2. TRANSPORT PROPERTIES

2.1   THERMAL CONDUCTIVITY

Summary

The recommended values for the thermal conductivity of liquid sodium in $W \cdot m^{-1} \cdot K^{-1}$, given in Table 2.1-1, were calculated with the polynomial

$$k = 124.67 - 0.11381\,T + 5.5226 \times 10^{-5}\,T^{2} - 1.1842 \times 10^{-8}\,T^{3} \quad . \qquad (1)$$

This polynomial is a constrained least squares fit to thermal conductivities in the temperature range 371 to 1500 K that were calculated using the method recommended by Cook and Fritsch[1] for the calculation of thermal conductivity from electrical resistivity. This method includes the contribution to thermal conductivity from electron-electron scattering and a second order correction to the Sommerfeld value of the Lorentz function in the Wiedemann-Franz law. The fit was constrained to give agreement with the thermal conductivity of the vapor at the critical temperature. The vapor thermal conductivity at the critical point was obtained from extrapolation of sodium vapor thermal conductivities recommended by Vargaftik and Yargin[2] in their review of experimental data and calculations of transport processes for alkali-metal vapors.

Figure 2.1-1 shows the recommended values for the thermal conductivity of sodium with the uncertainties as dashed lines. The uncertainties are given in Table 2.1-2.

Discussion

In this section, existing recommendations are compared with each other, with theory, and with experimental data to select the best method for calculation of the thermal conductivity of liquid sodium. Then, the details of the calculation are given including fits to related properties required in the calculation. Finally, an approximate equation is derived that represents the thermal conductivity in the range of experimental data and at higher temperatures to the critical temperature. Comparisons are made of this recommended equation with the calculated values and with values given in existing assessments.

Table 2.1-1   Thermal Conductivity of Liquid Sodium

Temperature (K)	Thermal Conductivity $(W \cdot m^{-1} \cdot K^{-1})$
371	89.44
400	87.22
500	80.09
600	73.70
700	68.00
800	62.90
900	58.34
1000	54.24
1100	50.54
1200	47.16
1300	44.03
1400	41.08
1500	38.24
1600	35.44
1700	32.61
1800	29.68
1900	26.57
2000	23.21
2100	19.54
2200	15.48
2300	10.97
2400	5.92
2500	0.27
2503.7	0.05

Examination of Existing Recommendations ─ Examination of recommendations from various assessments of the thermal conductivity of liquid sodium indicates significant differences over the range of experimental data (371 to 1500 K). Figure 2.1-2 shows the recommendations from Cook and Fritsch,[1] Bystrov et al.,[3] and Saksena et al.,[4] CINDAS,[5] and Fink and Leibowitz (F&L).[6] Both the recommendations of Saksena et al. and those of Fink and Leibowitz are based on the CINDAS values. The Fink and Leibowitz approximation, shown in Fig. 2.1-2, is a polynomial fit to the CINDAS values and an extrapolation to the critical point using the method of Grosse.[7] Saksena et al.[4] represent the thermal conductivity in the liquid by an electronic

Table 2.1-2   Estimated Uncertainties in the Recommended Values for the
               Thermal Conductivity of Liquid Sodium

Temperature (K)	k $(W \cdot m^{-1} \cdot K^{-1})$	Uncertainty, $\left(\dfrac{\delta k}{k} \right)$ (%)
$371 \leq T \leq 700$		5
$700 < T \leq 1100^{(a)}$	$k = 124.67 - 0.11381\,T$	12
$1100 \leq T \leq 1500^{(b)}$	$\quad + 5.5226 \times 10^{-5}T^2 - 1.1842 \times 10^{-8}T^3$	15
$T > 1500$		15

[a] $\dfrac{\delta k}{k}(\%) = -7.25 + 0.0175\ T$

[b] $\dfrac{\delta k}{k}(\%) = 3.75 + 0.0075\ T$

contribution plus a contribution due to structural scattering. contribution from the electrical resistivity using the Lorentz constant.   They assume the structural contribution has a $T^{4/7}$ dependence and determine the constant for the structural contribution by assuming the total thermal conductivity is given by the CINDAS values. Thus, their values for thermal conductivity are very close to the CINDAS recommendations. Recommendations by CINDAS and by Bystrov et al. are fits to combined sets of data of measurements of thermal conductivity and measurements of electrical resistivity converted to thermal conductivity using the Wiedemann-Franz law. Cook and Fritsch recommended values of thermal conductivity calculated from their fit to electrical conductivity converted to thermal conductivity using corrections to the Wiedemann-Franz law that

include higher order terms in the Lorentz constant and a contribution to thermal resistivity due to electron-electron scattering that is not present in electrical resistivity.

Selection of Method of Calculation — The method of Cook and Fritsch has been selected based on (1) the results of simultaneous measurements of thermal and electrical resistivities of alkali metals by Cook et al.,[8-15] (2) review of the theoretical basis, and (3) comparison of the separate data from electrical and thermal conductivity measurements. These reasons are discussed in detail below.

Simultaneous measurement of the thermal and electrical resistivities of solid alkali metals and of liquid potassium, cesium, and rubidium by Cook et al.[8-15] have shown that the thermal conductivity differs from the value obtained by application of the Wiedemann-Franz law:

$$k = \frac{L_0 T}{\rho} \quad , \tag{2}$$

where k is the thermal conductivity, ρ is the electrical resistivity, and L_0 is the Sommerfeld value of the Lorentz function:

$$L_0 = \frac{1}{3}\left(\frac{\pi k_B}{e}\right)^2 = 2.443 \times 10^{-8} \text{ W}\Omega\text{K}^{-2} \quad . \tag{3}$$

In their assessment of thermal conductivity of liquid alkali metals, Cook and Fritsch[1] examined contributions from many processes. They show that contributions from ionic conductivity and inelastic scattering of electrons are small and of opposite sign so that they cancel. However, they have included corrections to the Wiedemann-Franz law for second-order effects in the Lorentz function, L(T), and a contribution due to electron-electron scattering. The correction due to second-order effects in the Lorentz function; i.e., off-diagonal matrix elements is

$$k = \frac{\left(L_0 - S^2\right)T}{\rho} \quad , \tag{4}$$

where S is the thermoelectric power. The electron-electron scattering contribution to the thermal resistivity (W_{ee}) is a linear function of temperature:

$$W_{ee} = BT .\tag{5}$$

For liquid sodium, Cook and Fritsch assume B is equal to the value obtained by Cook[8] for solid sodium; i.e., B = 1.1 x 10^{-6} m·W^{-1}.

Thus, Cook and Fritsch determined the thermal conductivity of alkali metals using the relation

$$k = \left[W_{ee} + \frac{\rho_e}{\left(L_0 - S^2 \right) T} \right]^{-1} ,\tag{6}$$

where W_{ee} is the thermal resistivity due to electron-electron scattering, ρ_e is the electrical resistivity, L_0 is the Sommerfeld value of the Lorentz function, and S is the thermoelectric power.

MacDonald and Geldart[16] have calculated the electron-electron scattering contribution to the thermal resistivity of solid simple metals (including alkali metals) using an approximation to the scattering function based on the Landau Fermi-liquid theory and obtained reasonable agreement with values determined by Cook et al for the alkali metals. Theoretical calculations of the electron-electron scattering contribution, W_{ee}, for sodium by MacDonald and Geldart[16] and by Lundmark[17] give values of the linear constant B within the experimental uncertainty of values given by Cook.[8] According to Lundmark,[17] attribution of the deviations from the Wiedemann-Franz law to an electron-phonon contribution (which is small and goes as T^{-2}) and an electron-electron scattering contribution (which is linear in temperature) is now commonly accepted.

In assessing the different recommendations for the thermal conductivity of liquid sodium, the data tabulated by CINDAS[5] were examined to separate the thermal conductivity measurements from thermal conductivities calculated from electrical resistivity measurements via the Wiedemann-Franz law. Figure 2.1-3 gives a comparison of the thermal conductivity data from thermal conductivity measurements with recommendations by Cook and Fritsch (labeled Cook), CINDAS, and Bystrov et al. Data sets discussed in the CINDAS review[5] that were clearly outliers have not been included in the figure. The recommended equation of

Bystrov et al. gives values that are consistently high compared to the thermal conductivity measurements. Therefore, the equation by Bystrov et al. is not included in further comparisons.

Figure 2.1-4 shows the thermal conductivities from thermal conductivity measurements (labeled "thermal") and the thermal conductivities calculated from electrical resistivity measurements (labeled "E CINDAS") as tabulated by CINDAS. The values of thermal conductivity calculated by CINDAS from electrical resistivity measurements via the Wiedemann-Franz law are consistently high relative to thermal conductivity measurements. The quadratic fit of just the values from electrical conductivity measurements (labeled "quadratic fit") shows a systematic deviation from thermal conductivity measurements at similar temperatures. Comparison of deviations of this quadratic equation with the thermal conductivity measurements results in residuals which are positive for all but 12 of the 141 points. Fitting the combined set of data from thermal conductivity and electrical resistivity measurements results in the CINDAS recommendation being high relative to the thermal conductivity measurements.

Figure 2.1-5 shows the electrical resistivity data tabulated by CINDAS converted to thermal conductivity using Eq. (6), which is the method suggested by Cook and Fritsch. These data, labeled "Electrical" in Fig. 2.1-5, are consistent with the measured thermal conductivities.

Thus, the method given by Cook and Fritsch is recommended for determining the thermal conductivity of liquid sodium from the melting point to 1500 K.

Calculation — Calculation of the thermal conductivity from the electrical resistivity using the method suggested by Cook and Fritsch requires the electrical resistivity as a function of temperature, the absolute thermoelectric power for sodium as a function of temperature, and the contribution due to electron-electron scattering. The electrical resistivities required in Eq. (6) were calculated using the equation recommended by Cook and Fritsch. Cook and Fritsch assessed and fit the electrical resistivity data for sodium in the temperature range 371 to 1500 K. Their recommended equation for electrical resistivity in 10^{-8} Ωm is

$$
\begin{aligned}
\rho_e = &- 9.9141 + 8.2022 \times 10^{-2} T - 1.3215 \times 10^{-4} T^2 + 1.7212 \times 10^{-7} T^3 \\
&- 9.0265 \times 10^{-11} T^4 + 1.9553 \times 10^{-14} T^5 ,
\end{aligned}
\tag{7}
$$

where temperature is in kelvins. Electrical resistivities calculated with this equation are in good agreement with values recommended by CINDAS[18] and by Alekseev and Iakubov[19] as shown in

Fig. 2.1-6. Deviations between values from these three assessments are less than the 2% uncertainty of the experimental data quoted by Alekseev and Iakubov.

Calculation of the thermal conductivity from the electrical resistivity using Eq. (6) requires the thermoelectric power for sodium (S) for the second order correction to the Lorentz constant, L_0. Cook and Fritsch do not give an equation for the thermoelectric power for sodium but comment that experimental values disagree. Measurements of Seebeck coefficients in liquid sodium by Bressler and Anderson[20] show a linear increase in the absolute value from that at the melting point to -16 µV·K^{-1} at 700 K with a slight decrease in the absolute value to about -14.5 µV·K^{-1} at 873 K. Measurements by Bonilla et al.[21] indicate that the absolute value of the thermoelectric power continues to increase above 700 K. Cook and Fritsch assumed a linear increase in absolute value from the melting point to -16 µV·K^{-1} at 700 K and an increase in absolute value to -25 µV·K^{-1} at 1170 K, in accord with the experimental results given by Bonilla et al.

The thermoelectric potentials for sodium relative to platinum that are given by Bonilla et al. for the temperature range 400 to 1173 K have been fit using the method of least squares to the quadratic equation

$$E\ (Pt/Na)\ =\ 1016.53\ -\ 4.0791\,T\ +\ 4.658\ \times\ 10^{-3}\,T^{\,2}\ \ ,\qquad(8)$$

where the thermoelectric potential, E, is in µV and temperature, T, is in kelvins. The fit is shown in Fig. 2.1-7. The Seebeck coefficient of the thermoelectric power of sodium relative to platinum is the temperature derivative of the thermoelectric potential given by Bonilla et al. It is given in µV·K^{-1} by

$$-S(Na/Pt)\ =\ S(Pt/Na)\ =\ \frac{dE}{dT}\ =\ -4.0791\ +\ 9.316\ \times\ 10^{-3}\ T\ \ .\qquad(9)$$

The absolute thermoelectric power for sodium is equal to the sum of the thermoelectric power of sodium relative to platinum S(Na/Pt) and the absolute thermoelectric power of platinum. An equation for the absolute thermoelectric power for platinum was obtained by a linear least squares fit to the tabulated experimental values of the absolute thermoelectric power of platinum in the temperature range 400 to 1500 K given in Tables 4.2 and 4.3 of the New Series of Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology.[22] The equation obtained is

$$S(Pt) = -2.5809 - 0.01435\,T \quad , \tag{10}$$

where S is in $\mu V\cdot K^{-1}$ and T is in kelvins. Figure 2.1-8 shows graphs of the tabulated data in the temperature range 371 to 1500 K, the linear fit to these data, and three equations for the absolute thermoelectric power of platinum given in the Landolt-Bornstein handbook (labeled Eq. 31, 32, and 33 in the figure). These three equations fit individual sets of the tabulated experimental data. The linear fit obtained in this analysis is very close to Eq. (33) given in the Landolt-Bornstein handbook.

The absolute thermoelectric power for sodium was obtained by adding the thermoelectric power for sodium relative to platinum S(Na/Pt), the negative of the value given in Eq. (9), to the absolute thermoelectric power for platinum, given in Eq. (10). The equation obtained for the absolute thermoelectric power for sodium is

$$S(Na) = 1.4982 - 0.02367\,T \tag{11}$$

for $S(Na)$ in $\mu V\cdot K^{-1}$ and T in kelvins. The negative of the thermoelectric power for sodium is shown in Fig. 2.1-9, along with the values given by Cook and Fritsch, the negative of the thermoelectric power for platinum, and the thermoelectric power of sodium relative to platinum obtained from differentiation of the thermoelectric potential given by Bonilla et al.

Calculation of the thermal conductivity of sodium using Eq. (6) requires the thermal resistivity due to electron-electron scattering (W_{ee}). Because no additional data are available since the analysis by Cook and Fritsch, their recommended equation, Eq. (5), has been used to calculate this contribution from the melting point to 1500 K.

Values of the thermal conductivity for sodium were calculated from 371 to 1500 K using Eq. (6) and Eqs. (3, 5, 7, 11) for the parameters given in Eq. (6). Results of this calculation as a function of temperature are shown in Figs. 2.1-4 and 2.1-5 with the label "Calculation." Results are in excellent agreement with those tabulated by Cook and Fritsch. In accord with Cook and Fritsch, calculations of thermal conductivity from resistivity using Eq. (6) have been made only to 1500 K because at higher temperature, (1) higher order terms in the Lorentz function than the L_0 and S^2 terms may be necessary and (2) the value of B may differ from the value for the solid.

To extrapolate thermal conductivity to the critical temperature, the method suggested by Grosse[7] that was used by Fink and Leibowitz[7] to extrapolate the CINDAS values[5] was examined. It was not used because it is based on the Wiedemann-Franz law and extrapolation of the electrical resistivity. It has no means to include the electron-electron scattering contribution which increases linearly with temperature and becomes more pronounced at high temperatures. In addition, it includes no higher order corrections to the Lorentz function.

Recommended Equation for Entire Temperature Range — To obtain a simple expression for the thermal conductivity and to estimate values at higher temperatures, the calculated values in the temperature range 371 to 1500 K were fit by a least squares method to a cubic polynomial constrained at the critical point to give a value in accord with the thermal conductivity of the vapor. The value used for the thermal conductivity of sodium vapor at the critical temperature is from extrapolation of the values for the thermal conductivity of sodium vapor recommended by Vargaftik and Yargin.[2] Vargaftik and Yargin have analyzed experi-mental data and calculations of viscosity and thermal conductivity of alkali metal vapors. From their analyses and calculations, they recommended values for the thermal conductivity of sodium vapor along the saturation curve from 700 to 1500 K. In this temperature range, the sodium vapor thermal conductivity increases from 0.032 to 0.050 $W \cdot m^{-1} \cdot K^{-1}$, as shown in Fig. 2.1-10. These recommended values were extrapolated to 0.052 $W \cdot m^{-1} \cdot K^{-1}$ at the critical temperature, 2503.7 K. At the critical point, the thermal conductivity of the vapor and liquid become identical. Thus, the fit to the calculated values of the thermal conductivity of liquid sodium was constrained to be 0.052 $W \cdot m^{-1} \cdot K^{-1}$ at the critical temperature, 2503.7 K. The resulting equation is Eq. (1), the recommended equation. It is shown in Fig. 2.1-11 along with the thermal conductivity of the vapor from 700 to 1500 K, the calculated thermal conductivities of liquid sodium from 371 to 1500 K, and the value of the thermal conductivity at the critical temperature. Deviations of this equation from the calculated values are within ±3%.

In Fig. 2.1-12, values calculated with the recommended equation, Eq. (1), are compared with values from other assessments and calculated values. The recommended values show good agreement with the values calculated from Eq. (6) and with values tabulated by Cook and Fritsch. Values tabulated by Cook and Fritsch are within ±2% of the values from Eq. (1). Recommended values for temperatures from 1500 K to the critical temperature are consistent with values

recommended by Bystrov et al. At 2500 K, the recommended value (0.3 W·m·1·K^{-1}) is lower the value of Bystrov et al. (1.8 W·m^{-1}·K^{-1}) and significantly lower than the values near 6 W·m^{-1}·K^{-1} given by the extrapolation of the CINDAS values by Fink and Leibowitz (labeled "Fink & Leibowitz Extrap." in the figure), and the approximating polynomial given by Fink and Leibowitz. Deviations of the calculated values and values from other assessments from the recommended equation are shown in Fig. 2.1-13. The plotted deviations, expressed as a percent are defined by

$$Deviations = \frac{\left[k(Other) - k(Recommended)\right] \ 100\%}{k(Recommended)} \ . \tag{12}$$

From the melting point to 2200 K, largest deviations are found with respect to values given in the assessment by Bystrov et al.; they differ by ±13%. Large percent deviations are calculated near the critical point because the recommended equation approaches a lower value at 2503.7 K than do other calculations.   The Fink and Leibowitz calculations are based on a higher critical temperature, 2509.4 K.

Uncertainty

The uncertainty in the recommended values have been estimated from the uncertainty in the electrical resistivity (2%), and the uncertainty in the thermal conductivities given by CINDAS (5 to 15%), and the deviations of values from different assessments, shown above. From the melting point to 700 K the uncertainty is estimated as 5%. Above 700 K, the uncertainty increases to 12% at 1100 K and to 15% at 1500 K. The uncertainties are assumed to increase linearly with temperature. Between 700 and 1100 K, the uncertainty is approxi-mated by the linear equation

$$\frac{\delta k}{k}(\%) = -7.25 + 0.0175\,T \tag{13}$$
$$for \ 700 \ K \leq T \leq 1100 \ K \ .$$

Between 1100 and 1500 K, the uncertainty is approximated by

$$\frac{\delta k}{k}(\%) = 3.75 + 0.0075\,T \tag{13}$$

$$for\ 1100\ K \le T \le 1500\ K\ .$$

Above 1500 K, uncertainties are estimated as 15%. Uncertainties are shown as dotted lines in Fig. 2.1-1 and are given in Table 2.1-2.

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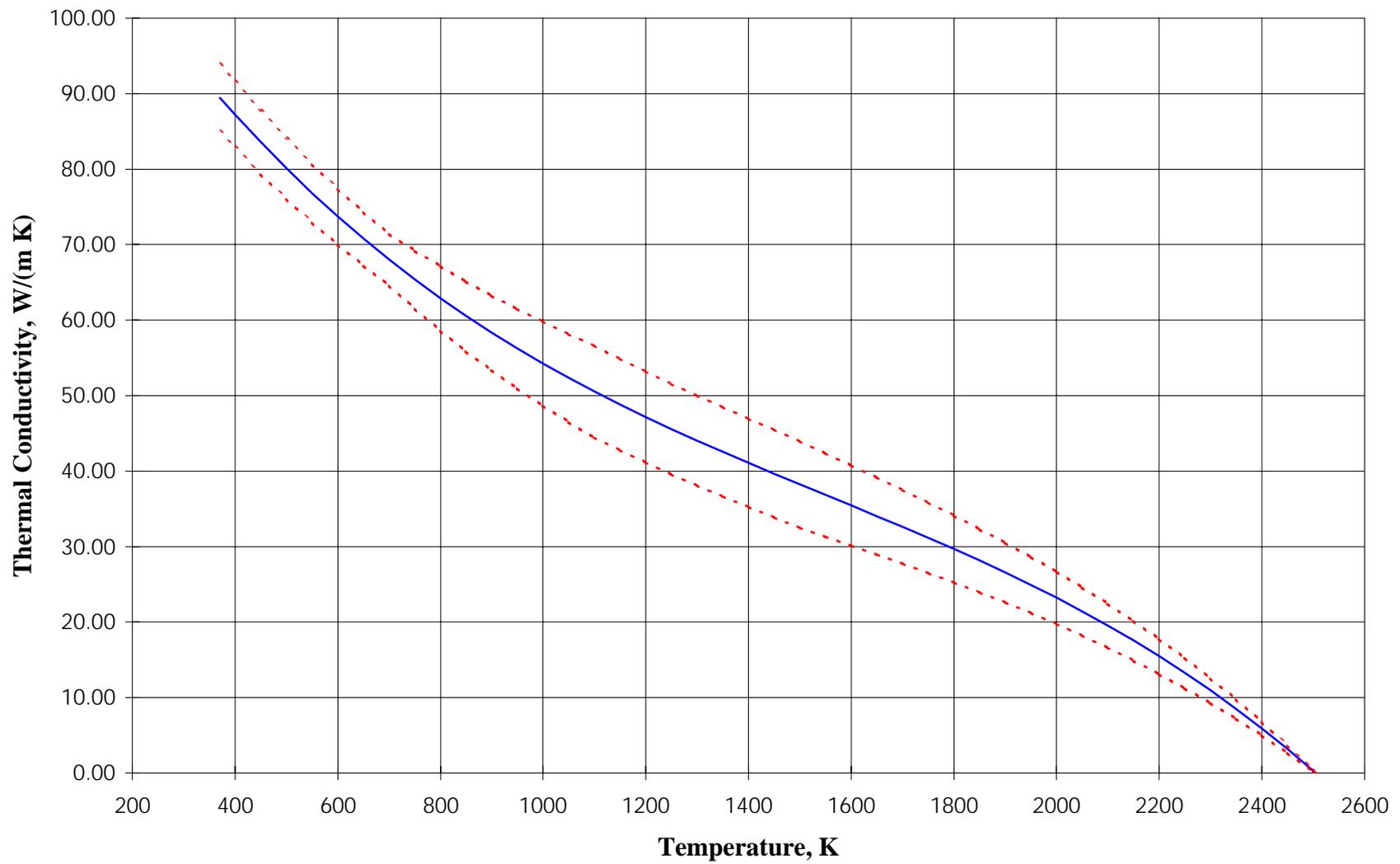
Fig. 2.1-1 Thermal Conductivity of Liquid Sodium
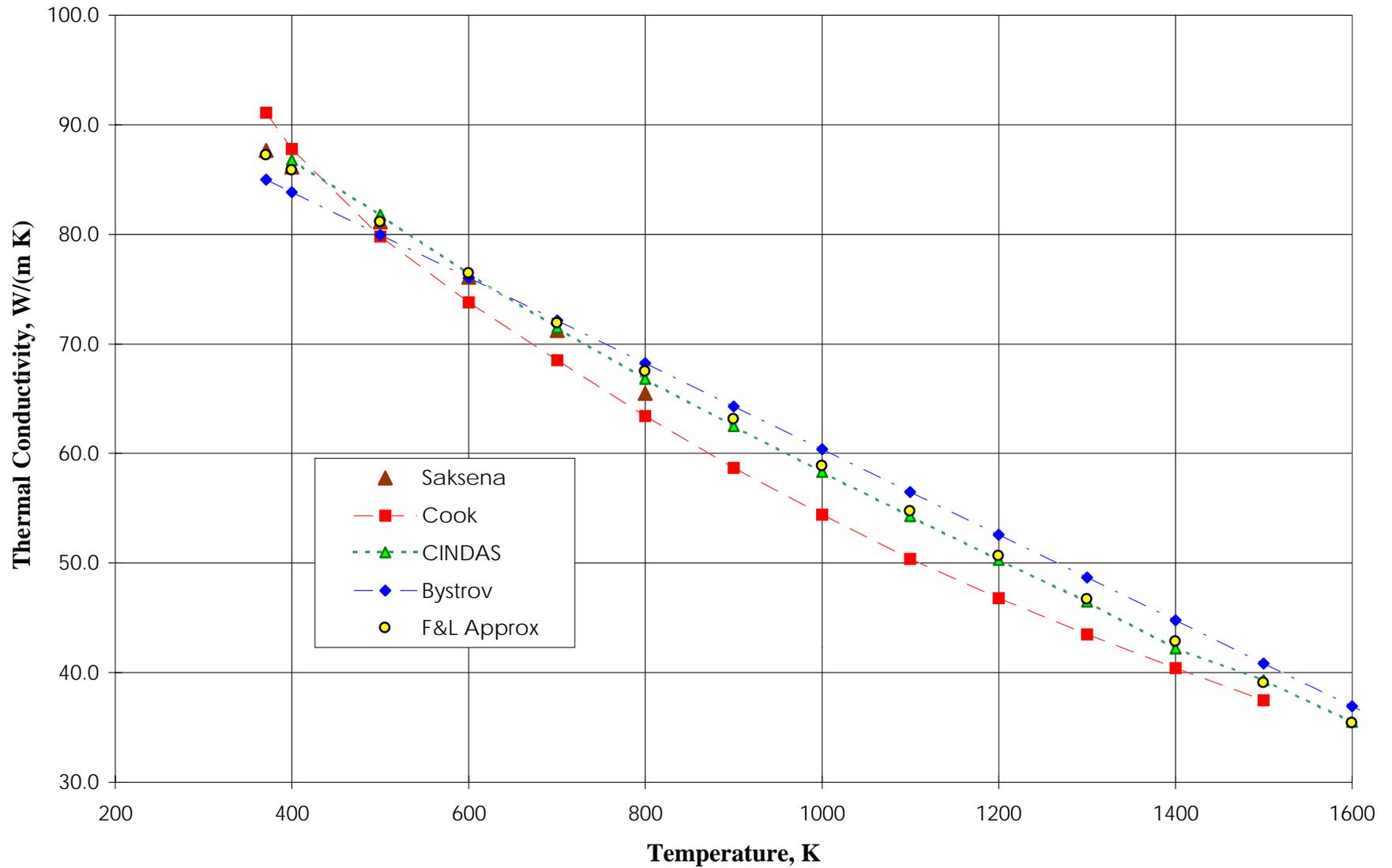
Fig. 2.1-2 Recommended Values for the Thermal Conductivity of Liquid Sodium from Five Assessments
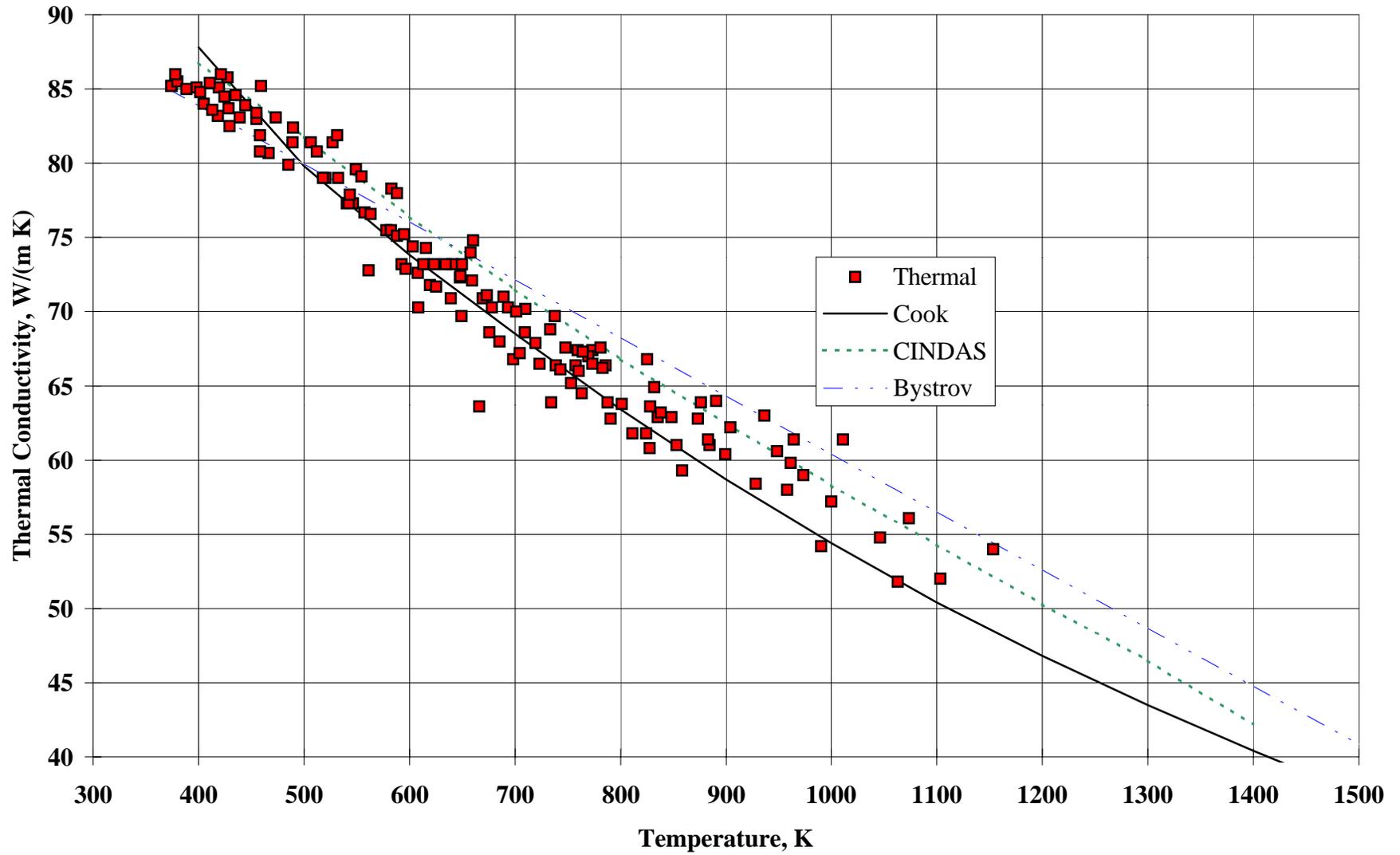
Fig. 2.1-3 Comparison of Data from Thermal Conductivity Measurements with Values from Cook and Fritsch, CINDAS, and Bystrov
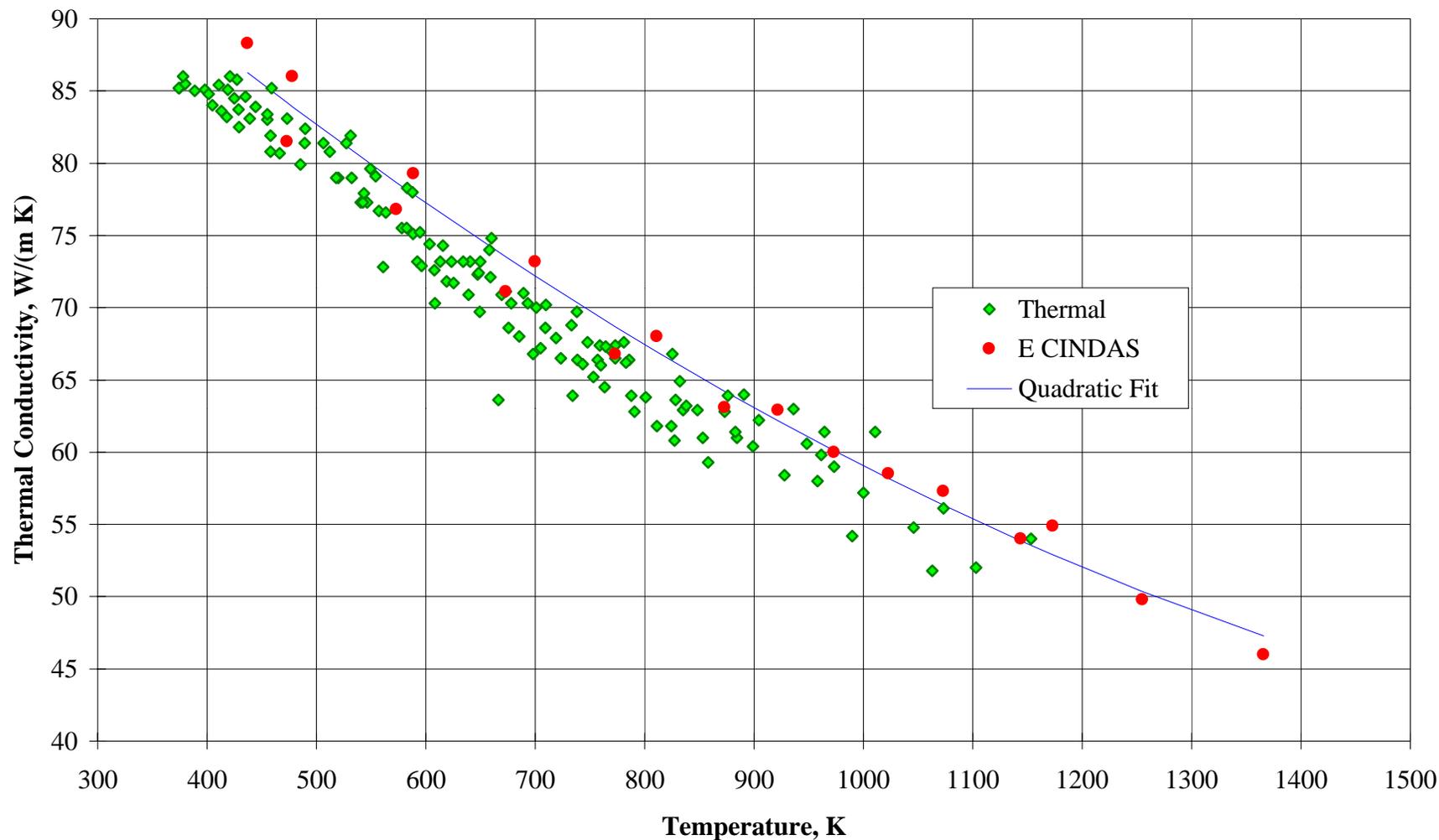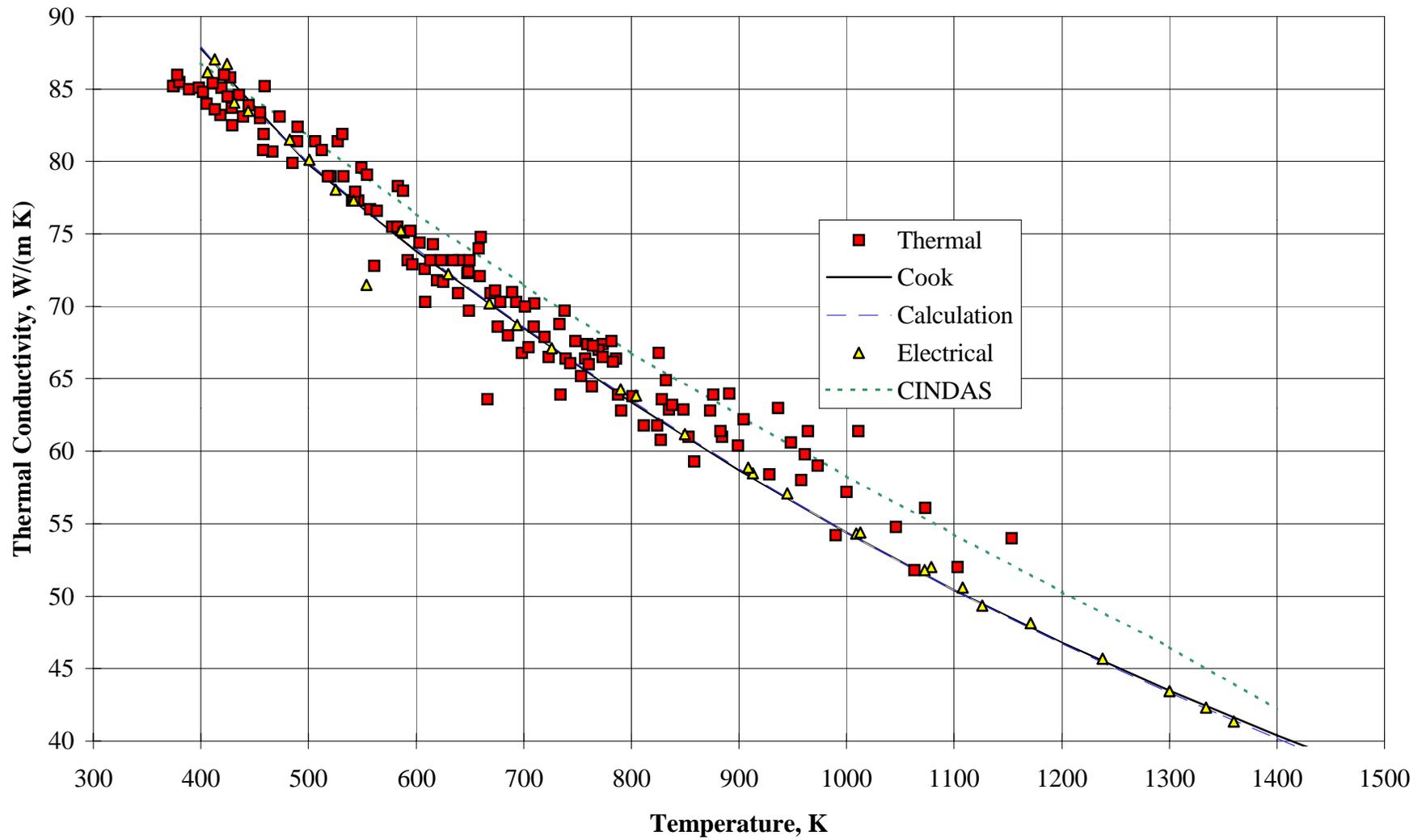
Fig. 2.1-4 Comparison of Data from Thermal Conductivity Measurments and Resistivity Data converted to Conductivity by CINDAS with Values from Quadratic Fit to Electrical Resistivities Converted to Thermal Conductivity by CINDAS

Fig 2.1-5 Comparison of Data from Thermal Conductivity Measurements and Resistivity Data Converted to Conductivity using Eq.(6) with Values from Cook and Fritsch, CINDAS, and the Calculation in this Assessment
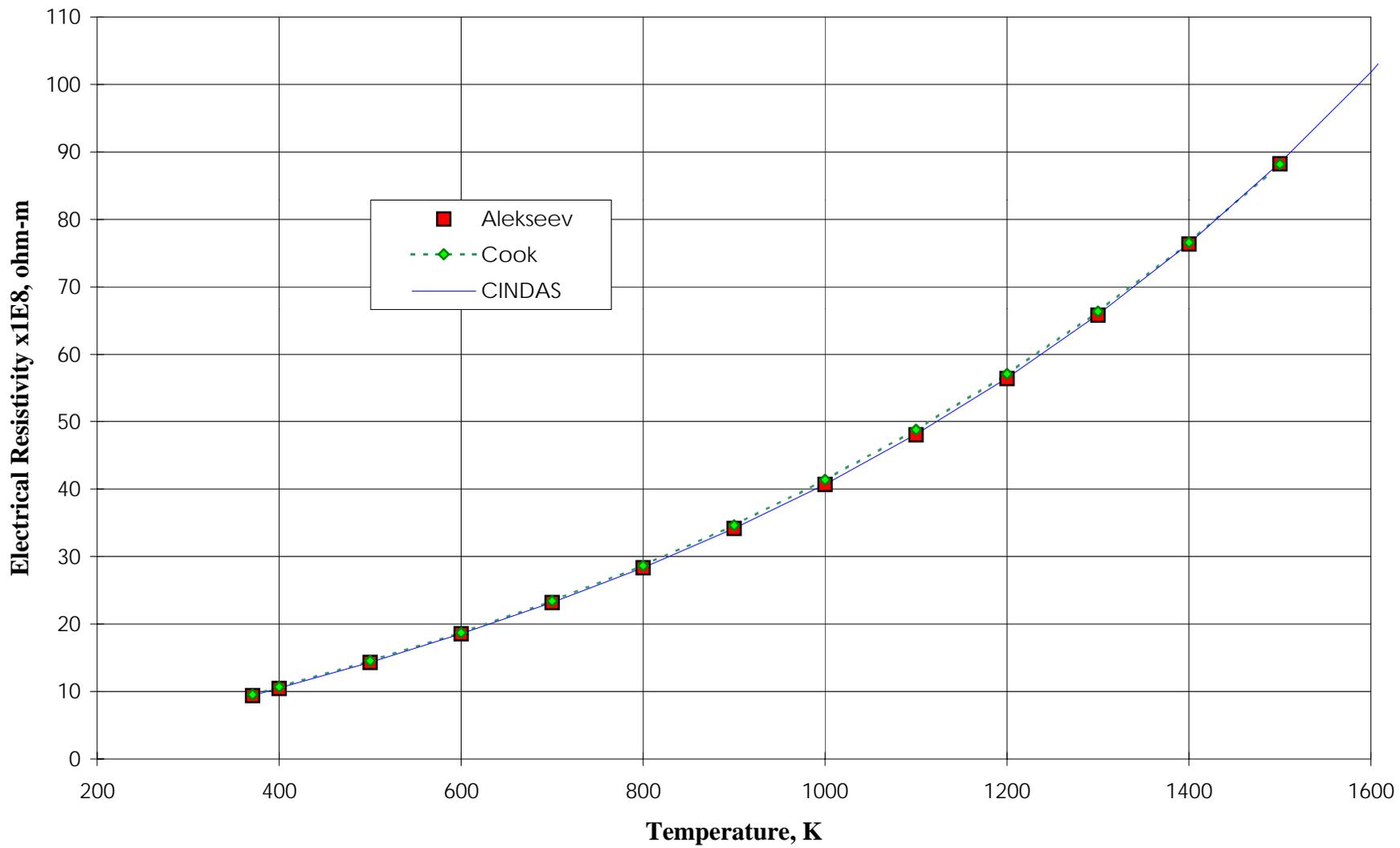
Fig. 2.1-6 Comparison of Values for the Electrical Resistivity from Cook and Fritsch, CINDAS, and Alekseev and Iakubov
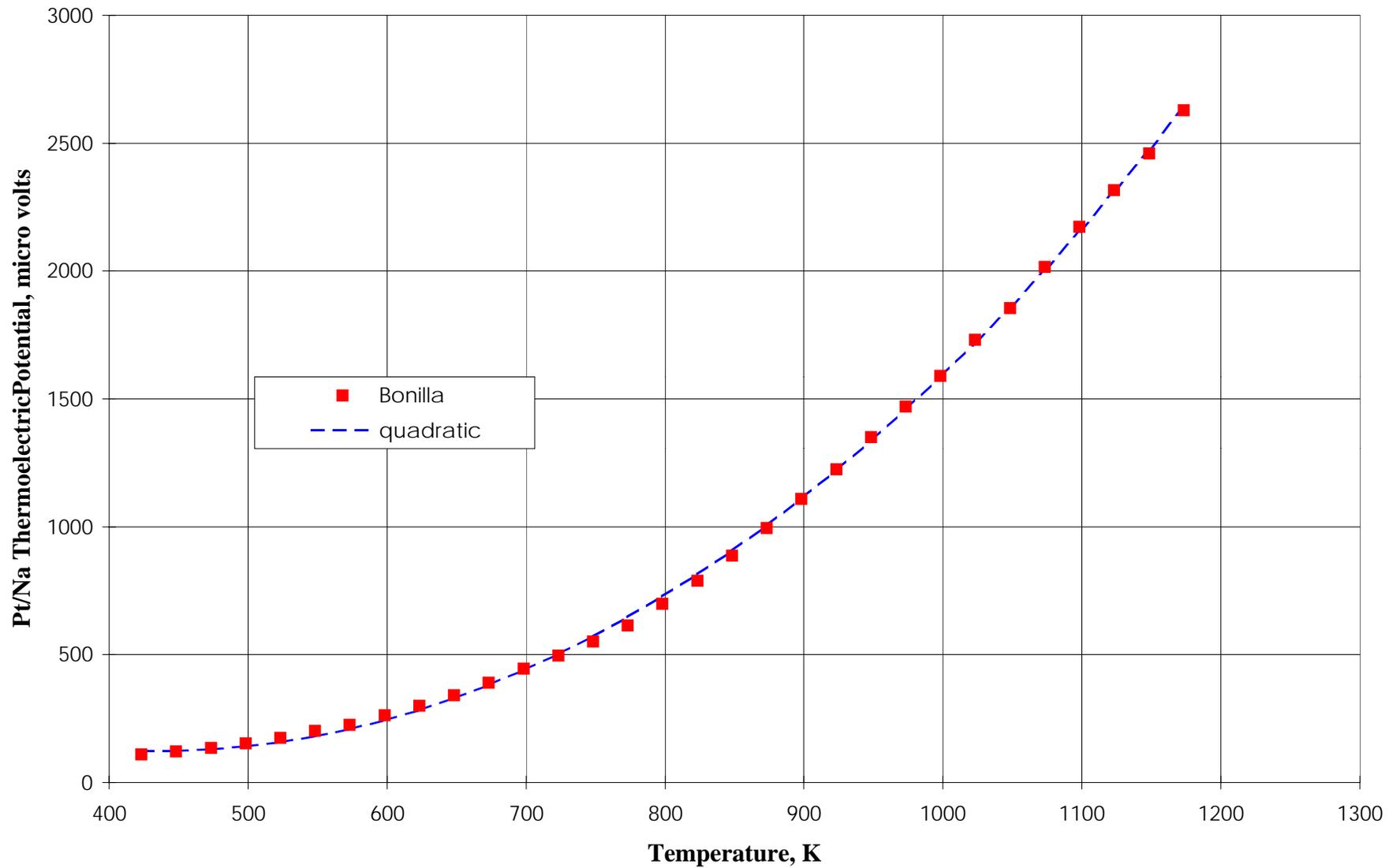
Fig 2.1-7 Quadratic Least Squares Fit to the Thermoelectric Potential of Pt Relative to Na given by Bonilla et al.
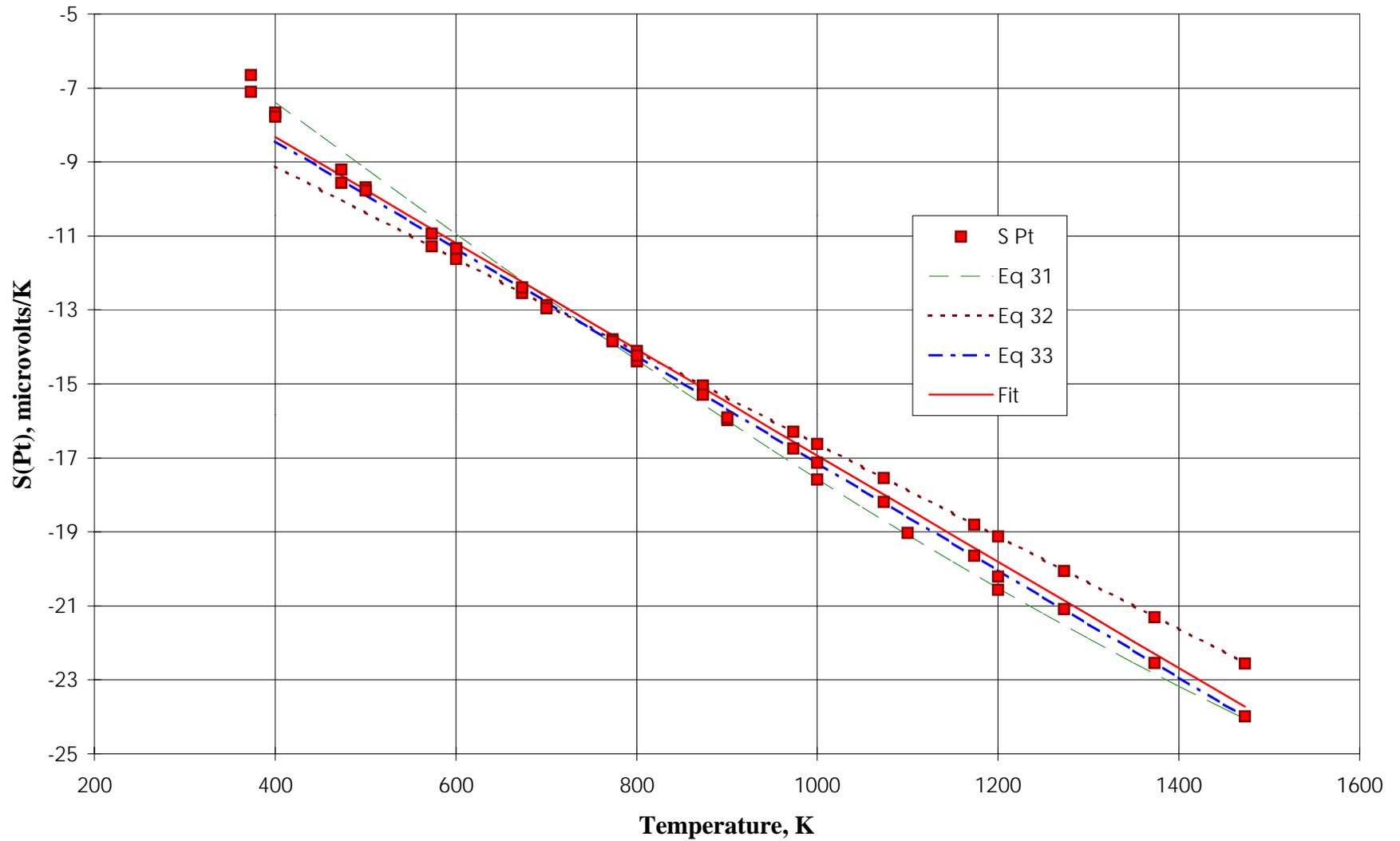
**Fig. 2.1-8 Linear Fit to the Absolute Thermoelectric Power of Pt.
Equations from Experiments are Included for Comparison**
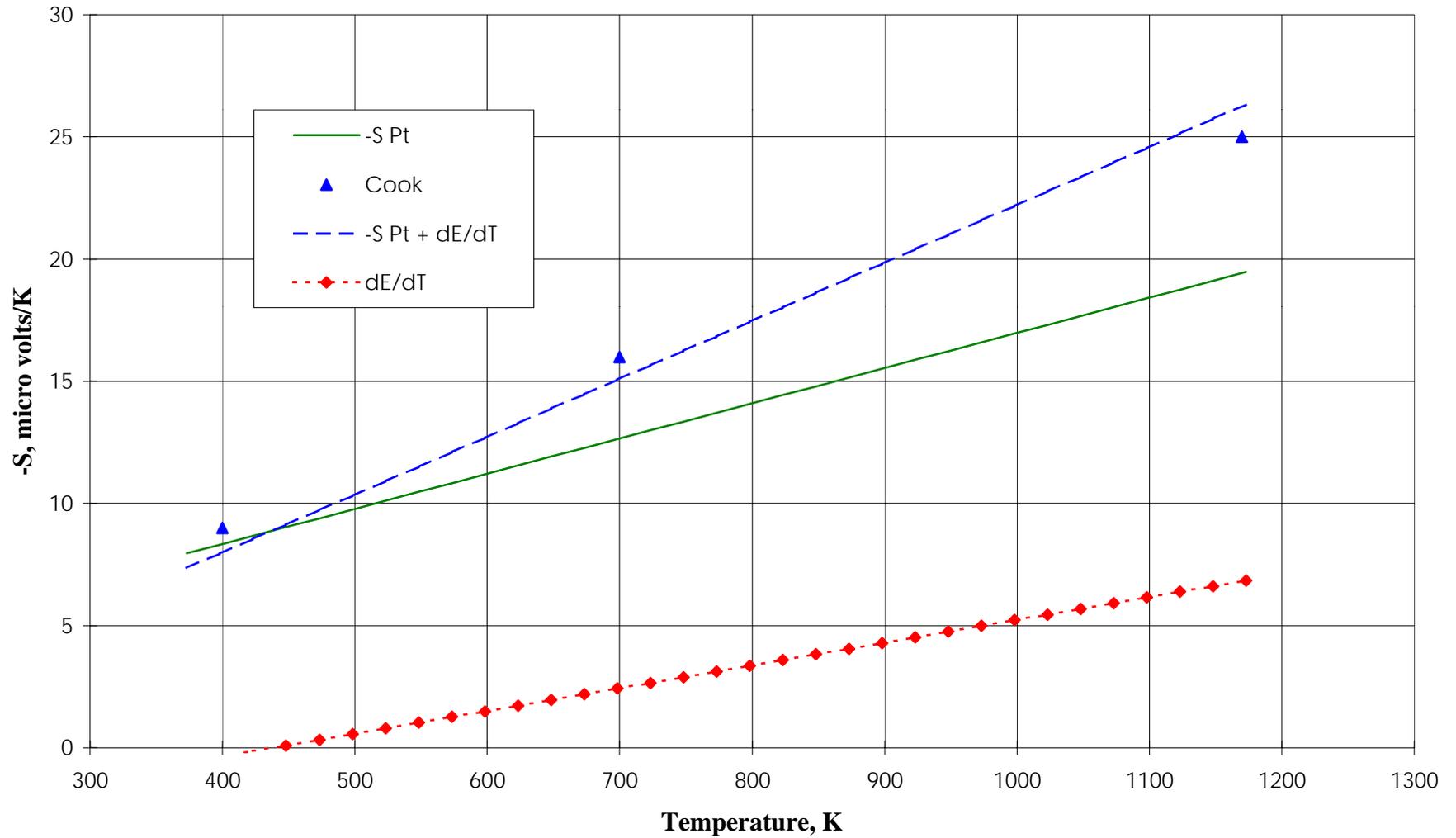
Fig. 2.1-9 The Negative of the Absolute Thermoelectric Power for Na and for Pt and Values given by Cook and Fritsch for Na. The Thermoelectric Power of Pt Relative to Na (dE/dT) is Included.
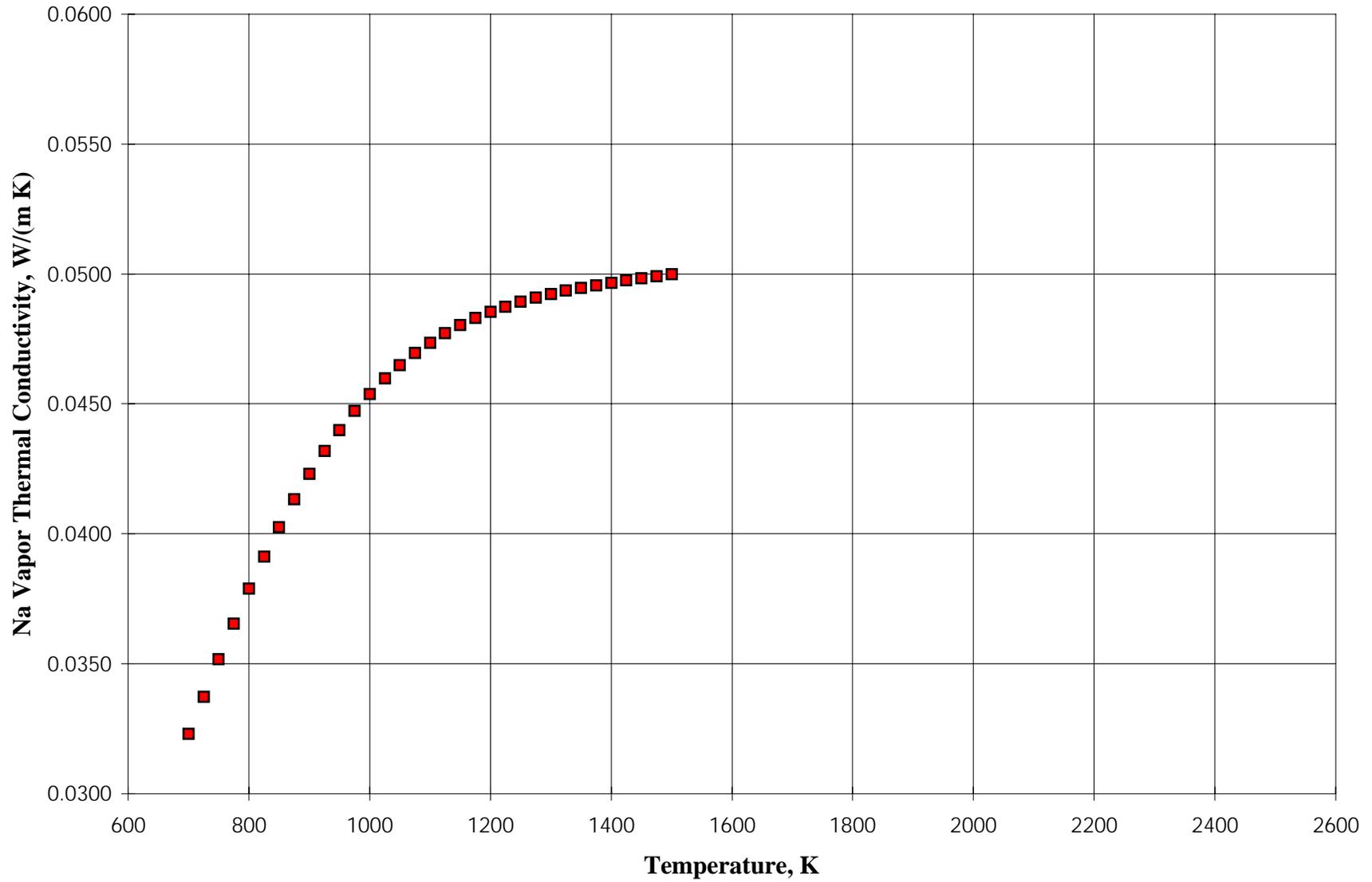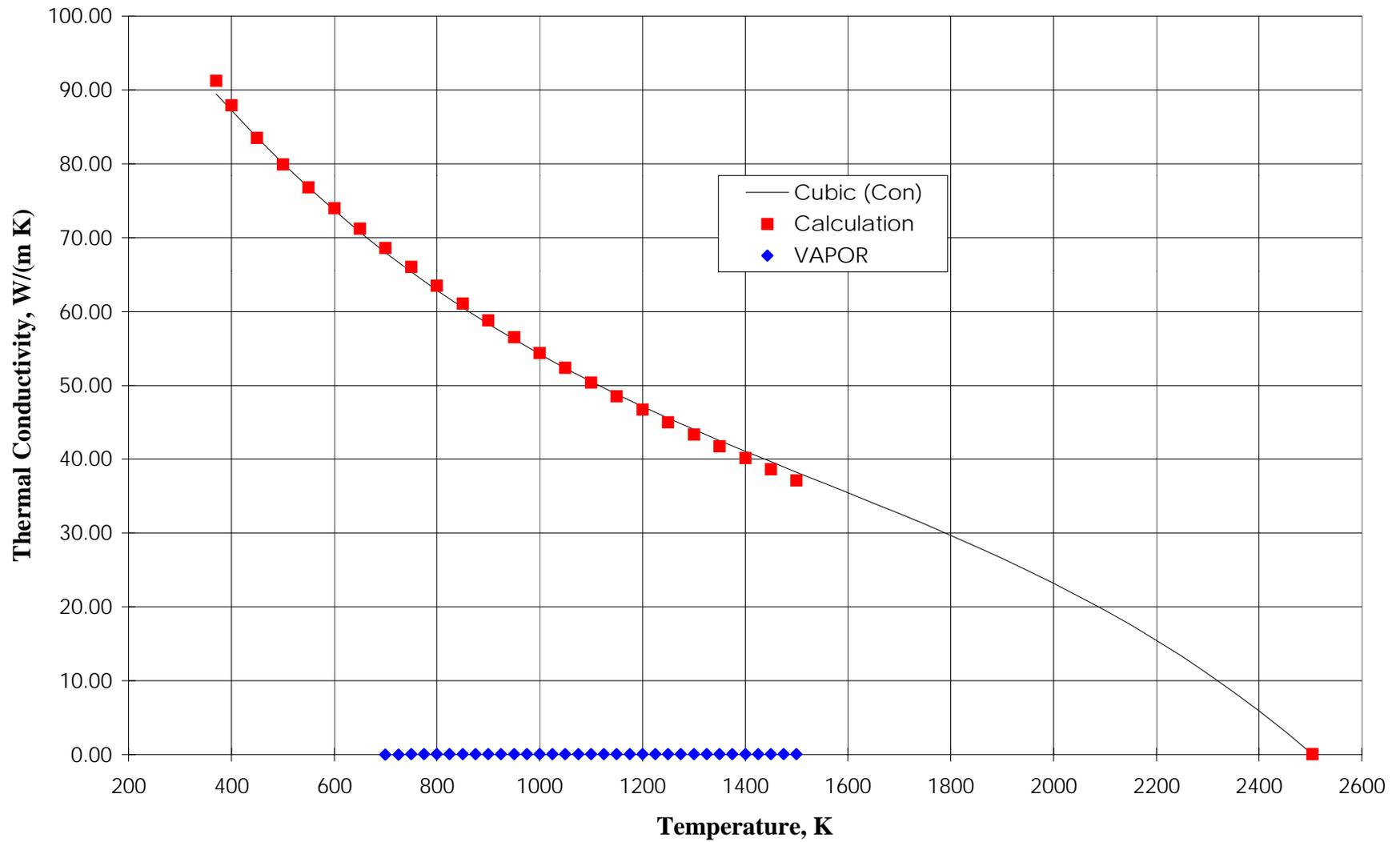
Fig. 2.1-10 Thermal Conductivity of Sodium Vapor

Fig. 2.1-11 Constrained Cubic Fit to Calculated Values of the Thermal Conductivity of Liquid Sodium, Calculated Values, and Vapor Thermal Conductivities
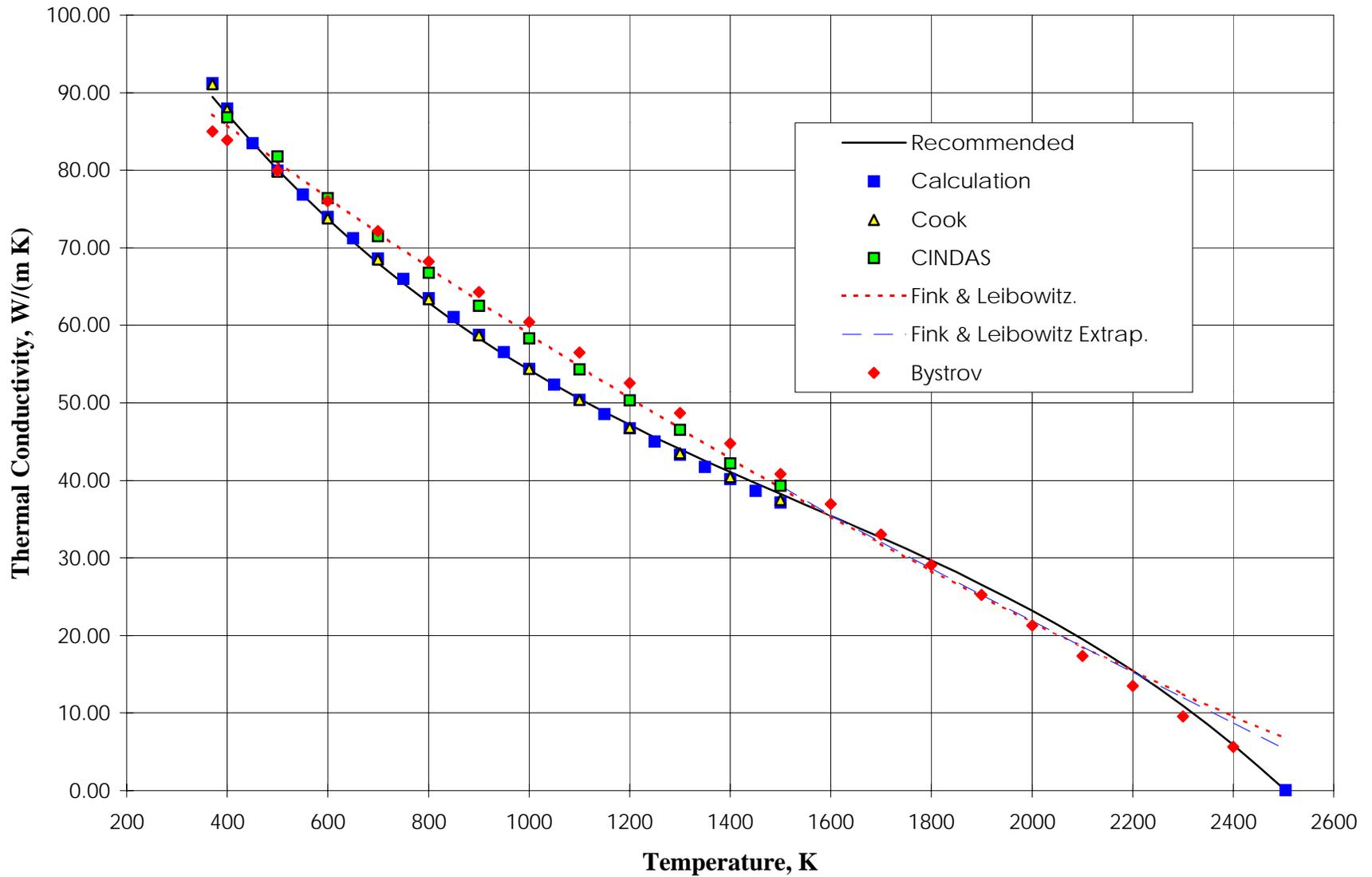
Fig. 2.1-12 Comparison of Recommended Values for the Thermal Conductivity of Sodium with Calculated Values from Other Assessments
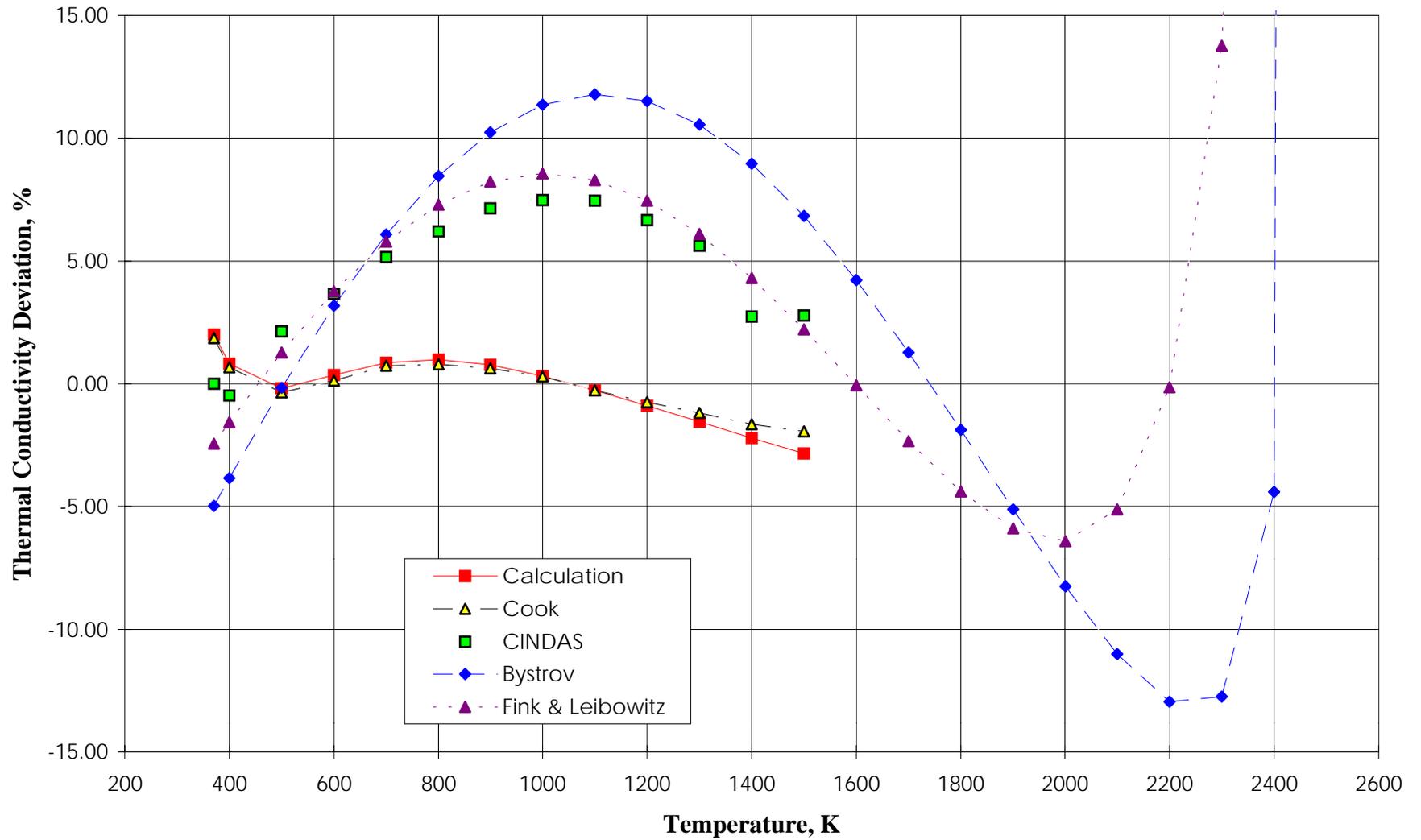
Fig. 2.1-13 Deviations of Values from Other assessments from Recommended Values of the Thermal Conductivity of Liquid Sodium