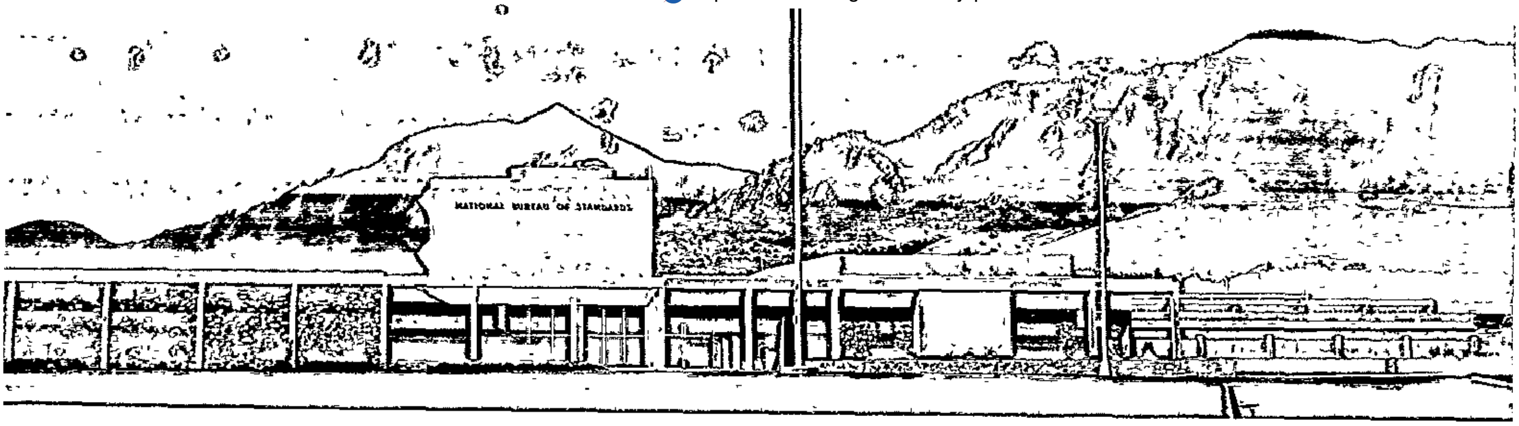

NBS REPORT

9712

CRYOGENIC THERMOCOUPLE TABLES

by

Larry L. Sparks, Robert L. Powell, and William J. Hall

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

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CRYOGENIC THERMOCOUPLE TABLES*

Larry L. Sparks, Robert L. Powell and William J. Hall

Experimental tests between 4 and 280 K have been completed on the following thermocouple materials: Chromel, copper, "normal" silver, platinum, silver-28 at.% gold, constantan, Alumel, and gold-(0.02, 0.03, 0.07) at.% Fe. Many thermocouple combinations can be made from the above materials — the four most important being copper vs constantan, Chromel vs constantan, Chromel vs Alumel, and Chromel vs gold-0.07 at.% iron. Results of the last combination are of particular interest for measurements near liquid hydrogen temperatures. The calibration cryostat is described briefly. Special methods of measurement and data analysis have been designed to study and minimize systematic errors. Simple illustrations of these measurement schemes are given. Interim tables and graphs of the thermoelectric voltage and thermopower are given for the four combinations listed above.

Key Words: Cryogenics, gold alloy, thermocouples.

1. Introduction

The rapid expansion of low temperature technology in the last 20 years has created a need for standardized thermocouple calibration tables in the cryogenic temperature range. With the cooperation of the American Society for Testing and Materials and thermocouple manufacturers throughout the country, we have now completed the experimental program that will allow establishment of acceptable standard tables for the materials commonly used at low temperatures. Later these tables will be joined smoothly to the existing high temperature standard tables at the ice point. This will then provide one continuous calibration for each thermocouple type over its entire temperature range of usefulness.

*This work was carried out at the National Bureau of Standards under the sponsorship of the National Aeronautics and Space Administration, Space Nuclear Propulsion Office (SNPO-C), Contract R-45.

In addition to the common materials (Chromel†, copper, platinum, "normal" silver, constantan, and Alumel†), several special materials have been measured. Silver-28 at. % gold was included as a possible replacement for platinum as the reference material below liquid nitrogen temperatures. Three gold-iron alloys were included because they retain a relatively high sensitivity down to, and even below, 10 K.

In 1932 Borelius and co-workers[1] showed that small amounts of transition metals in gold cause high thermopowers at very low temperatures. In the last few years several laboratories have been using various gold-iron alloys as the negative element in thermocouples. The gold-iron alloys are preferable to the previously used gold-cobalt alloys for two

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† Authors' Note: The words Chromel and Alumel are registered trade names. The correct ASA, ASTM, ISA, designations for the relevant thermocouple combinations and materials are as follows:

Type	Elements	Materials, Trade Names
E	EP (+)	Chromel, Tophel, T-1
	EN (-)	constantan, Advance, Cupron
K	KP (+)	Chromel, Tophel, T-1
	KN (-)	Alumel, Nial, T-2
T	TP (+)	copper
	TN (-)	constantan, Advance, Cupron

Names are usually given in this article because relatively few people are familiar with the designations KP, KN, etc. However, the use of the trade names does not constitute an endorsement of one manufacturer's products. All materials manufacturered in compliance with the established standards are equally suitable.

reasons: 1) they have a higher thermopower at low temperatures, and 2) they are in stable metallurgical solution (unlike the gold-cobalts) and therefore their output does not drift with time or 100 C annealing. The positive element usually has been copper, "normal" silver, or Chromel. We generally recommend the use of Chromel because it has a high positive thermopower in the upper temperature range where the gold-iron thermoelement is no longer strongly negative. This combination has sufficient sensitivity to be useful in the entire range from below 4 to 300 K. An additional advantage of Chromel over copper or "normal" silver is its relatively low thermal conductivity, as shown in table 1[2].

Table 1.

Thermal Conductivity of Three Thermocouple Materials		
Material	Thermal Conductivity	
	at (10 K) $\frac{\text{watts}}{\text{m}\cdot\text{K}}$	at (273 K) $\frac{\text{watts}}{\text{m}\cdot\text{K}}$
Cu	870	400
"normal" silver	200	380
Chromel	4	120

Until standardized materials and tables become available, users of the gold-iron alloys must perform their own detailed calibrations. Since this is time consuming and expensive, calibrations generally cover only the limited range of the particular experiment. We have now tested three gold-iron alloys against Chromel, platinum, and "normal" silver in the range from 4 to 280 K, but tables in the Appendix are given for only the Chromel vs gold-0.07 atomic percent iron combination.

2. Cryostat

A schematic of our cryostat is shown in figure 1, the critical parts of which are the two inner chambers. They are both surrounded by a high vacuum and a liquid nitrogen bath. The thermal insulation provided by this arrangement allows the use of liquid nitrogen, liquid hydrogen, or liquid helium as the thermocouple reference junction bath. The reference junction for the thermocouples is in the lower chamber. In addition to providing a reference temperature, this bath serves both as a heat sink for all incoming wires and as a source of refrigeration for the upper chamber.

The upper and lower chambers are connected by a tube which provides a wire duct and allows gas conduction between the lower and upper chambers. The variable junctions of the thermocouples are thermally anchored to a large copper block contained in the upper chamber. Refrigeration for the copper block is supplied by gas conduction from the lower chamber and also by conduction along the wires connecting the upper and lower chambers. A stable temperature difference is established between the two thermocouple junctions by balancing the refrigerator power with the power supplied to a heater coil wound on the copper block. Temperature drift of the block during a one-hour run is less than 3 mK.

In order to reduce the heat leak into the upper chamber as much as possible, all incoming wires are thermally tempered at liquid nitrogen temperatures before going into the lower chamber. All wires going into the upper chamber are of course also tempered in the reference cryogen. A thermal shield is between the copper block and the side walls of the upper chamber. An automatic heater control, operating from the output of a thermopile between the block and the shield, controls the temperature of the shield to be within 0.01 K of the block during all runs.

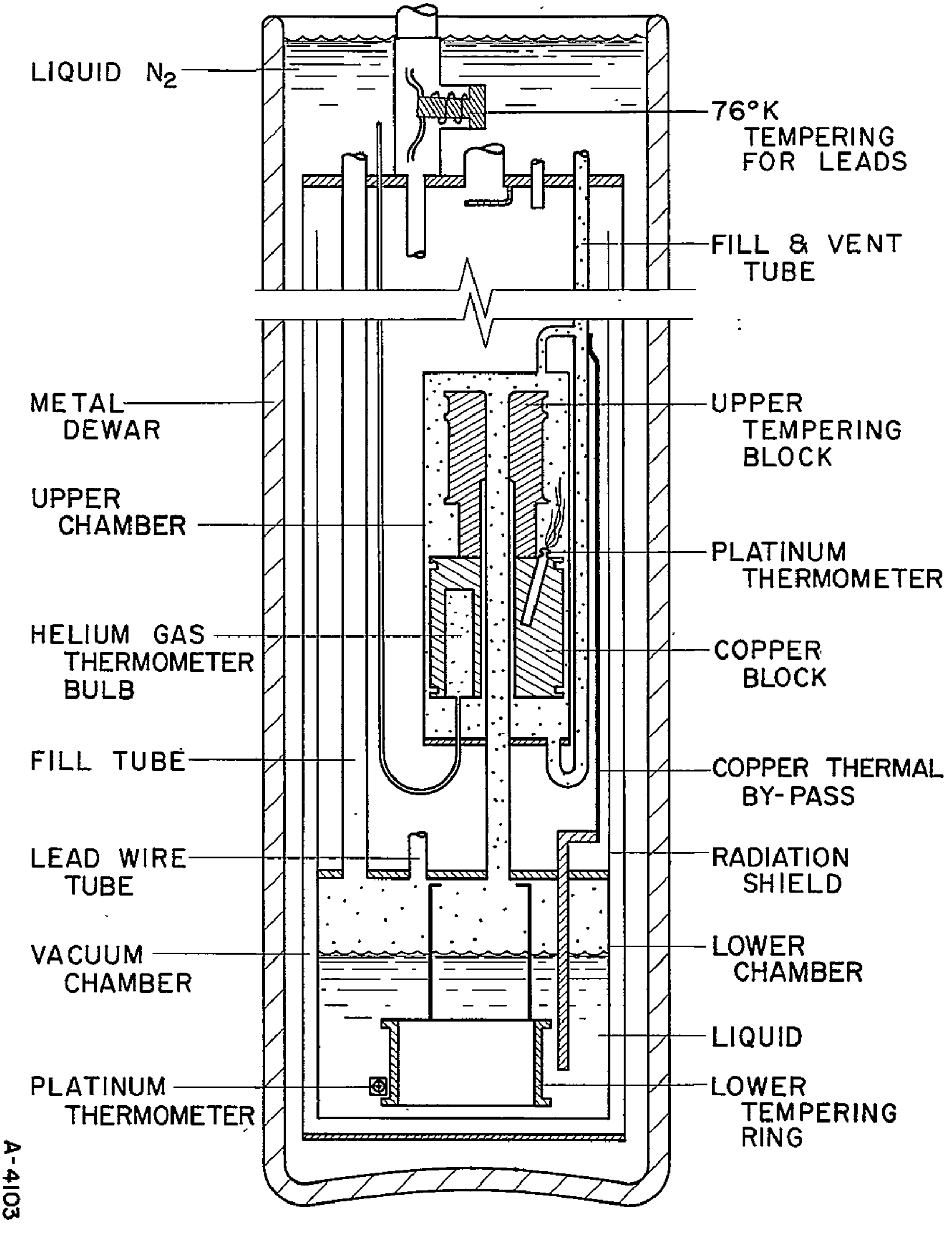

Figure 1 Thermocouple calibration cryostat.

Temperature determinations for the variable junction are made with platinum resistance thermometers when operating between 20 and 280 K and with germanium resistance thermometers when operating between 4 and 20 K. Three of each type of thermometer are actually installed in the upper copper block to provide a check on the primary thermometer and for use in the temperature control system. The temperature of the reference bath is calculated from readings of a single calibrated platinum thermometer whenever liquid hydrogen or liquid nitrogen are being used. The pressure of the inner system is manostatically controlled when these cryogens are used. Whenever liquid helium is being used, the inner system is at normal atmospheric pressure, and the bath temperature is then calculated from readings of the vapor pressure.

3. Instrumentation, Measurement and Materials

A block diagram of the measurement system is given in figure 2. The instrumentation is similar to many low level d. c. measurement systems. A six dial potentiometer is used to measure the thermocouple and germanium thermometer voltages. A G2 Mueller bridge that has been thermally isolated from room temperature fluctuations is used to determine the resistance of the platinum thermometers.

Our method of data analysis requires that we be able to intercompare any of the nineteen thermocouple wires. Out of the many possible combinations, 37 were of special importance. They fall into three groups: 1) four primary thermocouple combinations — i. e., Chromel vs constantan, Chromel vs Alumel, copper vs constantan, and Chromel vs gold-0. 07 at. % iron; 2) eleven calibration combinations — e. g., constantan vs reference platinum; and 3) twenty-two intercomparison combinations — e. g., constantan from one manufacturer vs constantan from another manufacturer.

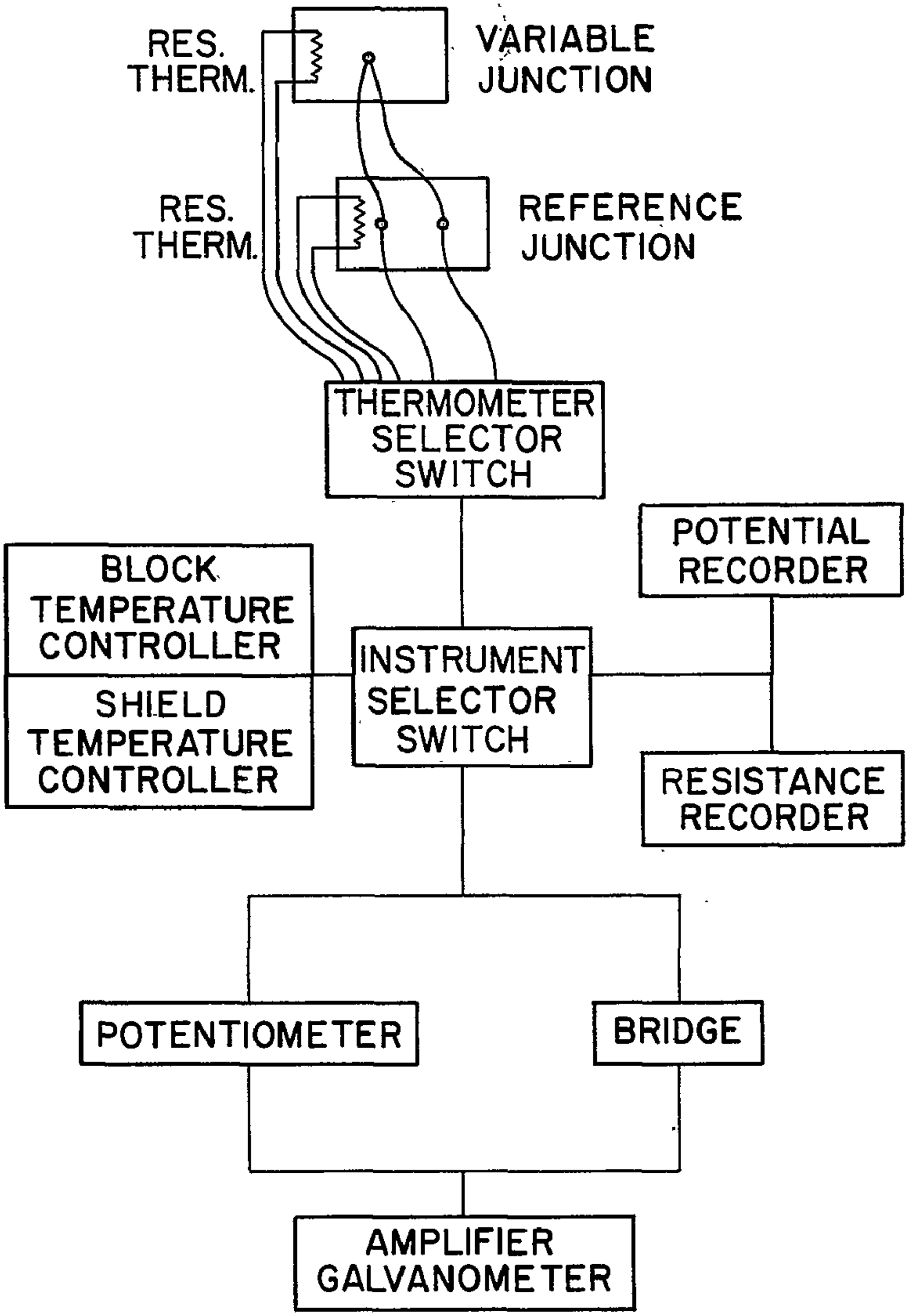

Figure 2 Thermocouple instrumentation system.

Figure 3 is an illustration of a typical set of voltage measurements used to determine the value of a single thermocouple pair – Chromel vs Au-0.07 at.% Fe in this example. In this figure, the letters represent actual voltage measurement paths, e.g., (A) represents the direct reading of Chromel vs gold-iron, (B) represents Chromel vs platinum, etc. The five voltage determinations are combined as follows to yield the calculated value of Chromel vs gold-iron:

$$\text{Calculated voltage} = \{2(A) + [(B) + (C)] + [(D) + (E)]\}/4.$$

The (A) reading is given a weight of 2 since it involves only one reading while the others require two readings.

This measurement scheme enables us to convert at least three types of systematic error into random errors. The random errors from these sources can then be included with the other scatter present in the experimental data. The sources of errors accounted for in this manner are operator prejudice, potentiometer dial inconsistencies, and spurious thermal voltages in the lead wires. The effect of any subconscious tendency of the operator to make the data appear repeatable in a sequence of measurements is eliminated from the final calculated value because computation of the final result involves the algebraic combination of five different voltages whose values vary considerably. In addition to eliminating operator prejudice, the five diverse measurements randomize errors associated with inconsistencies in potentiometer dial readings. Inhomogeneities in extension wires cause small spurious voltages that will change whenever temperature gradients along the wires change. Since a set of voltage readings takes many minutes to complete, variations in spurious voltages tend to be randomized by our method of calculation.

Materials included in this set of calibration wires are Chromel, copper, "normal" silver, platinum, silver-28 at.% gold, constantan,

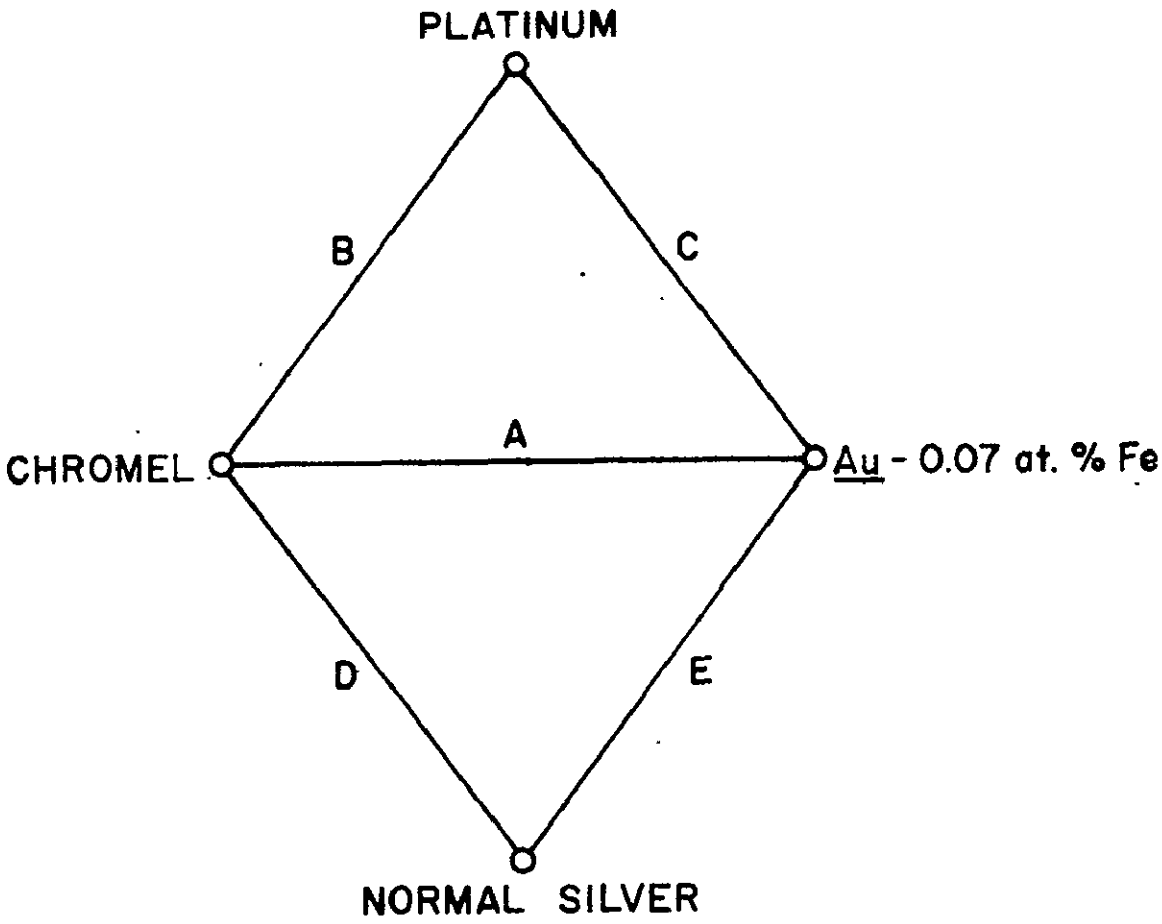

Figure 3 Typical Calibration measurement graph.

Alumel, and three gold-iron alloys (0. 02, 0. 03, 0. 07 at. % Fe in Au). An industry wide sampling was available for the regular commercial materials; therefore, the results for these materials will be acceptable as standards. An industry-wide sampling for the gold-iron alloys was not available, so the results for these alloys must be considered interim.

4. Data Analysis and Results

As mentioned previously, our data are taken using three different liquids in the reference bath. This allows us to cover the range from 4 to 280 K and still maintain temperature control in the upper block. The following temperature spans were used: liquid helium (4 to 26 K), liquid hydrogen (20 to 90 K), and liquid nitrogen (75 to 280 K). Figure 4 shows a least squares approximation to the experimental data for Chromel vs Au-0. 07 at. % Fe before the "range shift constants" are applied. The Law of Successive Temperatures[3] for thermocouples states: "If two dissimilar homogeneous metals produce a thermal voltage of E_1 when the junctions are at temperatures T_1 and T_2 and a thermal voltage of E_2 when the junctions are at T_2 and T_3, the thermal voltage generated when the junctions are at T_1 and T_3 will be $E_1 + E_2$." This law allows all of the voltages to be shifted to a common reference temperature. We call those shifts in voltages the "range shift constants," and they are treated as unknown constants in the least squares computer program. The calibration table is made continuous over the entire range by including the necessary shift constants. The final curves for the temperature dependence of the thermal voltage and thermopower of Chromel vs Au-0. 07 at. % Fe are shown in figures 5 and 6 respectively.

Since our method of data analysis is quite different from the usual power series expansion, it will be described briefly. The adjusted

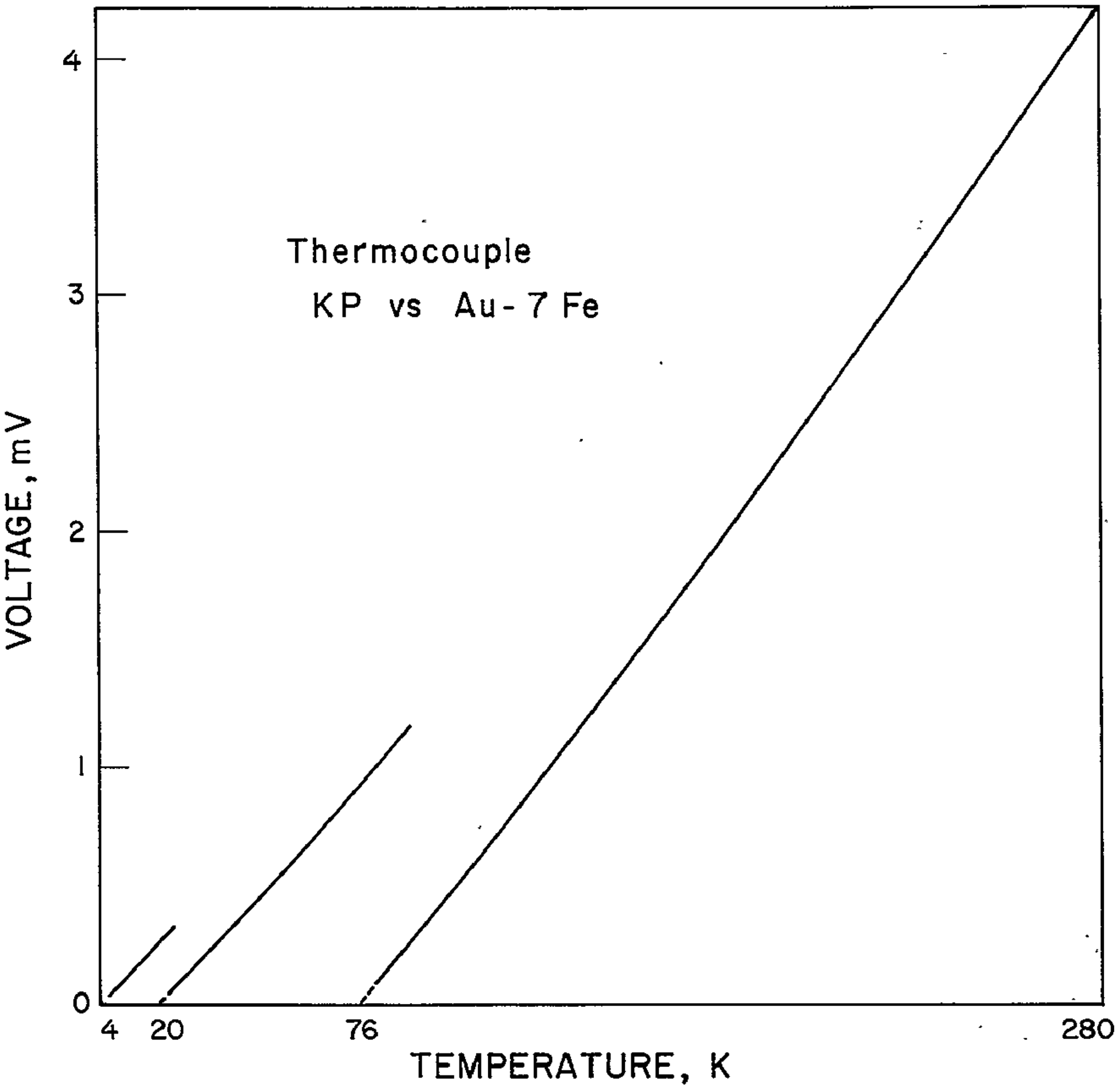

Figure 4 Thermoelectric voltage of Chromel versus. gold-0.07 atomic % Fe. Reference junctions at 4, 20, and 76K.

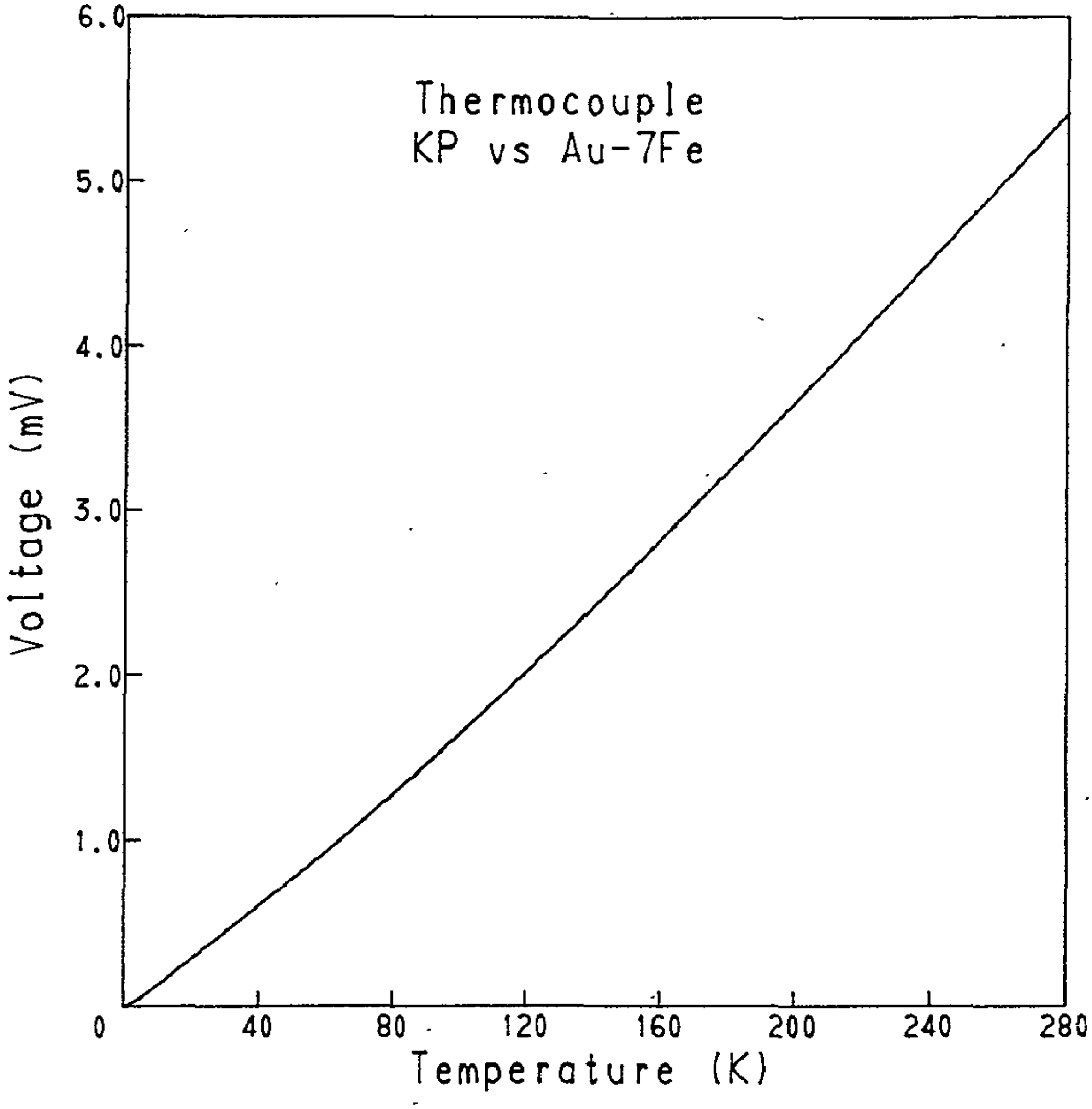

Figure 5 Thermoelectric voltage of Chromel versus gold-0.07 atomic % Fe. A common reference temperature of zero K.

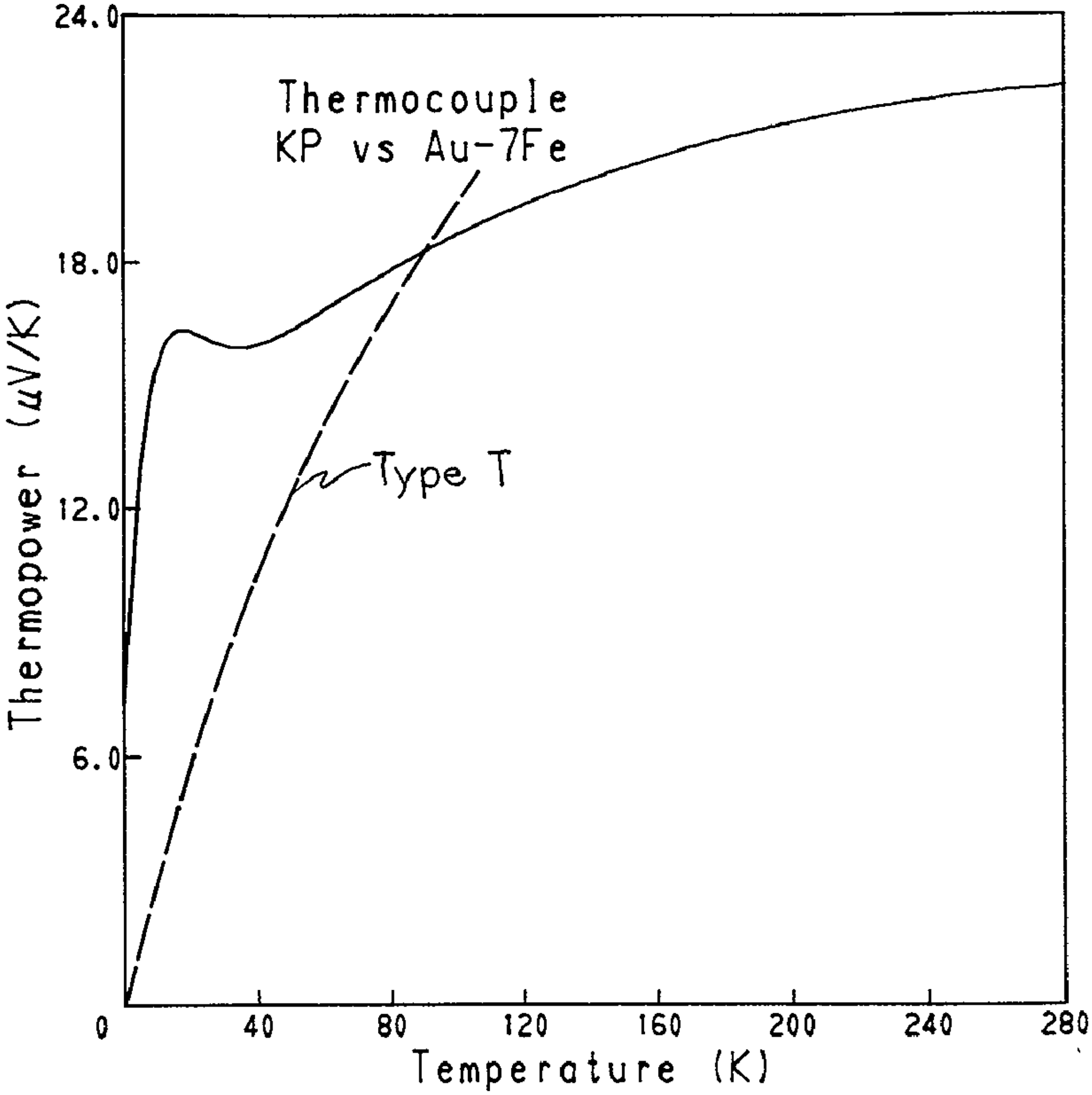

Figure 6 Thermopower of Chromel versus gold-0.07 atomic % Fe. A comparison curve for type T is included.

experimental values for the voltages of each thermocouple combination are approximated by a series of orthonormal polynomials in the L_2 norm (least squares), that is,

$$E(T) = \sum_{n=1}^{L} A_n F_n(T)$$

where

E	=	thermocouple potential in microvolts;
T	=	temperature in degrees kelvin;
L	=	the highest order for a best fit, different for different combinations;
A_n	=	constants to be determined by the fitting approximation; and
$F_n(T)$	=	orthonormal polynomials, orthonormal on the data points over the range of variation of the independent variable, T.

The conditions for orthonormality of $F_n(T)$ are

$$\sum_{i=1}^{N} F_m(T)F_n(T) = \delta_{mn} \qquad \delta_{mn} = 0 \text{ if } m \neq n$$
$$= 1 \text{ if } m = n;$$

where i is summed over the total number of experimental points, N. It should be stressed that the orthonormal polynomials $F_n(T)$ are determined by values of the independent variable T only. The $F_n(T)$ are generated from a truncated power series

$$F_n(T) = \sum_{j=1}^{n} C_{jn} T^j.$$

Once the $F_n(T)$ are determined, the coefficients A_n are determined by values of the dependent variable E. Therefore, the $F_n(T)$ are the same for all combinations, but the A_n are different for each thermocouple combination. The highest order, L, necessary for a best fit is also different for each combination.

A common problem in the numerical analysis of data fitting by polynomials is selection of the proper order for a best fit—an order high enough to represent the data with no loss of precision, but not so high as to introduce mathematical oscillations. This problem is well solved by our method of fitting by orthonormal polynomials. For true physical phenomena, the absolute values of the coefficients A_n decrease with increasing n as 1/n or $1/n^2$. However, for noise, the coefficients are random. Therefore, an inspection of a graph of $|A_n|$ vs n shows the noise level and the maximum value of n that is useable. In figure 7 such a graph is shown for the thermocouple KP vs Au-0. 07 at. % Fe. The first three points are range shift constants. The coefficient for order 7 is accidentally below the noise level of 2×10^{-1}.

The general polynomials $F_n(T)$ and the A_n and L for each thermocouple combination are given in Appendix E. An error analysis is also included in that appendix.

Thermopowers and thermopower derivatives are calculated from the differentiated expressions for thermal voltage.

Calibration tables for the four primary thermocouple systems result from our experimental research and analysis. These include types T, E, K, and Chromel vs Au-0. 07 at. % Fe. The tables for types T, E, and K are only minor modifications of the interim internal standard tables by Sparks and Powell, which were in turn modified versions of earlier[4, 5] work. The analyzed results are given in graphs and tables in Appendices A through D. The three graphs in each appendix represent the thermal voltage E, thermopower $S \equiv dE/dT$, and thermopower

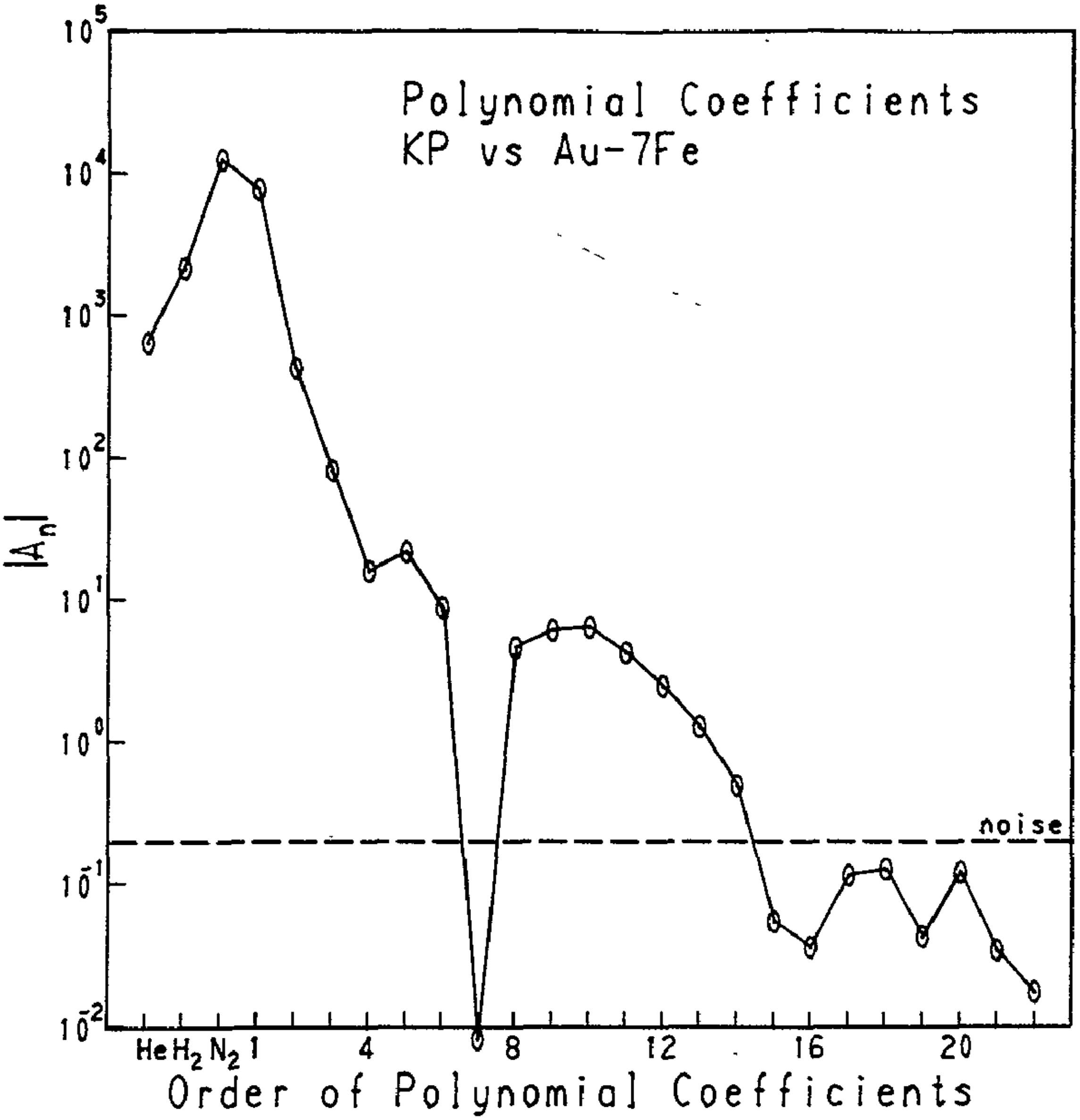

Figure 7 Polynomial coefficients for KP versus Au-0.07 atomic % Fe.

derivative dS/dT. Most of them are straightforward and need no explanation. However, the bump in the thermopower derivative for type T (fig. A-3) above 270 K causes an exception. The sudden upturn is probably not a true physical phenomenon, but rather a peculiarity of the data fitting caused by a slight error in voltage at the highest experimental temperature. Deviation plots for each type are included in Appendix E.

Since the essential information on the T, E, and K systems is in the literature,[4, 5] the remainder of the discussion will be primarily concerned with the Chromel vs Au-0.07 at.% Fe system. The principal reason for the interest shown in the gold-iron alloys has been their relatively high sensitivity in the liquid hydrogen and liquid helium ranges. Another significant property of the Chromel vs Au-0.07 at.% Fe system is its linearity, clearly seen in figure 5. The maximum voltage deviation from linearity is approximately 5 percent of the full scale voltage. This property is very important in applications where a reliable temperature difference is needed, but it is difficult to maintain a suitable reference temperature. Figure 6 represents the thermopower of the Chromel vs Au-0.07 at.% Fe combination. For purposes of comparison the thermopower of type T is shown by the dashed line. The hump in the thermopower is characteristic of all Au-Fe alloys. The position of the hump is affected by the solute concentration and, in general, the high temperature sensitivity increases and the low temperature sensitivity decreases as the iron concentration is increased.[6, 7] A theoretical explanation of the high thermoelectric power at low temperatures has not been fully developed. However, the theories of Kasuya, Bailyn, and de Vroomen[8] appear to offer the most reasonable explanations at present.

The estimated inaccuracies in the independent variable (temperature) for our calibrations are 2.2 mK in the helium range, 2.5 mK in the hydrogen range, and 2.0 mK in the nitrogen range. Inaccuracy of the dependent variable (voltage) varies with the thermocouple being used. For example, for the Chromel vs Au-0.07 at.% Fe system the inaccuracies are 0.034 μV in the liquid helium range, 0.135 μV in the hydrogen range, and 0.218 μV in the nitrogen range. A conservative estimate of the total inaccuracies to be found in the calibration of our particular Chromel vs Au-0.07 at. % Fe combination is as follows: ± 10 mK in the range from 4 to 20 K, ± 12 mK in the range from 20 to 75 K, and ± 15 mK in the range from 75 to 280 K. The temperature scales being used are the latest proposed international scale[9] above 20 K and the NBS acoustical scale below 20 K. The inaccuracies given do not include deviations of these temperature scales from the true thermodynamic scale.

5. Summary

We recommend type E (Chromel vs constantan) thermocouples for general engineering use above liquid hydrogen temperatures. Both elements of this thermocouple have low thermal conductivity and reasonably good homogeneity. This combination may be used over the wide temperature range from the normal boiling point of liquid hydrogen 20 K (the sensitivity is marginal in this region) up to approximately 1000C. For operation below 20 K, Chromel vs Au-0.07 at.% Fe is the most sensitive combination available. The usefulness of this combination is further enhanced by its linear characteristics.

The experimental research done on types T, E, and K qualify the calibration results to be acceptable as national standards; consequently, they will soon be joined to the existing high temperature standard tables to provide calibrations over the entire temperature range of usefulness for each material. The tests on Au-Fe alloys must be continued in order to establish the degree of uniformity between samples of materials from different producers.

An NBS Monograph will be published later with full details on the experimental apparatus, measurement methods, numberical analysis techniques, and thermocouple material characterizations. At that time the tables in the following appendices will be slightly altered so that they will join smoothly at the ice point to the high temperature tables already published.[10]

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Appendix A.

Interim Tables and Graphs for Thermocouple Type T, Copper vs Constantan.

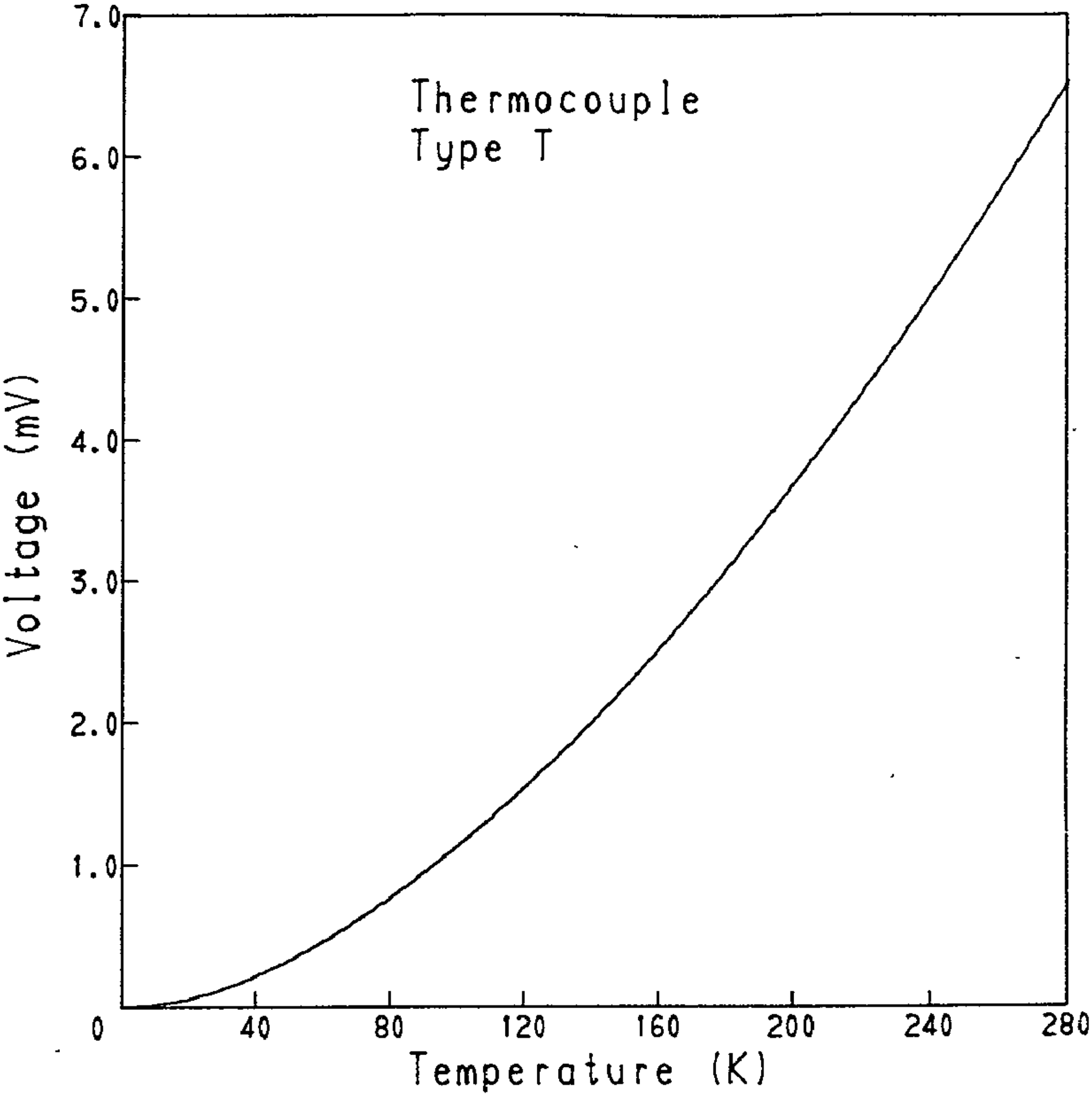

Figure A-1 Thermoelectric voltage of thermocouple type T, copper versus constantan.

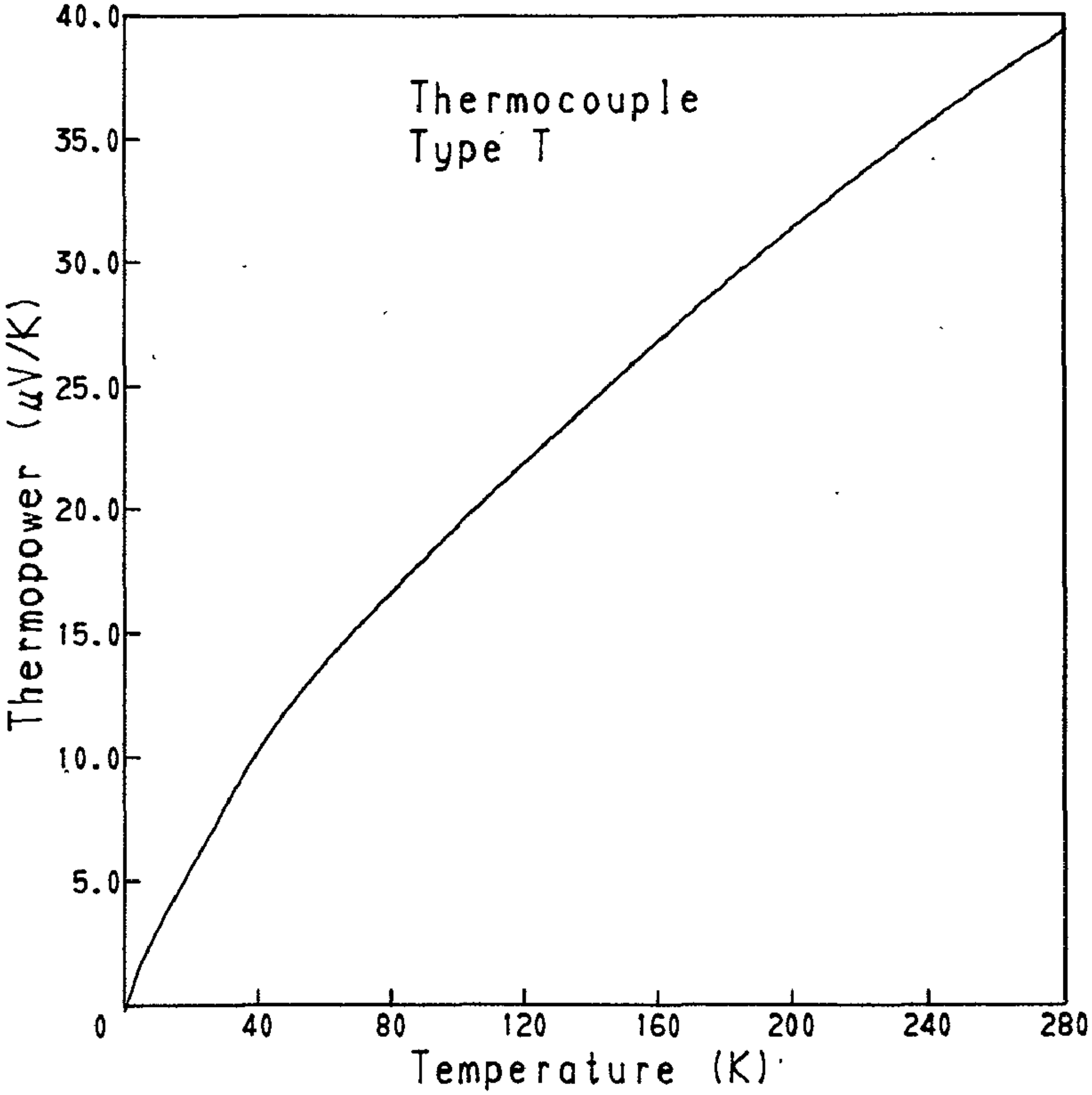

Figure A-2 Thermopower of thermocouple type T, copper versus constantan.

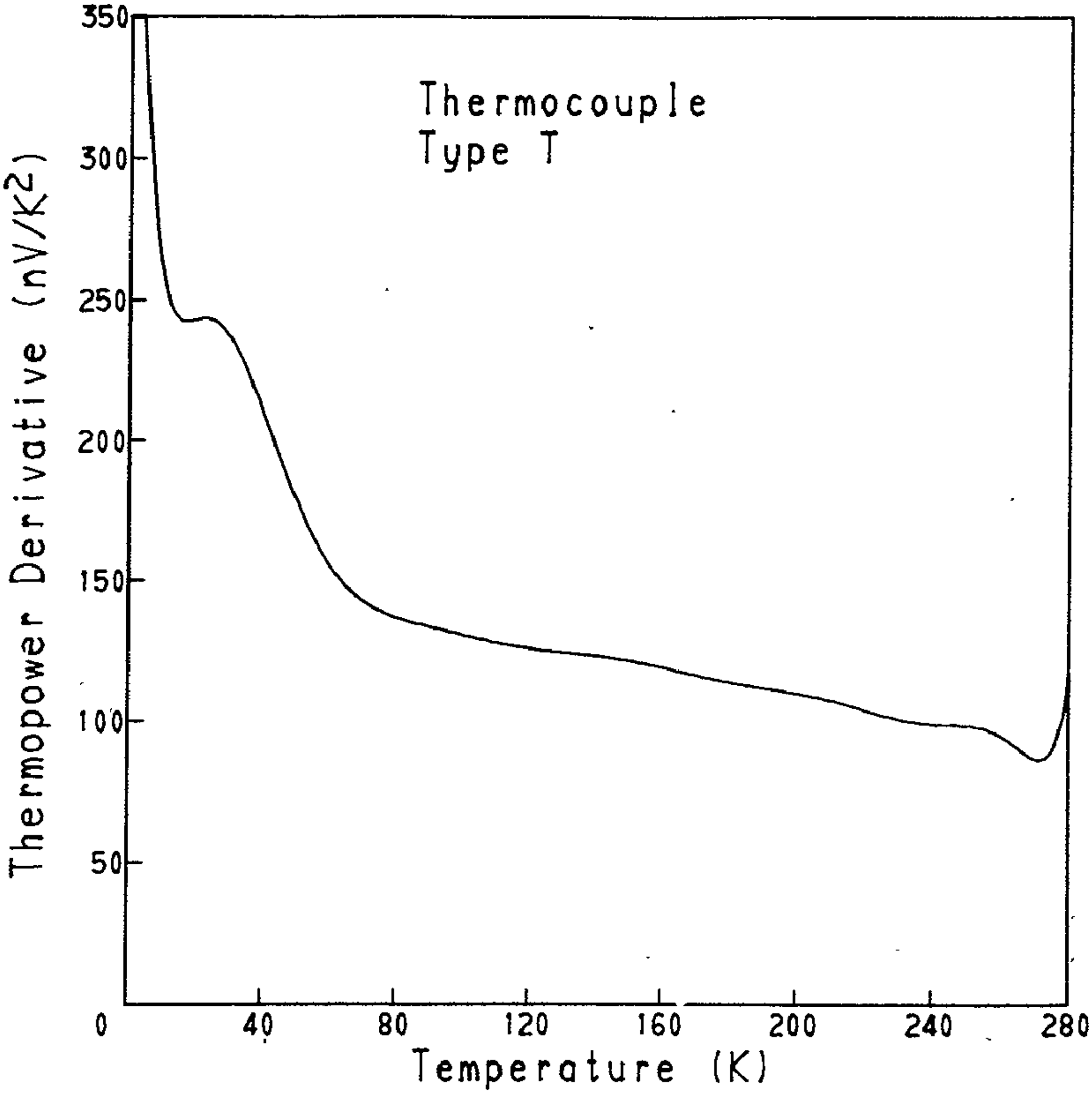

Figure A-3 Thermopower derivative of thermocouple type T, copper versus constantan.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K²
1	-0.09	0.147	0.4611
2	0.28	0.586	0.4179
3	1.07	0.985	0.3816
4	2.24	1.351	0.3515
5	3.76	1.690	0.3266
6	5.61	2.006	0.3064
7	7.77	2.304	0.2900
8	10.21	2.587	0.2770
9	12.94	2.859	0.2668
10	15.93	3.121	0.2590
11	19.18	3.377	0.2531
12	22.68	3.628	0.2489
13	26.43	3.876	0.2459
14	30.43	4.120	0.2440
15	34.67	4.364	0.2428
16	39.16	4.606	0.2423
17	43.89	4.848	0.2421
18	48.85	5.091	0.2422
19	54.07	5.333	0.2425
20	59.52	5.576	0.2428
21	65.22	5.818	0.2431
22	71.16	6.062	0.2432
23	77.34	6.305	0.2432
24	83.77	6.548	0.2430
25	90.44	6.791	0.2426
26	97.35	7.033	0.2419
27	104.50	7.274	0.2409
28	111.90	7.515	0.2398
29	119.53	7.754	0.2383
30	127.40	7.991	0.2366
31	135.51	8.227	0.2347
32	143.86	8.461	0.2325
33	152.43	8.692	0.2302
34	161.24	8.921	0.2276
35	170.27	9.147	0.2249
36	179.53	9.371	0.2220
37	189.01	9.591	0.2190
38	198.72	9.809	0.2160
39	208.63	10.023	0.2128
40	218.76	10.234	0.2096
41	229.10	10.442	0.2063
42	239.64	10.647	0.2030
43	250.39	10.848	0.1997
44	261.34	11.046	0.1965
45	272.48	11.241	0.1932
46	283.82	11.433	0.1901
47	295.35	11.621	0.1869
48	307.06	11.807	0.1839
49	318.96	11.989	0.1809
50	331.04	12.168	0.1780
51	343.30	12.345	0.1752
52	355.73	12.519	0.1725
53	368.33	12.690	0.1699
54	381.11	12.859	0.1674
55	394.05	13.025	0.1650
56	407.16	13.189	0.1628
57	420.43	13.350	0.1607
58	433.86	13.510	0.1586
59	447.44	13.668	0.1567
60	461.19	13.824	0.1549
61	475.09	13.978	0.1533
62	489.15	14.130	0.1517
63	503.35	14.281	0.1502
64	517.71	14.431	0.1489
65	532.21	14.579	0.1476
66	546.86	14.726	0.1464
67	561.66	14.872	0.1453
68	576.61	15.017	0.1443
69	591.70	15.160	0.1434
70	606.93	15.303	0.1425
71	622.30	15.445	0.1417
72	637.82	15.587	0.1410
73	653.48	15.727	0.1403
74	669.27	15.868	0.1397
75	685.21	16.007	0.1391
76	701.29	16.146	0.1386
77	717.50	16.284	0.1381
78	733.86	16.422	0.1376
79	750.35	16.559	0.1372
80	766.97	16.696	0.1368
81	783.74	16.833	0.1364
82	800.64	16.969	0.1360
83	817.68	17.105	0.1357
84	834.85	17.241	0.1354
85	852.16	17.376	0.1350
86	869.60	17.511	0.1347
87	887.18	17.645	0.1344
88	904.89	17.779	0.1341
89	922.74	17.913	0.1338
90	940.72	18.047	0.1335
91	958.83	18.180	0.1332
92	977.08	18.314	0.1329
93	995.46	18.446	0.1326
94	1013.97	18.579	0.1324
95	1032.62	18.711	0.1321
96	1051.39	18.843	0.1318
97	1070.30	18.975	0.1315
98	1089.34	19.106	0.1312
99	1108.51	19.237	0.1309
100	1127.82	19.368	0.1306

Table A-1 Thermal voltage, thermopower, and thermopower derivative for thermocouple type T, copper vs constantan.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
101	1147.25	19.498	0.1304
102	1166.81	19.629	0.1301
103	1186.51	19.758	0.1298
104	1206.33	19.888	0.1295
105	1226.28	20.017	0.1292
106	1246.37	20.147	0.1290
107	1266.58	20.275	0.1287
108	1286.92	20.404	0.1285
109	1307.38	20.532	0.1282
110	1327.98	20.660	0.1280
111	1348.71	20.788	0.1277
112	1369.56	20.916	0.1275
113	1390.54	21.043	0.1273
114	1411.64	21.170	0.1270
115	1432.88	21.297	0.1268
116	1454.24	21.424	0.1266
117	1475.73	21.551	0.1264
118	1497.34	21.677	0.1263
119	1519.08	21.803	0.1261
120	1540.95	21.929	0.1259
121	1562.94	22.055	0.1257
122	1585.06	22.181	0.1256
123	1607.30	22.306	0.1254
124	1629.67	22.431	0.1253
125	1652.16	22.557	0.1252
126	1674.78	22.682	0.1250
127	1697.53	22.807	0.1249
128	1720.39	22.932	0.1248
129	1743.39	23.056	0.1247
130	1766.51	23.181	0.1245
131	1789.75	23.305	0.1244
132	1813.12	23.430	0.1243
133	1836.61	23.554	0.1242
134	1860.23	23.678	0.1241
135	1883.97	23.802	0.1240
136	1907.83	23.926	0.1238
137	1931.82	24.050	0.1237
138	1955.93	24.174	0.1236
139	1980.17	24.297	0.1235
140	2004.52	24.420	0.1233
141	2029.01	24.544	0.1232
142	2053.61	24.667	0.1230
143	2078.34	24.790	0.1229
144	2103.19	24.913	0.1227
145	2128.17	25.035	0.1226
146	2153.26	25.158	0.1224
147	2178.48	25.280	0.1222
148	2203.82	25.402	0.1220
149	2229.28	25.524	0.1218
150	2254.87	25.646	0.1216
151	2280.58	25.767	0.1214
152	2306.40	25.889	0.1212
153	2332.35	26.010	0.1209
154	2358.42	26.130	0.1207
155	2384.61	26.251	0.1205
156	2410.93	26.371	0.1202
157	2437.36	26.491	0.1200
158	2463.91	26.611	0.1197
159	2490.58	26.731	0.1194
160	2517.37	26.850	0.1192
161	2544.28	26.969	0.1189
162	2571.31	27.088	0.1186
163	2598.46	27.206	0.1183
164	2625.72	27.325	0.1181
165	2653.10	27.442	0.1178
166	2680.61	27.560	0.1175
167	2708.22	27.677	0.1172
168	2735.96	27.795	0.1169
169	2763.81	27.911	0.1167
170	2791.78	28.028	0.1164
171	2819.87	28.144	0.1161
172	2848.07	28.260	0.1158
173	2876.39	28.376	0.1156
174	2904.82	28.491	0.1153
175	2933.37	28.606	0.1151
176	2962.04	28.721	0.1148
177	2990.81	28.836	0.1146
178	3019.71	28.950	0.1143
179	3048.71	29.065	0.1141
180	3077.84	29.179	0.1139
181	3107.07	29.292	0.1136
182	3136.42	29.406	0.1134
183	3165.88	29.519	0.1132
184	3195.46	29.632	0.1130
185	3225.15	29.745	0.1128
186	3254.95	29.858	0.1126
187	3284.86	29.971	0.1124
188	3314.89	30.083	0.1123
189	3345.03	30.195	0.1121
190	3375.28	30.307	0.1119
191	3405.64	30.419	0.1117
192	3436.12	30.531	0.1116
193	3466.71	30.642	0.1114
194	3497.40	30.753	0.1112
195	3528.21	30.864	0.1110
196	3559.13	30.975	0.1108
197	3590.16	31.086	0.1107
198	3621.30	31.197	0.1105
199	3652.56	31.307	0.1103
200	3683.92	31.417	0.1101

Table A-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type T, copper vs constantan.

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S μV/K	$\frac{dS}{dT}$ $\mu V/K^2$
201	3715.39	31.527	0.1099
202	3746.97	31.637	0.1097
203	3778.66	31.746	0.1094
204	3810.46	31.856	0.1092
205	3842.38	31.965	0.1090
206	3874.39	32.074	0.1087
207	3906.52	32.182	0.1084
208	3938.76	32.291	0.1082
209	3971.10	32.399	0.1079
210	4003.56	32.506	0.1076
211	4036.12	32.614	0.1073
212	4068.78	32.721	0.1070
213	4101.56	32.828	0.1067
214	4134.44	32.934	0.1063
215	4167.43	33.040	0.1060
216	4200.52	33.146	0.1056
217	4233.72	33.252	0.1053
218	4267.02	33.357	0.1049
219	4300.43	33.462	0.1046
220	4333.95	33.566	0.1042
221	4367.56	33.670	0.1038
222	4401.29	33.774	0.1035
223	4435.11	33.877	0.1031
224	4469.04	33.980	0.1028
225	4503.07	34.083	0.1024
226	4537.21	34.185	0.1021
227	4571.44	34.287	0.1018
228	4605.78	34.388	0.1015
229	4640.22	34.490	0.1012
230	4674.76	34.591	0.1009
231	4709.40	34.691	0.1006
232	4744.14	34.792	0.1004
233	4778.98	34.892	0.1001
234	4813.93	34.992	0.0999
235	4848.97	35.092	0.0998
236	4884.11	35.192	0.0996
237	4919.35	35.291	0.0995
238	4954.69	35.391	0.0994
239	4990.13	35.490	0.0993
240	5025.67	35.589	0.0992
241	5061.31	35.688	0.0991
242	5097.05	35.787	0.0991
243	5132.89	35.886	0.0990
244	5168.82	35.986	0.0990
245	5204.86	36.084	0.0990
246	5240.99	36.183	0.0989
247	5277.22	36.282	0.0989
248	5313.55	36.381	0.0988
249	5349.99	36.480	0.0987
250	5386.51	36.579	0.0986
251	5423.15	36.677	0.0985
252	5459.87	36.776	0.0983
253	5496.69	36.874	0.0981
254	5533.62	36.972	0.0978
255	5570.64	37.070	0.0975
256	5607.75	37.167	0.0971
257	5644.97	37.264	0.0966
258	5682.28	37.360	0.0960
259	5719.69	37.456	0.0954
260	5757.20	37.551	0.0947
261	5794.79	37.645	0.0939
262	5832.49	37.739	0.0931
263	5870.27	37.831	0.0922
264	5908.15	37.923	0.0913
265	5946.12	38.014	0.0903
266	5984.17	38.103	0.0894
267	6022.32	38.193	0.0885
268	6060.56	38.281	0.0877
269	6098.88	38.368	0.0870
270	6137.30	38.455	0.0865
271	6175.79	38.541	0.0863
272	6214.37	38.627	0.0865
273	6253.05	38.714	0.0871
274	6291.80	38.802	0.0884
275	6330.65	38.891	0.0903
276	6369.59	38.983	0.0932
277	6408.62	39.078	0.0972
278	6447.74	39.178	0.1024
279	6486.97	39.283	0.1092
280	6526.31	39.397	0.1178

Table A-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type T, copper vs constantan.

Appendix B.

Interim Tables and Graphs for Thermocouple Type E, Chromel vs Constantan.

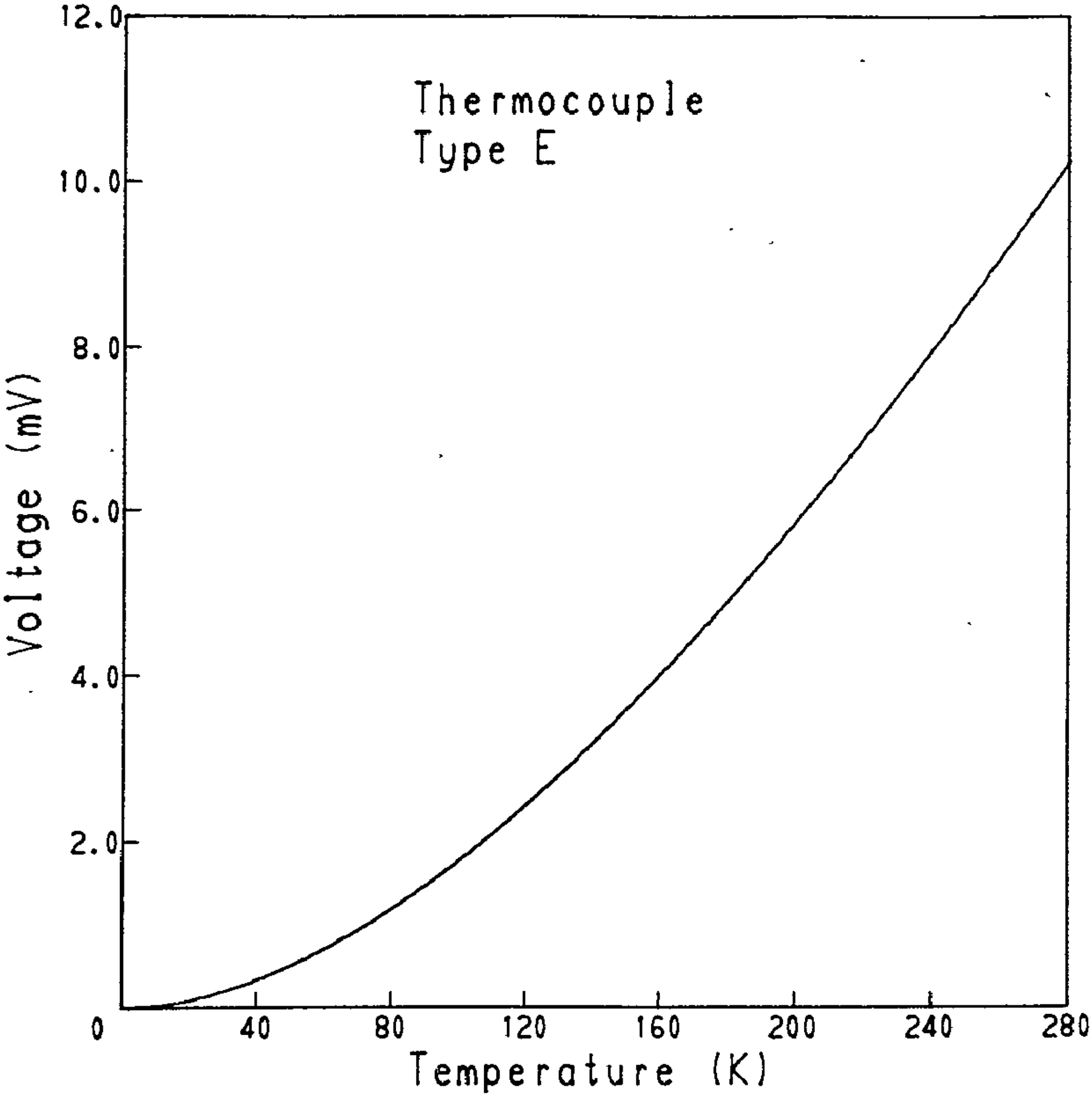

Figure B-1 Thermoelectric voltage of thermocouple type E, Chromel versus constantan.

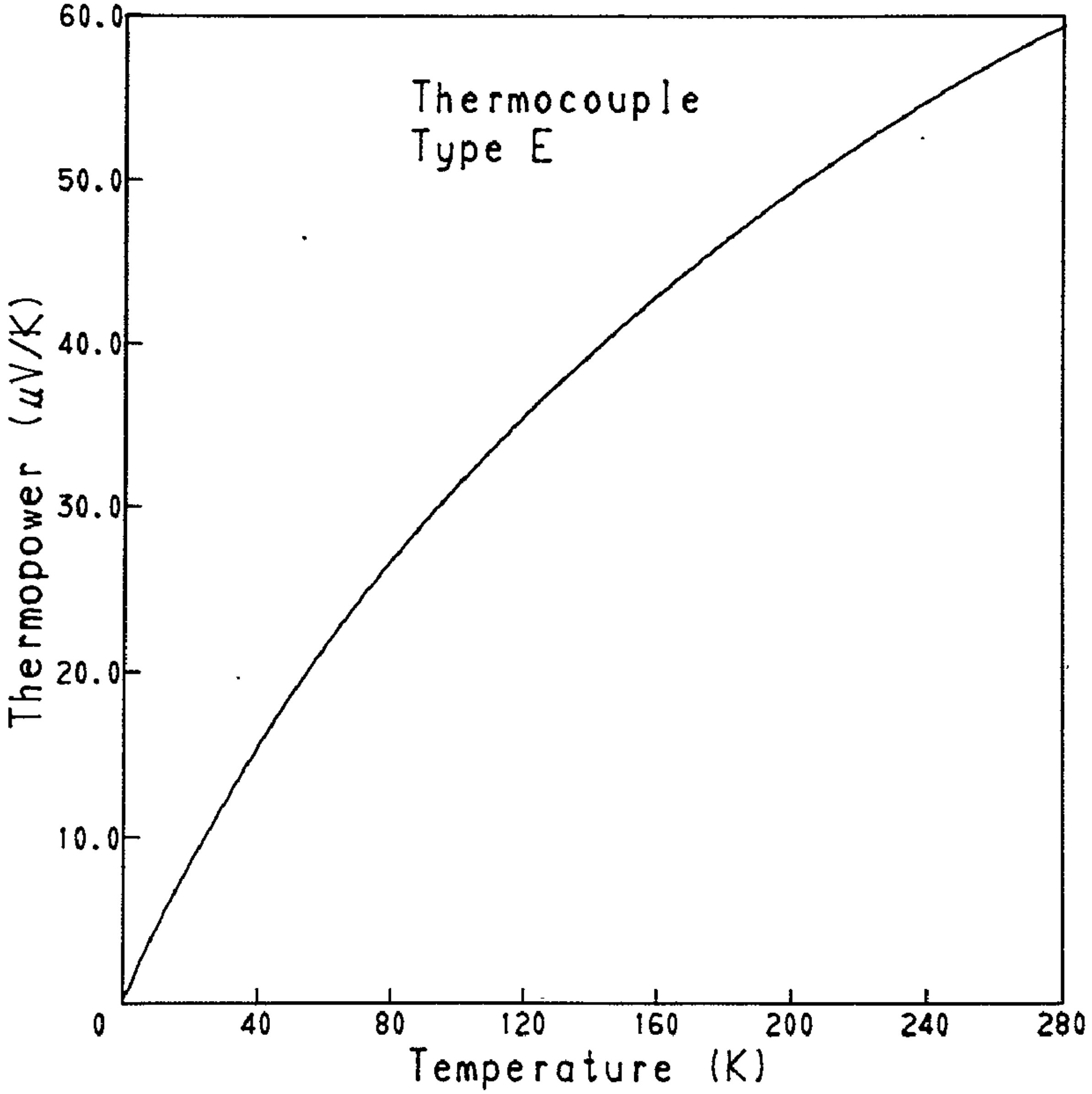

Figure B-2 Thermopower of thermocouple type E, Chromel versus constantan.

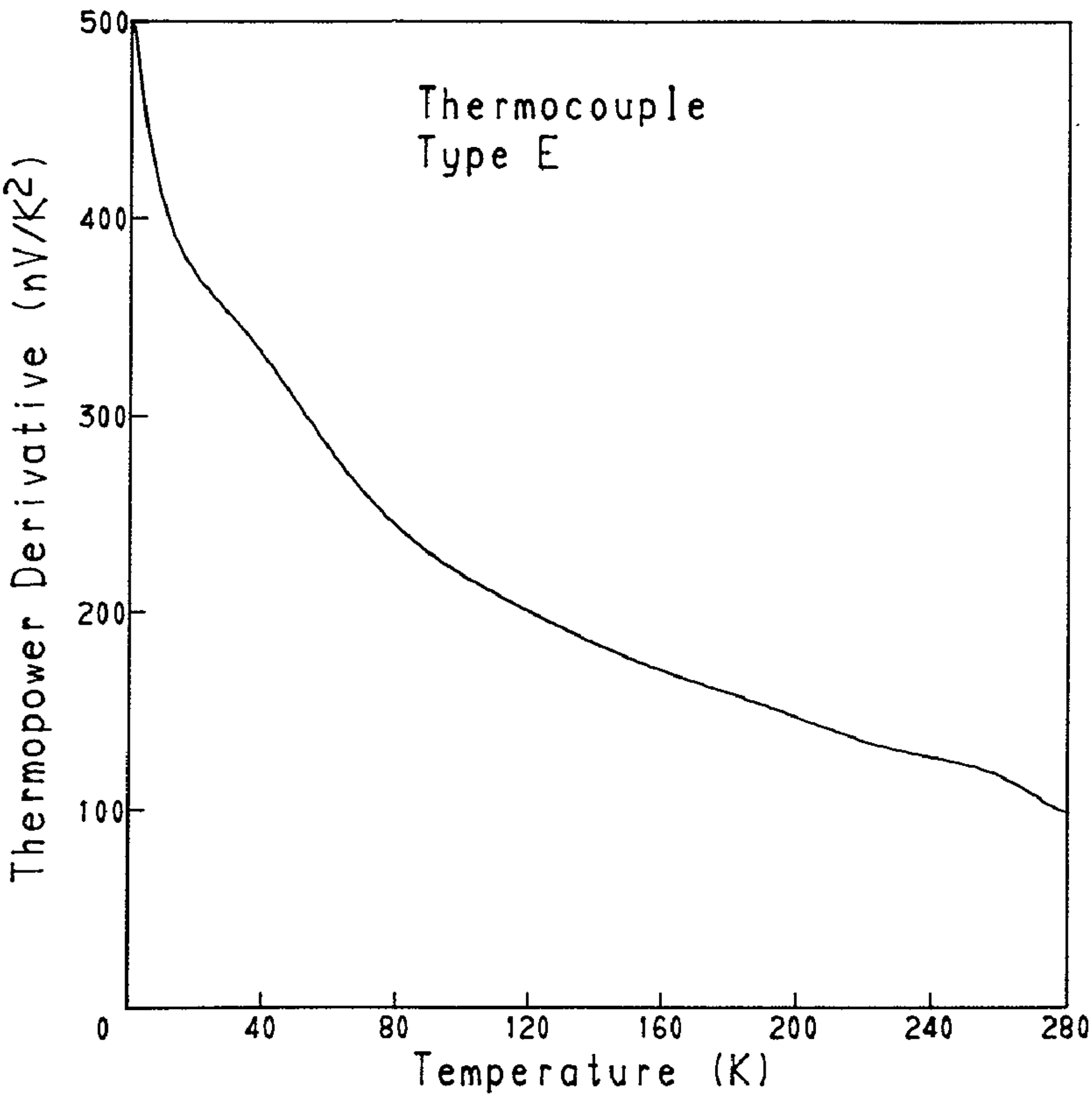

Figure B-3 Thermopower derivative of thermocouple type E, Chromel versus constantan.

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S μV/K	$\frac{dS}{dT}$ μV/K²	Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S μV/K	$\frac{dS}{dT}$ μV/K²
1	0.41	0.660	0.4962	51	522.68	19.001	0.3032
2	1.31	1.149	0.4812	52	541.83	19.303	0.3007
3	2.70	1.623	0.4678	53	561.28	19.603	0.2982
4	4.56	2.085	0.4557	54	581.04	19.900	0.2957
5	6.87	2.535	0.4449	55	601.08	20.194	0.2933
6	9.62	2.975	0.4353	56	621.42	20.486	0.2908
7	12.81	3.406	0.4267	57	642.05	20.776	0.2884
8	16.43	3.829	0.4190	58	662.97	21.063	0.2860
9	20.47	4.244	0.4122	59	684.18	21.348	0.2836
10	24.92	4.653	0.4061	60	705.67	21.630	0.2813
11	29.77	5.057	0.4006	61	727.44	21.911	0.2790
12	35.03	5.455	0.3957	62	749.49	22.188	0.2767
13	40.68	5.848	0.3914	63	771.82	22.464	0.2745
14	46.72	6.238	0.3875	64	794.42	22.737	0.2722
15	53.15	6.623	0.3839	65	817.29	23.008	0.2701
16	59.97	7.005	0.3807	66	840.43	23.277	0.2679
17	67.16	7.385	0.3778	67	863.84	23.544	0.2658
18	74.74	7.761	0.3751	68	887.52	23.809	0.2638
19	82.69	8.135	0.3726	69	911.46	24.072	0.2618
20	91.01	8.506	0.3703	70	935.66	24.333	0.2598
21	99.70	8.876	0.3681	71	960.13	24.592	0.2579
22	108.76	9.243	0.3660	72	984.85	24.849	0.2560
23	118.18	9.608	0.3640	73	1009.82	25.104	0.2542
24	127.97	9.971	0.3621	74	1035.05	25.357	0.2524
25	138.12	10.332	0.3602	75	1060.54	25.608	0.2506
26	148.64	10.691	0.3584	76	1086.27	25.858	0.2489
27	159.51	11.049	0.3565	77	1112.25	26.106	0.2473
28	170.73	11.404	0.3546	78	1138.48	26.353	0.2456
29	182.31	11.758	0.3528	79	1164.96	26.598	0.2441
30	194.25	12.110	0.3509	80	1191.68	26.841	0.2425
31	206.53	12.460	0.3490	81	1218.64	27.083	0.2410
32	219.17	12.808	0.3470	82	1245.84	27.323	0.2395
33	232.15	13.154	0.3450	83	1273.28	27.562	0.2381
34	245.47	13.498	0.3430	84	1300.96	27.799	0.2367
35	259.14	13.840	0.3409	85	1328.88	28.035	0.2354
36	273.15	14.179	0.3388	86	1357.03	28.270	0.2340
37	287.50	14.517	0.3366	87	1385.42	28.503	0.2327
38	302.19	14.853	0.3344	88	1414.04	28.735	0.2315
39	317.20	15.186	0.3322	89	1442.89	28.966	0.2302
40	332.56	15.517	0.3299	90	1471.97	29.196	0.2290
41	348.24	15.846	0.3276	91	1501.28	29.424	0.2279
42	364.25	16.172	0.3253	92	1530.82	29.652	0.2267
43	380.58	16.496	0.3229	93	1560.59	29.878	0.2256
44	397.24	16.818	0.3205	94	1590.58	30.103	0.2245
45	414.22	17.137	0.3181	95	1620.79	30.327	0.2234
46	431.51	17.454	0.3156	96	1651.23	30.549	0.2223
47	449.13	17.769	0.3131	97	1681.89	30.771	0.2213
48	467.05	18.081	0.3107	98	1712.77	30.992	0.2202
49	485.29	18.390	0.3082	99	1743.87	31.212	0.2192
50	503.83	18.697	0.3057	100	1775.19	31.430	0.2182

Table B-1 Thermal voltage, thermopower, and thermopower derivative for thermocouple type E, Chromel vs constantan.

Temp. K	Voltage=E μV	$\frac{dE}{dT}=S$ $\mu V/K$	$\frac{dS}{dT}$ $\mu V/K^2$	Temp. K	Voltage=E μV	$\frac{dE}{dT}=S$ $\mu V/K$	$\frac{dS}{dT}$ $\mu V/K^2$
101	1806.73	31.648	0.2172	151	3642.12	41.423	0.1760
102	1838.49	31.865	0.2162	152	3683.63	41.599	0.1754
103	1870.46	32.081	0.2153	153	3725.31	41.774	0.1747
104	1902.65	32.295	0.2143	154	3767.18	41.948	0.1741
105	1935.05	32.509	0.2134	155	3809.21	42.122	0.1734
106	1967.67	32.722	0.2125	156	3851.42	42.295	0.1728
107	2000.50	32.934	0.2115	157	3893.80	42.467	0.1722
108	2033.54	33.145	0.2106	158	3936.35	42.639	0.1716
109	2066.79	33.355	0.2097	159	3979.08	42.811	0.1709
110	2100.25	33.565	0.2088	160	4021.97	42.981	0.1703
111	2133.92	33.773	0.2079	161	4065.04	43.151	0.1697
112	2167.79	33.981	0.2070	162	4108.28	43.321	0.1692
113	2201.88	34.187	0.2062	163	4151.68	43.490	0.1686
114	2236.17	34.393	0.2053	164	4195.26	43.658	0.1680
115	2270.66	34.598	0.2044	165	4239.00	43.825	0.1674
116	2305.36	34.802	0.2035	166	4282.91	43.993	0.1668
117	2340.27	35.005	0.2027	167	4326.98	44.159	0.1663
118	2375.37	35.207	0.2018	168	4371.22	44.325	0.1657
119	2410.68	35.408	0.2009	169	4415.63	44.491	0.1651
120	2446.19	35.609	0.2001	170	4460.21	44.655	0.1646
121	2481.90	35.809	0.1992	171	4504.94	44.820	0.1640
122	2517.81	36.007	0.1984	172	4549.84	44.984	0.1635
123	2553.91	36.205	0.1975	173	4594.91	45.147	0.1629
124	2590.22	36.402	0.1967	174	4640.14	45.309	0.1624
125	2626.72	36.599	0.1958	175	4685.53	45.471	0.1618
126	2663.41	36.794	0.1950	176	4731.08	45.633	0.1613
127	2700.30	36.989	0.1942	177	4776.79	45.794	0.1607
128	2737.39	37.182	0.1933	178	4822.67	45.954	0.1601
129	2774.67	37.375	0.1925	179	4868.70	46.114	0.1596
130	2812.14	37.567	0.1917	180	4914.90	46.274	0.1590
131	2849.80	37.759	0.1909	181	4961.25	46.432	0.1585
132	2887.66	37.949	0.1901	182	5007.76	46.590	0.1579
133	2925.70	38.139	0.1893	183	5054.43	46.748	0.1573
134	2963.94	38.328	0.1885	184	5101.26	46.905	0.1567
135	3002.36	38.516	0.1877	185	5148.24	47.061	0.1562
136	3040.97	38.703	0.1869	186	5195.38	47.217	0.1556
137	3079.76	38.890	0.1861	187	5242.67	47.373	0.1550
138	3118.75	39.075	0.1854	188	5290.12	47.527	0.1544
139	3157.91	39.260	0.1846	189	5337.73	47.681	0.1538
140	3197.27	39.445	0.1838	190	5385.49	47.835	0.1532
141	3236.80	39.628	0.1831	191	5433.40	47.988	0.1526
142	3276.52	39.811	0.1823	192	5481.46	48.140	0.1520
143	3316.42	39.993	0.1816	193	5529.68	48.292	0.1514
144	3356.51	40.174	0.1809	194	5578.05	48.443	0.1508
145	3396.77	40.355	0.1802	195	5626.56	48.593	0.1502
146	3437.22	40.534	0.1795	196	5675.23	48.743	0.1495
147	3477.84	40.713	0.1787	197	5724.05	48.893	0.1489
148	3518.64	40.892	0.1781	198	5773.02	49.041	0.1483
149	3559.62	41.070	0.1774	199	5822.13	49.189	0.1477
150	3600.78	41.247	0.1767	200	5871.40	49.336	0.1470

Table B-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type E, Chromel vs constantan.

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S $\mu V/K$	$\frac{dS}{dT}$ $\mu V/K^2$
201	5920.81	49.483	0.1464
202	5970.36	49.629	0.1458
203	6020.06	49.775	0.1451
204	6069.91	49.919	0.1445
205	6119.90	50.064	0.1439
206	6170.04	50.207	0.1432
207	6220.32	50.350	0.1426
208	6270.74	50.492	0.1420
209	6321.30	50.634	0.1413
210	6372.01	50.775	0.1407
211	6422.85	50.915	0.1401
212	6473.84	51.055	0.1395
213	6524.96	51.194	0.1389
214	6576.22	51.333	0.1383
215	6627.63	51.471	0.1377
216	6679.17	51.608	0.1371
217	6730.84	51.745	0.1366
218	6782.66	51.882	0.1360
219	6834.61	52.017	0.1355
220	6886.69	52.152	0.1349
221	6938.91	52.287	0.1344
222	6991.27	52.421	0.1339
223	7043.75	52.555	0.1334
224	7096.38	52.688	0.1329
225	7149.13	52.821	0.1324
226	7202.02	52.953	0.1320
227	7255.04	53.085	0.1315
228	7308.19	53.216	0.1311
229	7361.47	53.347	0.1306
230	7414.88	53.477	0.1302
231	7468.42	53.607	0.1298
232	7522.09	53.737	0.1295
233	7575.89	53.866	0.1291
234	7629.83	53.995	0.1287
235	7683.88	54.124	0.1284
236	7738.07	54.252	0.1280
237	7792.39	54.380	0.1277
238	7846.83	54.507	0.1273
239	7901.40	54.634	0.1270
240	7956.10	54.761	0.1267
241	8010.92	54.888	0.1263
242	8065.87	55.014	0.1260
243	8120.95	55.140	0.1257
244	8176.15	55.265	0.1253
245	8231.48	55.390	0.1250
246	8286.93	55.515	0.1246
247	8342.51	55.639	0.1242
248	8398.21	55.763	0.1238
249	8454.04	55.887	0.1234
250	8509.99	56.010	0.1230

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S $\mu V/K$	$\frac{dS}{dT}$ $\mu V/K^2$
251	8566.06	56.133	0.1225
252	8622.25	56.255	0.1220
253	8678.57	56.377	0.1215
254	8735.01	56.498	0.1210
255	8791.56	56.619	0.1204
256	8848.24	56.739	0.1198
257	8905.04	56.858	0.1191
258	8961.96	56.977	0.1184
259	9019.00	57.095	0.1177
260	9076.15	57.212	0.1169
261	9133.42	57.329	0.1161
262	9190.81	57.445	0.1152
263	9248.31	57.559	0.1143
264	9305.93	57.673	0.1134
265	9363.66	57.786	0.1124
266	9421.50	57.898	0.1114
267	9479.45	58.009	0.1103
268	9537.51	58.119	0.1093
269	9595.69	58.227	0.1082
270	9653.97	58.335	0.1071
271	9712.36	58.442	0.1060
272	9770.85	58.547	0.1049
273	9829.45	58.651	0.1038
274	9888.15	58.755	0.1028
275	9946.96	58.857	0.1018
276	10005.87	58.958	0.1009
277	10064.88	59.059	0.1001
278	10123.98	59.159	0.0994
279	10183.19	59.258	0.0989
280	10242.50	59.356	0.0985

Table B-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type E, Chromel vs constantan.

Appendix C.

Interim Tables and Graphs for Thermocouple Type K, Chromel vs Alumel.

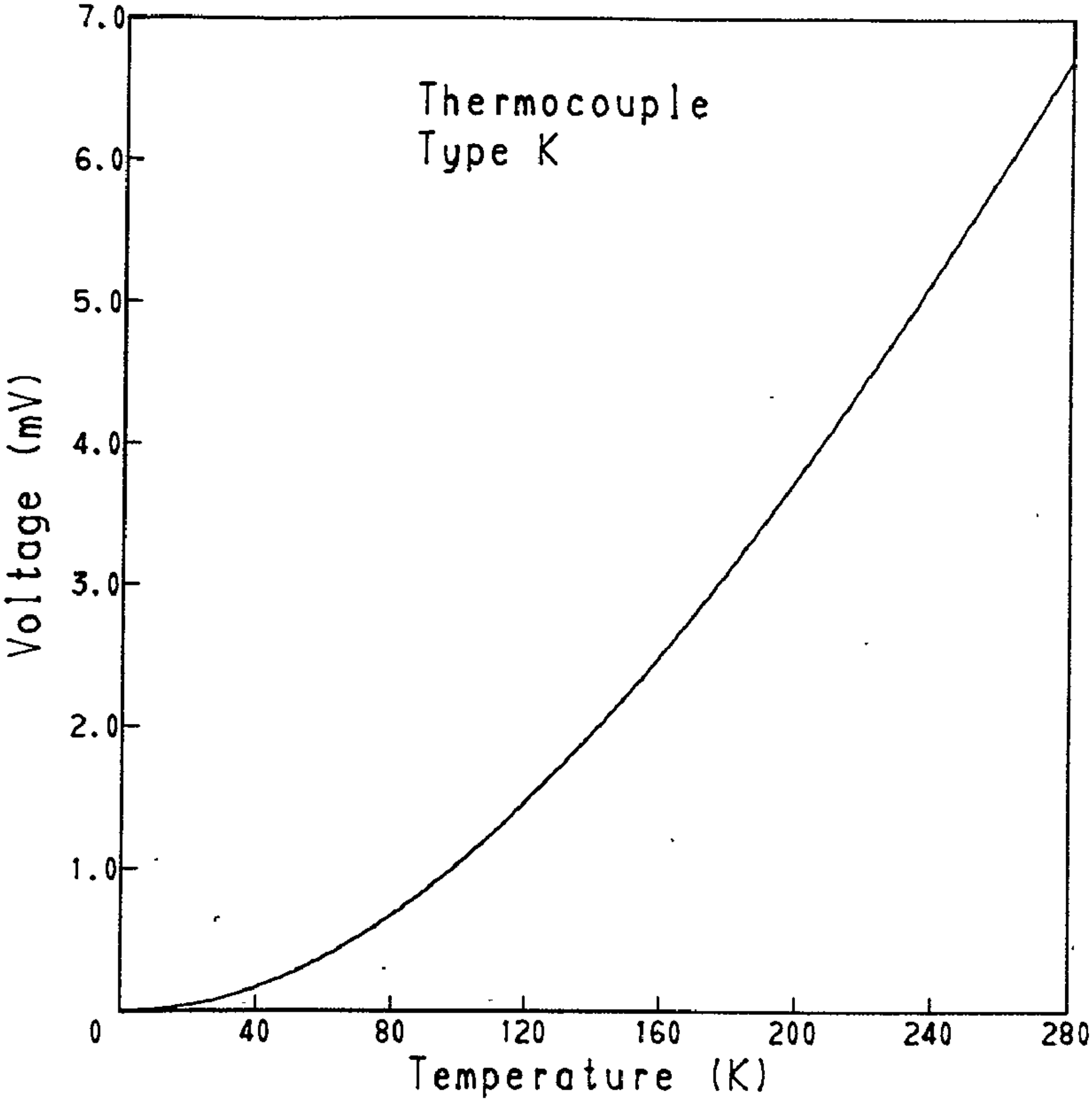

Figure C-1 Thermoelectric voltage of thermocouple type K, Chromel versus Alumel.

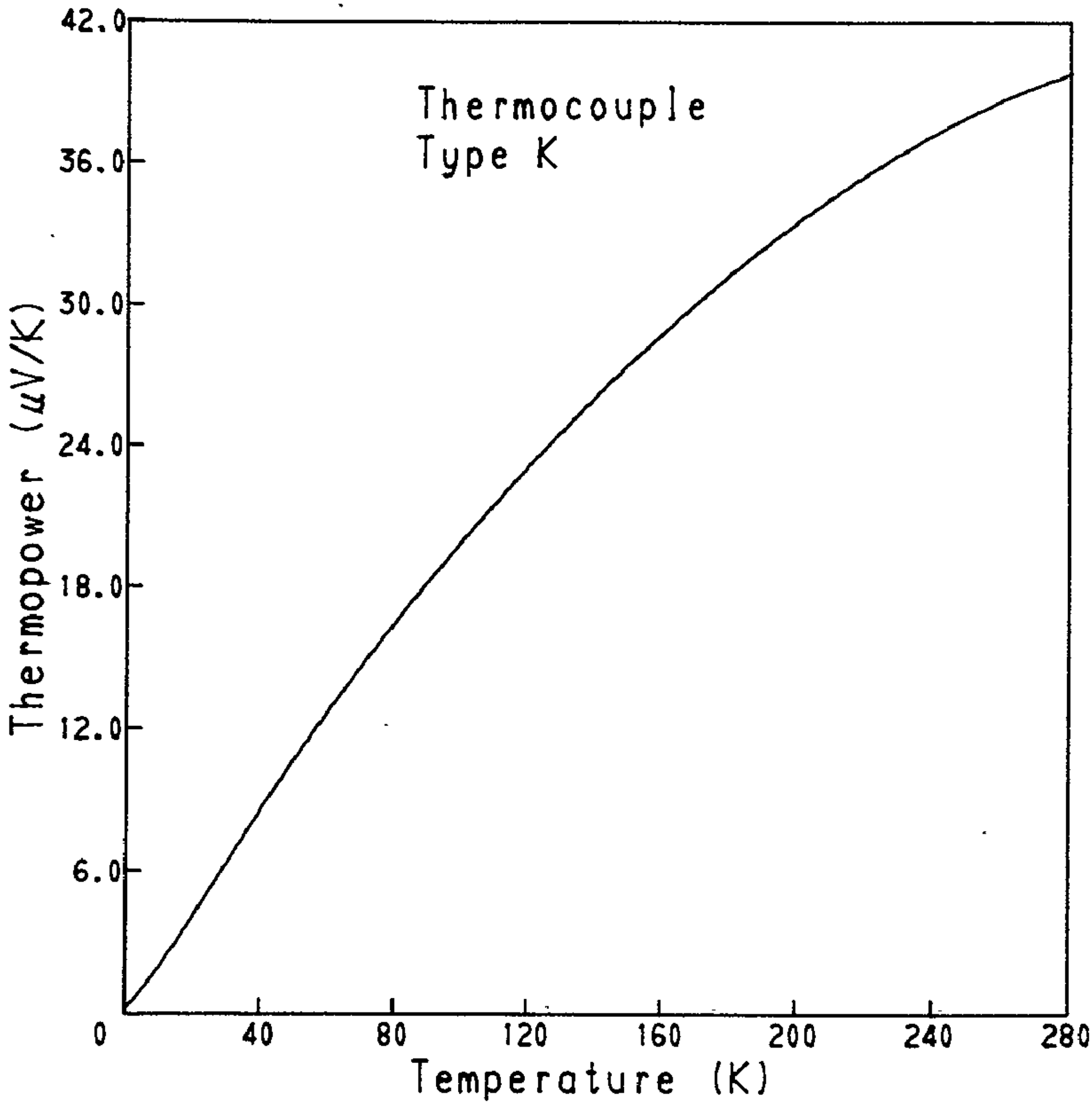

Figure C-2 Thermopower of thermocouple type K, Chromel versus Alumel.

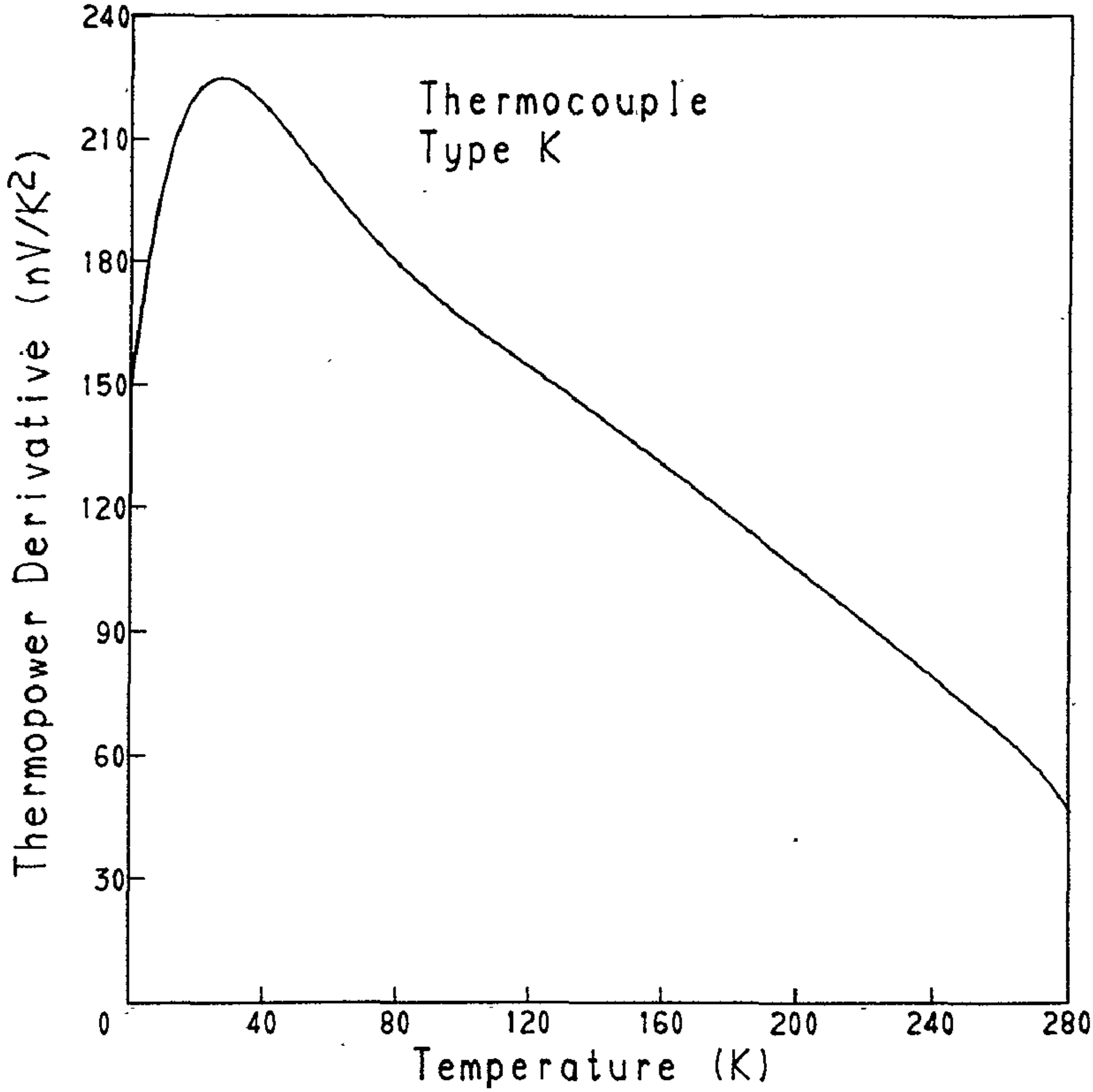

Figure C-3 Thermopower derivative of thermocouple type K, Chromel versus Alumel.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2	Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
1	0.30	0.382	0.1559	51	276.73	10.940	0.2066
2	0.77	0.541	0.1627	52	287.77	11.146	0.2056
3	1.39	0.707	0.1689	53	299.02	11.351	0.2045
4	2.18	0.879	0.1748	54	310.47	11.555	0.2035
5	3.15	1.056	0.1801	55	322.13	11.758	0.2024
6	4.30	1.239	0.1851	56	333.99	11.960	0.2013
7	5.63	1.426	0.1897	57	346.05	12.161	0.2003
8	7.15	1.618	0.1939	58	358.31	12.360	0.1993
9	8.86	1.814	0.1978	59	370.77	12.559	0.1982
10	10.78	2.014	0.2013	60	383.43	12.757	0.1972
11	12.89	2.217	0.2045	61	396.28	12.953	0.1962
12	15.21	2.423	0.2075	62	409.33	13.149	0.1952
13	17.74	2.631	0.2101	63	422.58	13.344	0.1942
14	20.48	2.843	0.2124	64	436.02	13.537	0.1932
15	23.42	3.056	0.2146	65	449.65	13.730	0.1922
16	26.59	3.272	0.2164	66	463.48	13.922	0.1912
17	29.97	3.489	0.2181	67	477.50	14.113	0.1903
18	33.57	3.708	0.2195	68	491.70	14.302	0.1894
19	37.38	3.928	0.2207	69	506.10	14.491	0.1884
20	41.42	4.149	0.2218	70	520.69	14.679	0.1875
21	45.68	4.371	0.2227	71	535.46	14.866	0.1866
22	50.17	4.594	0.2234	72	550.42	15.053	0.1857
23	54.87	4.818	0.2239	73	565.56	15.238	0.1849
24	59.80	5.042	0.2243	74	580.89	15.422	0.1840
25	64.96	5.267	0.2246	75	596.41	15.606	0.1832
26	70.34	5.491	0.2247	76	612.11	15.789	0.1823
27	75.94	5.716	0.2248	77	627.99	15.971	0.1815
28	81.77	5.941	0.2247	78	644.05	16.152	0.1807
29	87.82	6.165	0.2245	79	660.29	16.332	0.1799
30	94.10	6.390	0.2242	80	676.71	16.512	0.1791
31	100.60	6.614	0.2239	81	693.31	16.690	0.1784
32	107.33	6.837	0.2234	82	710.09	16.868	0.1776
33	114.28	7.061	0.2229	83	727.05	17.046	0.1769
34	121.45	7.283	0.2223	84	744.18	17.222	0.1761
35	128.84	7.505	0.2217	85	761.49	17.398	0.1754
36	136.46	7.727	0.2210	86	778.98	17.573	0.1747
37	144.29	7.947	0.2202	87	796.64	17.747	0.1740
38	152.35	8.167	0.2194	88	814.47	17.921	0.1733
39	160.63	8.386	0.2186	89	832.48	18.094	0.1726
40	169.12	8.604	0.2177	90	850.66	18.266	0.1719
41	177.84	8.821	0.2168	91	869.01	18.438	0.1712
42	186.77	9.038	0.2159	92	887.53	18.608	0.1706
43	195.91	9.253	0.2149	93	906.23	18.779	0.1699
44	205.27	9.468	0.2139	94	925.09	18.948	0.1693
45	214.85	9.681	0.2129	95	944.13	19.117	0.1686
46	224.63	9.893	0.2119	96	963.33	19.286	0.1680
47	234.63	10.105	0.2109	97	982.70	19.453	0.1674
48	244.84	10.315	0.2098	98	1002.23	19.620	0.1667
49	255.26	10.524	0.2088	99	1021.94	19.787	0.1661
50	265.89	10.733	0.2077	100	1041.81	19.952	0.1655

Table C-1 Thermal voltage, thermopower, and thermopower derivative for thermocouple type K, Chromel vs Alumel.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
101	1061.84	20.118	0.1649
102	1082.04	20.282	0.1643
103	1102.41	20.446	0.1637
104	1122.93	20.610	0.1631
105	1143.62	20.772	0.1625
106	1164.48	20.935	0.1619
107	1185.49	21.096	0.1613
108	1206.67	21.257	0.1607
109	1228.01	21.418	0.1602
110	1249.51	21.578	0.1596
111	1271.16	21.737	0.1590
112	1292.98	21.896	0.1584
113	1314.95	22.054	0.1579
114	1337.09	22.211	0.1573
115	1359.38	22.368	0.1567
116	1381.82	22.525	0.1561
117	1404.43	22.681	0.1556
118	1427.18	22.836	0.1550
119	1450.10	22.991	0.1544
120	1473.16	23.145	0.1538
121	1496.39	23.298	0.1533
122	1519.76	23.451	0.1527
123	1543.29	23.604	0.1521
124	1566.97	23.756	0.1516
125	1590.80	23.907	0.1510
126	1614.78	24.058	0.1504
127	1638.91	24.208	0.1498
128	1663.20	24.357	0.1493
129	1687.63	24.506	0.1487
130	1712.21	24.655	0.1481
131	1736.94	24.802	0.1475
132	1761.81	24.950	0.1470
133	1786.84	25.096	0.1464
134	1812.01	25.242	0.1458
135	1837.32	25.388	0.1452
136	1862.78	25.533	0.1446
137	1888.39	25.677	0.1441
138	1914.14	25.821	0.1435
139	1940.03	25.964	0.1429
140	1966.06	26.107	0.1423
141	1992.24	26.249	0.1417
142	2018.56	26.390	0.1411
143	2045.02	26.531	0.1405
144	2071.62	26.671	0.1399
145	2098.37	26.811	0.1393
146	2125.25	26.950	0.1387
147	2152.26	27.088	0.1381
148	2179.42	27.226	0.1375
149	2206.72	27.363	0.1370
150	2234.15	27.500	0.1364
151	2261.72	27.636	0.1357
152	2289.42	27.772	0.1351
153	2317.26	27.906	0.1345
154	2345.23	28.041	0.1339
155	2373.34	28.174	0.1333
156	2401.58	28.307	0.1327
157	2429.96	28.440	0.1321
158	2458.46	28.572	0.1315
159	2487.10	28.703	0.1309
160	2515.87	28.833	0.1303
161	2544.77	28.963	0.1297
162	2573.79	29.093	0.1291
163	2602.95	29.222	0.1285
164	2632.24	29.350	0.1278
165	2661.65	29.477	0.1272
166	2691.19	29.604	0.1266
167	2720.86	29.730	0.1260
168	2750.65	29.856	0.1254
169	2780.57	29.981	0.1248
170	2810.61	30.106	0.1241
171	2840.78	30.229	0.1235
172	2871.07	30.353	0.1229
173	2901.49	30.475	0.1223
174	2932.02	30.597	0.1217
175	2962.68	30.719	0.1210
176	2993.46	30.839	0.1204
177	3024.36	30.959	0.1198
178	3055.38	31.079	0.1192
179	3086.52	31.198	0.1185
180	3117.77	31.316	0.1179
181	3149.15	31.433	0.1173
182	3180.64	31.550	0.1166
183	3212.25	31.667	0.1160
184	3243.97	31.782	0.1154
185	3275.81	31.898	0.1147
186	3307.77	32.012	0.1141
187	3339.84	32.126	0.1135
188	3372.02	32.239	0.1128
189	3404.32	32.351	0.1122
190	3436.72	32.463	0.1116
191	3469.24	32.575	0.1109
192	3501.87	32.685	0.1103
193	3534.61	32.795	0.1097
194	3567.46	32.905	0.1090
195	3600.42	33.013	0.1084
196	3633.49	33.121	0.1077
197	3666.66	33.229	0.1071
198	3699.95	33.335	0.1064
199	3733.33	33.442	0.1058
200	3766.83	33.547	0.1052

Table C-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type K, Chromel vs Alumel.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
201	3800.43	33.652	0.1045
202	3834.13	33.756	0.1039
203	3867.94	33.860	0.1032
204	3901.85	33.962	0.1026
205	3935.86	34.065	0.1019
206	3969.98	34.166	0.1013
207	4004.20	34.267	0.1006
208	4038.51	34.367	0.0999
209	4072.93	34.467	0.0993
210	4107.45	34.566	0.0986
211	4142.06	34.664	0.0980
212	4176.78	34.762	0.0973
213	4211.59	34.859	0.0967
214	4246.49	34.955	0.0960
215	4281.50	35.051	0.0954
216	4316.60	35.146	0.0947
217	4351.79	35.240	0.0940
218	4387.08	35.334	0.0934
219	4422.46	35.427	0.0927
220	4457.93	35.520	0.0921
221	4493.50	35.611	0.0914
222	4529.15	35.702	0.0907
223	4564.90	35.793	0.0901
224	4600.74	35.883	0.0894
225	4636.67	35.972	0.0888
226	4672.68	36.060	0.0881
227	4708.79	36.148	0.0874
228	4744.98	36.235	0.0868
229	4781.25	36.321	0.0861
230	4817.62	36.407	0.0855
231	4854.07	36.492	0.0848
232	4890.60	36.577	0.0842
233	4927.22	36.661	0.0835
234	4963.93	36.744	0.0828
235	5000.71	36.826	0.0822
236	5037.58	36.908	0.0815
237	5074.53	36.989	0.0809
238	5111.56	37.070	0.0802
239	5148.67	37.150	0.0796
240	5185.86	37.229	0.0789
241	5223.12	37.308	0.0783
242	5260.47	37.386	0.0776
243	5297.90	37.463	0.0770
244	5335.40	37.540	0.0763
245	5372.97	37.616	0.0756
246	5410.63	37.691	0.0750
247	5448.36	37.766	0.0743
248	5486.16	37.840	0.0737
249	5524.04	37.913	0.0730
250	5561.98	37.986	0.0723
251	5600.01	38.058	0.0717
252	5638.10	38.129	0.0710
253	5676.26	38.200	0.0703
254	5714.50	38.270	0.0696
255	5752.80	38.339	0.0690
256	5791.18	38.407	0.0683
257	5829.62	38.475	0.0676
258	5868.13	38.543	0.0669
259	5906.70	38.609	0.0661
260	5945.34	38.675	0.0654
261	5984.05	38.740	0.0647
262	6022.82	38.804	0.0639
263	6061.66	38.868	0.0632
264	6100.56	38.931	0.0624
265	6139.52	38.993	0.0616
266	6178.54	39.054	0.0608
267	6217.63	39.114	0.0600
268	6256.77	39.174	0.0591
269	6295.97	39.232	0.0582
270	6335.24	39.290	0.0573
271	6374.55	39.347	0.0564
272	6413.93	39.403	0.0554
273	6453.36	39.458	0.0544
274	6492.84	39.512	0.0534
275	6532.38	39.565	0.0523
276	6571.97	39.616	0.0512
277	6611.62	39.667	0.0501
278	6651.31	39.716	0.0489
279	6691.05	39.765	0.0476
280	6730.84	39.812	0.0463

Table C-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple type K, Chromel vs Alumel.

Appendix D.

Preliminary Tables and Graphs for Chromel vs Gold-0.07 Atomic Percent Iron

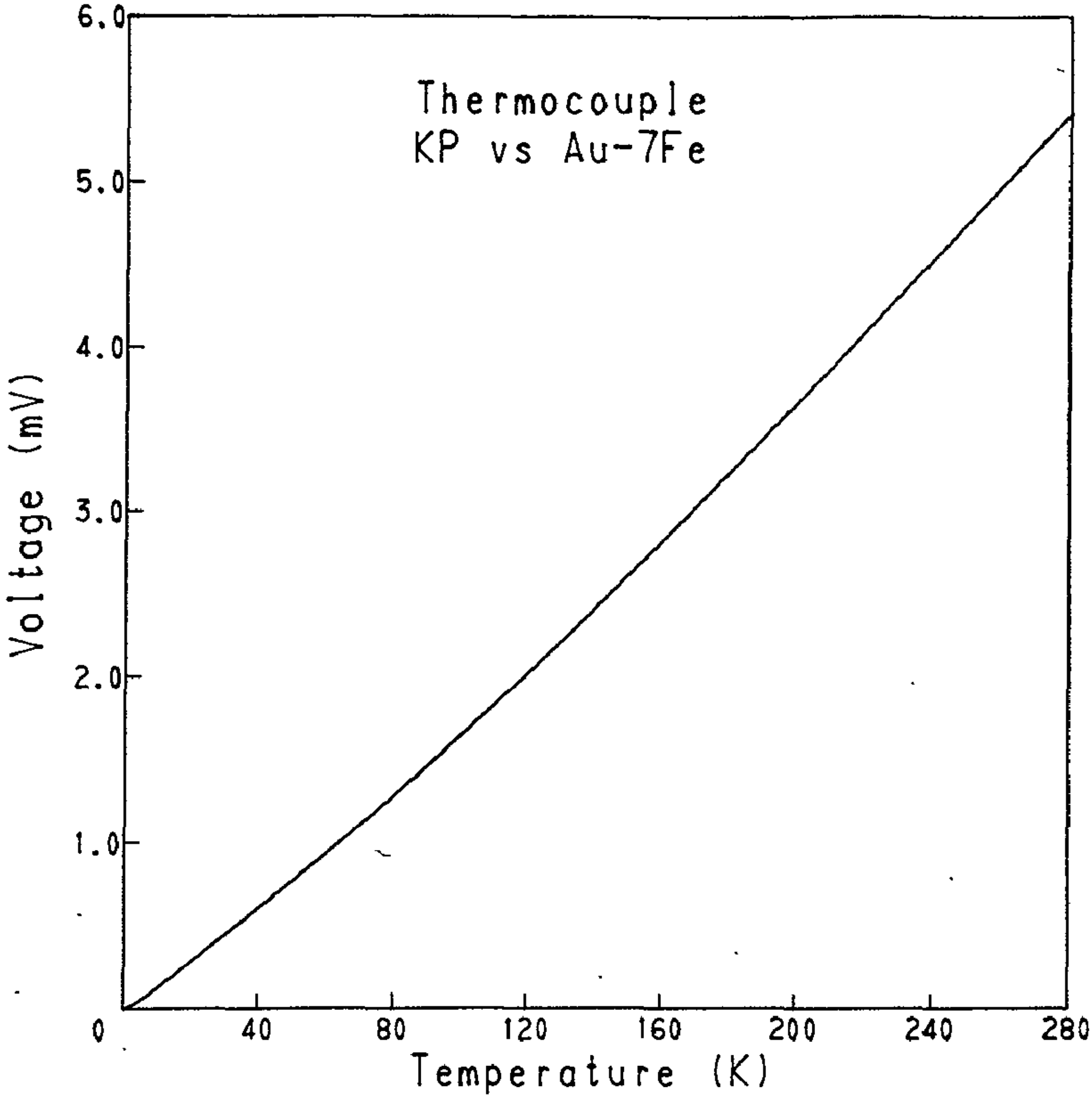

Figure D-1 Thermoelectric voltage of Chromel versus gold-0.07 at.% Fe.

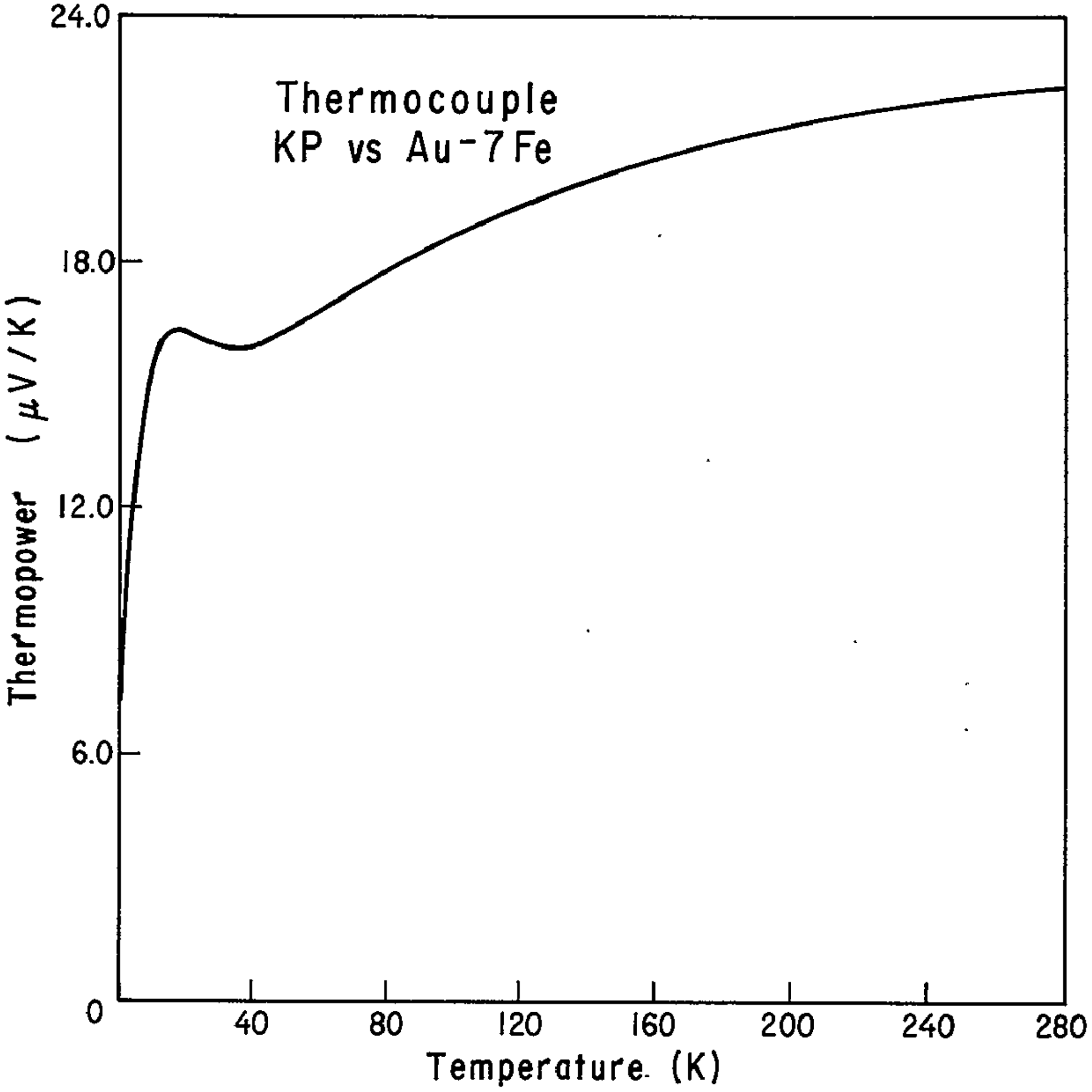

Figure D-2 Thermopower of Chromel versus gold-0.07 at.% Fe.

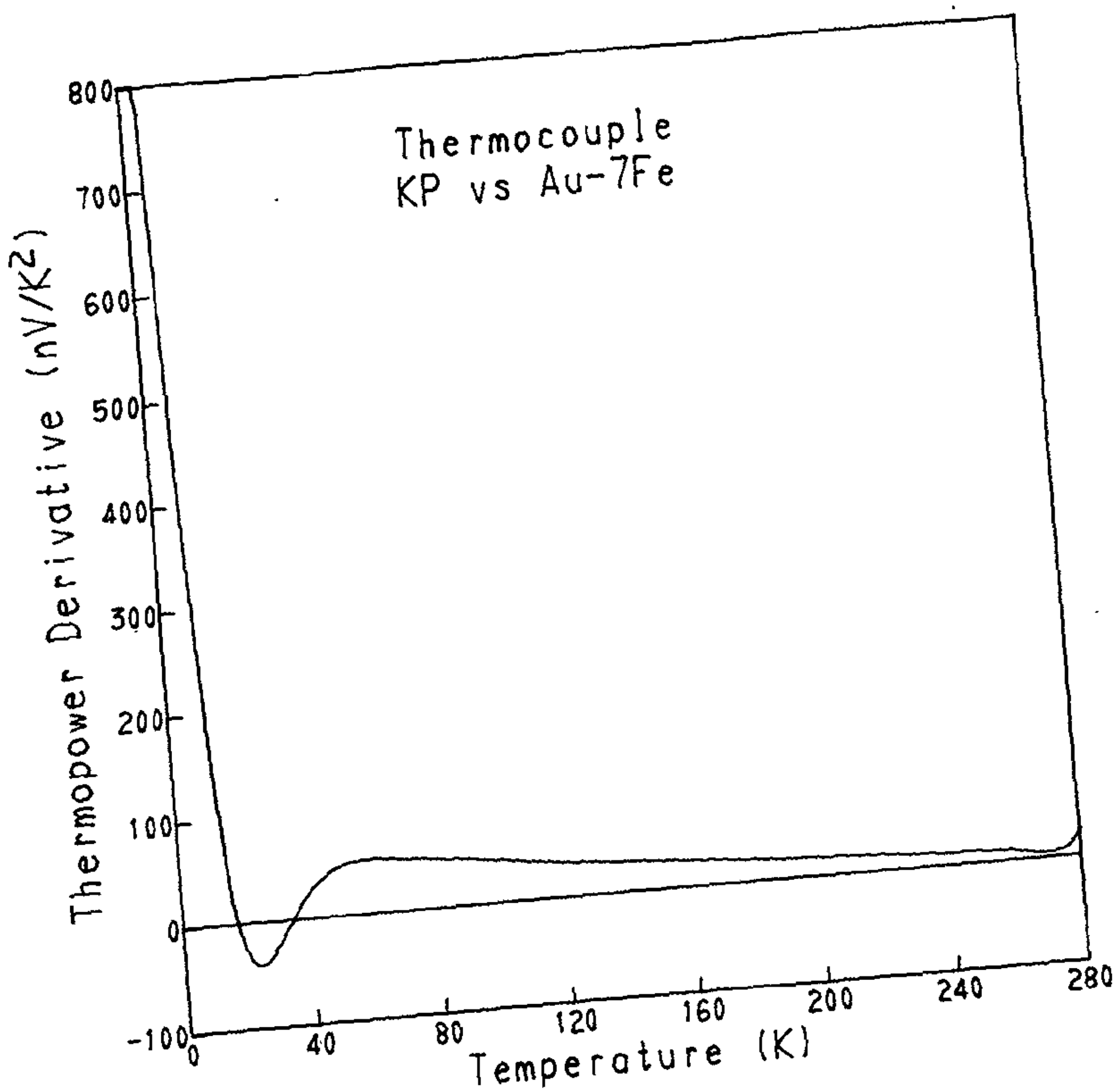

Figure D-3 Thermopower derivative of Chromel versus gold-0.07 at.% Fe.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K²
1	7.86	8.645	1.5000
2	17.21	10.035	1.2833
3	27.86	11.220	1.0917
4	39.59	12.226	0.9231
5	52.26	13.073	0.7749
6	65.69	13.782	0.6454
7	79.78	14.369	0.5325
8	94.40	14.852	0.4345
9	109.45	15.243	0.3499
10	124.86	15.555	0.2772
11	140.54	15.801	0.2151
12	156.44	15.989	0.1625
13	172.50	16.128	0.1183
14	188.68	16.228	0.0814
15	204.94	16.293	0.0509
16	221.26	16.331	0.0262
17	237.60	16.347	0.0064
18	253.95	16.346	-0.0091
19	270.29	16.330	-0.0209
20	286.60	16.305	-0.0295
21	302.89	16.272	-0.0354
22	319.15	16.235	-0.0389
23	335.36	16.195	-0.0406
24	351.54	16.154	-0.0406
25	367.67	16.114	-0.0394
26	383.77	16.076	-0.0371
27	399.82	16.040	-0.0339
28	415.85	16.008	-0.0301
29	431.84	15.980	-0.0258
30	447.81	15.957	-0.0212
31	463.76	15.938	-0.0164
32	479.69	15.924	-0.0115
33	495.61	15.915	-0.0065
34	511.52	15.911	-0.0017
35	527.43	15.912	0.0031
36	543.35	15.917	0.0077
37	559.27	15.927	0.0121
38	575.20	15.941	0.0163
39	591.15	15.960	0.0203
40	607.12	15.982	0.0239
41	623.12	16.007	0.0273
42	639.14	16.036	0.0305
43	655.19	16.068	0.0334
44	671.28	16.103	0.0360
45	687.40	16.140	0.0383
46	703.56	16.180	0.0404
47	719:76	16.221	0.0422
48	736.00	16.264	0.0439
49	752.29	16.309	0.0453
50	768.62	16.355	0.0465
51	785.00	16.402	0.0476
52	801.42	16.450	0.0484
53	817.89	16.498	0.0492
54	834.42	16.548	0.0497
55	850.99	16.598	0.0502
56	867.61	16.648	0.0505
57	884.29	16.699	0.0508
58	901.01	16.750	0.0509
59	917.79	16.801	0.0510
60	934.61	16.852	0.0510
61	951.49	16.903	0.0509
62	968.42	16.953	0.0508
63	985.40	17.004	0.0507
64	1002.43	17.055	0.0505
65	1019.51	17.105	0.0503
66	1036.64	17.155	0.0501
67	1053.82	17.205	0.0498
68	1071.05	17.255	0.0495
69	1088.33	17.304	0.0493
70	1105.66	17.354	0.0490
71	1123.03	17.402	0.0487
72	1140.46	17.451	0.0484
73	1157.94	17.499	0.0481
74	1175.46	17.547	0.0478
75	1193.03	17.595	0.0476
76	1210.65	17.642	0.0473
77	1228.31	17.689	0.0470
78	1246.03	17.736	0.0467
79	1263.79	17.783	0.0464
80	1281.59	17.829	0.0461
81	1299.44	17.875	0.0458
82	1317.34	17.921	0.0456
83	1335.29	17.966	0.0453
84	1353.28	18.011	0.0450
85	1371.31	18.056	0.0447
86	1389.39	18.101	0.0444
87	1407.51	18.145	0.0441
88	1425.68	18.189	0.0438
89	1443.89	18.233	0.0435
90	1462.14	18.276	0.0432
91	1480.44	18.319	0.0429
92	1498.78	18.362	0.0426
93	1517.16	18.404	0.0422
94	1535.59	18.446	0.0419
95	1554.06	18.488	0.0416
96	1572.56	18.529	0.0412
97	1591.11	18.570	0.0409
98	1609.70	18.611	0.0405
99	1628.34	18.651	0.0402
100	1647.01	18.691	0.0398

Table D-1 Thermal voltage, thermopower, and thermopower derivative for thermocouple Chromel vs gold-0.07 at.% iron.

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S μV/K	$\frac{dS}{dT}$ μV/K²
101	1665.72	18.731	0.0394
102	1684.47	18.770	0.0391
103	1703.26	18.809	0.0387
104	1722.09	18.848	0.0383
105	1740.95	18.886	0.0380
106	1759.86	18.924	0.0376
107	1778.80	18.961	0.0372
108	1797.78	18.998	0.0368
109	1816.80	19.035	0.0365
110	1835.85	19.071	0.0361
111	1854.94	19.107	0.0357
112	1874.06	19.143	0.0354
113	1893.22	19.178	0.0350
114	1912.42	19.213	0.0347
115	1931.65	19.247	0.0343
116	1950.91	19.281	0.0340
117	1970.21	19.315	0.0337
118	1989.54	19.349	0.0333
119	2008.91	19.382	0.0330
120	2028.31	19.415	0.0327
121	2047.74	19.447	0.0324
122	2067.20	19.480	0.0321
123	2086.70	19.512	0.0319
124	2106.23	19.543	0.0316
125	2125.78	19.575	0.0313
126	2145.37	19.606	0.0311
127	2165.00	19.637	0.0308
128	2184.65	19.668	0.0306
129	2204.33	19.698	0.0304
130	2224.04	19.728	0.0301
131	2243.79	19.758	0.0299
132	2263.56	19.788	0.0297
133	2283.36	19.818	0.0295
134	2303.20	19.847	0.0293
135	2323.06	19.876	0.0291
136	2342.95	19.905	0.0289
137	2362.87	19.934	0.0288
138	2382.82	19.963	0.0286
139	2402.80	19.991	0.0284
140	2422.80	20.020	0.0282
141	2442.83	20.048	0.0281
142	2462.90	20.076	0.0279
143	2482.99	20.104	0.0277
144	2503.10	20.131	0.0275
145	2523.25	20.159	0.0274
146	2543.42	20.186	0.0272
147	2563.62	20.213	0.0270
148	2583.85	20.240	0.0268
149	2604.10	20.267	0.0267
150	2624.38	20.293	0.0265

Temp. K	Voltage=E μV	$\frac{dE}{dT}$=S μV/K	$\frac{dS}{dT}$ μV/K²
151	2644.69	20.320	0.0263
152	2665.02	20.346	0.0261
153	2685.38	20.372	0.0259
154	2705.76	20.398	0.0257
155	2726.18	20.423	0.0255
156	2746.61	20.449	0.0253
157	2767.07	20.474	0.0251
158	2787.56	20.499	0.0249
159	2808.07	20.524	0.0246
160	2828.61	20.548	0.0244
161	2849.17	20.573	0.0242
162	2869.75	20.597	0.0240
163	2890.36	20.621	0.0237
164	2910.99	20.644	0.0235
165	2931.65	20.668	0.0233
166	2952.33	20.691	0.0230
167	2973.03	20.714	0.0228
168	2993.76	20.736	0.0226
169	3014.50	20.759	0.0223
170	3035.27	20.781	0.0221
171	3056.06	20.803	0.0219
172	3076.88	20.825	0.0216
173	3097.71	20.846	0.0214
174	3118.57	20.867	0.0212
175	3139.45	20.888	0.0209
176	3160.35	20.909	0.0207
177	3181.27	20.930	0.0205
178	3202.21	20.950	0.0203
179	3223.17	20.970	0.0201
180	3244.15	20.990	0.0199
181	3265.15	21.010	0.0197
182	3286.17	21.030	0.0195
183	3307.21	21.049	0.0193
184	3328.27	21.068	0.0191
185	3349.34	21.088	0.0190
186	3370.44	21.106	0.0188
187	3391.56	21.125	0.0187
188	3412.69	21.144	0.0185
189	3433.85	21.162	0.0184
190	3455.02	21.180	0.0182
191	3476.21	21.199	0.0181
192	3497.41	21.217	0.0180
193	3518.64	21.235	0.0178
194	3539.88	21.252	0.0177
195	3561.14	21.270	0.0176
196	3582.42	21.288	0.0175
197	3603.72	21.305	0.0174
198	3625.03	21.322	0.0173
199	3646.36	21.340	0.0172
200	3667.71	21.357	0.0171

Table D-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple Chromel vs gold-0.07 at.% iron.

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
201	3689.08	21.374	0.0170
202	3710.46	21.391	0.0169
203	3731.86	21.408	0.0168
204	3753.27	21.424	0.0167
205	3774.71	21.441	0.0166
206	3796.16	21.457	0.0164
207	3817.62	21.474	0.0163
208	3839.10	21.490	0.0162
209	3860.60	21.506	0.0161
210	3882.12	21.522	0.0159
211	3903.65	21.538	0.0158
212	3925.19	21.554	0.0157
213	3946.75	21.569	0.0155
214	3968.33	21.585	0.0154
215	3989.92	21.600	0.0152
216	4011.53	21.615	0.0150
217	4033.15	21.630	0.0148
218	4054.79	21.645	0.0147
219	4076.44	21.659	0.0145
220	4098.11	21.674	0.0143
221	4119.79	21.688	0.0141
222	4141.49	21.702	0.0139
223	4163.19	21.716	0.0137
224	4184.92	21.729	0.0135
225	4206.65	21.743	0.0133
226	4228.40	21.756	0.0131
227	4250.17	21.769	0.0129
228	4271.94	21.782	0.0127
229	4293.73	21.794	0.0125
230	4315.53	21.807	0.0123
231	4337.34	21.819	0.0121
232	4359.17	21.831	0.0120
233	4381.00	21.843	0.0118
234	4402.85	21.855	0.0117
235	4424.71	21.866	0.0115
236	4446.59	21.878	0.0114
237	4468.47	21.889	0.0113
238	4490.36	21.900	0.0112
239	4512.27	21.911	0.0111
240	4534.19	21.922	0.0110
241	4556.11	21.933	0.0109
242	4578.05	21.944	0.0109
243	4600.00	21.955	0.0108
244	4621.96	21.966	0.0107
245	4643.94	21.977	0.0107
246	4665.92	21.987	0.0107
247	4687.91	21.998	0.0106
248	4709.91	22.009	0.0106
249	4731.93	22.019	0.0105
250	4753.95	22.030	0.0105

Temp. K	Voltage=E µV	$\frac{dE}{dT}$=S µV/K	$\frac{dS}{dT}$ µV/K^2
251	4775.99	22.040	0.0104
252	4798.03	22.050	0.0103
253	4820.09	22.060	0.0102
254	4842.15	22.071	0.0100
255	4864.23	22.081	0.0099
256	4886.31	22.090	0.0097
257	4908.41	22.100	0.0094
258	4930.51	22.109	0.0091
259	4952.63	22.118	0.0088
260	4974.75	22.127	0.0085
261	4996.88	22.135	0.0081
262	5019.03	22.143	0.0076
263	5041.17	22.150	0.0072
264	5063.32	22.157	0.0067
265	5085.48	22.164	0.0062
266	5107.64	22.170	0.0057
267	5129.82	22.175	0.0053
268	5152.00	22.180	0.0049
269	5174.18	22.185	0.0046
270	5196.37	22.190	0.0044
271	5218.56	22.194	0.0044
272	5240.75	22.198	0.0046
273	5262.96	22.203	0.0052
274	5285.16	22.209	0.0061
275	5307.37	22.216	0.0075
276	5329.59	22.224	0.0095
277	5351.83	22.235	0.0122
278	5374.06	22.248	0.0157
279	5396.32	22.266	0.0204
280	5418.60	22.290	0.0262

Table D-1 (Cont.) Thermal voltage, thermopower, and thermopower derivative for thermocouple Chromel vs gold-0.07 at.% iron.

Appendix E.

Functional Representations and Error Analyses

As described in the "Data Analysis and Results" section, the thermal voltage can be represented by

$$E(T) = \sum_{n=1}^{L} A_n F_n(T),$$

where the orthonormal polynomials $F_n(T)$ are given by

$$F_n(T) = \sum_{j=1}^{n} C_{jn} T^j.$$

The $F_n(T)$ (up to n = 14) are given in table E-1 to twelve significant figures and are in a form convenient for rapid computation and minimum round-off error. Sometimes, but not always (as explained next), all fourteen functions are required to obtain a best fit.

In general, the more complex the shape of a curve, the more terms are required in an expansion. The curve for type K is relatively simple; only 10 polymonials are required. Curves for type T and KP vs Au-7 Fe are more complex; they require 14 polymonials. Type E is intermediate; 12 polynomials are needed. All of the necessary coefficients, A_n, for each of the four thermocouple combinations are given in table E-2. The numbers are all given with sufficient digits so that no significant precision is lost in the final calculation.

For most computers, double precision constants and software are required in the program if the final calculations are to retain all of the precision inherent in the experimental data. If the full array of functions and constants are used with a double precision program, then the resultant standard deviation of the data fits are 0.06, 0.11, 0.07, and 0.10 microvolts for Types T, E, K, and KP vs Au-7 Fe respectively.

$$F(1) = 2.62699813461*10^{-3}\ T$$

$$F(2) = [3.21644939212*10^{-5}\ T - 1.11693281748*10^{-2}\ ]T$$

$$F(3) = [(3.58986173360*10^{-7}\ T - 1.55665286232*10^{-4}\ )T$$
$$+ 1.81137186628*10^{-2}\ ]T$$

$$F(4) = [([5.34727798756*10^{-9}\ T - 3.04978248031*10^{-6}\ ]T$$
$$+ 5.54625790795*10^{-4}\ )T - 3.34631223797*10^{-2}\ ]T$$

$$F(5) = [([(6.07093013715*10^{-11}\ T - 4.27373422008*10^{-8}\ )T$$
$$+ 1.07117698644*10^{-5}\ ]T - 1.13757942812*10^{-3}\ )T + 4.64537228886*10^{-2}\ ]T$$

$$F(6) = [([([8.82359212161*10^{-13}T - 7.28186199261*10^{-10}]T$$
$$+ 2.24765904282*10^{-7}\ )T - 3.18943408270*10^{-5}\ ]T + 2.05429286434*10^{-3}\ )T$$
$$- 5.17871198112*10^{-2}\ ]T$$

$$F(7) = [([([(1.33824082457*10^{-14}T - 1.32030883347*10^{-11}\ )T$$
$$+ 5.13280189141*10^{-9}\ ]T - 9.93378385912*10^{-7}\ )T + 9.92080547172*10^{-5}\ ]T$$
$$- 4.75674883206*10^{-3}\ )T + 8.88149787156*10^{-2}\ ]T$$

$$F(8) = [([([([1.91122488586*10^{-16}T - 2.16756712456*10^{-13}\ ]T$$
$$+ 1.00341211234*10^{-10})T - 2.43627392132*10^{-8}\ ]T + 3.31519537388*10^{-6}\ )T$$
$$- 2.49826333327*10^{-4}\ ]T + 9.57847982898*10^{-3}\ )T - 1.50658460622*10^{-1}\ ]T$$

$$F(9) = [([([([(2.92664884243*10^{-18}T - 3.70219405097*10^{-15})T$$
$$+ 1.95708484602*10^{-12}]T - 5.60572545443*10^{-10})T + 9.43371886071*10^{-8}\ ]T$$
$$- 9.45983561819*10^{-6}\ )T + 5.47473023495*10^{-4}\ ]T - 1.67836957950*10^{-2}\ )T$$
$$+ 2.24869753823*10^{-1}\ ]T$$

Table E-1 The orthonormal polynomials $F_n(T)$.

$$F(10) = [([([([([3.95801534382*10^{-20}T - 5.60568859106*10^{-17}]T$$
$$+ 3.38786223933*10^{-14})T - 1.13998063262*10^{-11}]T + 2.33700771017*10^{-9})T$$
$$- 3.00187384267*10^{-7}]T + 2.39434643671*10^{-5})T - 1.13590924597*10^{-3}]T$$
$$+ 2.93458112010*10^{-2})T - 3.46535708754*10^{-1}]T$$

$$F(11) = [([([([([(5.38516736601*10^{-22}T - 8.32331470995*10^{-19})T$$
$$+ 5.56674670636*10^{-16}]T - 2.11051706773*10^{-13})T + 4.99234280040*10^{-11}]T$$
$$- 7.64420856213*10^{-9})T + 7.61267444043*10^{-7}]T - 4.83150710271*10^{-5})T$$
$$+ 1.86327527031*10^{-3}]T - 4.00410161322*10^{-2})T + 4.09499105085*10^{-1}]T$$

$$F(12) = [([([([([([8.26232811079*10^{-24}T - 1.39942629861*10^{-20}]T$$
$$+ 1.03886749337*10^{-17})T - 4.44101985907*10^{-15}]T + 1.20800316490*10^{-12})T$$
$$- 2.18094014408*10^{-10}]T + 2.64618560604*10^{-8})T - 2.13895663004*10^{-6}]T$$
$$+ 1.11909300262*10^{-4})T - 3.59443137275*10^{-3}]T + 6.49353202556*10^{-2})T$$
$$- 5.70479386855*10^{-1}]T$$

$$F(13) = [([([([([([(1.25461027145*10^{-25}T - 2.30105779284*10^{-22})T$$
$$+ 1.87043885148*10^{-19}]T - 8.87601372259*10^{-17})T + 2.72632243976*10^{-14}]T$$
$$- 5.67999046167*10^{-12})T + 8.17908913314*10^{-10}]T - 8.14274313875*10^{-8})T$$
$$+ 5.51731174858*10^{-6}]T - 2.46158777788*10^{-4})T + 6.84002302040*10^{-3}]T$$
$$- 1.08288591279*10^{-1})T + 8.46075126398*10^{-1}]T$$

$$F(14) = [([([([([([([1.85341453474*10^{-27}T - 3.66081814236*10^{-24}]T$$
$$+ 3.23482126555*10^{-21})T - 1.68761557726*10^{-18}]T + 5.77754988256*10^{-16})T$$
$$- 1.36460361321*10^{-13}]T + 2.27598282316*10^{-11})T - 2.69808964571*10^{-9}]T$$
$$+ 2.25818509834*10^{-7})T - 1.30847059620*10^{-5}]T + 5.06916388647*10^{-4})T$$
$$- 1.24180968293*10^{-2}]T + 1.76154785795*10^{-1})T - 1.25353229615]T$$

Table E-1 (Cont.) The orthonormal polynomials $F_n(T)$.

COEFFICIENT	TYPE T	TYPE E	TYPE K	KP VS AU-7FE
A(1)	10673.443	16803.061	11244.712	7823.267
A(2)	1947.355	2969.647	2175.001	433.939
A(3)	-158.544	-405.095	-297.946	-82.121
A(4)	44.522	65.071	5.299	-16.055
A(5)	-34.697	-22.933	-4.617	21.929
A(6)	10.896	3.050	-0.622	-8.975
A(7)	-0.253	1.794	2.145	0.008
A(8)	-2.966	-1.910	-1.907	4.704
A(9)	2.053	0.284	0.745	-6.097
A(10)	-1.085	0.131	-0.271	6.441
A(11)	-0.055	-0.720		-4.328
A(12)	0.467	0.437		2.494
A(13)	-0.568			-1.283
A(14)	0.464			0.496

Table E-2 Coefficients for a polynomial expansion representation of the thermocouple data.

However, any functional representation can be simplified at the cost of an increased standard deviation for the data fit. Again the standard deviation for any given order depends on the thermocouple type. In table E-3 are listed the approximate standard deviations for each order of polynomial expansion between 4 and the maximum number (14, 12, 10, or 14 respectively). It can be clearly seen that if, for example, only 1 microvolt precision is desired, then the order is usually about halved, to 7, 6, 5, or 11 respectively.

Computer economies can also be obtained by reducing the number of digits carried, by changing from double to single precision. Since there is no uniformity in what constitutes single or double precision (single can mean from about 8 to 12 decimal digits), we have tabulated the errors caused by using various different numbers of digits in computations. For full table reproduction precision (0.01 microvolt), 38 binary bits (12 decimal digits) must be carried for type T or KP vs Au-7 Fe thermocouples; 33 binary bits (10 decimal) for type E; and 26 binary (8 decimal) for type K. Table E-4 indicates the number of binary bits and decimal digits necessary to obtain various given precisions. The values in the table presume, of course, that a sufficient number of polynomials are used to eliminate any error that would be caused by using too low an order of fit. Since all large computers carry at least 24 binary bits in single precision, errors were not calculated for any fewer bits than that. The tables in Appendices A through D were calculated using 72 binary bits (22 decimals).

The deviations between calculated and experimental values of voltage are given in figures E-1 through E-4. Note that the deviations are in nanovolts.

NUMBER OF COEFFICIENTS	APPROXIMATE STANDARD DEVIATION			
	TYPE T	TYPE E	TYPE K	KP VS AU-7FE
4	9	13	1.5	6
5	7	5	0.9	5
6	2	0.6	0.5	2
7	0.8	0.5	0.4	1.9
8	0.6	0.4	0.38	1.7
9	0.4	0.2	0.15	1.5
10	0.2	0.17	0.07	1.4
11	0.15	0.15		1.0
12	0.13	0.11		0.6
13	0.10			0.3
14	0.06			0.10

Table E-3 Approximate standard deviations (in microvolts) for various orders of polynomial expansions.

Table E-4

Number of digits necessary in computations to reduce round-off errors below certain limits

Error Criteria	Number of Digits Necessary for Thermocouple							
	Type T		Type E		Type K		KP vs Au-7 Fe	
	binary	decimal	binary	decimal	binary	decimal	binary	decimal
Full table precision <0.01μV	38	12	33	10	26	8	38	12
Approx. exp. error <0.1μV	35	11	29	9	24	8	35	11
<1μV	32	10	24	8	24	8	32	10
<50μV	24	8					24	8

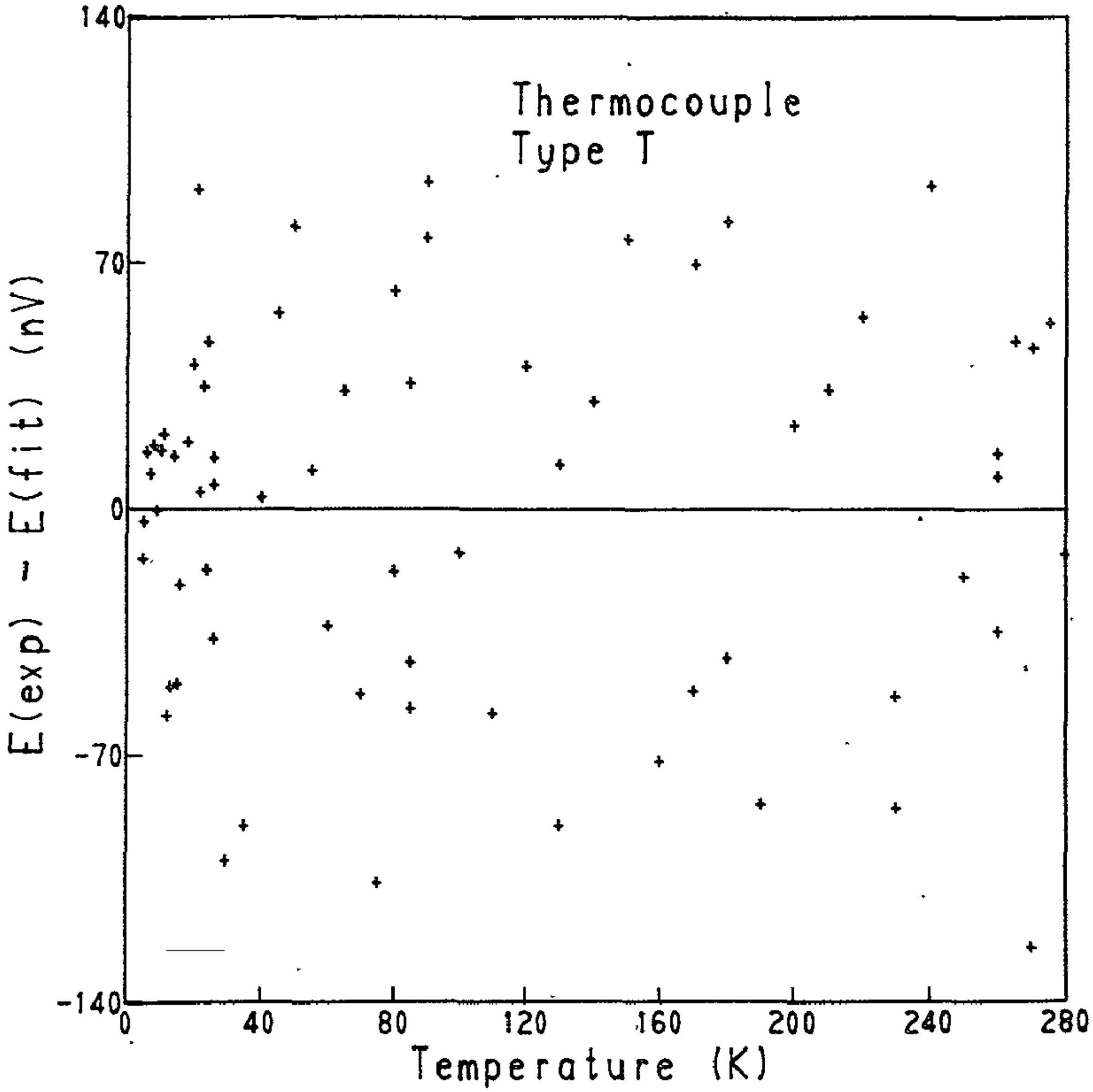

Figure E-1 Deviations between calculated and experimental values for thermocouple type T.

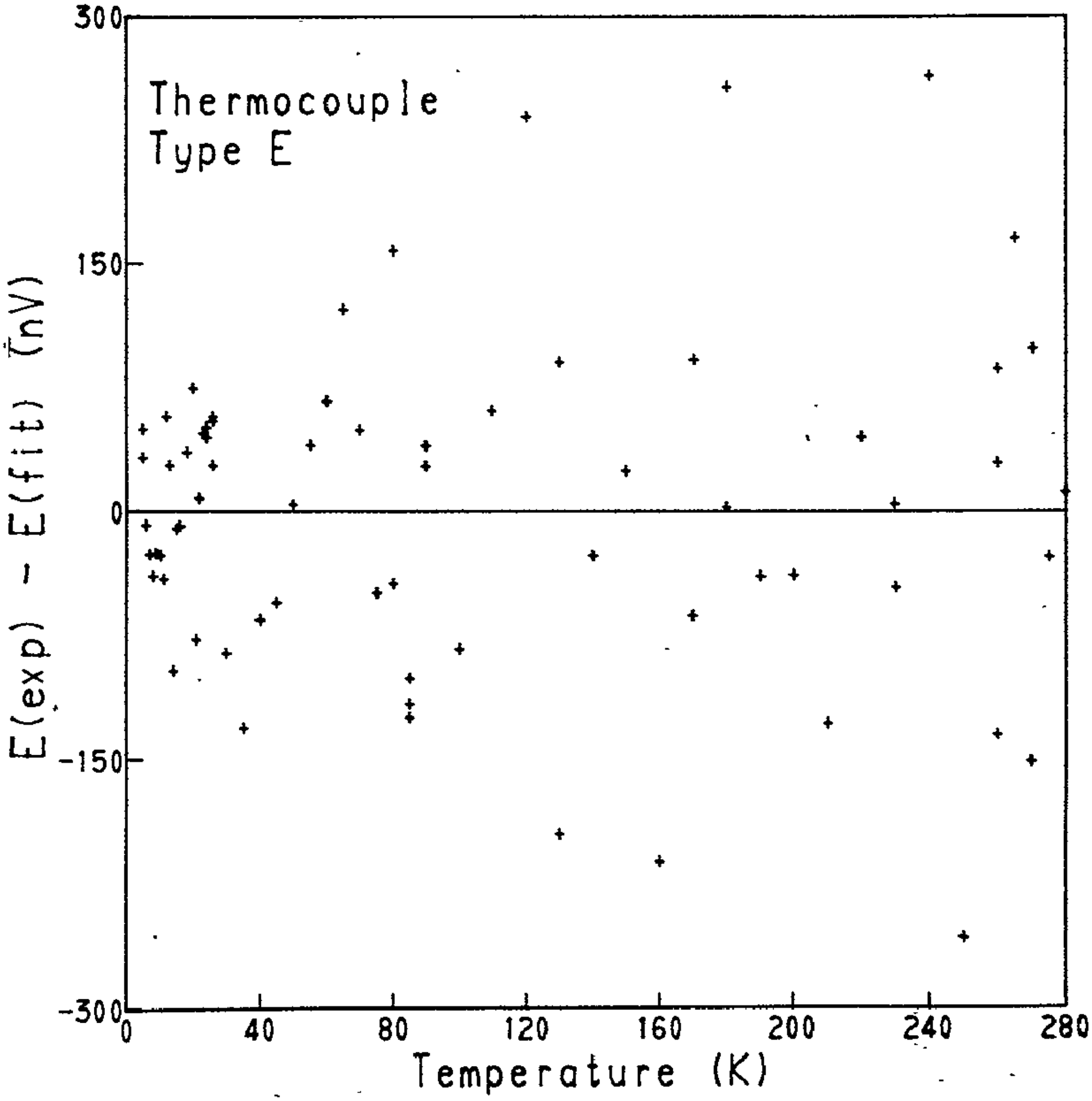

Figure E-2 Deviations between calculated and experimental values for thermocouple type E.

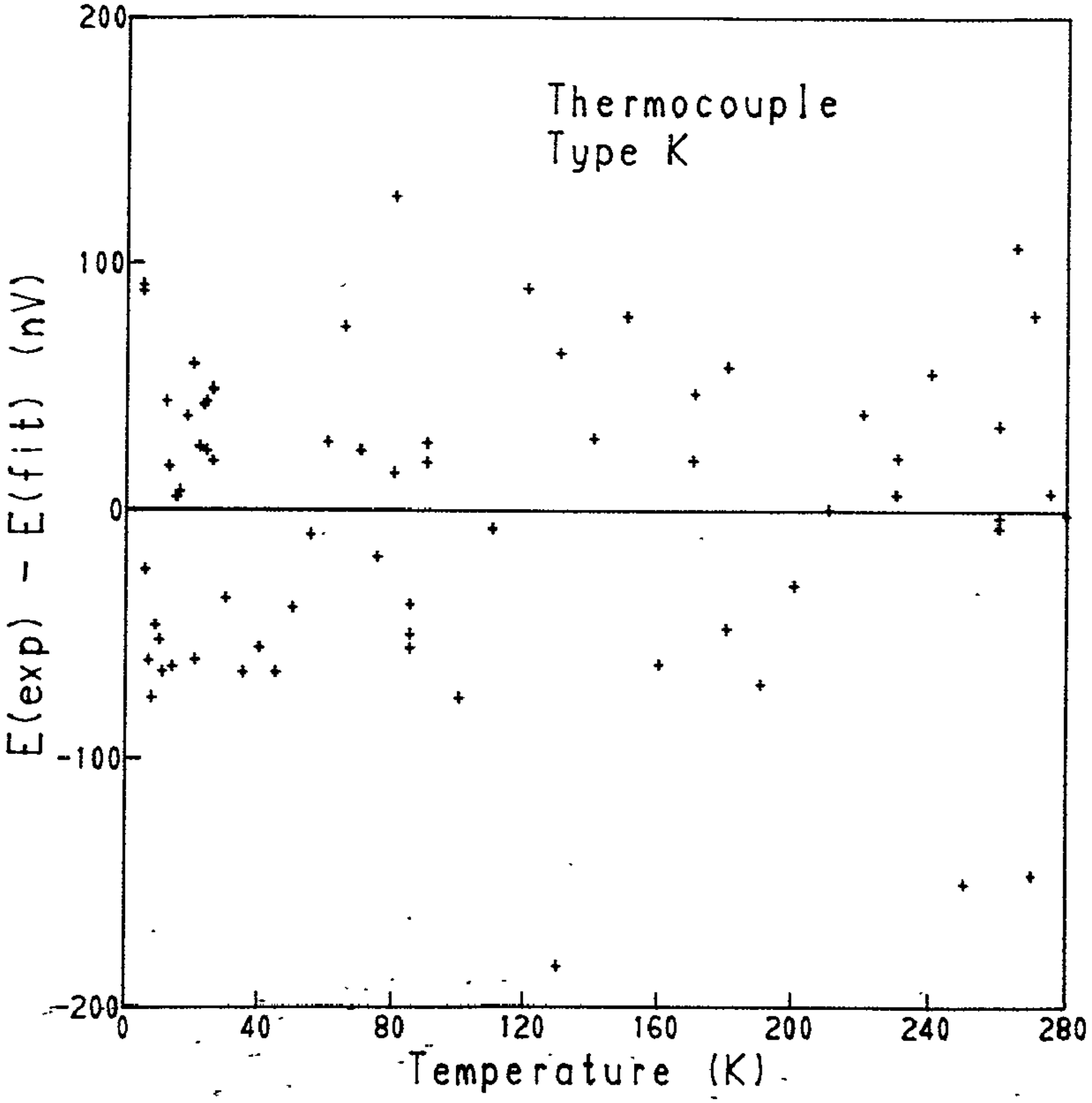

Figure E-3 Deviations between calculated and experimental values for thermocouple type K.

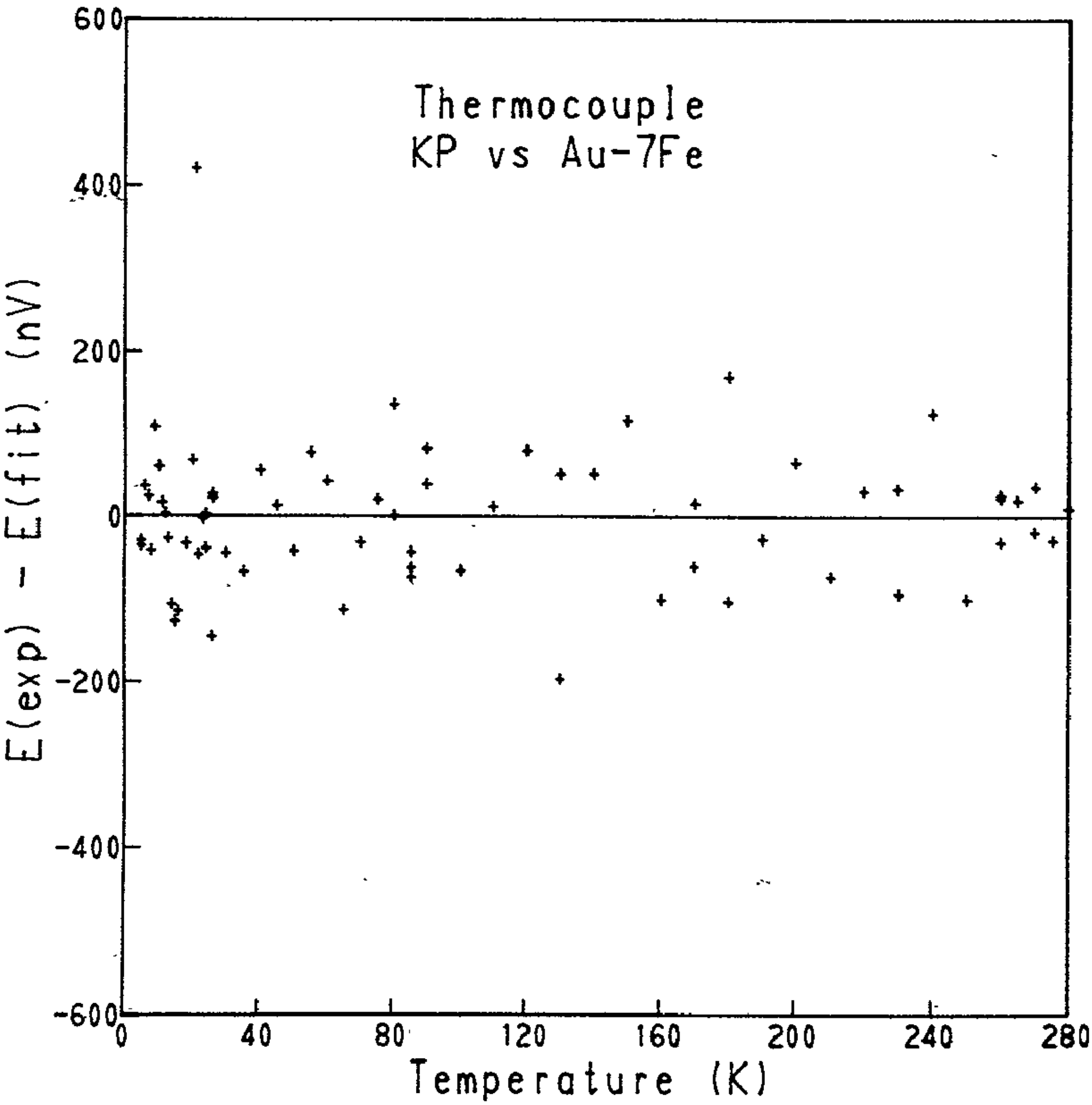

Figure E-4 Deviations between calculated and experimental values for Chromel versus Au-0.07 at.% Fe.

In addition to the errors caused by imprecisions of data fitting, other errors can be introduced by inaccuracies in measurement of the independent variable, temperature. These are approximately 2.2 mK between 4 and 20 K, 2.5 mK between 20 and 75 K, and 2.0 mK between 75 and 280 K. The equivalent voltage inaccuracies, given in table E-5, will depend on the sensitivities of each thermocouple type in each temperature range. Only above about 80 K do the temperature errors cause greater equivalent voltage errors than does the curve fitting.

Table E-5

Equivalent voltage errors caused by temperature inaccuracies

Temperature Range	Voltage Inaccuracies (in microvolts) for Thermocouple			
	Type T	Type E	Type K	KP vs Au-7Fe
LHe	0.01	0.02	0.01	0.03
LH_2	0.06	0.09	0.06	0.14
LN_2	0.30	0.46	0.31	0.22

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