RB-104

VAPOR PRESSURE DATA FOR THE MORE COMMON ELEMENTS

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The most recent data available concerning vapor pressures, melting and boiling points, and heats of sublimation have been selected, tabulated, and plotted for 57 elements, many of which are of special interest to workers in the fields of electronics and high vacuum technique. It has been found convenient to present vapor pressure data graphically as plots of *log p (mm Hg) vs. log T (°K)*, and also to tabulate the absolute temperatures for given pressures. This collection contains data published or available before March 1, 1957.

Introduction

In 1948, R. R. Law[1] published vapor pressure data for some 30 substances, presenting all information graphically on a single sheet as curves of *log p vs. log T*. Since the data used by Law were all of pre-war vintage, a new edition of the chart was prepared in 1954. This was based on the table found in Brewer's review article "The Thermodynamic and Physical Properties of the Elements"[2] and contains data up to 1948.

In the intervening years, a large volume of new information has come into existence, and the need for an up-to-date collection of vapor pressure data has become more and more pronounced. In 1955, E. Goldman[2b] published a collection of vapor pressure data of various metals and alloys. It was, however, largely based on prewar information and presented the data on a plot of *log p vs. T*. The present review, begun in December 1956, was initially based largely on the 1955 edition of "Metallurgical Thermochemistry" by Kubaschewski and Evans[3] as well as a comprehensive literature search carried out by the author. Upon completion of the first version, two unpublished compilations of data, by Stull and Sinke[4] and by Hultgren[5], became available which contained critical evaluations of data up to and including 1956. The present review is largely based on the three collections mentioned above.

Data

Presentation

Vapor pressure data may be presented very succinctly with the help of the equation

$$\log_{10} p = A\,T^{-1} + B \log_{10} T + C\,T + D \qquad (1)$$

where

p = pressure, given here as mm Hg
T = absolute temperature in °K
A, B, C, D = coefficients characteristic of element.

In this system, employed by Kubaschewski and Evans[3], the coefficients are readily tabulated in a minimum of space, but the evaluation of pressures for a given set of temperatures is quite cumbersome. The converse process – finding temperatures corresponding to given pressures – can only be done by trial and error and usually requires the service of a computing machine.

A more useful way of presenting vapor pressure data is to tabulate pressures corresponding to fixed temperatures, as was done by Stull and Sinke[4], or to quote temperatures for given pressures. Both systems of tabulation were employed by Hultgren[5]. In general, we are interested in the pressure range from 10^{-8} to 760 mm Hg for all elements; the corresponding temperatures lie anywhere between 0 and about 5000 degrees K. If curves are to be drawn from such tabulations, it is found that the points will be suitably spaced if pressure decades are employed. For this reason, temperatures have been tabulated at fixed pressures in the present bulletin.

Vapor pressure curves are usually presented as plots of *log p vs. 1/T*, largely because the resulting curves are straight lines over a limited temperature range and have slopes which directly yield heats of vaporization. Unfortunately, this type of temperature scale compresses the high temperature end so much that it is not feasible to present many vapor pressure curves on the same sheet over a wide temperature range. From a practical standpoint, the *log p vs. log T* plots, first introduced by Law,[1] are by far the most suitable and are employed in this bulletin.

Selection and Treatment

A compilation of this type is based on the data of many workers who measured vapor pressures by different techniques under widely differing experimental conditions. Thus, it is often very difficult to choose between two apparently equivalent sets of results, and at times the preference expressed may be subjective and arbitrary. Still, every effort has been made to include data, based on reliable experimental measurements, for those elements that are of some practical importance. The only exceptions are iridium, palladium and rhodium for which there exist, to date, only estimates.

The vapor pressure data available from the three major collections[3,4,5] were compared graphically by plotting *log p vs. log T*. Kubaschewski and Evans'[3] data, given as the coefficients of Eq. (1), were first converted into a tabulation of temperatures corresponding to fixed pressures with the help of a computing machine. They were then entered on the *log p vs. log T* plots, and smooth curves drawn through the points. Stull and Sinke[4] in their very complete and thorough collection tabulated vapor pressures as log_{10} *p (in atm)* at fixed temperatures. These data could be put directly on the *log p vs. log T* plots with the help of a special scale. Hultgren's data[5] for selected metals, tabulated as temperatures at fixed pressures (in atm) could be plotted directly.

Data based on Kubaschewski and Evans' collection[3] and on a literature search made by the author had already been plotted when the other two compilations became available. The curves were left unchanged wherever the pressures agreed with the other two sources to within about 20 percent, which is the accuracy to be expected from vapor pressure measurements. Where there were larger discrepancies, preference was usually given to the evaluations of Hultgren[5] and Stull and Sinke[4]. It was felt that Hultgren's evaluation of a few selected metals was likely to be somewhat more thorough than Stull and Sinke's collection covering most of the elements, and that either was preferable to the extensive but less up-to-date collection by Kubaschevski and Evans who treated most of the elements and many compounds. From the curves mentioned above, the temperatures corresponding to fixed pressures were read off and tabulated.

For those elements having two or more important gaseous species of known concentrations, total vapor pressure curves were obtained by summing the individual curves graphically. These have been marked with a "Σ" preceding the chemical symbol. In those cases where the atomic species is known to be the predominant contributor to the total vapor pressure, contributions from molecular species were neglected and the symbol given without any subscript. For the few elements that consist largely of one molecular species, the appropriate subscript has been added.

Results

Table I presents the vapor pressure data, the melting and boiling points, the temperature range (where available) over which the original experimental data were obtained, and the literature references. The uncertainty in pressure considered tolerable, ± 20 percent, corresponds to a temperature uncertainty of between 1 and 2 percent. To simplify matters, temperatures have been tabulated to three figures between 100 and 1000 degrees K, to the nearest 5 degrees between 1000 and 2000 degrees K, and to the nearest 10 degrees above 2000 degrees K, which corresponds to the smallest increments that can be read on the graph. Thus it should be remembered that the last figure quoted is not always significant. In the reference column, the three collections rather than the original articles have been quoted, thereby avoiding the repetition of a very extensive bibliography.

Figs. 1(a) and 1(b) present the vapor pressure data in graphical form. The curves were placed on two separate sheets in such a way as to minimize interference. The circled point shown on most curves is the melting point. Where the melting point falls outside the pressure range of the graph, the letters "s" (solid) or "1" (liquid) have been appended to the chemical symbol. The last column of Table I indicates on which sheet a given element will be found.

In Table II have been collected the most recent values available for the heats of sublimation, ΔH_{298}, quoted for the individual elemental species at 298 degrees K. These heats are of considerable practical interest because they are a measure of lattice energies. The accuracy of the values quoted in this bulletin lies somewhere between ± 0.01 and 10 kcal/mole. It was often difficult to make objective assessments of the limits of accuracy in some of the quoted references and in others it was not available for all entries. For this reason, estimated errors have not been tabulated, but indications of accuracy may be had from the number of significant figures given.

Discussion

Every effort has been made to include in this collection of vapor pressure data all information available as of March 1, 1957. It is expected that this collection will be kept up-to-date with the issuance of additions and corrections at suitable intervals.

Aside from the three entries where data are based on estimates (iridium, palladium and rhodium), there are three elements that need to be discussed: silicon, aluminum and uranium. The vapor pressure data presented for

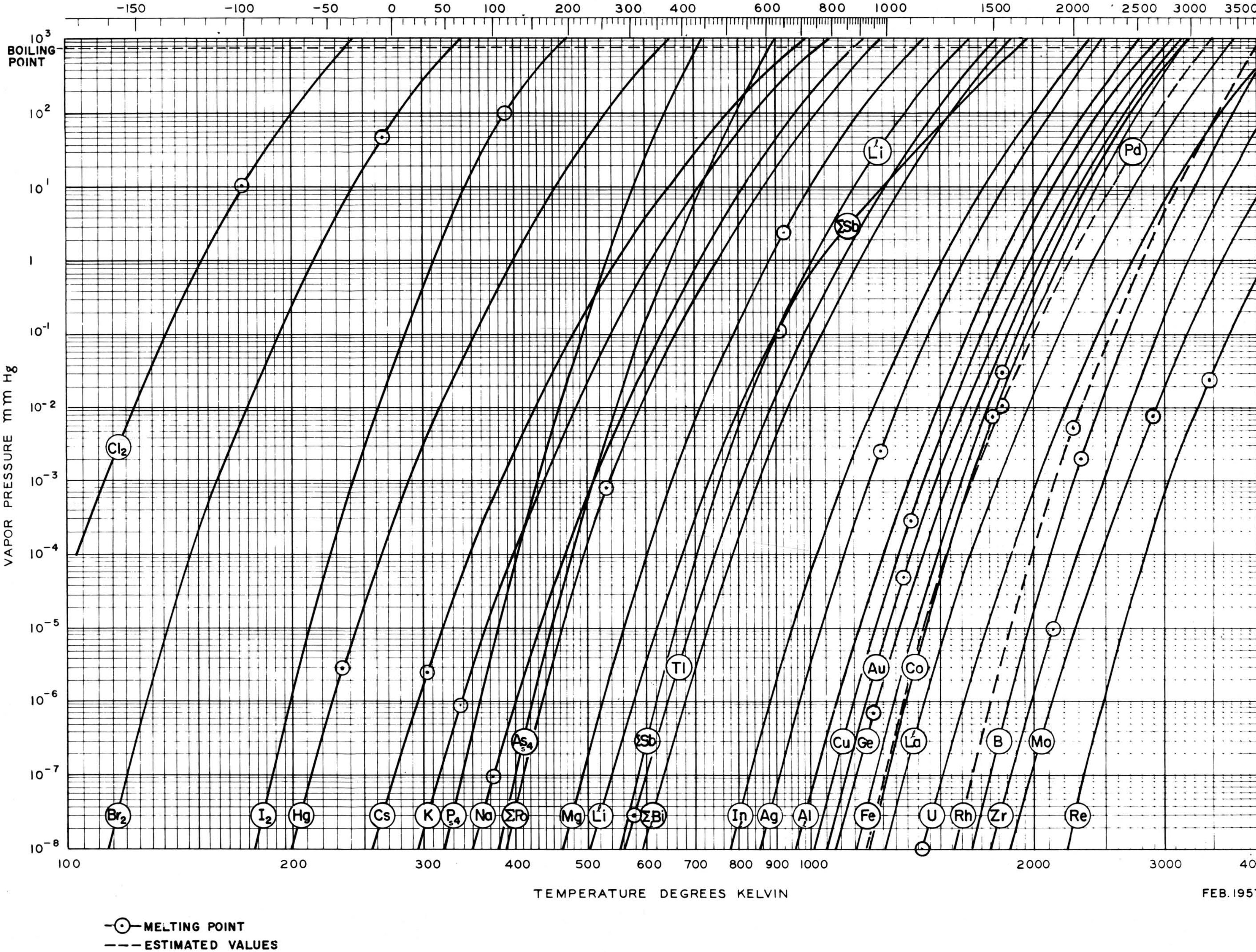
VAPOR PRESSURE DATA AND MELTING AND BOILING POINTS FOR THE MORE COMMON ELEMENTS

SYMBOL	ELEMENT	DATA TEMP. RANGE °K	M.P. °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (mm Hg)											B.P. °K	REF.	CURVE SHEET
				10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10^{1}	10^{2}			
Ag	SILVER	994-1273	1234	852	903	961	1030	1105	1195	1305	1440	1610	1830	2120	2435	3,4,5	A
Al	ALUMINUM	1410-1468	932	950	1010	1080	1155	1245	1355	1480	1620	1820	2050	2350	2720	3,4	A
As_4	ARSENIC		1090	377	400	423	447	477	510	550	590	645	710	790	886	4	A
Au	GOLD	1000-1260	1336	1045	1115	1180	1260	1355	1470	1605	1780	1980	2240	2580	2982	4,5	A
B	BORON		2300	1650	1735	1850	1960	2100	2250	2430	2650	2930	3300	3730	4200	4	A
Ba	BARIUM	1333-1411	983	560	600	640	690	740	810	900	1000	1140	1310	1570	1910	4	B
Be	BERYLLIUM	1172-1552	1556	972	1030	1100	1175	1260	1365	1485	1640	1840	2060	2370	2750	3,4	B
ΣBi	BISMUTH	682-770	544	590	629	672	723	781	851	934	1035	1165	1330	1555	1832	3,4	A
Br_2	BROMINE		266	113	120	128	137	147	159	174	192	214	243	282	331	3,4	A
ΣC	CARBON			1950	2030	2140	2250	2380	2520	2700	2900	3140	3420	3800	(4200)	4	B
Ca	CALCIUM	800-920	1123	555	590	630	675	725	790	865	960	1090	1240	1480	1765	4	B
Cd	CADMIUM	473-533	594	346	368	393	422	455	494	540	594	665	759	883	1038	3,4,5	B
Cl_2	CHLORINE		172					103	112	123	136	153	172	201	239	4	A
Co	COBALT	1363-1522	1768	1200	1265	1345	1435	1535	1650	1790	1970	2180	2440	2770	3150	3,4	A
Cr	CHROMIUM	1162-1561	2176	1125	1180	1250	1335	1435	1540	1665	1830	2010	2240	2550	2938	4,5	B
Cs	CESIUM		303	256	274	295	319	348	383	425	479	550	646	786	958	3,4	A
Cu	COPPER	1242-1879	1357	1005	1065	1135	1215	1305	1415	1545	1700	1895	2140	2460	2851	3,4,5	A
Fe	IRON	1356-1519	1812	1150	1220	1290	1380	1480	1595	1740	1910	2120	2370	2710	3130	5	A
Ga	GALLIUM	1230-1518	310	845	899	961	1030	1115	1210	1330	1470	1645	1870	2170	2510	3,4	B
Ge	GERMANIUM	1510-1885	1210	1085	1150	1225	1310	1415	1535	1680	1855	2070	2350	2710	3100	3,4	A
Hg	MERCURY		234	199	213	228	245	265	289	318	354	398	456	534	630	3,4	A
I_2	IODINE		387	178	188	199	212	226	242	262	285	312	345	388	456	3,4	A
In	INDIUM	1000-1348	429	770	820	877	943	1020	1110	1220	1350	1515	1730	2010	2364	3, 5	A
Ir	IRIDIUM	EST.	2727	1720	1840	1950	2070	2220	2380	2580	2800	3100	3440	3900	(4400)	4	B
K	POTASSIUM	373-1033	337	294	314	337	364	396	435	481	539	614	715	857	1039	3,4	A
La	LANTHANUM	1600-1900	1193	1260	1330	1430	1535	1650	1800	1970	2170	2420	2730	3180	3640	4	A
Li	LITHIUM	732-1353	454	505	539	577	621	672	733	806	896	1010	1155	1355	1604	3,4	A
Mg	MAGNESIUM	1009-1293	923	462	490	524	560	603	655	715	790	885	1000	1175	1377	4,5	A

SYMBOL	ELEMENT	DATA TEMP. RANGE °K	M.P. °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (mm Hg)											B.P. °K	REF.	CURVE SHEET
				10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10^{1}	10^{2}			
Mn	MANGANESE	EST.	1517	807	855	910	970	1040	1125	1220	1340	1500	1700	1975	2324	4,5	B
Mo	MOLYBDENUM	2070-2504	2850	1855	1970	2110	2260	2440	2650	2900	3200	3570	4040		5100	3,4	A
Na	SODIUM	537-1201	371	350	373	400	431	468	511	563	628	710	818	967	1163	3,4	A
Nd	NEODYMIUM		1297	1005	1070	1150	1230	1335	1465	1615	1810	2050	2370	2800	3360	4	B
Ni	NICKEL	1307-1583	1725	1185	1260	1330	1415	1520	1630	1770	1940	2150	2400	2750	3112	4,5	B
P_4	PHOSPHORUS		870	320	335	355	380	403	430	460	495	535	580	640	704	4	A
Pb	LEAD		601	617	658	705	760	824	900	992	1105	1250	1435	1695	2024	3,4	B
Pd	PALLADIUM	EST.	1823	1180	1255	1330	1430	1535	1660	1820	2000	2240	2560	2940	3400	4	A
ΣPo	POLONIUM	711-1018	527	387	408	432	460	493	536	587	655	745	860	1025	1235	4	A
Pt	PLATINUM		2043	1560	1650	1755	1875	2015	2180	2350	2590	2860	3210	3630	4100	4	B
Rb	RUBIDIUM		312	270	288	312	337	368	406	449	501	573	665	800	974	4	B
Re	RHENIUM		3453	2200	2330	2480	2640	2830	3060	3330	3670				5900	4	A
Rh	RHODIUM	EST.	2239	1550	1640	1745	1860	1980	2130	2300	2520	2800	3120	3530	(4000)	4	A
ΣS	SULFUR		392	241	256	272	291	313	339	370	408	456	519	606	717	3,4	B
ΣSb	ANTIMONY		903	550	580	615	655	700	750	815	890	1030	1250	1570	1910	4	A
ΣSe	SELENIUM		490	357	375	394	417	440	470	505	550	620	702	820	958	4	B
ΣSi	SILICON		1688	1200	1270	1355	1450	1555	1680	1820	1990	2200	2430	2740	3060	11	B
Sn	TIN	1424-1688	505	937	999	1070	1155	1250	1365	1500	1670	1885	2160	2540	2952	3,4,5	B
Sr	STRONTIUM		1043	499	533	571	615	667	729	804	896	1015	1170	1380	1640	3,4	B
Ta	TANTALUM	2000-3270	3270	2230	2360	2510	2670	2860	3080	3340	3645	4010			5700	3,4	B
Te_2	TELLURIUM		723	451	476	503	534	569	609	656	711	793	906	1065	1260	3,4	B
Ti	TITANIUM	1587-1764	1945	1330	1415	1500	1600	1715	1850	2000	2200	2450	2750	3130	3559	5	B
Tl	THALLIUM		577	558	595	637	685	741	808	888	986	1110	1270	1480	1740	3,4	A
U	URANIUM	1630-1970	1403	1405	1495	1600	1715	1855	2010	2200	2430	2720	3070	3540	4200	3,4	A
V	VANADIUM	1662-1882	2130	1428	1510	1600	1705	1824	1960	2120	2310	2560	2840	3220	3650	3,4	B
W	TUNGSTEN		(3650)	2340	2480	2640	2820	3030	3280	3570	3915				5800	3,4	B
Xe	XENON		161									105	120	140	165	4	B
Zn	ZINC	512-650	693	396	421	449	481	519	563	615	678	758	864	1005	1179	3,4,5	B
Zr	ZIRCONIUM	1949-2054	2125	1745	1850	1975	2110	2275	2460	2670	2920	3250	3620		4688	5	A

VAPOR PRESSURE CURVES FOR THE MORE COMMON ELEMENTS

SHEET A



VAPOR PRESSURE CURVES FOR THE MORE COMMON ELEMENTS

SHEET B

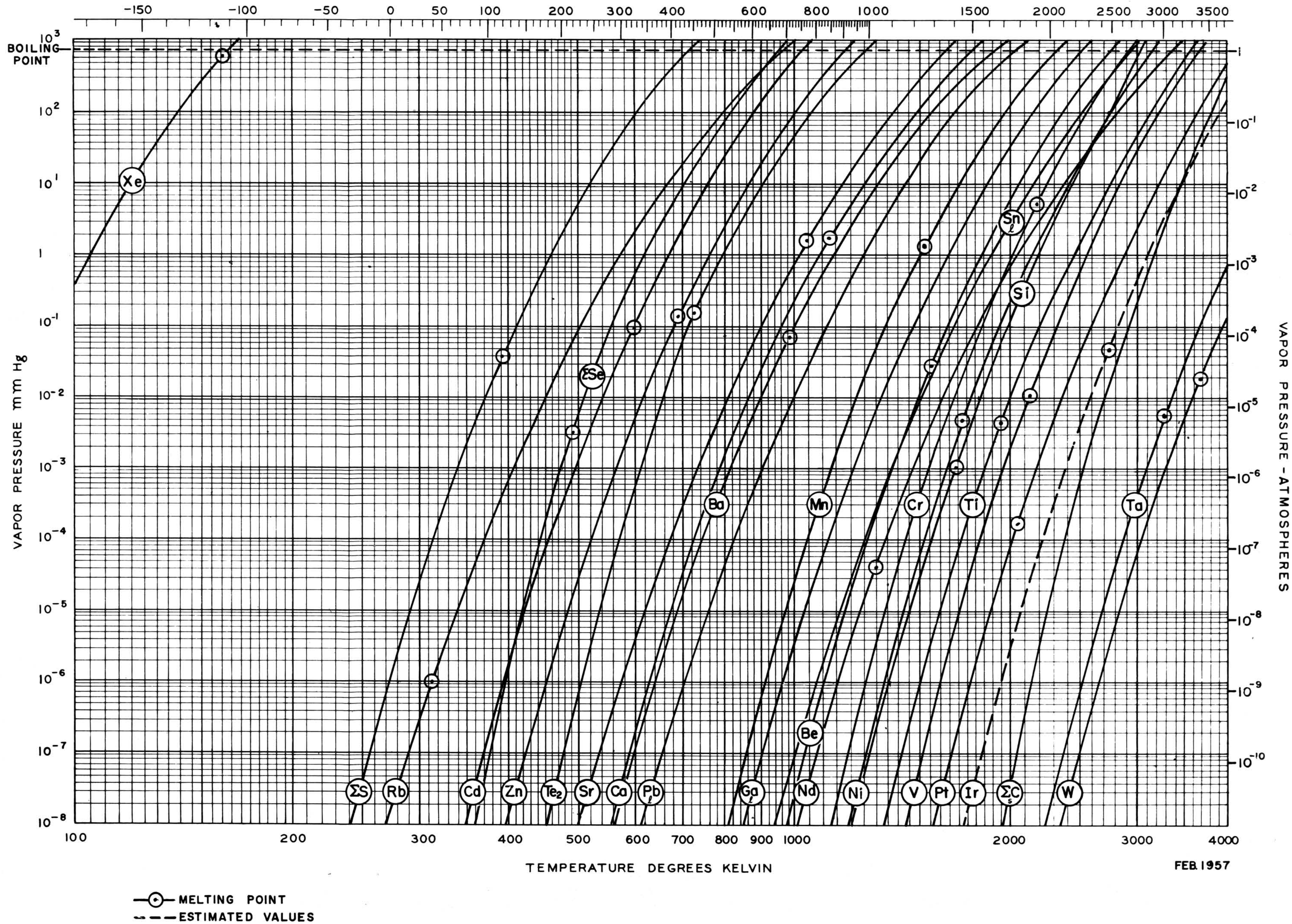


TABLE II

HEATS OF SUBLIMATION OF ELEMENTAL SPECIES AT 298°K

SPECIES	ΔH_{298} kcal/mole	REF.	SPECIES	ΔH_{298} kcal/mole	REF.	SPECIES	ΔH_{298} kcal/mole	REF.
Ag_1	68.2	5	Ge_1	92	7	Re_1	187	6
Ag_2	99	8	Ge_2	119	9	Rh_1	(133)	4
Al_1	77.5	4,7	Hg_1	14.65	4,7	S_1	57.5	7
As_1	>69	4	Hg_2	27.4	7	S_2	30.8	4,7
As_2	>48	4	I_2	14.88	4,7	S_4	28	7
As_4	34.5	4,7	In_1	57	4,7	S_6	28	7
Au_1	84.7	5	Ir_1	(150)	4	S_8	24.4	4,7
Au_2	119	8	K_1	21.42	4	Sb_1	63	7
B_1	141	4,7	K_2	30.6	4	Sb_2	56	7
B_2	213	7	La_1	100	4,7	Sb_4	49	7
Ba_1	41.7	4	Li_1	38.44	4	Se_1	49.4	4
Be_1	77.9	4	Li_2	50.5	4	Se_2	34.1	4
Bi_1	47.5	4	Mg_1	35.4	5	Se_6	35.4	4
Bi_2	55.3	4	Mn_1	67.1	5	Si_1	105	7
Br_2	7.45	4	Mo_1	157.5	4	Si_2	138	9
C_1	170.9	7	Na_1	25.85	7	Sn_1	72.0	5
C_2	200	9	Na_2	33.4	7	Sn_2	96	9
C_3	190	10	Nd_1	76.8	4	Sr_1	39.1	4
Ca_1	42.3	4,7	Ni_1	101.2	5	Ta_1	186.8	4
Ca_2	79	7	P_1	80	4	Te_1	46.5	4
Cd_1	26.78	5	P_2	42.7	4	Te_2	39.6	4
Cd_2	50.8	7	P_4	30.8	4	Ti_1	112.8	5
Cl_2	4.878 (@ 239°K)	4	Pb_1	46.8	4	Tl_1	43	4
Co_1	101.6	4	Pb_2	71	9	U_1	117.2	4
Cr_1	94.9	5	Pd_1	(94)	4	V_1	122.7	4,7
Cs_1	18.7	4	Po_1	34.5	4	W_1	200	4
Cs_2	26.6	4	Po_2	32.9	4	Xe_1	3.02 (@ 165°K)	4
Cu_1	81.0	5	Pt_1	134.8	4	Zn_1	31.22	5
Cu_2	115	8	Rb_1	19.6	4	Zn_2	56	7
Fe_1	99	7	Rb_2	27.6	4	Zr_1	146	4,5
Ga_1	65	4						

silicon were obtained by this author by an indirect method[11]. Recent, measurements of silicon carbide by Searcy seem to have yielded[6,12] a silicon pressure of 1.6×10^{-6} mm Hg at 1500 degrees K (about 10 times lower than the present value) and ΔH_{298} = 113 kcal/mole, but to date no further experimental data or details have been received. The data for aluminum are based on a study by Brewer and Searcy[13] who used beryllium oxide and tantalum carbide crucibles and observed considerable scattering of points. If the tantalum carbide results may be discarded, and if the effects of BeO-Al interaction are negligible, as suggested by Brewer[6], then their data are much more consistent and will yield ΔH_{298} = 78.4 kcal/mole. The vapor pressures given for uranium in Table I are consistent with ΔH_{298} = 117.2 kcal/mole, as quoted in Table II. The heat of sublimation preferred by Brewer is ΔH_{298} = 122.7 kcal/mole.

Wall-size charts (17" × 22") of the vapor pressure curves [Figs. 1(a) and 1(b)] are available from the Industry Service Laboratory, New York.

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