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Enthalpies of dissolution of elements in liquid tin. A review III. Elements of columns IIB, IIIA, IVA, VA and VIA of the Periodic Table

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Abstract

In the framework of a general compilation devoted to the enthalpies of dissolution of elements in liquid tin, data concerning the partial enthalpies at infinite dilution of elements of columns IIB, IIIA, IVA, VA and VIA of the Periodic Table in tin have been collected from the literature. When the quantity of data was sufficiently large, they were fitted against temperature and the corresponding equations are reported in this paper. Selected equations are given for the elements of the whole Periodic Table, where known.

Keywords: Partial enthalpy; Dissolution; Tin; IIB, IIIA, IVA, VA and VIA elements

1. Introduction

In two previous papers, we reported selected data concerning the partial enthalpies of solution of copper, silver, gold and rare earth metals [1], alkali, alkaline earth and transition metals [2] in liquid tin in order to bring up to date the compilation of Boom [3]. We now report the results on IIB, IIIA, IVA, VA and VIA elements of the Periodic Table. As in our previous works, all the data are with reference to the liquid state. When data taken from the literature were referred to the solid state, they were transferred to the liquid state using the enthalpies of transition given by the SGTE group [4].

2. Results

2.1. Column IIB (Table 1)

There are 18 papers [5–22] dealing with the enthalpy of mixing of zinc–tin binary alloys, but Scheil and Wolf [16] and Scheil and Müller [17] did not give any numerical data. The collected data are highly scattered with respect to temperature, as shown in Fig. 1. However, they can be fitted roughly as follows:

$$\Delta h^{\infty}_{\mathrm{Zn}}\,(\mathrm{kJ\,mol^{-1}}) = 10.8 - 1 \times 10^{-3} T$$

Of the 13 data [3,5–7,23–26] selected by Boom [3] for cadmium, those of Kawakami [5,6], Elliott and Chipman [23] and Pool [10] (at 655 and 750 K) were not taken into account for the linear fitting versus temperature (Fig. 2). The remaining data were fitted according to the following equation:

$$\Delta h^{\infty}_{\mathrm{Cd}}\,(\mathrm{kJ\,mol^{-1}}) = 9.05 - 2.9 \times 10^{-3} T$$

There are four data for mercury [5,27–29] in a restricted temperature range (423–595 K), but no value can be selected due to the very large scattering.

2.2. Column IIIA (Table 2)

We found 13 papers concerning the limiting partial enthalpy of aluminium in tin [14,30–40]. The data of Predel and Ruge [14] were derived by Boom [3] from the figure of the authors. All the data agree well with a linear

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Table 1
Limiting partial enthalpies of column IIB metals in liquid tin with respect to temperature, referred to liquid metals (^{r}: rejected data)

Element	Ref.	T (K)	Δh_i^{∞} (kJ mol^{-1})
Zn	[5,6]	723	10.54
	[7]	703	9.70
		798	8.49
	[8]	600	9.98
	[9]	623	10.91
	[10]	655	10.47
		700	9.97
		750	10.19
	[11]	650	9.42
	[12]	600	9.22
	[13]	573	10.38
		673	10.17
	[14]	833	8.62
	[15]	598	9.06
	[18]	750	8.97
	[19]	773	10.42^{r}
		776	9.96^{r}
		721	10.71^{r}
	[20]	773	11.81
	[21]	723	9.41
	[22]	750	9.79
Cd	[5,6]	623	5.65^{r}
	[23]	873	7.70^{r}
	[7]	623	7.20
		723	6.69
	[24]	517	7.36
	[10]	655	8.22^{r}
		700	7.32
		750	6.19^{r}
	[25]	532	7.60
		541	7.53
	[26]	698	6.95
	[3]	598	7.28
Hg	[27]	595	3.7
	[28]	475	3.2
	[29]	423	1.9
	[5]	523	1.9

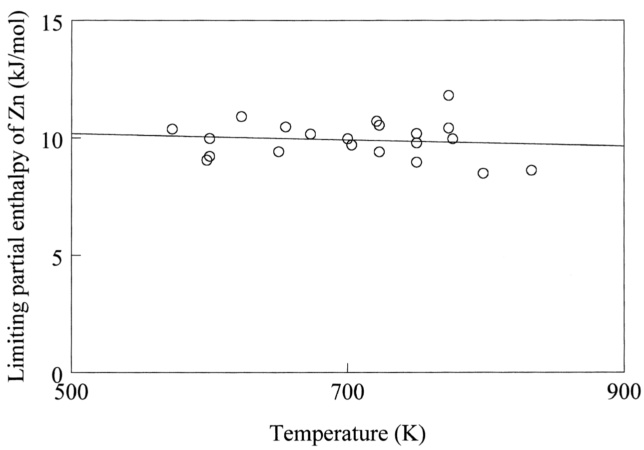

Fig. 1. Limiting partial enthalpy of zinc in liquid tin versus temperature, referred to liquid zinc.

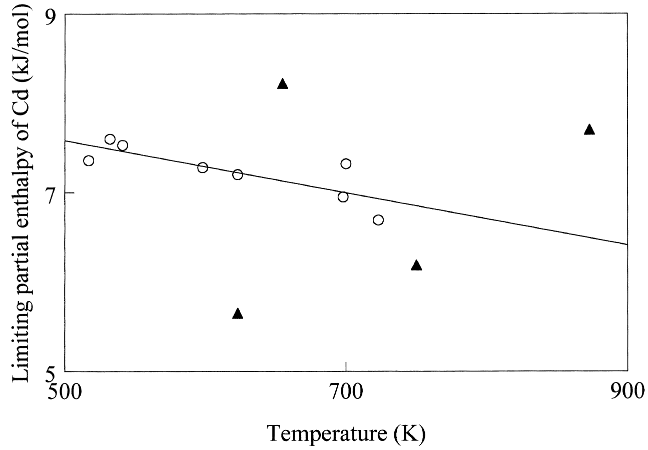

Fig. 2. Limiting partial enthalpy of cadmium in liquid tin versus temperature, referred to liquid cadmium (▲, rejected data).

fitting with respect to temperature (Fig. 3) and lead to the following equation:

$$\Delta h_{\mathrm{Al}}^{\infty}\ (\mathrm{kJ\ mol^{-1}}) = 15.52 - 1.2 \times 10^{-3} T$$

There are seven papers dealing with gallium [9,15,31,34,41–43] corresponding to 10 data at different temperatures. The linear fitting (Fig. 4) lead to the rejection of the data of Predel et al. [41] at 623 K. The selected data correspond to the following equation:

$$\Delta h_{\mathrm{Ga}}^{\infty}\ (\mathrm{kJ\ mol^{-1}}) = 2.37 + 1.1 \times 10^{-3} T$$

No new data were found in the literature for indium and thallium in addition to the 12 (indium) [26,31,34,44–50] (Fig. 5) and five (thallium) [15,31,51] (Fig. 6) previously selected by Boom [3]. For indium, however, the data of Pool and Lundin [34] were recalculated according to new heat capacity data for pure indium, leading to −0.88 instead of −1.02 kJ mol^{-1} at 750 K. In the case of indium, the scattering is somewhat high, as shown in Fig. 5. The data lead to the following equations:

$$\Delta h_{\mathrm{In}}^{\infty}\ (\mathrm{kJ\ mol^{-1}}) = 0.08 - 1.2 \times 10^{-3} T$$

$$\Delta h_{\mathrm{Tl}}^{\infty}\ (\mathrm{kJ\ mol^{-1}}) = 4.18 - 0.3 \times 10^{-3} T$$

2.3. Column IVA (Table 3)

The 10 data found in the literature [9,36,52–57] for germanium lead to rejection of the values of Kleppa and King [9], Beardmore et al. [52] and Predel and Stein [53], which differ strongly from the linear fitting (Fig. 7). The remaining data were well fitted versus temperature as follows:

$$\Delta h_{\mathrm{Ge}}^{\infty}\ (\mathrm{kJ\ mol^{-1}}) = 2.87 + 0.33 \times 10^{-3} T$$

Fig. 8 shows the data collected from the literature [5,6,15,48,58–60] for lead. Five [5,6,48,52,59] differ

Table 2
Limiting partial enthalpies of column IIIA metals in liquid tin with respect to temperature, referred to liquid metals (^{r}: rejected data)

Element	Ref.	T (K)	Δh_i^∞ (kJ mol^{-1})
Al	[30]	1073	14.64
	[31]	573	14.71
		623	14.73
	[32]	973	12.94
		573	14.64
	[33]	745	14.56
	[34]	750	15.21
	[35]	960	14.41
	[36]	960	14.50
	[37]	656	14.20
	[14]	780	15.23
	[38]	775	15.15
	[39]	1273	15.10
	[40]	1233	12.79
Ga	[31]	513	2.93
		573	2.97
		623	2.93
	[9]	623	3.22
		623	3.13
	[34]	750	3.20
	[41]	623	3.77^r
	[15]	598	2.82
	[42]	700	3.01
	[43]	743	3.15
In	[44]	723	−0.59
	[45]	644	−0.69
	[46]	700	−0.95
	[31]	513	−0.59
		573	−0.63
		623	−0.63
	[34]	750	−0.88
	[47]	705	−0.85
	[48]	573	−0.44
	[49]	521	−0.71
	[26]	698	−0.82
	[50]	587	−0.52
Tl	[31]	513	4.02
		573	4.02
		623	4.02
	[51]	623	4.00
	[15]	598	3.85

strongly from the selected linear fitting and were ignored. The others lead to the following equation:

$$\Delta h_{\mathrm{Pb}}^\infty\ (\mathrm{kJ\ mol^{-1}}) = 5.38 + 0.33 \times 10^{-3} T$$

2.4. Column VA (Table 4)

No other work than that of Guadagno and Pool [61] was found concerning the enthalpy of dissolution of phosphorus in tin. Their value at 750 K (23.70 kJ mol^{-1}) was selected.

Three papers deal with the dissolution of arsenic in tin [14,61,62] in a restricted temperature range (750–873 K). The data, when fitted against temperature (Fig. 9), lead to

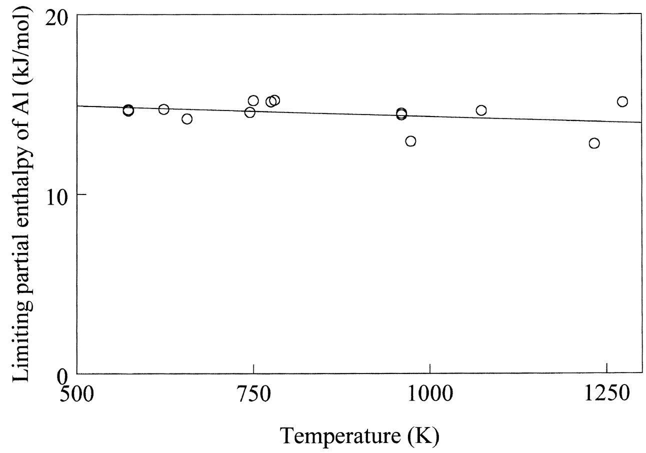

Fig. 3. Limiting partial enthalpy of aluminium in liquid tin versus temperature, referred to liquid aluminium.

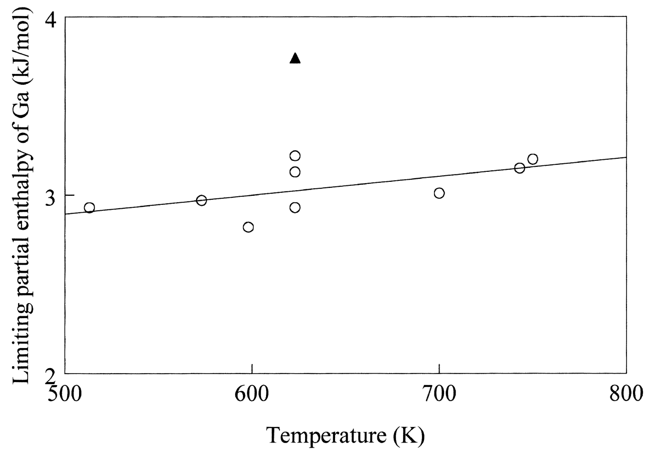

Fig. 4. Limiting partial enthalpy of gallium in liquid tin versus temperature, referred to liquid gallium (▲, rejected data).

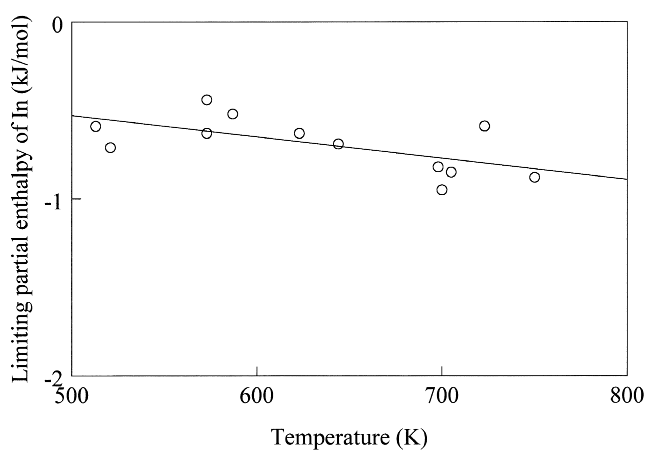

Fig. 5. Limiting partial enthalpy of indium in liquid tin versus temperature, referred to liquid indium.

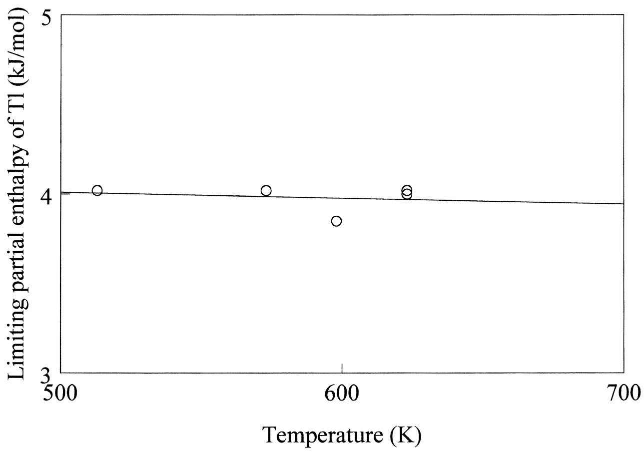

Fig. 6. Limiting partial enthalpy of thallium in liquid tin versus temperature, referred to liquid thallium.

a strong temperature dependence according to the following equation:

$$\Delta h^{\infty}_{As}\ (\mathrm{kJ\ mol^{-1}}) = -44.89 + 44.2 \times 10^{-3} T$$

Eight data were found for antimony [14,26,30,44,61,63–65] from 623 to 1073 K. After linear fitting (Fig. 10), those of Kawakami [30], Wittig and Gehring [64] and Yazawa et al. [65] were eliminated. The last five values were fitted according to the following equation:

$$\Delta h^{\infty}_{Sb}\ (\mathrm{kJ\ mol^{-1}}) = -10.08 + 7.8 \times 10^{-3} T$$

Table 3
Limiting partial enthalpies of column IVA metals in liquid tin with respect to temperature, referred to liquid metals (^{r}: rejected data)

Element	Ref.	T (K)	Δh_i^{∞} (kJ mol^{-1})
Ge	[9]	623	4.77^r
	[52]	623	4.77^r
	[36]	963.5	3.21
	[53]	786	0.71^r
		919	2.80
		1003	3.14
	[54]	874	3.36
	[55]	1500	6.18^r
	[56]	600	3.11
	[57]	1083	3.39
Pb	[5,6]	623	3.31^r
	[58]	623	5.65
		723	5.65
	[52]	523	4.60^r
	[48]	654	6.47^r
		777	6.47^r
	[15]	523	5.34
		548	5.64
		598	5.66
	[59]	1040	6.40^r
	[60]	1050	5.69

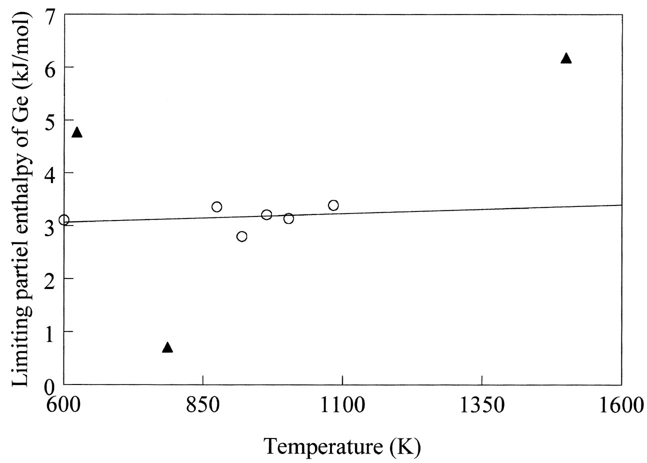

Fig. 7. Limiting partial enthalpy of germanium in liquid tin versus temperature, referred to liquid germanium (▲, rejected data).

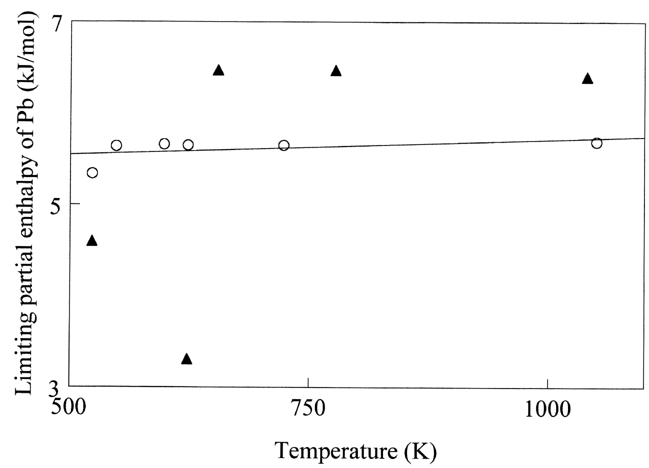

Fig. 8. Limiting partial enthalpy of lead in liquid tin versus temperature, referred to liquid lead (▲, rejected data).

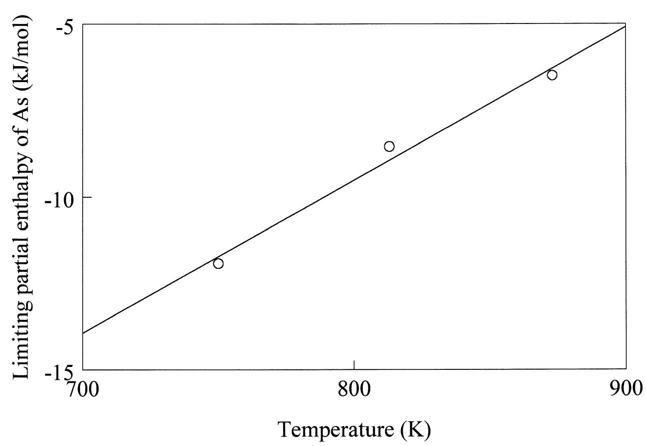

Fig. 9. Limiting partial enthalpy of arsenic in liquid tin versus temperature, referred to liquid arsenic.

Table 4
Limiting partial enthalpies of column VA metals in liquid tin with respect to temperature, referred to liquid metals (^{r}: rejected data)

Element	Ref.	T (K)	Δh_i^{∞} (kJ mol^{-1})
P	[61]	750	23.70
As	[61]	750	11.92
	[14]	813	8.54
	[62]	873	6.49
Sb	[30]	1073	-8.78^{r}
	[44]	723	−4.48
	[61]	750	−4.31
	[63]	623	−5.14
	[26]	698	−4.59
	[14]	833	−4.59
	[64]	973	-5.18^{r}
	[65]	1003	-3.45^{r}
Bi	[6]	623	2.01^{r}
	[66]	608	0.46
	[65]	690	0.51
	[67]	725	0.51
	[68]	587	0.54
	[15]	598	0.57
	[14]	813	3.85^{r}

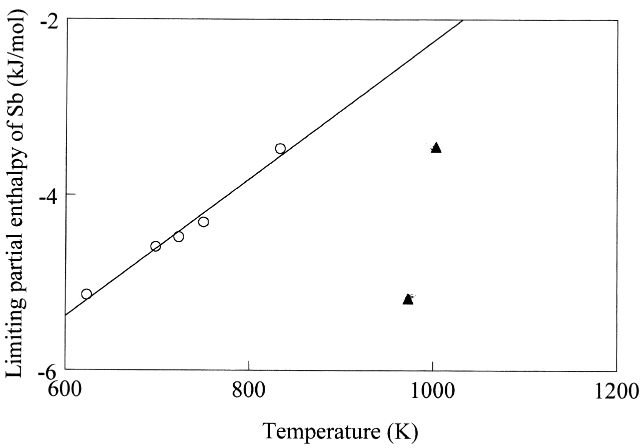

Fig. 10. Limiting partial enthalpy of antimony in liquid tin versus temperature, referred to liquid antimony (▲, rejected data).

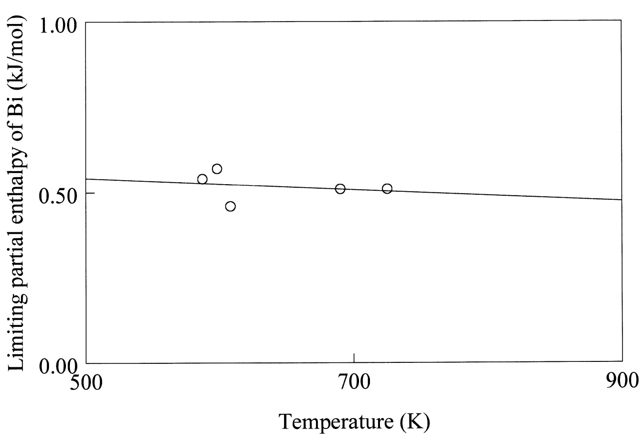

Fig. 11. Limiting partial enthalpy of bismuth in liquid tin versus temperature, referred to liquid bismuth.

Table 5
Limiting partial enthalpies of column VIA metals in liquid tin with respect to temperature, referred to liquid metals (^{r}: rejected data)

Element	Ref.	T (K)	Δh_i^{∞} (kJ mol^{-1})
Se	[69]	921	−54.69
		1036	−52.03
		1073	−53.72
		1118	−50.39
		1175	−50.96
Te	[10]	750	−31.85
		655	-28.29^{r}
	[70]	725	−31.38
		775	−31.80
	[71]	1140	-30.39^{r}
	[72]	737	−31.04
	[73]	873	−32.5
	[74]	273	−30.33
	[75]	298	−30.54
	[76]	606	−30.40

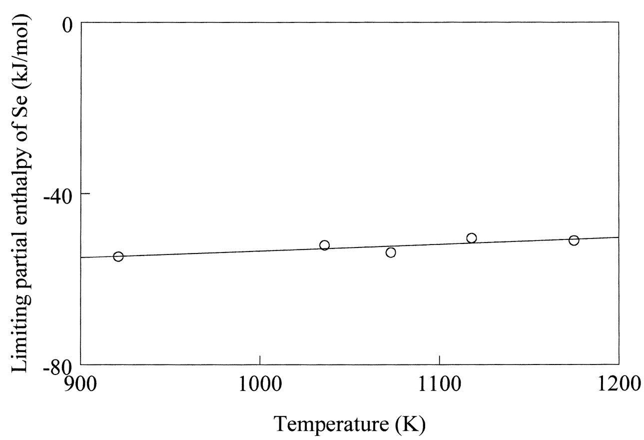

Fig. 12. Limiting partial enthalpy of selenium in liquid tin versus temperature, referred to liquid selenium.

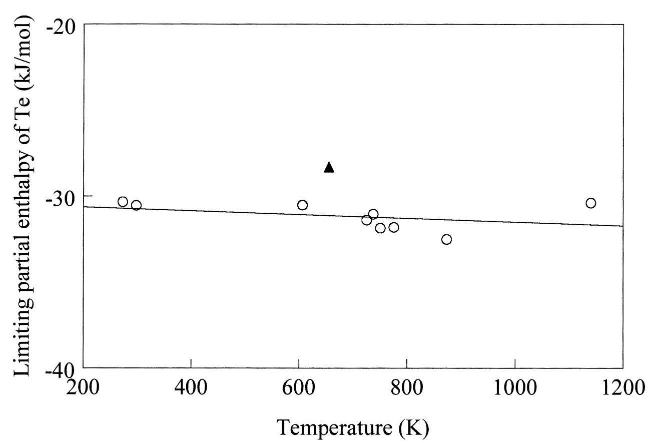

Fig. 13. Limiting partial enthalpy of tellurium in liquid tin versus temperature, referred to liquid tellurium (▲, rejected data).

Table 6
Selected data of the limiting partial enthalpies of elements of the Periodic Table in liquid tin referred to liquid metals at temperature T. a, b and c are numerical values of the parameters of the equation Δh_i^∞ (kJ mol^{-1}) = $a + bT + cT^2$. ΔT is the temperature interval of validity. n is the number of experimental determinations. *Estimated value

Element	a	10^3 b	10^6 c	ΔT	n
Li	−64.0	7.9		700–937	3
Na	−51.64	11		623–873	5
K	−56.2			850	1
Be	68			1474	2
Mg	−36.5	7		573–1213	11
Ca	−158.8	24		725–775	3
Sr	−189.6	42		704–1773	3
Ba	−228.9	64		704–1773	3
Y	−145.0	−4		1000–1920	3
La	−525.5	436	−120	632–1890	17
	(−394.9)	(170)		(632–1472)	16
Ce	−795.4	1120	−530	634–1178	6
Pr	−270			750	3
Nd	−255			750	3
Sm	−340.6	150		750–1173	3
Eu	−178			957	1
Gd	−218.4	50		969–1478	4
Dy	−167.4	13		960–1478	5
Er	−126.8	0.7		963–1470	6
Yb	−157			770–857	2
Ti	61.96			1173	1
Zr	72.7			1173	1
Hf	33.95			1173	1
V	56.33			1173	1
	28.4			1883	1
Nb	28			1173	1
Ta	42.60			1173	1
Cr	46*			–	8
Mo	59.2			2473	1
W	19.47			1173	1
Mn	−15.39	9.5		750	4
Fe	27*			769–1173	1
Rh	−213.7	90		700–775	4
Ir	−173.5			1173	1
Ni	−86.16	31		623–1093	14
Pd	−145.68	28		656–914	11
Pt	−134			–	6
Cu	−13.31	21	−6.3	561–1400	37
Ag	−0.78	11	−5.8	513–1078	44
Au	−44.68	18	−3.5	513–1373	53
Zn	10.8	−1		573–833	18
Cd	9.05	−2.9		517–723	8
Hg	–				4
Al	15.52	−1.2		573–1273	14
Ga	2.37	1.1		513–750	9
In	0.08	−1.2		513–750	12
Tl	4.18	−0.3		513–623	5
Ge	2.87	0.33		600–1083	6
Pb	5.38	0.33		523–1050	6
P	23.70			750	1
As	−44.89	44.2		750–873	3
Sb	−10.08	7.8		623–833	3
Bi	0.63	−0.2		587–690	5
Se	−69.06	15.7		921–1175	5
Te	−30.4	−1.1		273–873	8

Five data were selected for bismuth between 587 and 725 K [14,15,65,67,68] and two were rejected [6,66] (Fig. 11). The selected equation is the following:

$$\Delta h_{\mathrm{Bi}}^\infty\,(\mathrm{kJ\ mol^{-1}}) = 0.63 - 0.2 \times 10^{-3}T$$

2.5. Column VIA (Table 5)

There is no data for the dissolution of sulfur in liquid tin and only one work devoted to the dissolution of selenium, that of Kotchi et al. [69] performed by calorimetry at five temperatures from 921 to 1175 K (Fig. 12), leading to the following equation with respect to temperature:

$$\Delta h_{\mathrm{Se}}^\infty\,(\mathrm{kJ\ mol^{-1}}) = -69.06 + 15.7 \times 10^{-3}T$$

For tellurium, we found eight papers [10,70–76] in a large temperature range (273–1140 K). The data can be well fitted linearly with respect to temperature (Fig. 13):

$$\Delta h_{\mathrm{Te}}^\infty\,(\mathrm{kJ\ mol^{-1}}) = -30.4 - 1.1 \times 10^{-3}T$$

The data of Pool et al. [10] at 750 K agree with the equation, but not at 655 K, and this last value was not taken into account.

3. Conclusion

With our two previous papers [1,2], this compilation covers the whole Periodic Table of elements since there is no data for actinides nor for non-metals of column VIIA. We have regrouped in Table 6 all selected data from our previous papers [1,2] and from this one.

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