

Lead (Pb)

REFERENCE STATE

0 to 600.6 K crystal
600.6 to 2019.022 K liquid
above 2019.022 K ideal monatomic gas

Refer to the individual tables for details.

$A_r = 207.2$ Lead (Pb)

Pb_r(ref)

| T/K | C _p ^o | Enthalpy Reference Temperature = T _r = 298.15 K | | Standard State Pressure = p ^o = 0.1 MPa | | log K _r |
|----------|-----------------------------|--|---|--|-------------------------------|--------------------|
| | | S ^o - [G ^o - H ^o (T _r)]/T | H ^o - H ^o (T _r) | Δ _f H ^o | Δ _f G ^o | |
| 0 | 0 | INFINITE | 0 | 0 | 0 | 0 |
| 100 | 24.426 | 36.829 | 87.950 | -6.878 | 0 | 0 |
| 200 | 25.870 | 54.272 | 67.210 | -5.112 | 0 | 0 |
| 298.15 | 26.836 | 64.785 | 0 | -2.587 | 0 | 0 |
| 300 | 26.853 | 64.951 | 0.050 | 0 | 0 | 0 |
| 400 | 27.723 | 72.796 | 65.849 | 2.779 | 0 | 0 |
| 500 | 28.549 | 79.071 | 67.886 | 5.592 | 0 | 0 |
| 600 | 29.404 | 84.336 | 70.201 | 8.481 | 0 | 0 |
| 600.600 | 29.414 | 84.366 | 70.215 | 8.499 | 0 | 0 |
| 600.600 | 30.627 | 92.514 | 70.215 | 13.273 | 0 | 0 |
| 700 | 30.332 | 96.984 | 73.693 | 16.303 | 0 | 0 |
| 800 | 30.016 | 101.013 | 76.863 | 19.321 | 0 | 0 |
| 900 | 29.698 | 104.530 | 79.746 | 22.306 | 0 | 0 |
| 1000 | 29.397 | 107.643 | 82.383 | 25.261 | 0 | 0 |
| 1100 | 29.091 | 110.431 | 84.808 | 28.185 | 0 | 0 |
| 1200 | 28.786 | 112.949 | 87.050 | 31.079 | 0 | 0 |
| 1300 | 28.652 | 115.247 | 89.132 | 33.950 | 0 | 0 |
| 1400 | 28.623 | 117.368 | 91.074 | 36.812 | 0 | 0 |
| 1500 | 28.673 | 119.344 | 92.893 | 39.677 | 0 | 0 |
| 1600 | 28.786 | 121.198 | 94.605 | 42.549 | 0 | 0 |
| 1700 | 28.978 | 122.948 | 96.221 | 45.435 | 0 | 0 |
| 1800 | 29.109 | 124.606 | 97.753 | 48.336 | 0 | 0 |
| 1900 | 29.296 | 126.185 | 99.208 | 51.256 | 0 | 0 |
| 2000 | 29.497 | 127.693 | 100.595 | 54.196 | 0 | 0 |
| 2019.022 | 29.541 | 127.972 | 100.851 | 54.758 | 0 | 0 |
| 2019.022 | 24.831 | 215.927 | 100.851 | 232.340 | 0 | 0 |
| 2100 | 25.499 | 216.916 | 105.308 | 234.378 | 0 | 0 |
| 2200 | 26.365 | 218.122 | 110.408 | 236.971 | 0 | 0 |
| 2300 | 27.261 | 219.314 | 115.118 | 239.652 | 0 | 0 |
| 2400 | 28.173 | 220.493 | 119.484 | 242.423 | 0 | 0 |
| 2500 | 29.084 | 221.662 | 123.547 | 245.286 | 0 | 0 |
| 2600 | 29.979 | 222.820 | 127.343 | 248.240 | 0 | 0 |
| 2700 | 30.844 | 223.968 | 130.901 | 251.281 | 0 | 0 |
| 2800 | 31.669 | 225.105 | 134.245 | 254.407 | 0 | 0 |
| 2900 | 32.444 | 226.230 | 137.388 | 257.613 | 0 | 0 |
| 3000 | 33.160 | 227.342 | 140.377 | 260.894 | 0 | 0 |
| 3100 | 33.813 | 228.440 | 143.200 | 264.243 | 0 | 0 |
| 3200 | 34.598 | 229.523 | 145.881 | 267.654 | 0 | 0 |
| 3300 | 34.913 | 230.589 | 148.432 | 271.120 | 0 | 0 |
| 3400 | 35.350 | 231.639 | 150.864 | 274.635 | 0 | 0 |
| 3500 | 35.757 | 232.669 | 153.186 | 278.190 | 0 | 0 |
| 3600 | 36.048 | 233.680 | 155.408 | 281.780 | 0 | 0 |
| 3700 | 36.296 | 234.672 | 157.537 | 285.398 | 0 | 0 |
| 3800 | 36.485 | 235.642 | 159.580 | 289.037 | 0 | 0 |
| 3900 | 36.618 | 236.592 | 161.542 | 292.693 | 0 | 0 |
| 4000 | 36.700 | 237.520 | 163.430 | 296.359 | 0 | 0 |
| 4100 | 36.737 | 238.427 | 165.248 | 300.031 | 0 | 0 |
| 4200 | 36.733 | 239.312 | 167.001 | 303.705 | 0 | 0 |
| 4300 | 36.692 | 240.176 | 168.693 | 307.377 | 0 | 0 |
| 4400 | 36.619 | 241.019 | 170.327 | 311.042 | 0 | 0 |
| 4500 | 36.518 | 241.841 | 171.907 | 314.699 | 0 | 0 |
| 4600 | 36.395 | 242.642 | 173.456 | 318.345 | 0 | 0 |
| 4700 | 36.252 | 243.423 | 174.917 | 321.978 | 0 | 0 |
| 4800 | 36.093 | 244.185 | 176.352 | 325.595 | 0 | 0 |
| 4900 | 35.923 | 244.927 | 177.744 | 329.196 | 0 | 0 |
| 5000 | 35.743 | 245.651 | 179.095 | 332.779 | 0 | 0 |
| 5100 | 35.557 | 246.357 | 180.407 | 336.344 | 0 | 0 |
| 5200 | 35.367 | 247.046 | 181.682 | 339.890 | 0 | 0 |
| 5300 | 35.172 | 247.717 | 182.922 | 343.417 | 0 | 0 |
| 5400 | 34.985 | 248.373 | 184.128 | 346.923 | 0 | 0 |
| 5500 | 34.796 | 249.013 | 185.302 | 350.414 | 0 | 0 |
| 5600 | 34.612 | 249.639 | 186.445 | 353.885 | 0 | 0 |
| 5700 | 34.434 | 250.250 | 187.559 | 357.337 | 0 | 0 |
| 5800 | 34.263 | 250.847 | 188.645 | 360.772 | 0 | 0 |
| 5900 | 34.097 | 251.431 | 189.704 | 364.189 | 0 | 0 |
| 6000 | 33.942 | 252.003 | 190.738 | 367.590 | 0 | 0 |

PREVIOUS: March 1962 (1 atm)

CURRENT: March 1962 (1 bar)

Lead (Pb)

Pb_r(ref)

Lead (Pb) $A_r = 207.26$ Lead (Pb) $Pb_1(cr)$

CRYSTAL

$S^\circ(298.15\text{ K}) = 64.785 \pm 0.54\text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
 $T_{fus} = 600.38 \pm 0.00\text{ K}$
 $\Delta_f H^\circ(0\text{ K}) = 0\text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_f H^\circ(298.15\text{ K}) = 0\text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_{sub} H^\circ = 4.77 \pm 0.01\text{ kJ}\cdot\text{mol}^{-1}$

Enthalpy of Formation
 Zero by definition.

Heat Capacity and Entropy

Heat Capacity measurements have been reported by Horowitz, *et al.*¹ (1–4 K, 14–21 K, 64–77 K), Meads, *et al.*² (15–300 K), Douglas and Devir³ (298.15 K), and many others whose work is listed by Kelley.⁴

Heat capacities from 15 to 300 K and 1 to 4 K (in superconducting state) were taken from Meads *et al.*² and Horowitz *et al.*¹ respectively. The missing data below the melting point were obtained by graphical extrapolation and joined smoothly to the data of Douglas and Devir³ on approaching the melting point.

Fusion Data

The melting point of pure Pb(cr) was found by McLaren and Mardock⁵ to be $327.426 \pm 0.002^\circ\text{C}$. $\Delta_{sub} H^\circ$ was given by Douglas and Devir.³

Sublimation Data

The enthalpy of sublimation, $\Delta_{sub} H^\circ(298.15\text{ K})$, is the enthalpy of formation of the ideal gas, $\Delta_f H^\circ(298.15\text{ K})$. See the ideal gas table for details.

References

- ¹M. Horowitz, A. A. Silvini, S. F. Malaker and J. G. Daunt, *Phys. Rev.* **88**, 1182 (1952).
- ²P. V. Meads, W. R. Forsythe and W. F. Giangue, *J. Am. Chem. Soc.* **63**, 1902 (1941).
- ³T. B. Douglas and J. L. Dever, *J. Am. Chem. Soc.* **76**, 4824 (1954).
- ⁴K. K. Kelley, U. S. Bur. Mines Bull. 584, 232 pp. (1960).
- ⁵E. H. McLaren and E. G. Mardock, *Can. J. Phys.* **38**, 577 (1960).

| T/K | C_p° | Enthalpy Reference Temperature = $T_r = 298.15\text{ K}$ | | Standard State Pressure = $p^\circ = 0.1\text{ MPa}$ | | $\log K_f$ |
|---------|-------------|--|--------------------------|--|---------------------|------------|
| | | $S^\circ - [G^\circ - H^\circ(T_r)]/T$ | $H^\circ - H^\circ(T_r)$ | $\Delta_f H^\circ$ | $\Delta_f G^\circ$ | |
| 0 | 0 | INFINITE | -6.878 | 0. | 0. | 0. |
| 100 | 24.426 | 36.829 | -5.112 | 0. | 0. | 0. |
| 200 | 24.870 | 54.272 | -2.587 | 0. | 0. | 0. |
| 250 | 26.363 | 60.096 | -1.282 | 0. | 0. | 0. |
| 298.15 | 26.836 | 64.785 | 0. | 0. | 0. | 0. |
| 300 | 26.853 | 64.951 | 0.050 | 0. | 0. | 0. |
| 350 | 27.288 | 69.124 | 1.403 | 0. | 0. | 0. |
| 400 | 27.723 | 72.796 | 2.779 | 0. | 0. | 0. |
| 450 | 28.139 | 76.085 | 4.175 | 0. | 0. | 0. |
| 500 | 28.549 | 79.071 | 5.592 | 0. | 0. | 0. |
| 600 | 29.404 | 84.336 | 8.481 | 0. | 0. | 0. |
| 600.600 | 29.414 | 84.366 | 8.499 | --- | CRYSTAL <--> LIQUID | --- |
| 700 | 30.367 | 88.941 | 11.470 | -4.833 | 0.796 | -0.059 |
| 800 | 31.342 | 93.060 | 14.556 | -4.765 | 1.598 | -0.104 |
| 900 | 32.313 | 96.808 | 17.738 | -4.568 | 2.582 | -0.138 |
| 1000 | 33.288 | 100.263 | 21.018 | -4.242 | 3.138 | -0.164 |
| 1100 | 34.263 | 103.481 | 24.396 | -3.789 | 3.856 | -0.183 |
| 1200 | 35.238 | 106.504 | 27.871 | -3.208 | 4.526 | -0.197 |
| 1300 | 36.208 | 109.363 | 31.443 | -2.506 | 5.143 | -0.207 |
| 1400 | 37.183 | 112.082 | 35.113 | -1.700 | 5.701 | -0.213 |
| 1500 | 38.158 | 114.681 | 38.880 | -0.797 | 6.199 | -0.216 |

PREVIOUS:

CURRENT: March 1962

Lead (Pb)

 $Pb_1(cr)$

Pb₁(l)

A_r = 207.2 Lead₁(Pb)

LIQUID

Lead (Pb)

S°(298.15 K) = [71.710] J·K⁻¹·mol⁻¹
 T_{fus} = 600.58 ± 0.00 K

Enthalpy Reference Temperature = T_r = 298.15 K

Standard State Pressure = P° = 0.1 MPa

Δ_fH°(298.15 K) = [4.283] kJ·mol⁻¹
 Δ_{sub}H° = 4.77 ± 0.01 kJ·mol⁻¹

Enthalpy of Formation

The enthalpy of formation of the liquid, Δ_fH°(298.15 K), is calculated from that of the crystal by adding Δ_{sub}H° and the difference in enthalpy, H°(600.58 K) - H°(298.15 K), between the crystal and liquid.

Heat Capacity and Entropy

Heat capacity values from T_{fus} to 1200 K were taken from Douglas and Dever.¹ Heat capacity values below T_{fus} and above 1200 K were extrapolated, a glass transition being assumed at 400 K.

The entropy is calculated in a manner analogous to that used for the enthalpy of formation.

Vaporization Data

T_{vap} is calculated as the temperature at which Δ_gG° = 0 for the process Pb(l) = Pb(g). Δ_{sub}H° is calculated as the corresponding enthalpy of formation difference at T_{vap}. At temperatures below T_{vap}, the amount of Pb₂(g) in the vapor is negligible.

References

¹T. B. Douglas and J. L. Dever, J. Am. Chem. Soc. 76, 4824 (1954).

| T/K | C _p ^o | S° - [C° - H°(T)]/T | H° - H°(T) | Δ _f H° | Δ _g G° | log K _r |
|----------|-----------------------------|---------------------|------------|-------------------|-------------------|--------------------|
| 0 | | | | | | |
| 100 | | | | | | |
| 200 | | | | | | |
| 250 | | | | | | |
| 298.15 | 26.836 | 71.710 | 0 | 4.283 | 2.218 | -0.389 |
| 300 | 26.853 | 71.876 | 0.050 | 4.283 | 2.205 | -0.384 |
| 400 | 27.723 | 72.720 | 0.283 | 4.283 | 1.513 | -0.198 |
| 400.000 | 27.723 | 72.720 | 2.719 | GLASS -> LIQUID | | |
| 400.000 | 31.254 | 79.720 | 2.719 | TRANSITION | | |
| 500 | 30.945 | 86.661 | 5.889 | 4.579 | 0.784 | -0.082 |
| 600 | 30.635 | 92.284 | 8.972 | 4.773 | 0.005 | 0 |
| 600.600 | 30.627 | 92.314 | 8.990 | CRYSTAL -> LIQUID | | |
| 700 | 30.332 | 96.984 | 12.021 | 0 | 0 | 0 |
| 800 | 30.016 | 101.013 | 15.038 | 0 | 0 | 0 |
| 900 | 29.698 | 104.530 | 18.023 | 0 | 0 | 0 |
| 1000 | 29.397 | 107.643 | 20.978 | 0 | 0 | 0 |
| 1100 | 29.091 | 110.431 | 23.902 | 0 | 0 | 0 |
| 1200 | 28.786 | 112.949 | 26.796 | 0 | 0 | 0 |
| 1300 | 28.652 | 115.247 | 29.667 | 0 | 0 | 0 |
| 1400 | 28.623 | 117.368 | 32.530 | 0 | 0 | 0 |
| 1500 | 28.673 | 119.344 | 35.394 | 0 | 0 | 0 |
| 1600 | 28.786 | 121.198 | 38.267 | 0 | 0 | 0 |
| 1700 | 28.928 | 122.948 | 41.152 | 0 | 0 | 0 |
| 1800 | 29.109 | 124.606 | 44.054 | 0 | 0 | 0 |
| 1900 | 29.296 | 126.185 | 46.974 | 0 | 0 | 0 |
| 2000 | 29.497 | 127.693 | 49.914 | 0 | 0 | 0 |
| 2019.022 | 29.541 | 127.972 | 50.475 | FUGACITY = 1 bar | | |
| 2100 | 29.706 | 129.137 | 52.874 | -177.221 | 7.115 | -0.177 |
| 2200 | 29.920 | 130.524 | 55.855 | -176.833 | 15.884 | -0.377 |
| 2300 | 30.133 | 131.859 | 58.858 | -176.511 | 24.636 | -0.560 |
| 2400 | 30.347 | 133.146 | 61.882 | -176.259 | 33.376 | -0.726 |
| 2500 | 30.556 | 134.389 | 64.927 | -176.077 | 42.107 | -0.880 |
| 2600 | 30.761 | 135.591 | 67.993 | -175.964 | 50.832 | -1.021 |
| 2700 | 30.962 | 136.756 | 71.079 | -175.920 | 59.553 | -1.152 |
| 2800 | 31.171 | 137.885 | 74.186 | -175.939 | 68.275 | -1.274 |
| 2900 | 31.376 | 138.983 | 77.313 | -176.018 | 76.998 | -1.387 |
| 3000 | 31.581 | 140.050 | 80.461 | -176.151 | 85.725 | -1.493 |

PREVIOUS:

CURRENT: March 1982

Lead (Pb)

Pb₁(l)

Pb₁(cr,l)

A_r = 207.2 Lead (Pb)

CRYSTAL-LIQUID

0 to 600.6 K crystal
above 600.6 K liquid

Refer to the individual tables for details.

| T/K | C _p ^o | Enthalpy Reference Temperature = T _r = 298.15 K | | Standard State Pressure = p ^o = 0.1 MPa | | log K _f |
|----------|-----------------------------|--|---|--|-------------------------------|--------------------|
| | | S ^o - [G ^o - H ^o (T _r)]/T | H ^o - H ^o (T _r) | Δ _f H ^o | Δ _f G ^o | |
| | | J·K ⁻¹ ·mol ⁻¹ | kJ·mol ⁻¹ | kJ·mol ⁻¹ | kJ·mol ⁻¹ | |
| 0 | 0 | INFINITE | | | | |
| 100 | 24.426 | 36.829 | -6.878 | 0 | 0 | 0 |
| 200 | 25.870 | 54.272 | -5.112 | 0 | 0 | 0 |
| 250 | 26.363 | 60.096 | -2.587 | 0 | 0 | 0 |
| 298.15 | 26.836 | 64.785 | -1.282 | 0 | 0 | 0 |
| 300 | 26.853 | 64.951 | 0 | 0 | 0 | 0 |
| 400 | 27.123 | 72.796 | 0.050 | 0 | 0 | 0 |
| 500 | 28.549 | 79.071 | 2.779 | 0 | 0 | 0 |
| 600 | 29.404 | 84.336 | 5.592 | 0 | 0 | 0 |
| 600.600 | 29.414 | 84.366 | 8.481 | 0 | 0 | 0 |
| 600.600 | 30.627 | 92.314 | 8.499 | 0 | 0 | 0 |
| 700 | 30.332 | 96.984 | 13.273 | CRYSTAL <-> LIQUID TRANSITION | 0 | 0 |
| 800 | 30.016 | 101.013 | 16.303 | 0 | 0 | 0 |
| 900 | 29.698 | 104.530 | 19.321 | 0 | 0 | 0 |
| 1000 | 29.397 | 107.643 | 22.306 | 0 | 0 | 0 |
| 1100 | 29.091 | 110.431 | 25.261 | 0 | 0 | 0 |
| 1200 | 28.786 | 112.949 | 28.185 | 0 | 0 | 0 |
| 1300 | 28.652 | 115.247 | 31.079 | 0 | 0 | 0 |
| 1400 | 28.623 | 117.368 | 33.950 | 0 | 0 | 0 |
| 1500 | 28.673 | 119.344 | 36.812 | 0 | 0 | 0 |
| 1600 | 28.786 | 121.198 | 39.677 | 0 | 0 | 0 |
| 1700 | 28.928 | 122.948 | 42.549 | 0 | 0 | 0 |
| 1800 | 29.109 | 124.606 | 45.433 | 0 | 0 | 0 |
| 1900 | 29.296 | 126.183 | 48.336 | 0 | 0 | 0 |
| 2000 | 29.497 | 127.693 | 51.256 | 0 | 0 | 0 |
| 2019.022 | 29.541 | 127.972 | 54.758 | 0 | 0 | 0 |
| 2100 | 29.706 | 129.137 | 57.156 | --- FUGACITY = 1 bar --- | 7.115 | -0.177 |
| 2200 | 29.920 | 130.324 | 60.138 | | 15.884 | -0.377 |
| 2300 | 30.133 | 131.859 | 63.140 | | 24.636 | -0.560 |
| 2400 | 30.347 | 133.146 | 66.164 | | 33.376 | -0.726 |
| 2500 | 30.556 | 134.389 | 69.210 | | 42.107 | -0.880 |
| 2600 | 30.761 | 135.591 | 72.275 | | 50.832 | -1.021 |
| 2700 | 30.962 | 136.756 | 75.362 | | 59.553 | -1.152 |
| 2800 | 31.171 | 137.885 | 78.468 | | 68.275 | -1.274 |
| 2900 | 31.376 | 138.983 | 81.595 | | 76.998 | -1.387 |
| 3000 | 31.581 | 140.050 | 84.743 | | 85.725 | -1.493 |

PREVIOUS:

CURRENT: March 1962

Lead (Pb)

Pb₁(cr,l)

Lead (Pb) $A_r = 207.2$ Lead (Pb) $Pb_1(g)$

IPb(g) = 59819.4 ± 0.3 cm⁻¹ $\Delta_f H^\circ(0 K) = 195.88 \pm 0.80$ kJ·mol⁻¹ $\log K_r$
 S°(298.15 K) = 175.374 ± 0.020 J·K⁻¹·mol⁻¹ $\Delta_f H^\circ(298.15 K) = 195.20 \pm 0.80$ kJ·mol⁻¹

| Electronic State | Levels, cm ⁻¹ | Quantum Weights, g |
|-----------------------------|--------------------------|--------------------|
| ³ P ₀ | 0.00 | 1 |
| ³ P ₁ | 7819.2626 | 3 |
| ³ P ₂ | 10650.3271 | 5 |
| ¹ D ₂ | 21457.90 | 5 |
| ¹ S ₀ | 29466.81 | 1 |

Enthalpy of Formation

The adopted enthalpy of formation value for Pb(g), $\Delta_f H^\circ(298.15 K) = 195.20 \pm 0.80$ kJ·mol⁻¹, is that recommended by CODATA.¹ This value was calculated, according to CODATA, from the vapor pressure measurements cited by Hultgren *et al.*,² and the more recent measurements by Andon *et al.*,³ Chang, *et al.*,⁴ Kim and Cosgarea,⁵ and Shiu and Miner.⁶

Heat Capacity and Entropy

The information on electronic energy levels and quantum weights, given by Moore,^{7,8} is incomplete because many theoretically predicted levels have not been observed. Our calculations indicate that any reasonable method of filling in these missing levels (for n<21) and cutting off the summation in the partition function⁹ has little effect on the thermodynamic functions to 6000 K. This is a result of the high energy of all levels other than those listed above; the next excited state is approximately 34950 cm⁻¹ above the ground state. Although we list only a few levels above, all levels listed by Moore^{7,8} are considered in the calculation. The reported uncertainty in S°(298.15 K) is due to uncertainties in the relative atomic mass and the fundamental constants. Extension of these calculations above 6000 K may require consideration of the excited states (n>21) and use of different fill and cutoff procedures.⁹

The thermal functions at 298.15 K differ from the CODATA recommendations¹ for two reasons. First, the entropy differs by 0.1094 J·K⁻¹·mol⁻¹ because this table uses a reference pressure of 1 bar, whereas CODATA recommendations are based on 1 atm. Second, small changes, 0.005 J·K⁻¹·mol⁻¹, arise due to the use of slightly different values for the fundamental constants.

References

- J. D. Cox, chairman, CODATA Task Group on Key Values for Thermodynamics, *J. Chem. Thermodyn.* **10**, 903 (1978); CODATA Bulletin No. 28, (1978).
- R. Hultgren, P. D. Desai, *et al.*, Selected Values of the Thermodynamic Properties of the Elements, American Society for Metals, Metals Park, Ohio, (1973).
- J. L. Andon, J. F. Martin and K. C. Mills, *J. Chem. Soc. A1788* (1971).
- Y. A. Chang, G. C. Willhite, M. Lathrop and I. Gyuk, *Acta Met.* **19**, 795 (1971).
- J. H. Kim and A. Cosgarea, Jr., *J. Chem. Phys.* **44**, 806 (1966).
- D. H. Shiu and Z. A. Munir, *Metallurg. Trans.* **2**, 2953 (1973).
- C. E. Moore, U. S. Nat. Bur. Stand., NSRDS-NBS-35, Volume III, 1970, [Reprint of NBS Circular 467, Volume III, 1958].
- C. E. Moore, U. S. Nat. Bur. Stand., NSRDS-34, 8 pp. (1970).
- J. R. Downey, Jr. The Dow Chemical Company Co., Rept. AFOSR-TR-78-0960, Contract No. F44670-75-1-0048, (1978).

| T/K | Enthalpy Reference Temperature = T _r = 298.15 K | | Standard State Pressure = P° = 0.1 MPa | | log K _r |
|----------|--|--------------------------------------|--|----------------------|--------------------|
| | C _p ^a | S° - [G° - H°(T _r)]/T | H° - H°(T _r) | Δ _f G° | |
| | J·K ⁻¹ ·mol ⁻¹ | J·K ⁻¹ ·mol ⁻¹ | KJ·mol ⁻¹ | KJ·mol ⁻¹ | |
| 0 | 0 | INFINITE | -6.197 | 195.881 | INFINITE |
| 100 | 20.786 | 152.667 | -4.119 | 184.610 | -96.430 |
| 200 | 20.786 | 167.075 | -2.040 | 171.187 | -45.252 |
| 250 | 20.786 | 171.713 | -1.001 | 167.577 | -35.013 |
| 298.15 | 20.786 | 175.374 | 0 | 162.228 | -28.422 |
| 300 | 20.786 | 175.503 | 0.038 | 162.023 | -28.211 |
| 350 | 20.786 | 178.707 | 0.778 | 156.520 | -23.559 |
| 400 | 20.786 | 181.483 | 1.717 | 151.064 | -19.727 |
| 450 | 20.786 | 183.931 | 3.156 | 145.651 | -16.907 |
| 500 | 20.786 | 186.121 | 4.196 | 140.278 | -14.655 |
| 600 | 20.786 | 189.911 | 6.274 | 129.648 | -11.287 |
| 700 | 20.787 | 193.115 | 8.353 | 119.958 | -8.951 |
| 800 | 20.790 | 195.891 | 10.432 | 110.409 | -7.209 |
| 900 | 20.801 | 198.340 | 12.511 | 100.976 | -5.861 |
| 1000 | 20.829 | 200.533 | 14.592 | 91.642 | -4.787 |
| 1100 | 20.888 | 202.520 | 16.678 | 83.394 | -3.913 |
| 1200 | 20.991 | 204.342 | 18.771 | 76.221 | -3.187 |
| 1300 | 21.155 | 206.028 | 20.878 | 70.113 | -2.576 |
| 1400 | 21.394 | 207.604 | 23.005 | 65.063 | -2.054 |
| 1500 | 21.717 | 209.091 | 25.160 | 60.983 | -1.604 |
| 1600 | 22.132 | 210.505 | 27.352 | 57.912 | -1.212 |
| 1700 | 22.640 | 211.862 | 29.589 | 55.801 | -0.867 |
| 1800 | 23.239 | 213.172 | 31.883 | 54.627 | -0.628 |
| 1900 | 23.922 | 214.447 | 34.240 | 54.386 | -0.488 |
| 2000 | 24.680 | 215.693 | 36.669 | 54.167 | -0.444 |
| 2099.022 | 24.831 | 215.927 | 37.140 | 54.167 | --- |
| 2100 | 25.499 | 216.916 | 39.178 | 0 | 0 |
| 2200 | 26.365 | 218.122 | 41.771 | 0 | 0 |
| 2300 | 27.261 | 219.314 | 44.452 | 0 | 0 |
| 2400 | 28.173 | 220.493 | 47.224 | 0 | 0 |
| 2500 | 29.084 | 221.662 | 50.086 | 0 | 0 |
| 2600 | 29.979 | 222.820 | 53.040 | 0 | 0 |
| 2700 | 30.844 | 223.968 | 56.081 | 0 | 0 |
| 2800 | 31.669 | 225.105 | 59.217 | 0 | 0 |
| 2900 | 32.444 | 226.230 | 62.403 | 0 | 0 |
| 3000 | 33.160 | 227.342 | 65.694 | 0 | 0 |
| 3100 | 33.813 | 228.440 | 69.043 | 0 | 0 |
| 3200 | 34.498 | 229.523 | 72.454 | 0 | 0 |
| 3300 | 35.213 | 230.589 | 75.921 | 0 | 0 |
| 3400 | 35.960 | 231.639 | 79.435 | 0 | 0 |
| 3500 | 36.737 | 232.669 | 82.990 | 0 | 0 |
| 3600 | 36.048 | 233.680 | 86.580 | 0 | 0 |
| 3700 | 36.296 | 234.672 | 90.198 | 0 | 0 |
| 3800 | 36.485 | 235.642 | 93.837 | 0 | 0 |
| 3900 | 36.618 | 236.592 | 97.493 | 0 | 0 |
| 4000 | 36.700 | 237.520 | 101.159 | 0 | 0 |
| 4100 | 36.737 | 238.427 | 104.831 | 0 | 0 |
| 4200 | 36.733 | 239.312 | 108.505 | 0 | 0 |
| 4300 | 36.692 | 240.176 | 112.177 | 0 | 0 |
| 4400 | 36.619 | 241.019 | 115.842 | 0 | 0 |
| 4500 | 36.518 | 241.841 | 119.499 | 0 | 0 |
| 4600 | 36.395 | 242.642 | 123.145 | 0 | 0 |
| 4700 | 36.252 | 243.423 | 126.778 | 0 | 0 |
| 4800 | 36.093 | 244.185 | 130.395 | 0 | 0 |
| 4900 | 35.923 | 244.927 | 133.996 | 0 | 0 |
| 5000 | 35.743 | 245.651 | 137.579 | 0 | 0 |
| 5100 | 35.557 | 246.357 | 141.144 | 0 | 0 |
| 5200 | 35.367 | 247.046 | 144.690 | 0 | 0 |
| 5300 | 35.175 | 247.717 | 148.217 | 0 | 0 |
| 5400 | 34.985 | 248.373 | 151.725 | 0 | 0 |
| 5500 | 34.796 | 249.013 | 155.214 | 0 | 0 |
| 5600 | 34.612 | 249.639 | 158.685 | 0 | 0 |
| 5700 | 34.434 | 250.250 | 162.137 | 0 | 0 |
| 5800 | 34.263 | 250.847 | 165.572 | 0 | 0 |
| 5900 | 34.097 | 251.431 | 168.989 | 0 | 0 |
| 6000 | 33.942 | 252.003 | 172.390 | 0 | 0 |

PREVIOUS: March 1962 (1 atm) CURRENT: March 1983 (1 bar)

Lead, Ion (Pb⁺)

$M_r = 207.19945$

IDEAL GAS

$IP(Pb^+, g) = 121243 \pm 3 \text{ cm}^{-1}$
 $S^\circ(298.15 \text{ K}) = 181.137 \pm 0.02 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$
 $\Delta_f H^\circ(0 \text{ K}) = 911.480 \pm 0.5 \text{ kJ} \cdot \text{mol}^{-1}$
 $\Delta_f H^\circ(298.15 \text{ K}) = [916.996] \text{ kJ} \cdot \text{mol}^{-1}$

| Electronic Levels and Quantum Weights | |
|---------------------------------------|-------|
| State | g_i |
| $^1P_{1/2}$ | 2 |
| $^3P_{3/2}$ | 4 |

Enthalpy of Formation

$\Delta_f H^\circ(Pb^+, g, 0 \text{ K})$ is calculated from $\Delta_f H^\circ(Pb, g, 0 \text{ K})$ using the spectroscopic value of $IP(Pb) = 59819.4 \pm 0.3 \text{ cm}^{-1}$ ($715.599 \pm 0.004 \text{ kJ} \cdot \text{mol}^{-1}$) from Moore.² The ionization limit is converted from cm^{-1} to $\text{kJ} \cdot \text{mol}^{-1}$ using the factor, $1 \text{ cm}^{-1} = 0.01196266 \text{ kJ} \cdot \text{mol}^{-1}$, which is appearance potential data.

$\Delta_f H^\circ(Pb^+, g, 298.15 \text{ K})$ is calculated from $\Delta_f H^\circ(Pb, g, 0 \text{ K})$ by using $IP(Pb)$ with JANAF¹ enthalpies, $H^\circ(0 \text{ K}) - H^\circ(298.15 \text{ K})$, for $Pb(g)$, $Pb^+(g)$, and $e^-(ref)$. $\Delta_f H^\circ(Pb \rightarrow Pb^+ + e^-, 298.15 \text{ K})$ differs from a room temperature threshold energy due to inclusion of these enthalpies and to threshold effects discussed by Rosenstock *et al.*⁴ $\Delta_f H^\circ(298.15 \text{ K})$ should be changed by $-6.197 \text{ kJ} \cdot \text{mol}^{-1}$ if it is to be used in the ion convention that excludes the enthalpy of the electron.

Heat Capacity and Entropy

The information on electronic energy levels and quantum weights, given by Moore,^{2,6} is incomplete because many theoretically predicted levels have not been observed. Our calculations indicate that any reasonable method of filling in these missing levels and cutting off the summation in the partition function⁷ has no effect on the thermodynamic functions to 6000 K. This is a result of the high energy of all levels other than the ground state and the first excited state; the next excited state is 57911 cm^{-1} , above the ground state. Since inclusion of these excited states has no effect on the thermodynamic functions (to 6000 K), we list only the ground state and the first excited states. The reported uncertainty in $S^\circ(298.15 \text{ K})$ is due to uncertainties in the relative ionic mass and the fundamental constants. Extension of these calculations above 6000 K may require consideration of the excited states and use of different fill and cutoff procedures.⁸

References

- JANAF Thermochemical Tables: $Pb(g)$, 3-31-62; $e^-(ref)$, 3-31-82.
- E. Moore, U. S. Nat. Bur. Stand., NSRDS-NBS-34 (1970).
- E. R. Cohen and B. N. Taylor, J. Phys. Chem. Ref. Data 2, 663 (1973).
- H. M. Rosenstock, K. Draxl *et al.*, J. Phys. Chem. Ref. Data 6, Supp. 1, 783 pp. (1977).
- R. D. Levin and S. G. Lias, U. S. Nat. Bur. Stand., NSRDS-NBS-71, 634 pp. (1982).
- C. E. Moore, U. S. Nat. Bur. Stand., NSRDS-NBS-35, Volume 3, (1971) [Reprint of NBS Circular 467, Volume 3, 1958].
- J. R. Downey, Jr., The Dow Chemical Company, AFOSR-TR-0960, Contract No. F44620-75-1-0048, (1978).

| T/K | C _v | S ^o - [C _v - R ln(T ₂ /T ₁)]/T | Enthalpy Reference Temperature = T ₂ = 298.15 K | | H ^o - H ^o (T ₂) | Δ _f G ^o | log K _r | Pb ⁺ (g) |
|--------|----------------|---|--|--------------------------------------|---|-------------------------------|--------------------|---------------------|
| | | | J·K ⁻¹ ·mol ⁻¹ | J·K ⁻¹ ·mol ⁻¹ | | | | |
| 0 | 0 | INFINITE | 0 | 0 | -6.197 | 911.480 | | |
| 100 | 20.786 | 158.430 | 199.618 | 199.618 | -4.119 | | | |
| 200 | 20.786 | 172.838 | 183.039 | 183.039 | -2.040 | | | |
| 250 | 20.786 | 177.476 | 181.480 | 181.480 | -1.001 | | | |
| 298.15 | 20.786 | 181.137 | 181.137 | 181.137 | 0 | 916.996 | | |
| 300 | 20.786 | 181.138 | 181.138 | 181.138 | 0.038 | | | |
| 350 | 20.786 | 184.470 | 181.391 | 181.391 | 1.078 | | | |
| 400 | 20.786 | 187.246 | 181.953 | 181.953 | 2.117 | | | |
| 450 | 20.786 | 189.694 | 182.680 | 182.680 | 3.156 | | | |
| 500 | 20.786 | 191.884 | 183.493 | 183.493 | 4.196 | | | |
| 600 | 20.786 | 195.674 | 185.217 | 185.217 | 6.774 | | | |
| 700 | 20.786 | 198.978 | 186.943 | 186.943 | 8.333 | | | |
| 800 | 20.786 | 201.653 | 188.614 | 188.614 | 10.431 | | | |
| 900 | 20.786 | 203.802 | 190.202 | 190.202 | 12.510 | | | |
| 1000 | 20.786 | 206.292 | 191.705 | 191.705 | 14.589 | | | |
| 1100 | 20.786 | 208.273 | 193.121 | 193.121 | 16.667 | | | |
| 1200 | 20.786 | 210.081 | 194.460 | 194.460 | 18.746 | | | |
| 1300 | 20.787 | 211.745 | 195.726 | 195.726 | 20.825 | | | |
| 1400 | 20.788 | 213.286 | 196.926 | 196.926 | 22.903 | | | |
| 1500 | 20.790 | 214.720 | 198.065 | 198.065 | 24.982 | | | |
| 1600 | 20.794 | 216.062 | 199.149 | 199.149 | 27.061 | | | |
| 1700 | 20.802 | 217.323 | 200.181 | 200.181 | 29.141 | | | |
| 1800 | 20.813 | 218.512 | 201.167 | 201.167 | 31.222 | | | |
| 1900 | 20.830 | 219.638 | 202.109 | 202.109 | 33.304 | | | |
| 2000 | 20.854 | 220.707 | 203.013 | 203.013 | 35.388 | | | |
| 2100 | 20.886 | 221.725 | 203.880 | 203.880 | 37.475 | | | |
| 2200 | 20.927 | 222.698 | 204.713 | 204.713 | 39.566 | | | |
| 2300 | 20.979 | 223.629 | 205.516 | 205.516 | 41.661 | | | |
| 2400 | 21.041 | 224.523 | 206.289 | 206.289 | 43.762 | | | |
| 2500 | 21.116 | 225.383 | 207.036 | 207.036 | 45.870 | | | |
| 2600 | 21.202 | 226.213 | 207.757 | 207.757 | 47.985 | | | |
| 2700 | 21.301 | 227.015 | 208.456 | 208.456 | 50.110 | | | |
| 2800 | 21.411 | 227.792 | 209.133 | 209.133 | 52.246 | | | |
| 2900 | 21.534 | 228.543 | 209.789 | 209.789 | 54.393 | | | |
| 3000 | 21.667 | 229.278 | 210.427 | 210.427 | 56.553 | | | |
| 3100 | 21.811 | 229.990 | 211.046 | 211.046 | 58.727 | | | |
| 3200 | 21.964 | 230.683 | 211.649 | 211.649 | 60.915 | | | |
| 3300 | 22.126 | 231.364 | 212.236 | 212.236 | 63.120 | | | |
| 3400 | 22.296 | 232.037 | 212.809 | 212.809 | 65.341 | | | |
| 3500 | 22.472 | 232.675 | 213.367 | 213.367 | 67.579 | | | |
| 3600 | 22.653 | 233.311 | 213.912 | 213.912 | 69.835 | | | |
| 3700 | 22.839 | 233.934 | 214.445 | 214.445 | 72.110 | | | |
| 3800 | 23.029 | 234.546 | 214.966 | 214.966 | 74.403 | | | |
| 3900 | 23.220 | 235.146 | 215.476 | 215.476 | 76.716 | | | |
| 4000 | 23.413 | 235.737 | 215.975 | 215.975 | 79.048 | | | |
| 4100 | 23.606 | 236.317 | 216.464 | 216.464 | 81.398 | | | |
| 4200 | 23.798 | 236.888 | 216.944 | 216.944 | 83.769 | | | |
| 4300 | 23.989 | 237.451 | 217.414 | 217.414 | 86.158 | | | |
| 4400 | 24.177 | 238.004 | 217.876 | 217.876 | 88.566 | | | |
| 4500 | 24.362 | 238.550 | 218.329 | 218.329 | 90.993 | | | |
| 4600 | 24.543 | 239.087 | 218.774 | 218.774 | 93.439 | | | |
| 4700 | 24.720 | 239.617 | 219.212 | 219.212 | 95.902 | | | |
| 4800 | 24.892 | 240.139 | 219.646 | 219.646 | 98.383 | | | |
| 4900 | 25.059 | 240.654 | 220.066 | 220.066 | 100.880 | | | |
| 5000 | 25.220 | 241.162 | 220.483 | 220.483 | 103.394 | | | |
| 5100 | 25.375 | 241.663 | 220.894 | 220.894 | 105.924 | | | |
| 5200 | 25.523 | 242.157 | 221.298 | 221.298 | 108.469 | | | |
| 5300 | 25.665 | 242.645 | 221.696 | 221.696 | 111.028 | | | |
| 5400 | 25.800 | 243.126 | 222.088 | 222.088 | 113.602 | | | |
| 5500 | 25.928 | 243.600 | 222.475 | 222.475 | 116.188 | | | |
| 5600 | 26.049 | 244.069 | 222.857 | 222.857 | 118.787 | | | |
| 5700 | 26.164 | 244.531 | 223.233 | 223.233 | 121.398 | | | |
| 5800 | 26.271 | 244.987 | 223.604 | 223.604 | 124.020 | | | |
| 5900 | 26.371 | 245.437 | 223.970 | 223.970 | 126.652 | | | |
| 6000 | 26.465 | 245.881 | 224.332 | 224.332 | 129.294 | | | |

PREVIOUS:

CURRENT: March 1983 (1 bar)

Lead, Ion (Pb⁺)

Pb⁺(g)

Pb⁺(g)

M_r = 207.20055 Lead, Ion (Pb⁺)

IDEAL GAS

Lead, Ion (Pb⁺)

EA(Pb, g) = 0.364 ± 0.008 eV
 S^o(298.15 K) = 186.900 ± 0.002 J·K⁻¹·mol⁻¹
 $\Delta H_f^o(0\text{ K}) = 160.76 \pm 3 \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta H_f^o(298.15\text{ K}) = [153.882] \text{ kJ}\cdot\text{mol}^{-1}$

| Electronic Level and Quantum Weight State | ϵ_e , cm ⁻¹ | g _r |
|---|---------------------------------|----------------|
| ⁴ S _{3/2} | 0.0 | 4 |

Enthalpy of Formation

$\Delta H_f^o(\text{Pb}^+, \text{g}, 0\text{ K})$ is calculated from $\Delta H_f^o(\text{Pb}, \text{g}, 0\text{ K})$ using the adopted electron affinity of EA(Pb) = 0.364 ± 0.008 eV (35 120 ± 0.772 kJ·mol⁻¹). This value, recommended by Hotop and Lineberger,² is based on a laser photodetachment electron spectroscopy study.³ Additional information on Pb⁺(g) may be obtained in the critical discussions of Hotop and Lineberger,^{2,4} Rosenstock *et al.*,⁵ and Massey.⁶

$\Delta H_f^o(\text{Pb}^+, \text{g}, 298.15\text{ K})$ is obtained from $\Delta H_f^o(\text{Pb}, \text{g}, 0\text{ K})$ by using EA(Pb) with JANAF¹ enthalpies, $H_f^o(0\text{ K}) - H_f^o(298.15\text{ K})$, for Pb⁺(g), Pb(g), and e⁻ (ref. $\Delta H_f^o(\text{Pb}^+ \rightarrow \text{Pb} + \text{e}^-, 298.15\text{ K})$ differs from a room-temperature threshold energy due to inclusion of these enthalpies and to threshold effects discussed by Rosenstock *et al.*,⁵ $\Delta H_f^o(298.15\text{ K})$ should be changed by + 6.197 kJ·mol⁻¹ if it is to be used in the ion convention that excludes the enthalpy of the electron.

Heat Capacity and Entropy

The ground state electronic configuration for Pb⁺(g) is given by Hotop and Lineberger^{2,4} and Rosenstock *et al.*,⁵ Lacking any experimental evidence as to the stability of any excited states, we assume that no stable excited states exist.

References

- ¹JANAF Thermochemical Tables: Pb(g), 3-31-83; e⁻ (ref), 3-31-82.
- ²H. Hotop and W. C. Lineberger, *J. Phys. Chem. Ref. Data*, 14, 731 (1985).
- ³C. S. Feigerle, R. R. Cordermann and W. C. Lineberger, *J. Chem. Phys.* 74, 1513 (1981).
- ⁴H. Hotop and W. C. Lineberger, *J. Phys. Chem. Ref. Data* 4, 539 (1975).
- ⁵H. M. Rosenstock, K. Draxl *et al.*, *J. Phys. Chem. Ref. Data* 6, Supp. 1, 783 pp. (1977).
- ⁶H. S. W. Massey, "Negative Ions", 3rd ed., Cambridge University Press, Cambridge, 741 pp. (1976).

| T/K | Enthalpy Reference Temperature = T _r = 298.15 K | | Standard State Pressure = P ^o = 0.1 MPa | | log K _r |
|--------|--|---|--|-----------------|--------------------|
| | C _p ^o | S ^o - [C _p ^o - H ^o (T _r)]/T | H ^o - H ^o (T _r) | ΔH ^o | |
| 0 | 0. | INFINITE | -6.197 | 160.761 | -21.677 |
| 100 | 20.786 | 164.193 | -4.119 | 160.761 | -21.510 |
| 200 | 20.786 | 178.601 | -1.802 | 160.761 | -17.700 |
| 250 | 20.786 | 183.239 | -1.001 | 160.761 | -14.868 |
| 298.15 | 20.786 | 186.900 | 0. | 153.882 | -12.685 |
| 300 | 20.786 | 187.029 | 0.038 | 153.833 | -10.955 |
| 350 | 20.786 | 190.233 | 1.078 | 152.479 | -9.397 |
| 400 | 20.786 | 193.009 | 1.716 | 151.104 | -8.265 |
| 450 | 20.786 | 195.457 | 1.884 | 149.707 | -7.430 |
| 500 | 20.786 | 197.647 | 1.996 | 148.290 | -6.874 |
| 600 | 20.786 | 201.437 | 2.153 | 145.401 | -6.197 |
| 700 | 20.786 | 204.641 | 2.332 | 142.079 | -5.596 |
| 800 | 20.786 | 207.417 | 2.527 | 138.379 | -5.065 |
| 900 | 20.786 | 209.865 | 2.731 | 134.356 | -4.600 |
| 1000 | 20.786 | 212.055 | 2.946 | 131.076 | -4.200 |
| 1100 | 20.786 | 214.036 | 3.171 | 128.622 | -3.874 |
| 1200 | 20.786 | 215.845 | 3.406 | 126.997 | -3.607 |
| 1300 | 20.786 | 217.508 | 3.651 | 125.697 | -3.377 |
| 1400 | 20.786 | 219.049 | 3.906 | 124.206 | -3.172 |
| 1500 | 20.786 | 220.483 | 4.171 | 122.592 | -3.000 |
| 1600 | 20.786 | 221.824 | 4.446 | 120.942 | -2.857 |
| 1700 | 20.786 | 223.085 | 4.731 | 119.333 | -2.738 |
| 1800 | 20.786 | 224.273 | 5.026 | 117.770 | -2.640 |
| 1900 | 20.786 | 225.396 | 5.331 | 116.258 | -2.559 |
| 2000 | 20.786 | 226.463 | 5.646 | 114.792 | -2.492 |
| 2100 | 20.786 | 227.477 | 5.971 | 113.377 | -2.436 |
| 2200 | 20.786 | 228.444 | 6.306 | 112.009 | -2.390 |
| 2300 | 20.786 | 229.368 | 6.651 | 110.684 | -2.352 |
| 2400 | 20.786 | 230.252 | 7.006 | 109.401 | -2.321 |
| 2500 | 20.786 | 231.101 | 7.371 | 108.157 | -2.296 |
| 2600 | 20.786 | 231.916 | 7.746 | 107.000 | -2.276 |
| 2700 | 20.786 | 232.701 | 8.131 | 105.929 | -2.260 |
| 2800 | 20.786 | 233.457 | 8.526 | 104.942 | -2.248 |
| 2900 | 20.786 | 234.186 | 8.931 | 104.037 | -2.239 |
| 3000 | 20.786 | 234.891 | 9.346 | 103.212 | -2.232 |
| 3100 | 20.786 | 235.572 | 9.771 | 102.466 | -2.227 |
| 3200 | 20.786 | 236.232 | 10.206 | 101.798 | -2.223 |
| 3300 | 20.786 | 236.872 | 10.651 | 101.207 | -2.220 |
| 3400 | 20.786 | 237.492 | 11.106 | 100.692 | -2.218 |
| 3500 | 20.786 | 238.095 | 11.571 | 100.252 | -2.216 |
| 3600 | 20.786 | 238.680 | 12.046 | 99.886 | -2.215 |
| 3700 | 20.786 | 239.250 | 12.531 | 99.593 | -2.214 |
| 3800 | 20.786 | 239.804 | 13.026 | 99.371 | -2.213 |
| 3900 | 20.786 | 240.344 | 13.531 | 99.219 | -2.212 |
| 4000 | 20.786 | 240.870 | 14.046 | 99.126 | -2.211 |
| 4100 | 20.786 | 241.384 | 14.571 | 99.091 | -2.210 |
| 4200 | 20.786 | 241.885 | 15.106 | 99.111 | -2.209 |
| 4300 | 20.786 | 242.374 | 15.651 | 99.184 | -2.208 |
| 4400 | 20.786 | 242.852 | 16.206 | 99.318 | -2.207 |
| 4500 | 20.786 | 243.319 | 16.771 | 99.512 | -2.206 |
| 4600 | 20.786 | 243.776 | 17.346 | 99.766 | -2.205 |
| 4700 | 20.786 | 244.223 | 17.931 | 100.080 | -2.204 |
| 4800 | 20.786 | 244.660 | 18.526 | 100.454 | -2.203 |
| 4900 | 20.786 | 245.089 | 19.131 | 100.888 | -2.202 |
| 5000 | 20.786 | 245.509 | 19.746 | 101.382 | -2.201 |
| 5100 | 20.786 | 245.920 | 20.371 | 101.936 | -2.200 |
| 5200 | 20.786 | 246.324 | 21.006 | 102.550 | -2.199 |
| 5300 | 20.786 | 246.720 | 21.651 | 103.224 | -2.198 |
| 5400 | 20.786 | 247.108 | 22.306 | 103.958 | -2.197 |
| 5500 | 20.786 | 247.490 | 22.971 | 104.752 | -2.196 |
| 5600 | 20.786 | 247.864 | 23.646 | 105.606 | -2.195 |
| 5700 | 20.786 | 248.232 | 24.331 | 106.520 | -2.194 |
| 5800 | 20.786 | 248.594 | 25.026 | 107.494 | -2.193 |
| 5900 | 20.786 | 248.949 | 25.731 | 108.528 | -2.192 |
| 6000 | 20.786 | 249.298 | 26.446 | 109.622 | -2.191 |

PREVIOUS:

CURRENT: March 1983 (1 bar)

Lead, Ion (Pb⁺)

Pb₃S₄(cr)

Lead Sulfide (Pbs)

M_r = 239.26

CRYSTAL

Lead Sulfide (Pbs)

$S^{\circ}(298.15\text{ K}) = 91.34 \pm 1.7\text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
 $T_{\text{fus}} = 1386.5 \pm 1.5\text{ K}$
 $\Delta H_f^{\circ}(0\text{ K}) = -98.55 \pm 2.1\text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta H_f^{\circ}(298.15\text{ K}) = -98.32 \pm 2.1\text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_{\text{red}}H^{\circ} = 18.83 \pm 6.3\text{ kJ}\cdot\text{mol}^{-1}$

Enthalpy of Formation

2nd and 3rd law analyses are made of the equilibrium data of Jellinek *et al.*,¹ Sudo,² and Stubbs and Birchenall,³ the Gibbs free energies (via emf measurements) of Kapustinskii and Makolkina,⁴ and of Kiukkola and Wagner,⁵ and the emf data reported by Thompson and Flengas.⁶ The results of our analyses using auxiliary data⁷ are summarized in the following table.

| Source | Reaction* | T/K | Data Points | $\Delta H_f^{\circ}(298.15\text{ K})$, kcal·mol ⁻¹ | 2nd law | 3rd law | Drift | $\Delta H_f^{\circ}(298.15\text{ K})$, kcal·mol ⁻¹ |
|--------|-----------|----------|-------------|--|---------|---------|--------------|--|
| 1 | A | 788–1273 | 7 | -18.4 ± 0.8 | -18.60 | -18.60 | -0.16 ± 0.80 | -22.5 |
| 2 | A | 855–1048 | Equation | -18.0 | -20.12 | -20.12 | -2.2 | -24.0 |
| 3 | A | 859–1193 | 30 | -19.3 ± 0.1 | -19.76 | -19.76 | -0.42 ± 0.12 | -23.6 |
| 4 | B | 288–308 | 3 | -17.7 ± 0.5 | -16.63 | -16.63 | 3.7 ± 1.6 | -21.5 |
| 5 | C | 523–573 | 2 | -24.7 | -23.84 | -23.84 | 1.5 | -23.5 |
| 5 | D | 600–700 | 4 | -24.5 ± 0.2 | -24.79 | -24.79 | -0.45 ± 0.32 | -23.4 |
| 6 | E | 773–1071 | 12 | -40.7 ± 0.5 | -39.63 | -39.63 | 1.2 ± 0.6 | -23.2 |

* A) PbO + H₂S(g) = PbS(cr) + H₂(g)
 B) Pb(cr) + H₂S(g) = PbS(cr) + H₂(g)
 C) Pb(cr) + S(l) = PbS(cr)

D) PbO + S(l) = PbS(cr)
 E) PbO + 1/2 S₂(g) = PbS(cr)

The experiences of Jellinek *et al.*¹ are unsatisfactory⁸ and are superseded by two later studies^{2,3} of the same equilibrium. The Gibbs energies of Kapustinskii and Makolkina⁴ may be dismissed as biased on the basis of inconsistencies in both ΔH_f° and entropy (drift). The other studies^{2,3,5,6} are consistent with the adopted $\Delta H_f^{\circ}(298.15\text{ K})$ of $23.5 \pm 0.5\text{ kcal}\cdot\text{mol}^{-1}$.

We also calculate $\Delta H_f^{\circ} = -23.5\text{ kcal}\cdot\text{mol}^{-1}$ from $\Delta H_f^{\circ}(293\text{ K}) = -13.38 \pm 0.2\text{ kcal}\cdot\text{mol}^{-1}$ for the reaction $\text{Pb}(\text{NO}_3)_2(\text{aq}) + 3000\text{ H}_2\text{O} + \text{H}_2\text{S}(\text{aq}) \rightarrow \text{PbS}(\text{cr}) + 2\text{HNO}_3(\text{aq}) + 2000\text{ H}_2\text{O}$ studied calorimetrically by Zeumer and Roth.⁹ The uncertainty of this calorimetric ΔH_f° may approach $\pm 1\text{ kcal}\cdot\text{mol}^{-1}$ due to the auxiliary data¹⁰ and approximations used in our calculation. Recent DTA data¹¹ for Pb(cr) + S(l) → PbS(cr) gave $\Delta H_f^{\circ}(480\text{ K}) = -23.4 \pm 0.3\text{ kcal}\cdot\text{mol}^{-1}$ which we reduce to $\Delta H_f^{\circ}(298.15\text{ K}) = -22.5 \pm 1\text{ kcal}\cdot\text{mol}^{-1}$. The uncertainty assigned¹¹ to ΔH_f° appears to be too optimistic. Korshunov¹² obtained $\Delta H_f^{\circ} = -22.38\text{ kcal}\cdot\text{mol}^{-1}$ by combustion of S–Mg–Pb mixtures in a bomb, but the chemical reactions probably were not characterized adequately.

Heat Capacity and Entropy

C_p° is from the work of Parkinson and Quarrington,¹³ C_p° given as smoothed values, 20–260 K and of Anderson,¹⁴ (54–289 K) which were graphically smoothed and extrapolated to 300 K. The data of Parkinson and Quarrington and Anderson are in good agreement; Anderson's values show more scatter. The largest deviation of the Parkinson and Quarrington values from the adopted values is +0.4% at 210 K. Anderson's points are mostly within less than $\pm 1\%$ of the selected values.

Above 300 K, C_p° values are derived from the drop calorimetric enthalpies of Thompson and Flengas,¹⁵ (353–1281 K) with the constraint to join smoothly with the low temperature data. The observed enthalpies differ from the adopted values by +4% at 400 K, above 500 K the deviation is generally within $\pm 0.4\%$.

Also considered were the low temperature heat capacities measured by Eastman and Rodebush,¹⁶ (64–283 K) and Kelley's equations¹⁷ which are based on the work of Bornemann and Hengstenberg,¹⁸ (273–873 K). The Eastman and Rodebush data appears to be high above 200 K. At 900 K the enthalpy calculated from Kelley's equation is 4% higher than the adopted value.

$S^{\circ}(20\text{ K})$ of $0.83\text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$, given by Kelley and King¹⁹ is adopted here.

Fusion Data – Refer to the liquid table for details.

Sublimation Data – Refer to the ideal gas table for details.

References

1. K. Jellinek and A. Deibel, *Z. Electrochem.* **35**, 451 (1929); K. Jellinek and J. Zakowski, *Z. Anorg. Chem.* **142**, 26 (1925).
2. K. Sudo, *Sci. Repts. Research Insts., Tohoku Univ.* **A2**, 325 (1950); *Chem. Abstr.* **45**, 10011h (1951).
3. J. R. Stubbs and C. E. Birchenall, *Trans. AIME* **215**, 535 (1959).
4. A. F. Kapustinskii and I. A. Makolkina, *J. Phys. Chem. USSR* **12**, 371 (1938).
5. K. Kiukkola and C. Wagner, *J. Electrochem. Soc.* **104**, 379 (1957).
6. W. T. Thompson and S. N. Flengas, *J. Electrochem. Soc.* **118**, 419 (1971).
7. JANAF Thermochemical Tables: Pb(O), 3 31 62; H₂S(g), S(l), S₂(g), 12–31–65.

Continued on page 1847

Lead Sulfide (Pbs)

Pb₃S₄(cr)

| T/K | C_p° | Enthalpy Reference Temperature = T, = 298.15 K | | Standard State Pressure = P ^o = 0.1 MPa | | log K _r |
|--------|---------------|--|----------------------------|--|----------------------|--------------------|
| | | $S^{\circ} - [G^{\circ} - H^{\circ}(T)]/T$ | $H^{\circ} - H^{\circ}(T)$ | $\Delta_f H^{\circ}$ | $\Delta_f G^{\circ}$ | |
| 0 | 0 | INFINITE | -11.511 | -98.545 | -98.545 | INFINITE |
| 100 | 39.748 | 41.296 | -9.244 | -98.734 | -98.734 | 51.152 |
| 200 | 47.614 | 71.920 | -4.781 | -98.437 | -97.239 | 25.396 |
| 298.15 | 49.438 | 91.343 | 0 | -98.324 | -96.683 | 16.939 |
| 300 | 49.455 | 91.649 | 0.091 | -98.324 | -96.675 | 16.833 |
| 400 | 50.459 | 105.008 | 5.085 | -100.657 | -96.024 | 12.339 |
| 500 | 51.463 | 117.375 | 97.013 | -102.502 | -94.688 | 9.292 |
| 600 | 52.384 | 126.839 | 101.217 | -103.584 | -93.039 | 8.100 |
| 700 | 53.346 | 134.988 | 105.473 | -103.584 | -90.400 | 6.746 |
| 800 | 54.308 | 142.176 | 109.620 | -110.310 | -87.616 | 5.771 |
| 900 | 55.271 | 148.627 | 113.602 | -110.310 | -83.658 | 4.855 |
| 1000 | 56.191 | 154.498 | 117.402 | -163.312 | -74.763 | 3.905 |
| 1100 | 57.153 | 159.900 | 121.023 | -162.439 | -65.949 | 3.132 |
| 1200 | 58.074 | 164.912 | 124.474 | -161.459 | -57.220 | 2.491 |
| 1300 | 59.036 | 169.599 | 127.767 | -160.375 | -48.577 | 1.952 |
| 1400 | 59.957 | 174.008 | 130.914 | -159.206 | -40.070 | 1.493 |
| 1500 | 60.877 | 178.176 | 133.927 | -157.962 | -31.550 | 1.099 |
| 1600 | 61.714 | 182.132 | 136.817 | -156.653 | -23.164 | 0.756 |
| 1700 | 62.531 | 185.898 | 139.595 | -155.288 | -14.863 | 0.457 |
| 1800 | 63.388 | 189.497 | 142.268 | -153.869 | -6.643 | 0.193 |

PREVIOUS:

CURRENT: June 1973

Pb₂S₃(l)

Lead Sulfide (PbS)

LIQUID

Lead Sulfide (PbS)

$M_r = 239.26$

$\Delta H_f^\circ(298.15 \text{ K}) = [84.064] \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_{\text{liq}}H^\circ = 18.83 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$

$S^\circ(298.15 \text{ K}) = [100.795] \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
 $T_{\text{fus}} = 1386.5 \pm 1.5 \text{ K}$

Enthalpy of Formation
 $\Delta H_f^\circ(\text{PbS}, l, 298.15 \text{ K})$ is calculated from that of the crystal by adding $\Delta_{\text{liq}}H^\circ$ and the difference in enthalpy, $H^\circ(1386.5 \text{ K}) - H^\circ(298.15 \text{ K})$, between the crystal and liquid.

Heat Capacity and Entropy
 The heat capacity of PbS(l) is estimated to be $16.0 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$. This appears reasonable as the C_p° value for PbO(l) is $15.535 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$.¹ A glass transition is assumed at 900 K. Below this temperature, the heat capacity values used are those of PbS(cr). $S^\circ(298.15 \text{ K})$ is calculated in a manner similar to that used for $\Delta H_f^\circ(298.15 \text{ K})$.

Fusion Data
 Employing cryoscopic measurements, Pelton and Flengas¹ and Bell and Flengas² determined the melting point of PbS to be 1113.4°C and 1111.9°C , respectively. Pelton and Flengas¹ estimated an accuracy of $\pm 1^\circ\text{C}$. Miller and Komarek,³ in studying the retrograde solubility in the Pb-S system, reported $T_{\text{fus}} = 1113.3 \pm 0.5^\circ\text{C}$. The latter authors have summarized many early determinations of T_{fus} which were in the range $1103\text{--}1135^\circ\text{C}$. We adopt $1386.5 \pm 1.5 \text{ K}$ for T_{fus} of PbS.

Kelley⁴ adopted $\Delta_{\text{liq}}H^\circ = 4.150 \text{ kcal}\cdot\text{mol}^{-1}$ based on melting point data obtained by Friedrich⁵ for the PbS-Cu₂S system and by Truette⁶ for the PbS-PbCl₂ system. Maier⁷ recalculated $\Delta_{\text{liq}}H^\circ$ from Friedrich's data and obtained $4.155 \text{ kcal}\cdot\text{mol}^{-1}$. Kelley⁴ also calculated $\Delta_{\text{liq}}H^\circ = 5.03 \text{ kcal}\cdot\text{mol}^{-1}$ from data on the PbS-Ag₂S system obtained by Friedrich. Other inconclusive works are discussed by Kelley.⁴ In the preceding calculations, $\Delta_{\text{liq}}H^\circ$ was derived from a graph of $\log X$ versus $1/T$ where X is the mole fraction of PbS in the melt and T is the liquidus temperature.

We calculate a $\Delta_{\text{liq}}H^\circ$ value for each melting point composition data pair and plot this value against ΔT , the melting point depression of PbS. The resulting plot is extrapolated to $\Delta T = 0$ to obtain $\Delta_{\text{liq}}H^\circ$. Friedrich's data then yields $\Delta_{\text{liq}}H^\circ = 4.33 \pm 0.15 \text{ kcal}\cdot\text{mol}^{-1}$. Truette's data has considerable scatter but indicates a value of $4.6 \text{ kcal}\cdot\text{mol}^{-1}$ for $\Delta_{\text{liq}}H^\circ$. An analysis of the data reported by Kohlmeier and Monzer⁸ for the PbS-PbO system yields $\Delta_{\text{liq}}H^\circ = 5 \pm 1 \text{ kcal}\cdot\text{mol}^{-1}$. Unfortunately, these three studies necessitate long extrapolations as the ΔT values are in the range 60–550 K. However, these three binary systems form simple, single eutectic phase diagrams and all are consistent with a $\Delta_{\text{liq}}H^\circ$ value of $4.5 \text{ kcal}\cdot\text{mol}^{-1}$.

Recent work by Pelton and Flengas¹ on PbS alkali halide systems involved ΔT values of 2–17 K so that a much shorter extrapolation is possible. An analysis of their data is tabulated below.

| T/K | C _p ^o | S ^o - [C _p ^o - H ^o (T)]/T | H ^o - H ^o (T) | Δ _{liq} H ^o | ΔG ^o | log K _r |
|----------|-----------------------------|---|-------------------------------------|---------------------------------|---------------------|--------------------|
| 298.15 | 49.438 | 100.795 | 0. | -84.064 | -85.242 | 14.934 |
| 300 | 49.455 | 101.101 | 0.091 | -84.064 | -85.250 | 14.843 |
| 400 | 50.459 | 115.459 | 5.083 | -86.396 | -85.544 | 11.171 |
| 500 | 51.463 | 126.827 | 10.181 | -88.042 | -85.153 | 8.896 |
| 600 | 52.384 | 136.291 | 15.373 | -89.323 | -84.449 | 7.352 |
| 700 | 53.346 | 144.440 | 20.661 | -90.205 | -82.755 | 6.175 |
| 800 | 54.308 | 151.677 | 26.045 | -90.049 | -80.916 | 5.283 |
| 900 | 55.271 | 158.078 | 31.522 | -89.814 | -77.904 | 4.521 |
| 900.000 | 55.271 | 158.078 | 31.522 | GLASS <--> LIQUID | TRANSITION | |
| 900.000 | 66.944 | 158.078 | 31.522 | -147.930 | -70.014 | 3.657 |
| 1000 | 66.944 | 165.131 | 38.217 | -146.032 | -62.315 | 2.959 |
| 1100 | 66.944 | 171.512 | 44.911 | -144.118 | -54.788 | 2.385 |
| 1200 | 66.944 | 177.236 | 51.606 | -142.197 | -47.422 | 1.905 |
| 1300 | 66.944 | 182.695 | 58.300 | --- | CRYSTAL <--> LIQUID | --- |
| 1386.500 | 66.944 | 187.007 | 64.091 | -140.283 | -40.204 | 1.500 |
| 1400 | 66.944 | 187.656 | 64.994 | -138.386 | -33.122 | 1.153 |
| 1500 | 66.944 | 192.275 | 71.689 | -136.513 | -26.165 | 0.854 |
| 1600 | 66.944 | 196.595 | 78.383 | -134.667 | -19.335 | 0.594 |
| 1700 | 66.944 | 200.654 | 85.078 | -132.850 | -12.593 | 0.365 |
| 1800 | 66.944 | 204.480 | 91.772 | -131.065 | -5.861 | 0.164 |
| 1900 | 66.944 | 208.099 | 98.466 | -129.512 | 0.578 | -0.105 |
| 2000 | 66.944 | 211.553 | 105.161 | | | |

Even in the PbS KCl system, the scatter is such that it is impossible to precisely define $\Delta_{\text{liq}}H^\circ$. We adopt a value of $\Delta_{\text{liq}}H^\circ = 4.5 \pm 1.5 \text{ kcal}\cdot\text{mol}^{-1}$. This value is consistent with all systems discussed above except for PbS-NaCl.

It should be noted that our analyses treated all systems as though no association, dissociation, or compound formation occurs in the melt. It is possible that the occurrence of any or all of these factors would cause the data to be consistent with a $\Delta_{\text{liq}}H^\circ$ which might be larger than the adopted value and even outside our uncertainty limits. For example, Pelton and Flengas¹ discussed their results in the PbS alkali halide systems in terms of an estimated $\Delta_{\text{liq}}H^\circ = 8.7 \text{ kcal}\cdot\text{mol}^{-1}$. Their conclusions need modifications with use of our adopted $\Delta_{\text{liq}}H^\circ = 4.5 \text{ kcal}\cdot\text{mol}^{-1}$. In addition Blachnik and Kluge⁹ have compared SnS and PbS; a difficulty arises in that PbS does not have the same crystal structure as GeS and SnS.⁹ Thus, $\Delta_{\text{liq}}H^\circ$ is not necessarily expected to be the same for all three species.

PbS(l)

Lead Sulfide (PbS)

LIQUID

Lead Sulfide (PbS)

$M_r = 239.26$

$\Delta H_f^\circ(298.15 \text{ K}) = [84.064] \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_{\text{liq}}H^\circ = 18.83 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$

$S^\circ(298.15 \text{ K}) = [100.795] \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
 $T_{\text{fus}} = 1386.5 \pm 1.5 \text{ K}$

Enthalpy of Formation
 $\Delta H_f^\circ(\text{PbS}, l, 298.15 \text{ K})$ is calculated from that of the crystal by adding $\Delta_{\text{liq}}H^\circ$ and the difference in enthalpy, $H^\circ(1386.5 \text{ K}) - H^\circ(298.15 \text{ K})$, between the crystal and liquid.

Heat Capacity and Entropy
 The heat capacity of PbS(l) is estimated to be $16.0 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$. This appears reasonable as the C_p° value for PbO(l) is $15.535 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$.¹ A glass transition is assumed at 900 K. Below this temperature, the heat capacity values used are those of PbS(cr). $S^\circ(298.15 \text{ K})$ is calculated in a manner similar to that used for $\Delta H_f^\circ(298.15 \text{ K})$.

Fusion Data
 Employing cryoscopic measurements, Pelton and Flengas¹ and Bell and Flengas² determined the melting point of PbS to be 1113.4°C and 1111.9°C , respectively. Pelton and Flengas¹ estimated an accuracy of $\pm 1^\circ\text{C}$. Miller and Komarek,³ in studying the retrograde solubility in the Pb-S system, reported $T_{\text{fus}} = 1113.3 \pm 0.5^\circ\text{C}$. The latter authors have summarized many early determinations of T_{fus} which were in the range $1103\text{--}1135^\circ\text{C}$. We adopt $1386.5 \pm 1.5 \text{ K}$ for T_{fus} of PbS.

Kelley⁴ adopted $\Delta_{\text{liq}}H^\circ = 4.150 \text{ kcal}\cdot\text{mol}^{-1}$ based on melting point data obtained by Friedrich⁵ for the PbS-Cu₂S system and by Truette⁶ for the PbS-PbCl₂ system. Maier⁷ recalculated $\Delta_{\text{liq}}H^\circ$ from Friedrich's data and obtained $4.155 \text{ kcal}\cdot\text{mol}^{-1}$. Kelley⁴ also calculated $\Delta_{\text{liq}}H^\circ = 5.03 \text{ kcal}\cdot\text{mol}^{-1}$ from data on the PbS-Ag₂S system obtained by Friedrich. Other inconclusive works are discussed by Kelley.⁴ In the preceding calculations, $\Delta_{\text{liq}}H^\circ$ was derived from a graph of $\log X$ versus $1/T$ where X is the mole fraction of PbS in the melt and T is the liquidus temperature.

We calculate a $\Delta_{\text{liq}}H^\circ$ value for each melting point composition data pair and plot this value against ΔT , the melting point depression of PbS. The resulting plot is extrapolated to $\Delta T = 0$ to obtain $\Delta_{\text{liq}}H^\circ$. Friedrich's data then yields $\Delta_{\text{liq}}H^\circ = 4.33 \pm 0.15 \text{ kcal}\cdot\text{mol}^{-1}$. Truette's data has considerable scatter but indicates a value of $4.6 \text{ kcal}\cdot\text{mol}^{-1}$ for $\Delta_{\text{liq}}H^\circ$. An analysis of the data reported by Kohlmeier and Monzer⁸ for the PbS-PbO system yields $\Delta_{\text{liq}}H^\circ = 5 \pm 1 \text{ kcal}\cdot\text{mol}^{-1}$. Unfortunately, these three studies necessitate long extrapolations as the ΔT values are in the range 60–550 K. However, these three binary systems form simple, single eutectic phase diagrams and all are consistent with a $\Delta_{\text{liq}}H^\circ$ value of $4.5 \text{ kcal}\cdot\text{mol}^{-1}$.

Recent work by Pelton and Flengas¹ on PbS alkali halide systems involved ΔT values of 2–17 K so that a much shorter extrapolation is possible. An analysis of their data is tabulated below.

| T/K | C _p ^o | S ^o - [C _p ^o - H ^o (T)]/T | H ^o - H ^o (T) | Δ _{liq} H ^o | ΔG ^o | log K _r |
|----------|-----------------------------|---|-------------------------------------|---------------------------------|---------------------|--------------------|
| 298.15 | 49.438 | 100.795 | 0. | -84.064 | -85.242 | 14.934 |
| 300 | 49.455 | 101.101 | 0.091 | -84.064 | -85.250 | 14.843 |
| 400 | 50.459 | 115.459 | 5.083 | -86.396 | -85.544 | 11.171 |
| 500 | 51.463 | 126.827 | 10.181 | -88.042 | -85.153 | 8.896 |
| 600 | 52.384 | 136.291 | 15.373 | -89.323 | -84.449 | 7.352 |
| 700 | 53.346 | 144.440 | 20.661 | -90.205 | -82.755 | 6.175 |
| 800 | 54.308 | 151.677 | 26.045 | -90.049 | -80.916 | 5.283 |
| 900 | 55.271 | 158.078 | 31.522 | -89.814 | -77.904 | 4.521 |
| 900.000 | 55.271 | 158.078 | 31.522 | GLASS <--> LIQUID | TRANSITION | |
| 900.000 | 66.944 | 158.078 | 31.522 | -147.930 | -70.014 | 3.657 |
| 1000 | 66.944 | 165.131 | 38.217 | -146.032 | -62.315 | 2.959 |
| 1100 | 66.944 | 171.512 | 44.911 | -144.118 | -54.788 | 2.385 |
| 1200 | 66.944 | 177.236 | 51.606 | -142.197 | -47.422 | 1.905 |
| 1300 | 66.944 | 182.695 | 58.300 | --- | CRYSTAL <--> LIQUID | --- |
| 1386.500 | 66.944 | 187.007 | 64.091 | -140.283 | -40.204 | 1.500 |
| 1400 | 66.944 | 187.656 | 64.994 | -138.386 | -33.122 | 1.153 |
| 1500 | 66.944 | 192.275 | 71.689 | -136.513 | -26.165 | 0.854 |
| 1600 | 66.944 | 196.595 | 78.383 | -134.667 | -19.335 | 0.594 |
| 1700 | 66.944 | 200.654 | 85.078 | -132.850 | -12.593 | 0.365 |
| 1800 | 66.944 | 204.480 | 91.772 | -131.065 | -5.861 | 0.164 |
| 1900 | 66.944 | 208.099 | 98.466 | -129.512 | 0.578 | -0.105 |
| 2000 | 66.944 | 211.553 | 105.161 | | | |

PbS(l)

Lead Sulfide (PbS)

LIQUID

Lead Sulfide (PbS)

$M_r = 239.26$

$\Delta H_f^\circ(298.15 \text{ K}) = [84.064] \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_{\text{liq}}H^\circ = 18.83 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$

$S^\circ(298.15 \text{ K}) = [100.795] \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
 $T_{\text{fus}} = 1386.5 \pm 1.5 \text{ K}$

Enthalpy of Formation
 $\Delta H_f^\circ(\text{PbS}, l, 298.15 \text{ K})$ is calculated from that of the crystal by adding $\Delta_{\text{liq}}H^\circ$ and the difference in enthalpy, $H^\circ(1386.5 \text{ K}) - H^\circ(298.15 \text{ K})$, between the crystal and liquid.

Heat Capacity and Entropy
 The heat capacity of PbS(l) is estimated to be $16.0 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$. This appears reasonable as the C_p° value for PbO(l) is $15.535 \text{ cal}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$.¹ A glass transition is assumed at 900 K. Below this temperature, the heat capacity values used are those of PbS(cr). $S^\circ(298.15 \text{ K})$ is calculated in a manner similar to that used for $\Delta H_f^\circ(298.15 \text{ K})$.

Fusion Data
 Employing cryoscopic measurements, Pelton and Flengas¹ and Bell and Flengas² determined the melting point of PbS to be 1113.4°C and 1111.9°C , respectively. Pelton and Flengas¹ estimated an accuracy of $\pm 1^\circ\text{C}$. Miller and Komarek,³ in studying the retrograde solubility in the Pb-S system, reported $T_{\text{fus}} = 1113.3 \pm 0.5^\circ\text{C}$. The latter authors have summarized many early determinations of T_{fus} which were in the range $1103\text{--}1135^\circ\text{C}$. We adopt $1386.5 \pm 1.5 \text{ K}$ for T_{fus} of PbS.

Kelley⁴ adopted $\Delta_{\text{liq}}H^\circ = 4.150 \text{ kcal}\cdot\text{mol}^{-1}$ based on melting point data obtained by Friedrich⁵ for the PbS-Cu₂S system and by Truette⁶ for the PbS-PbCl₂ system. Maier⁷ recalculated $\Delta_{\text{liq}}H^\circ$ from Friedrich's data and obtained $4.155 \text{ kcal}\cdot\text{mol}^{-1}$. Kelley⁴ also calculated $\Delta_{\text{liq}}H^\circ = 5.03 \text{ kcal}\cdot\text{mol}^{-1}$ from data on the PbS-Ag₂S system obtained by Friedrich. Other inconclusive works are discussed by Kelley.⁴ In the preceding calculations, $\Delta_{\text{liq}}H^\circ$ was derived from a graph of $\log X$ versus $1/T$ where X is the mole fraction of PbS in the melt and T is the liquidus temperature.

We calculate a $\Delta_{\text{liq}}H^\circ$ value for each melting point composition data pair and plot this value against ΔT , the melting point depression of PbS. The resulting plot is extrapolated to $\Delta T = 0$ to obtain $\Delta_{\text{liq}}H^\circ$. Friedrich's data then yields $\Delta_{\text{liq}}H^\circ = 4.33 \pm 0.15 \text{ kcal}\cdot\text{mol}^{-1}$. Truette's data has considerable scatter but indicates a value of $4.6 \text{ kcal}\cdot\text{mol}^{-1}$ for $\Delta_{\text{liq}}H^\circ$. An analysis of the data reported by Kohlmeier and Monzer⁸ for the PbS-PbO system yields $\Delta_{\text{liq}}H^\circ = 5 \pm 1 \text{ kcal}\cdot\text{mol}^{-1}$. Unfortunately, these three studies necessitate long extrapolations as the ΔT values are in the range 60–550 K. However, these three binary systems form simple, single eutectic phase diagrams and all are consistent with a $\Delta_{\text{liq}}H^\circ$ value of $4.5 \text{ kcal}\cdot\text{mol}^{-1}$.

Recent work by Pelton and Flengas¹ on PbS alkali halide systems involved ΔT values of 2–17 K so that a much shorter extrapolation is possible. An analysis of their data is tabulated below.

| T/K | C _p ^o | S ^o - [C _p ^o - H ^o (T)]/T | H ^o - H ^o (T) | Δ _{liq} H ^o | ΔG ^o | log K _r |
|----------|-----------------------------|---|-------------------------------------|---------------------------------|---------------------|--------------------|
| 298.15 | 49.438 | 100.795 | 0. | -84.064 | -85.242 | 14.934 |
| 300 | 49.455 | 101.101 | 0.091 | -84.064 | -85.250 | 14.843 |
| 400 | 50.459 | 115.459 | 5.083 | -86.396 | -85.544 | 11.171 |
| 500 | 51.463 | 126.827 | 10.181 | -88.042 | -85.153 | 8.896 |
| 600 | 52.384 | 136.291 | 15.373 | -89.323 | -84.449 | 7.352 |
| 700 | 53.346 | 144.440 | 20.661 | -90.205 | -82.755 | 6.175 |
| 800 | 54.308 | 151.677 | 26.045 | -90.049 | -80.916 | 5.283 |
| 900 | 55.271 | 158.078 | 31.522 | -89.814 | -77.904 | 4.521 |
| 900.000 | 55.271 | 158.078 | 31.522 | GLASS <--> LIQUID | TRANSITION | |
| 900.000 | 66.944 | 158.078 | 31.522 | -147.930 | -70.014 | 3.657 |
| 1000 | 66.944 | 165.131 | 38.217 | -146.032 | -62.315 | 2.959 |
| 1100 | 66.944 | 171.512 | 44.911 | -144.118 | -54.788 | 2.385 |
| 1200 | 66.944 | 177.236 | 51.606 | -142.197 | -47.422 | 1.905 |
| 1300 | 66.944 | 182.695 | 58.300 | --- | CRYSTAL <--> LIQUID | --- |
| 1386.500 | 66.944 | 187.007 | 64.091 | -140.283 | -40.204 | 1.500 |
| 1400 | 66.944 | 187.656 | 64.994 | -138.386 | -33.122 | 1.153 |
| 1500 | 66.944 | 192.275 | 71.689 | -136.513 | -26.165 | 0.854 |
| 1600 | 66.944 | 196.595 | 78.383 | -134.667 | -19.335 | 0.594 |
| 1700 | 66.944 | 200.654 | 85.078 | -132.850 | -12.593 | 0.365 |
| 1800 | 66.944 | 204.480 | 91.772 | -131.065 | -5.861 | 0.164 |
| 1900 | 66.944 | 208.099 | 98.466 | -129.512 | 0.578 | -0.105 |
| 2000 | 66.944 | 211.553 | 105.161 | | | |

Even in the PbS KCl system, the scatter is such that it is impossible to precisely define $\Delta_{\text{liq}}H^\circ$. We adopt a value of $\Delta_{\text{liq}}H^\circ = 4.5 \pm 1.5 \text{ kcal}\cdot\text{mol}^{-1}$. This value is consistent with all systems discussed above except for PbS-NaCl.

It should be noted that our analyses treated all systems as though no association, dissociation, or compound formation occurs in the melt. It is possible that the occurrence of any or all of these factors would cause the data to be consistent with a $\Delta_{\text{liq}}H^\circ$ which might be larger than the adopted value and even outside our uncertainty limits. For example, Pelton and Flengas¹ discussed their results in the PbS alkali halide systems in terms of an

CRYSTAL-LIQUID

0 to 1386.5 K crystal
above 1386.5 K liquid

Refer to the individual tables for details.

Lead (PbS)

Pb₃S₄(cr,l)

M_r = 239.26

Lead Sulfide (PbS)

| T/K | Enthalpy Reference Temperature = T _r = 298.15 K | | Standard State Pressure = p° = 0.1 MPa | | log K _r |
|----------|--|--------------------------------------|--|----------------------|--------------------|
| | C _p ^o | S° - [C° - H°(T _r)]/T | H° - H°(T _r) | Δ _r G° | |
| | J·K ⁻¹ ·mol ⁻¹ | J·K ⁻¹ ·mol ⁻¹ | KJ·mol ⁻¹ | KJ·mol ⁻¹ | |
| 0 | 0 | 0 | INFINITE | -98.545 | INFINITE |
| 100 | 39.748 | 41.296 | 133.734 | -97.928 | 51.152 |
| 200 | 47.614 | 71.920 | 93.823 | -97.239 | 25.396 |
| 298.15 | 49.438 | 91.343 | 91.343 | -96.685 | 16.939 |
| 300 | 49.455 | 91.649 | 91.344 | -96.675 | 16.833 |
| 400 | 50.459 | 106.008 | 93.295 | -96.074 | 12.530 |
| 500 | 51.463 | 117.375 | 97.013 | -94.688 | 9.892 |
| 600 | 52.384 | 126.839 | 101.217 | -93.039 | 8.100 |
| 700 | 53.346 | 134.988 | 105.473 | -90.400 | 6.746 |
| 800 | 54.308 | 142.176 | 109.620 | -87.616 | 5.721 |
| 900 | 55.271 | 148.627 | 113.602 | -83.658 | 4.855 |
| 1000 | 56.191 | 154.498 | 117.402 | -74.763 | 3.905 |
| 1100 | 57.153 | 159.900 | 121.023 | -65.949 | 3.132 |
| 1200 | 58.074 | 164.912 | 124.474 | -57.220 | 2.491 |
| 1300 | 59.036 | 169.599 | 127.767 | -48.577 | 1.932 |
| 1386.500 | 59.832 | 173.428 | 130.497 | -40.204 | 1.500 |
| 1386.500 | 66.944 | 187.007 | 130.497 | -33.122 | 1.153 |
| 1400 | 66.944 | 187.636 | 131.045 | -26.165 | 0.854 |
| 1500 | 66.944 | 192.275 | 134.975 | -19.325 | 0.594 |
| 1600 | 66.944 | 196.595 | 138.693 | -12.593 | 0.365 |
| 1700 | 66.944 | 200.654 | 142.219 | -5.961 | 0.164 |
| 1800 | 66.944 | 204.480 | 145.573 | 0.578 | -0.015 |
| 1900 | 66.944 | 208.099 | 148.769 | | |
| 2000 | 66.944 | 211.533 | 151.823 | | |

CRYSTAL <---> LIQUID TRANSITION

PREVIOUS:

CURRENT: June 1973

Lead Sulfide (PbS)

Pb₃S₄(cr,l)

Pb₂S₂(g)

Lead Sulfide (PbS)

IDEAL GAS

Lead Sulfide (PbS)

$M_r = 239.26$ $\Delta_f H^\circ(0\text{ K}) = 133.66 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$ $\Delta_f H^\circ(298.15\text{ K}) = 131.80 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$

| T/K | C _p ^a | S ^b - [C ^a - H ^c (T)]/T | H ^c - H ^c (T) | $\Delta_f H^\circ$ | log K _r |
|--|-----------------------------|--|-------------------------------------|--------------------|--------------------|
| Enthalpy Reference Temperature = T _r = 298.15 K | | | | | |
| Standard State Pressure = p ^o = 0.1 MPa | | | | | |
| Enthalpy Reference Temperature = T _r = 298.15 K | | | | | |
| T/K | C _p ^a | S ^b - [C ^a - H ^c (T)]/T | H ^c - H ^c (T) | $\Delta_f H^\circ$ | log K _r |
| 0 | 0 | INFINITE | -9.430 | 133.656 | INFINITE |
| 100 | 29.787 | 216.077 | -6.509 | 134.121 | -61.349 |
| 200 | 33.139 | 237.771 | -3.360 | 133.104 | -26.413 |
| 250 | 34.305 | 245.259 | -1.672 | 132.467 | -19.475 |
| 298.15 | 35.085 | 251.412 | 0 | 131.796 | -15.016 |
| 300 | 35.110 | 251.629 | 0.065 | 131.769 | 85.425 |
| 350 | 35.671 | 257.086 | 1.835 | 131.020 | -14.874 |
| 400 | 36.073 | 261.771 | 3.629 | 128.008 | -11.605 |
| 450 | 36.370 | 266.144 | 5.441 | 126.497 | -9.179 |
| 500 | 36.596 | 269.988 | 7.265 | 124.902 | -7.331 |
| 600 | 36.912 | 276.690 | 10.942 | 122.104 | -5.872 |
| 700 | 37.121 | 282.597 | 14.644 | 119.428 | -4.721 |
| 800 | 37.272 | 287.564 | 18.364 | 117.130 | -3.877 |
| 900 | 37.386 | 291.761 | 21.997 | 115.130 | -3.277 |
| 1000 | 37.477 | 295.705 | 25.841 | 113.353 | -2.877 |
| 1100 | 37.554 | 299.280 | 29.592 | 111.796 | -2.580 |
| 1200 | 37.620 | 302.551 | 33.351 | 110.441 | -2.341 |
| 1300 | 37.679 | 305.564 | 37.116 | 109.247 | -2.141 |
| 1400 | 37.734 | 308.359 | 40.887 | 108.191 | -1.979 |
| 1500 | 37.785 | 310.964 | 44.663 | 107.252 | -1.841 |
| 1600 | 37.836 | 313.404 | 48.444 | 106.421 | -1.721 |
| 1700 | 37.886 | 315.699 | 52.230 | 105.686 | -1.616 |
| 1800 | 37.945 | 317.867 | 56.022 | 105.044 | -1.521 |
| 1900 | 38.008 | 319.920 | 59.819 | 104.491 | -1.436 |
| 2000 | 38.081 | 321.871 | 63.624 | 104.010 | -1.361 |
| 2100 | 38.166 | 323.731 | 67.436 | 103.591 | -1.296 |
| 2200 | 38.266 | 325.509 | 71.257 | 103.226 | -1.241 |
| 2300 | 38.386 | 327.213 | 75.090 | 102.911 | -1.196 |
| 2400 | 38.527 | 328.849 | 78.937 | 102.641 | -1.161 |
| 2500 | 38.693 | 330.425 | 82.796 | 102.411 | -1.136 |
| 2600 | 38.887 | 331.946 | 86.675 | 102.221 | -1.121 |
| 2700 | 39.128 | 333.418 | 90.574 | 102.071 | -1.116 |
| 2800 | 39.416 | 334.845 | 94.499 | 101.961 | -1.116 |
| 2900 | 39.759 | 336.232 | 98.449 | 101.891 | -1.121 |
| 3000 | 39.986 | 337.581 | 102.431 | 101.861 | -1.126 |
| 3100 | 40.349 | 338.898 | 106.447 | 101.871 | -1.131 |
| 3200 | 40.750 | 340.186 | 110.502 | 101.921 | -1.136 |
| 3300 | 41.189 | 341.446 | 114.609 | 102.021 | -1.141 |
| 3400 | 41.666 | 342.683 | 118.771 | 102.171 | -1.146 |
| 3500 | 42.179 | 343.898 | 122.993 | 102.371 | -1.151 |
| 3600 | 42.729 | 345.094 | 127.276 | 102.621 | -1.156 |
| 3700 | 43.314 | 346.272 | 131.621 | 102.921 | -1.161 |
| 3800 | 43.932 | 347.436 | 136.031 | 103.271 | -1.166 |
| 3900 | 44.581 | 348.585 | 140.501 | 103.671 | -1.171 |
| 4000 | 45.259 | 349.722 | 145.031 | 104.121 | -1.176 |
| 4100 | 45.964 | 350.848 | 149.621 | 104.621 | -1.181 |
| 4200 | 46.692 | 351.959 | 154.271 | 105.171 | -1.186 |
| 4300 | 47.440 | 353.072 | 158.981 | 105.771 | -1.191 |
| 4400 | 48.206 | 354.172 | 163.741 | 106.421 | -1.196 |
| 4500 | 48.985 | 355.264 | 168.561 | 107.121 | -1.201 |
| 4600 | 49.774 | 356.349 | 173.431 | 107.871 | -1.206 |
| 4700 | 50.570 | 357.428 | 178.351 | 108.671 | -1.211 |
| 4800 | 51.368 | 358.501 | 183.321 | 109.521 | -1.216 |
| 4900 | 52.166 | 359.568 | 188.341 | 110.421 | -1.221 |
| 5000 | 52.959 | 360.630 | 193.411 | 111.371 | -1.226 |
| 5100 | 53.745 | 361.687 | 198.541 | 112.371 | -1.231 |
| 5200 | 54.519 | 362.738 | 203.721 | 113.421 | -1.236 |
| 5300 | 55.279 | 363.784 | 208.951 | 114.521 | -1.241 |
| 5400 | 56.022 | 364.824 | 214.231 | 115.671 | -1.246 |
| 5500 | 56.744 | 365.858 | 219.561 | 116.871 | -1.251 |
| 5600 | 57.443 | 366.887 | 224.941 | 118.121 | -1.256 |
| 5700 | 58.117 | 367.910 | 230.371 | 119.421 | -1.261 |
| 5800 | 58.764 | 368.926 | 235.851 | 120.771 | -1.266 |
| 5900 | 59.382 | 369.936 | 241.381 | 122.171 | -1.271 |
| 6000 | 59.969 | 370.939 | 246.961 | 123.621 | -1.276 |

$\Delta_f H^\circ(0\text{ K}) = 133.66 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta_f H^\circ(298.15\text{ K}) = 131.80 \pm 6.3 \text{ kJ}\cdot\text{mol}^{-1}$

| State | ϵ_r , cm ⁻¹ | g_i | Electronic State and Molecular Constants ($\sigma=1$) | B_e , cm ⁻¹ | α_e , cm ⁻¹ | r_e , Å |
|------------------|---------------------------------|-------|---|--------------------------|-------------------------------|-----------|
| X 0 ⁺ | 0 | 1 | 429.40 | 1.30 | 0.11633 | 2.287 |
| a 1 | 14821.9 | 2 | 285.9 | 0.88 | 0.09267 | 2.562 |
| A 0 ⁺ | 18768.9 | 1 | 260.83 | 0.363 | 0.09634 | 2.513 |
| B 1 | 21774.5 | 2 | 282.17 | 0.856 | 0.09992 | 2.467 |
| C 0 ⁺ | 23150.7 | 1 | 303.93 | 1.436 | [0.09347] | [2.522] |
| C' 1 | 24952.3 | 2 | 283.95 | 1.171 | [0.09358] | [2.549] |
| D 1 | 29587.4 | 2 | 297.83 | 1.365 | 0.10160 | 2.447 |
| E 0 ⁺ | 34000 | 1 | [262.32] | [1.114] | [0.09095] | [2.585] |

Enthalpy of Formation
 Vago and Barrow¹ observed the convergence in the E-X system at 2715 Å. The dissociation energy for PbS(g) is calculated to be 81.85 ± 0.40 kcal·mol⁻¹. Barrow *et al.*² analyzed the PbS absorption spectrum in terms of type C coupling and assigned the electronically excited E state to be 0⁺. If the non-crossing rule is applicable,² then the most likely dissociation products are Pb(²P_{1/2}) and S(³P₁). Using auxiliary data,³ $\Delta_f H^\circ(\text{PbS}, g, 298.15\text{ K}) = 32.00 \pm 0.40 \text{ kcal}\cdot\text{mol}^{-1}$.

Colin and Drowart⁴ have studied the sublimation and dissociation of PbS by means of a Knudsen effusion cell coupled with a mass spectrometer. A 2nd and 3rd law analysis by Colin and Drowart⁴ of four sets of experiments (865–1100 K) yielded an average value of 55.7 ± 1.4 kcal·mol⁻¹ for the enthalpy of sublimation. It is anticipated that this result is roughly 0.5 kcal·mol⁻¹ too large since the Gibbs energy functions for the sublimation used by Colin and Drowart⁴ are approximately 0.5 cal·K⁻¹·mol⁻¹ greater than those presently adopted at 1000 K.³

Colin and Drowart⁴ presented data for 13 experiments in which either Pb, S₂, or both Pb and S₂ partial pressures were measured in addition to the PbS partial pressure. The missing pressure is calculated using the formula $[P(\text{Pb})P(\text{S}_2)]^{1/2} = 2$ as in Colin and Drowart.⁴

| Source | Reaction* | T/K | Data Points | Method | $\Delta_f H^\circ(298.15\text{ K})$, kcal·mol ⁻¹ | Drift | $\Delta_f H^\circ(298.15\text{ K})$, kcal·mol ⁻¹ |
|--------|-----------|-----------|-------------|--------------------------|--|-------|--|
| 4 | A | 990–1043 | 5 | calc. P(S ₂) | 30.20 ± 14.63 | 29.04 | 33.12 |
| | A | 979–1118 | 4 | calc. P(Pb) | 36.48 ± 10.22 | 28.31 | 33.86 |
| | A | 1012–1182 | 4 | all P meas. | 21.97 ± 4.67 | 29.32 | 32.85 |
| | B | 979–1182 | 13* | Knudsen-mass spec. | 55.25 ± 0.69 | 55.55 | 32.05 |
| 5 | B | 1123–1268 | 12* | Entrainment | 59.48 ± 0.66 | 55.00 | 31.50 |
| 6 | B | 878–1069 | 6 | Knudsen | 55.38 ± 0.44 | 54.88 | 31.38 |
| 7 | B | 776–927 | ** | Langmuir | 53.16 | 57.24 | 33.74 |
| 8 | B | 825–1025 | ** | | 54.56 | 54.95 | 31.45 |
| 9 | B | 1048–1193 | 10 | Knudsen | 57.66 ± 1.16 | 56.12 | 32.62 |
| 10 | B | 1113–1378 | 11 | Entrainment | 57.27 ± 1.35 | 54.34 | 30.84 |
| 11 | B | 877–1020 | 12 | torsion-effusion | 55.99 ± 0.87 | 54.55 | 31.05 |
| | B | | 17* | torsion-effusion | 57.71 ± 0.53 | 54.55 | 31.05 |
| | B | 860–975 | 20 | torsion-Langmuir | 53.58 ± 1.94 | 54.68 | 31.18 |
| | B | | 7 | torsion-Langmuir | 53.69 ± 0.70 | 54.55 | 31.05 |

* A) PbS(g) = Pb(g) + 1/2 S₂(g) B) PbS(cr) = PbS(g)
 ** Actual data not presented, smoothed data used.

One point rejected due to statistical test. The value adopted for $\Delta_f H^\circ(\text{PbS}, g, 298.15\text{ K})$ is 31.5 ± 1.5 kcal·mol⁻¹. Most of the uncertainty is attributable to the possible decomposition and/or reaction during sublimation. Colin and Drowart⁴ and Isakova *et al.*¹⁰ considered the effect of decomposition whereas many of the other investigators analyzed their data in terms of PbS(g) formation only. In addition, Hansen and Munir¹¹ attest to the congruency of sublimation using x-ray observations on samurcrites which had lost at least 30% of their initial weight as a result of heating. The adopted $\Delta_f H^\circ(298.15\text{ K})$ is somewhat of a compromise between the spectroscopic work,¹ the mass spectrometric work,⁴ and the bulk of the sublimation studies. Correspondingly, $D_0(\text{PbS}, g) = 82.4 \pm 1.5 \text{ kcal}\cdot\text{mol}^{-1}$. $D_0(\text{PbS}, g) = 86.5 \text{ kcal}\cdot\text{mol}^{-1}$ is calculated by applying the Hildenbrand formula¹² to the linear Birge-Sponer extrapolation of the ground state vibrational levels. Using auxiliary data,³ $\Delta_f H^\circ(298.15\text{ K}) = 27.4 \text{ kcal}\cdot\text{mol}^{-1}$ is obtained.

Continued on page 1847

Lead Sulfide (PbS)

Pb₂S₂(g)

PREVIOUS: June 1973 (1 atm)

CURRENT: June 1973 (1 bar)

IDEAL GAS

Lead (Pb₂)

$S^\circ(298.15\text{ K}) = [281.334] \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$

$\Delta H_f^\circ(0\text{ K}) = 336.4 \pm 19.2 \text{ kJ}\cdot\text{mol}^{-1}$
 $\Delta H_f^\circ(298.15\text{ K}) = 332.6 \pm 19.2 \text{ kJ}\cdot\text{mol}^{-1}$

| Electronic Levels and Quantum Weights State | $\epsilon_e, \text{cm}^{-1}$ | g_e |
|---|------------------------------|-------|
| $[\sum_g^2]$ | 0 | [3] |

$\omega_e = 256.5 \text{ cm}^{-1}$
 $B_e = [0.01727] \text{ cm}^{-1}$
 $\omega_e x_e = 2.96 \text{ cm}^{-1}$
 $\alpha = [0.00020] \text{ cm}^{-1}$

$\sigma = 2$
 $r_e = [3.08] \text{ \AA}$

Enthalpy of Formation

The enthalpy of formation is calculated from the dissociation energy of Pb₂(g) as reported by Gaydon.¹

Heat Capacity and Entropy

The values of ω_e and $\omega_e x_e$ are obtained from Herzberg.² Those for B_e and α_e are estimated according to the method suggested by Herzberg. The bond distance (r_e) is calculated from the moment of inertia, $I = 1630 \times 10^{-40} \text{ g cm}^2$, estimated by Kelley and King.³ The ground state configuration is assumed to be $^3\Sigma$ by comparison to that for Si₂(g) reported by Douglas.⁴

References

- ¹A. G. Gaydon, "Dissociation Energies," Chapman and Hall, Ltd., London, (1953).
- ²G. Herzberg, "Spectra of Diatomic Molecules", D. Van Nostrand Company, Inc., New York, (1950).
- ³K. K. Kelley and E. G. King, U. S. Bur. Mines Bull. 592, 149 pp. (1961).
- ⁴A. E. Douglas, Can. J. Phys. 33, 801 (1955).

Lead (Pb₂)

Pb₂(g)

| T/K | C _p ^a | Enthalpy Reference Temperature = T ₁ = 298.15 K | | H ^o - H(T) ^b | ΔH ^o | log K _c |
|--------|-----------------------------|--|--|------------------------------------|-----------------|--------------------|
| | | S ^o - [S ^o - H(T)]/T | Standard State Pressure = P ^o = 0.1 MPa | | | |
| 0 | 0 | INFINITE | INFINITE | -10.004 | 336.381 | INFINITE |
| 100 | 32.267 | 243.142 | 313.231 | -7.009 | 335.843 | 318.893 |
| 200 | 35.750 | 266.807 | 284.681 | -3.575 | 334.278 | 306.576 |
| 250 | 36.473 | 274.869 | 281.939 | -1.768 | 333.425 | 294.755 |
| 298.15 | 36.921 | 281.334 | 281.334 | 0 | 332.628 | 287.380 |
| 300 | 36.935 | 281.562 | 281.335 | 0.068 | 332.597 | 287.099 |
| 350 | 37.258 | 287.281 | 281.785 | 1.924 | 331.745 | 279.583 |
| 400 | 37.502 | 292.273 | 282.791 | 3.793 | 330.864 | 272.191 |
| 450 | 37.697 | 296.702 | 284.095 | 5.673 | 329.951 | 264.911 |
| 500 | 37.861 | 300.682 | 285.558 | 7.562 | 329.005 | 257.735 |
| 600 | 38.133 | 307.610 | 288.673 | 11.362 | 327.027 | 245.665 |
| 700 | 38.362 | 313.810 | 291.810 | 15.187 | 325.209 | 235.532 |
| 800 | 38.568 | 318.492 | 294.850 | 19.034 | 323.527 | 229.728 |
| 900 | 38.761 | 322.196 | 297.751 | 22.900 | 321.917 | 220.194 |
| 1000 | 38.945 | 325.299 | 300.504 | 26.786 | 320.389 | 196.889 |
| 1100 | 39.123 | 331.010 | 303.111 | 30.689 | 306.947 | 185.784 |
| 1200 | 39.298 | 334.422 | 305.580 | 34.611 | 305.080 | 174.852 |
| 1300 | 39.470 | 337.574 | 307.921 | 38.549 | 303.277 | 164.073 |
| 1400 | 39.640 | 340.505 | 310.145 | 42.504 | 301.508 | 153.432 |
| 1500 | 39.808 | 343.246 | 312.261 | 46.477 | 299.751 | 142.916 |
| 1600 | 39.976 | 345.820 | 314.279 | 50.466 | 297.996 | 132.518 |
| 1700 | 40.142 | 348.249 | 316.207 | 54.472 | 296.231 | 122.229 |
| 1800 | 40.308 | 350.548 | 318.051 | 58.494 | 294.450 | 112.045 |
| 1900 | 40.473 | 352.732 | 319.819 | 62.533 | 292.649 | 101.961 |
| 2000 | 40.638 | 354.812 | 321.517 | 66.589 | 290.825 | 91.972 |
| 2100 | 40.803 | 356.799 | 323.151 | 70.661 | 288.967 | 82.095 |
| 2200 | 40.967 | 358.701 | 324.724 | 74.750 | 287.064 | 72.470 |
| 2300 | 41.131 | 360.525 | 326.241 | 78.855 | 285.118 | 63.091 |
| 2400 | 41.295 | 362.279 | 327.706 | 82.976 | 283.136 | 53.955 |
| 2500 | 41.459 | 363.968 | 329.123 | 87.114 | 281.114 | 45.065 |
| 2600 | 41.622 | 365.598 | 330.495 | 91.268 | 279.058 | 36.418 |
| 2700 | 41.785 | 367.172 | 331.824 | 95.438 | 276.968 | 28.013 |
| 2800 | 41.949 | 368.694 | 333.114 | 99.625 | 274.846 | 19.846 |
| 2900 | 42.112 | 370.169 | 334.366 | 103.828 | 272.682 | 11.917 |
| 3000 | 42.275 | 371.599 | 335.584 | 108.047 | 270.476 | 4.228 |
| 3100 | 42.438 | 372.988 | 336.768 | 112.283 | 268.228 | -2.974 |
| 3200 | 42.601 | 374.338 | 337.921 | 116.535 | 265.946 | -6.118 |
| 3300 | 42.764 | 375.653 | 339.045 | 120.805 | 263.621 | -9.250 |
| 3400 | 42.927 | 376.931 | 340.140 | 125.087 | 261.254 | -12.364 |
| 3500 | 43.089 | 378.177 | 341.209 | 129.368 | 258.846 | -15.445 |
| 3600 | 43.252 | 379.393 | 342.253 | 133.705 | 256.394 | -18.484 |
| 3700 | 43.415 | 380.581 | 343.273 | 138.039 | 253.900 | -21.483 |
| 3800 | 43.578 | 381.741 | 344.270 | 142.388 | 251.363 | -24.441 |
| 3900 | 43.740 | 382.875 | 345.245 | 146.754 | 248.784 | -27.359 |
| 4000 | 43.903 | 383.984 | 346.200 | 151.136 | 246.163 | -30.233 |
| 4100 | 44.066 | 385.070 | 347.135 | 155.535 | 243.500 | -33.063 |
| 4200 | 44.228 | 386.134 | 348.051 | 159.949 | 240.794 | -35.847 |
| 4300 | 44.391 | 387.177 | 348.949 | 164.380 | 238.046 | -38.585 |
| 4400 | 44.553 | 388.199 | 349.829 | 168.828 | 235.256 | -41.276 |
| 4500 | 44.716 | 389.202 | 350.693 | 173.291 | 232.424 | -43.920 |
| 4600 | 44.878 | 390.187 | 351.541 | 177.771 | 229.550 | -46.518 |
| 4700 | 45.041 | 391.154 | 352.373 | 182.269 | 226.634 | -49.070 |
| 4800 | 45.204 | 392.104 | 353.191 | 186.779 | 223.676 | -51.576 |
| 4900 | 45.366 | 393.037 | 353.995 | 191.307 | 220.676 | -54.036 |
| 5000 | 45.529 | 393.955 | 354.785 | 195.852 | 217.634 | -56.450 |
| 5100 | 45.691 | 394.859 | 355.562 | 200.413 | 214.550 | -58.818 |
| 5200 | 45.854 | 395.747 | 356.326 | 204.990 | 211.424 | -61.140 |
| 5300 | 46.016 | 396.622 | 357.078 | 209.584 | 208.256 | -63.416 |
| 5400 | 46.179 | 397.484 | 357.819 | 214.194 | 205.056 | -65.646 |
| 5500 | 46.341 | 398.333 | 358.548 | 218.820 | 201.822 | -67.829 |
| 5600 | 46.503 | 399.169 | 359.266 | 223.462 | 198.554 | -70.000 |
| 5700 | 46.666 | 399.994 | 359.973 | 228.120 | 195.252 | -72.161 |
| 5800 | 46.828 | 400.807 | 360.670 | 232.795 | 191.916 | -74.312 |
| 5900 | 46.991 | 401.609 | 361.357 | 237.486 | 188.546 | -76.453 |
| 6000 | 47.153 | 402.400 | 362.034 | 242.193 | 185.146 | -78.584 |

PREVIOUS: September 1963 (1 atm) CURRENT: September 1963 (1 bar)

Lead (Pb₂)

Pb₂(g)

Lead

Continued from Page 1842

- ⁸F. D. Richardson and J. H. E. Jeffes, *J. Iron Steel Inst. (London)* **171**, 165 (1952).
⁹H. Zeumer and W. A. Roth, *Z. Phys. Chem.* **A173**, 365 (1935).
¹⁰U. S. Nat. Bur. Stand. Tech. Note 270-3, 264 pp. (1968).
¹¹Shamsuddin and S. Misra, *Curr. Sci.* **42**, 119 (1973).
¹²I. A. Korshunov, *J. Gen. Chem. (USSR)* **10**, 2087 (1940).
¹³D. H. Parkinson and J. E. Quarrington, *Proc. Phys. Soc. (London)* **67A**, 569 (1954).
¹⁴C. T. Anderson, *J. Amer. Chem. Soc.* **54**, 107 (1932).
¹⁵W. T. Thompson and S. N. Flengas, *Can. J. Chem.* **49**, 1550 (1971).
¹⁶E. D. Eastman and W. H. Roddebush, *J. Amer. Chem. Soc.* **40**, 489 (1918).
¹⁷K. K. Kelley, *U. S. Bur. Mines Bull.* **584**, 232 pp (1960).
¹⁸K. Bornemann and O. Hengstenberg, *Metall u. Erz.* **17**, 313, 339 (1920).
¹⁹K. K. Kelley and E. G. King, *U. S. Bur. Mines Bull.* **592**, 149 pp. (1961).
- ²⁰W. Truthe, *Z. Anorg. Chem.* **76**, 161 (1912).
²¹C. G. Maier, *U. S. Bur. Mines RI* **3263** (1934).
²²E. J. Kohlmeier and W. Monzer, *Z. Anorg. Chem.* **252**, 74 (1944).
²³R. Blachnik and W. Kluge, *Thermochim. Acta* **3**, 317 (1972).
²⁴E. J. Kohlmeier, *Metall u. Erz.* **29**, 105 (1932).
²⁵E. J. Kohlmeier and H. Brinkman, *Z. Anorg. Chem.* **292**, 275 (1957).
²⁶JANAF Thermochemical Tables: PbO(l), 12-31-71, PbS(g), 6-30-73; PbO(l), 3-31-62; S₂(g), 12-31-65.

Continued from Page 1843

- ²⁷R. Colin and J. Drowart, *J. Chem. Phys.* **37**, 1120 (1962).
²⁸R. Schenck and A. Albers, *Z. Anorg. Chem.* **105**, 145 (1919).
²⁹B. K. Veselowski, *J. Appl. Chem. (USSR)* **15**, 398 (1942).
³⁰C. M. Hsiao and A. W. Schlechten, *J. Metals* **4**, 65 (1952).
³¹O. G. Miller and M. A. Abdeev, *Tr. Altaisk Gorno Met. Nauch.-Issledov. Inst. akad. Nauk Kazakh SSR* **7**, 182 (1958); *Chem. Abstr.* **54**, 4297f (1960).
³²K. Sudo, *Sci. Repts. Research Insts., Tohoku Univ.* **A12**, 54 (1960).
³³R. A. Isakova, V. N. Nesterov, and A. S. Shendyapin, *Russ. J. Inorg. Chem.* **8**, 8 (1963).
³⁴E. E. Hansen and Z. A. Munir, *High Temp. Sci.* **2**, 169 (1970).
³⁵D. L. Hildenbrand and E. Mirad, *J. Chem. Phys.* **51**, 807 (1969).
³⁶B. Rosen, Ed., "Spectroscopic Data Relative to Diatomic Molecules," Pergamon Press, New York, (1970).
³⁷H. Bell and A. Harvey, *Proc. Phys. Soc. (London)* **50**, 427 (1938).
³⁸G. D. Rochester and H. G. Howell, *Proc. Roy. Soc. (London)* **148**, 157 (1935).

Continuation of discussions of selected Pb species

Continued from Page 1845

Heat Capacity and Entropy

The tabulated electronic and molecular constants are taken from Rosen¹³ as reviewed and compiled by Barrow. The constants came from the work of Bell and Harvey,¹⁴ Rochester and Howell,¹⁵ Vago and Barrow¹ and Barrow *et al.*² The state designations are those which are consistent with type C coupling. In this case, the state designations Σ, Π, etc., no longer have meaning. The estimated values in the tabulation are derived from comparisons of known values in the PbS(g) and PbO(g) systems.³ The functions are calculated from the partition function $Q = Q_{\Sigma} Q_{\Omega} \exp(-C_{\Sigma}/T)$; the values for Q_{Σ} and Q_{Ω} were calculated with first order anharmonic corrections.

References

- ¹E. E. Vago and R. F. Barrow, *Proc. Phys. Soc. (London)* **59**, 449 (1947).
²R. F. Barrow, P. W. Fry and R. C. LeBarry, *Proc. Phys. Soc. (London)* **81**, 697 (1963).
³JANAF Thermochemical Tables: Pb(g), 3-31-62; S(g), 6-30-71; PbS(cr), 6-30-73; S₂(g), 12-31-65; PbO(g), 12-31-71.
⁴R. Colin and J. Drowart, *J. Chem. Phys.* **37**, 1120 (1962).
⁵R. Schenck and A. Albers, *Z. Anorg. Chem.* **105**, 145 (1919).
⁶B. K. Veselowski, *J. Appl. Chem. (USSR)* **15**, 398 (1942).
⁷C. M. Hsiao and A. W. Schlechten, *J. Metals* **4**, 65 (1952).
⁸O. G. Miller and M. A. Abdeev, *Tr. Altaisk Gorno Met. Nauch.-Issledov. Inst. akad. Nauk Kazakh SSR* **7**, 182 (1958); *Chem. Abstr.* **54**, 4297f (1960).
⁹K. Sudo, *Sci. Repts. Research Insts., Tohoku Univ.* **A12**, 54 (1960).
¹⁰R. A. Isakova, V. N. Nesterov, and A. S. Shendyapin, *Russ. J. Inorg. Chem.* **8**, 8 (1963).
¹¹E. E. Hansen and Z. A. Munir, *High Temp. Sci.* **2**, 169 (1970).
¹²D. L. Hildenbrand and E. Mirad, *J. Chem. Phys.* **51**, 807 (1969).
¹³B. Rosen, Ed., "Spectroscopic Data Relative to Diatomic Molecules," Pergamon Press, New York, (1970).
¹⁴H. Bell and A. Harvey, *Proc. Phys. Soc. (London)* **50**, 427 (1938).
¹⁵G. D. Rochester and H. G. Howell, *Proc. Roy. Soc. (London)* **148**, 157 (1935).