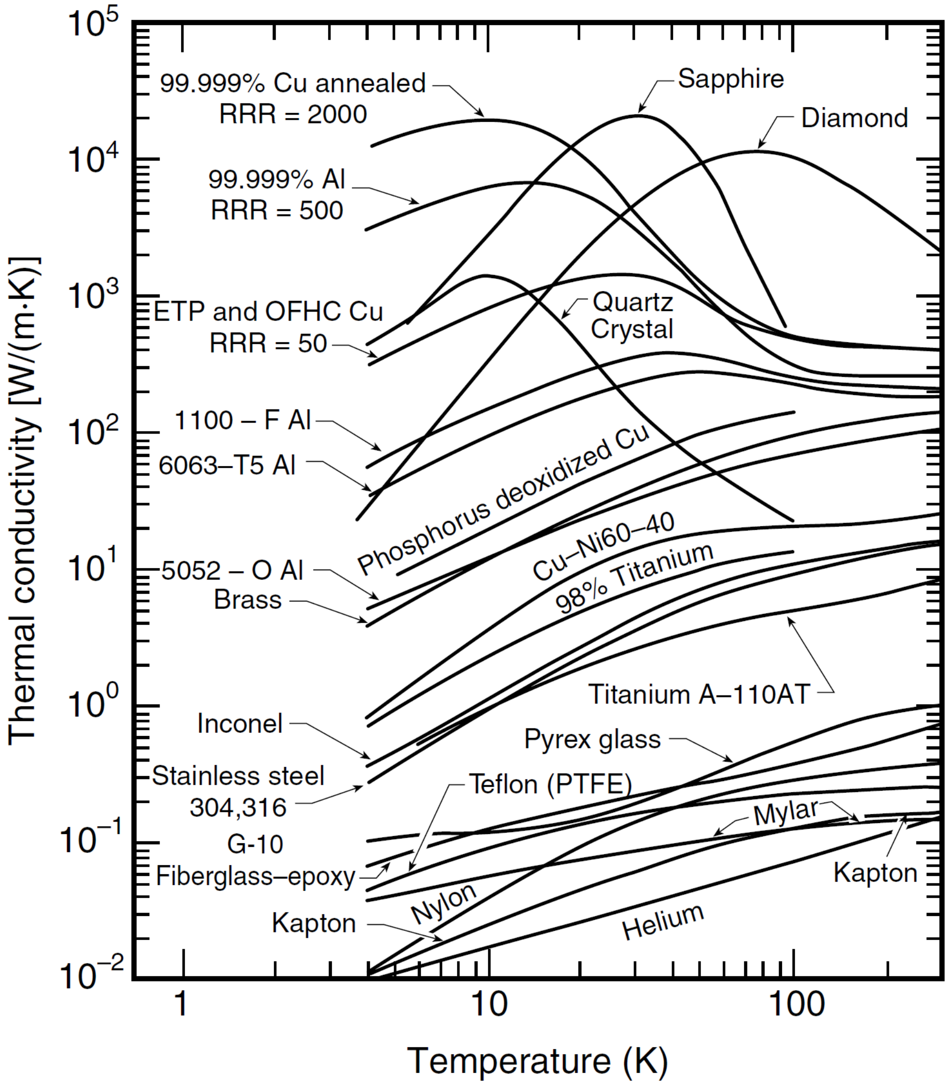
Contents

Thermal Conductivity

Thermal Conductivity Overview





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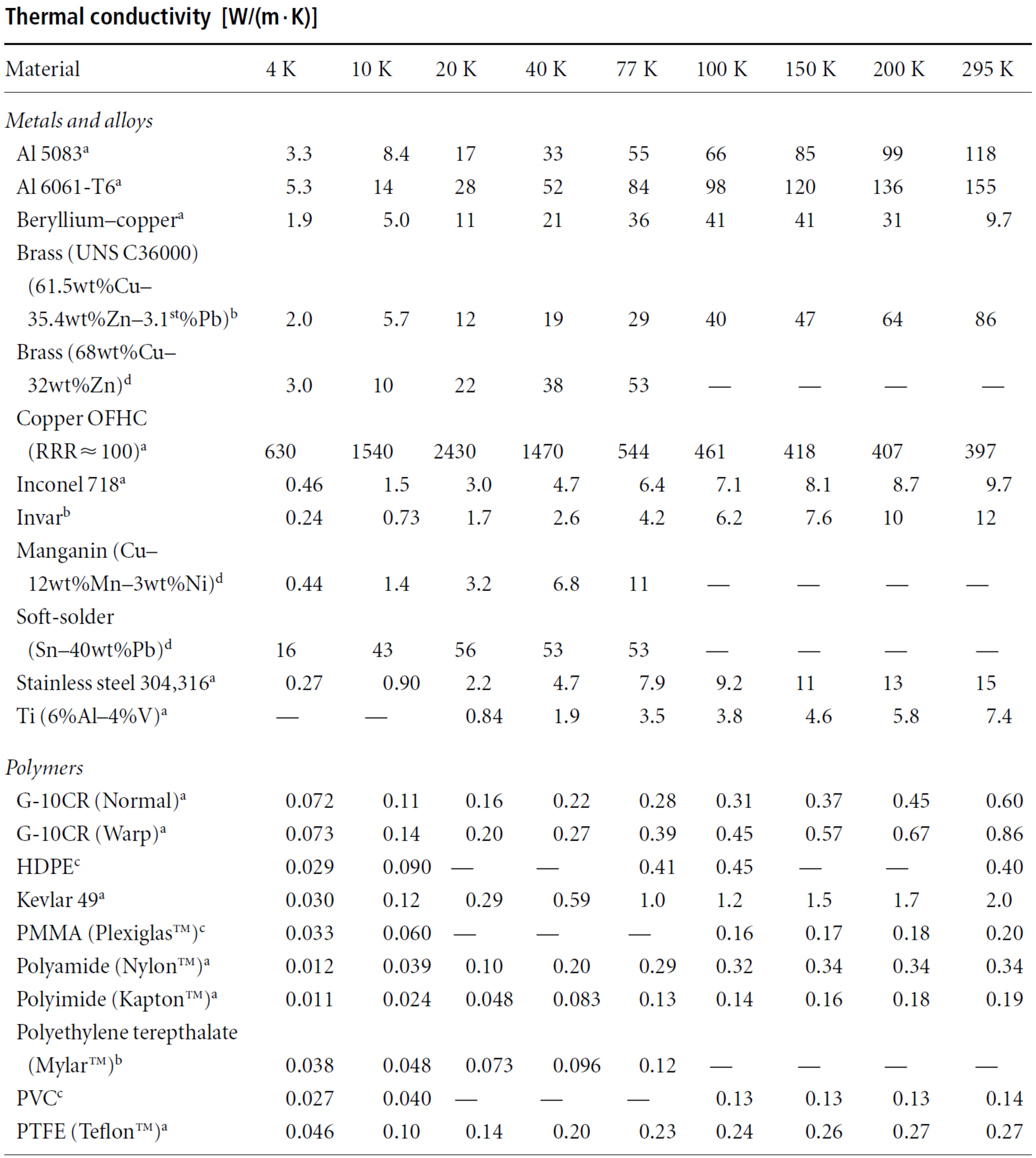
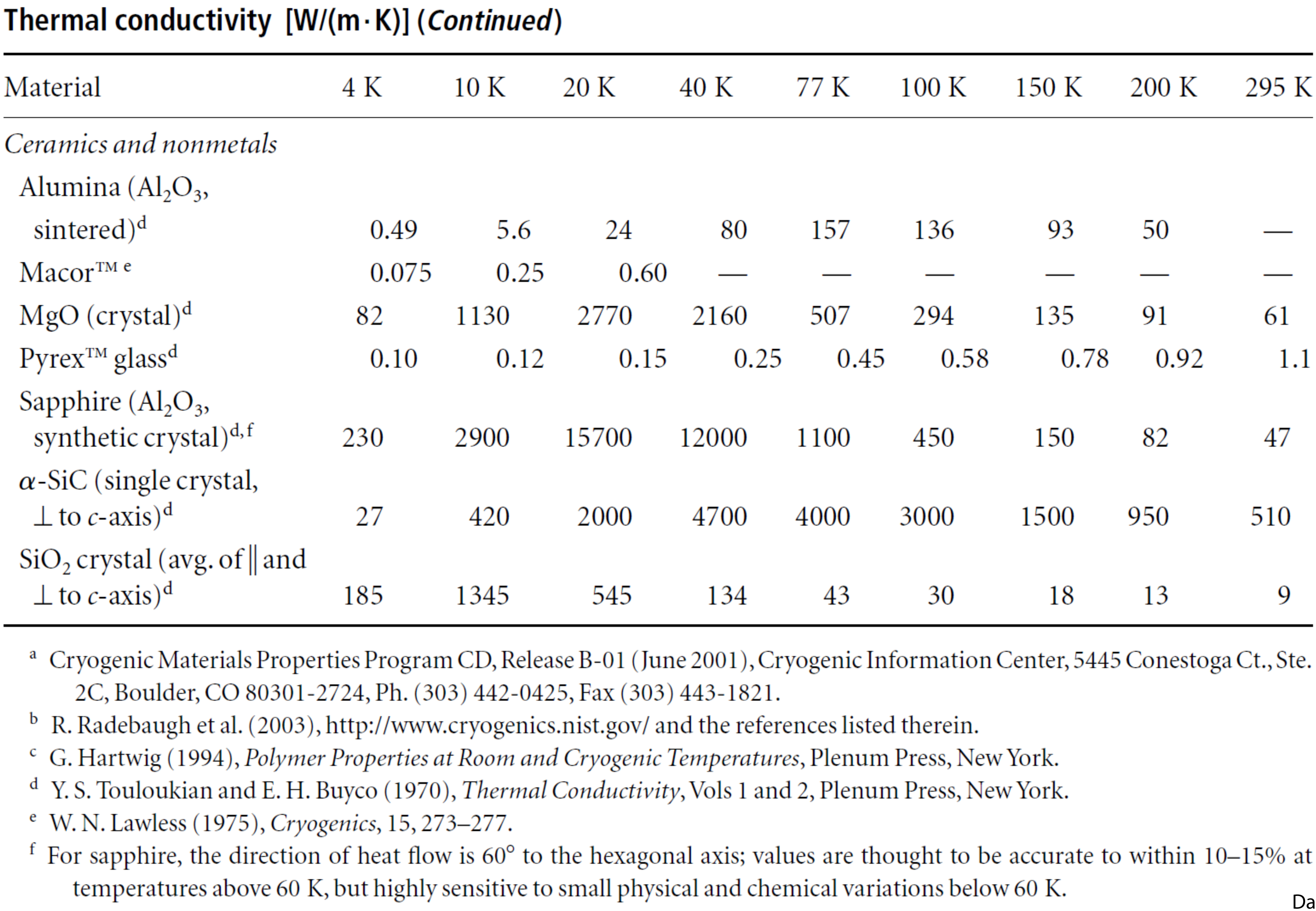


Thermal conductivity [W/(m·K)]

Material	4 K	10 K	20 K	40 K	77 K	100 K	150 K	200 K	295 K
Metals and alloys									
Al 5083[a]	3.3	8.4	17	33	55	66	85	99	118
Al 6061-T6[a]	5.3	14	28	52	84	98	120	136	155
Beryllium–copper[a]	1.9	5.0	11	21	36	41	41	31	9.7
Brass (UNS C36000) (61.5wt%Cu–35.4wt%Zn–3.1st%Pb)[b]	2.0	5.7	12	19	29	40	47	64	86
Brass (68wt%Cu–32wt%Zn)[d]	3.0	10	22	38	53	—	—	—	—
Copper OFHC (RRR ≈ 100)[a]	630	1540	2430	1470	544	461	418	407	397
Inconel 718[a]	0.46	1.5	3.0	4.7	6.4	7.1	8.1	8.7	9.7
Invar[b]	0.24	0.73	1.7	2.6	4.2	6.2	7.6	10	12
Manganin (Cu–12wt%Mn–3wt%Ni)[d]	0.44	1.4	3.2	6.8	11	—	—	—	—
Soft-solder (Sn–40wt%Pb)[d]	16	43	56	53	53	—	—	—	—
Stainless steel 304,316[a]	0.27	0.90	2.2	4.7	7.9	9.2	11	13	15
Ti (6%Al–4%V)[a]	—	—	0.84	1.9	3.5	3.8	4.6	5.8	7.4
Polymers									
G-10CR (Normal)[a]	0.072	0.11	0.16	0.22	0.28	0.31	0.37	0.45	0.60
G-10CR (Warp)[a]	0.073	0.14	0.20	0.27	0.39	0.45	0.57	0.67	0.86
HDPE[c]	0.029	0.090	—	—	0.41	0.45	—	—	0.40
Kevlar 49[a]	0.030	0.12	0.29	0.59	1.0	1.2	1.5	1.7	2.0
PMMA (Plexiglas™)[c]	0.033	0.060	—	—	—	0.16	0.17	0.18	0.20
Polyamide (Nylon™)[a]	0.012	0.039	0.10	0.20	0.29	0.32	0.34	0.34	0.34
Polyimide (Kapton™)[a]	0.011	0.024	0.048	0.083	0.13	0.14	0.16	0.18	0.19
Polyethylene terepthalate (Mylar™)[b]	0.038	0.048	0.073	0.096	0.12	—	—	—	—
PVC[c]	0.027	0.040	—	—	—	0.13	0.13	0.13	0.14
PTFE (Teflon™)[a]	0.046	0.10	0.14	0.20	0.23	0.24	0.26	0.27	0.27

Data from: Ekin (2007)



Thermal conductivity [W/(m·K)] (*Continued*)

Material	4 K	10 K	20 K	40 K	77 K	100 K	150 K	200 K	295 K
Ceramics and nonmetals									
Alumina (Al_2O_3, sintered)[d]	0.49	5.6	24	80	157	136	93	50	—
Macor™ [e]	0.075	0.25	0.60	—	—	—	—	—	—
MgO (crystal)[d]	82	1130	2770	2160	507	294	135	91	61
Pyrex™ glass[d]	0.10	0.12	0.15	0.25	0.45	0.58	0.78	0.92	1.1
Sapphire (Al_2O_3, synthetic crystal)[d,f]	230	2900	15700	12000	1100	450	150	82	47
α-SiC (single crystal, $\perp$ to c-axis)[d]	27	420	2000	4700	4000	3000	1500	950	510
SiO_2 crystal (avg. of $\parallel$ and $\perp$ to c-axis)[d]	185	1345	545	134	43	30	18	13	9

[a] Cryogenic Materials Properties Program CD, Release B-01 (June 2001), Cryogenic Information Center, 5445 Conestoga Ct., Ste. 2C, Boulder, CO 80301-2724, Ph. (303) 442-0425, Fax (303) 443-1821.

[b] R. Radebaugh et al. (2003), http://www.cryogenics.nist.gov/ and the references listed therein.

[c] G. Hartwig (1994), *Polymer Properties at Room and Cryogenic Temperatures*, Plenum Press, New York.

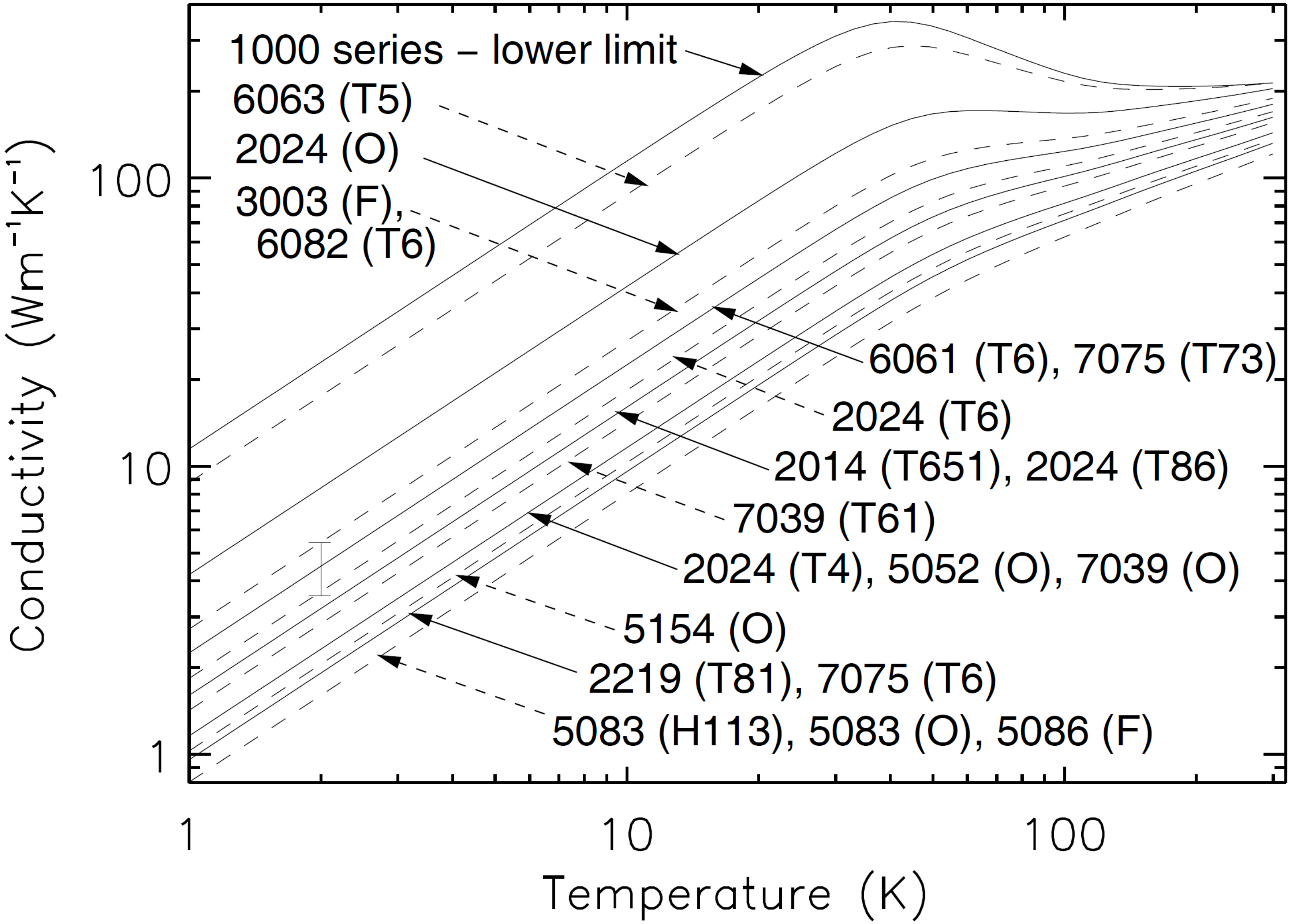
[d] Y. S. Touloukian and E. H. Buyco (1970), *Thermal Conductivity*, Vols 1 and 2, Plenum Press, New York.

[e] W. N. Lawless (1975), *Cryogenics*, 15, 273–277.

[f] For sapphire, the direction of heat flow is 60° to the hexagonal axis; values are thought to be accurate to within 10–15% at temperatures above 60 K, but highly sensitive to small physical and chemical variations below 60 K.

Data from: Ekin (2007)

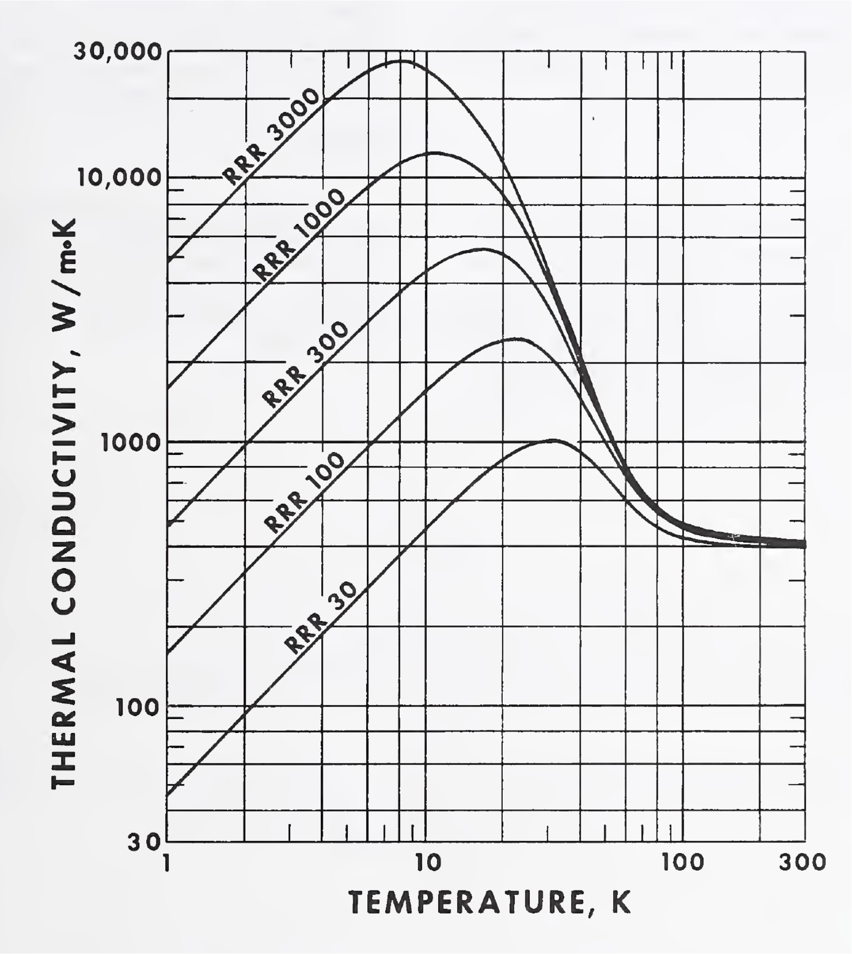
Aluminum

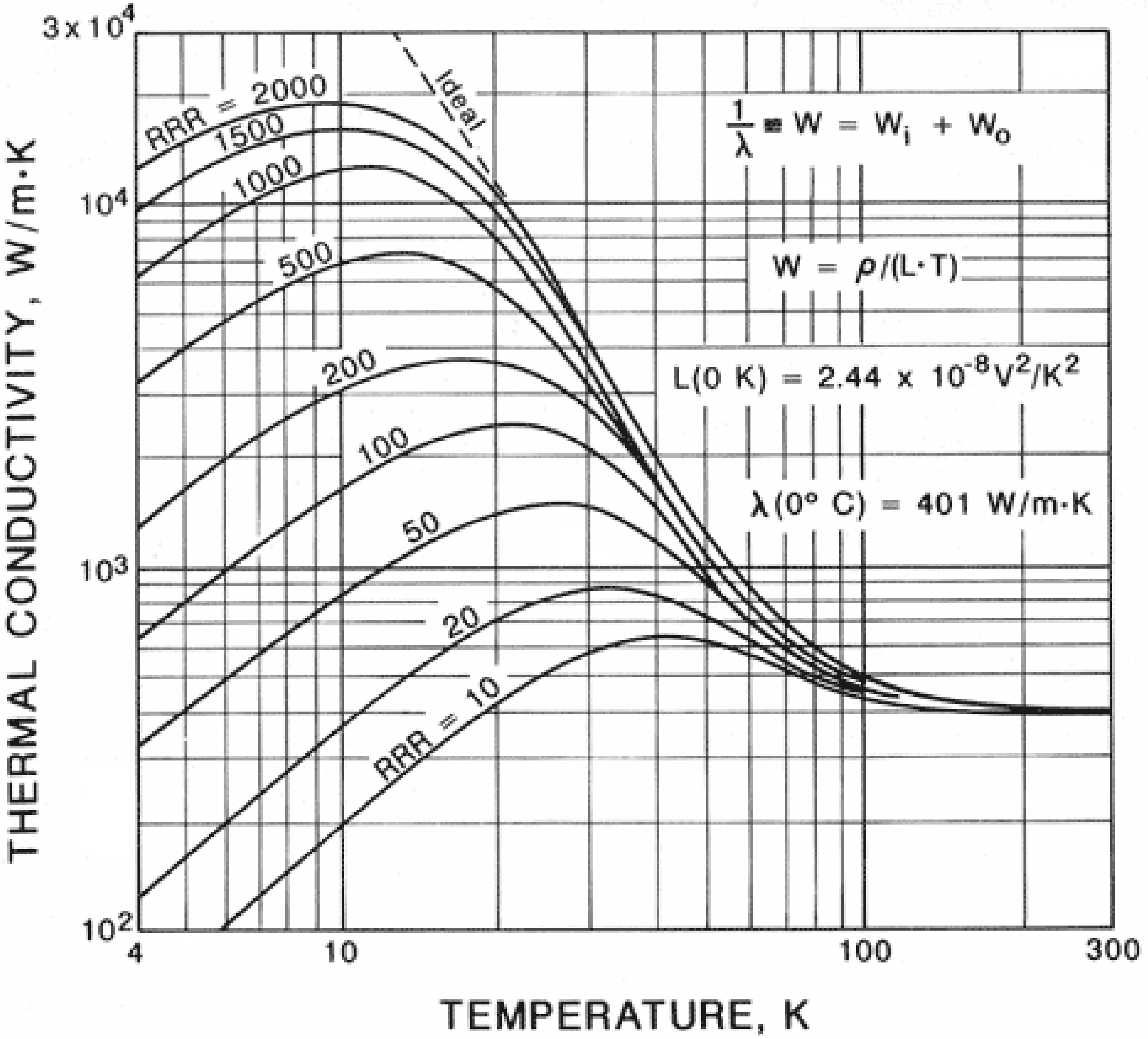


A. Woodcraft, "Predicting the thermal conductivity of aluminium alloys in the cryogenic to room temperature range", Cryogenics 45(6): 421-432, 2005.

Thermal Conductivity of Copper

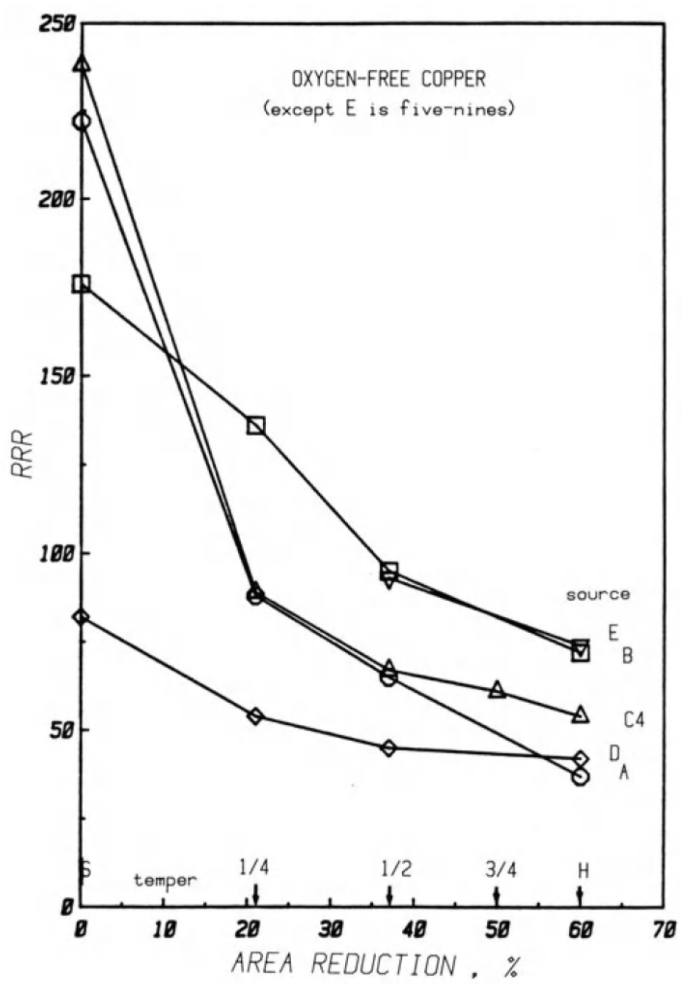
Copper Thermal Conductivity



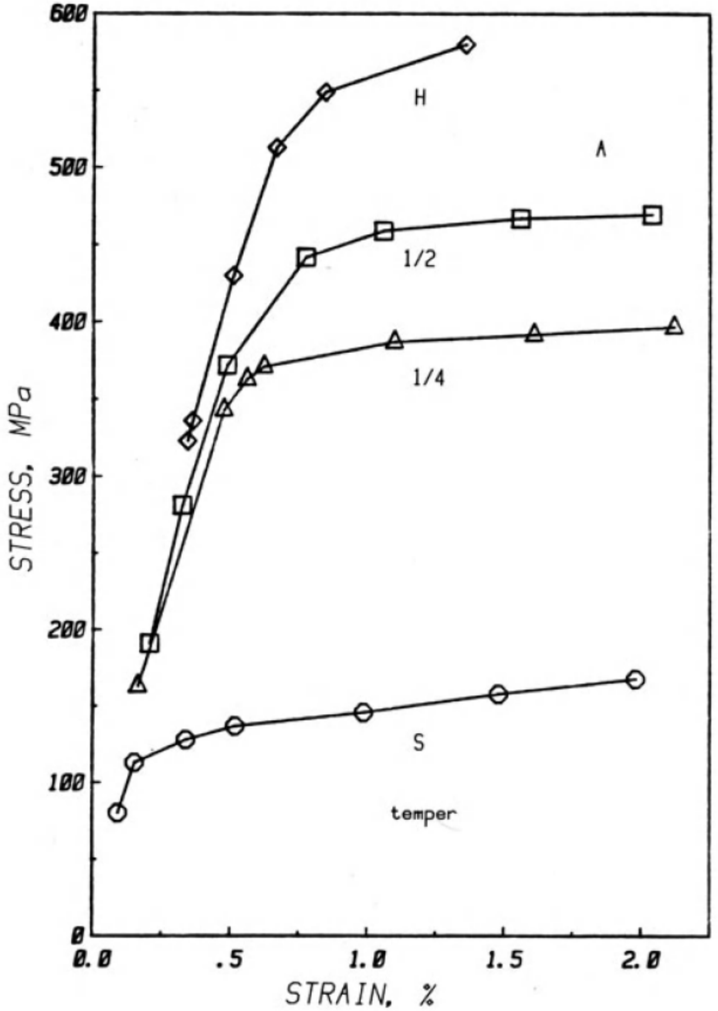


Copper Temper vs Thermal Conductivity

(THE EFFECT OF MILL TEMPER ON THE MECHANICAL AND MAGNETORESISTIVE PROPERTIES OF OXYGEN-FREE COPPER IN LIQUID HELIUM - F. R. Fickett)

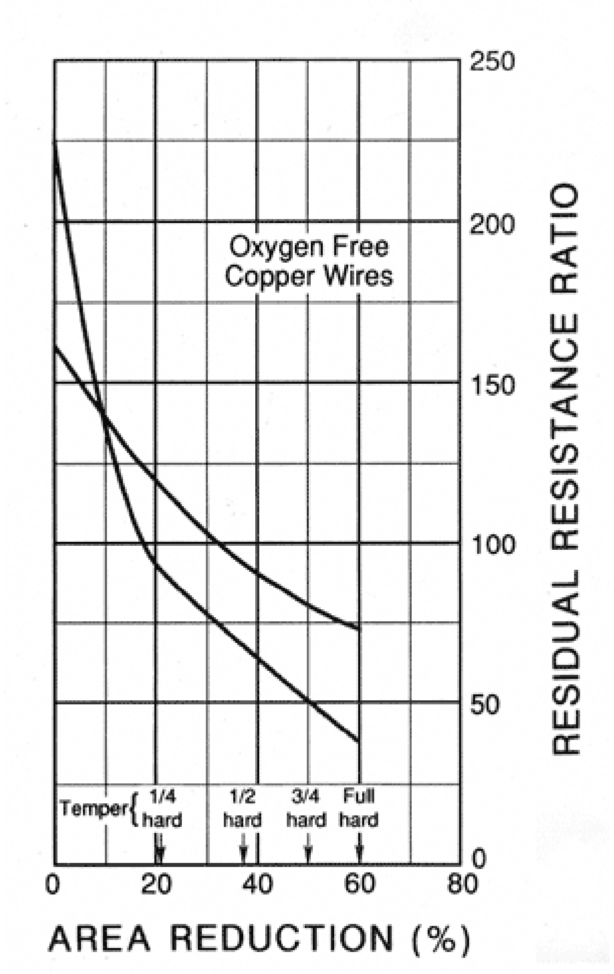


- The effect of drawing on the residual resistance ratio of copper. Area reductions corresponding to the various tempers are shown by the arrows.



- The effect of temper on the stress-strain behavior of oxygen-free copper at 4 K.

Copper Temper vs Thermal Conductivity



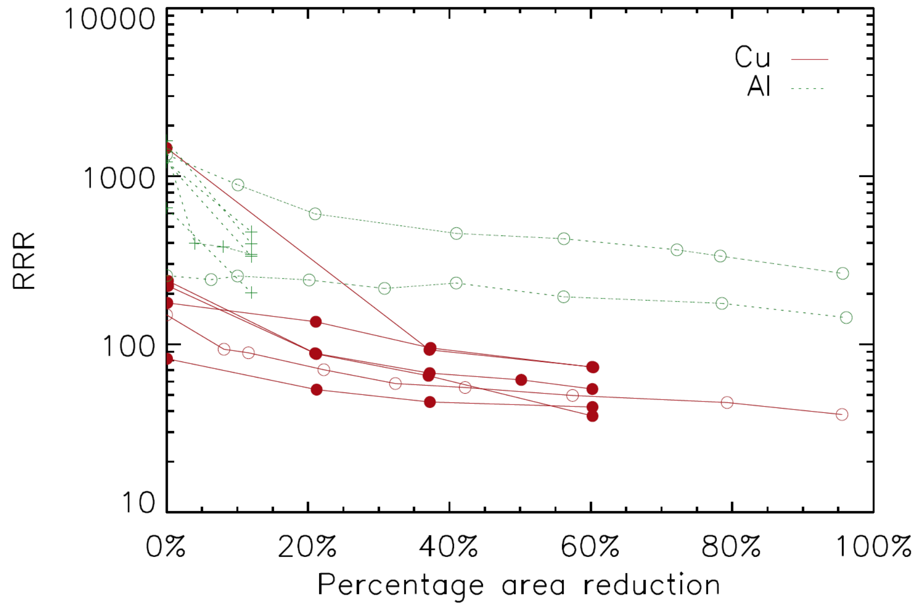
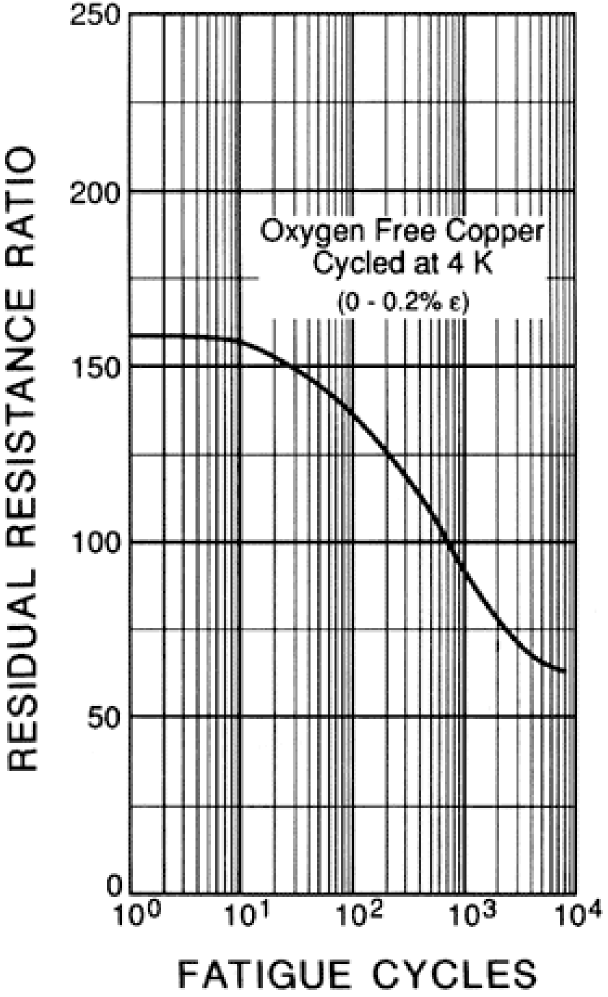


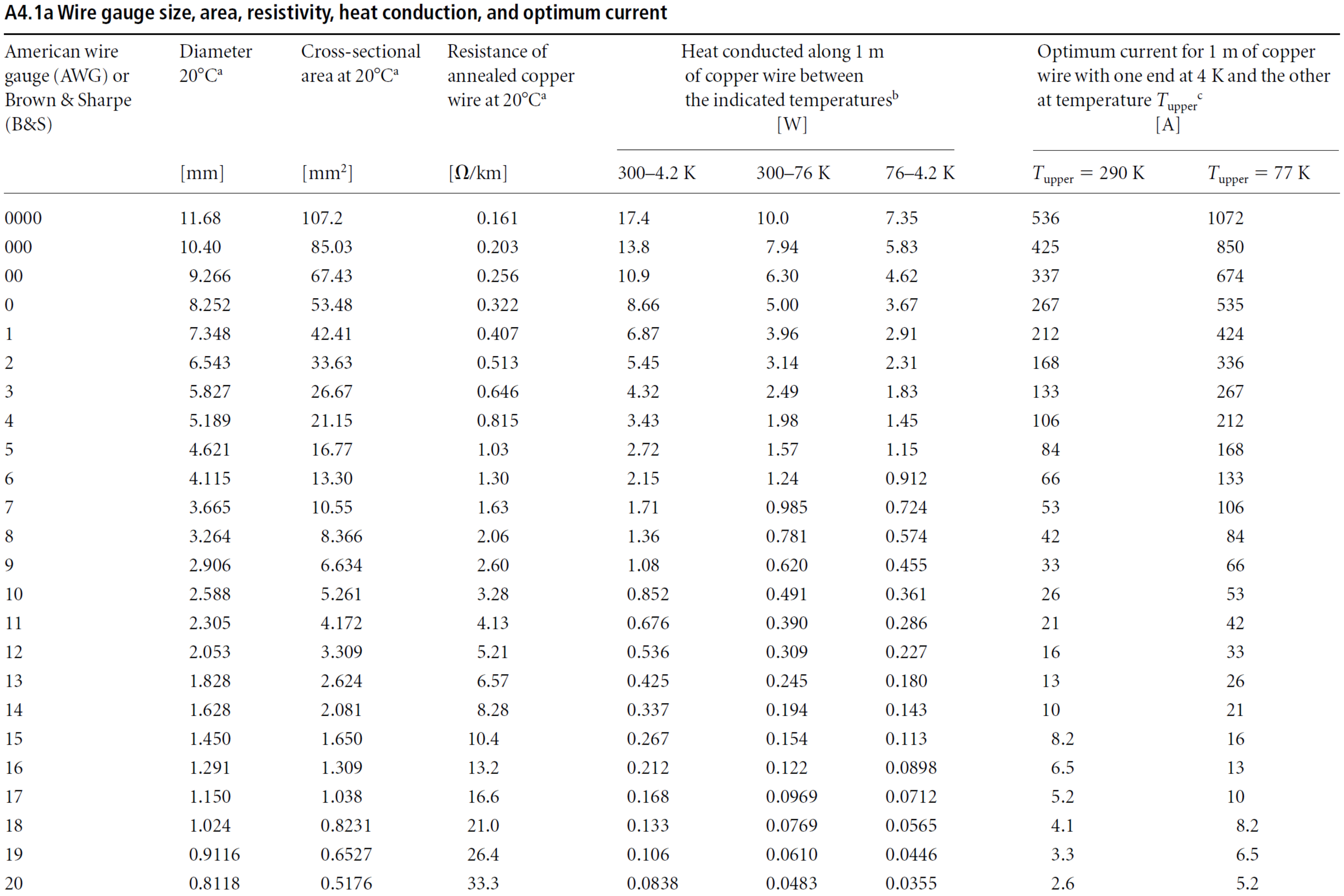
Figure 6: The effect of deformation on the RRR of pure aluminium (dashed lines) and copper (solid lines) for rod samples (Refs. [69] (●) and [70] (○)) and foils (Ref. [39] (+)). Samples are for 4N purity aluminium and OFHC copper, except where marked as 5N purity.

Copper Thermal Cycling vs Thermal Conductivity



Wiring/Tubing

Copper Wire 1

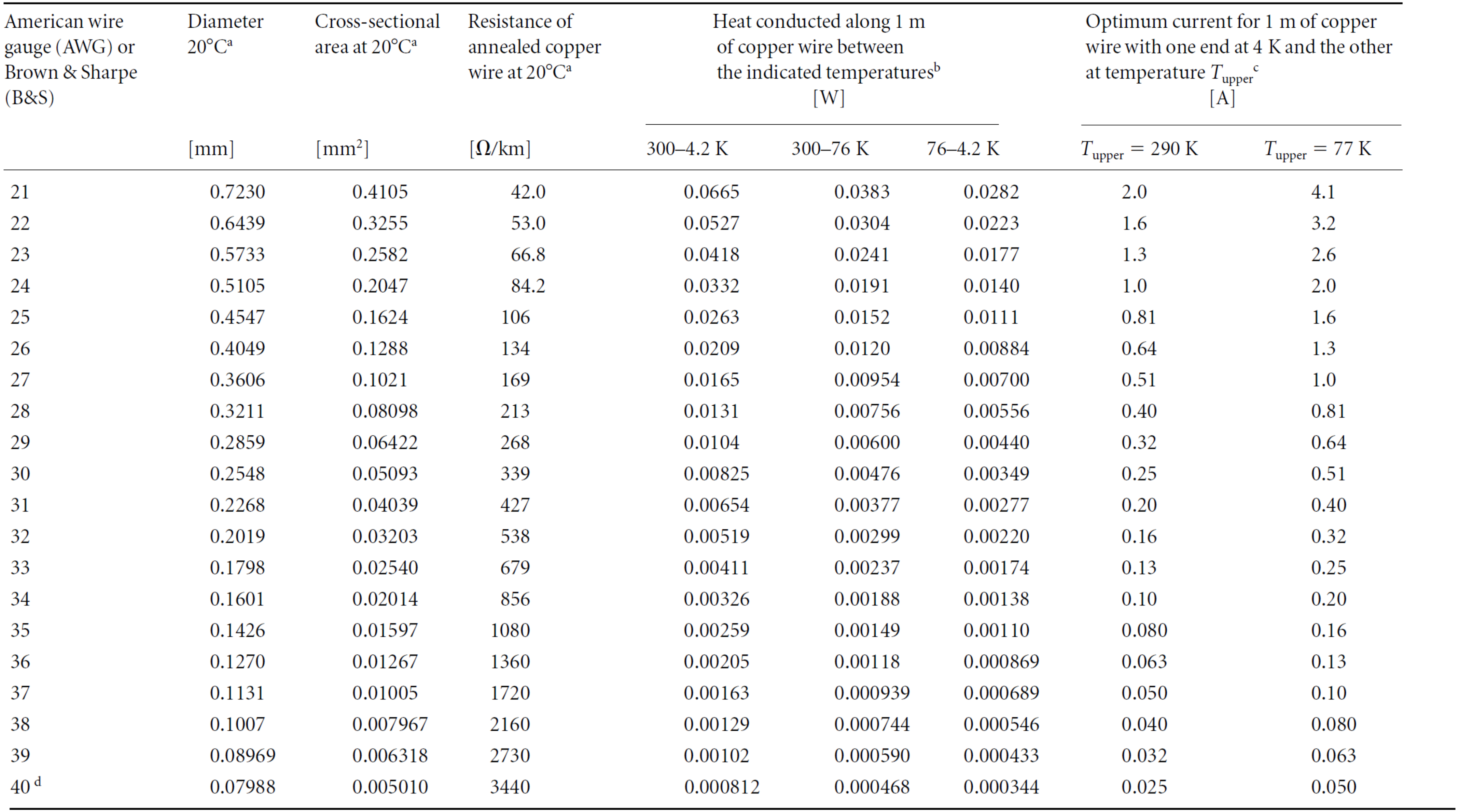


A4.1a Wire gauge size, area, resistivity, heat conduction, and optimum current

American wire gauge (AWG) or Brown & Sharpe (B&S)	Diameter 20°C[a]	Cross-sectional area at 20°C[a]	Resistance of annealed copper wire at 20°C[a]	Heat conducted along 1 m of copper wire between the indicated temperatures[b] [W]			Optimum current for 1 m of copper wire with one end at 4 K and the other at temperature T_{upper}[c] [A]	
	[mm]	[mm^2]	[Ω/km]	300–4.2 K	300–76 K	76–4.2 K	T_{upper} = 290 K	T_{upper} = 77 K
0000	11.68	107.2	0.161	17.4	10.0	7.35	536	1072
000	10.40	85.03	0.203	13.8	7.94	5.83	425	850
00	9.266	67.43	0.256	10.9	6.30	4.62	337	674
0	8.252	53.48	0.322	8.66	5.00	3.67	267	535
1	7.348	42.41	0.407	6.87	3.96	2.91	212	424
2	6.543	33.63	0.513	5.45	3.14	2.31	168	336
3	5.827	26.67	0.646	4.32	2.49	1.83	133	267
4	5.189	21.15	0.815	3.43	1.98	1.45	106	212
5	4.621	16.77	1.03	2.72	1.57	1.15	84	168
6	4.115	13.30	1.30	2.15	1.24	0.912	66	133
7	3.665	10.55	1.63	1.71	0.985	0.724	53	106
8	3.264	8.366	2.06	1.36	0.781	0.574	42	84
9	2.906	6.634	2.60	1.08	0.620	0.455	33	66
10	2.588	5.261	3.28	0.852	0.491	0.361	26	53
11	2.305	4.172	4.13	0.676	0.390	0.286	21	42
12	2.053	3.309	5.21	0.536	0.309	0.227	16	33
13	1.828	2.624	6.57	0.425	0.245	0.180	13	26
14	1.628	2.081	8.28	0.337	0.194	0.143	10	21
15	1.450	1.650	10.4	0.267	0.154	0.113	8.2	16
16	1.291	1.309	13.2	0.212	0.122	0.0898	6.5	13
17	1.150	1.038	16.6	0.168	0.0969	0.0712	5.2	10
18	1.024	0.8231	21.0	0.133	0.0769	0.0565	4.1	8.2
19	0.9116	0.6527	26.4	0.106	0.0610	0.0446	3.3	6.5
20	0.8118	0.5176	33.3	0.0838	0.0483	0.0355	2.6	5.2

Data from: Ekin (2007)

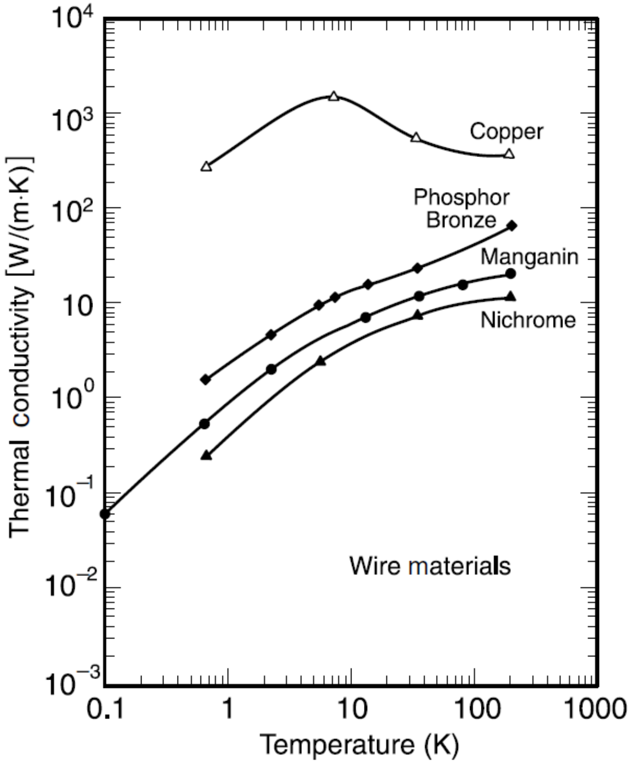
Copper Wire 2



American wire gauge (AWG) or Brown & Sharpe (B&S)	Diameter 20°C[a] [mm]	Cross-sectional area at 20°C[a] [mm^2]	Resistance of annealed copper wire at 20°C[a] [Ω/km]	Heat conducted along 1 m of copper wire between the indicated temperatures[b] [W] 300–4.2 K	300–76 K	76–4.2 K	Optimum current for 1 m of copper wire with one end at 4 K and the other at temperature T_{upper}[c] [A] T_{upper} = 290 K	T_{upper} = 77 K
21	0.7230	0.4105	42.0	0.0665	0.0383	0.0282	2.0	4.1
22	0.6439	0.3255	53.0	0.0527	0.0304	0.0223	1.6	3.2
23	0.5733	0.2582	66.8	0.0418	0.0241	0.0177	1.3	2.6
24	0.5105	0.2047	84.2	0.0332	0.0191	0.0140	1.0	2.0
25	0.4547	0.1624	106	0.0263	0.0152	0.0111	0.81	1.6
26	0.4049	0.1288	134	0.0209	0.0120	0.00884	0.64	1.3
27	0.3606	0.1021	169	0.0165	0.00954	0.00700	0.51	1.0
28	0.3211	0.08098	213	0.0131	0.00756	0.00556	0.40	0.81
29	0.2859	0.06422	268	0.0104	0.00600	0.00440	0.32	0.64
30	0.2548	0.05093	339	0.00825	0.00476	0.00349	0.25	0.51
31	0.2268	0.04039	427	0.00654	0.00377	0.00277	0.20	0.40
32	0.2019	0.03203	538	0.00519	0.00299	0.00220	0.16	0.32
33	0.1798	0.02540	679	0.00411	0.00237	0.00174	0.13	0.25
34	0.1601	0.02014	856	0.00326	0.00188	0.00138	0.10	0.20
35	0.1426	0.01597	1080	0.00259	0.00149	0.00110	0.080	0.16
36	0.1270	0.01267	1360	0.00205	0.00118	0.000869	0.063	0.13
37	0.1131	0.01005	1720	0.00163	0.000939	0.000689	0.050	0.10
38	0.1007	0.007967	2160	0.00129	0.000744	0.000546	0.040	0.080
39	0.08969	0.006318	2730	0.00102	0.000590	0.000433	0.032	0.063
40[d]	0.07988	0.005010	3440	0.000812	0.000468	0.000344	0.025	0.050

Data from: Ekin (2007)

Wires



$$LI/A \cong 10 \times 10^6 \text{ A/m}. \tag{4.2}$$

Optimum copper-wire size for connections between 77 K and 4.2 K (steady state)

$$\dot{q}_{\text{copper leads}}/I = 84 \text{ mW/A}, \tag{4.3}$$

Heat flux through a *pair* of optimally sized copper leads, 290–4 K

and

$$\dot{q}_{\text{copper leads}}/I = 18 \text{ mW/A}. \tag{4.4}$$

Heat flux through a *pair* of optimally sized copper leads, 77–4 K

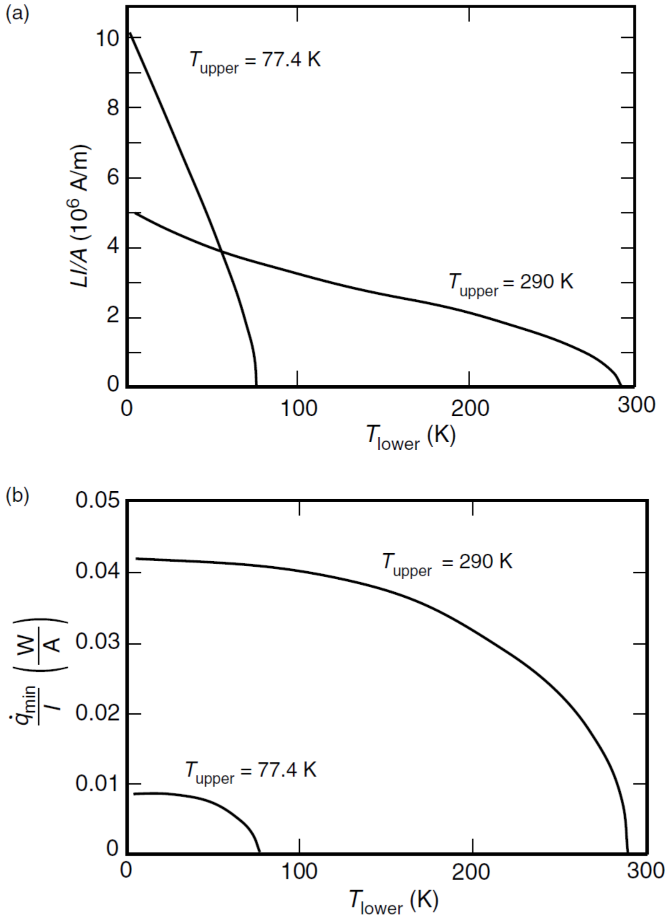
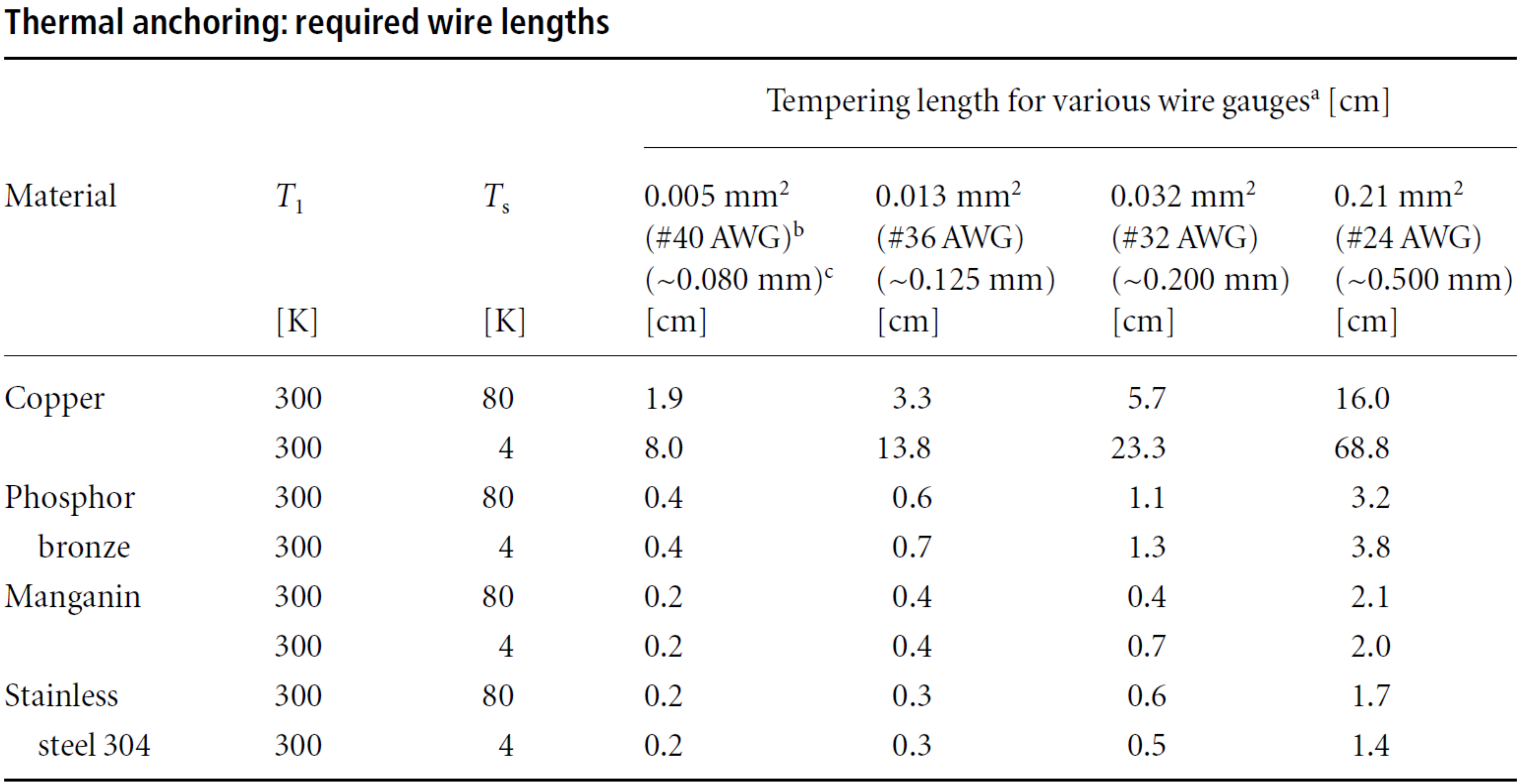


Fig. 4.16 Optimum wire diameter (a), and minimum heat input (b) for a single copper wire conducting current I from a region of the cryostat at temperature T_{upper} to a temperature T_{lower}. (We assume that the copper wire has a typical residual resistance ratio of 100 and that no heat transfers from the wire to the evaporating helium gas.) In graph (a), L is the length of the conductor between the upper and lower temperatures, and A is the optimum cross-sectional area. In graph (b), $\dot{q}_{min}$ is the corresponding minimum heat input (from McFee 1959).

Data from: Ekin (2007)

Thermal Anchoring Copper Wire

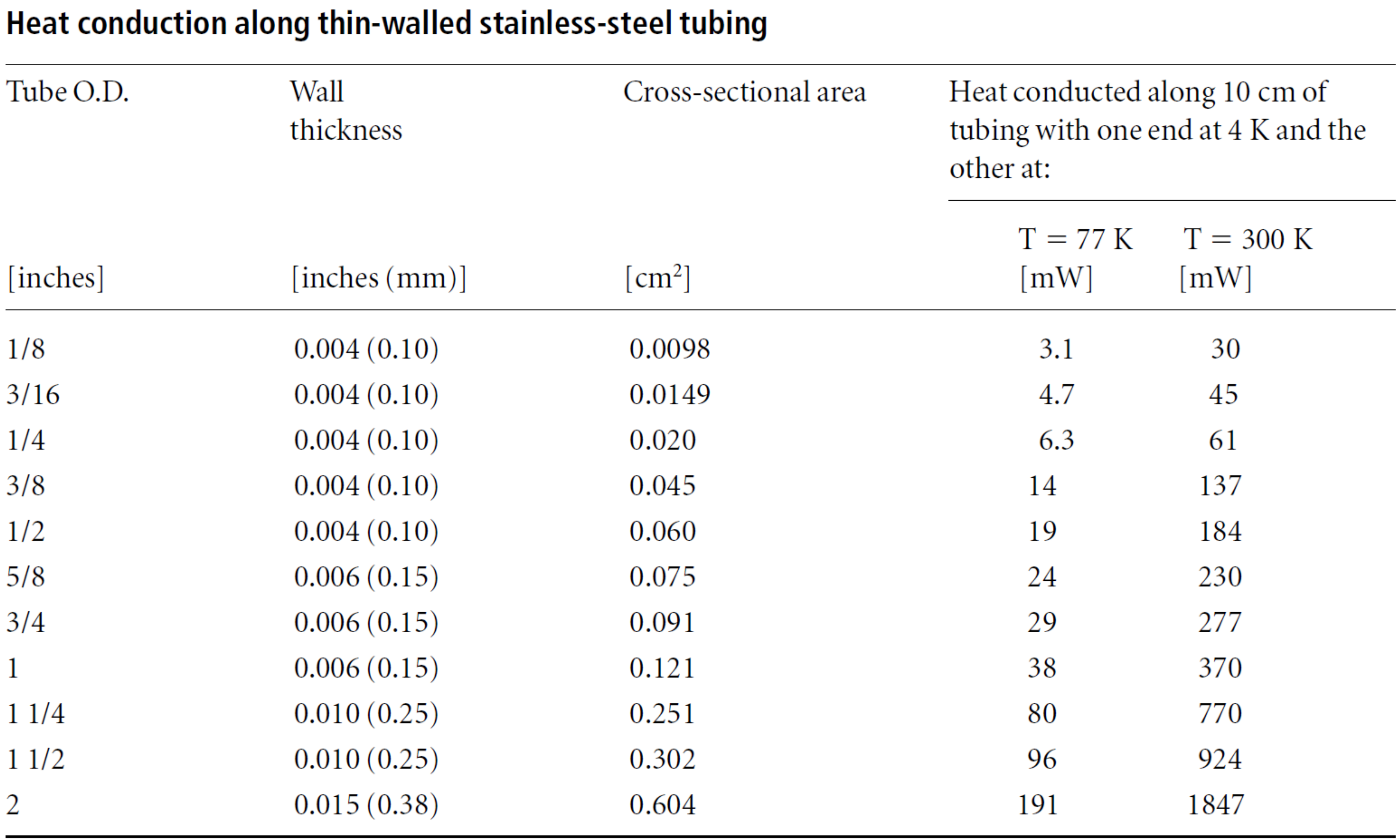


Thermal anchoring: required wire lengths

			Tempering length for various wire gauges[a] [cm]			
Material	T_1 [K]	T_s [K]	0.005 mm^2 (#40 AWG)[b] (~0.080 mm)[c] [cm]	0.013 mm^2 (#36 AWG) (~0.125 mm) [cm]	0.032 mm^2 (#32 AWG) (~0.200 mm) [cm]	0.21 mm^2 (#24 AWG) (~0.500 mm) [cm]
Copper	300	80	1.9	3.3	5.7	16.0
	300	4	8.0	13.8	23.3	68.8
Phosphor	300	80	0.4	0.6	1.1	3.2
bronze	300	4	0.4	0.7	1.3	3.8
Manganin	300	80	0.2	0.4	0.4	2.1
	300	4	0.2	0.4	0.7	2.0
Stainless	300	80	0.2	0.3	0.6	1.7
steel 304	300	4	0.2	0.3	0.5	1.4

Data from: Ekin (2007)

Stainless Steel Tubing Thermal Conduction



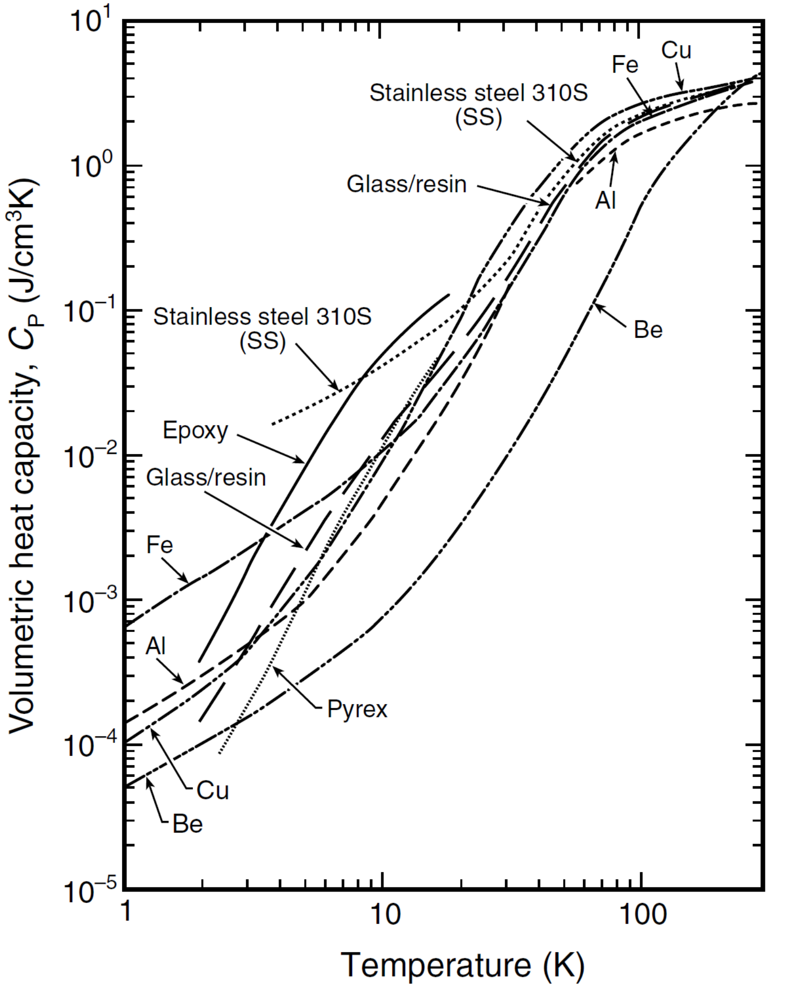
Heat conduction along thin-walled stainless-steel tubing

Tube O.D.	Wall thickness	Cross-sectional area	Heat conducted along 10 cm of tubing with one end at 4 K and the other at:	
			T = 77 K	T = 300 K
[inches]	[inches (mm)]	[cm^2]	[mW]	[mW]
1/8	0.004 (0.10)	0.0098	3.1	30
3/16	0.004 (0.10)	0.0149	4.7	45
1/4	0.004 (0.10)	0.020	6.3	61
3/8	0.004 (0.10)	0.045	14	137
1/2	0.004 (0.10)	0.060	19	184
5/8	0.006 (0.15)	0.075	24	230
3/4	0.006 (0.15)	0.091	29	277
1	0.006 (0.15)	0.121	38	370
1 1/4	0.010 (0.25)	0.251	80	770
1 1/2	0.010 (0.25)	0.302	96	924
2	0.015 (0.38)	0.604	191	1847

Data from: Ekin (2007)

Heat Capacity/ Enthalpy

Heat Capacity



Data from: Ekin (2007)

Copper Enthalpy

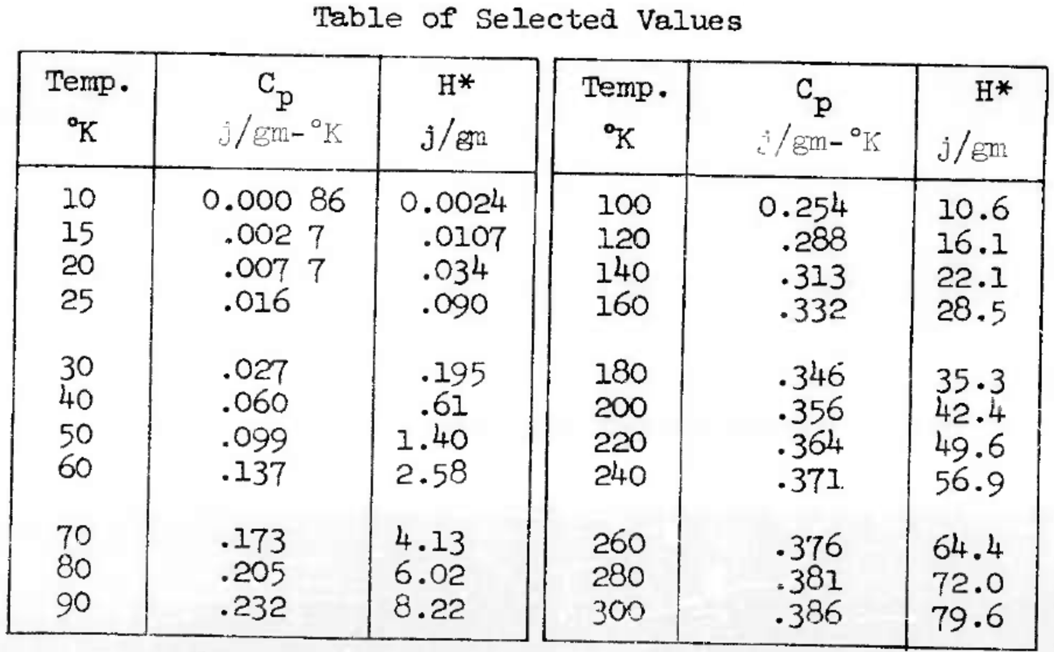
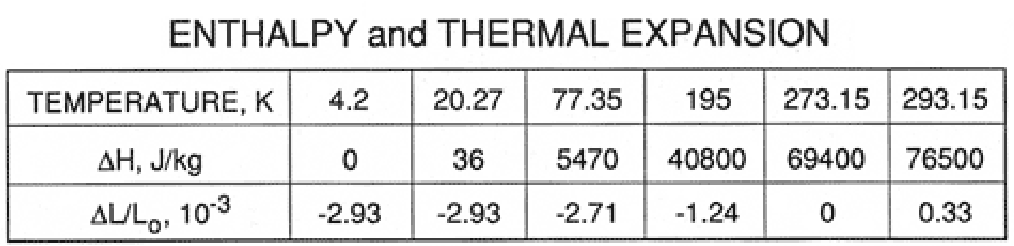


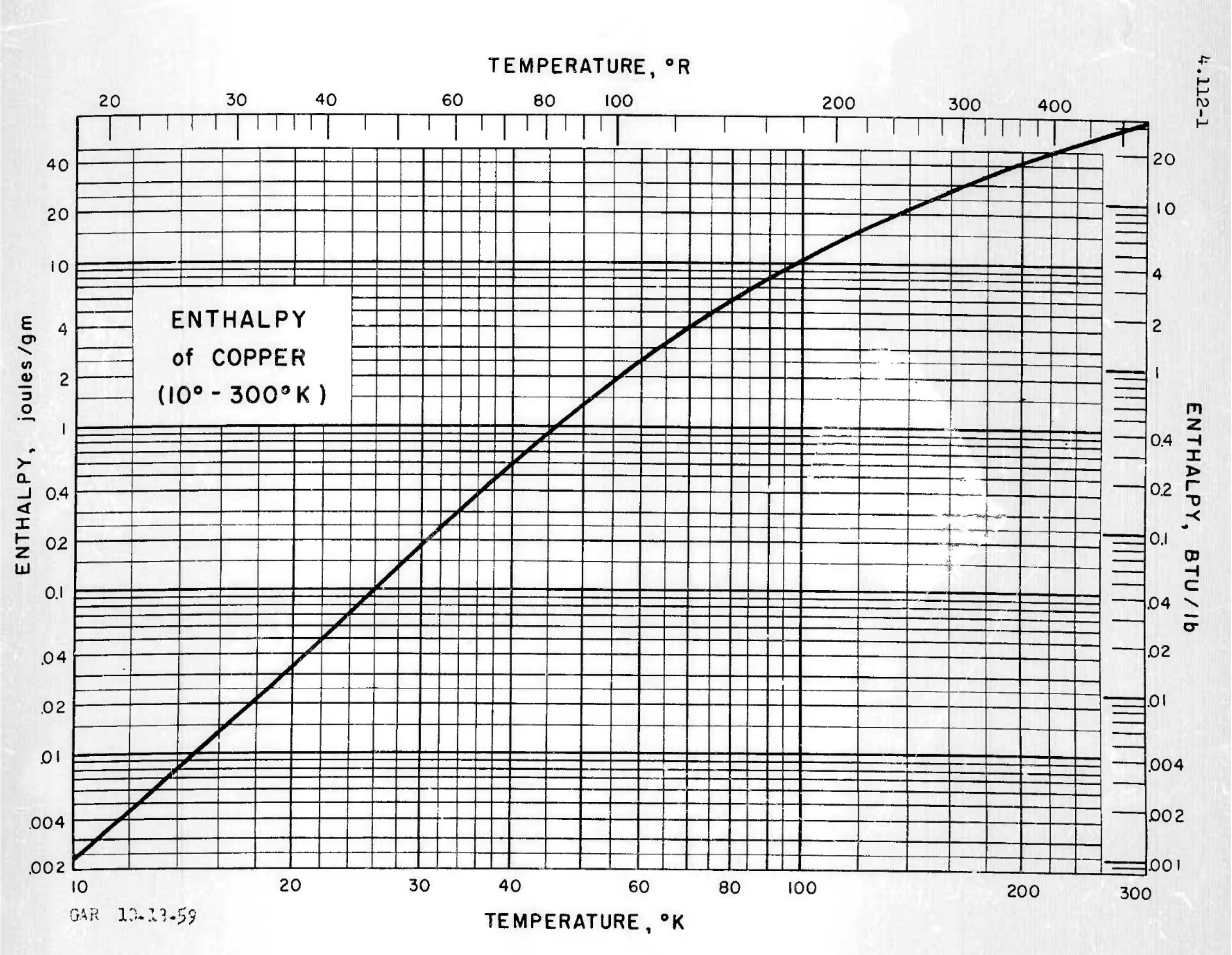
Table of Selected Values

Temp. °K	C_p j/gm-°K	H* j/gm	Temp. °K	C_p j/gm-°K	H* j/gm
10	0.000 86	0.0024	100	0.254	10.6
15	.002 7	.0107	120	.288	16.1
20	.007 7	.034	140	.313	22.1
25	.016	.090	160	.332	28.5
30	.027	.195	180	.346	35.3
40	.060	.61	200	.356	42.4
50	.099	1.40	220	.364	49.6
60	.137	2.58	240	.371	56.9
70	.173	4.13	260	.376	64.4
80	.205	6.02	280	.381	72.0
90	.232	8.22	300	.386	79.6



ENTHALPY and THERMAL EXPANSION

TEMPERATURE, K	4.2	20.27	77.35	195	273.15	293.15
ΔH, J/kg	0	36	5470	40800	69400	76500
$\Delta L/L_o$, 10^{-3}	-2.93	-2.93	-2.71	-1.24	0	0.33



Aluminum Enthalpy

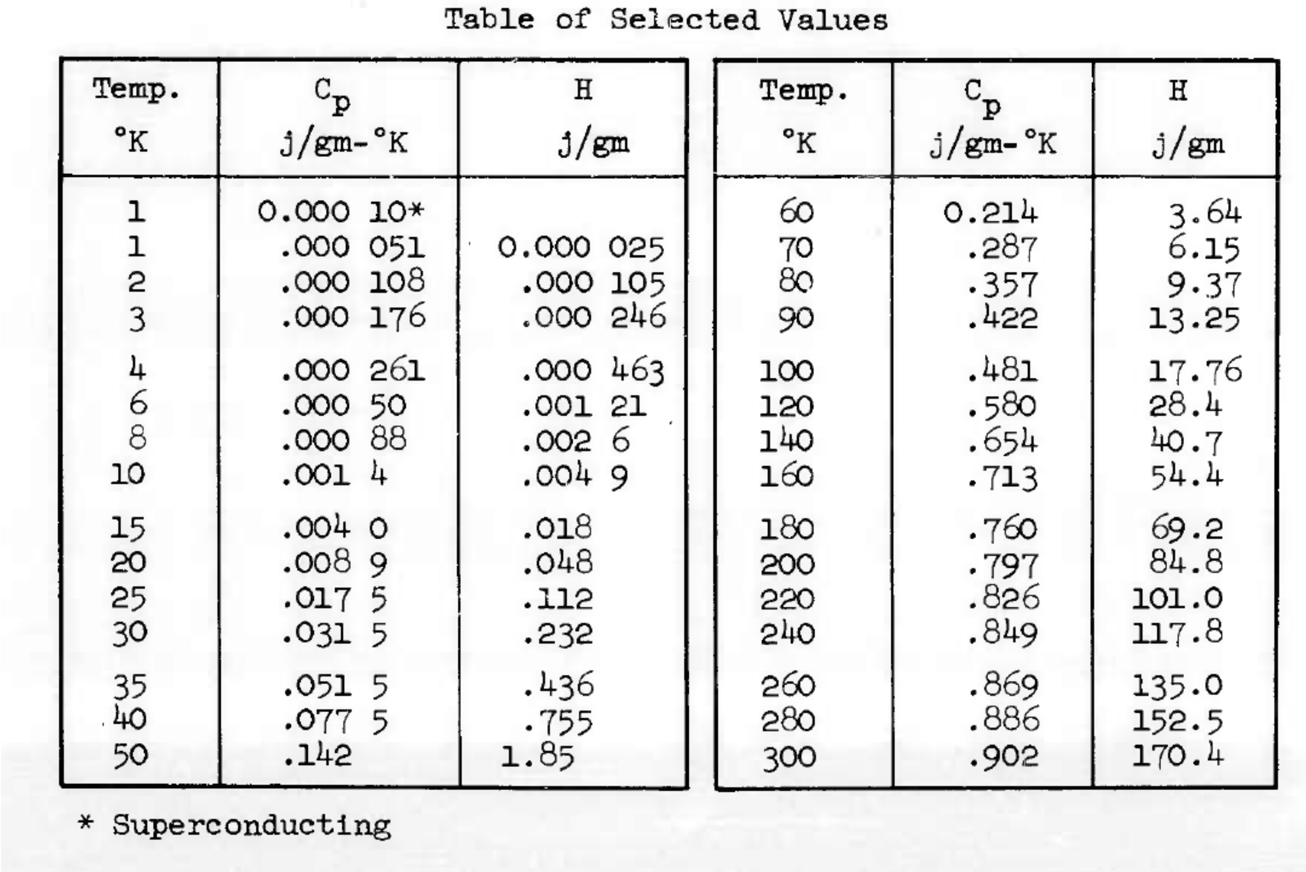
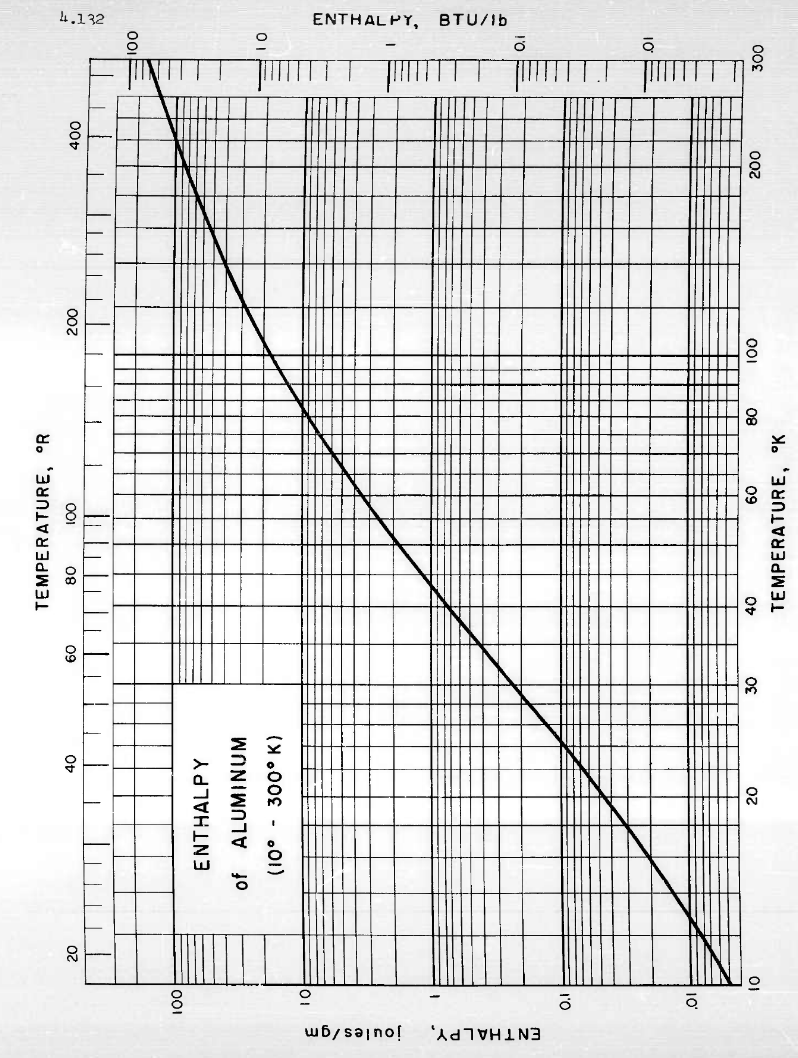


Table of Selected Values

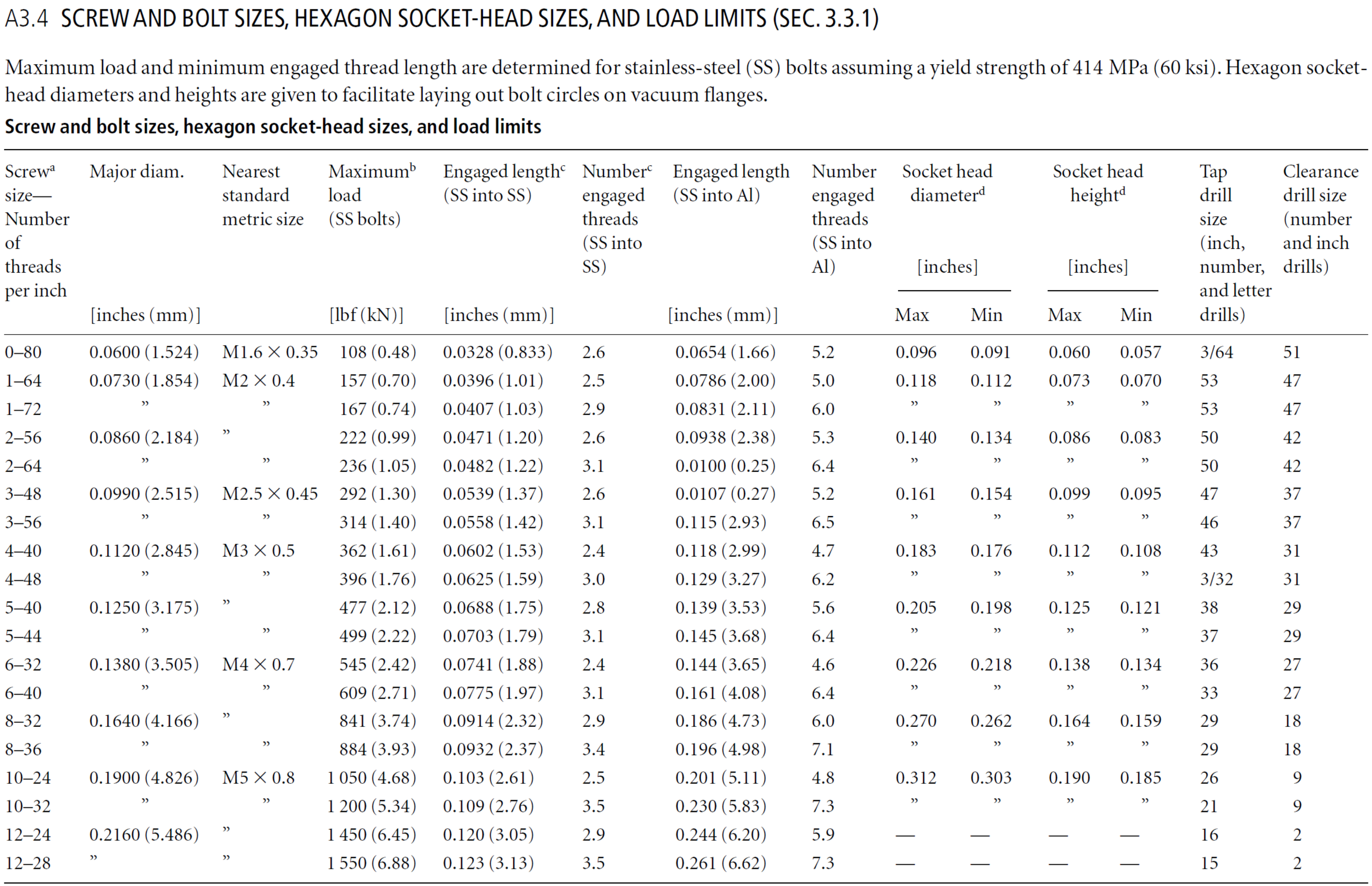
Temp. °K	C_p j/gm-°K	H j/gm	Temp. °K	C_p j/gm-°K	H j/gm
1	0.000 10*		60	0.214	3.64
1	.000 051	0.000 025	70	.287	6.15
2	.000 108	.000 105	80	.357	9.37
3	.000 176	.000 246	90	.422	13.25
4	.000 261	.000 463	100	.481	17.76
6	.000 50	.001 21	120	.580	28.4
8	.000 88	.002 6	140	.654	40.7
10	.001 4	.004 9	160	.713	54.4
15	.004 0	.018	180	.760	69.2
20	.008 9	.048	200	.797	84.8
25	.017 5	.112	220	.826	101.0
30	.031 5	.232	240	.849	117.8
35	.051 5	.436	260	.869	135.0
40	.077 5	.755	280	.886	152.5
50	.142	1.85	300	.902	170.4

* Superconducting



Thermal Contact

Screw Forces 1



A3.4 SCREW AND BOLT SIZES, HEXAGON SOCKET-HEAD SIZES, AND LOAD LIMITS (SEC. 3.3.1)

Maximum load and minimum engaged thread length are determined for stainless-steel (SS) bolts assuming a yield strength of 414 MPa (60 ksi). Hexagon socket-head diameters and heights are given to facilitate laying out bolt circles on vacuum flanges.

Screw and bolt sizes, hexagon socket-head sizes, and load limits

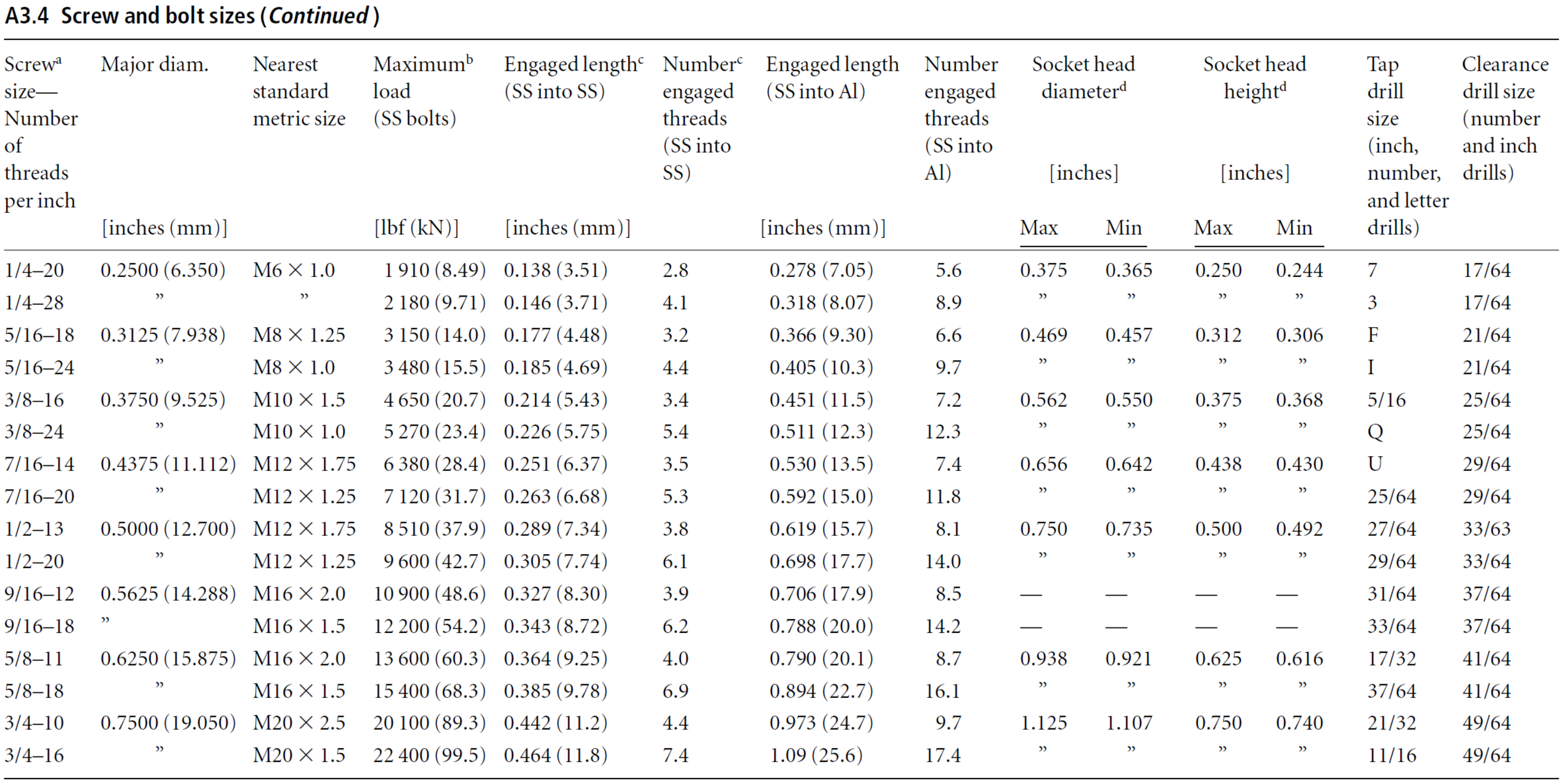
Screw[a] size—Number of threads per inch	Major diam. [inches (mm)]	Nearest standard metric size	Maximum[b] load (SS bolts) [lbf (kN)]	Engaged length[c] (SS into SS) [inches (mm)]	Number[c] engaged threads (SS into SS)	Engaged length (SS into Al) [inches (mm)]	Number engaged threads (SS into Al)	Socket head diameter[d] [inches]		Socket head height[d] [inches]		Tap drill size (inch, number, and letter drills)	Clearance drill size (number and inch drills)
								Max	Min	Max	Min		
0–80	0.0600 (1.524)	M1.6 × 0.35	108 (0.48)	0.0328 (0.833)	2.6	0.0654 (1.66)	5.2	0.096	0.091	0.060	0.057	3/64	51
1–64	0.0730 (1.854)	M2 × 0.4	157 (0.70)	0.0396 (1.01)	2.5	0.0786 (2.00)	5.0	0.118	0.112	0.073	0.070	53	47
1–72	”	”	167 (0.74)	0.0407 (1.03)	2.9	0.0831 (2.11)	6.0	”	”	”	”	53	47
2–56	0.0860 (2.184)	”	222 (0.99)	0.0471 (1.20)	2.6	0.0938 (2.38)	5.3	0.140	0.134	0.086	0.083	50	42
2–64	”	”	236 (1.05)	0.0482 (1.22)	3.1	0.0100 (0.25)	6.4	”	”	”	”	50	42
3–48	0.0990 (2.515)	M2.5 × 0.45	292 (1.30)	0.0539 (1.37)	2.6	0.0107 (0.27)	5.2	0.161	0.154	0.099	0.095	47	37
3–56	”	”	314 (1.40)	0.0558 (1.42)	3.1	0.115 (2.93)	6.5	”	”	”	”	46	37
4–40	0.1120 (2.845)	M3 × 0.5	362 (1.61)	0.0602 (1.53)	2.4	0.118 (2.99)	4.7	0.183	0.176	0.112	0.108	43	31
4–48	”	”	396 (1.76)	0.0625 (1.59)	3.0	0.129 (3.27)	6.2	”	”	”	”	3/32	31
5–40	0.1250 (3.175)	”	477 (2.12)	0.0688 (1.75)	2.8	0.139 (3.53)	5.6	0.205	0.198	0.125	0.121	38	29
5–44	”	”	499 (2.22)	0.0703 (1.79)	3.1	0.145 (3.68)	6.4	”	”	”	”	37	29
6–32	0.1380 (3.505)	M4 × 0.7	545 (2.42)	0.0741 (1.88)	2.4	0.144 (3.65)	4.6	0.226	0.218	0.138	0.134	36	27
6–40	”	”	609 (2.71)	0.0775 (1.97)	3.1	0.161 (4.08)	6.4	”	”	”	”	33	27
8–32	0.1640 (4.166)	”	841 (3.74)	0.0914 (2.32)	2.9	0.186 (4.73)	6.0	0.270	0.262	0.164	0.159	29	18
8–36	”	”	884 (3.93)	0.0932 (2.37)	3.4	0.196 (4.98)	7.1	”	”	”	”	29	18
10–24	0.1900 (4.826)	M5 × 0.8	1 050 (4.68)	0.103 (2.61)	2.5	0.201 (5.11)	4.8	0.312	0.303	0.190	0.185	26	9
10–32	”	”	1 200 (5.34)	0.109 (2.76)	3.5	0.230 (5.83)	7.3	”	”	”	”	21	9
12–24	0.2160 (5.486)	”	1 450 (6.45)	0.120 (3.05)	2.9	0.244 (6.20)	5.9	—	—	—	—	16	2
12–28	”	”	1 550 (6.88)	0.123 (3.13)	3.5	0.261 (6.62)	7.3	—	—	—	—	15	2

Yield Strength (ksi)	
Brass	30
Aluminum	45
Copper	17
Stainless	57*

Copper~ 30% of listed Load
Brass~60% of listed Load
Aluminum ~ 80% of listed Load

Data from: Ekin (2007)

Screw Forces 2

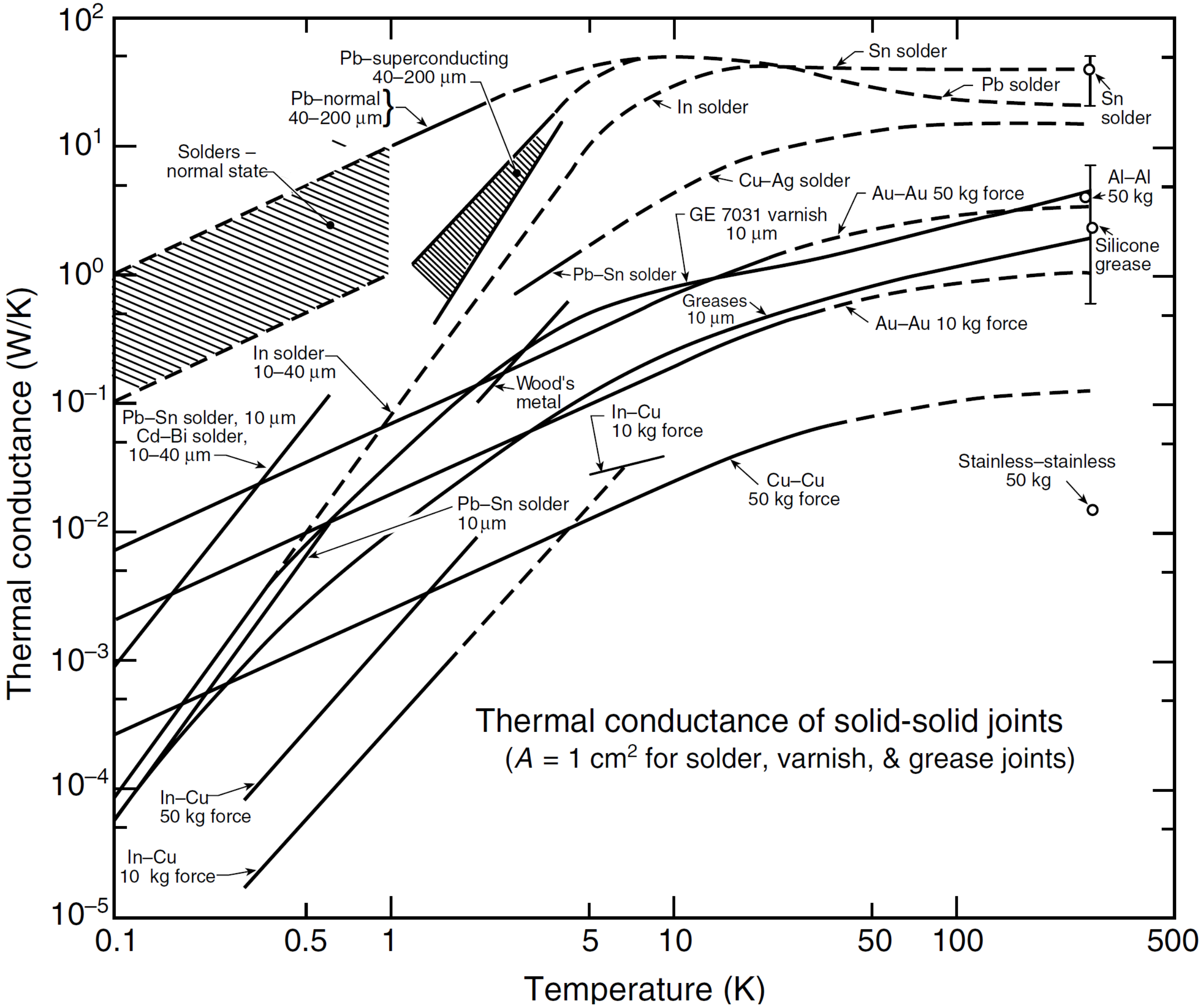


A3.4 Screw and bolt sizes (*Continued*)

Screw^a size—Number of threads per inch	Major diam. [inches (mm)]	Nearest standard metric size	Maximum^b load (SS bolts) [lbf (kN)]	Engaged length^c (SS into SS) [inches (mm)]	Number^c engaged threads (SS into SS)	Engaged length (SS into Al) [inches (mm)]	Number engaged threads (SS into Al)	Socket head diameter^d [inches]		Socket head height^d [inches]		Tap drill size (inch, number, and letter drills)	Clearance drill size (number and inch drills)
								Max	Min	Max	Min		
1/4–20	0.2500 (6.350)	M6 × 1.0	1 910 (8.49)	0.138 (3.51)	2.8	0.278 (7.05)	5.6	0.375	0.365	0.250	0.244	7	17/64
1/4–28	”	”	2 180 (9.71)	0.146 (3.71)	4.1	0.318 (8.07)	8.9	”	”	”	”	3	17/64
5/16–18	0.3125 (7.938)	M8 × 1.25	3 150 (14.0)	0.177 (4.48)	3.2	0.366 (9.30)	6.6	0.469	0.457	0.312	0.306	F	21/64
5/16–24	”	M8 × 1.0	3 480 (15.5)	0.185 (4.69)	4.4	0.405 (10.3)	9.7	”	”	”	”	I	21/64
3/8–16	0.3750 (9.525)	M10 × 1.5	4 650 (20.7)	0.214 (5.43)	3.4	0.451 (11.5)	7.2	0.562	0.550	0.375	0.368	5/16	25/64
3/8–24	”	M10 × 1.0	5 270 (23.4)	0.226 (5.75)	5.4	0.511 (12.3)	12.3	”	”	”	”	Q	25/64
7/16–14	0.4375 (11.112)	M12 × 1.75	6 380 (28.4)	0.251 (6.37)	3.5	0.530 (13.5)	7.4	0.656	0.642	0.438	0.430	U	29/64
7/16–20	”	M12 × 1.25	7 120 (31.7)	0.263 (6.68)	5.3	0.592 (15.0)	11.8	”	”	”	”	25/64	29/64
1/2–13	0.5000 (12.700)	M12 × 1.75	8 510 (37.9)	0.289 (7.34)	3.8	0.619 (15.7)	8.1	0.750	0.735	0.500	0.492	27/64	33/63
1/2–20	”	M12 × 1.25	9 600 (42.7)	0.305 (7.74)	6.1	0.698 (17.7)	14.0	”	”	”	”	29/64	33/64
9/16–12	0.5625 (14.288)	M16 × 2.0	10 900 (48.6)	0.327 (8.30)	3.9	0.706 (17.9)	8.5	—	—	—	—	31/64	37/64
9/16–18	”	M16 × 1.5	12 200 (54.2)	0.343 (8.72)	6.2	0.788 (20.0)	14.2	—	—	—	—	33/64	37/64
5/8–11	0.6250 (15.875)	M16 × 2.0	13 600 (60.3)	0.364 (9.25)	4.0	0.790 (20.1)	8.7	0.938	0.921	0.625	0.616	17/32	41/64
5/8–18	”	M16 × 1.5	15 400 (68.3)	0.385 (9.78)	6.9	0.894 (22.7)	16.1	”	”	”	”	37/64	41/64
3/4–10	0.7500 (19.050)	M20 × 2.5	20 100 (89.3)	0.442 (11.2)	4.4	0.973 (24.7)	9.7	1.125	1.107	0.750	0.740	21/32	49/64
3/4–16	”	M20 × 1.5	22 400 (99.5)	0.464 (11.8)	7.4	1.09 (25.6)	17.4	”	”	”	”	11/16	49/64

Data from: Ekin (2007)

Solid-Solid Joints



Data from: Ekin (2007)

Metal-Metal Thermal Contact

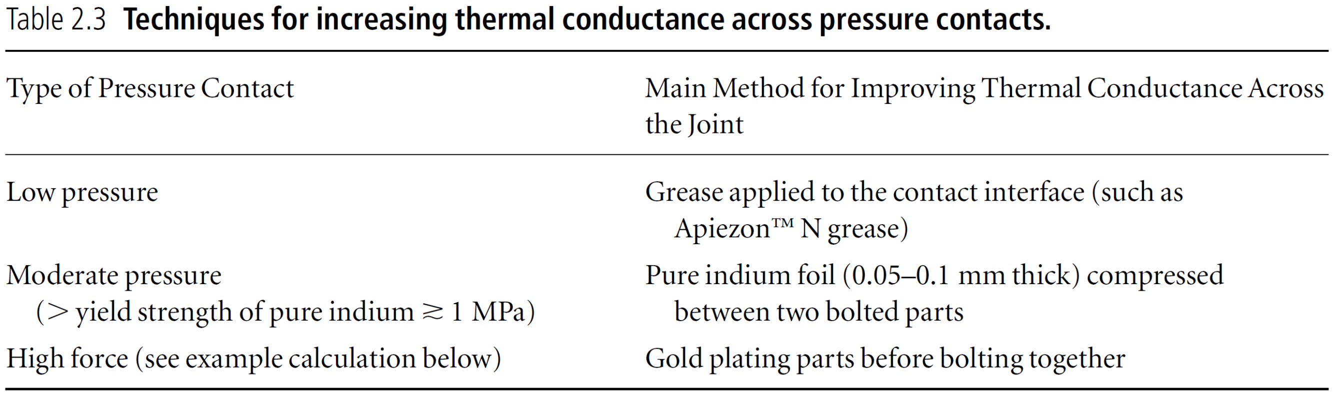
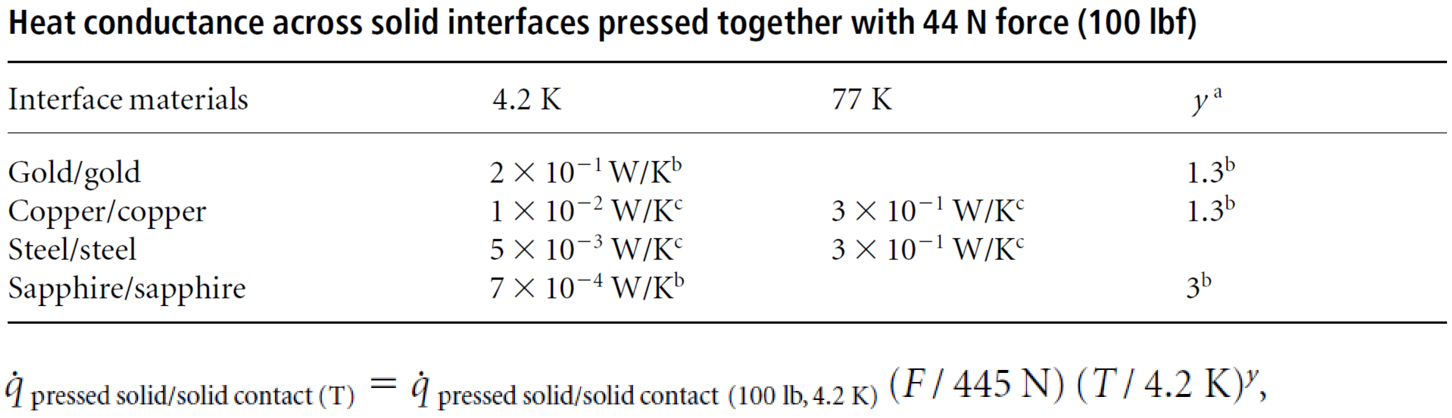


Table 2.3 **Techniques for increasing thermal conductance across pressure contacts.**

Type of Pressure Contact	Main Method for Improving Thermal Conductance Across the Joint
Low pressure	Grease applied to the contact interface (such as Apiezon™ N grease)
Moderate pressure (> yield strength of pure indium ≳ 1 MPa)	Pure indium foil (0.05–0.1 mm thick) compressed between two bolted parts
High force (see example calculation below)	Gold plating parts before bolting together



Heat conductance across solid interfaces pressed together with 44 N force (100 lbf)

Interface materials	4.2 K	77 K	y[a]
Gold/gold	2×10^{-1} W/K[b]		1.3[b]
Copper/copper	1×10^{-2} W/K[c]	3×10^{-1} W/K[c]	1.3[b]
Steel/steel	5×10^{-3} W/K[c]	3×10^{-1} W/K[c]	
Sapphire/sapphire	7×10^{-4} W/K[b]		3[b]

$$\dot{q}_{\text{pressed solid/solid contact (T)}} = \dot{q}_{\text{pressed solid/solid contact (100 lb, 4.2 K)}} \, (F / 445\ \text{N}) \, (T / 4.2\ \text{K})^{y},$$

If *high force* is available and the *contact area is limited:*

Cu/Cu:

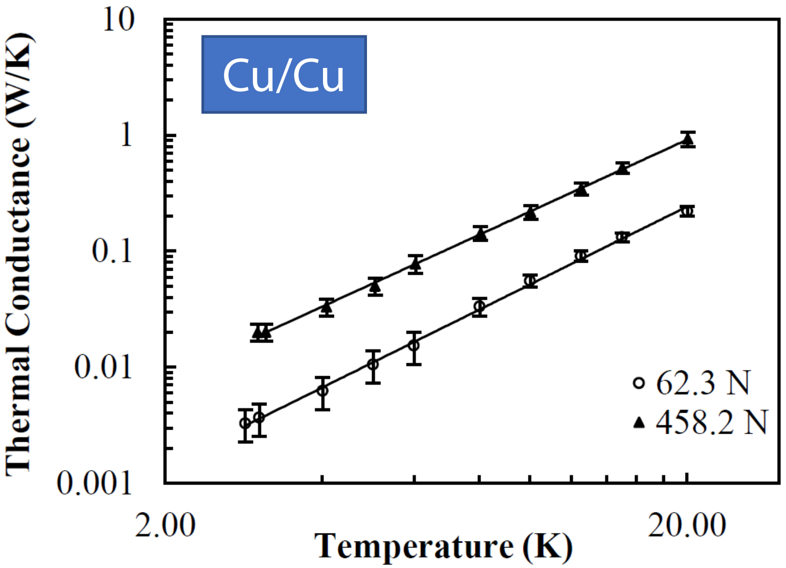
No grease if loads > 200 lb (4–40 screw).

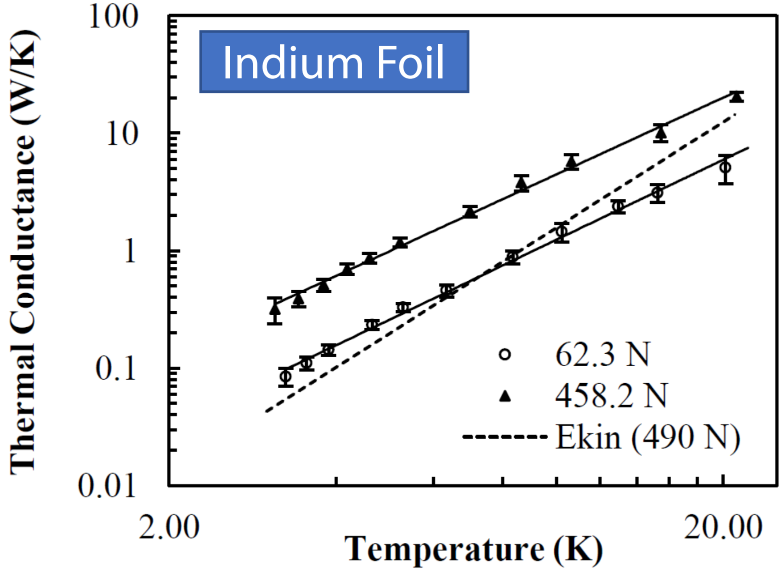
Gold Plated:

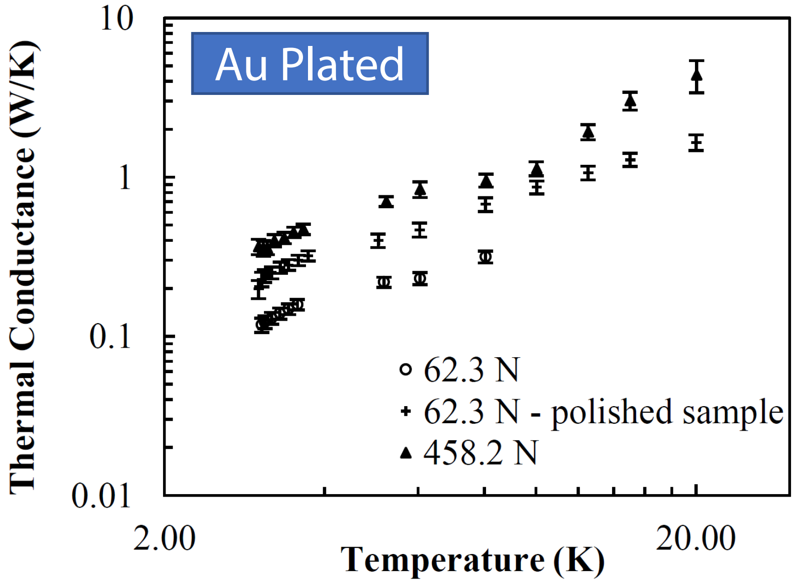
No grease crossover > 10 lb (0–80 screw)

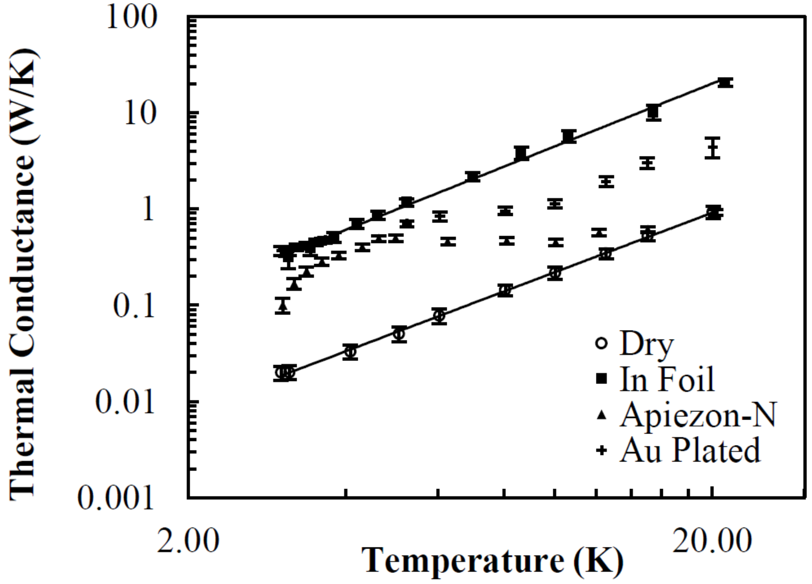
Data from: Ekin (2007)

Metal-Metal Thermal Contact









Copper and Aluminum Thermal Contact

(Thermal Contact Conductance NASA Technical Memorandum 110429)

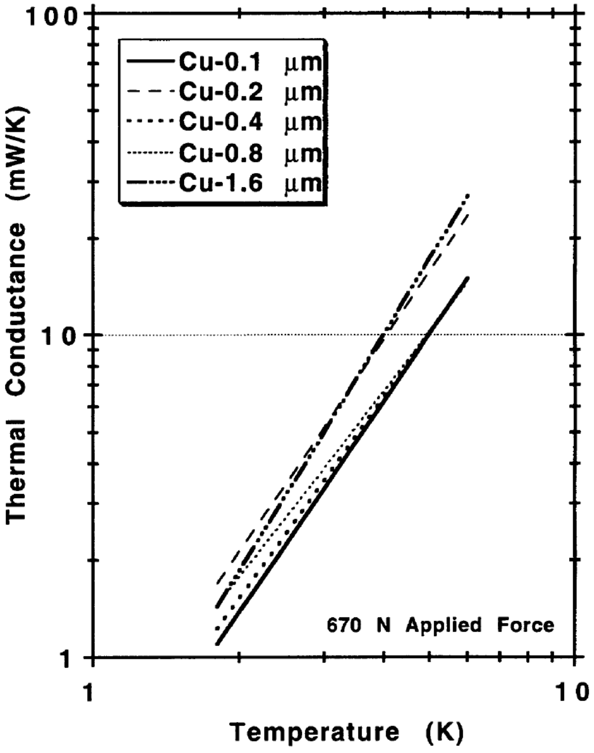


Figure 7. Thermal conductance of uncoated Copper for various surface finishes.

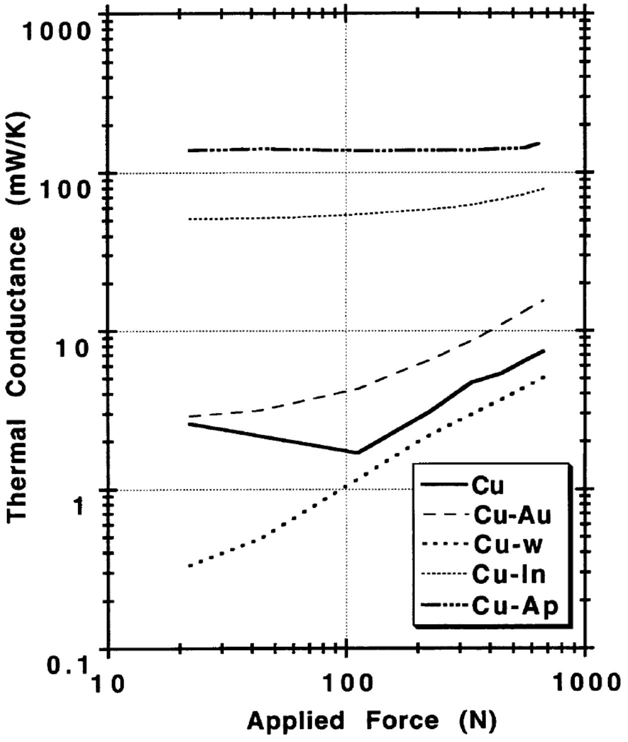


Figure 11. Thermal conductance vs. applied force for 0.8 µm Copper at 4.2 K.

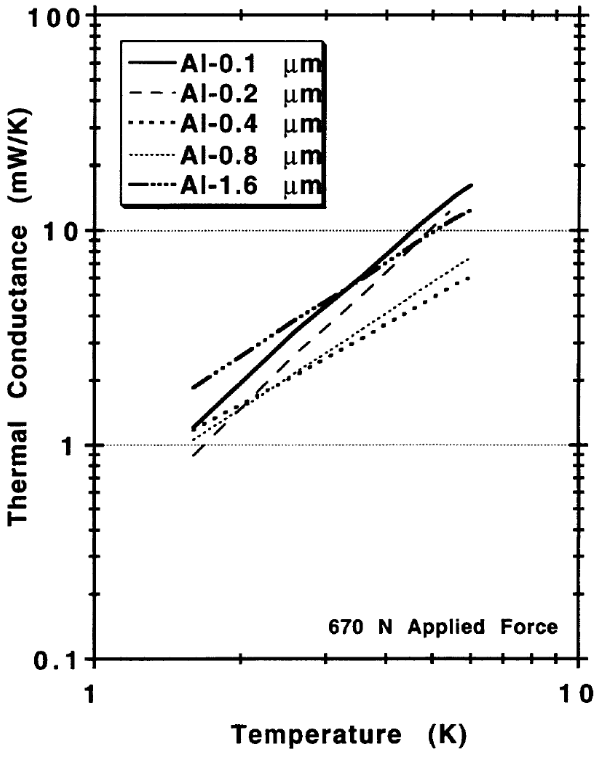


Figure 5. Thermal conductance of uncoated Aluminum for various surface finishes.

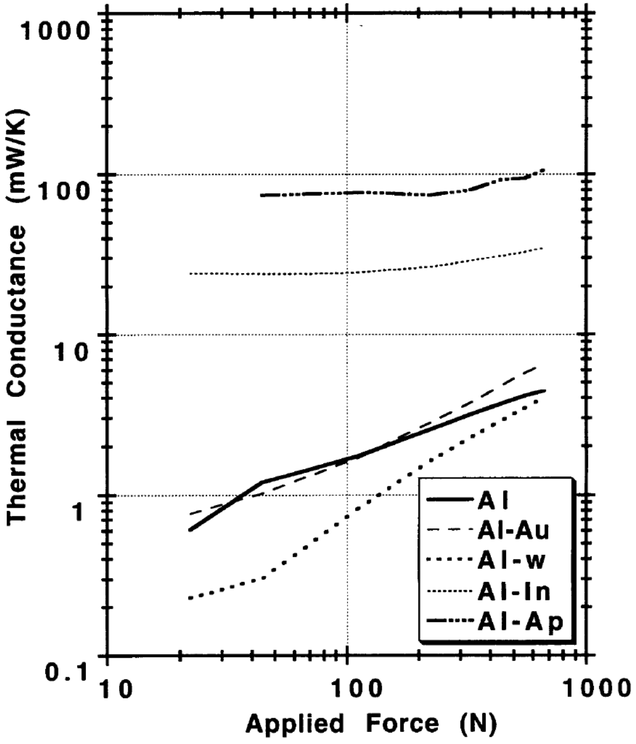


Figure 9. Thermal conductance vs. applied force for 0.8 µm Aluminum at 4.2 K.

Some Experiments on Thermal Contact at Low Temperatures

TABLE I. Thermal conductance of various contacts in watts/degree.

Materials	Temp. at which contact made	4.2° K Load lb 50	100	150	200	250	4700	77°K Load lb 50	100	150	200	250
Cu rod-Cu rod	R.T.[a] 4.2°K	5.5×10^{-3}	1.02×10^{-2} 3.3×10^{-3}	1.46×10^{-2}	1.9×10^{-2}	2.3×10^{-2}		1.6×10^{-1}	3.25×10^{-1}	4.9×10^{-1}	6.6×10^{-1}	
Cu cone-Cu socket	4.2°K	1.75×10^{-3}	3×10^{-3}	4×10^{-3}	4.9×10^{-3}		2.5×10^{-1}					

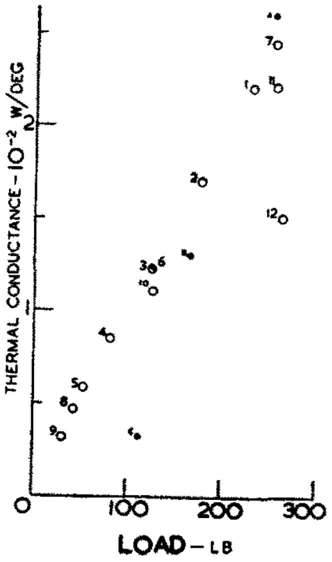
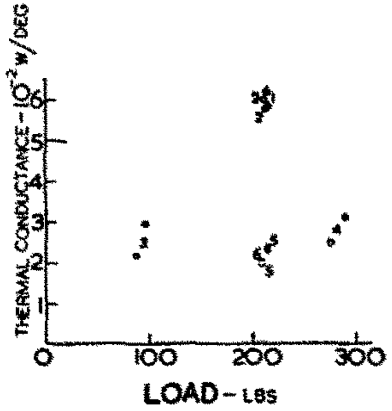


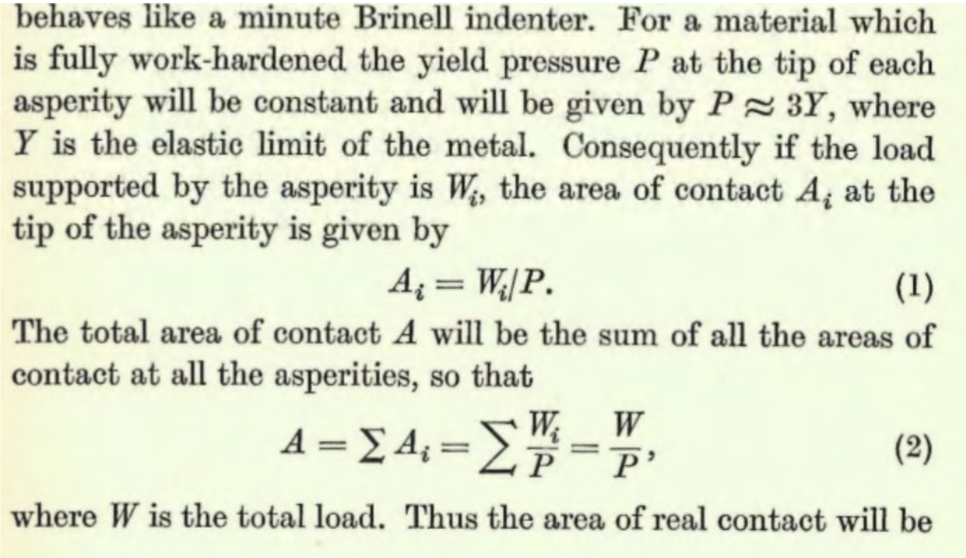
FIG. 3. The variation of thermal conductance with load at 4.2°K for two copper rods. Contact was made at room temperature. After point 11 the contact was opened. Other points shown, obtained on different runs: A. Contact made at room temperature. Electrical conductance 15 times greater than point 7. B. Contact made at room temperature. Electrical conductance 4 times greater than point 2. C. Contact made at liquid-helium temperature. Electrical conductance 1/1000 that of point 3.

before. Figure 6 shows that the conductances were almost identical in both cases and varied similarly through the cycles, indicating that the determining factor is the total load. This result is not unexpected, as it can be shown[12] that the real area of contact between two surfaces depends on the total load and not on the over-all areas used. The exact form of the relation between real area and load depends on the work-hardening which occurs as a result of the load, but the relation is nearly linear.

FIG. 6. The variation of thermal conductance with load at 4.2°K for two different areas. ○ 1 cm diameter circle, ● 5 mm square. The load cycles were almost identical: Contact was made at room temperature and the load was maintained at 260 lb while the apparatus was precooled. After immersing in helium and calibrating the thermometers the load had decreased to point 1. The load was left for $\frac{3}{4}$ hour and fell to point 2. After 3 the load was reduced to zero but the contact did not quite open. After 5 the load was again reduced to zero, then increased to 320 lb and reduced to point 6.



The Hardness of Metals-D. Tabor



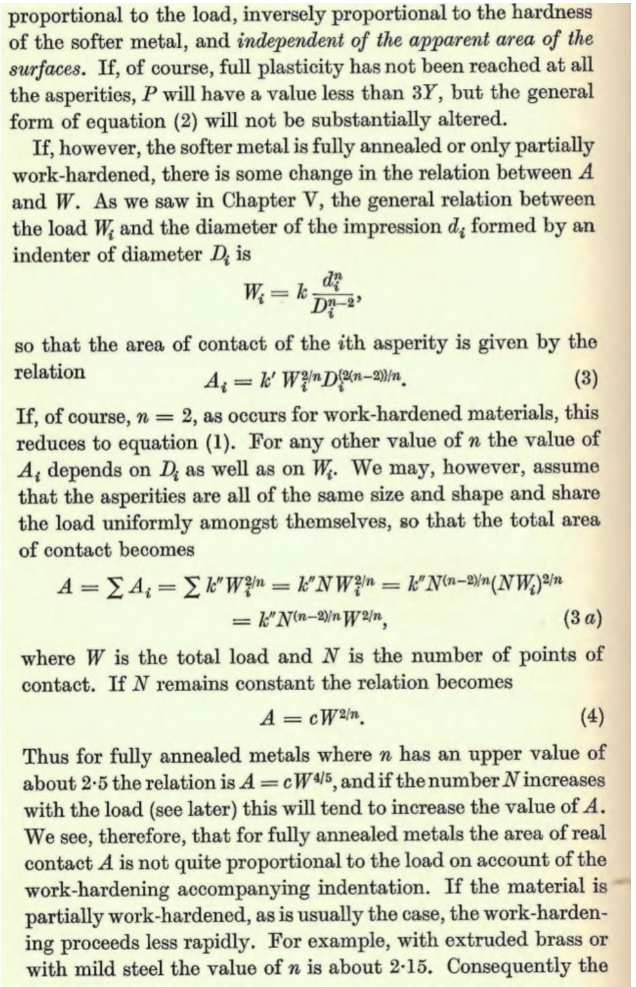
behaves like a minute Brinell indenter. For a material which is fully work-hardened the yield pressure P at the tip of each asperity will be constant and will be given by $P \approx 3Y$, where Y is the elastic limit of the metal. Consequently if the load supported by the asperity is W_i, the area of contact A_i at the tip of the asperity is given by

$$A_i = W_i/P. \tag{1}$$

The total area of contact A will be the sum of all the areas of contact at all the asperities, so that

$$A = \sum A_i = \sum \frac{W_i}{P} = \frac{W}{P}, \tag{2}$$

where W is the total load. Thus the area of real contact will be



proportional to the load, inversely proportional to the hardness of the softer metal, and *independent of the apparent area of the surfaces*. If, of course, full plasticity has not been reached at all the asperities, P will have a value less than $3Y$, but the general form of equation (2) will not be substantially altered.

If, however, the softer metal is fully annealed or only partially work-hardened, there is some change in the relation between A and W. As we saw in Chapter V, the general relation between the load W_i and the diameter of the impression d_i formed by an indenter of diameter D_i is

$$W_i = k\frac{d_i^n}{D_i^{n-2}},$$

so that the area of contact of the ith asperity is given by the relation

$$A_i = k' W_i^{2/n} D_i^{\{2(n-2)\}/n}. \tag{3}$$

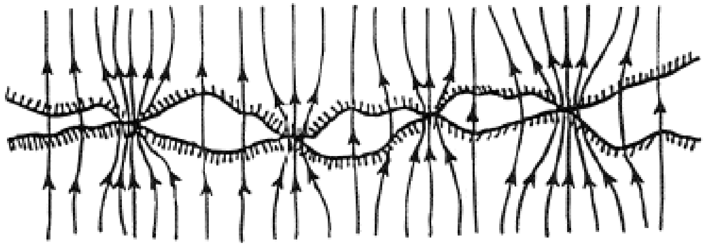
If, of course, $n = 2$, as occurs for work-hardened materials, this reduces to equation (1). For any other value of n the value of A_i depends on D_i as well as on W_i. We may, however, assume that the asperities are all of the same size and shape and share the load uniformly amongst themselves, so that the total area of contact becomes

$$\begin{aligned} A = \sum A_i = \sum k'' W_i^{2/n} = k'' N W_i^{2/n} &= k'' N^{(n-2)/n} (N W_i)^{2/n} \\ &= k'' N^{(n-2)/n} W^{2/n}, \end{aligned} \tag{3 a}$$

where W is the total load and N is the number of points of contact. If N remains constant the relation becomes

$$A = cW^{2/n}. \tag{4}$$

Thus for fully annealed metals where n has an upper value of about 2·5 the relation is $A = cW^{4/5}$, and if the number N increases with the load (see later) this will tend to increase the value of A. We see, therefore, that for fully annealed metals the area of real contact A is not quite proportional to the load on account of the work-hardening accompanying indentation. If the material is partially work-hardened, as is usually the case, the work-hardening proceeds less rapidly. For example, with extruded brass or with mild steel the value of n is about 2·15. Consequently the



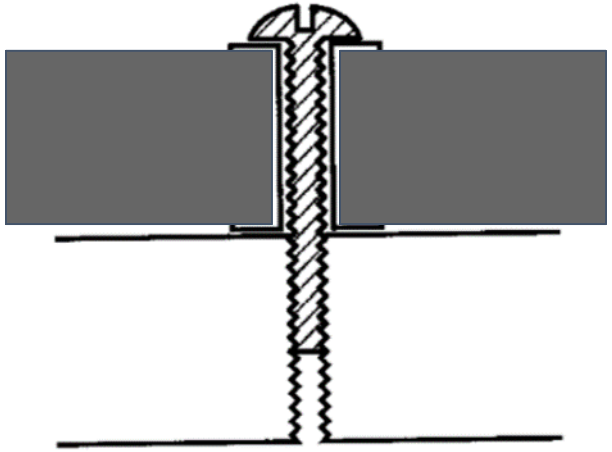
Thermal Contraction

Matching Differential Thermal Contraction

- Goal: minimize stresses induced upon cooling down, while also maintaining good thermal contact. Closely balance changes without exceeding any material strengths
- One specific example: securing radiation shield panels

$$\Delta L = L_p\left(\frac{\Delta L_p}{L_p}\right) - L_s\left(\frac{\Delta L_s}{L_s}\right) + n_w L_w\left(\frac{\Delta L_w}{L_w}\right)$$

- Goal: ΔL < 0, without over-stressing material



4 K Shield: 0.25" Cu panel

Stainless screw…
ΔL > 0

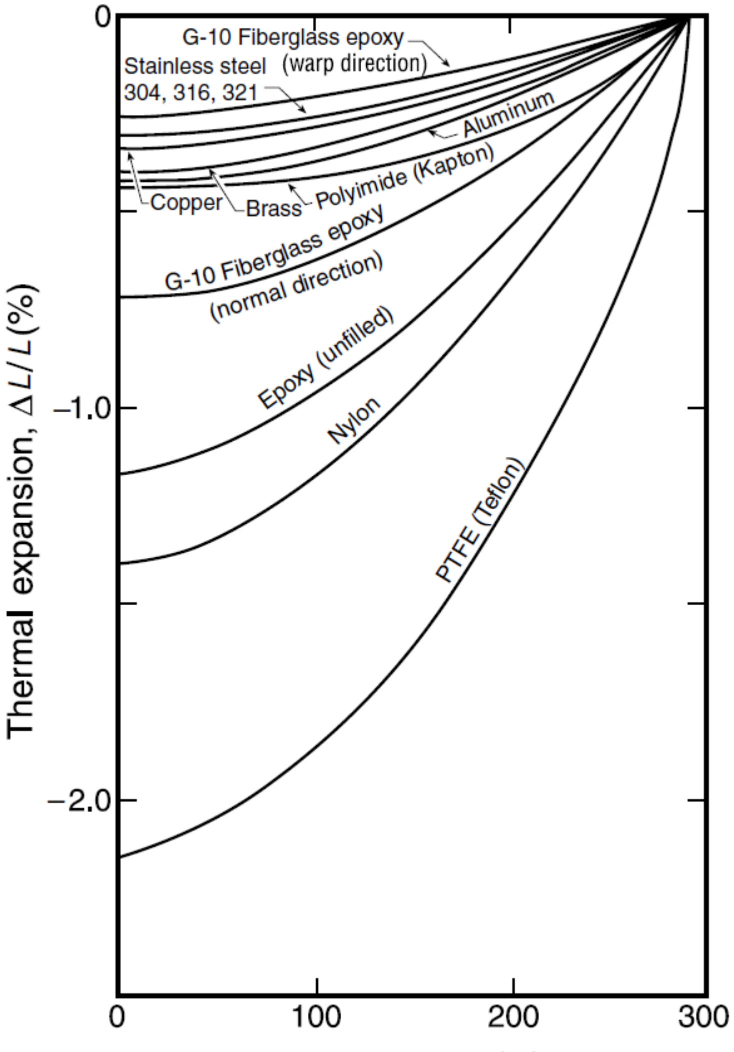
Brass screw…
ΔL < 0 by 1/10 of a mil

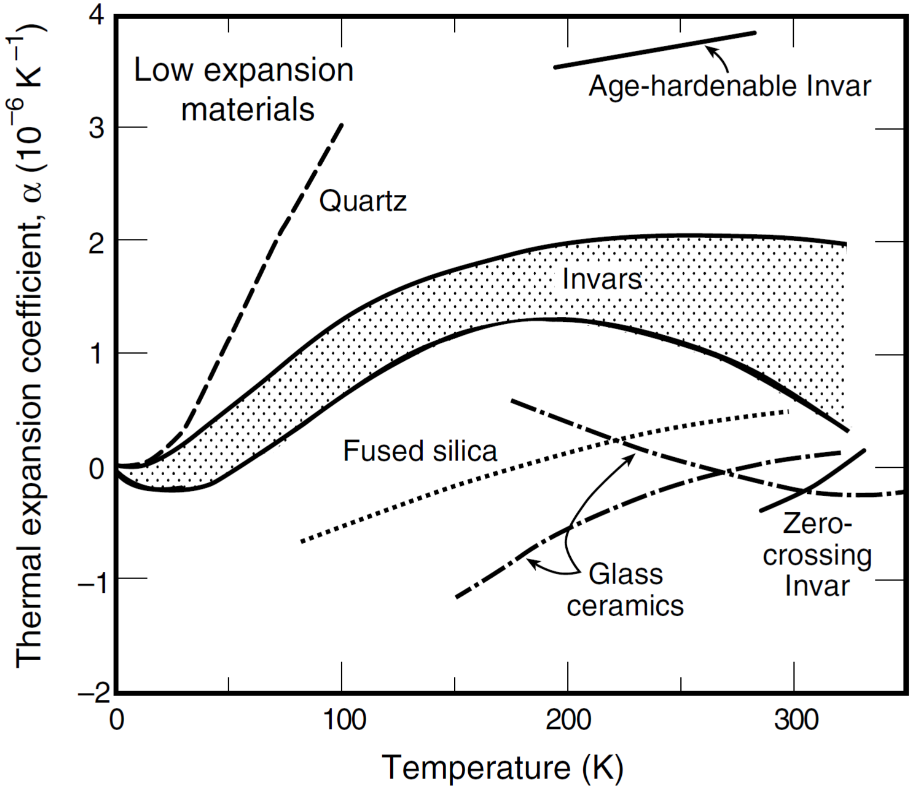
77 K Shield: 0.25" Al panel

Brass screw…
ΔL > 0

Brass screw + 2 SS washers…
ΔL < 0 by 1/20 of a mil

Thermal Contraction - Overview

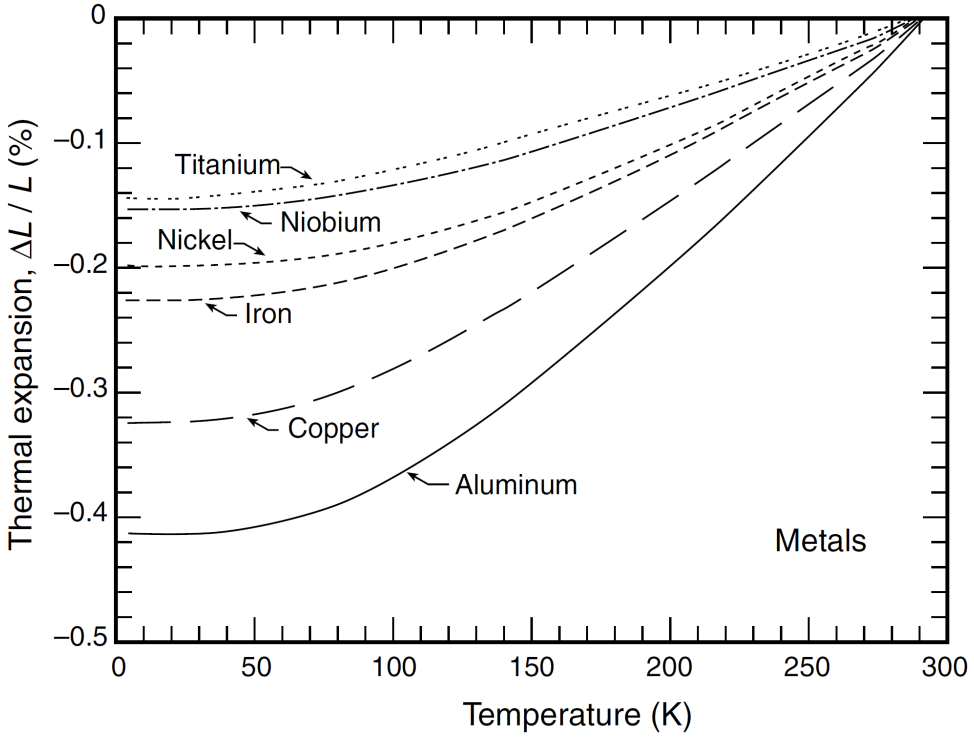


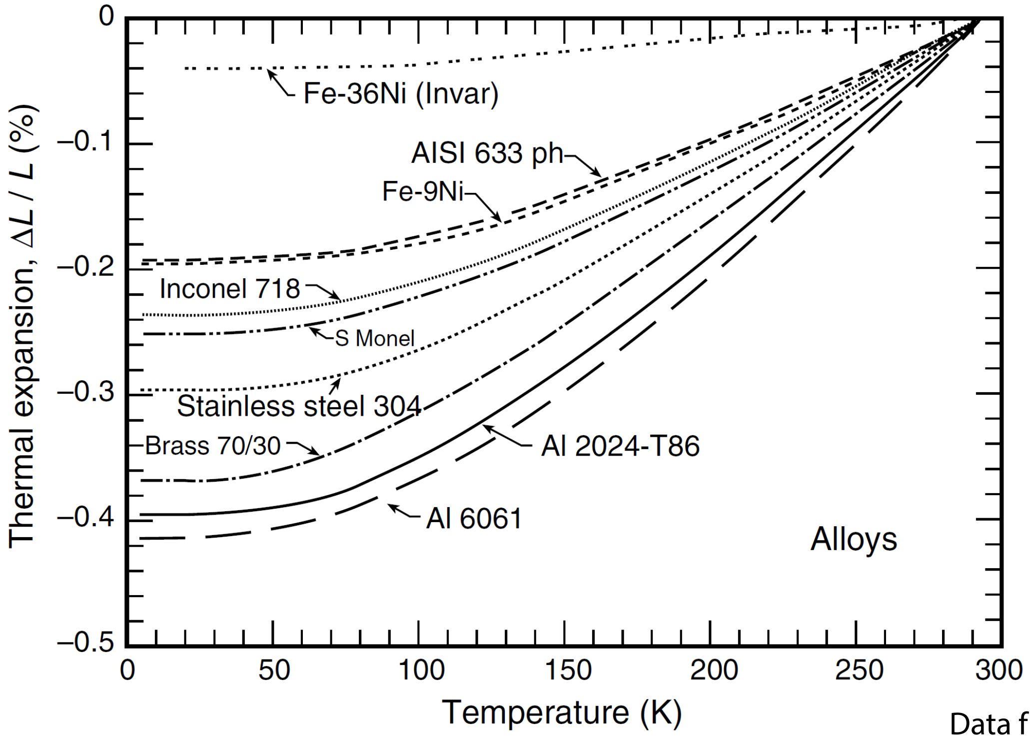


Data from: Ekin (2007)

Thermal Contraction - Metals

ABCs: aluminum > brass > copper > stainless

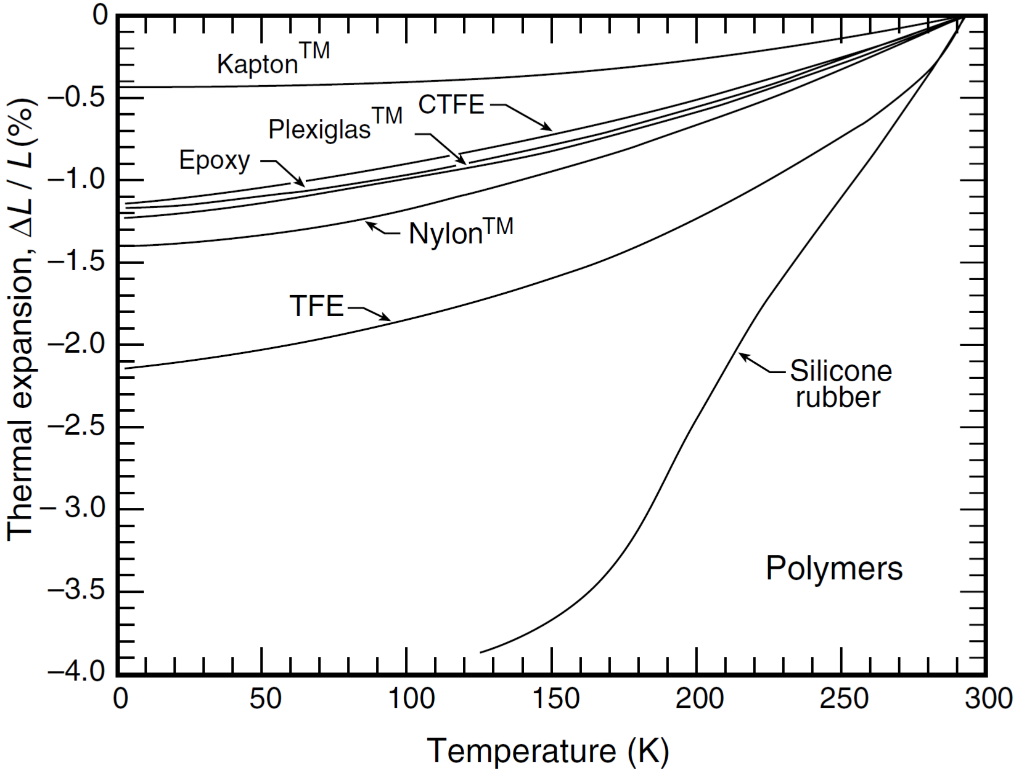


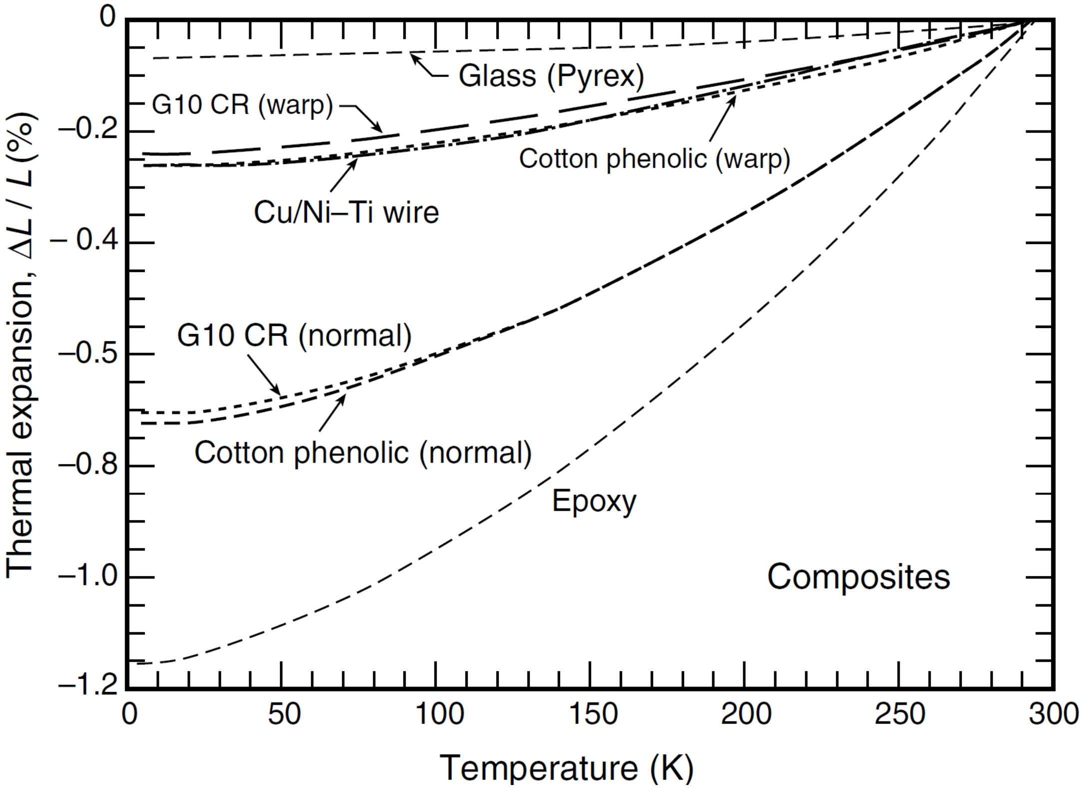


Data from: Ekin (2007)

Thermal Contraction - Nonmetals

Stycast 2850FT designed for contraction ~matched to that of Cu





Data from: Ekin (2007)

Epoxy Thermal Contraction

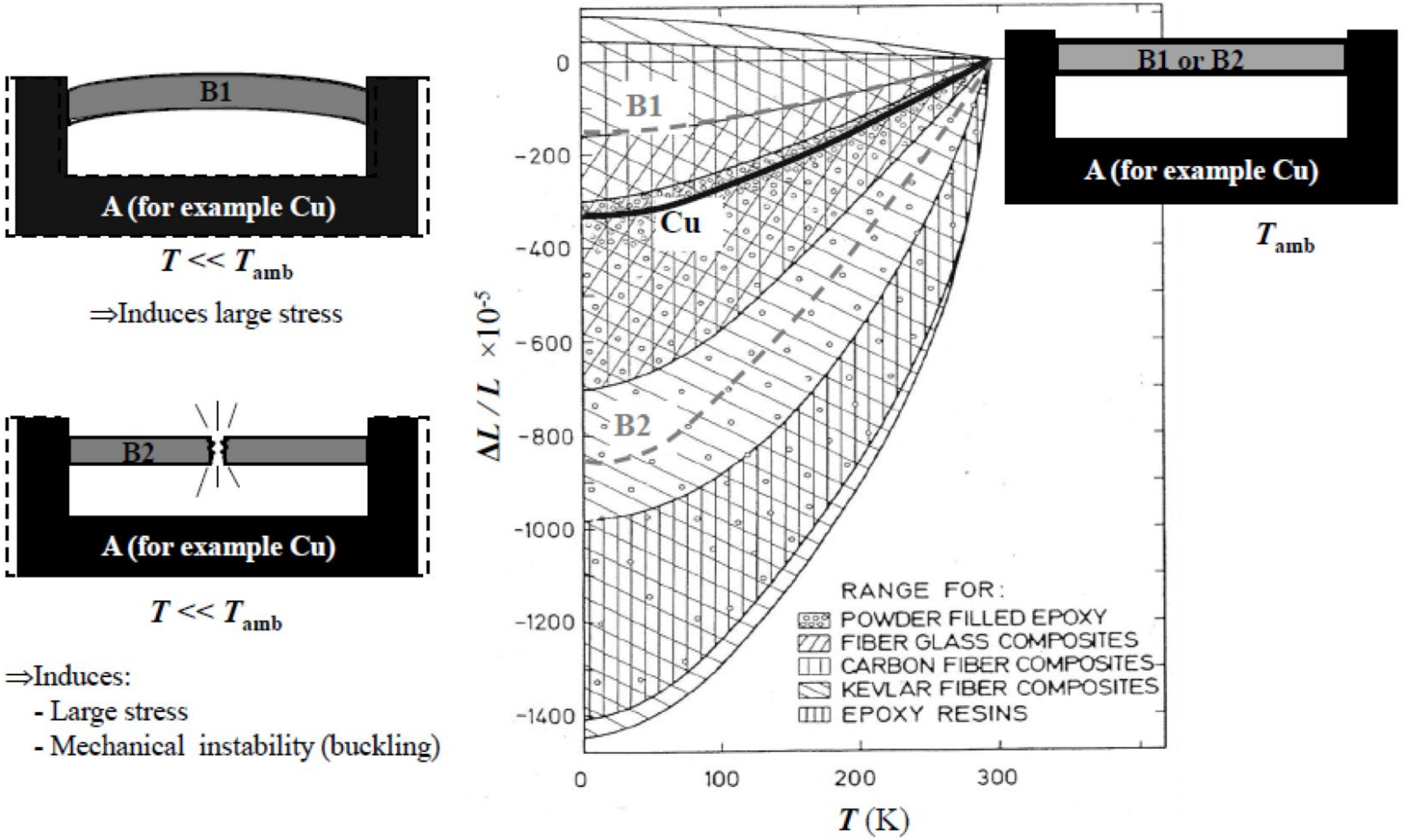


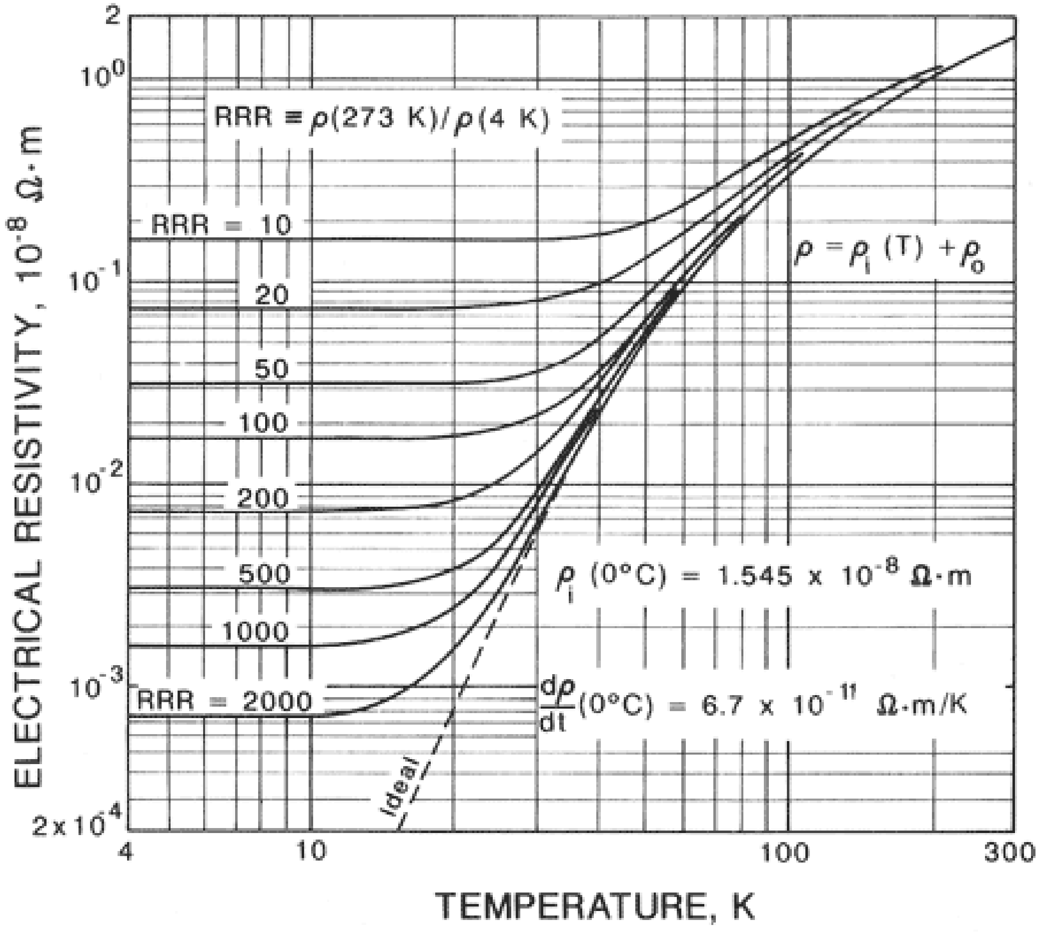
Fig. 9: Mechanical consequences of cooling a 'rigid' assembly of two solid materials having different thermal expansion coefficients.

Stycast 2850FT designed for contraction ~matched to that of Cu

Data from: Ekin (2007)

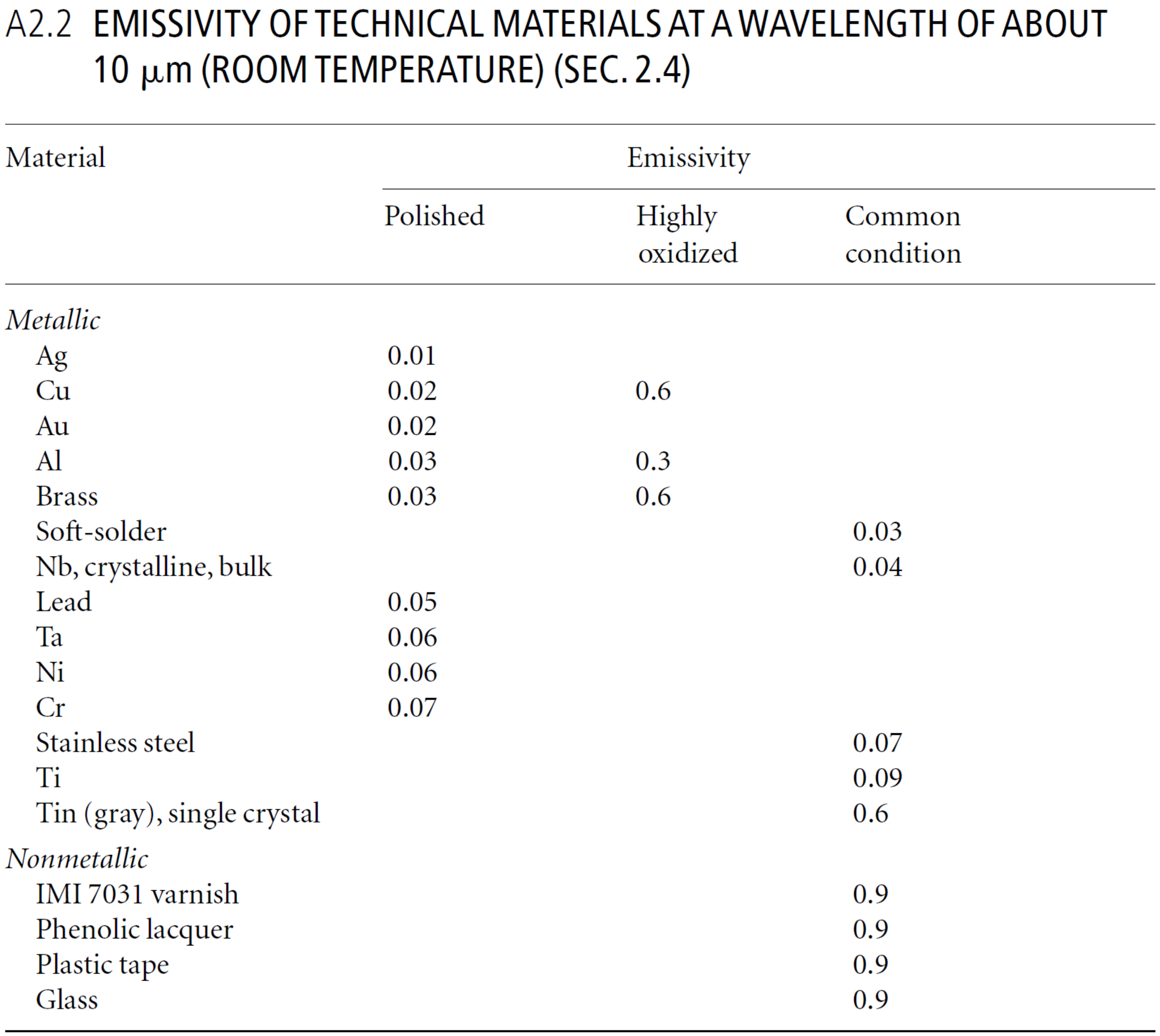
Electrical

Electrical Resisitivity



Radiation/Insulation

Emissivity

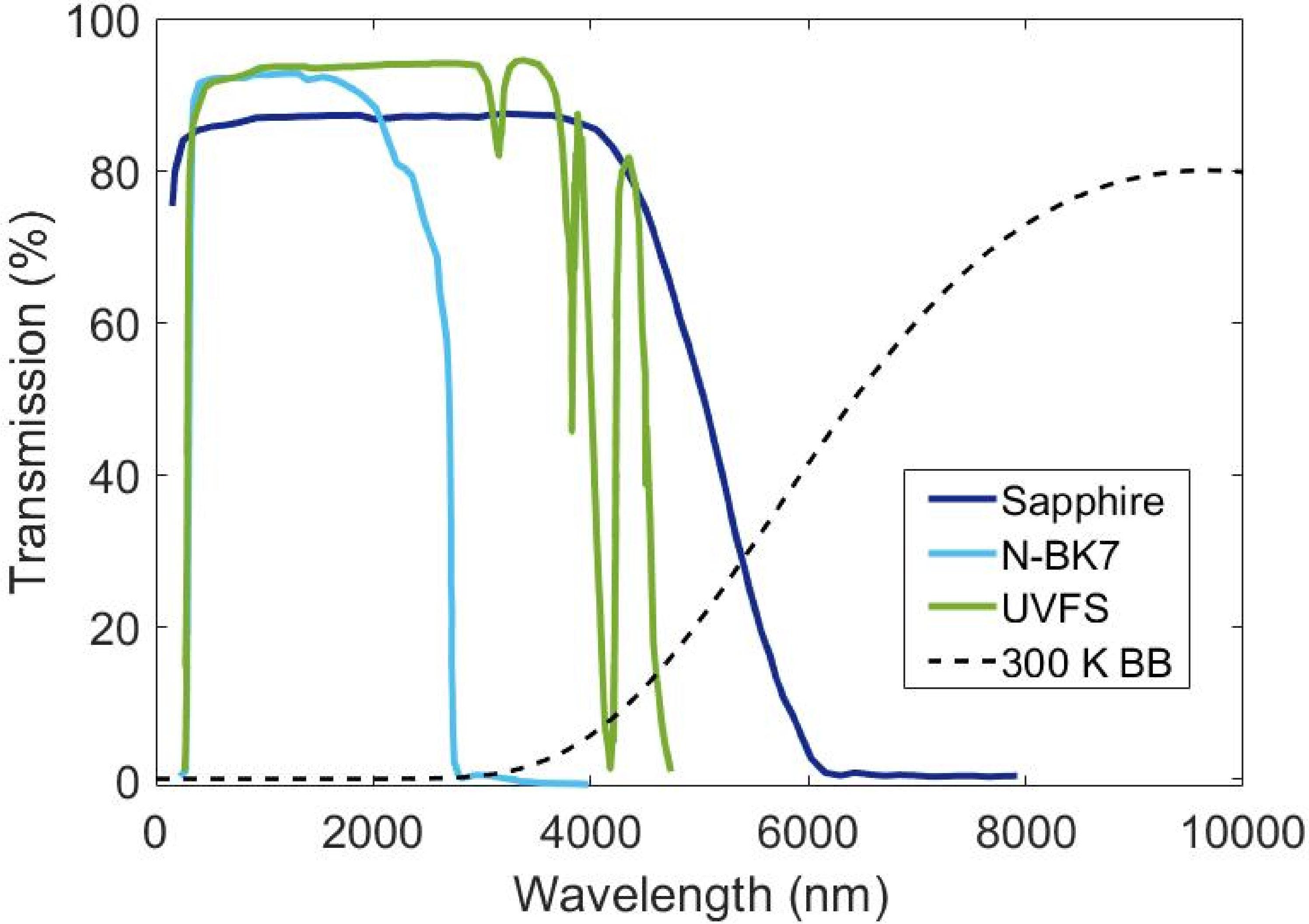


A2.2 **EMISSIVITY OF TECHNICAL MATERIALS AT A WAVELENGTH OF ABOUT 10 μm (ROOM TEMPERATURE) (SEC. 2.4)**

Material	Emissivity		
	Polished	Highly oxidized	Common condition
Metallic			
Ag	0.01		
Cu	0.02	0.6	
Au	0.02		
Al	0.03	0.3	
Brass	0.03	0.6	
Soft-solder			0.03
Nb, crystalline, bulk			0.04
Lead	0.05		
Ta	0.06		
Ni	0.06		
Cr	0.07		
Stainless steel			0.07
Ti			0.09
Tin (gray), single crystal			0.6
Nonmetallic			
IMI 7031 varnish			0.9
Phenolic lacquer			0.9
Plastic tape			0.9
Glass			0.9

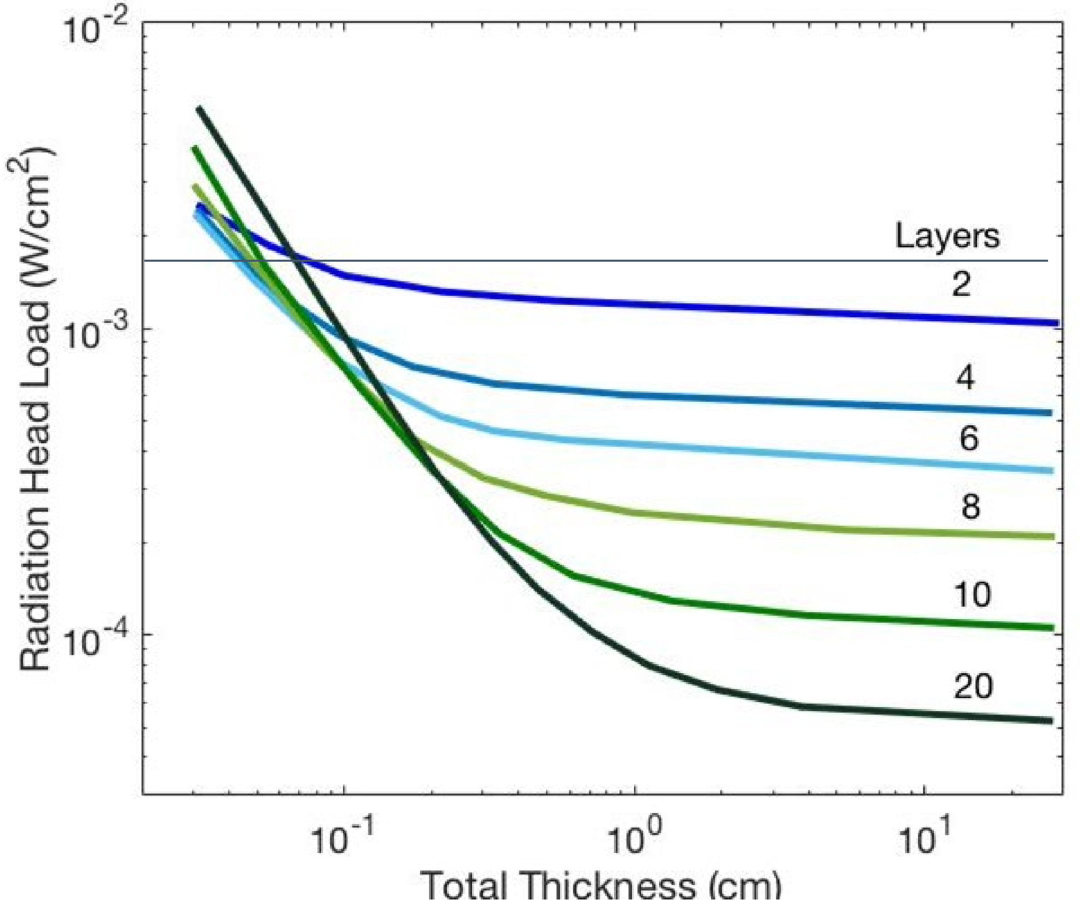
Data from: Ekin (2007)

Windows



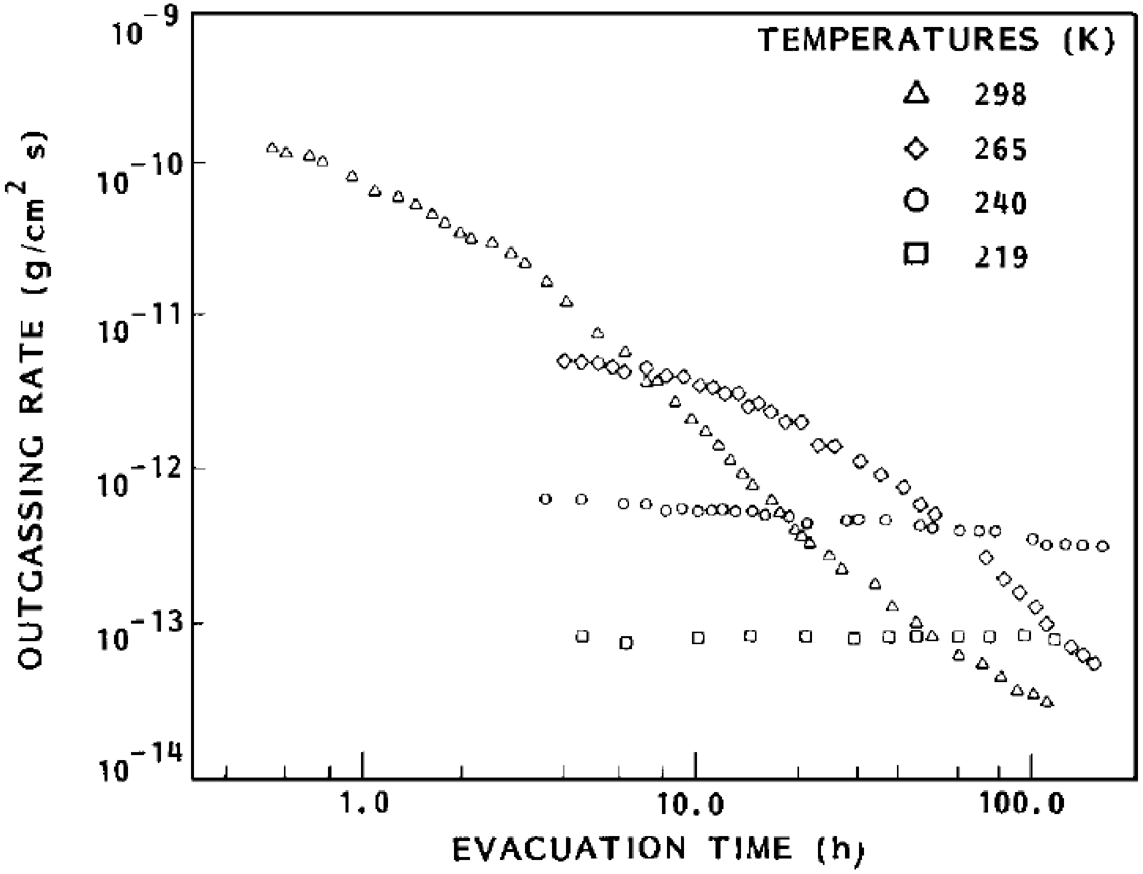
Data compiled from: ESCO (UVFS), Thorlabs (N-BK7 and Sapphire)

Superinsulation

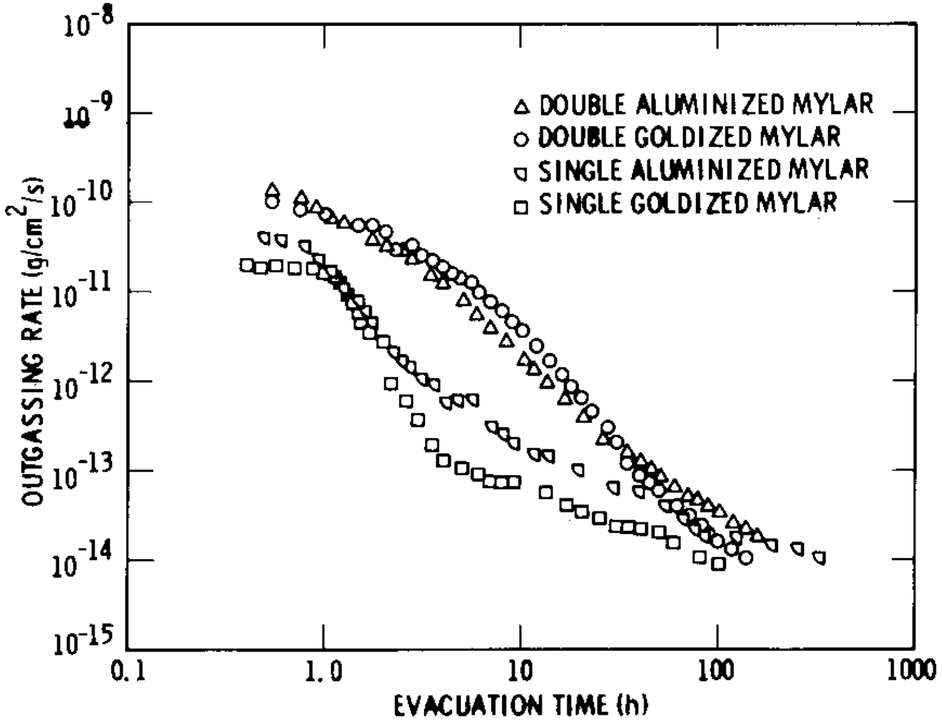


Data from: NASA Aluminized Mylar study (1997)

Effect of temperature and preconditioning on the outgassing rate of double aluminized mylar and dacron net http://dx.doi.org/10.1116/1.572411



Outgassing rate of multilayer insulation materials at ambient temperature



IG. 2. Outgassing rate of metallized Mylar shields.

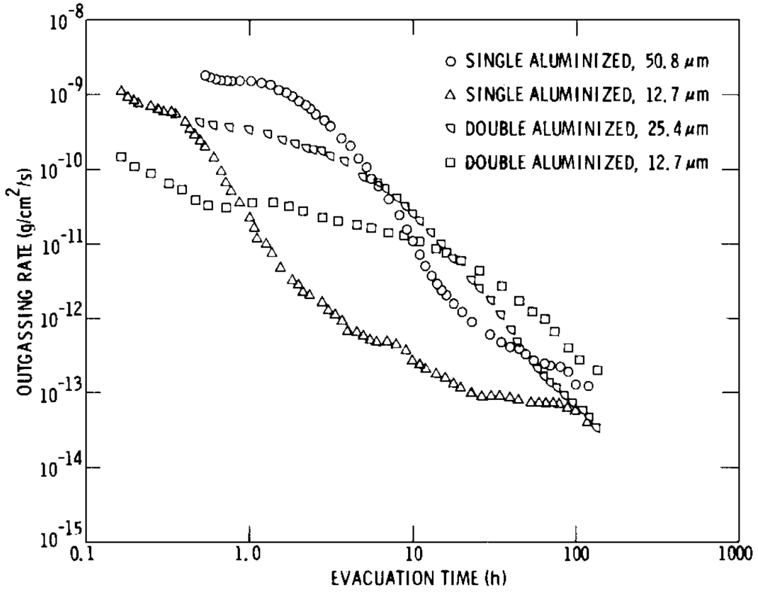
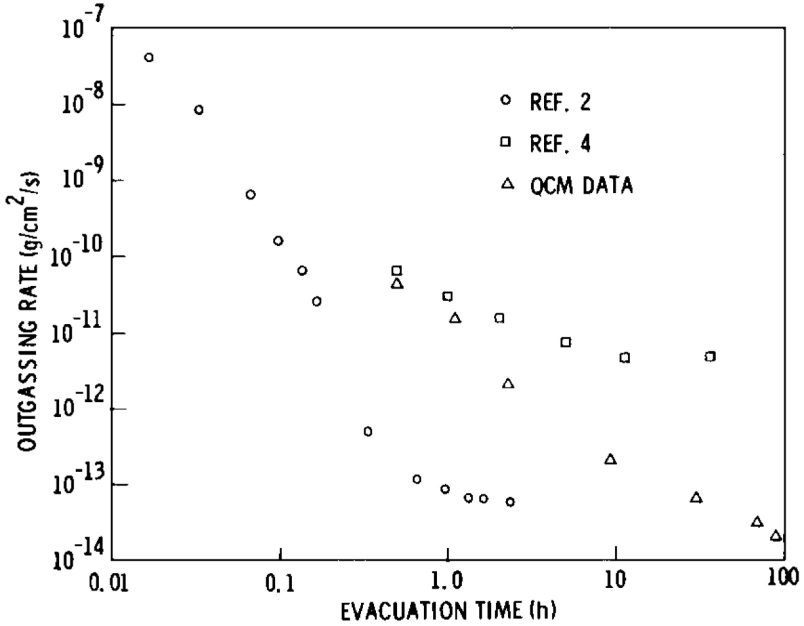
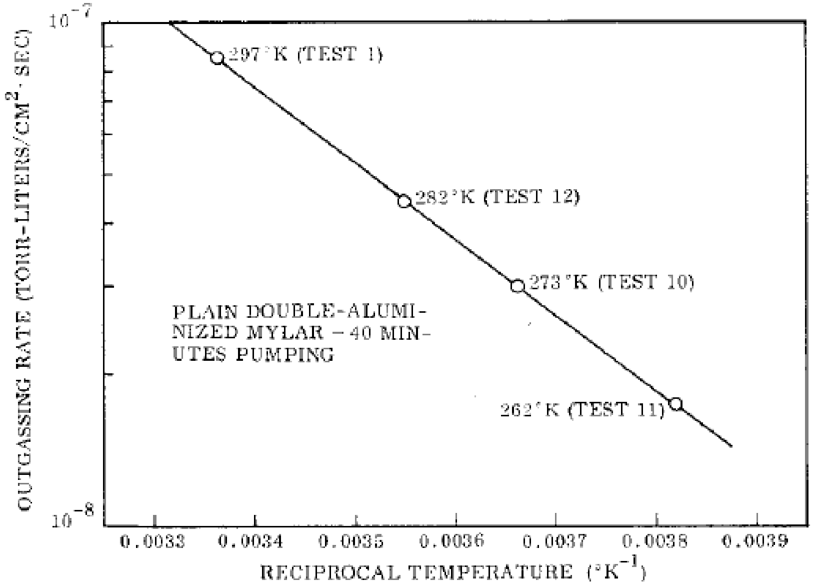


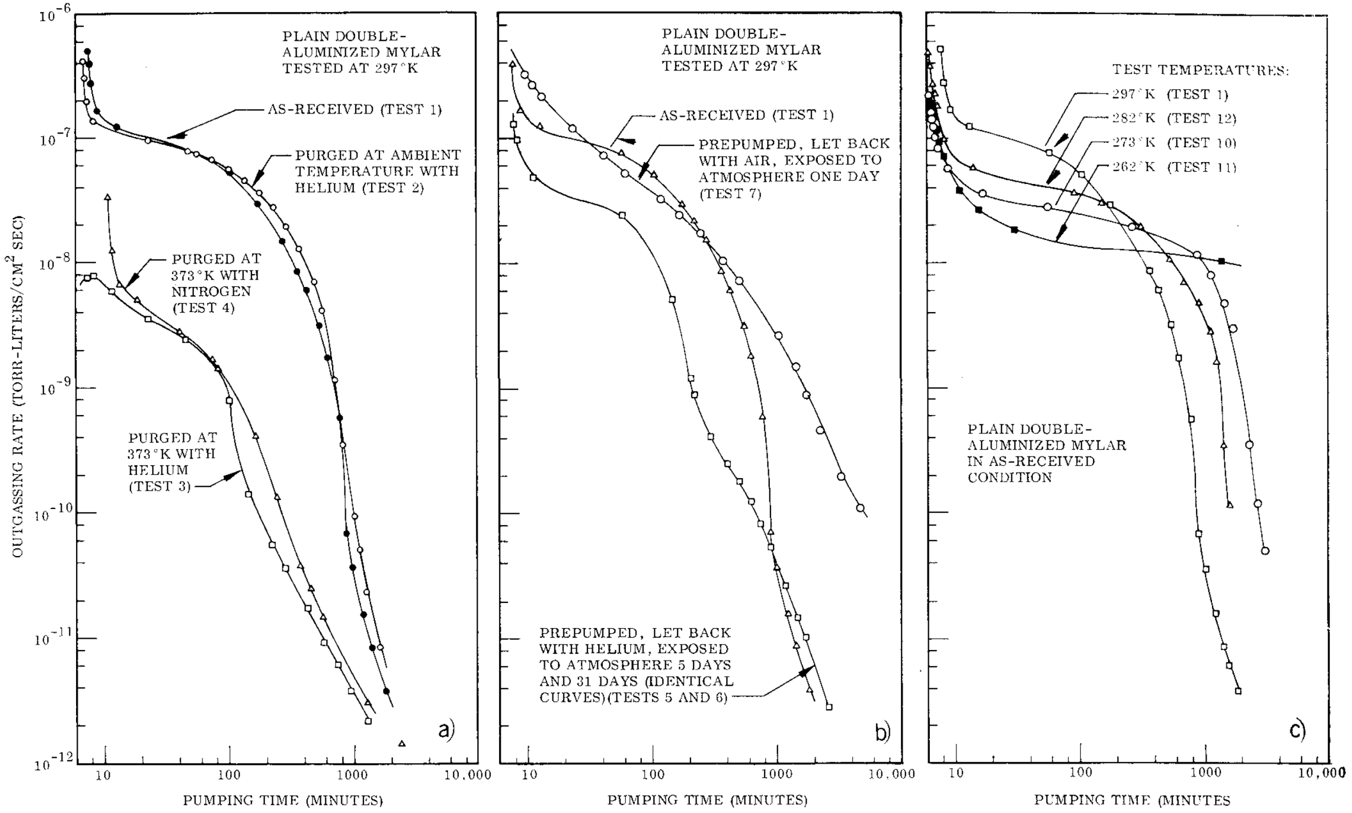
FIG. 3. Outgassing rate of metallized Kapton shields.



(b)

Outgassing Behavior of Multilayer Insulation Materials
A. P. M. GLASSFORD





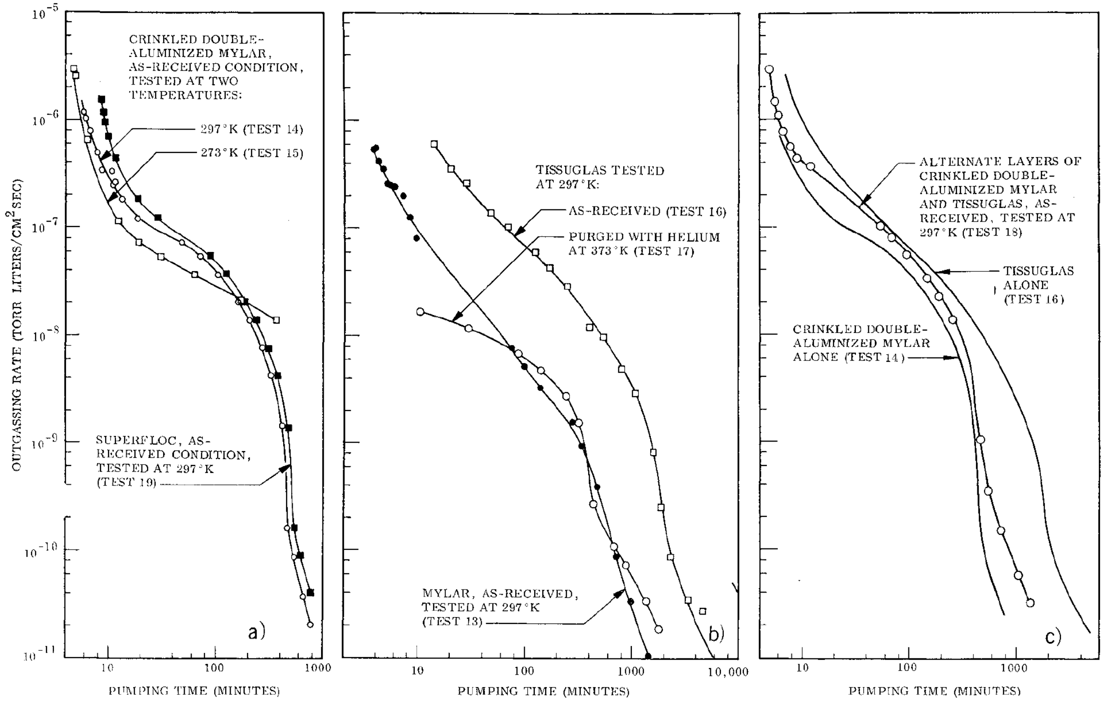
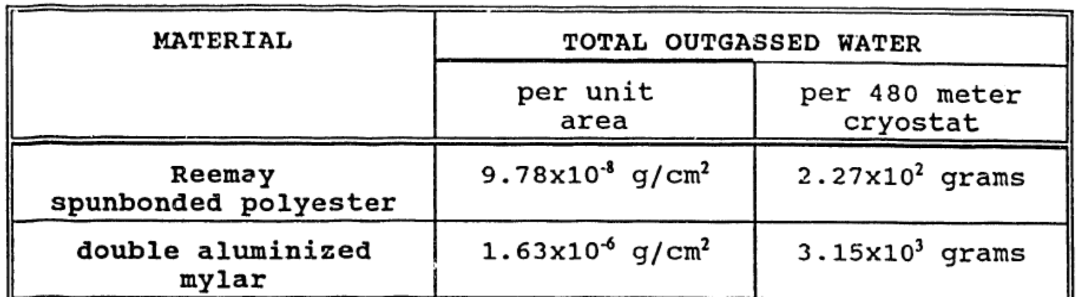


Fig. 4 Outgassing rates of various materials: a) crinkled double-aluminized Mylar at two temperatures, and Superfloc, b) Tissuglas in as-received and hot-purged condition, and plain Mylar, and c) mixed Tissuglas/crinkled double-aluminized Mylar, and the separate components.

OUTGASSING RATE OF REEMAY SPUNBONDED POLYESTER AND DUPONT DOUBLE ALUMINIZED MYLAR (DAM)

R.J. Todd, D. Pate, K.M. Welch
Brookhaven National Laboratory
August 1992



MATERIAL	TOTAL OUTGASSED WATER	
	per unit area	per 480 meter cryostat
Reemay spunbonded polyester	9.78×10^{-8} g/cm^2	2.27×10^2 grams
double aluminized mylar	1.63×10^{-6} g/cm^2	3.15×10^3 grams

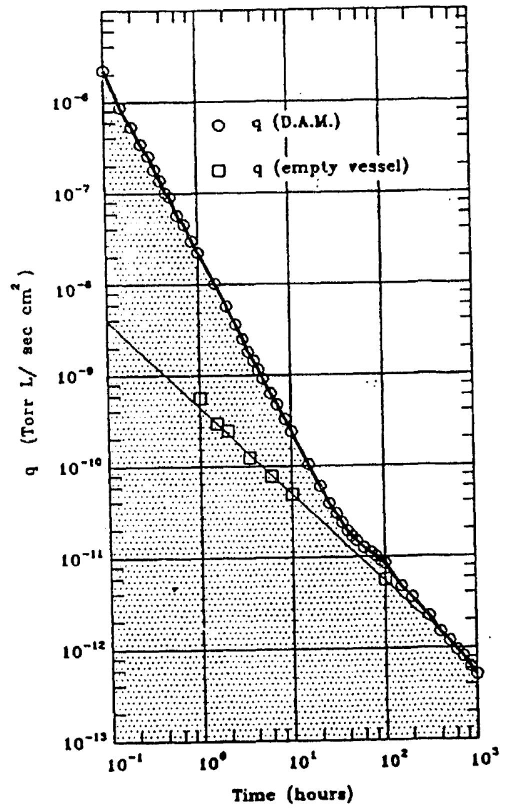


Figure 3.1 DAM Outgassing Rate vs. Time

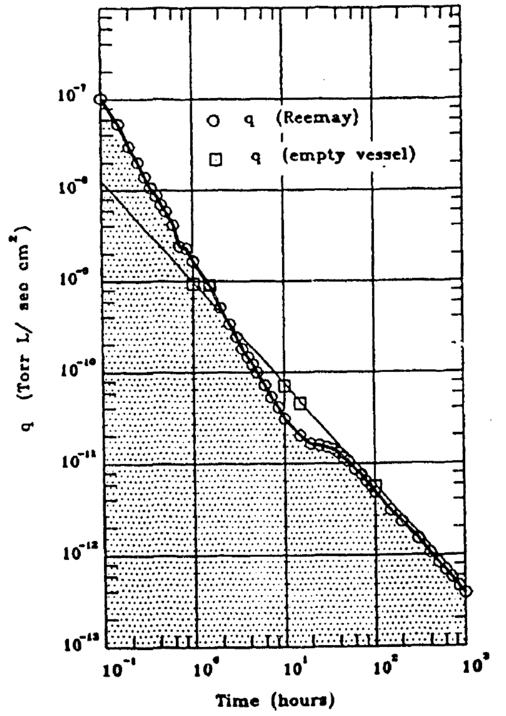
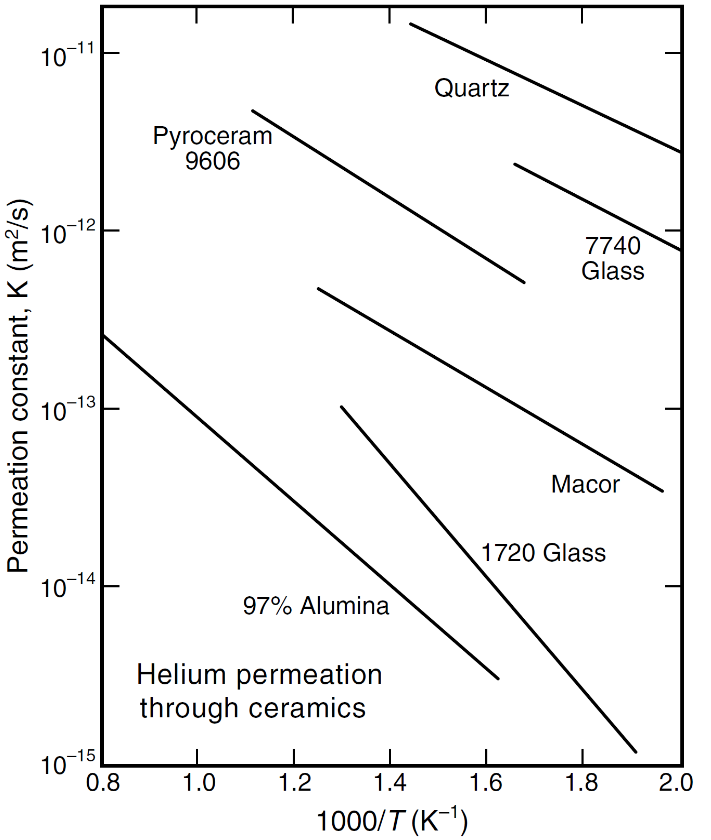


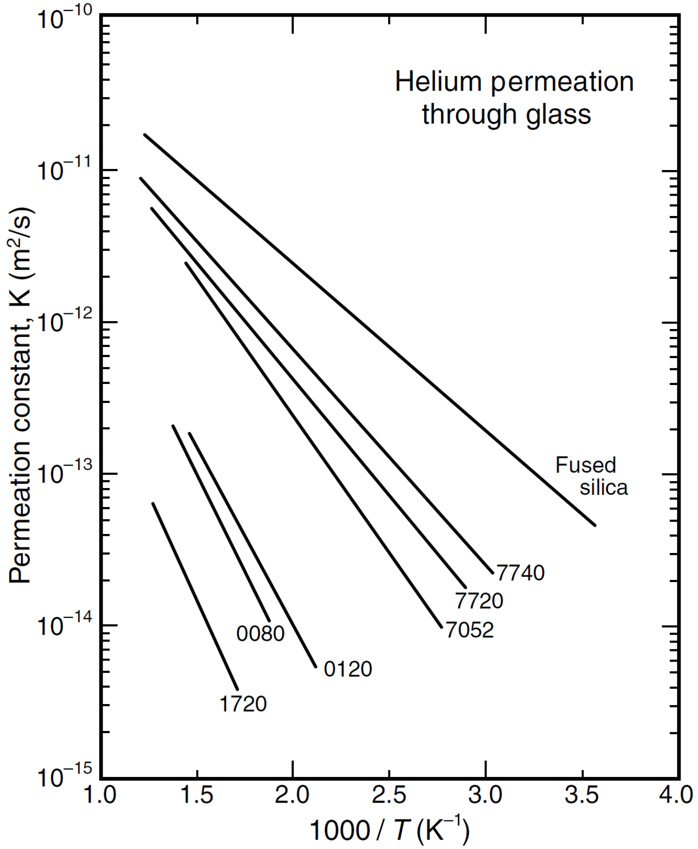
Figure 3.2 Reemay Outgassing Rate vs. Time

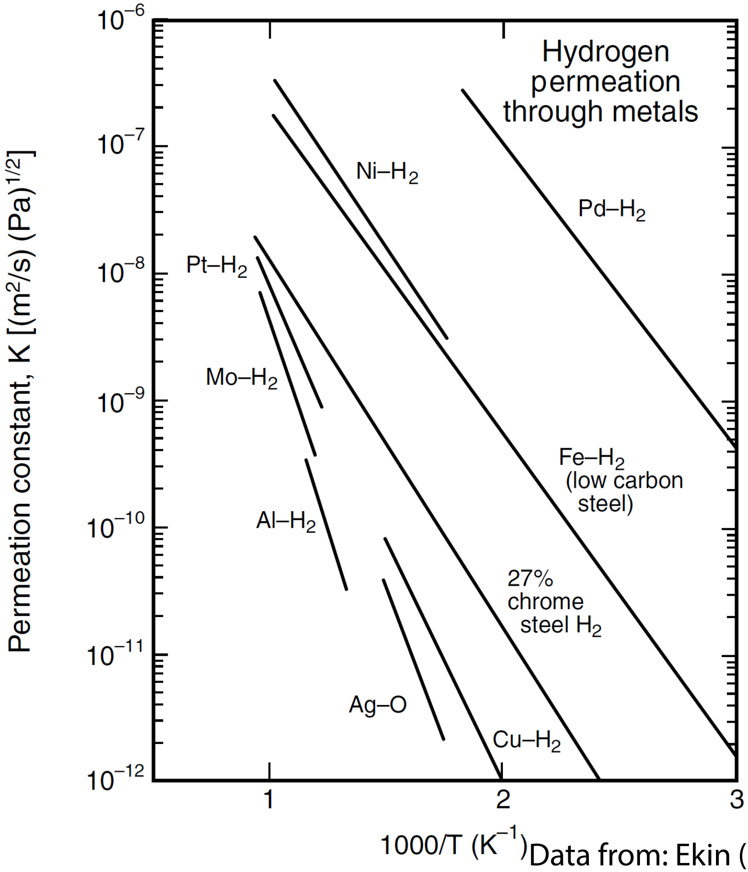
Outgassing/Permeation

Helium Permeation

Material	Permeation constant K in [m²/s] at 23°C				
	Nitrogen	Oxygen	Hydrogen	Helium	Argon
Polythene™ [a]	9.9×10^{-13}	3.0×10^{-12}	8.2×10^{-12}	5.7×10^{-12}	2.7×10^{-12}
PTFE (Teflon™)[a]	2.5×10^{-12}	8.2×10^{-12}	2.0×10^{-11}	5.7×10^{-10}	4.8×10^{-12}
Perspex™ [a]	—	—	2.7×10^{-12}	5.7×10^{-12}	—
Nylon 31™ [a]	—	—	1.3×10^{-13}	3.0×10^{-13}	—
Polystyrene™ [a]	—	5.1×10^{-13}	1.3×10^{-11}	1.3×10^{-11}	—
Polystyrene™ [b]	6.4×10^{-12}	2.0×10^{-11}	7.4×10^{-11}	—	—
Polyethylene™ [b]	$6–11 \times 10^{-13}$	$2.5–3.4 \times 10^{-12}$	$6–12 \times 10^{-12}$	$4–5.7 \times 10^{-12}$	—
Mylar 25-V-200™ [b]	—	—	4.8×10^{-13}	8.0×10^{-13}	—
CS2368B (Neoprene™)[a]	2.1×10^{-13}	1.5×10^{-12}	8.2×10^{-12}	7.9×10^{-12}	1.3×10^{-12}
Viton A™ [a]	—	—	2.2×10^{-12}	8.2×10^{-12}	—
Polyimide (Kapton™)[c]	3.2×10^{-14}	1.1×10^{-13}	1.2×10^{-12}	2.1×10^{-12}	—



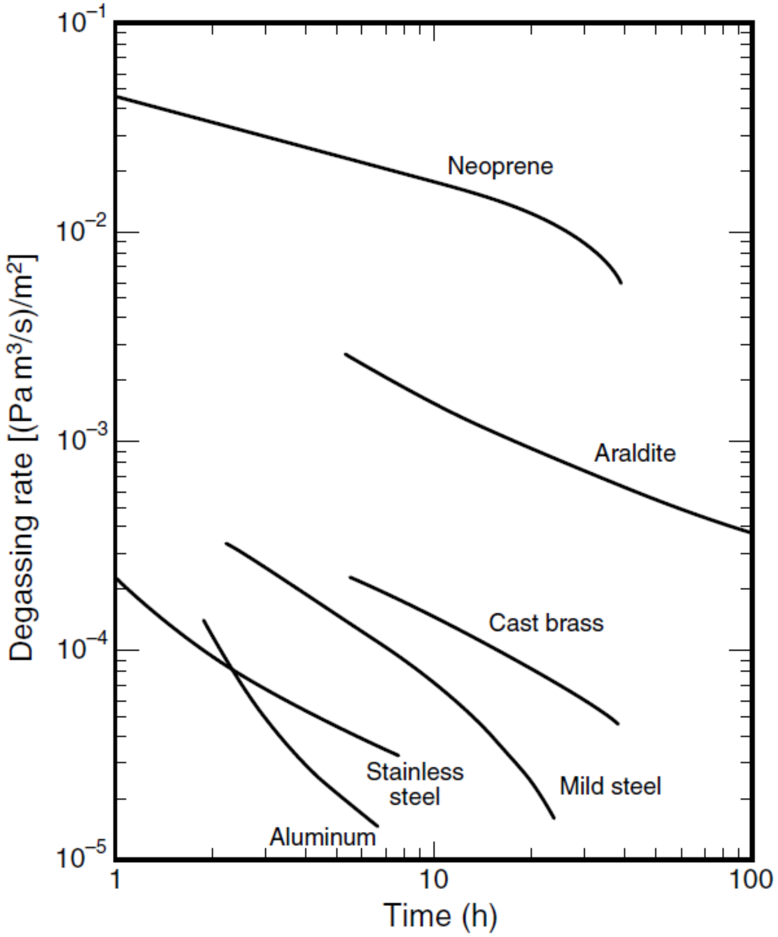




Data from: Ekin (2007)

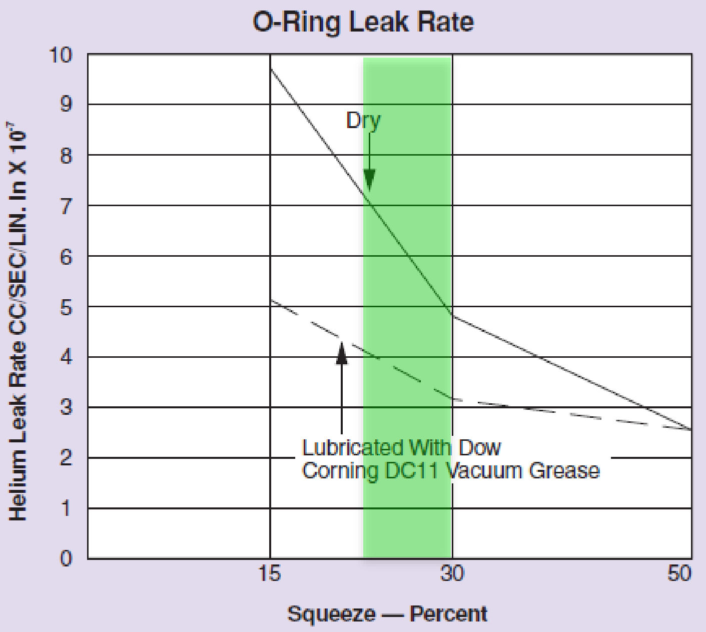
Degassing Rates

Material	Degassing rate at room temperature before baking [Pa m^3/(s m^2)]	Baking temperature [°C]	Degassing rate at room temp. after 24 h bake [Pa m^3/(s m^2)]
Araldite ATI™ epoxy [a]	3.4×10^{-4}	85	—
Mycalex™ [a]	2.7×10^{-6}	300	—
Nylon 31™ [a]	1.1×10^{-4}	120	8.0×10^{-7}
Perspex™ [a]	1.3×10^{-5}	85	7.8×10^{-6}
Polythene™ [a]	4.0×10^{-4}	80	6.6×10^{-6}
PTFE (Teflon™) [b]	2.0×10^{-4}	—	4.7×10^{-7}
Viton A™ [a]	1.3×10^{-4}	200	2.7×10^{-6}
Polyimide (Kapton™) [c]	—	200*	6.6×10^{-8}
	—	300*	4.0×10^{-8}
Kalrez™ [d]	—	300	4.0×10^{-8}
Viton E60C™ [d]	—	150	$\sim 1 \times 10^{-6}$
	—	300	3.0×10^{-8}



Data from: Ekin (2007)

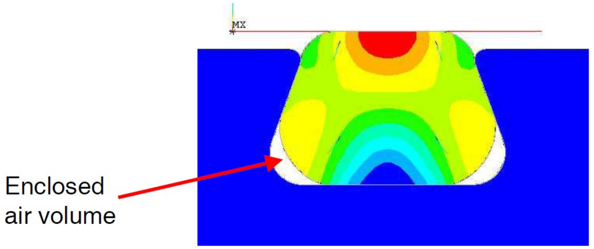
O-ring Seals- “Face Seal Glands”

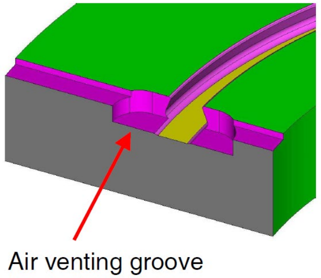


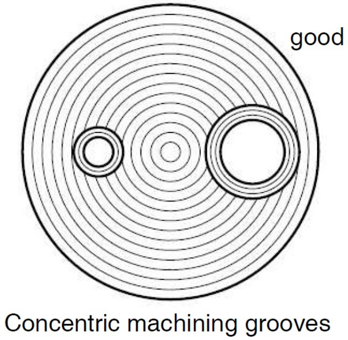
O-ring I.D. = 4.850, W. = .070, CPD = B0612-70 (Butyl)
Temperature = 25°C (77°F), Pressure Differential = 4.1 Bar (60 psi)

Parker O-ring Handbook

	Permeation Rate, He, tL/sec/lin. cm, 23°C	Outgassing Rate, tL/sec./lin.cm., 23°C	Temp-erature Limit,°C	Relative Cost
Butyl	3×10^{-8}	1×10^{-5}	86	Lowest
Nitrile	9×10^{-8}	1×10^{-6}	135	Low
Viton	5×10^{-8}	3×10^{-8} Pre-baked	150	Medium
Perflouro	1×10^{-6}	3×10^{-8}	200	Highest







Cryopumping

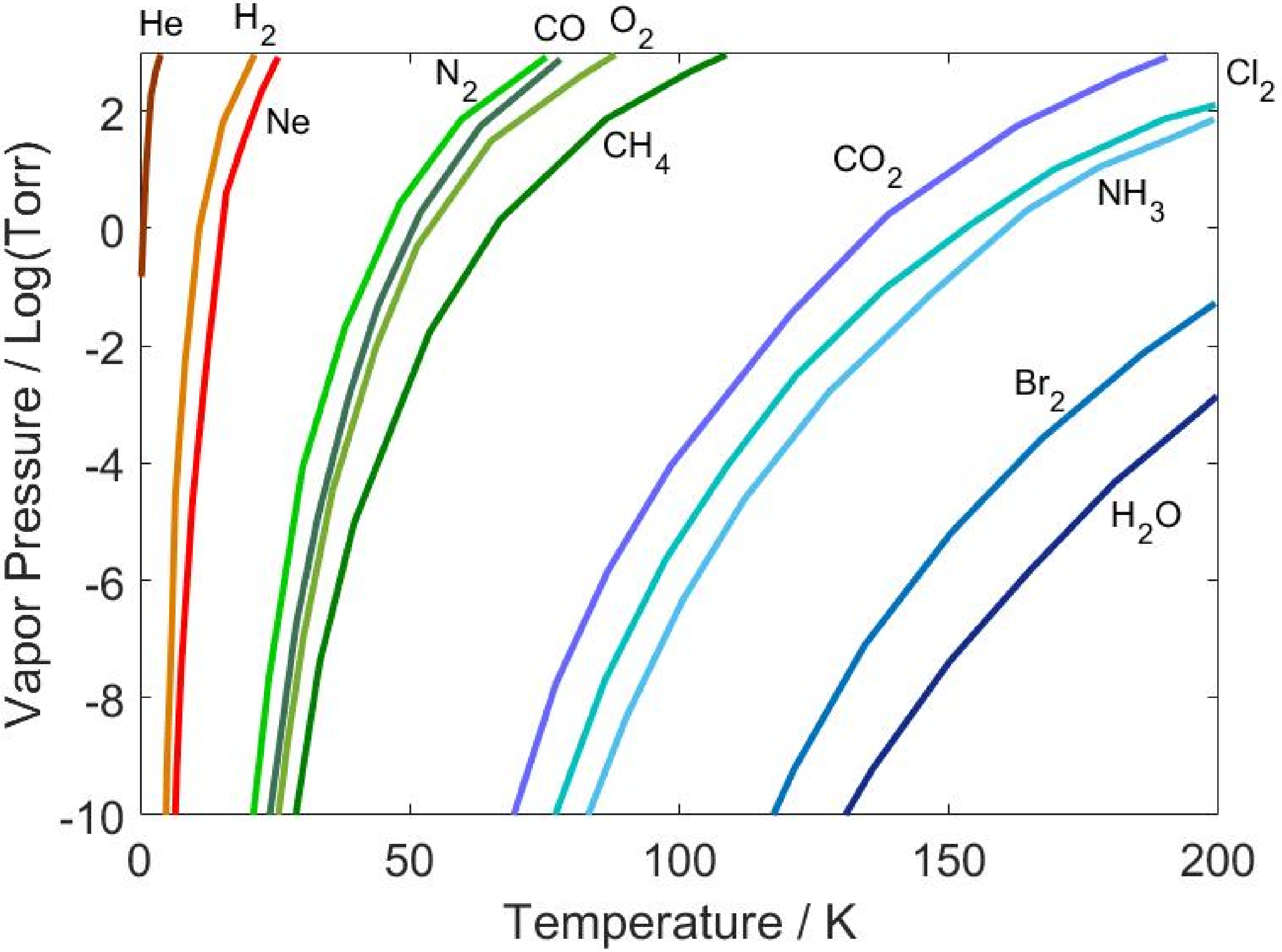
Many gases effectively pumped simply by reducing temperature of chamber surfaces (**blue** and **green** curves)

- Add model of particles hitting surfaces

He, **H**, and **Ne** retain reasonably high vapor pressures even at 4 K

Requires special pumping techniques: charcoal sorbs

Vapor pressure over an adsorbed layer

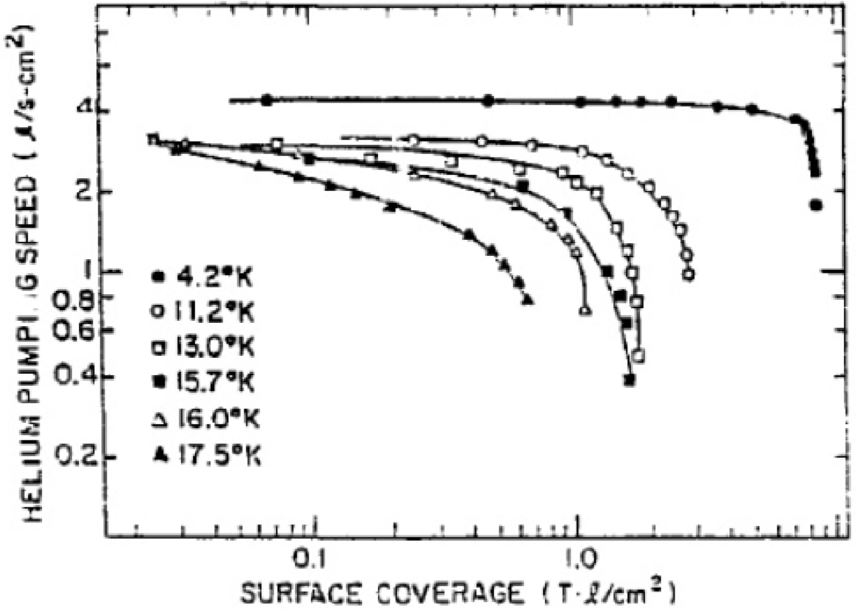


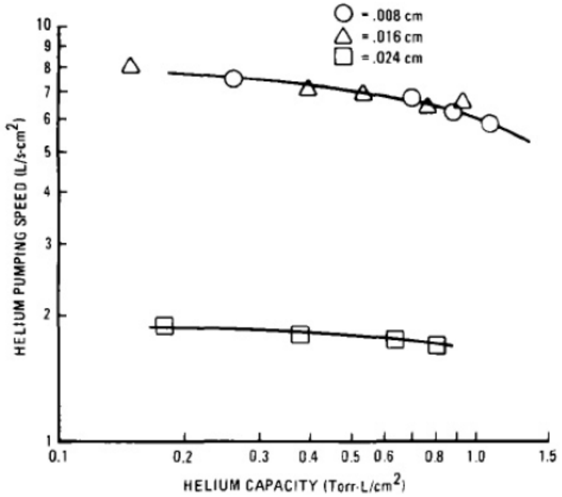
Data from Ulvac Cryogenics

Cryosorption Pumping

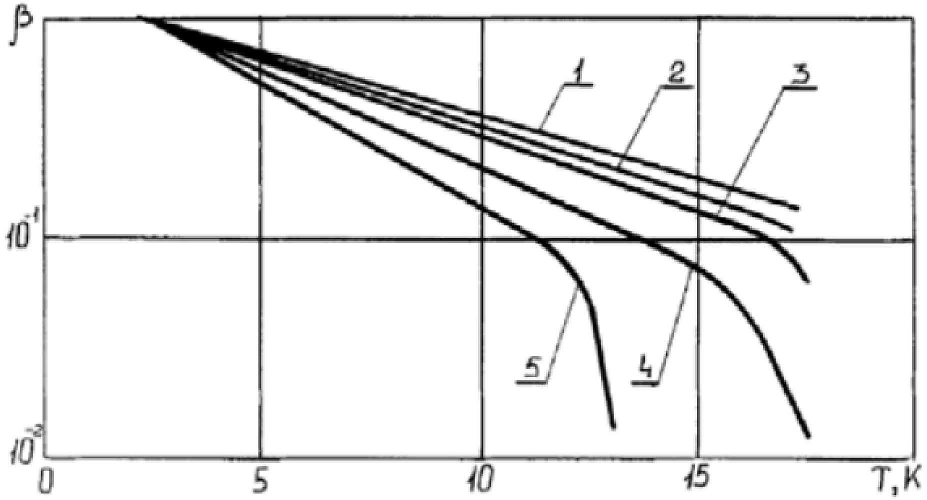
- Need to ensure He heat of adsorption carried away efficiently
- Typical pore size ~ 0.5 - 2 mm, and huge surface area: 107 cm2/g
- 1 cc of charcoal can pump ~ 100 cc of He gas

- After sticking, adsorbed He moves into bulk of the sorb via 2D surface diffusion. Temperatures < 3 K make this diffusion inefficient, decreasing pumping
- Typical pumping speed ~ 6 L/s/cm2, (peak pumping speed typical until sorbs filled to ~75% capacity)



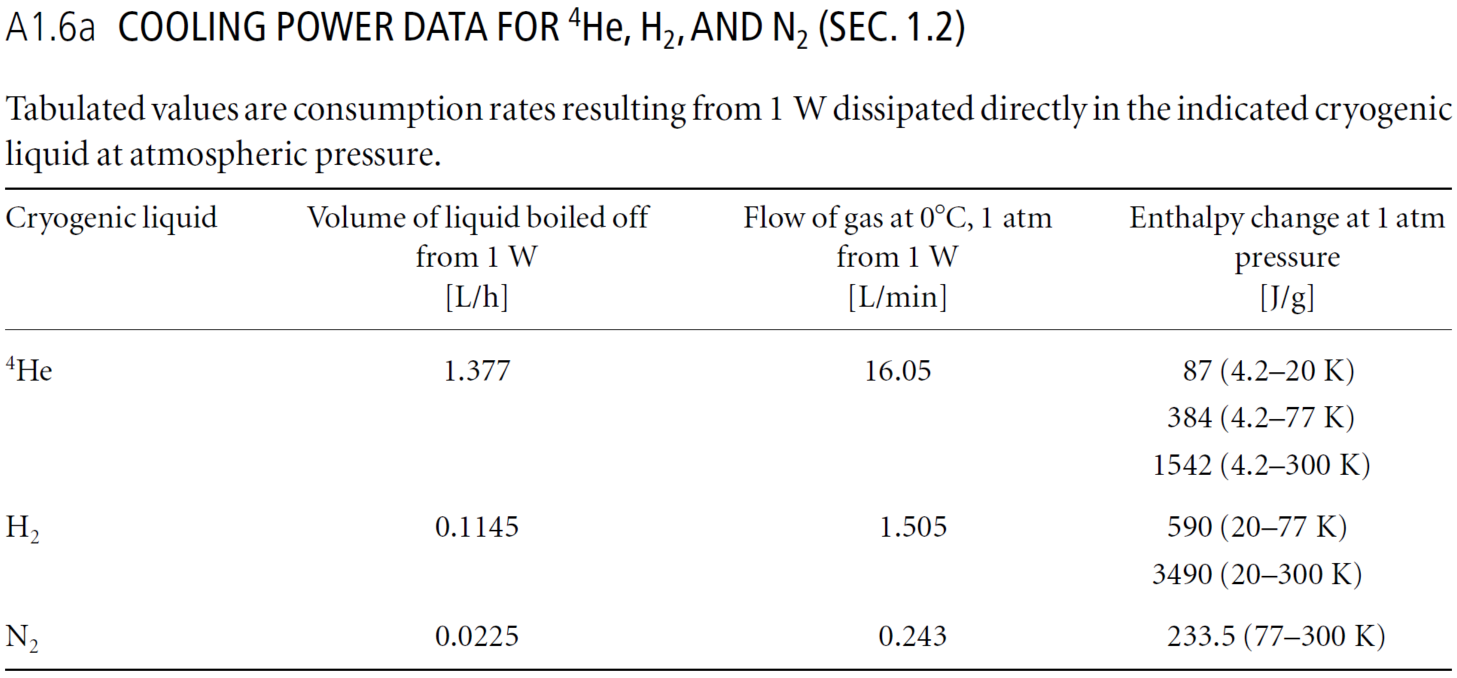


Tobin (1987)



Gurevich (1990)
Hsueh (1978)

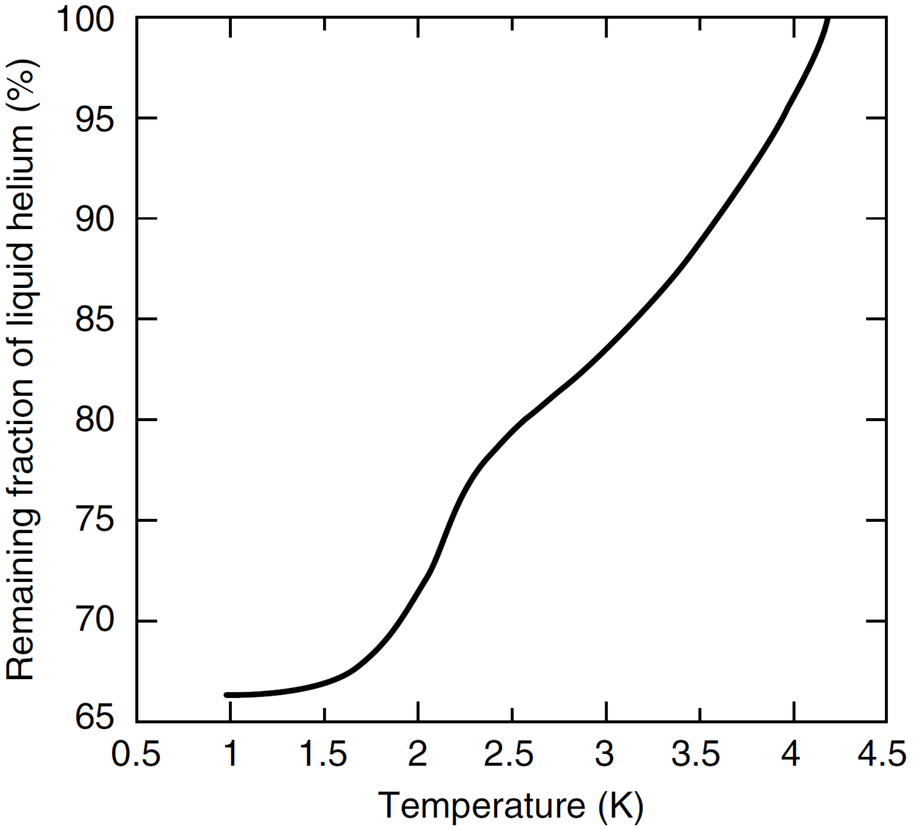
Cryogens Cooling Power



A1.6a **COOLING POWER DATA FOR ^{4}He, H_2, AND N_2 (SEC. 1.2)**

Tabulated values are consumption rates resulting from 1 W dissipated directly in the indicated cryogenic liquid at atmospheric pressure.

Cryogenic liquid	Volume of liquid boiled off from 1 W [L/h]	Flow of gas at 0°C, 1 atm from 1 W [L/min]	Enthalpy change at 1 atm pressure [J/g]
^{4}He	1.377	16.05	87 (4.2–20 K) 384 (4.2–77 K) 1542 (4.2–300 K)
H_2	0.1145	1.505	590 (20–77 K) 3490 (20–300 K)
N_2	0.0225	0.243	233.5 (77–300 K)



Data from: Ekin (2007)