

## 1. THERMODYNAMIC PROPERTIES

### 1.1 ENTHALPY AND HEAT CAPACITY

#### 1.1.1 ENTHALPY

##### Summary

Recommended values for the enthalpy increments of liquid sodium and sodium vapor relative to the solid at 298.15 K are given in Table 1.1-1 in  $\text{kJ}\cdot\text{kg}^{-1}$ . CODATA<sup>(1)</sup> values for the enthalpy of liquid sodium along the saturation curve are recommended for the temperature range 371 to 2000 K. The equation, given by Cordfunke and Konings,<sup>(2)</sup> for the CODATA values for the enthalpy of liquid sodium in  $\text{kJ}\cdot\text{kg}^{-1}$ , is

$$H(l, T) - H(s, 298.15) = - 365.77 + 1.6582 T - 4.2395 \times 10^{-4} T^2 + 1.4847 \times 10^{-7} T^3 + 2992.6 T^{-1} \quad (1)$$

*for 371 K ≤ T ≤ 2000 K.*

Above 2000 K, the law of rectilinear diameters was used to extrapolate the average of the liquid and vapor enthalpies to the critical point. The enthalpy of liquid (vapor) sodium relative to the solid at 298.15 K is the average enthalpy minus (plus) one half the enthalpy of vaporization. In  $\text{kJ}\cdot\text{kg}^{-1}$ , the average enthalpy is given by

$$H(\text{AVG}, T) - H(s, 298.15) = E + FT \quad (2)$$

*for 2000 K ≤ T ≤ 2503.7 K ,*

where

$$E = 2128.4 ,$$

$$F = 0.86496 .$$

Table 1.1-1 Sodium Enthalpy Increment,  $H(T) - H(s, 298.15 \text{ K})$ 

Temperature (K)	Liquid (kJ · kg <sup>-1</sup> )	Vapor (kJ · kg <sup>-1</sup> )
371.	207.	4739.
400.	247.	4757.
500.	382.	4817.
600.	514.	4872.
700.	642.	4921.
800.	769.	4966.
900.	895.	5007.
1000.	1020.	5044.
1100.	1146.	5079.
1200.	1273.	5111.
1300.	1402.	5140.
1400.	1534.	5168.
1500.	1671.	5193.
1600.	1812.	5217.
1700.	1959.	5238.
1800.	2113.	5256.
1900.	2274.	5268.
2000.	2444.	5273.
2100.	2625.	5265.
2200.	2822.	5241.
2300.	3047.	5188.
2400.	3331.	5078.
2500.	3965.	4617.
2503.7	4294.	4294.

The enthalpy of vaporization,  $\Delta H_g$ , in kJ·kg<sup>-1</sup>, is given by

$$\Delta H_g = 393.37 \left( 1 - \frac{T}{T_C} \right) + 4398.6 \left( 1 - \frac{T}{T_C} \right)^{0.29302} \quad (3)$$

for  $371 \text{ K} \leq T \leq 2503.7 \text{ K}$ ,

where  $T_C$  is the critical temperature, 2503.7 K, and  $T$  is the temperature in kelvins.

The enthalpy of sodium vapor (total vapor over the saturated liquid) was calculated from the sum of the enthalpy of the liquid along the saturation curve and the enthalpy of vaporization given in Eq. (3). Thus, below 2000 K, the enthalpy of the vapor is given by the

sum of Eq. (1) and Eq. (3). Above 2000 K, the enthalpy of the vapor is Eq. (2) plus one half Eq. (3).

Recommended values for the enthalpies of liquid sodium and sodium vapor and the average enthalpy are shown in Fig. 1.1-1. Uncertainty bands have been included up to 2400 K. Above 2400 K, uncertainties in the values for the enthalpies of the liquid and vapor increase rapidly to 12% at 2500 K. Uncertainties for the recommended liquid and vapor enthalpies at a number of temperatures are given in Tables 1.1-2 and 1.1-3, respectively.

### Discussion

**Liquid** — Recommended values for the enthalpy of liquid sodium along the saturation curve are given in  $\text{kJ}\cdot\text{kg}^{-1}$  in Table 1.1-1 and in  $\text{J}\cdot\text{mol}^{-1}$  in Table 1.1-4. The CODATA recommended value for the molecular weight of the liquid (22.98977 grams/mole) was used to convert from  $\text{J}\cdot\text{mol}^{-1}$  to  $\text{kJ}\cdot\text{kg}^{-1}$ . The recommended values for the enthalpy of liquid sodium from 371 to 2000 K are from the assessment by CODATA.<sup>(1)</sup> The CODATA values are identical with values tabulated by Glushko et al.<sup>(3)</sup> CODATA values have been recommended in the books by Bystrov et al.<sup>(4)</sup> and by Cordfunke and Konings.<sup>(2)</sup> Bystrov et al. state that the CODATA values "...are based primarily on values of enthalpy along the saturation curve, determined by the mixing method in calorimeters of different types."<sup>(4)</sup> In the CODATA assessment, the different sets of data were weighted according to the experimental accuracy. Highest weights were given to data of Ginnings et al.,<sup>(5)</sup> Shpil'rain et al.,<sup>(6)</sup> Fredrickson and Chasanov,<sup>(7)</sup> and Martin.<sup>(8)</sup> Data from other measurements were included in the CODATA assessment but at a lesser weight. The CODATA equation has been selected rather than the values from the JANAF Tables<sup>(9)</sup> or the SGTE equation<sup>(10)</sup> (equation recommended by the Scientific Group Thermodata Europe) because the CODATA equation has a simpler form and has been recommended in other reputable reviews.<sup>(2,4)</sup>

Equation (1), which reproduces the CODATA values for the enthalpy of liquid sodium, should not be extrapolated to the critical temperature (2503.7 K) because use of this equation above 2300 K leads to unphysical values of related thermodynamic properties; i.e., isothermal compressibility, thermal-expansion coefficient. Therefore, values for the enthalpy of liquid sodium above 2000 K were calculated from extrapolation of the average of the liquid and vapor enthalpies to the critical point using the law of rectilinear diameters. For  $T \geq 2000$  K, the average enthalpy in  $\text{kJ}\cdot\text{kg}^{-1}$  is defined in Eq. (2). The constants  $E$  and  $F$  in

Table 1.1-2 Estimated Uncertainty in the Recommended Values for Enthalpy of Liquid Sodium

Temperature (K)	$H(l, T) - H(s, 298.15)$ (kJ · kg <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta H_l}{H_l}\right)$ (%)
371 1000 <sup>(a)</sup> 1600 <sup>(a)</sup> 2000 <sup>(a)</sup>	$-365.77 + 1.6582 T - 4.2375 \times 10^{-4} T^2$ $+ 1.4847 \times 10^{-7} T^3 + 2992.6 T^{-1}$	1. 1. 1.5 2.
2050 2400 <sup>(a)</sup> 2500 <sup>(a)</sup>	$2128.4 + 0.86496 T - \frac{1}{2} \Delta H_g$ where $\Delta H_g = 393.37 \left(1 - \frac{T}{T_C}\right)$ $+ 4398.6 \left(1 - \frac{T}{T_C}\right)^{0.29302}$	10. 10. 12.

<sup>(a)</sup>Uncertainty is assumed to vary linearly with temperature between these temperatures.

$$1000 \text{ to } 1600 \text{ K,} \quad \left(\frac{\delta H_l}{H_l}\right) (\%) = 0.17 + 8.3 \times 10^{-4} T$$

$$1600 \text{ to } 2000 \text{ K,} \quad \left(\frac{\delta H_l}{H_l}\right) (\%) = -0.5 + 1.25 \times 10^{-3} T$$

$$2400 \text{ to } 2500 \text{ K,} \quad \left(\frac{\delta H_l}{H_l}\right) (\%) = -38 + 0.02 T$$

Table 1.1-3 Estimated Uncertainty in the Recommended Values for Enthalpy of Sodium Vapor

Temperature (K)	$H(g, T) - H(s, 298.15)$ (kJ · kg <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta H_g}{H_g}\right)^{(a)}$ (%)
371	$H_l + \Delta H_g^{(b)}$	1.
1000	where $H_l = -365.77 + 1.6582 T - 4.2375$	1.
1400	$\times 10^{-4} T^2 + 1.4847 \times 10^{-7} T^3$	1.5
1600	$+ 2992.6 T^{-1}$	2.8
1800		4.
2000		4.
2050	$H_{AVG} + \frac{1}{2} \Delta H_g$	10.
2400	where $H_{AVG} = 2128.4 + 0.86496 T$	10.
2500		12.

<sup>(a)</sup>T < 2000 K,

$$(\delta H_g)^2 = (\delta H_l)^2 + (\delta \Delta H_g)^2$$

2000 < T < 2400 K,

$$(\delta H_g)^2 = (\delta H_{AVG})^2 + \left(\frac{\delta \Delta H_g}{4}\right)^2$$

2400 to 2500 K,

$\left(\frac{\delta H_g}{H_g}\right)$  is assumed to vary linearly with

$$\left(\frac{\delta H_g}{H_g}\right) (\%) = -38 + 0.02 T$$

$$^{(b)}\Delta H_g = 393.37 \left(1 - \frac{T}{T_C}\right) + 4398.6 \left(1 - \frac{T}{T_C}\right)^{0.29302}$$

Table 1.1-4 The Enthalpy and Heat Capacity of Solid and Liquid Sodium Per Mole of Sodium<sup>(a)</sup>

Temperature (K)	H(T) - H(s, 298.15) (J · mol <sup>-1</sup> )	C <sub>P</sub> <sup>(b)</sup> (J · mol <sup>-1</sup> · K <sup>-1</sup> )
298.15	0	28.230
300.	52	28.262
371.	2154	31.509
371.	4752	31.799
400.	5670	31.532
500.	8779	30.659
600.	11807	29.921
700.	14769	29.353
800.	17684	28.973
900.	20570	28.787
1000.	23448	28.799
1100.	26337	29.012
1200.	29257	29.427
1300.	32229	30.045
1400.	35273	30.866
1500.	38409	31.891
1600.	41658	33.120
1700.	45040	34.553
1800.	48575	36.190
1900.	52285	38.032
2000.	56188	40.078

<sup>(a)</sup>Table is based on CODATA values from Cordfunke and Konings.<sup>(2)</sup>

<sup>(b)</sup>C<sub>P</sub> tabulated here is the derivative of the enthalpy along the saturation curve. It deviates from the values given in Table 1.1-5 by less than 0.3% below 1900 K, 0.39% at 1900 K, and 1.15% at 2000 K.

Eq. (2) were determined by matching the values of the liquid enthalpy and its first derivative with respect to temperature at 2000 K. This is preferred to determination of constants by a linear fit to the average enthalpy from 371 to 2000 K, because matching at 2000 K prevents discontinuities in related thermodynamic properties. Because the average enthalpy (shown in Fig. 1.1-1) is not exactly a straight line, greatest deviations between values calculated with Eq. (2) and the average enthalpy occur at low temperatures. At 400 K deviations are 1.1%, whereas above 1600 K, deviations are less than 0.03%. The enthalpies of liquid sodium and sodium vapor were calculated above 2000 K by, respectively, subtracting and adding one half of the enthalpy of vaporization (Eq. [3]) to the average enthalpy defined in Eq. (2).

The recommended values of the enthalpies of liquid sodium along the saturation curve are in good agreement with values from the JANAF Tables,<sup>(9)</sup> values calculated from the equation recommended by the Scientific Group Thermodata Europe (SGTE),<sup>(10)</sup> and values from two assessments by Fink and Leibowitz,<sup>(11,12)</sup> as shown in Fig. 1.1-2. Deviations from recommended values, expressed as a percent defined as

$$Deviations = \left( \frac{[ H(Other) - H(Recommended) ] 100\%}{H(Recommended)} \right) \quad (4)$$

are shown in Fig. 1.1-3. Lines have been included as a guide between the points at which the percent deviations were calculated. The recommended values agree within 0.4% with values to 1600 K given in the JANAF Tables.<sup>(9)</sup> Maximum deviations from the two assessments by Fink and Leibowitz are about 1%. Better agreement is found below 1600 K with the 1979 assessment<sup>(11)</sup> (F&L 79 in Fig. 1.1-3) than with the one from the IUPAC handbook,<sup>(12)</sup> edited by Ohse (F&L-Ohse), because the latter assessment included data that was given little weight in the CODATA assessment. Comparison with values calculated using the equation recommended by SGTE gave the largest deviations. Values from the six-term SGTE equation deviated from the CODATA values by 1.3% at 2000 K and from the recommended equations by 1.5% at 2200 K.

**Vapor** — The enthalpy of the vapor over saturated liquid sodium has been calculated as the sum of the enthalpy of liquid sodium on the saturation curve and the enthalpy of vaporization. Below 2000 K, this is the sum of the liquid enthalpy from the CODATA equation, Eq. (1), and the enthalpy of vaporization, Eq. (3). Above 2000 K, the enthalpy of

sodium vapor is given by the sum of the average of the liquid and vapor enthalpies, Eq. (2), plus one half of the enthalpy of vaporization, Eq. (3). Values are tabulated in  $\text{kJ}\cdot\text{kg}^{-1}$  in Table 1.1-1.

The quasi-chemical method of Golden and Tokar<sup>(13)</sup> has been used in the calculation of the enthalpy of vaporization up to 1600 K. This quasi-chemical approach assumed that the vapor is composed of monomers, dimers, and tetramers. The equilibrium constants of Stone et al.<sup>(14)</sup> for the monomer, dimer, and tetramer were used in the determination of the enthalpy of vaporization up to 1600 K. These calculated enthalpies of vaporization were fit to an equation, Eq. (3), which has proper behavior at the critical temperature. Thus, Eq. (3) represents the enthalpy of vaporization for the entire liquid range.

In recent equation of state calculations by Vargaftik and Voljak<sup>(15)</sup> and by Bystrov et al.,<sup>(4)</sup> the vapor was assumed to be composed of monomers, dimers, and positive ions. The equations obtained by the quasi-chemical method would be equivalent to these equations of state using virial expansions with the equilibrium constants replaced by group integrals if identical components of the gas had been assumed. Assuming different components led to different diatomic fractions and different average molecular weights as a function of temperature. Note that different assumptions in the formulation of the equations of state by Vargaftik and Voljak<sup>(15)</sup> and by Bystrov et al.<sup>(4)</sup> also led to differences in the diatomic fractions and molecular weights as a function of temperature. Consequently, comparisons for the vapor should be made with respect to mass not mole because the mass is the same for the different formulations.

Recommended values of the enthalpy of sodium vapor and those given by Vargaftik and Voljak,<sup>(15)</sup> by Bystrov et al.,<sup>(4)</sup> and by Fink and Leibowitz<sup>(11)</sup> are shown in Fig. 1.1-4. Comparison of the recommended values for sodium vapor enthalpy with values calculated by Vargaftik and Voljak, and by Bystrov et al. using equations of state show good agreement. Good agreement was also obtained with values from Fink and Leibowitz,<sup>(11)</sup> which were calculated using the quasi-chemical method for the heat of vaporization below 1644 K and an extrapolation to the critical point above 1644 K. Deviations from the recommended values, expressed as percents defined as in Eq. (4), are shown in Fig. 1.1-5. Lines have been included between the calculated points to guide the eye. This graph shows that deviations of enthalpies calculated by Vargaftik and Voljak and those tabulated by Bystrov et al. are within 1.2%.

Enthalpies given by Fink and Leibowitz<sup>(11)</sup> differ by 1.02% or less up to 2400 K and by 3% at 2500 K. The larger deviations as the critical point is reached are expected because of differences in the critical temperature in the two assessments. Fink and Leibowitz<sup>(11)</sup> used 2504.9 K for the critical temperature. The critical temperature in this analysis is 2503.7 K.

### Uncertainty

The uncertainties in the recommended CODATA values for the enthalpy of liquid sodium below 2000 K have been estimated from uncertainties given by Bystrov et al.<sup>(4)</sup> and from deviations of other recommended equations. The uncertainties in the CODATA values for enthalpy of sodium are: 0.3% at 298 K, 0.5% at 1000 K, and 1.5% at 2000 K. Comparison of the deviations from other assessments with the recommended values for liquid sodium enthalpy (Fig. 1.1-3) indicate that deviations on the order of 1% occur below 1000 K because of deviations in different data used in the different analyses. Thus, an estimated uncertainty of 1% below 1000 K is consistent with deviations from available data. The uncertainty at 1600 K is estimated as 1.5% and that at 2000 K is estimated as 2%. Uncertainties are assumed to increase linearly with temperature from 1000 to 1600 K and from 1600 to 2000 K. These linear equations are given in Table 1.1-2.

Uncertainties for the liquid above 2000 K were calculated from the uncertainties in the dependent parameters assuming that all uncertainties are independent. If  $x_i$  are the dependent parameters, the square of the uncertainty in the calculated quantity ( $\delta H$ ) is given by

$$(\delta H)^2 = \sum \left( \frac{\partial H}{\partial x_i} \right)^2 (\delta x_i)^2 \quad , \quad (5)$$

where  $\delta x_i$  are the uncertainties in the dependent parameters. Thus, above 2000 K, the uncertainty in the liquid enthalpy ( $\delta H$ ) is a function of the uncertainty in the average enthalpy ( $\delta H_{AVG}$ ) and the uncertainty in the enthalpy of vaporization ( $\delta \Delta H_g$ ):

$$(\delta H)^2 = (\delta H_{AVG})^2 + \frac{1}{4}(\delta \Delta H_g)^2 \quad . \quad (6)$$

The uncertainty in the liquid enthalpy varies from about 10% in the 2000 to 2400 K range to 12% at 2500 K. Between 2400 and 2500 K, calculated uncertainties in enthalpy are approximated by a linear equation in temperature that is given in Table 1.1-2.

For temperatures below 2000 K, the uncertainty in the vapor enthalpy ( $\delta H_g$ ) is the square root of the sum of the squares of the uncertainties in the liquid enthalpy and in the enthalpy of vaporization:

$$\delta H_g = \sqrt{(\delta H_l)^2 + (\delta \Delta H_g)^2} \quad (7)$$

Above 2000 K, the uncertainty in the vapor enthalpy ( $\delta H_g$ ) is identical to the uncertainty in the liquid enthalpy and is given by Eq. (6). Calculated uncertainties in the enthalpy of sodium vapor are 1% from 371 to 1000 K. They increase to 1.5% at 1400 K. From 1400 to 2000 K, calculated uncertainties are tabulated every 200 K in Table 1.1-3. Comparison of calculated uncertainties with deviations of other assessments from the recommended values for the enthalpy of sodium vapor (graphed in Fig. 1.1-5) shows that most assessments are within the 1% uncertainty below 1000 K. Deviations from recommendations are significantly less than the estimated uncertainties above 2000 K.

### 1.1.2 HEAT CAPACITY

#### Summary

Recommended values for the heat capacities at constant pressure and the heat capacities at constant volume for the liquid and vapor in  $\text{kJ}\cdot\text{kg}^{-1}$  are given in Tables 1.1-5 and Table 1.1-6. Values in  $\text{kJ}\cdot\text{mol}^{-1}$  for the heat capacity at constant pressure have been included in Table 1.1-4. Liquid heat capacities are shown in Fig. 1.1-6; vapor heat capacities are shown in Fig. 1.1-7. Estimates of the uncertainties in the tabulated values are given in Tables 1.1-7 through 1.1-10.

**Heat Capacity at Constant Pressure,  $C_p$**  — The heat capacities at constant pressure of liquid sodium and sodium vapor have been calculated from the heat capacity along the saturation curve ( $C_\sigma$ ) using the thermodynamic relation

$$C_p = C_\sigma + \left( \frac{T \alpha_p \gamma_\sigma}{\rho} \right) \quad (8)$$

Table 1.1-5 Heat Capacity of Liquid Sodium

Temperature (K)	$C_p$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	$C_v$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )
371.	1.383	1.262
400.	1.372	1.241
500.	1.334	1.170
600.	1.301	1.104
700.	1.277	1.045
800.	1.260	0.994
900.	1.252	0.951
1000.	1.252	0.914
1100.	1.261	0.885
1200.	1.279	0.862
1300.	1.305	0.844
1400.	1.340	0.830
1500.	1.384	0.819
1600.	1.437	0.811
1700.	1.500	0.803
1800.	1.574	0.795
1900.	1.661	0.784
2000.	1.764	0.768
2100.	1.926	0.768
2200.	2.190	0.791
2300.	2.690	0.872
2400.	4.012	1.172
2469.	8.274	2.463
2500.	39.279	16.371

Table 1.1-6 Heat Capacity of Sodium Vapor

Temperature (K)	$C_p$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	$C_v$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )
400.	0.86	0.49
500.	1.25	0.84
600.	1.80	1.31
700.	2.28	1.71
800.	2.59	1.93
900.	2.72	1.98
1000.	2.70	1.92
1100.	2.62	1.81
1200.	2.51	1.68
1300.	2.43	1.58
1400.	2.39	1.51
1500.	2.36	1.44
1600.	2.34	1.39
1700.	2.41	1.38
1800.	2.46	1.36
1900.	2.53	1.33
2000.	2.66	1.30
2100.	2.91	1.30
2200.	3.40	1.34
2300.	4.47	1.44
2400.	8.03	1.76
2500.	417.03	17.03

Table 1.1-7 Estimated Uncertainties in the Recommended Values for Heat Capacity at Constant Pressure of Liquid Sodium

Temperature (K)	$C_P$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta C_P}{C_P}\right)$ (%)
371 ≤ T ≤ 1000	$C_P = C_\sigma + \left(\frac{T \alpha_P \gamma_\sigma}{\rho}\right)$	2
1000 < T ≤ 1600		3
1600 < T ≤ 2000		20
2000 < T ≤ 2200		30
2200 < T ≤ 2400		35
2400 < T ≤ 2503		50

Table 1.1-8 Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Volume of Liquid Sodium

Temperature (K)	$C_V$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta C_V}{C_V}\right)$ (%)
371 ≤ T ≤ 1000	$C_V = C_P \left(\frac{\beta_S}{\beta_T}\right)$	5
1000 < T ≤ 1600		10
1600 < T ≤ 2000		40
2000 < T ≤ 2200		65
2200 < T ≤ 2400		80
2400 < T ≤ 2503		90

Table 1.1-9 Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Pressure of Sodium Vapor

Temperature (K)	$C_P$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta C_P}{C_P}\right)$ (%)
371 ≤ T ≤ 500	$C_P = C_\sigma + \left(\frac{T \alpha_p \gamma_\sigma}{\rho_g}\right)$	50
500 < T ≤ 1000		20
1000 < T ≤ 1600		15
1600 < T ≤ 2000		35
2000 < T ≤ 2200		50
2200 < T ≤ 2400		60
2400 < T ≤ 2503		65

where  $\alpha_p$  is the thermal-expansion coefficient,  $\gamma_\sigma$  is the partial derivative of the pressure with respect to temperature along the saturation curve, and  $\rho$  is the density. These thermodynamic properties are defined in the discussion section.

**Heat Capacity at Constant Volume,  $C_V$**

**Liquid** — The heat capacity at constant volume of saturated liquid sodium was calculated from the heat capacity at constant pressure and the adiabatic and isothermal compressibilities ( $\beta_S, \beta_T$ ) using the thermodynamic relation

$$C_V = C_P \left(\frac{\beta_S}{\beta_T}\right) . \quad (9)$$

Table 1.1-10 Estimated Uncertainties in the Recommended Values for the Heat Capacity at Constant Volume of Sodium Vapor

Temperature (K)	$C_P$ (kJ · kg <sup>-1</sup> · K <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta C_V}{C_V}\right)$ (%)
371 ≤ T ≤ 500	$C_V = C_P - \left(\frac{T \alpha_P \gamma_V}{\rho_g}\right)$	75
500 < T ≤ 1000		30
1000 < T ≤ 1600		20
1600 < T ≤ 2000		35
2000 < T ≤ 2200		45
2200 < T ≤ 2400		55
2400 < T ≤ 2503		65

**Vapor** — The heat capacity at constant volume of saturated sodium vapor was calculated using the thermodynamic relation

$$C_V = C_P - \left(\frac{T \alpha_P \gamma_V}{\rho_g}\right), \quad (10)$$

where  $C_P$ ,  $\alpha_P$ , and  $\rho_g$  are, respectively, the heat capacity at constant pressure, the thermal-expansion coefficient, and the density for sodium vapor, and  $\gamma_V$  is the thermal-pressure coefficient. Equations for these thermodynamic properties are given below in the discussion of heat capacity.

#### Discussion

**Heat Capacity at Constant Pressure,  $C_P$**  — The liquid and vapor heat capacities at constant pressure were calculated from the thermodynamic relation given in Eq. (8). The heat capacity along the saturation curve,  $C_\sigma$ , is defined as

$$C_{\sigma} = T \left( \frac{\partial S}{\partial T} \right)_{\sigma} . \quad (11)$$

It is related to the partial derivative of the enthalpy along the saturation curve by

$$C_{\sigma} = \left( \frac{\partial H}{\partial T} \right)_{\sigma} - \left( \frac{\gamma_{\sigma}}{\rho} \right) , \quad (12)$$

where

$$\gamma_{\sigma} = \left( \frac{\partial P}{\partial T} \right)_{\sigma} .$$

In Eqs. (8, 11-13)  $P$  is the vapor pressure,  $\rho$  is the liquid (vapor) density, and  $H$  is the liquid (vapor) enthalpy, given above. The vapor pressure,  $P$ , is given by an equation derived by Browning and Potter:<sup>(16)</sup>

$$\ln P = a + \frac{b}{T} + c \ln T . \quad (14)$$

Then  $\gamma_{\sigma}$ , the temperature derivative of the pressure along the saturation curve is

$$\gamma_{\sigma} = \left( -\frac{b}{T^2} + \frac{c}{T} \right) \exp \left( a + \frac{b}{T} + c \ln T \right) , \quad (15)$$

and the coefficients in Eqs. (14, 15) for  $P$  in MPa and  $T$  in kelvins are defined as

$$\begin{aligned} a &= 11.9463 , \\ b &= -12633.7 , \\ c &= -0.4672 . \end{aligned}$$

**$C_p$  Liquid**—For saturated liquid sodium, the thermal-expansion coefficient ( $\alpha_p$ ) was calculated from the thermodynamic relation

$$\alpha_p = \alpha_{\sigma} + \beta_T \gamma_{\sigma} , \quad (16)$$

where  $\beta_T$  is the isothermal compressibility and  $\alpha_{\sigma}$  is the coefficient of thermal expansion along the saturation curve defined as

$$\alpha_{\sigma} = - \left( \frac{1}{\rho_l} \right) \left( \frac{\partial \rho_l}{\partial T} \right)_{\sigma} . \quad (17)$$

The liquid density  $\rho_l$  is given by

$$\rho = \rho_C + f \left( 1 - \frac{T}{T_C} \right) + g \left( 1 - \frac{T}{T_C} \right)^h , \quad (18)$$

where the parameters for density in  $\text{kg}\cdot\text{m}^{-3}$  and temperature ( $T$ ) in kelvins are

$$\begin{aligned} \rho_C &= 219., \\ f &= 275.32, \\ g &= 511.58, \\ h &= 0.5, \end{aligned}$$

and  $\rho_C$  is the density at the critical temperature,  $219 \text{ kg}\cdot\text{m}^{-3}$ .

The isothermal compressibility ( $\beta_T$ ) is defined by the thermodynamic relation

$$\beta_T = \left[ \frac{\beta_S C_{\sigma} + \left( \frac{T}{\rho_l} \right) \alpha_{\sigma} (\alpha_{\sigma} + \beta_S \gamma_{\sigma})}{C_{\sigma} - \left( \frac{T}{\rho_l} \right) \gamma_{\sigma} (\alpha_{\sigma} + \beta_S \gamma_{\sigma})} \right] , \quad (19)$$

where  $\beta_S$  is the adiabatic compressibility given by

$$\beta_S = \beta_{S, m} \left[ \frac{1 + \left( \frac{\theta}{b} \right)}{(1 - \theta)} \right] , \quad (20)$$

with

$$\theta = \left[ \frac{(T - T_m)}{(T_C - T_m)} \right] ,$$

and the adiabatic compressibility at the melting point,  $\beta_{S, m}$ , is equal to

$$\beta_{s, m} = 1.717 \times 10^{-4} \text{ MPa}^{-1} ,$$

and

$$b = 3.2682 ,$$

$$T_m = 371 \text{ K} ,$$

$$T_C = 2503.7 \text{ K} .$$

Equation (20) for the adiabatic compressibility ( $\beta_s$ ) was obtained by fitting the adiabatic compressibilities from the melting point to 1773 K, calculated from the density and speed of sound in liquid sodium ( $v$ ) using the relation

$$\beta_s = \left( \frac{1}{\rho v^2} \right) , \quad (21)$$

where the speed of sound in  $\text{m}\cdot\text{s}^{-1}$  is given by the quadratic equation determined from the fit to the available data by Fink and Leibowitz:<sup>(11)</sup>

$$v = 2660.7 - 0.37667 T - 9.0356 \times 10^{-5} T^2 \quad (22)$$

*for 371 K  $\leq$  T  $\leq$  1773 K .*

At high temperatures, the heat capacity at constant pressure for liquid sodium differs from the heat capacity along the saturation curve ( $C_\sigma$ ) and from the partial derivative of the enthalpy along the saturation curve. From Eqs. (11, 12), the heat capacity at constant pressure is related to the partial derivative with respect to temperature of the enthalpy along the saturation curve ( $\partial H/\partial T)_\sigma$  by

$$C_p = \left( \frac{\partial H}{\partial T} \right)_\sigma + \left( \frac{\gamma_\sigma}{\rho} \right) (T \alpha_p - 1) . \quad (23)$$

The heat capacity at constant pressure ( $C_p$ ), the heat capacity along the saturation curve ( $C_\sigma$ ), and the partial derivative, with respect to temperature of the enthalpy along the saturation curve, are shown for liquid sodium in Fig. 1.1-8. At about 1900 K,  $T \alpha_p$  becomes greater than unity and the heat capacity at constant pressure becomes greater than the partial derivative of the enthalpy along the saturation curve. Deviations of  $C_\sigma$  and  $(\partial H/\partial T)_\sigma$  from  $C_p$  increase as the critical temperature is approached, as shown by the deviation plot in Fig. 1.1-9.

Values of  $C_p$  tabulated by CODATA,<sup>(1)</sup> are just the first term in Eq. (23); i.e., the derivative of the enthalpy along the saturation curve. Cordfunke and Konings,<sup>(2)</sup> and Bystrov et al.<sup>(4)</sup> tabulate the CODATA values with no correction at high temperatures. The JANAF Tables<sup>(9)</sup> give heat capacities only to 1600 K. Up to this temperature there is no significant difference between the heat capacity at constant pressure and the temperature derivative of the enthalpy along the saturation curve. Heat capacities at constant pressure were given by Fink and Leibowitz<sup>(11)</sup> to the critical point using the appropriate thermodynamic relations. The values recommended in this assessment are compared to those from Fink and Leibowitz, the CODATA values, and the JANAF values in Fig. 1.1-10. Deviations defined as

$$Deviations = \left( \frac{[C_p - C_p(Recommended)]}{C_p(Recommended)} 100\% \right)$$

are shown in Fig. 1.1-11. Deviations of the CODATA values from those recommended are less than 0.3% up to 1900 K, 0.39 % at 1900 K, and 1.15% at 2000 K. Deviations of heat capacities given in the JANAF tables are within 1.8%. Values recommended by Fink and Leibowitz deviate from current recommendations by less than 0.8% up to 1400 K. Figure 1.1-11 shows that above 1300 K, percent deviations increase with temperature to 3% at 1900 K, 4% at 2200 K, and 8% at 2400 K. At 2500 K, deviations are 46%. These large deviations are related to the increase in  $C_p$  as the critical temperature is reached and the different critical temperatures in the two assessments. The critical temperature in the Fink and Leibowitz assessment was 2509.4 K, whereas in this assessment the critical temperature is 2503.7 K.

**$C_p$  Vapor** — The heat capacity at constant pressure for sodium vapor was calculated from Eq. (8) with the thermodynamic parameters for the vapor defined by Eqs. (11-15). The thermal-expansion coefficient for sodium vapor was calculated from the relation

$$(\alpha_p)_g = \left[ \frac{(\alpha_\sigma)_g}{1 - \left( \frac{\gamma_\sigma}{\gamma_V} \right)} \right], \quad (25)$$

where the vapor coefficient of thermal expansion along the saturation curve  $(\alpha_\sigma)_g$  is defined as

$$(\alpha_{\sigma})_g = - \left( \frac{1}{\rho_g} \right) \left( \frac{\partial \rho_g}{\partial T} \right)_{\sigma} . \quad (26)$$

The vapor density was calculated from the enthalpy of vaporization, the derivative of the pressure, and the liquid density using the relation

$$\rho_g = \left( \frac{\Delta H_g}{T\gamma_{\sigma}} + \frac{1}{\rho_l} \right)^{-1} . \quad (27)$$

In Eq. (25),  $\gamma_v$  is the thermal-pressure coefficient. Below 1600 K, the thermal-pressure coefficient was calculated using the quasi-chemical approximation.<sup>(13)</sup> Values calculated via the quasi-chemical approximation, shown in Fig. 1.1-12, were fit to an equation so that a functional form is available for calculation of all the vapor properties. This equation for  $\gamma_v$  in MPa·K<sup>-1</sup> is

$$\gamma_v = \left( -\frac{b}{T^2} + \frac{c}{T} + d + 2eT \right) \exp \left( a + \frac{b}{T} + c \ln T + dT + eT^2 \right) \quad (28)$$

*for 371 K ≤ T ≤ 1600 K ,*

where

$$\begin{aligned} a &= 8.35307 , \\ b &= -12905.6 , \\ c &= -0.45824 , \\ d &= 2.0949 \times 10^{-3} , \\ e &= -5.0786 \times 10^{-7} . \end{aligned}$$

At the critical point, the thermal-pressure coefficient ( $\gamma_v$ ) must equal  $\gamma_{\sigma}$ , the slope of the vapor pressure curve. Above 1600 K, the thermal-pressure coefficient was extrapolated to the critical point using the same form of equation used by Fink and Leibowitz:<sup>(11)</sup>

$$\gamma_v = \gamma_v^c + A \left( 1 - \frac{T}{T_c} \right)^{\frac{1}{2}} + B \left( 1 - \frac{T}{T_c} \right)$$

*for 1600 K ≤ T ≤ 2500 K ,*

where

$$\begin{aligned}\gamma_V^C &= \gamma_\sigma^C = 4.6893 \times 10^{-2} , \\ A &= -2.5696 \times 10^{-3} , \\ B &= 3.5628 \times 10^{-5} , \\ T_C &= 2503.7 \text{ K} .\end{aligned}$$

The superscript or subscript  $C$  in Eq. (29) denotes the value at the critical temperature ( $T_C$ ). The parameters  $A$  and  $B$  in Eq. (29) were determined by matching the value and temperature derivative of the thermal-pressure coefficient at 1600 K. The equation fitting the thermal-pressure coefficient below 1600 K and the extrapolation to the critical point are shown in Fig. 1.1-12. The derivative of the vapor pressure ( $\gamma_\sigma$ ) has been included in the figure.

In Fig. 1.1-13, the recommended values for the heat capacity at constant pressure for sodium vapor above the saturated liquid are compared with values from quasi-chemical calculations by Fink and Leibowitz,<sup>(11)</sup> values from equation of state calculations by Bystrov et al.,<sup>(4)</sup> and values from equation of state calculations of Vargaftik and Voljak.<sup>(15)</sup> At 400 K, the recommended heat capacity is lower than the values given by both the Fink and Leibowitz calculation and that of Vargaftik and Voljak. Between 500 and 700 K, recommended values are above those given by these two calculations. Below 1600 K, values from the calculations of Bystrov et al. are consistently low relative to the recommended values and the other two sets of calculations, as shown in the deviation plots in Fig. 1.1-14. The deviations from the recommended values are defined as in Eq. (24) for liquid heat capacities. The similarity in shape of the deviations over some temperature ranges indicate the possibility of systematic error due to the choice of functional forms for the equations used in the calculation of vapor heat capacities. Deviations with respect to the other calculations are generally on the order of 10% except at low and high temperatures. Agreement on the order of 6% or less was found with values recommended by Fink and Leibowitz for the 700 to 1600 K temperature range. For temperatures up to 2200 K, agreement was on the order of or less than 10%. However, at 2500 K, values deviated by 56% due to different values in the critical temperature and the increase in heat capacity as the critical temperature is approached. The large deviations of the low temperature values given by Fink and Leibowitz and those recommended arise from differences in the derivative of the vapor enthalpies at low temperatures, shown in Fig. 1.1-15. The significant differences at low temperatures arise from differences in the contribution to the

derivative from the enthalpy of vaporization. Although both calculations used the quasi-chemical method to obtain values for the enthalpy of vaporization below 1600 K, Fink and Leibowitz<sup>(11)</sup> obtained the derivative by numerical differentiation, whereas here the functional fit was differentiated. Use of a functional form to represent the thermal-pressure coefficient rather than the values from the quasi-chemical approximation also increased the differences between these calculations.

**$C_V$  Liquid** — The recommended values for the heat capacity at constant volume of liquid sodium are shown in Fig. 1.1-16 along with values recommended in the assessment by Fink and Leibowitz.<sup>(11)</sup> Figure 1.1-16 shows that differences in the recommended values from the two assessments increase with temperature. This is due to the different critical temperatures in the two assessments and increases in deviations of dependent parameters with temperature in the two assessments. Deviations are within 2% up to 1200 K. At 1800 K, recommended values differ by 20%. Differences are on the order of 50% at temperatures equal or greater than 2200 K.

**$C_V$  Vapor** — Recommended values for the heat capacity at constant volume for sodium vapor are shown in Fig. 1.1-17 along with values recommended in the assessments by Fink and Leibowitz,<sup>(11)</sup> by Bystrov et al.<sup>(4)</sup> and by Vargaftik and Voljak.<sup>(15)</sup> Deviations of these other assessments from the recommended values defined as

$$Deviations = \left( \frac{[C_V(Other) - C_V(Recommended)] 100\%}{C_V(Recommended)} \right) \quad (30)$$

are shown in Fig. 1.1-18. Trends are similar to those for  $C_p$  vapor as expected because the two heat capacities are related. However maximum deviations are greater for  $C_V$ . As for  $C_p$ , values from the equation of state calculation of Bystrov et al. below 1600 K are lower than recommended values and also lower than values from other calculations. The deviations at low temperature from values given by Fink and Leibowitz arise from the same source (derivative of enthalpy of vaporization and thermal-pressure coefficient) as for  $C_p$ . Fink and Leibowitz values deviate by +35% at 400 K but by -21% at 500 K. Between 600 and 1600 K, they are within 6%. Between 1600 and 2300 K, they are within 8% but increase to 23% at 2400 K. At 2500 K, Fink and Leibowitz's recommended value deviates by only 5%. Deviations of

Vargaftik and Voljak's values are generally within 5% except for low temperatures where they are as high as 21%. Bystrov's values deviate by as much as 14%.

Ratios of the heat capacity at constant pressure to the heat capacity at constant volume for the vapor are shown in Fig. 1.1-19. Better agreement exists between the different recommendations for the ratio than for the individual heat capacities.

### Uncertainties

Because the functional forms of the thermodynamic relations used to calculate the heat capacities are so complex and the dependent parameters are not independent of each other, the square of the uncertainties cannot be simply calculated from the square of the uncertainties of the dependent parameters as was done for enthalpy (Eq. [5]). Consequently, a number of factors were considered in estimating the heat capacity uncertainties. These included: (1) uncertainty estimates given in other assessments, (2) deviations between recommended values from different assessments, (3) calculation of uncertainties from uncertainties assuming no dependence between parameters, and (4) sensitivity of calculated properties to the uncertainties of measured properties which includes calculations of error propagation.

$C_p$  *Liquid* — Bystrov et al.<sup>(4)</sup> give the uncertainties for the CODATA heat capacities at constant pressure as 0.1% at 298 K, 3% at 1000 K, and 8% at 2000 K. At low temperatures, recommended values of the heat capacity at constant pressure are identical to the CODATA values, which are just the derivative of the enthalpy increment along the saturation curve. Thus, the main uncertainty in the heat capacity at constant pressure is due to the uncertainty in this derivative. Below 1600 K, the uncertainty was approximated as twice the uncertainty in the enthalpy increment along the saturation curve. At higher temperatures, other uncertainties begin to have some affect but contribute little unless they are large. Equations (8-23) indicate that the heat capacity at constant pressure is a function of the derivatives of enthalpy, pressure, and density and also functions of density and speed of sound. Dependence on the speed of sound in sodium enters through the thermal-expansion coefficient which is a function of the compressibility. From examination of the propagation of errors in these basic properties, errors due to the thermal expansion coefficient and the compressibility were found to have little effect on the value of the heat capacity at constant pressure. Thus above 1600 K, the uncertainty in the heat capacity at constant pressure was approximated as

$$\delta C_p = \sqrt{(2 \delta H)^2 + (2 \delta P)^2 + (\delta \rho)^2} \quad (31)$$

A factor of two times the uncertainty in enthalpy increment and vapor pressure were used because the heat capacity is dependent upon the temperature derivatives of these properties and the error in the derivative is usually greater than the error in the function. For simplicity, single values are given for the percent uncertainties for each temperature interval in Table 1.1-7. The value chosen is the largest calculated uncertainty in each temperature interval. For temperatures above 2400 K, an uncertainty of 50% is estimated based not on Eq. (31) but on the deviations between the 2500 K heat capacities calculated in this assessment and the 1979 assessment by Fink and Leibowitz.<sup>(11)</sup> Uncertainty bands are shown as dotted lines in the graph of the heat capacity at constant pressure for liquid sodium in Fig. 1.1-20. The estimated uncertainties given in Table 1.1-7 are similar to those given by Fink and Leibowitz and by Bystrov et al. up to 1000 K. However, at higher temperatures, they are larger than those given by Bystrov et al. but similar to those given by Fink and Leibowitz. The Fink and Leibowitz estimates are 27% for 1644 to 2200 K, 36% for 2200 to 2400 K and 80% above 2400 K.

**$C_v$  Liquid** — The uncertainties of the recommended values for the heat capacity at constant volume for liquid sodium are given in Table 1.1-8. They were calculated from the uncertainties in the dependent parameters: adiabatic compressibility, isothermal compressibility, and heat capacity at constant pressure. Employing the approximation that the errors from these parameters are independent and using unity to approximate the contributions from the partial derivatives that multiply the square of each uncertainty in the sum gives the relation

$$\delta C_v = \sqrt{(\delta C_p)^2 + (\delta \beta_s)^2 + (\delta \beta_T)^2} \quad (31)$$

In Table 1.1-8, uncertainties given for each temperature interval are the largest calculated in that interval rounded to the nearest 5%. In Fig. 1.1-21, the dotted lines are the uncertainty bands. Uncertainties calculated using Eq. (32) are in good agreement with estimates given by Fink and Leibowitz.<sup>(11)</sup>

**$C_p$  Vapor** — Examination of the propagation of uncertainties in the calculation of the heat capacity at constant pressure for the vapor indicated that uncertainties in the thermal-expansion coefficient could not be ignored as was the case for the liquid. The uncertainties in

the heat capacity at constant pressure for sodium vapor were calculated from the uncertainty in the heat capacity along the saturation curve,  $C_\sigma$ , and the uncertainty in the vapor thermal-expansion coefficient with the approximations that these uncertainties are independent and the partial derivatives of  $C_p$  with respect to  $C_\sigma$  and  $\alpha_p$  are unity; thus,

$$\delta C_p = \sqrt{(\delta C_\sigma)^2 + (\delta \alpha_p)^2} . \quad (33)$$

The uncertainty in the heat capacity along the saturation curve,  $C_\sigma$ , was calculated from the square root of the sum of the squares of twice the uncertainties in the vapor enthalpy plus the uncertainty in the vapor density. Because the uncertainty in the vapor density is a function of the uncertainties in the liquid density, heat of vaporization, and the pressure, the uncertainty in the pressure was not explicitly included in the sum for the uncertainty in  $C_\sigma$ . The uncertainty in the thermal-expansion coefficient was calculated from uncertainties in the vapor density and the thermal-pressure coefficient, assuming these uncertainties are independent. Thus, both terms in Eq. (33) are functions of the uncertainty in the vapor density. The uncertainty in the vapor heat capacity at constant pressure is given as a function of temperature in Table 1.1-9 and shown as dotted uncertainty bands in Fig. 1.1-22. Throughout each interval, the highest uncertainty in the interval rounded to the nearest 5% was used. The high uncertainty at low temperatures arises from uncertainties in the thermal-pressure coefficient and the derivative of the vapor pressure at low temperatures. Estimated uncertainties given in Table 1.1-9 are higher than those of Bystrov et al. at all temperatures and higher than those given by Fink and Leibowitz<sup>(11)</sup> at low temperatures (below 500 K) but are similar to those of Fink and Leibowitz above 1000 K. Fink and Leibowitz give uncertainties of 16% below 1644 K, 36% from 1644 to 2000 K, 50% for 2000 to 2400 K and 100% above 2400 K. Bystrov et al. give uncertainties of 2% at 1000 K, 3% at 1400 K, and 24% at 1800 K.

**$C_v$  Vapor** — The uncertainty in the heat capacity at constant volume for the vapor was calculated from uncertainties in the heat capacity at constant pressure, the vapor density, the vapor thermal-expansion coefficient, and the thermal-pressure coefficient using the relation

$$\delta C_v = \sqrt{(\delta C_p)^2 + (\delta \alpha_p)^2 + (\delta \rho)^2 + (\delta \gamma_v)^2} . \quad (34)$$

This relation assumes independence of these errors, which is an approximation, and ignores the contributions from the partial derivatives. Uncertainties are given in Table 1.1-10 for various

temperature intervals and shown in Fig. 1.1-23. Comparison with the uncertainties given by Fink and Leibowitz<sup>(11)</sup> gives similar conclusions as for those for the vapor heat capacity at constant pressure. Fink and Leibowitz estimate uncertainties of 28% below 1644 K, 40% from 1644 to 2000 K, 60% from 2000 to 2400 K, and 100% above 2400 K. Comparison of recommendations from various assessments indicate all lie within the uncertainty estimates given in Table 1.1-10.

#### Polynomial Approximation

The CODATA equation, which is the derivative of the enthalpy increment along the saturation curve, may be used as a polynomial approximation to the heat capacity at constant pressure; this equation is

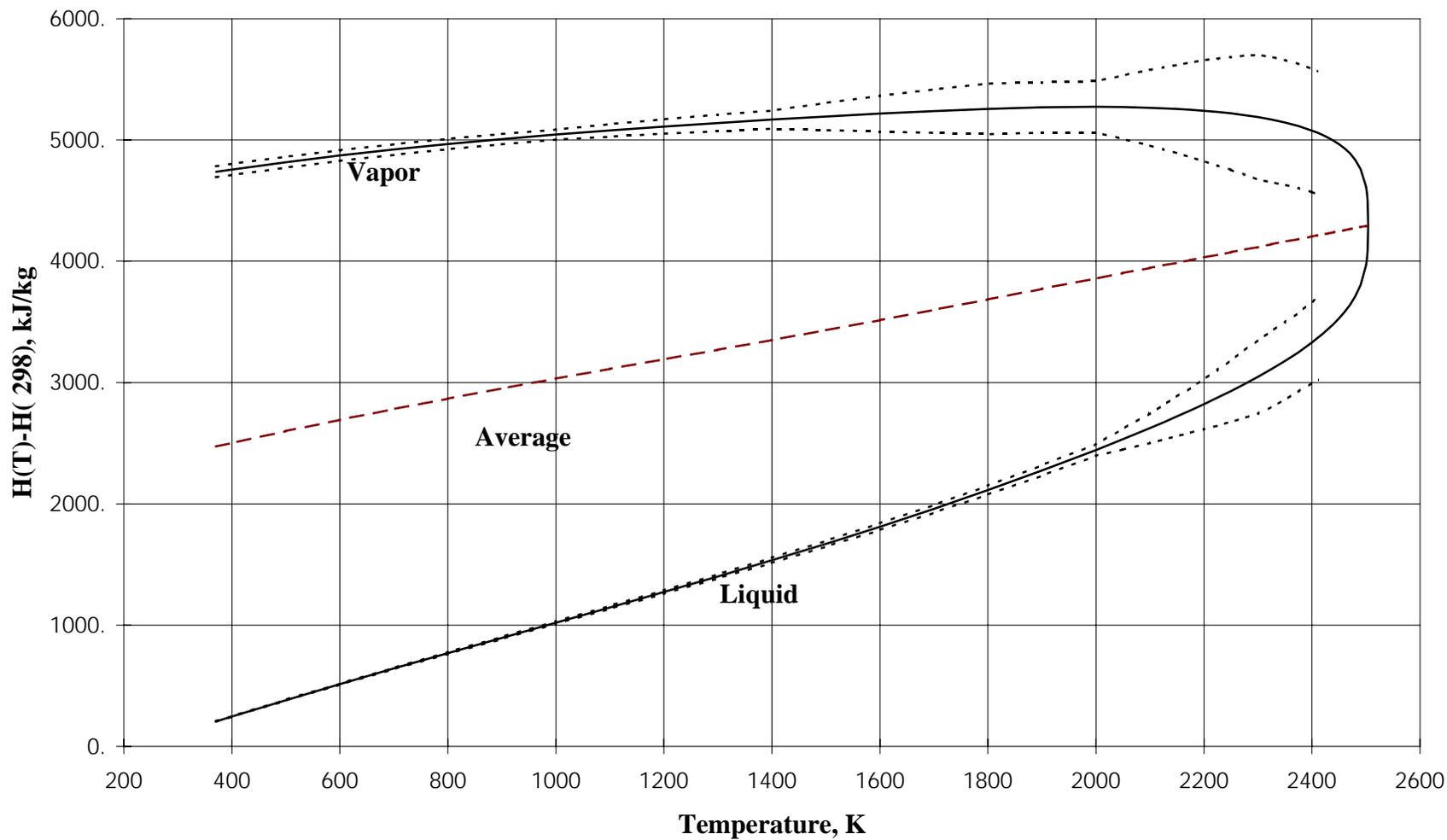
$$C_p \approx + 1.6582 - 8.4790 \times 10^{-4} T + 4.4541 \times 10^{-7} T^2 - 2992.6 T^{-2} \quad (35)$$

Up to 1900 K, deviations of values calculated with this polynomial expression from the recommended values are less than 0.3%. Deviations are 0.39% at 1900 K and 1.15% at 2000 K. Above 2000 K, deviations increase as the critical temperature is approached, as shown in Figs. 1.1-8 and 1.1-9, which respectively compare the derivative along the saturation curve with  $C_o$  and  $C_p$  and give deviations from  $C_p$ . The deviation at 2400 K is 15.5%. At 2500 K, it is 32%.

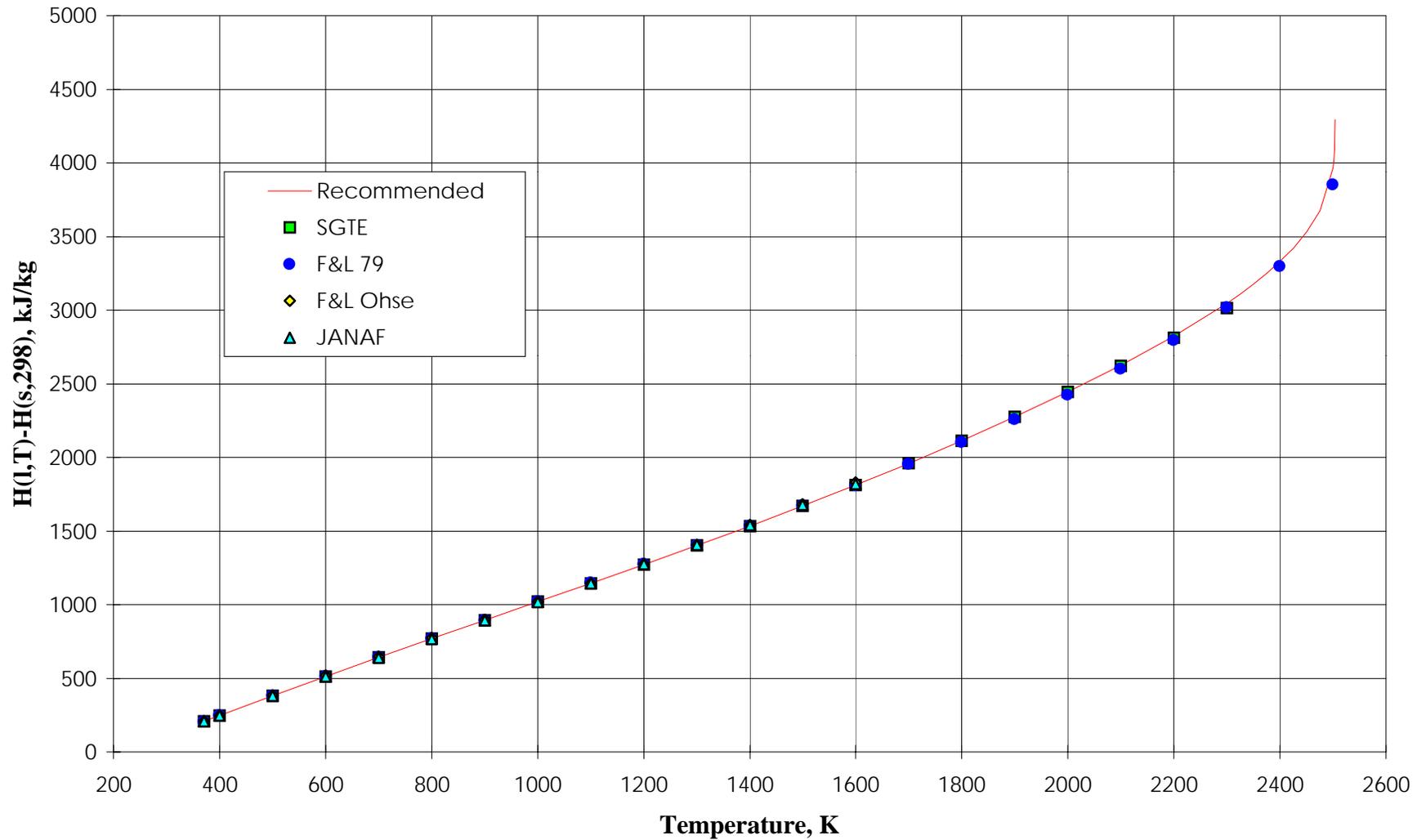
## REFERENCES

1. J. D. Cox, D. D. Wagman, and V. A. Medvedev, **CODATA Key Values for Thermodynamics**, Hemisphere Publishing Corp., New York (1989).
2. E. H. P. Cordfunke and R. J. M. Konings, **Thermochemical Data for Reactor Materials and Fission Products**, North Holland Elsevier Science Pub. Co. Inc., New York (1990).
3. V. P. Glushko, L. V. Gurvich, G. A. Bergman, I. V. Veyts, V. A. Medvedev, G. A. Khachkuruzov, and V. S. Yungman, **Termodinamicheskie Svoistva Individual'nykh Veshchestv**, Tom Iv, Nauka, Moskva (1982).
4. P. I. Bystrov, D. N. Kagan, G. A. Krechetova, and E. E. Shpil'rain, **Liquid-Metal Coolants for Heat Pipes and Power Plants**, ed, V. A. Kirillin, Hemisphere Pub. Corp., New York (1990).
5. D. C. Ginnings, T. B. Douglas, and A. F. Ball, **J. Res. NBS** **45**, 22 (1950).
6. E. E. Shpil'rain, Y. A. Soldatenk, K. A. Yakimovich, V. A. Fomin, V. A. Savchenko, A. M. Belova, D. N. Kagan, and F. I. Krainova, **Teplofiz Vys. Temp.** **3**, 930 (1965); [English translation **High Temp.** **3**, 870 (1965)].
7. D. R. Fredrickson and M. G. Chasanov, **J. Chemical Thermodynamics** **5**, 485 (1973).
8. D. L. Martin, **Phys. Rev.** **154**, 571 (1967).
9. M. W. Chase, Jr., C A. Davies, J. R. Downey, Jr., D. J. Frurip, R. A. McDonald, and A.N. Syverud, *JANAF Thermochemical Tables, Third Edition*, **J. Phys. & Chem. Ref. Data** **14**, **1985**, **Supplement 1**, Am. Chem. Soc. (1986).
10. A. T. Dinsdale, **CALPHAD** **15**, 317 (1991)
11. J. K. Fink and L. Leibowitz, *Thermophysical Properties of Sodium*, **ANL-CEN-RSD-79-1**, Argonne National Laboratory Report (May 1979).
12. J. K. Fink and L. Leibowitz, *Enthalpy, Entropy and Specific Heat - Data Assessment*, Chapter 6.3.2 in **Handbook of Thermodynamic and Transport Properties of Alkali Metals**, R. W. Ohse, Editor, International Union of Pure and Applied Chemistry, Blackwell Science Publications, Boston (1985).
13. G. H. Golden and T. V. Tokar, *Thermophysical Properties of Sodium*, **ANL-7323**, Argonne National Laboratory Report (1967).

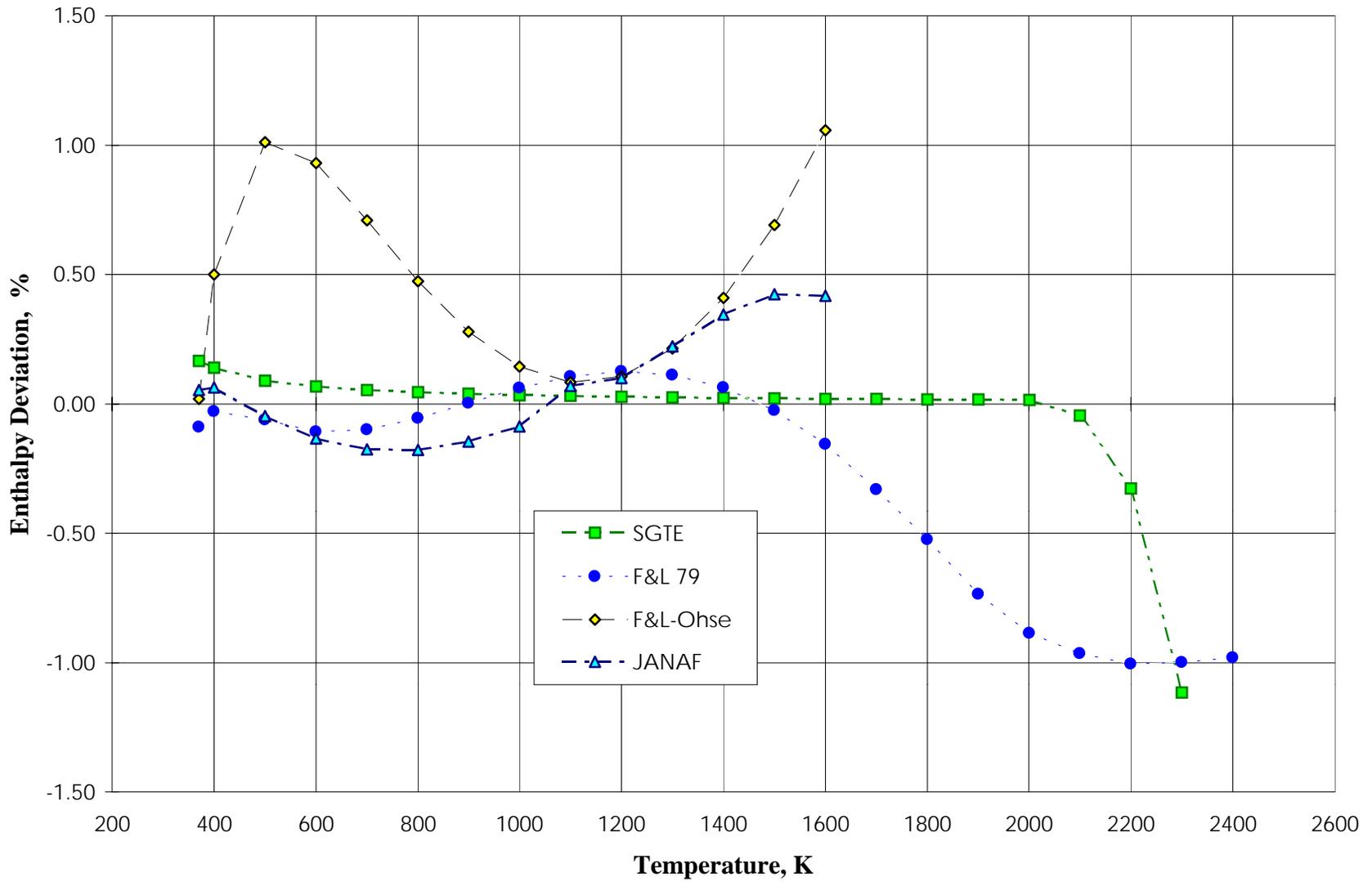
14. J. P. Stone, C. T. Ewing, J. R. Spann, E. W. Steinkuller, D. D. Williams, and R. R. Miller, *High-Temperature Properties of Sodium*, **NRL-6241**, Naval Research Laboratory Report (September 1965).
15. N. B. Vargaftik and L. D. Voljak, *Thermodynamic Properties of Alkali Metal Vapours at Low Pressures*, Chapter 6.6.1 in **Handbook of Thermodynamic and Transport Properties of Alkali Metals**, R. W. Ohse, editor, International Union of Pure and Applied Chemistry, Blackwell Science Publications, Boston (1985).
16. P. Browning and P. E. Potter, *An Assessment of the Experimentally Determined Vapour Pressures of the Liquid Alkali Metals*, Chapter 6.2 in **Handbook of Thermodynamic and Transport Properties of Alkali Metals**, R. W. Ohse, Editor, International Union of Pure and Applied Chemistry, Blackwell Scientific Publications, Boston (1985).



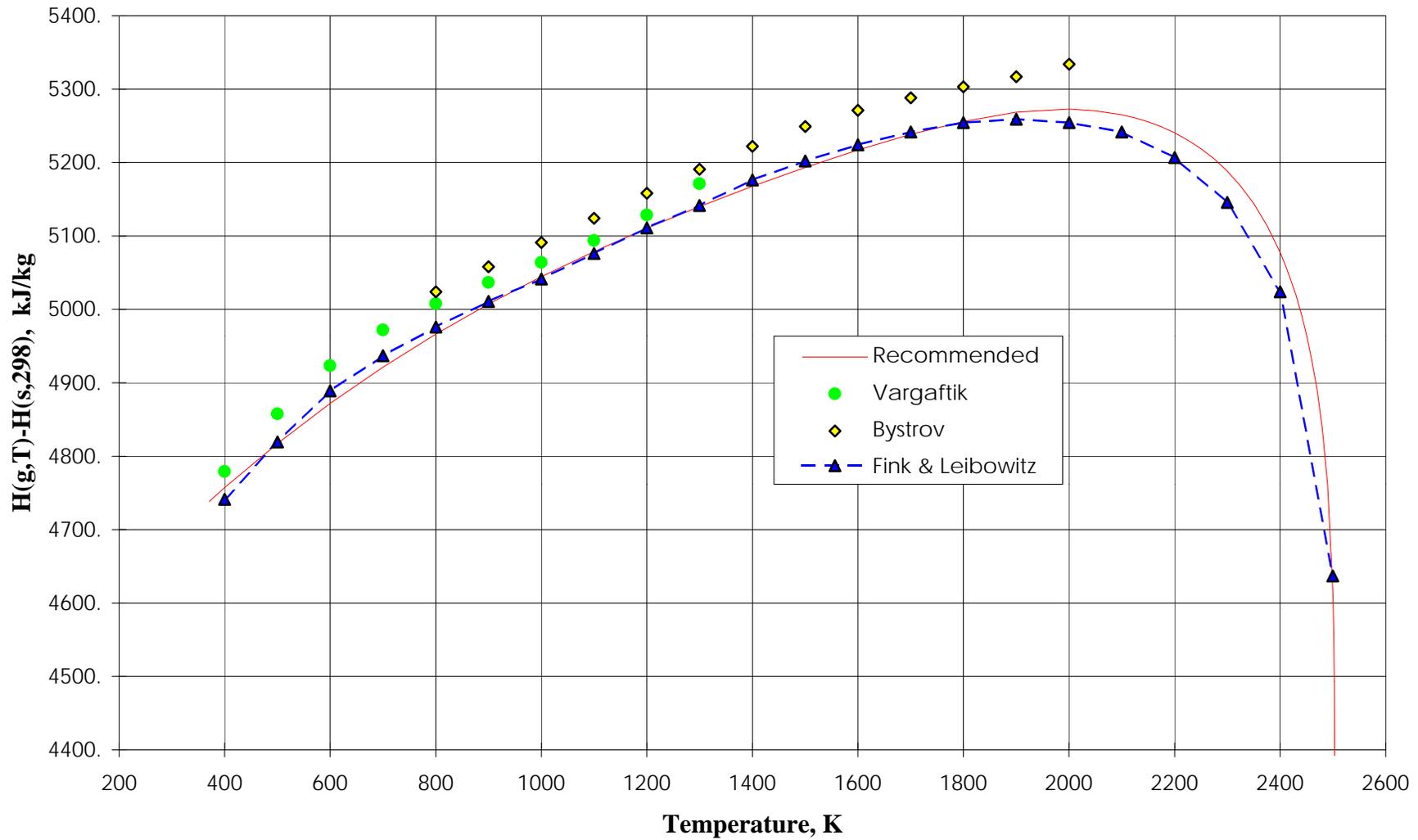
**Fig. 1.1-1 Enthalpy Increments for Liquid and Vapor Sodium and the Average of the Liquid and Vapor Enthalpy Increments. Dotted Lines Give Uncertainties, Which Increase Discontinuously to 10% at 2000 K**



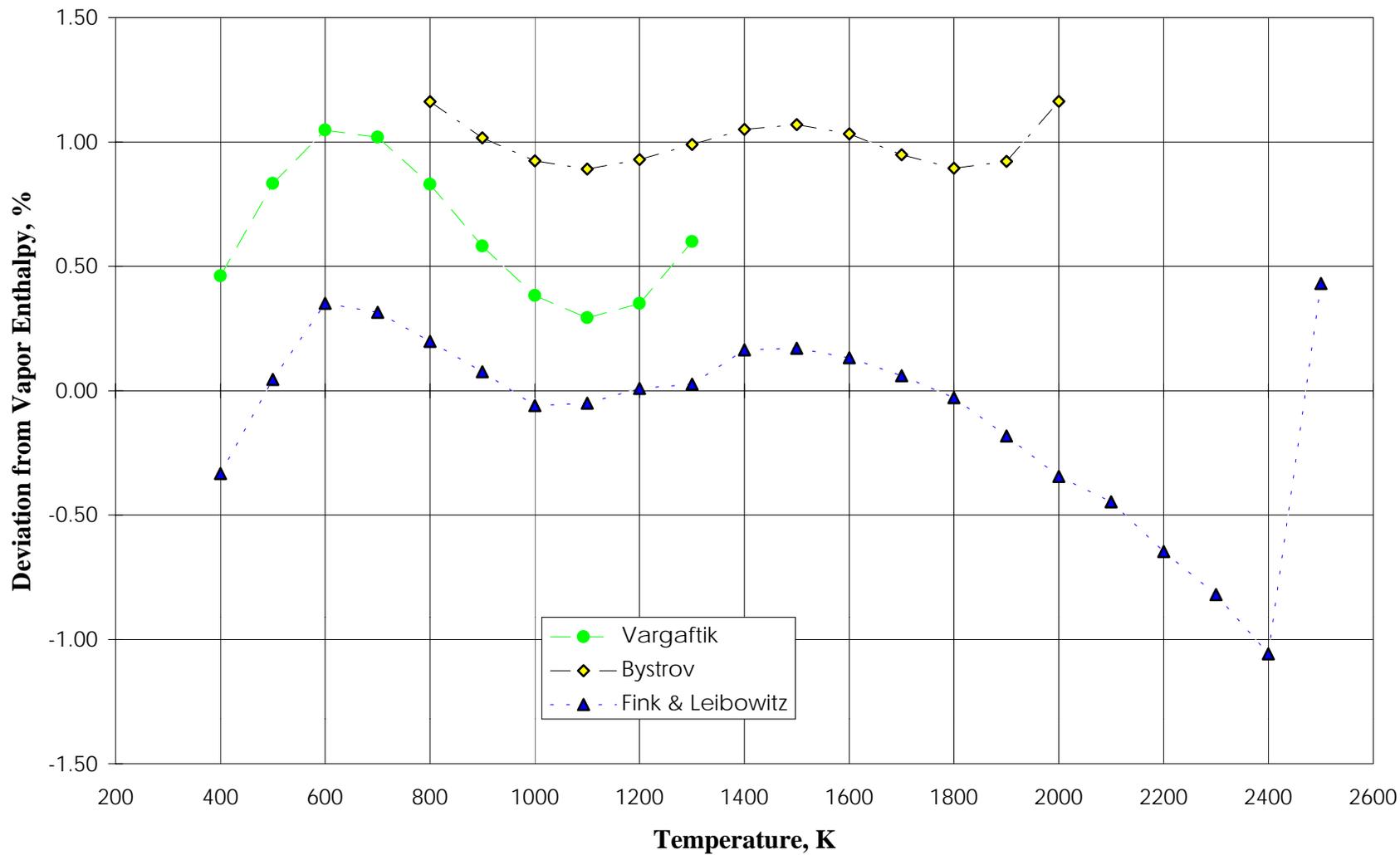
**Fig. 1.1-2 Comparison of Recommended Values for the Enthalpy Increment of Liquid Sodium with Values from Other Assessments**



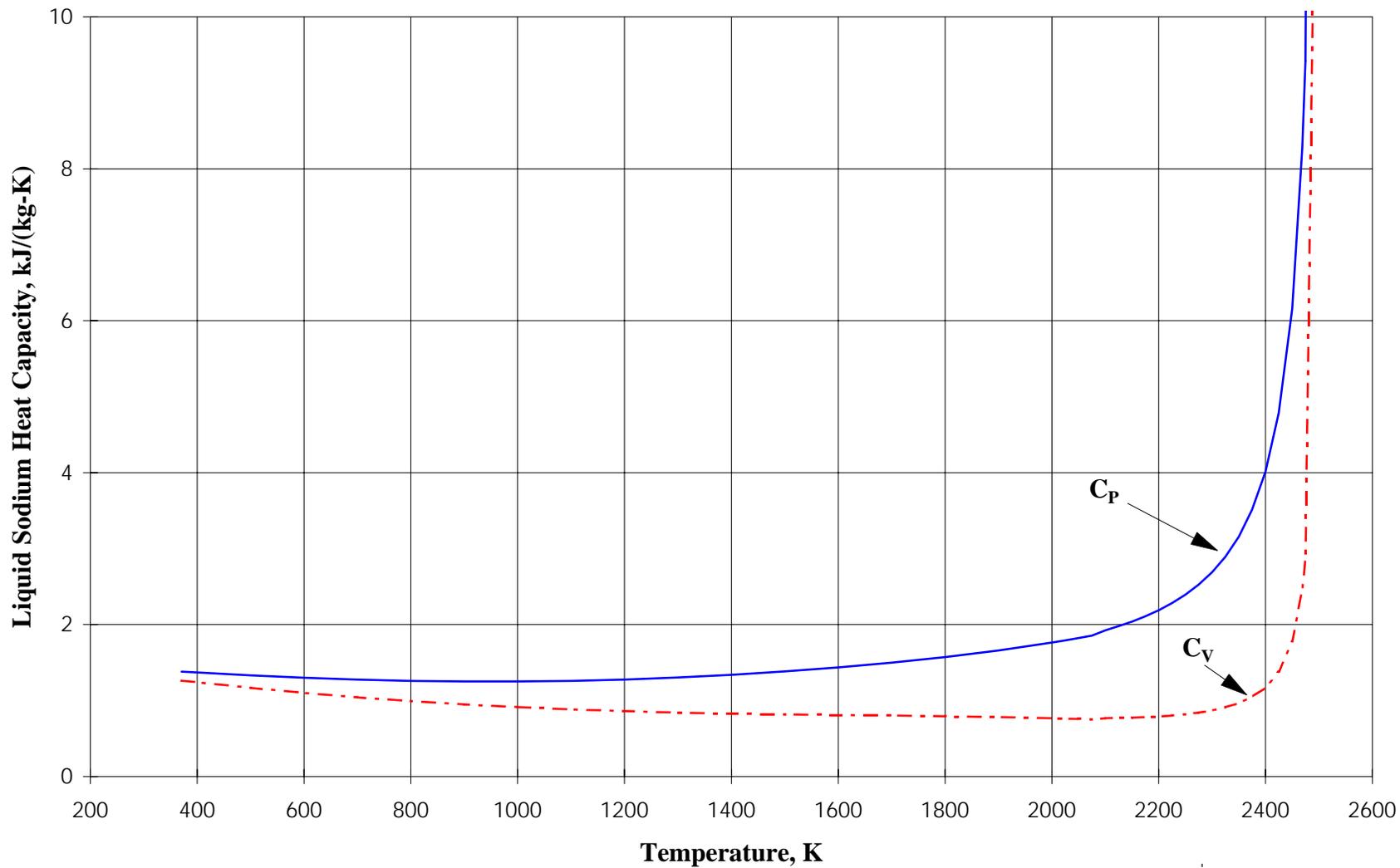
**Fig. 1.1-3 Deviations of Values from Other Assessments from the Recommended Values for the Enthalpy of Liquid Sodium**



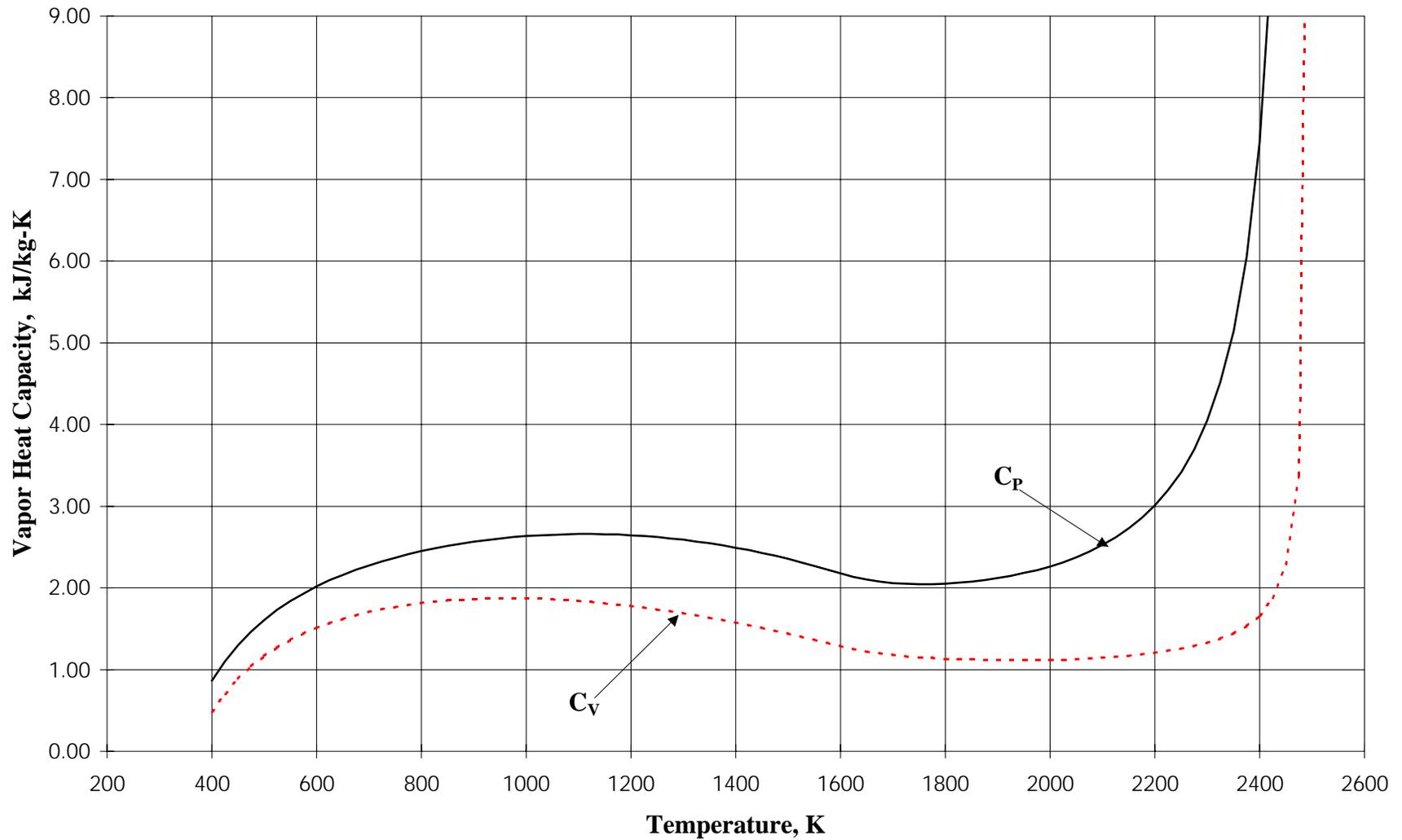
**Fig. 1.1-4 Comparison of Recommended Values for the Enthalpy Increment of Sodium Vapor with Values from Other Assessments**



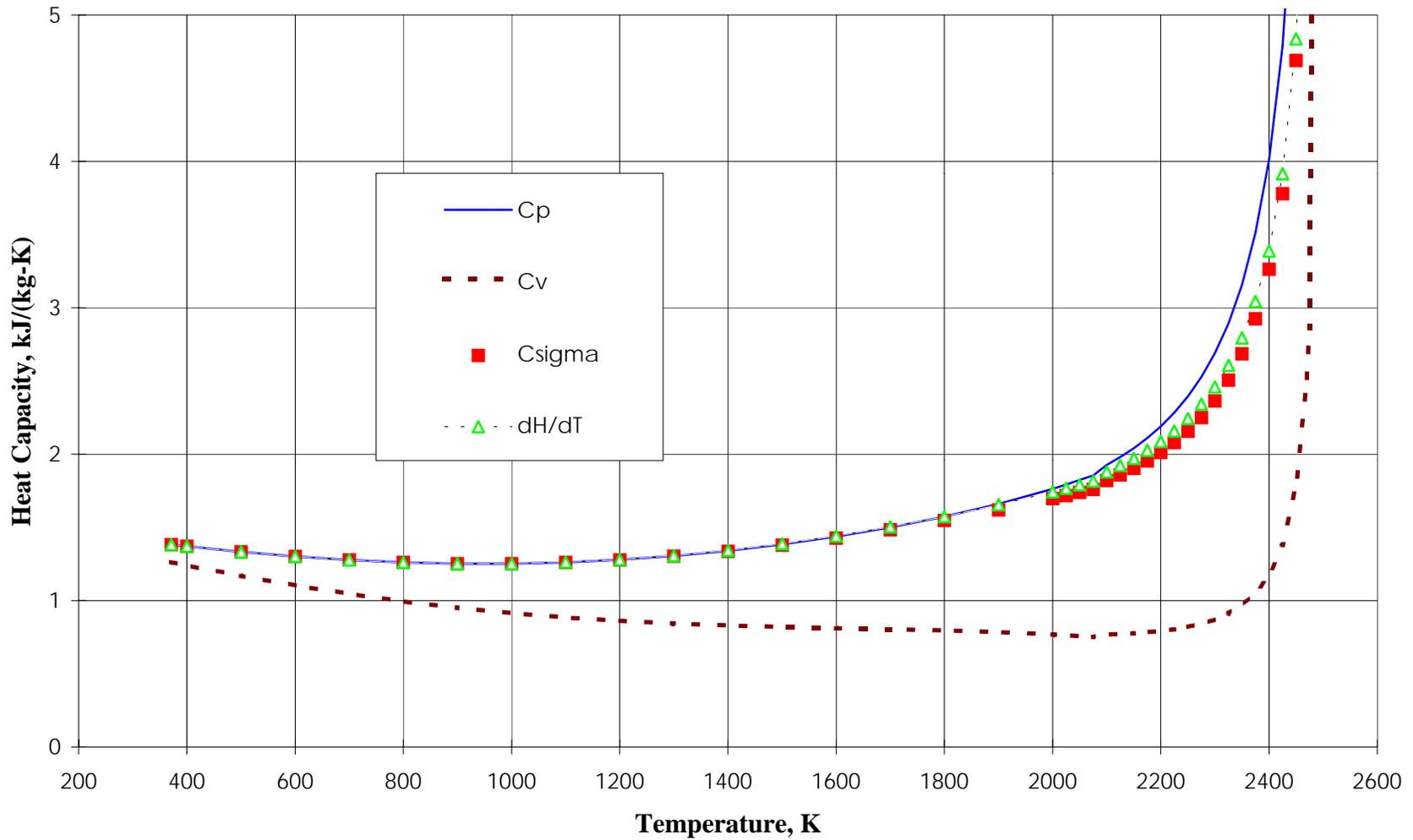
**Fig. 1.1-5 Deviations of Values from Other Assessments from the Recommended Values for the Enthalpy of Sodium Vapor**



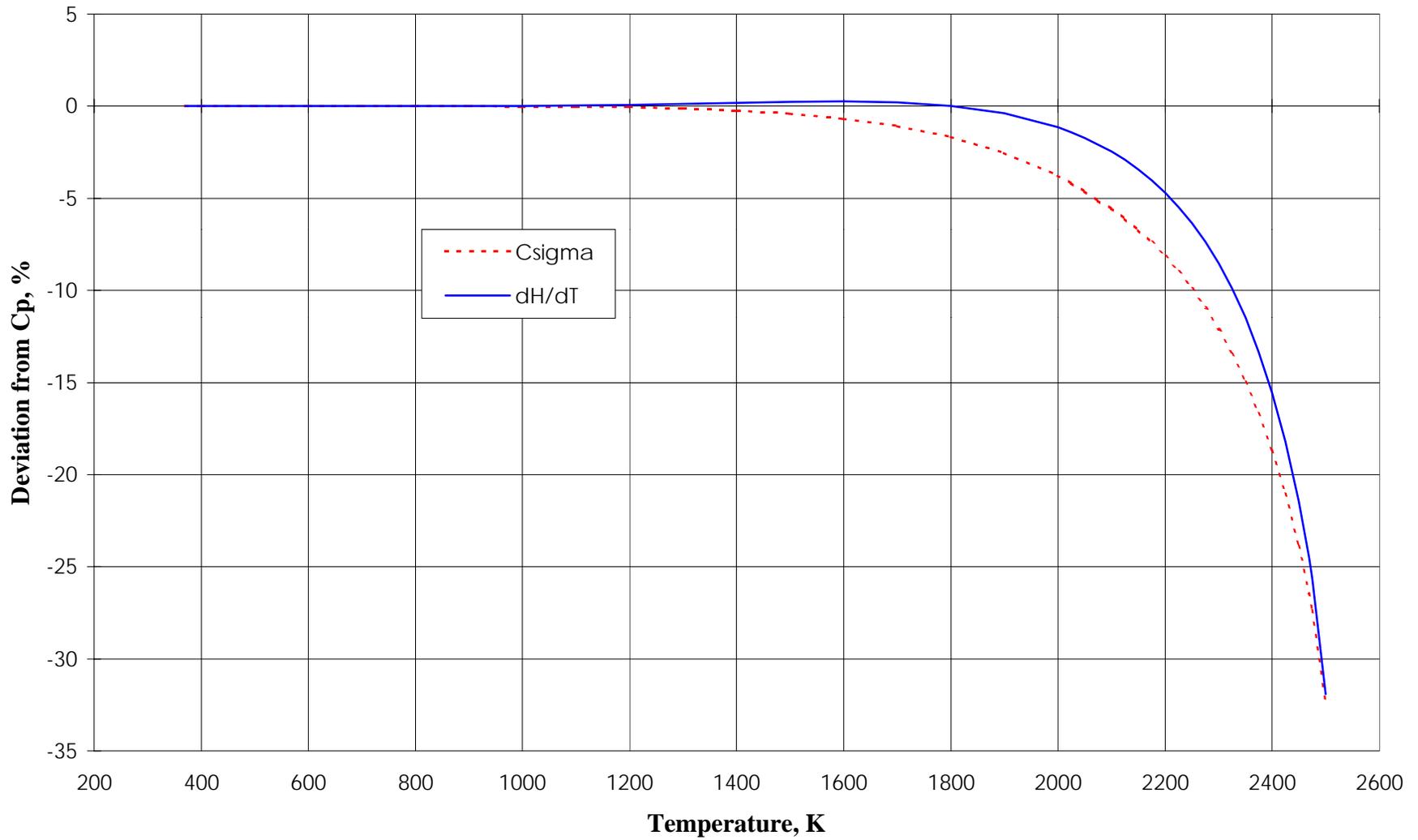
**Fig. 1.1-6 Recommended Values for the Heat Capacity at Constant Pressure,  $C_p$ , and the Heat Capacity at Constant Volume,  $C_v$ , of Liquid Sodium**



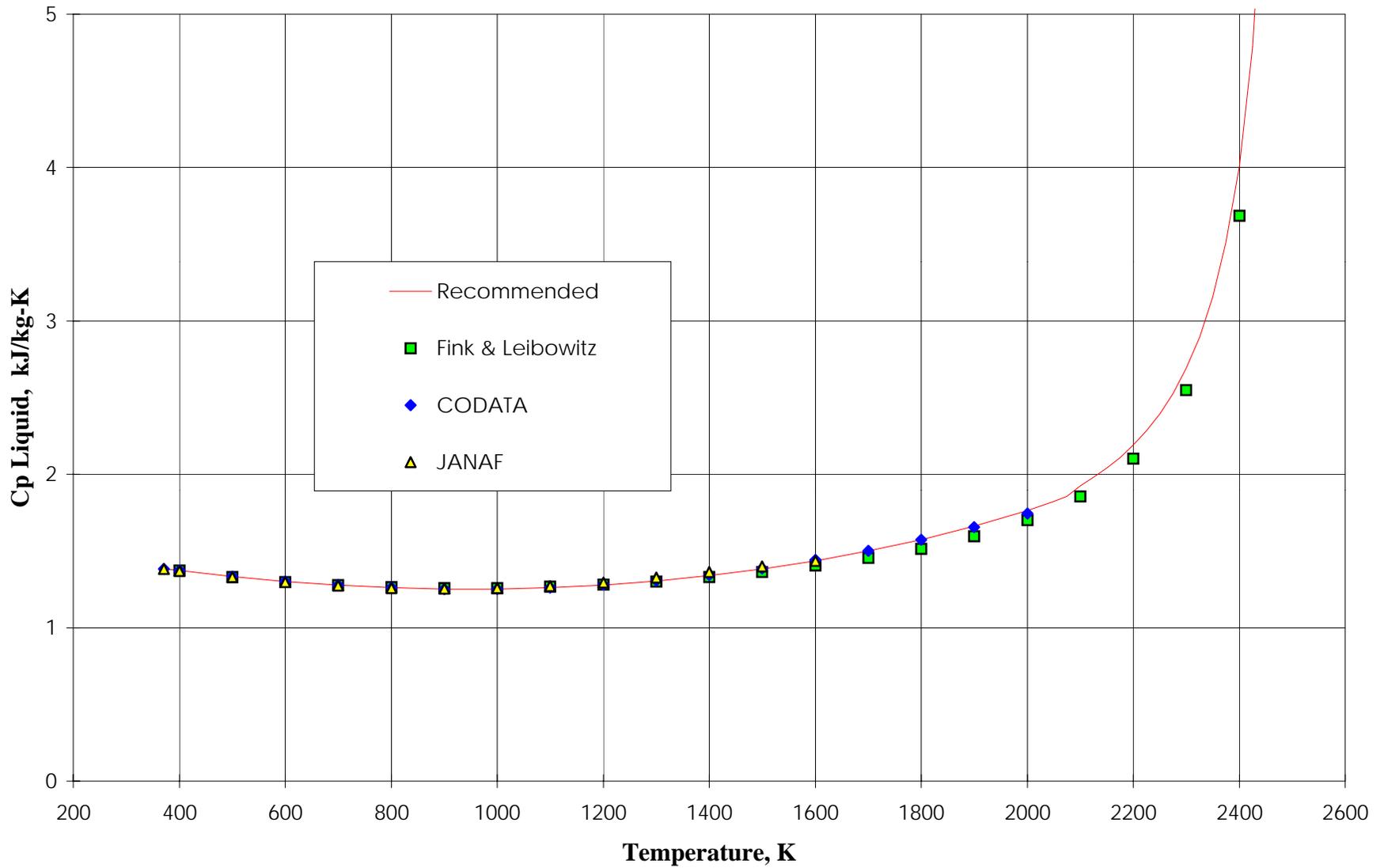
**Fig. 1.1-7 Recommended Values of the Heat Capacity at Constant Pressure,  $C_p$ , and the Heat Capacity at constant Volume,  $C_v$ , of Sodium Vapor**



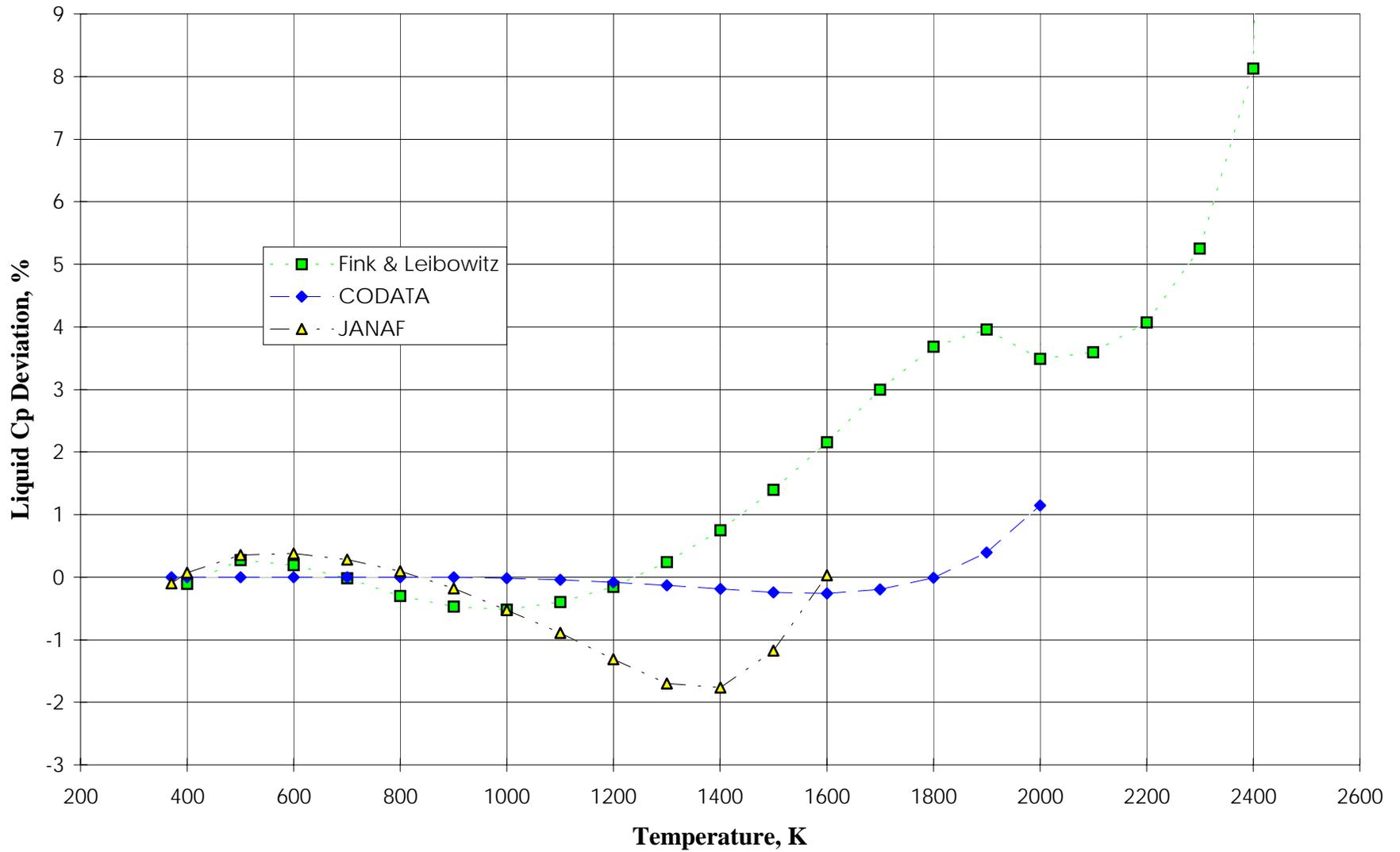
**Fig. 1.1-8 Comparison of the Heat Capacity at Constant Pressure, Heat Capacity at Constant Volume, Heat Capacity Along the Saturation Curve, and the Temperature Derivative of the Saturation Enthalpy**



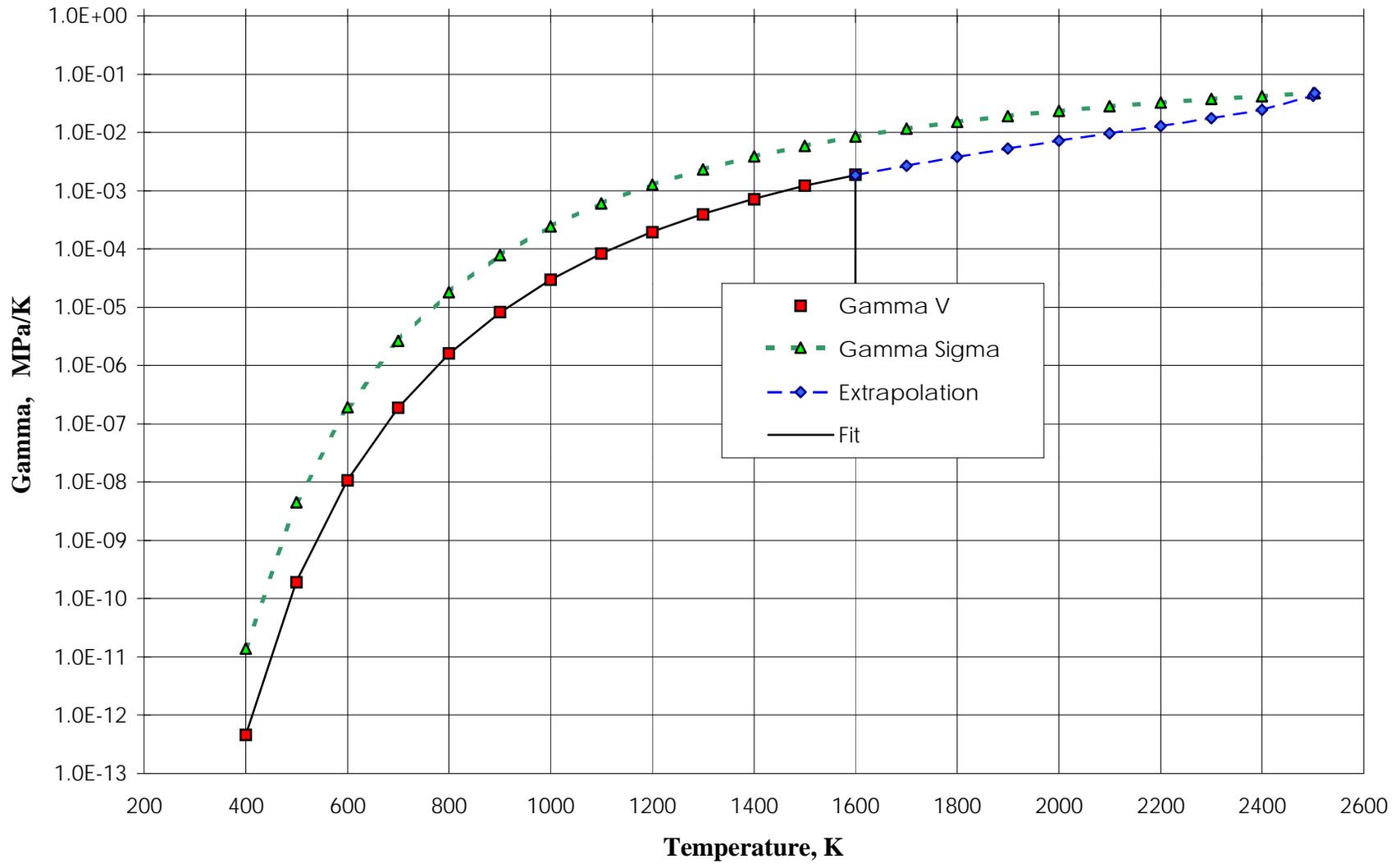
**Fig. 1.1-9 Deviations of the Heat Capacity Along the Saturation Curve and the Temperature Derivative of the Saturation Enthalpy from the Heat Capacity at Constant Pressure**



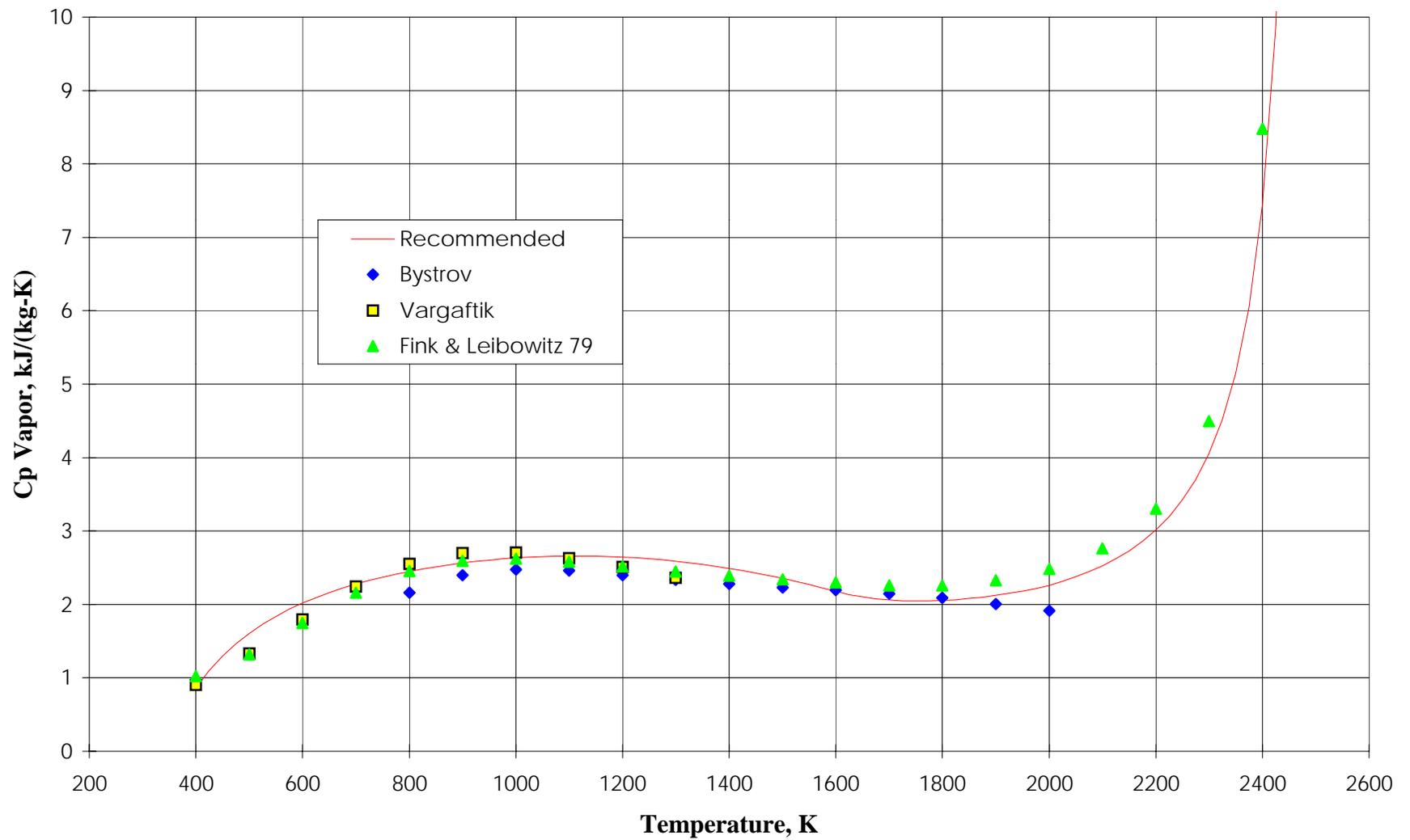
**Fig. 1.1-10 Comparison of the Recommended Values for the Heat Capacity at Constant Pressure for Liquid Sodium with Values from Other Assessments**



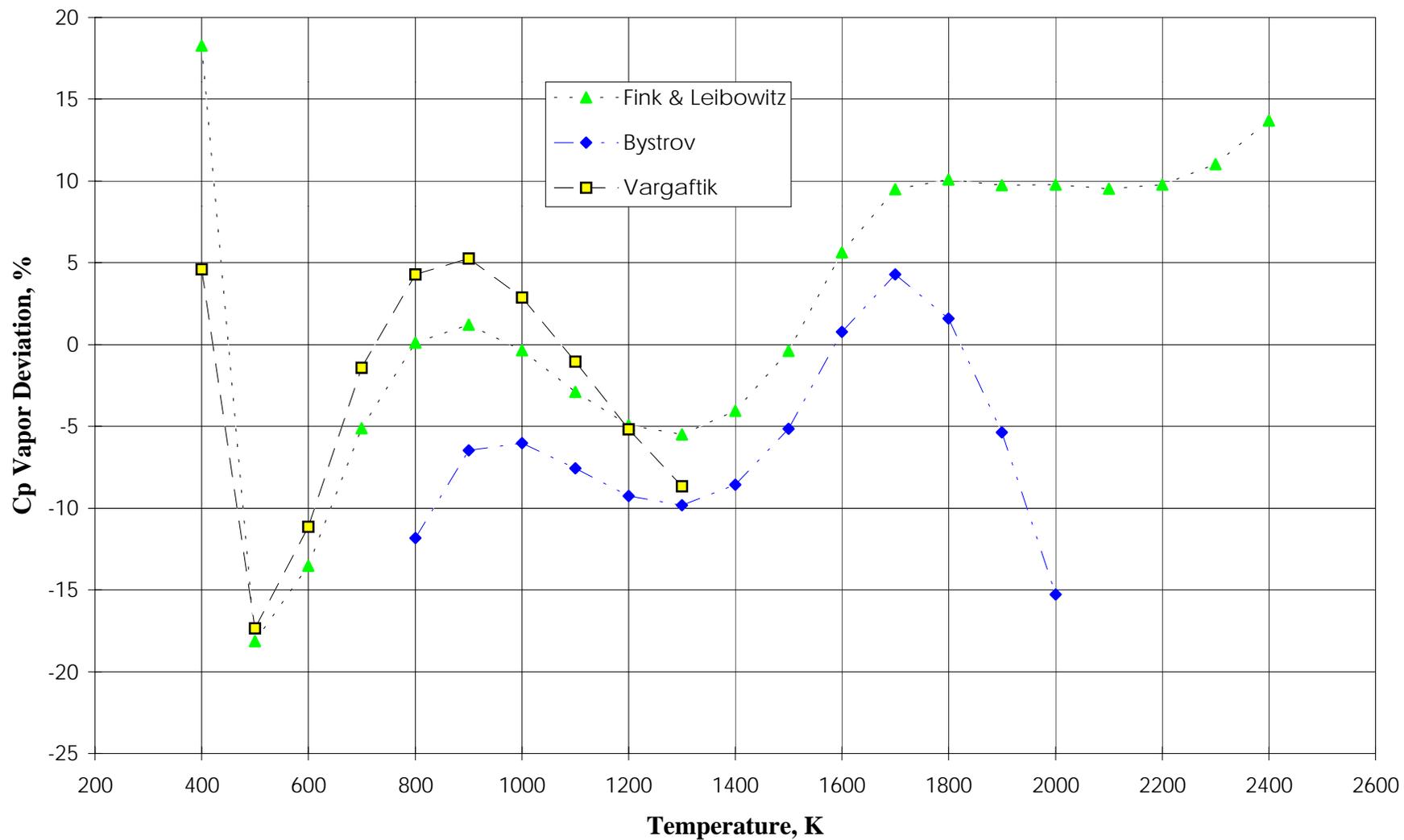
**Fig. 1.1-11 Deviations of Values from Other Assessments from the Recommended Values for the Heat Capacity at Constant Pressure of Liquid Sodium**



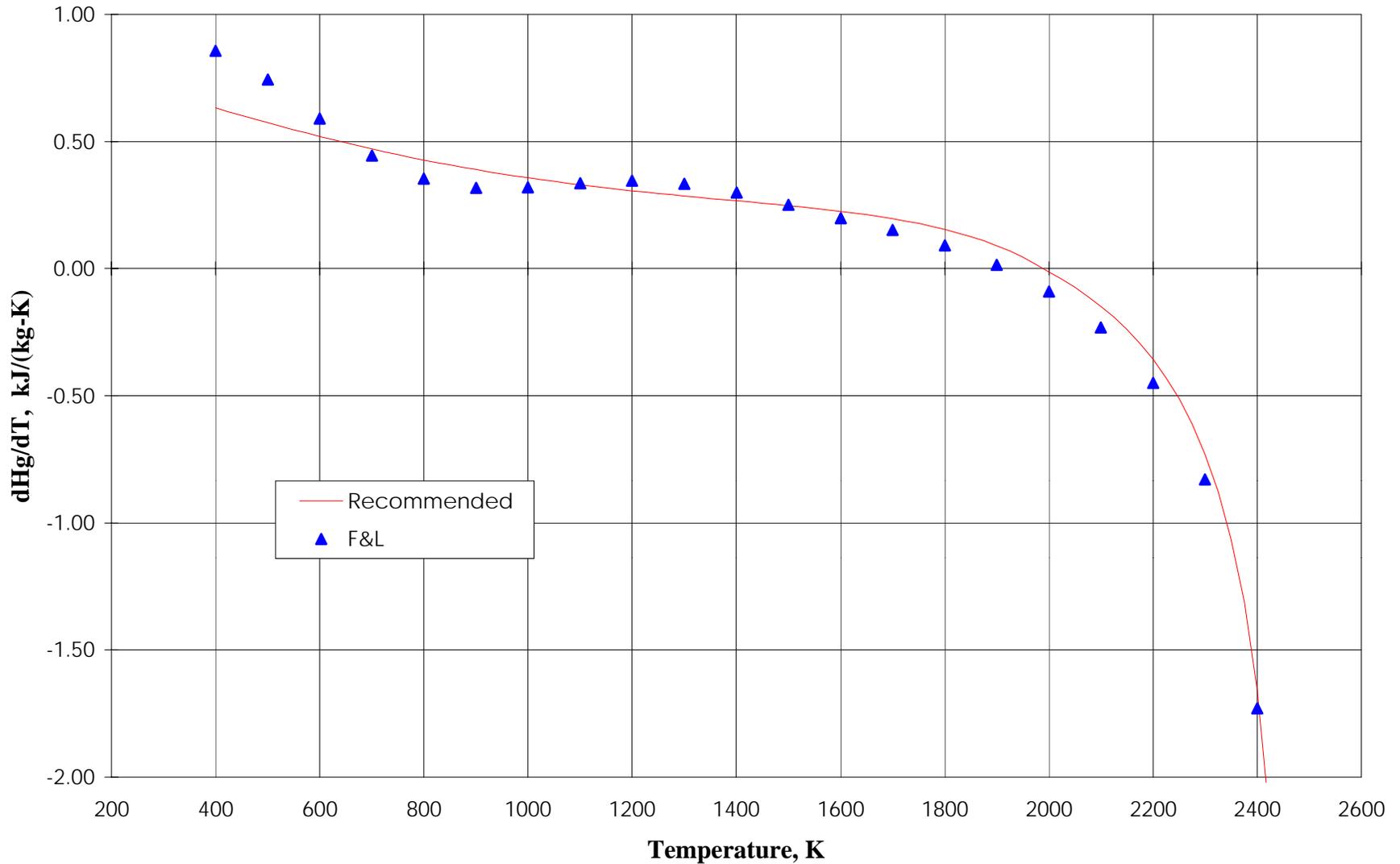
**Fig. 1.1-12 Fit to Quasi-Chemical Values of the Thermal Pressure Coefficient,  $\gamma_V$ , and Extrapolation above 1600 K to Agree with  $\gamma_\sigma$  at the Critical Point**



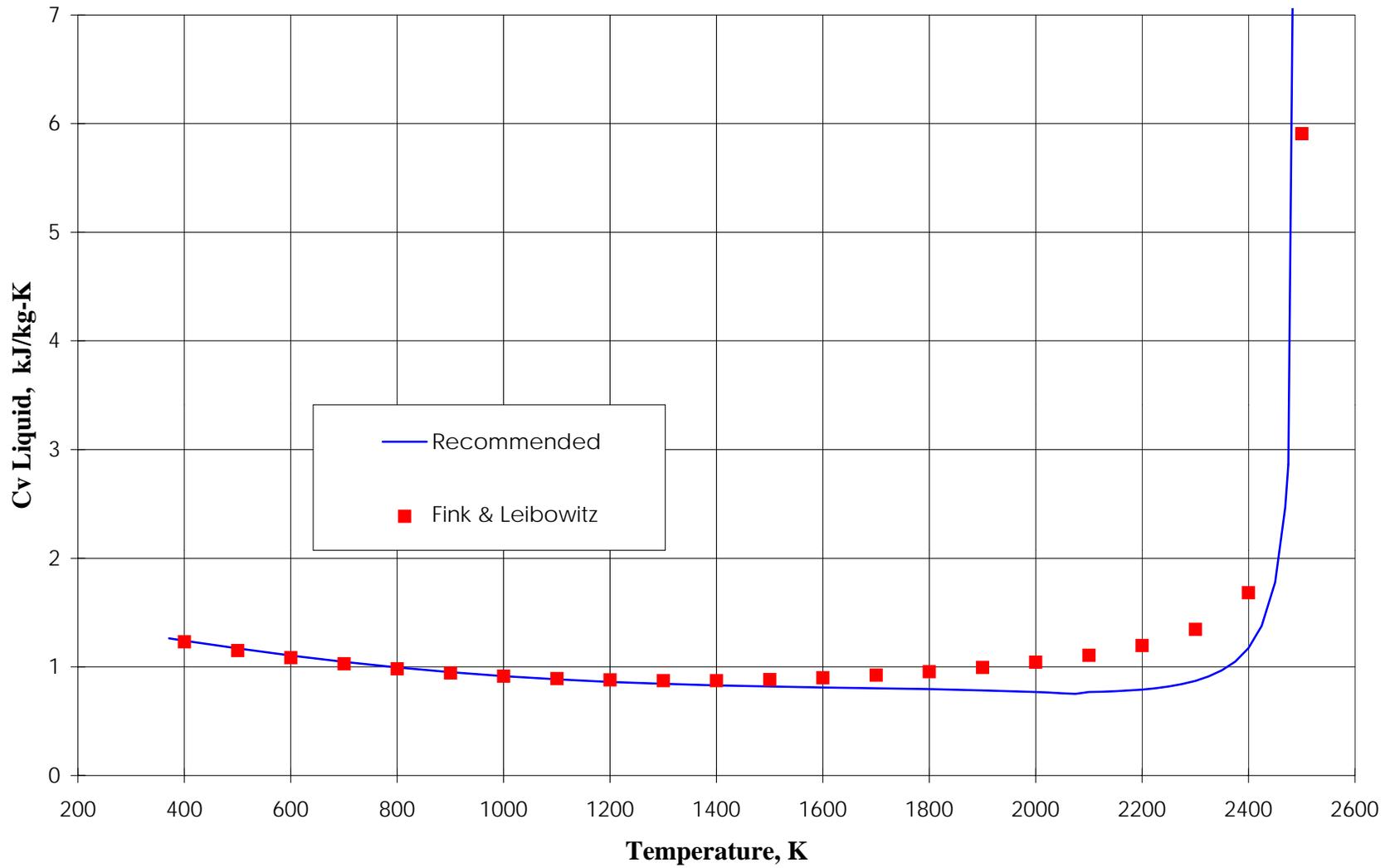
**Fig. 1.1-13 Comparison of the Recommended Values for the Heat Capacity at Constant Pressure for Sodium Vapor with Values from Other Assessments**



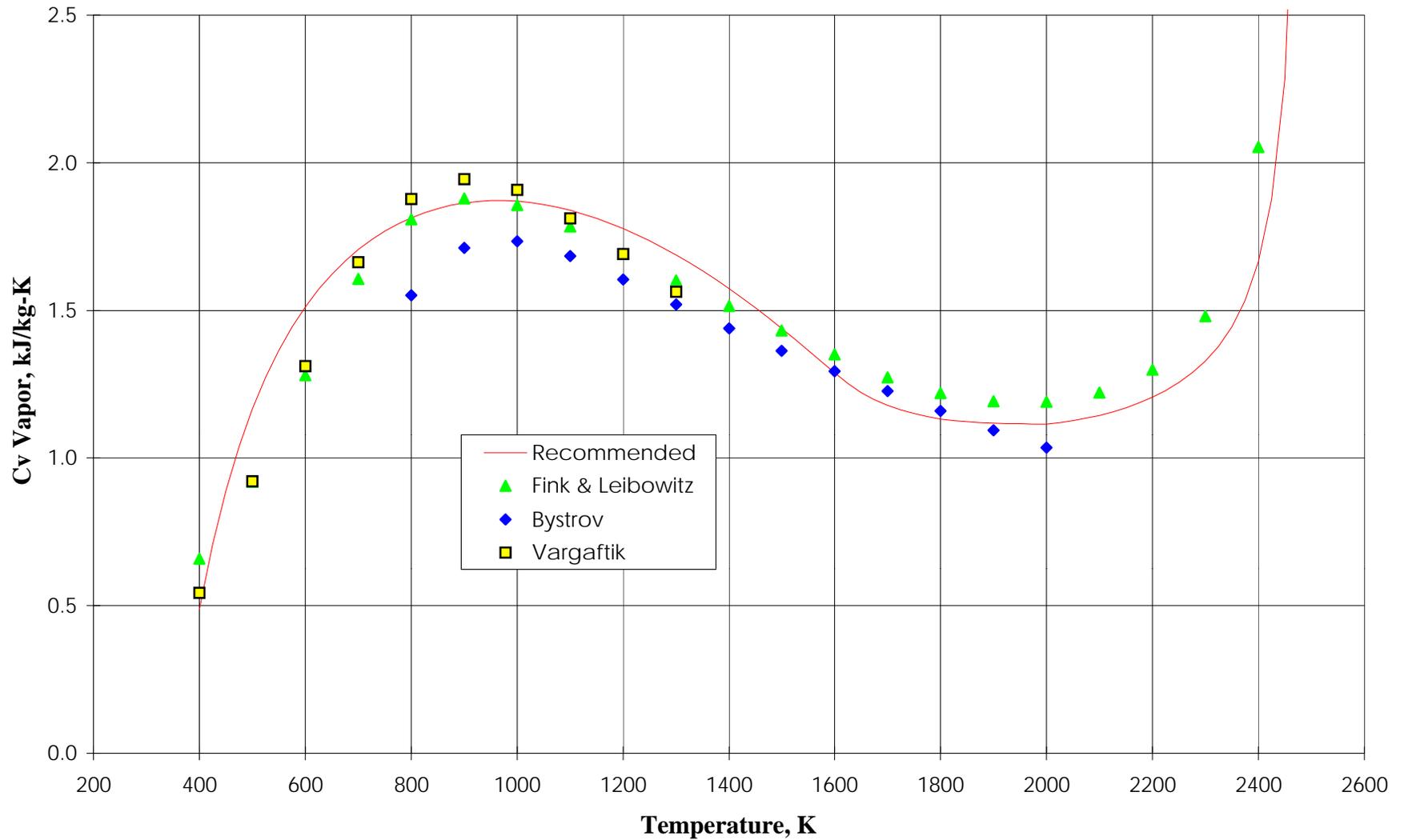
**Fig. 1.1-14 Deviation of Values from Other Assessments from the Recommended Values for the Heat Capacity at Constant Pressure of Sodium Vapor**



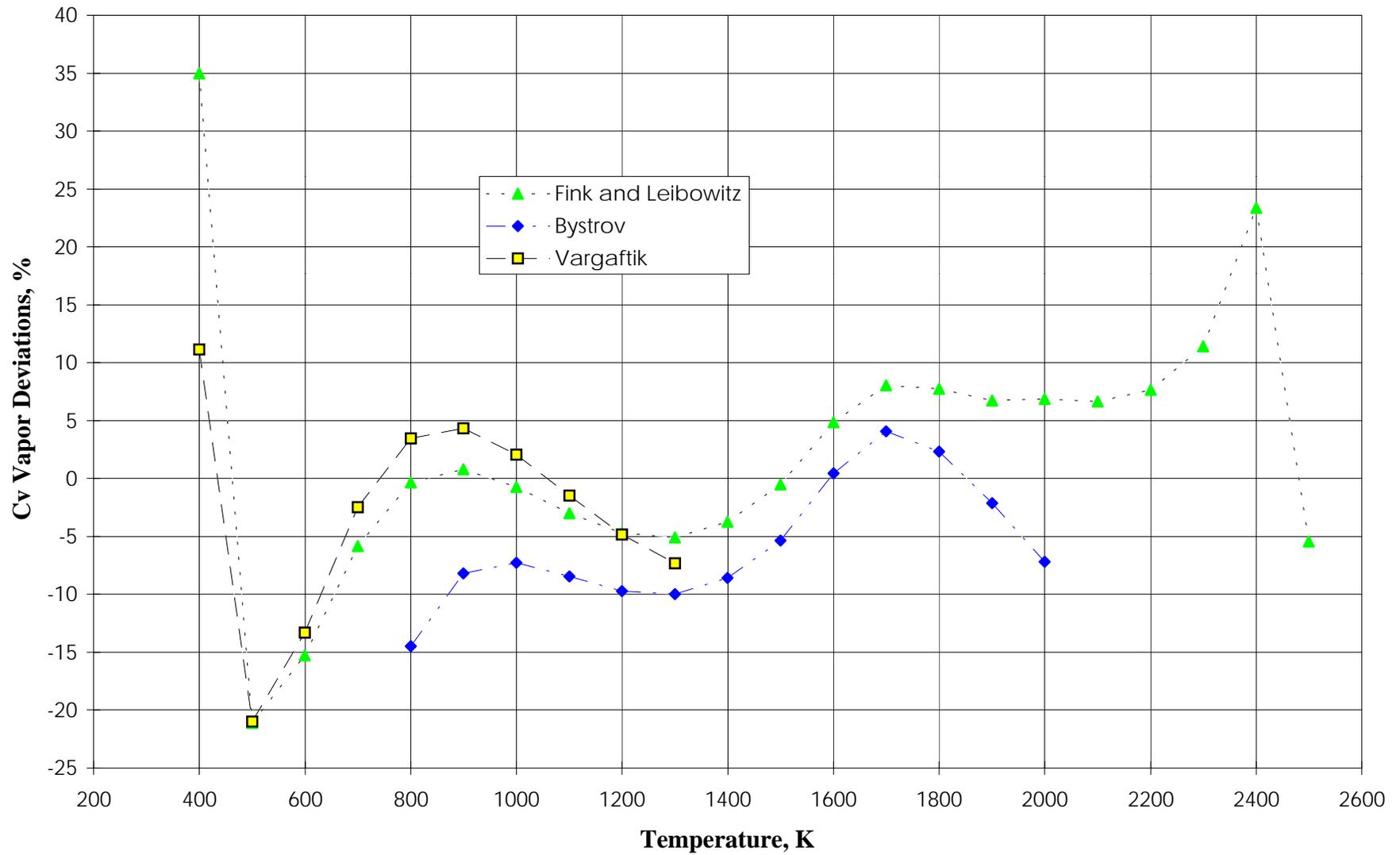
**Fig. 1.1-15 Comparison of the Values for the Temperature Derivative of the Vapor Enthalpy from this Calculation with the Fink and Leibowitz<sup>11</sup> Values (F&L) Calculated Using the Quasi-Chemical Method**



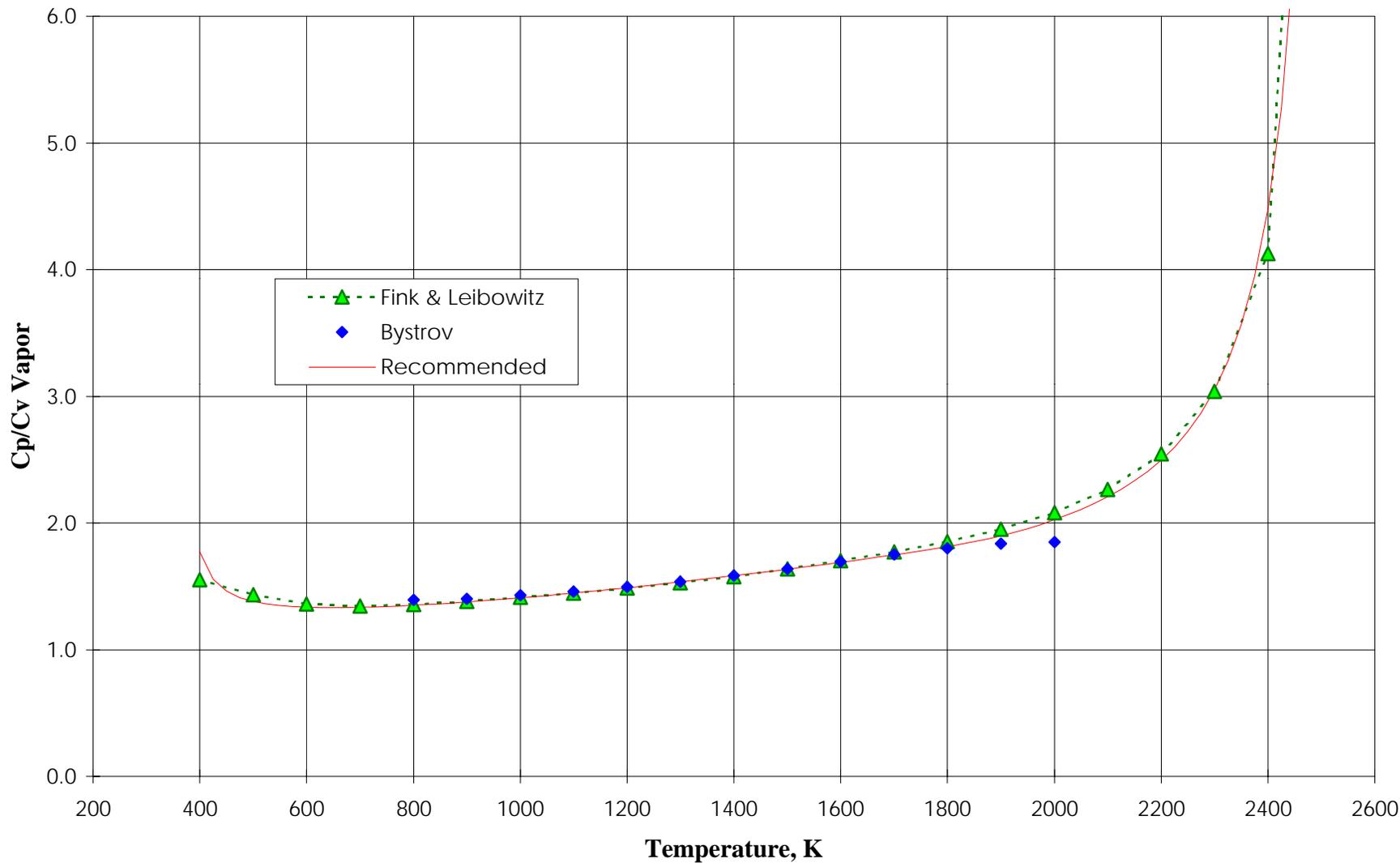
**Fig 1.1-16 Comparison of the Recommended Values for the Heat Capacity at Constant Volume for Liquid Sodium with Values from Other Assessments**



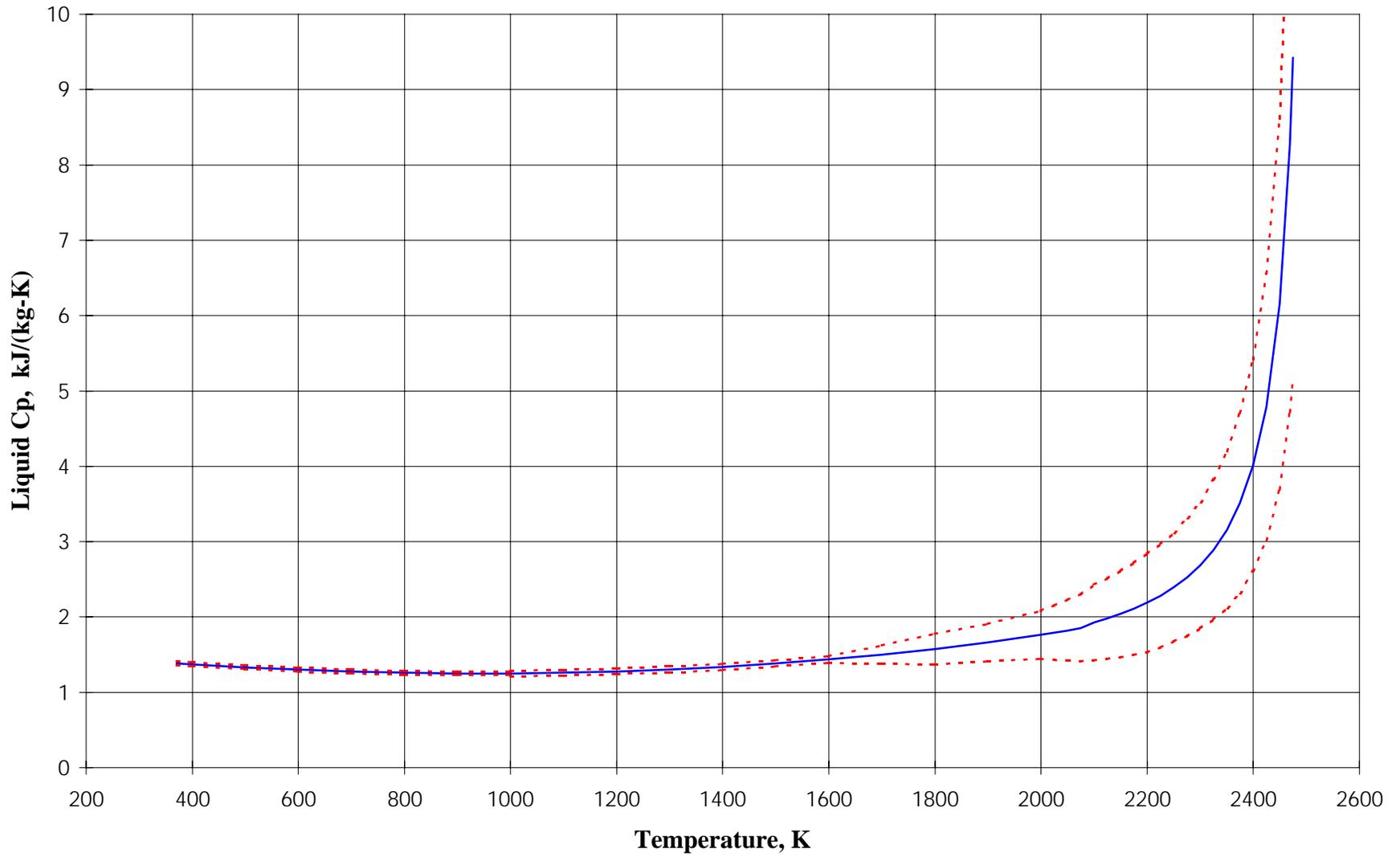
**Fig. 1.1-17 Comparison of the Recommended Values for the Heat Capacity at Constant Volume for Sodium Vapor with Values from Other Assessments**



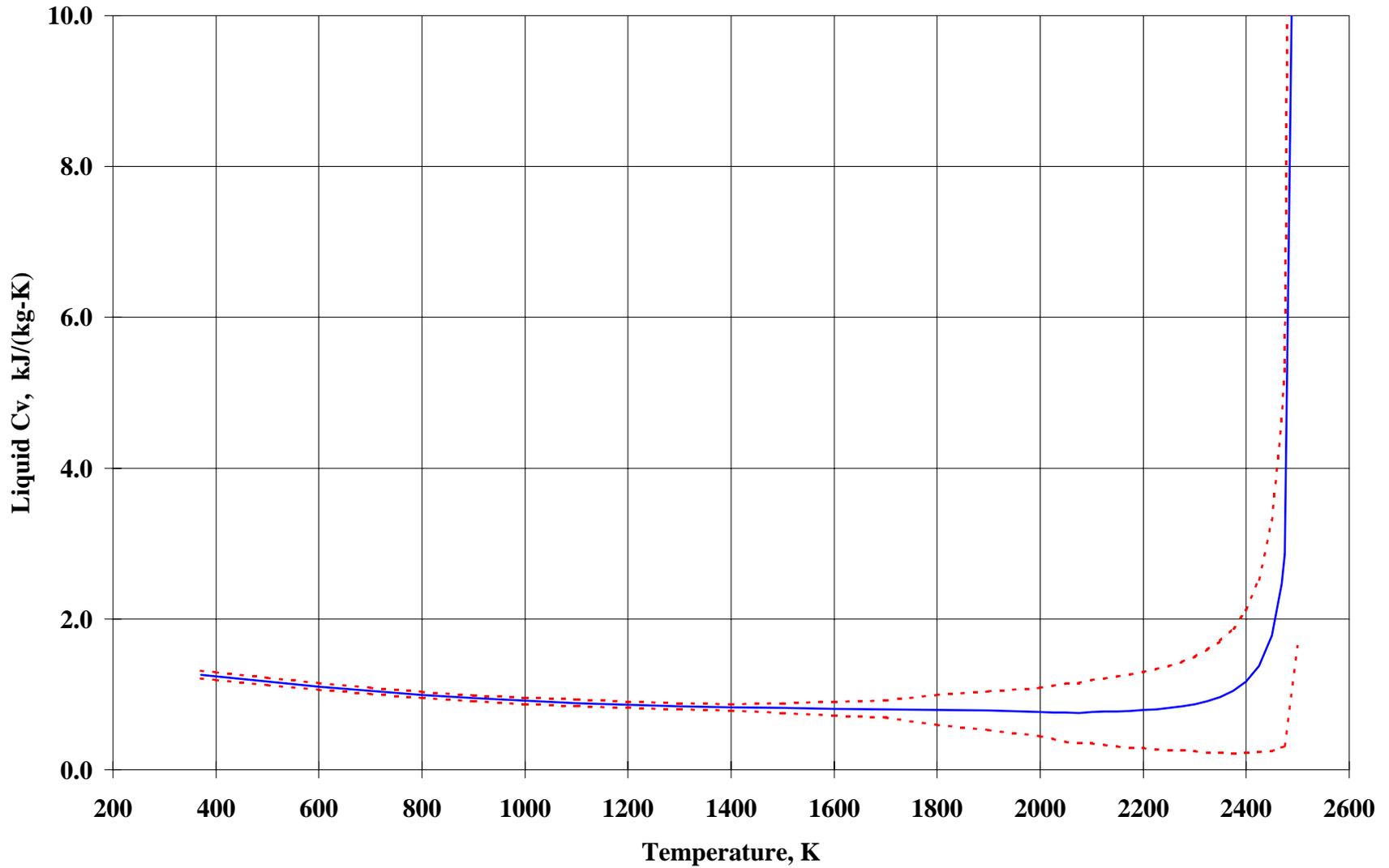
**Fig. 1.1-18 Deviation of Values from Other Assessments from the Recommended Values for the Heat Capacity at Constant Volume of Sodium Vapor**



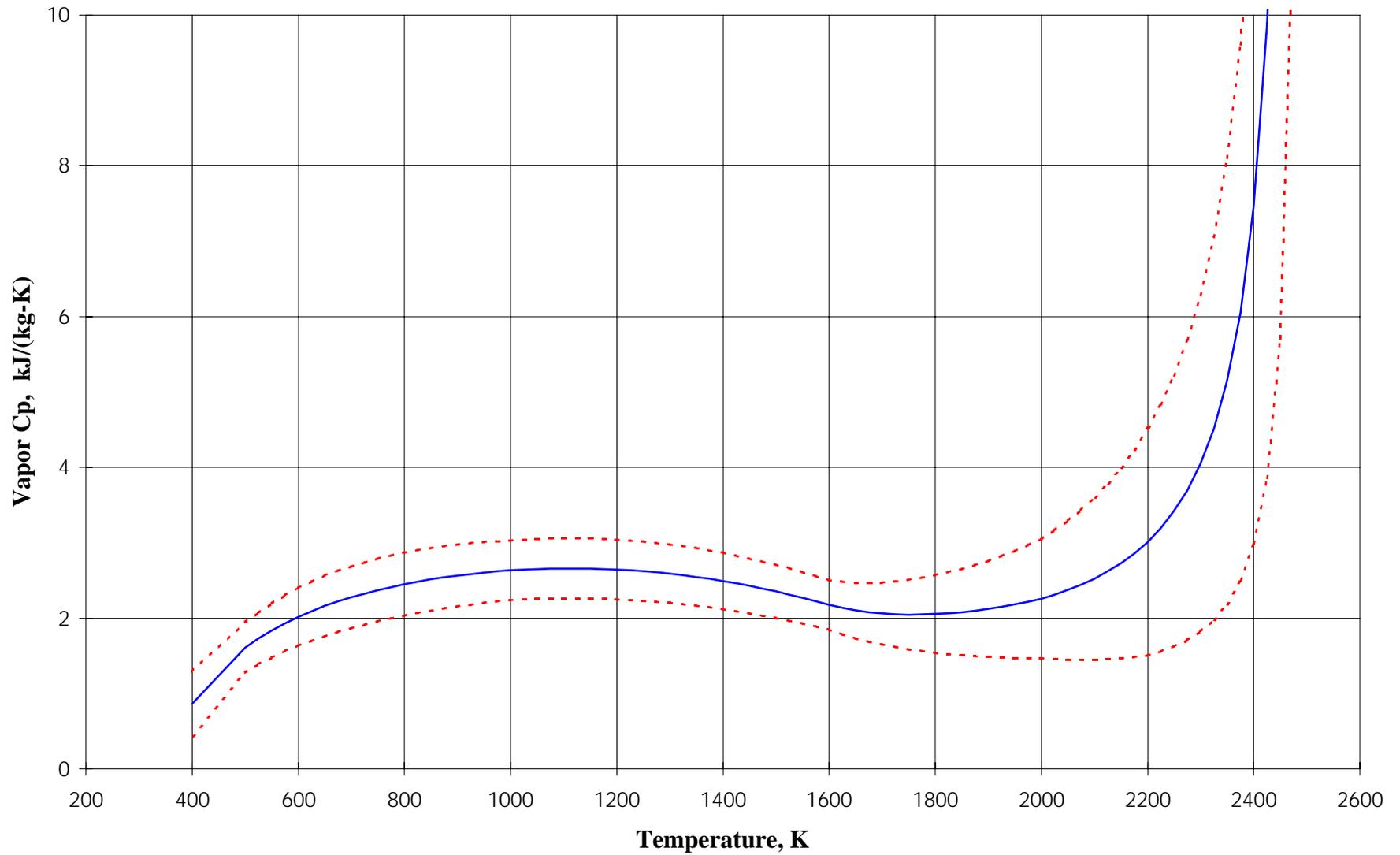
**Fig. 1.1-19 Comparison of the Ratio of the Recommended Values for the Heat Capacity at Constant Pressure and Constant Volume for Sodium Vapor with Values of the Ratio from Other Assessments**



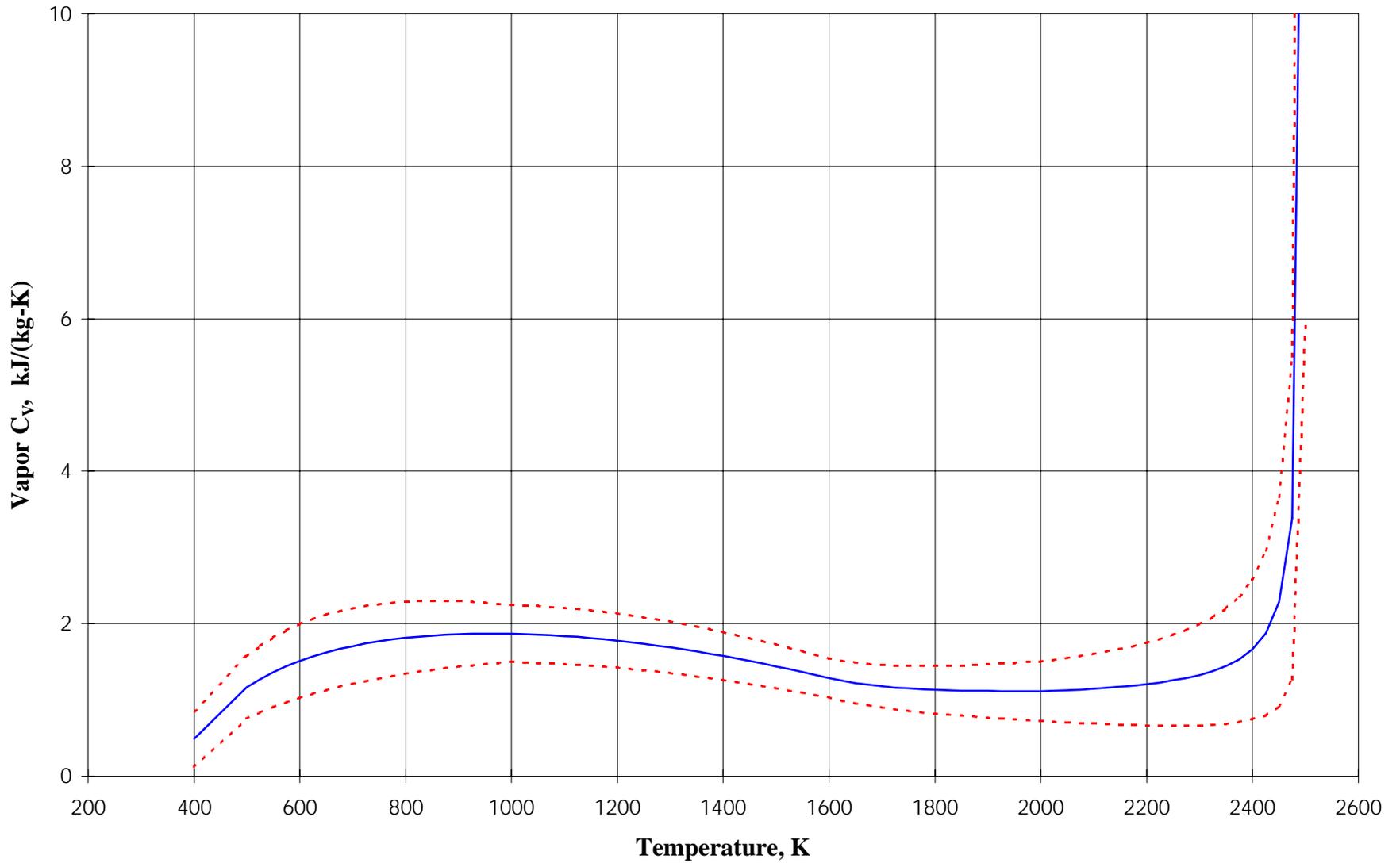
**Fig. 1.1-20 The Heat Capacity at Constant Pressure for Liquid Sodium with Estimated Uncertainties (dotted lines)**



**Fig. 1.1-21 The Heat Capacity at Constant Volume for Liquid Sodium with Estimated Uncertainties (dotted lines)**



**Fig. 1.1-22 The Heat Capacity at Constant Pressure for Sodium Vapor with Estimated Uncertainties (dotted lines)**



**Fig. 1.1-23 The Heat Capacity at Constant Volume for Sodium Vapor with Estimated Uncertainties (dotted lines)**