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Thermodynamic Properties of Aluminum

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This work reviews and discusses the data on the thermodynamic properties of aluminum available through May 1984. However, two papers dated 1985 which are useful to this work are also included. These properties include heat capacity, enthalpy, enthalpy of transition and melting, vapor pressure, and enthalpy of vaporization. The recommended values for heat capacity cover the temperature range from 0.1 to 2800 K. The recommended values for enthalpy, entropy, Gibbs energy function, and vapor pressure cover the temperature range from 298.15 to 2800 K.

KEY WORDS: aluminum; critical evaluation; enthalpy; enthalpy of transition; enthalpy of melting; enthalpy of vaporization; entropy; Gibbs energy function; heat capacity; recommended values; vapor pressure.

1. INTRODUCTION

The principal objective of this work is to critically evaluate and analyze available data and information on the heat capacity, enthalpy, and vapor pressure of aluminum and to generate the recommended values of these and other thermodynamic properties from 298.15 to 2800 K. The recommended values for heat capacity are reported from 0.1 to 2800 K.

The general background information of this investigation is given in Sect. 2 for both heat capacity and vapor pressure. The discussion of the thermodynamic properties and the details of data analysis are reported in Sect. 3.

It is worth noting that the effect of conversion to IPTS-68 on these properties is well within the uncertainties of these values. The measurements on the thermodynamic properties which have been carried

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out on the International Practical Temperature Scale of 1948 or 1958 were not converted to IPTS-68. The value of the gas constant, $R = 8.31441\ \mathrm{J \cdot mol^{-1} \cdot K^{-1}}$, is used in all calculations.

2. GENERAL BACKGROUND

Thermodynamic properties in general may be divided into the following categories:

1. low-temperature ($T < 298.15$ K) heat capacity, C_p°;
2. high-temperature ($T > 298.15$ K) heat capacity, C_p°;
3. high-temperature enthalpies, $H^\circ(T) - H^\circ$ (298.15 K);
4. ideal-gas properties; and
5. vapor pressure.

2.1. Low-Temperature Heat Capacity

The heat capacity of pure metals at low temperature is composed, in the absence of phase transformations or magnetic effects, of electronic and lattice-vibrational contributions. The electronic contribution which is proportional to T in the simplest model persists to the lowest temperatures that can be achieved experimentally. Toward higher temperatures it increases less rapidly than the lattice-vibrational contribution. For many metals it has been shown that near 0 K,

$$C_p^\circ = \gamma T + \beta T^3 \qquad (1)$$

where γT is the electronic contribution (electronic specific heat) and βT^3 is the lattice-vibrational contribution. A plot of C_p° / T versus T^2 enables one to identify these contributions at low temperatures.

2.2. High-Temperature Heat Capacity

The measurements in this temperature range encounter difficulties because the radiant heat-exchange coefficient increases as T^3. Commonly used methods are adiabatic calorimetry, differential scanning calorimetry, and the electric-pulse method. One of the results of such measurements is the rise in C_p° observed near the melting point. Earlier, impurities in the specimen were blamed for such a rise. However, a lesser rise was clearly indicated later on very pure samples. The enthalpy of the liquid state has been accurately measured for only a few metals.

2.3. High-Temperature Enthalpies

The usual method for measuring relative enthalpies is by "drop calorimetry." The C_p° can be calculated from smoothed enthalpy data using $C_p^\circ = d[H^\circ(T) - H^\circ(298.15\text{ K})]/dT$. These types of calculations involve small differences between large numbers and hence reduce the accuracy to some extent.

In this investigation the procedure was adopted to plot the average heat capacity, hereafter called the y function, versus temperature:

$$y(T) = [H^\circ(T) - H^\circ\,(298.15\text{ K})]/(T - 298.15) \tag{2}$$

The advantage of this method is that $y(T)$ does not change rapidly with T. This makes it easier to plot with precision on graph paper of a reasonable size. However, "anomalies" in C_p°, such as those near magnetic transitions, are poorly defined in this procedure and may be missed altogether.

Once the function $y(T)$, which best represents the average heat capacity data, has been chosen, C_p° values can be calculated from the relation

$$C_p^\circ = y(T) + (T - 298.15)\frac{dy}{dT} \tag{3}$$

Values of relative enthalpy $[H(T) - H(298.15\text{ K})]$ are calculated from $y(T)$ using Eq. (2).

In order to obtain a reliable and consistent set of thermodynamic functions, the procedure followed in this work is somewhat different from the one generally used. Both C_p° and enthalpy obtained from the literature are treated simultaneously. Rather than averaging all the values with equal weight, C_p° and enthalpy (y-function) data are plotted on fairly large-size paper and the recommended curve is drawn by giving the highest weight to those measurements that have been carried out on the best-characterized samples using the most reliable techniques. In some cases it was necessary to adjust either C_p° or the preliminary recommended enthalpy values in order to obtain C_p° values consistent with the experimental enthalpy data. Slopes of the C_p° and enthalpy curves reported by individual investigators were also taken into account in the final analysis. C_p° values were further smoothed by a computer using the least-squares method.

An excellent check is available because the C_p° values thus obtained can be integrated to yield $H^\circ(T) - H^\circ(298.15\text{ K})$ values. Also from the C_p° values, values of $S^\circ(T) - S^\circ(298.15\text{ K})$ can be calculated by integration of C_p°/T values. Combining $S^\circ(T) - S^\circ(298.15\text{ K})$ and $H^\circ(T) - H^\circ(298.15\text{ K})$ values with $S^\circ(298.15\text{ K})$ generated from the low-temperature data yield values for the Gibbs energy function, $[G^\circ(T) - H^\circ(298.15\text{ K})]/T$.

For liquid metals, a constant C_p° is often assumed (as in the present work) since enthalpy data usually cover a small temperature range. The entropy of melting ($\Delta_{\rm fus}S^\circ$) is calculated from the enthalpy of melting ($\Delta_{\rm fus}H^\circ$) value.

2.4. Ideal-Gas Properties

These properties are obtained from statistical calculations using the electronic energy levels. Most metallic elements produce monatomic vapors. The principal electronic energy levels for most elements are well established. New studies have also added many more levels.

2.5. Vapor Pressure Data

The Clausius–Clapeyron equation provides a test of internal consistency for vapor pressure measurements which is known as the Second Law test:

$$d \ln p/d(1/T) = -\Delta_{\rm vap}H^\circ/R \tag{4}$$

Since $\Delta_{\rm vap}H^\circ$ often changes only a little when the temperature range covered in the measurements is limited, a plot of $\ln p$ versus $1/T$ should give a straight line whose slope determines the $\Delta_{\rm vap}H^\circ$ value in that temperature range. In practice, nonlinear behavior of $\ln p$ with $1/T$ may indicate the need for rejectig an entire (p, T) data set. Also, systematic errors may shift the slope ($\Delta_{\rm vap}H^\circ$) drastically without changing the linearity of the plotted experimental data. Since $\Delta_{\rm vap}H^\circ$ is used to calculate vapor pressures at temperatures beyond the measured range, this kind of error in determining the slope may result in erroneous vapor pressure values.

Another, more stringent, self-consistency test known as the Third Law test is often used:

$$\Delta_{\rm sub}H^\circ(298.15\ {\rm K}) = -T\Delta\{[G^\circ(T) - H^\circ(298.15\ {\rm K})]/T\} - RT \ln p \tag{5}$$

The $\Delta_{\rm sub}H^\circ(298.15\ {\rm K})$ value can be calculated from the vapor pressure measurement at a given temperature. Any systematic error can be spotted from the temperature trend shown by $\Delta_{\rm sub}H^\circ(298.15\ {\rm K})$ values. In actual practice, in many cases, these values deviate remarkably from one another; but they do not show a temperature trend, so that satisfying the Third Law test will not ensure accurate vapor pressure values.

Most vapor pressure measurement techniques such as Langmuir, Knudsen, and torsion-effusion methods are valid only at low pressures, where gases behave ideally. Vapor pressure calculations assume that gases remain ideal to the boiling point. For higher-boiling metals, the difference between the true boiling point and that predicted by the above calculations should be smaller.

3. THERMODYNAMIC PROPERTIES OF ALUMINUM

3.1. Phases and Structures

Aluminum has an fcc (A1) structure isotypic with Cu. Its atomic weight is 26.98154 and its melting point is 933.61 K based on IPTS-1968 [1]. It is a superconductor below $T_c = 1.160 \pm 0.01$ based on the C_p° measurements of Phillips [2]. Other measurements of T_c are listed in Table I.

3.2. Low-Temperature Heat Capacity

There have been numerous measurements of the electronic heat capacity coefficient, γ. The recommended value was based on the values of Phillips [2], Harris and Mapother [4], Hartman et al. [11], and Harris [16]. These and other literature values are listed in Table II.

The recommended values (nonsuperconducting) below 4 K are based on the measurements of Phillips [2], Gobrecht and Saint-Paul [3], Hopkins [6], Kok and Keesom [10], Berg [13], and Dixon et al. [14]. The recommended values from 4 to 298.15 K are based on the data of Hopkins [6], Kok and Keesom [10], Berg [13], Giauque and Meads [19], Griffiths and Griffiths [20], Maier and Anderson [23], and Downie and Martin [60]. The data of Makarounis [21] and Tsiovkin and Sukhanov [22] agree with the recommended values, while those of Krylovskii et al. [24] are up to 3% lower than the recommended values.

Recently, Downie and Martin [60] made very careful measurements of what they termed commercial “spec pure” aluminum samples. They left out some important information, however, such as purity (especially oxygen content) and heat treatment (especially annealing), which might account for their slightly lower C_p° values. We feel that more studies are required to corroborate their lower C_p° values, especially from 100 to 294 K.

The recommended C_p° value of 24.225 $\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$ at 298.15 K was based not only on the low-temperature data but also on the lower end of the high-temperature data and is slightly higher than those recommended by Chase [65] and used by Ditmars et al. [26], all of whom appear to

Table I. Superconducting Transition Temperature of Aluminum

Source	T_c (K)
Phillips [2]	1.160
Gobrecht and Saint-Paul [3]	1.150
Harris and Mapother [4]	1.1793 ± 0.003
Rorer et al. [5]	1.173
	1.183
	1.188
Hopkins [6]	1.180
Martin [7]	1.1715 ± 0.002
King [8]	1.168
Goodman [9]	1.180
Recommended value	1.160 ± 0.01

have given substantial weight to the data of Downie and Martin [60] and rejected completely the data of Giauque and Meads [19]. We do not feel that there is sufficient justification to ignore Giauque's work. The low-temperature data resulted in the thermodynamic quantities at 298.15 K listed in Table III.

For the superconducting state the recommended C_p° values are based on the data of Phillips [2]. The data of Hopkins [6] are about 3% higher, those of Goodman [9] are up to 0–10% higher from 0.5 to 0.8 K and

Table II. Electronic Specific Heat Coefficient of Aluminum

Source	$\gamma(\mathrm{mJ \cdot mol^{-1} \cdot K^{-2}})$
Phillips [2]	1.350 ± 0.0008
Harris and Mapother [4]	1.349 ± 0.0016
Kok and Keesom [10]	1.458
Hartman et al. [11]	1.351 ± 0.004
Dicke and Green [12]	1.362
Berg [13]	1.348
Dixon et al. [14]	1.360 ± 0.001
Zavaritskii [15]	1.270
Harris [16]	1.349 ± 0.015
Waki [17]	1.360
Howling et al. [18]	1.367
Recommended value	1.350 ± 0.001

Table III. Thermodynamic Constants of Aluminum at 298.15 K

Source	C_p° (J·mol^{-1}·K^{-1})	S° (J·mol^{-1}·K^{-1})	H° (J·mol^{-1})
Present work	24.225	28.246	4543
Ditmars et al. [26]	24.209	28.275	4540
Glushko et al. [51]	24.354	28.350	4565
Downie and Martin [60]	24.21	28.24	4535
Chase [65]	24.209	28.275	4540
Hultgren et al. [66]	24.351	28.326	4556

Table IV. Recommended Low-Temperature Heat Capacity of Aluminum[a]

T (K)	C_p° (J·mol^{-1}·K^{-1})	C_p° (J·mol^{-1}·K^{-1})	T (K)	C_p° (J·mol^{-1}·K^{-1})
0.1	0.000000837[b]	0.000135[c]	110.0	14.400
0.3	0.0000663[b]	0.000406[c]	120.0	15.637
0.5	0.000491[b]	0.000678[c]	125.0	16.187
1.0	0.00278[b]	0.00138[c]	130.0	16.697
1.16	0.00366[b]	0.00161[c]	140.0	17.615
2.0	0.00290		150.0	18.453
3.0	0.00472		160.0	19.190
4.0	0.00699		170.0	19.852
5.0	0.00986		175.0	20.157
6.0	0.0135		180.0	20.439
7.0	0.0177		190.0	20.968
10.0	0.0369		200.0	21.435
15.0	0.0982		210.0	21.840
20.0	0.223		220.0	22.203
25.0	0.456		225.0	22.369
30.0	0.837		230.0	22.530
40.0	2.064		240.0	22.828
50.0	3.827		250.0	23.101
60.0	5.800		260.0	23.358
70.0	7.776		270.0	23.600
75.0	8.745		273.15	23.672
80.0	9.690		280.0	23.832
90.0	11.424		290.0	24.052
100.0	12.996		298.15	24.225

[a] $C_{(\text{electronic})} = \gamma T$. $\gamma = 1.350 \pm 0.001$ mJ·mol^{-1}·K^{-2}.

	Crystal, Al(s)	Gas, Al(g)
$H^\circ(298.15\ \text{K}) - H^\circ(0\ \text{K})$	4543 ± 10 J·mol^{-1}	6919 ± 0.07 J·mol^{-1}
$S^\circ(298.15\ \text{K})$	28.25 ± 0.01 J·mol^{-1}·K^{-1}	164.444 ± 0.002 J·mol^{-1}·K^{-1}

[b] Superconductor.

[c] Nonsuperconductor in magnetic field.

trend to 20% lower above 0.8 K, while those of Goodman [25] agree well below 0.5 K and then trend to 7% lower near 1 K. The measurements of Martin [7] yield up to 5% lower values and those of Gobrecht and Saint-Paul [3] scatter ±3% around the recommended values.

Integration of the recommended C_p° values yields $H^\circ(298.15\text{ K}) - H^\circ(0\text{ K}) = 4543 \pm 10\text{ J}\cdot\text{mol}^{-1}$ and integration of the C_p°/T values yields $S^\circ(298.15\text{ K}) = 28.25 \pm 0.01\text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$. C_p° values are shown in Fig. 1 along with the experimental data and are tabulated in Table IV.

3.3. High-Temperature Heat Capacity (Solid)

The procedure followed to analyze the data in this temperature range (298.15–933.61 K) was to evaluate true (C_p°) and mean (y) heat capacity data simultaneously:

$$y(T) = [H^\circ(T) - H^\circ(298.15\text{ K})]/(T - 298.15\ K) \tag{6}$$

from which C_p° may be derived by differentiations:

$$C_p^\circ = y(T) + (T - 298.15)\frac{dy}{dT} \tag{7}$$

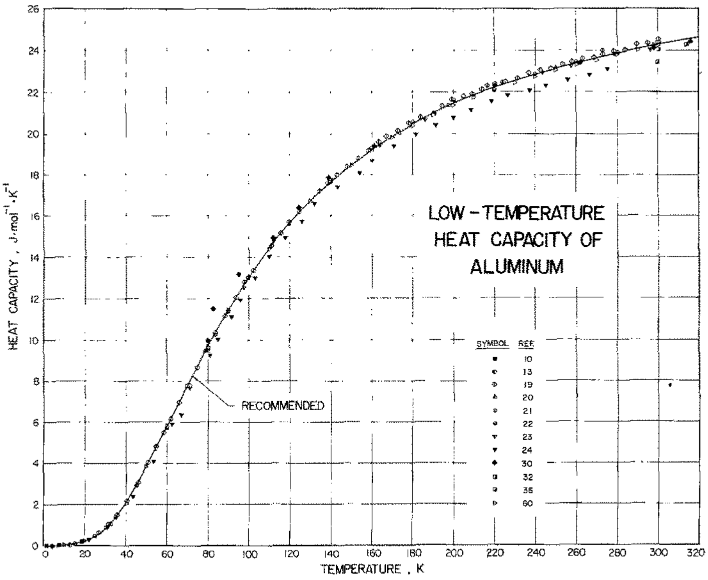

Fig. 1. Low-temperature heat capacity of aluminum.

Table V. Percentage Deviation in Enthalpy of Aluminum from Recommended Values Given in Table VII

Source	Deviation (%)
Ditmars et al. [26]	−0.6 to 0.1
Kendall and Hultgren [31]	−0.4 to −2
Marchidan and Ciopec [33]	±3
McDonald [34]	±2.5
Awbery and Griffiths [35]	±3
Wust et al. [37]	4 (<750 K) −1.5 (>750 K)
Seekamp [38]	−2
Eastman et al. [39]	0.1 to 2
Schubel [40]	−0.5 to −2
Umino [41]	1 to 4 (<500 K) −1 to −6 (>500 K)
Pochapsky [42]	−0.2 to −4

There has been an overall good agreement among various data reported in the literature. The recommended enthalpy values are based on the literature data, with substantial weight being given to the measurements of Ditmars et al. [26]. Agreement of enthalpy measurements reported in the literature with the recommended values is listed in Table V. A systematic

Table VI. Percentage Deviation in C_p° of Aluminum from Recommended Values Given in Table VII

Source	Deviation (%)
Brooks and Bingham [27]	±0.2 (<400 K) Up to 4 (>400 K)
Bingham [28]	±1
Clechet et al. [29]	−0.3 (<510 K) 0.1 (>510 K)
Takahashi et al. [30]	−1 (<700 K) −2 (>700 K)
Leadbetter [32]	−0.7 to −3
Schmidt et al. [36]	−4 (<933 K) 0.9 (933 K)
Dosch and Wendlandt [50]	−18 (373 K) Up to 7 (>373 K)
Kramer and Noelting [61]	Up to 1 (<600 K) Up to 5 (>600 K)

Table VII. Recommended High-Temperature Thermodynamic Properties of Aluminum[a]

T (K)	Condensed phase				Gas phase Al(g)			
	C_p° $(\mathrm{J \cdot mol^{-1} \cdot K^{-1}})$	$H^\circ - H^\circ(T_r)$ $(\mathrm{J \cdot mol^{-1}})$	S° $(\mathrm{J \cdot mol^{-1} \cdot K^{-1}})$	$-[G^\circ - H^\circ(T_r)]/T$	C_p° $(\mathrm{J \cdot mol^{-1} \cdot K^{-1}})$	$H^\circ - H^\circ(T_r)$ $(\mathrm{J \cdot mol^{-1}})$	S° $(\mathrm{J \cdot mol^{-1} \cdot K^{-1}})$	$-[G^\circ - H^\circ(T_r)]/T$
298.15	24.225	0	0.000	28.246	21.390	0	0.000	164.444
300	24.259	45	0.150	28.246	21.383	40	0.132	164.444
350	25.053	1,278	3.951	28.545	21.227	1,105	3.415	164.703
400	25.712	2,548	7.341	29.217	21.117	2,163	6.243	165.280
450	26.307	3,849	10.404	30.098	21.047	3,217	8.725	166.020
500	26.875	5,178	13.205	31.095	20.995	4,268	10.941	166.849
550	27.452	6,536	15.794	32.156	20.958	5,317	12.938	167.716
600	28.058	7,924	18.208	33.248	20.930	6,364	14.763	168.600
650	28.717	9,343	20.480	34.352	20.907	7,410	16.435	169.480
700	29.418	10,796	22.633	35.456	20.891	8,455	17.986	170.352
750	30.154	12,285	24.688	36.553	20.877	9,499	19.425	171.204
800	30.933	13,812	26.658	37.639	20.866	10,543	20.774	172.039
850	31.738	15,279	28.558	38.711	20.857	11,586	22.037	172.851
900	32.555	16,986	30.395	39.767	20.849	12,628	23.230	173.643
933.61(s)	33.107	18,090	31.599	40.468	20.844	13,329	23.994	174.162
933.61(l)	31.757	28,670	42.931	40.468	20.844	13,329	23.994	174.162
1,000	31.757	30,778	45.114	42.582	20.836	14,712	25.426	175.158

1,100	31.757	33,954	48.141	45.520	20.827	16,796	27.412	176.587
1,200	31.757	37,130	50.904	48.209	20.821	18,878	29.224	177.936
1,300	31.757	40,305	53.446	50.688	20.816	20,960	30.890	179.211
1,400	31.757	43,481	55.800	52.988	20.811	23,041	32.432	180.418
1,500	31.757	46,657	57.991	55.132	20.808	25,122	33.868	181.564
1,600	31.757	49,833	60.040	57.141	20.805	27,203	35.211	182.653
1,700	31.757	53,008	61.965	59.030	20.803	29,283	36.472	183.691
1,800	31.757	56,184	63.781	60.813	20.801	31,363	37.661	184.681
1,900	31.757	59,360	65.498	62.502	20.800	33,443	38.786	185.628
2,000	31.757	62,535	67.127	64.105	20.798	35,523	39.853	186.535
2,100	31.757	65,711	68.676	65.631	20.797	37,603	40.867	187.405
2,200	31.757	68,887	70.153	67.087	20.796	39,683	41.835	188.241
2,300	31.757	72,062	71.565	68.480	20.795	41,762	42.759	189.046
2,400	31.757	75,238	72.917	69.813	20.795	43,842	43.644	189.821
2,500	31.757	78,414	74.213	71.093	20.794	45,921	44.493	190.569
2,600	31.757	81,590	75.458	72.324	20.794	48,001	45.309	191.291
2,700	31.757	84,765	76.657	73.508	20.794	50,080	46.093	191.989
2,793	31.757	87,719	77.731	74.570	20.794	52,014	46.796	192.617
2,800	31.757	87,941	77.810	74.649	20.794	52,159	46.848	192.663

$T_{\mathrm{fus}} = 933.61^{b}$, $\Delta_{\mathrm{fus}} H^\circ = 10{,}580\ (\pm 150)\ \mathrm{J \cdot mol^{-1}}$, $\Delta_{\mathrm{fus}} S^\circ = 11.332\ (\pm 0.16)\ \mathrm{J \cdot mol^{-1} \cdot K^{-1}}$

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[a] Enthalpy reference temperature = $T_r = 298.15$ K.

[b] Secondary reference point on the International Practical Temperature Scale (IPTS-68).

plot of the percentage deviation in y values from various measurements is shown in Fig. 2. The recommended C_p° values obtained in this manner compare with heat capacity data reported in the literature as listed in Table VI.

The recommended enthalpy and C_p° values are listed in Table VII. The $S^\circ(T) - S^\circ(298.15\ \mathrm{K})$ values are calculated by integration of C_p°/T values. Combining the $S^\circ(T) - S^\circ(298.15\ \mathrm{K})$, $H^\circ(T) - H^\circ(298.15\ \mathrm{K})$ values with $S^\circ(298.15\ \mathrm{K})$ from low-temperature data, the Gibbs energy function $[G^\circ(T) - H^\circ(298.15\ \mathrm{K})]/T$ values reported in Table VII were generated.

3.4. High-Temperature Heat Capacity (Liquid)

The recommended value for the enthalpy of melting, $\Delta_{\mathrm{fus}}H^\circ = 10580\ (\pm 150)\ \mathrm{J \cdot mol^{-1}}$ was obtained by extrapolating solid and liquid enthalpies to the melting point $T_{\mathrm{fus}} = 933.61$ K. The values reported in the literature are listed in Table VIII.

The recommended values in the liquid region are based on the enthalpy measurements of McDonald [34] and of Awbery and Griffiths

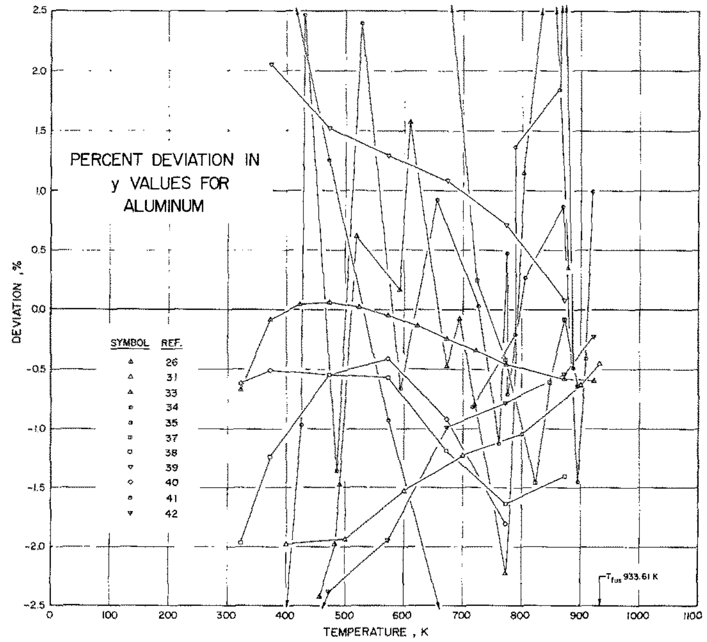

Fig. 2. Percentage deviation in y values for aluminum calculated from the recommended enthalpy values given in Table VII.

Table VIII. Values for Enthalpy of Melting of Aluminum

Source	$\Delta_{\text{fus}}H^\circ$ (J · mol^{-1})
McDonald [34]	10,711 ± 210
Awbery and Griffiths [35]	10,376
Schmidt et al. [36]	10,710 ± 10
Wust et al. [37]	10,627
Speros and Woodhouse [43]	10,736
Schurmann and Trager [44]	10,753
Oelsen et al. [45]	11,129
Oelsen et al. [46]	10,586
Wittig [47]	10,460
Awbery [48]	10,293
Berthon et al. [62]	10,544
Recommended value	10,580 (±150)

[35]. The data of Umino [41] are about 16% lower, those of Wust et al. [37] are about 4% lower, and those of Schmidt et al. [36] are about 3% lower. Batalin et al. [49] and Umino [41] report a constant value of 26.778 and 26.078 J · mol^{-1} · K^{-1}, respectively, for the heat capacity of liquid aluminum. The recommended constant value of 31.757 J · mol^{-1} · K^{-1} derived from the recommended enthalpy values

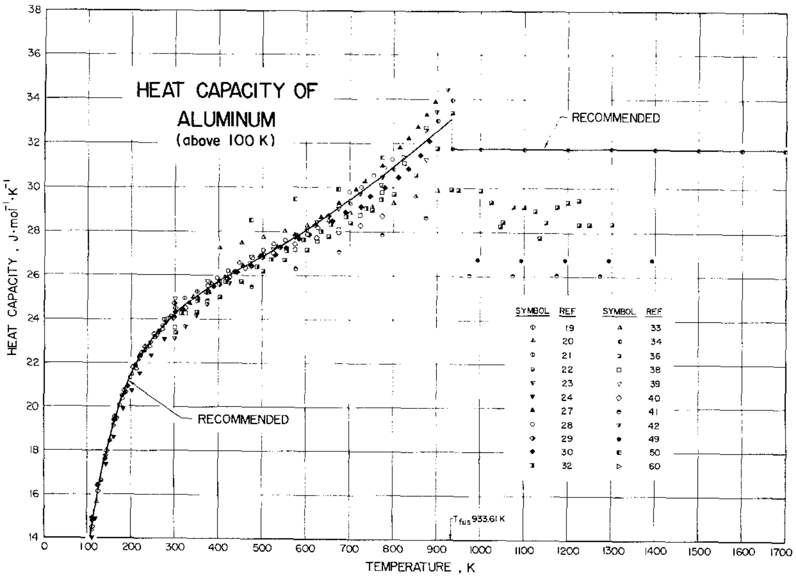

Fig. 3. Heat capacity of aluminum (above 100 K).

Table IX. Values for Enthalpy of Sublimation of Aluminum at 298.15 K

Source	$\Delta_{\mathrm{sub}}H°(298.15\ \mathrm{K})\ (\mathrm{kJ \cdot mol^{-1}})$
Kulifeev and Ukhlinov [52], 1383–1572 K	
Knudsen method	312.92 ± 1.58
Potter and Hildenbrand [53], 1476–1572 K	
Torsion effusion method	329.97 ± 0.47
Priselkov et al. [54], 1273–1473 K	
Knudsen method	314.91 ± 1.94
Johnson et al. [55], 1313–1370 K	
Mass spectrometer	327.6 ± 1.7
Porter et al. [56], 1511–1723 K	
Mass spectrometer	323.00 ± 8.0
Brewer and Searcy [57], 1410–1468 K	
Knudsen method	328.38 ± 2.66[a]
Baur and Brunner [58], 1734–2237 K	
Knudsen method	312.41 ± 3.73
Farkas [59], 1476 K	
Knudsen method	324.69 ± 4.0
Bhogeswara Rao and Motzfeldt [63], 1556 K	
Absorption spectroscopy	333.00
Bodrov and Nikolaev [64], 1318–1548 K	
Knudsen method	318.64 ± 1.62
Recommended value	329.70 ± 2.10

[a] Excluding measurements with TaC cell which were temperature dependent.

agrees well with that reported by McDonald [34] and by Kramer and Noelting [61].

The recommended C_p° values along with experimental data are shown in Fig. 3. The uncertainty in these values is estimated to be within ±3% below 10 K, ±2% from 10 to 298.15 K, ±1.5% from 298.15 to 933.61 K, and ±3% above 933.61 K.

3.5. Ideal-Gas Properties

Thermodynamic quantities for Al(g) reported in Table VII are calculated from the $C_p^\circ(\mathrm{g})$ values and $164.444\ \mathrm{J \cdot mol^{-1} \cdot K^{-1}}$ for $S°(298.15\ \mathrm{K})(\mathrm{g})$ reported by Glushko et al. [51].

3.6. Vapor Pressure Data

Various vapor pressure measurements were tested with the aid of the Third Law using the following equation:

$$\Delta_{\mathrm{sub}}H°(298.15\ \mathrm{K}) = -RT \ln p - T\Delta \frac{[G°(T) - H°(298.15\ \mathrm{K})]}{T} \qquad (8)$$

However, the mass spectrometric determinations of vapor pressure were tested with the application of the Second Law. The recommended value of $\Delta_{\mathrm{sub}}H^\circ(298.15\ \mathrm{K})$ is based on the $\Delta_{\mathrm{sub}}H^\circ(298.15\ \mathrm{K})$ values listed in Table IX, giving considerable weight to that of Potter and Hildenbrand [53].

Once the recommended value of $\Delta_{\mathrm{sub}}H^\circ(298.15\ \mathrm{K})$ is derived, the values of ΔG°, p, and ΔH° reported in Table X can be calculated using the

Table X. Recommended Vapor Pressure of Aluminum,[a] $\mathrm{Al(s, l) = Al(g)}$

T (K)	p (atm)	ΔG°	ΔH°	p (atm)	T (K)
		(J·mol^{-1})			
298.15	2.25×10^{-51}	289.093	329,700	10^{-10}	1,018
300	5.11×10^{-51}	288,841	329,695	10^{-9}	1,086
400	1.13×10^{-36}	275,275	329,315	10^{-8}	1,164
500	4.44×10^{-28}	261,823	328,790	10^{-7}	1,253
600	2.33×10^{-22}	248,489	328,140	10^{-6}	1,358
700	2.78×10^{-18}	235,273	327,359	10^{-5}	1,483
800	3.11×10^{-15}	222,180	326,431	10^{-4}	1,634
900	7.21×10^{-13}	209,212	325,342	10^{-3}	1,820
933.61(s)	3.44×10^{-12}	204,882	324,939	10^{-2}	2,056
933.61(l)	3.44×10^{-12}	204,882	314,359	10^{-1}	2,366
1,000	5.05×10^{-11}	197,124	313,634	1	2,793
1,100	1.55×10^{-9}	185,526	312,542	$\Delta_{\mathrm{vap}}S^\circ(2793\ \mathrm{K})$	
1,200	2.66×10^{-8}	174,028	311,448	$= 105.26 \pm (0.8)\ \mathrm{J \cdot mol^{-1} \cdot K^{-1}}$	
1,300	2.92×10^{-7}	162,620	310,355	$\Delta_{\mathrm{sub}}H^\circ(0\ \mathrm{K})$	
1,400	2.26×10^{-6}	151,298	309,260	$= 327.346 \pm (2.1)\ \mathrm{kJ \cdot mol^{-1}}$	
1,500	1.33×10^{-5}	140,052	308,165		
1,600	6.20×10^{-5}	128,881	307,070		
1,700	2.41×10^{-4}	117,776	305,975		
1,800	7.99×10^{-4}	106,738	304,879		
1,900	2.33×10^{-3}	95,761	303,783		
2,000	6.08×10^{-3}	84,840	302,688		
2,100	1.45×10^{-2}	73,975	301,592		
2,200	3.16×10^{-2}	63,161	300,496		
2,300	6.46×10^{-2}	52,398	299,400		
2,400	0.124	41,681	298,304		
2,500	0.225	31,010	297,207		
2,600	0.389	20,386	296,111		
2,700	0.646	9,801	295,015		
2,793	1.000	0	293,995		
2,800	1.032	−739	293,918		

[a] atm = 101,325 Pa. ΔG° refers to $\Delta_{\mathrm{sub}}G^\circ$ when $T < T_{\mathrm{fus}}$ and $\Delta_{\mathrm{vap}}G^\circ$ when $T > T_{\mathrm{fus}}$ (and similarly for ΔH°).

Gibbs energy values for Al(s, l) and Al(g) from Table VII and the following relations:

$$\Delta G^\circ = T\Delta \frac{[G^\circ(T) - H^\circ(298.15\ \mathrm{K})]}{T} + \Delta_{\mathrm{sub}} H^\circ(298.15\ \mathrm{K}) \qquad (9)$$

$$\Delta G^\circ = -RT \ln p \qquad (10)$$

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